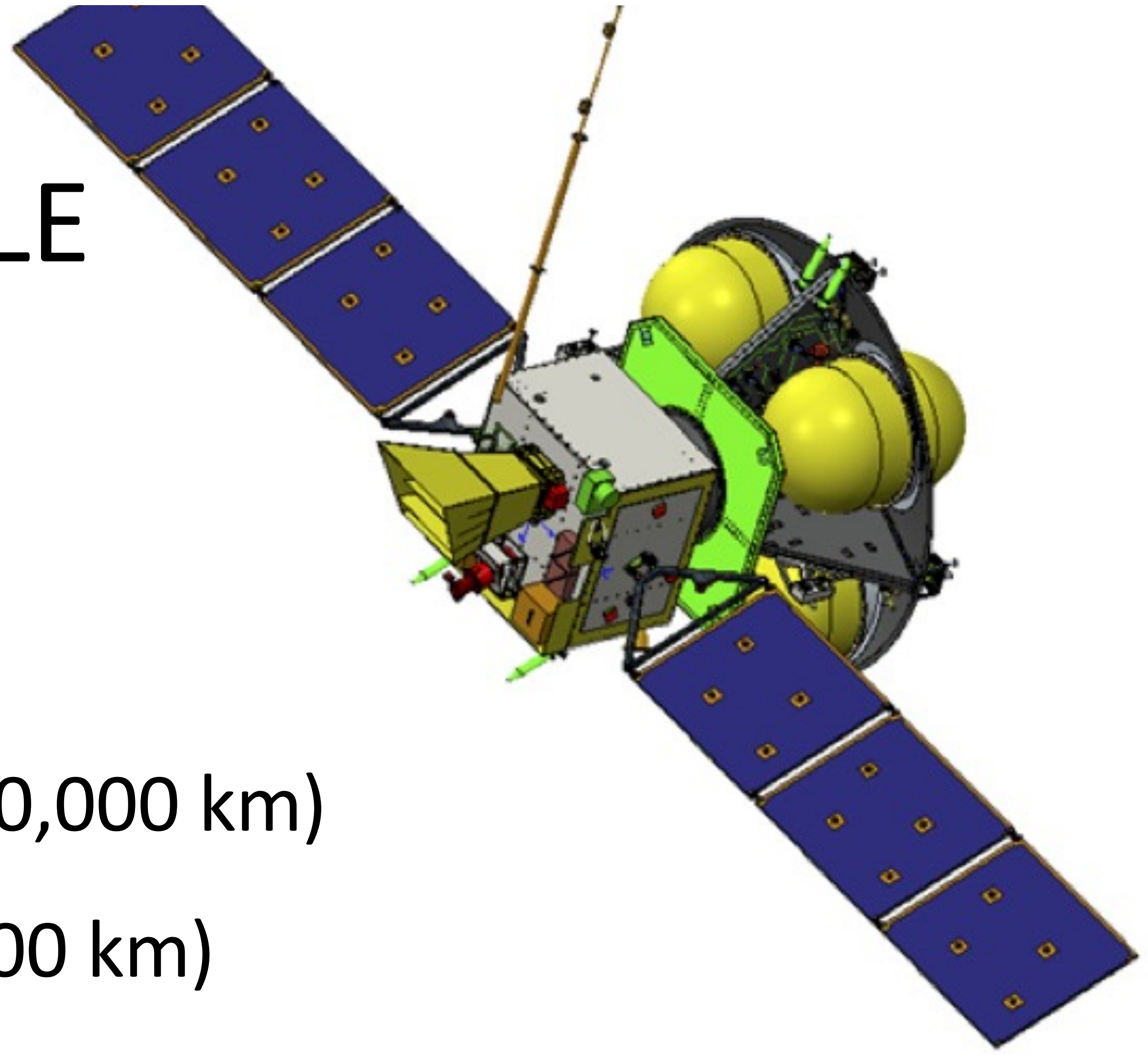
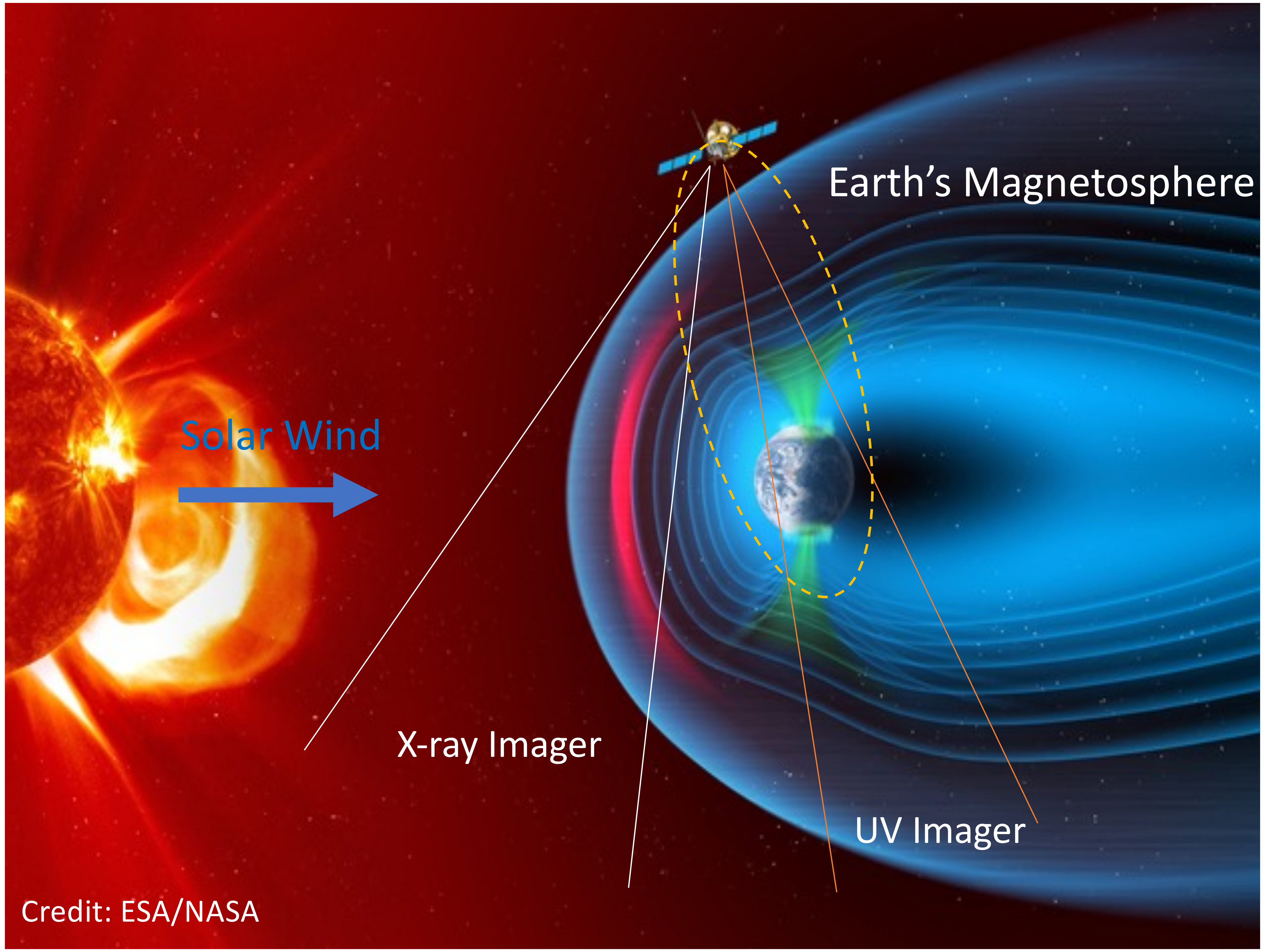
The SMILE-Soft X-ray Imager Charge Distortion Model

Claudio Pagani and the Uni. Leicester SXI Ground Segment team, IACHEC Spring Virtual Workshop, 25/5/2022

Solar wind Magnetosphere Ionosphere Link Explorer: SMILE



SMILE is a collaborative science mission between the
European Space Agency (ESA) and the Chinese Academy of Sciences (CAS)



Orbit:

Apogee ~ 19 RE (~120,000 km)

Perigee ~ 1 RE (~6, 000 km)

Inclination: ~73°

Period: ~51 hours

Launch: March 2025

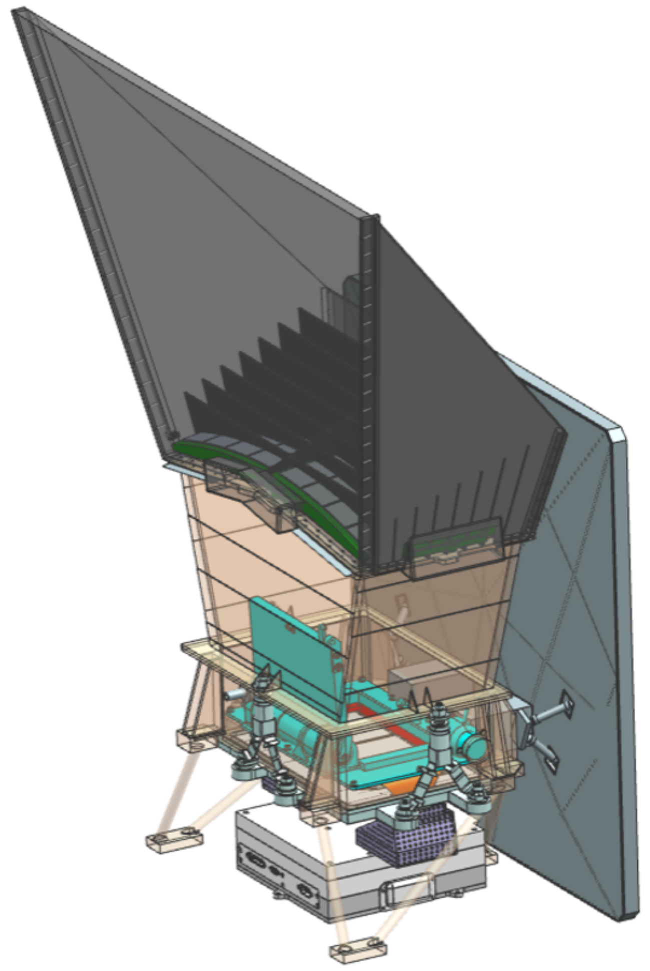
Launcher: Vega-C

Nominal Mission Length = 3 Years

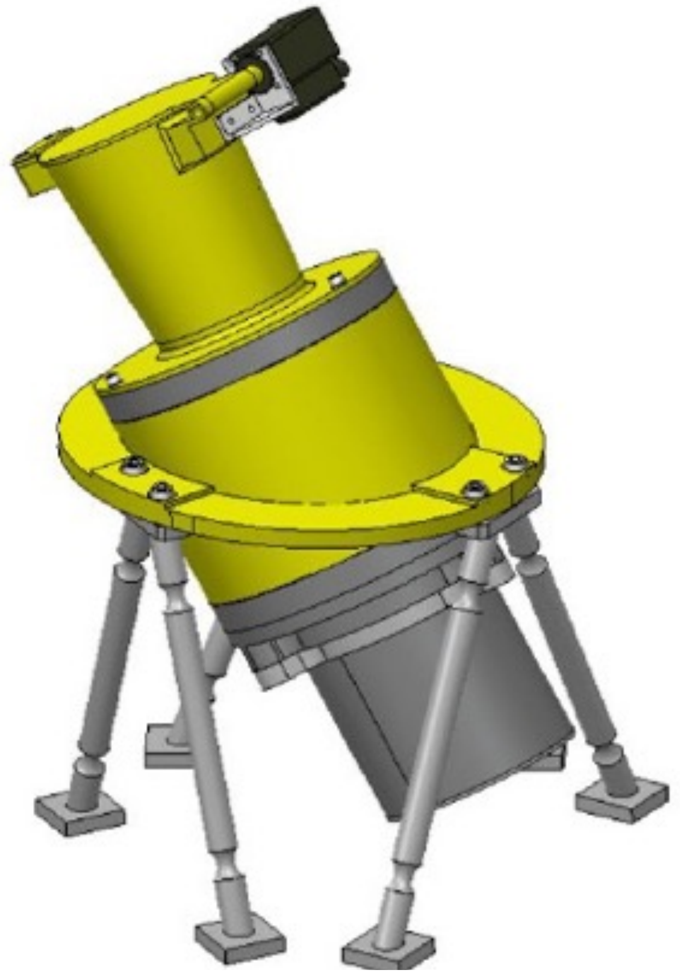
Maximum Mission Length ~ 7 Years

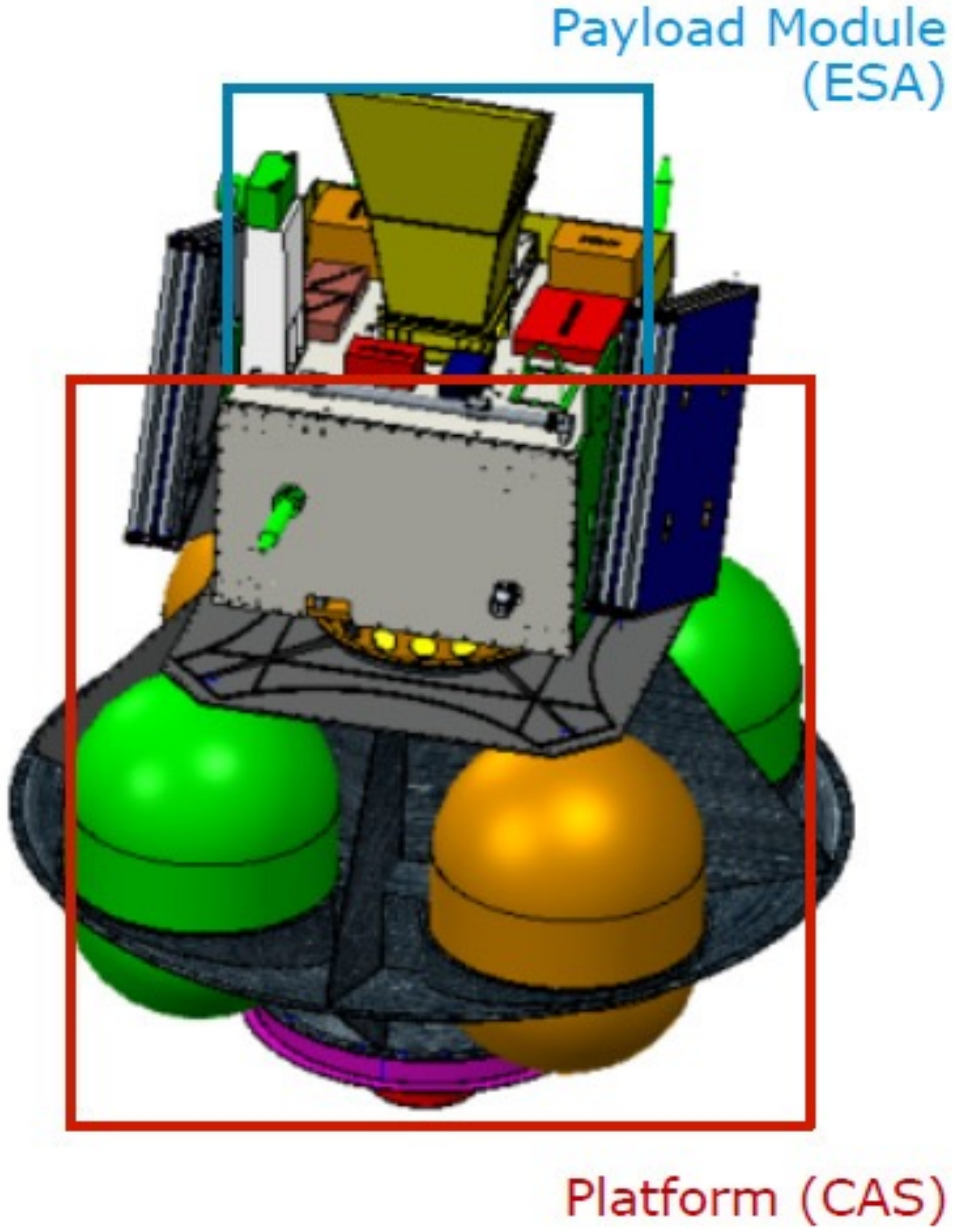
SMILE Instruments and Spacecraft

Soft X-ray Imager (SXI)
PI: Steve Sembay (Uni. Leicester, UK)

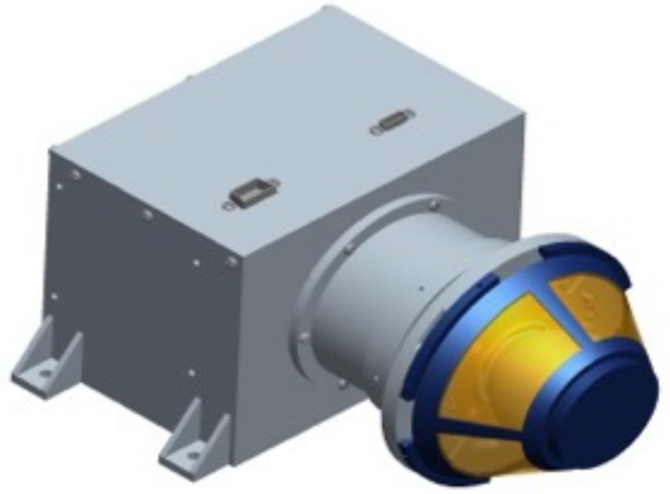


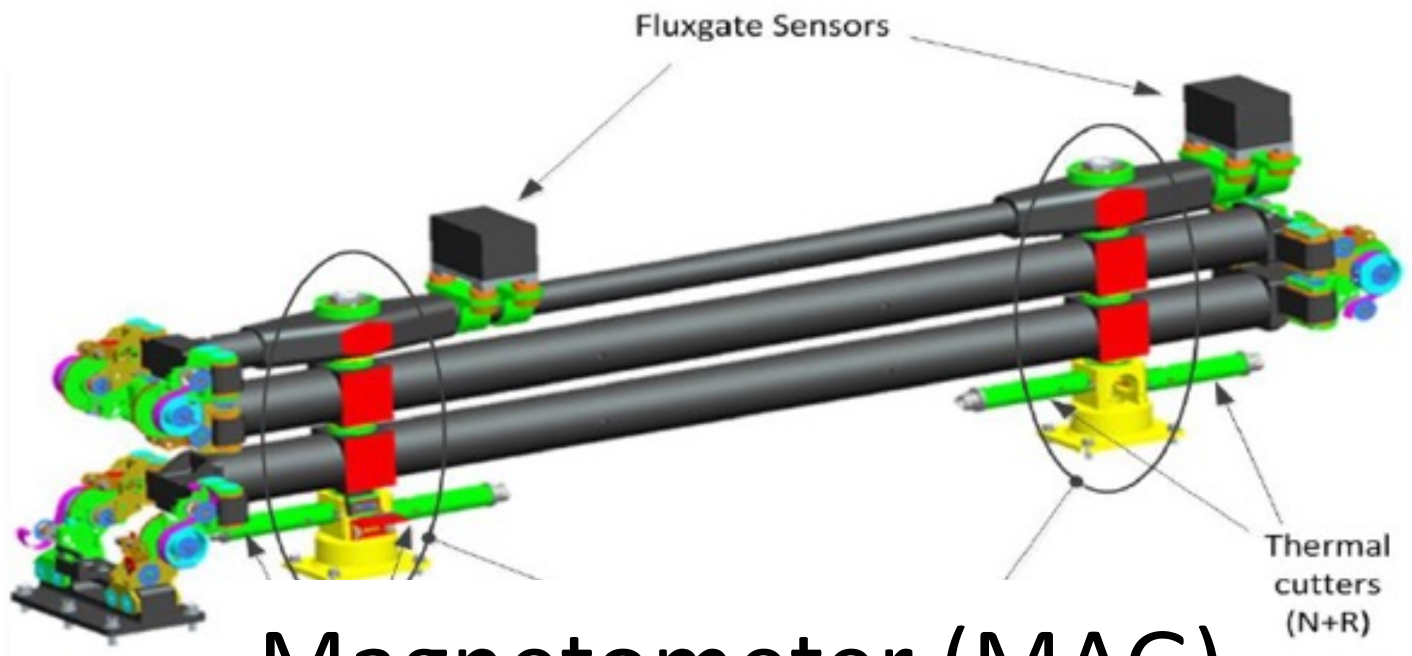
Ultraviolet Imager (UVI)
PI: X. Zhang (NSSC, China)





Light Ion Analyser (LIA)
PI: Lei Dai (NSSC, China)





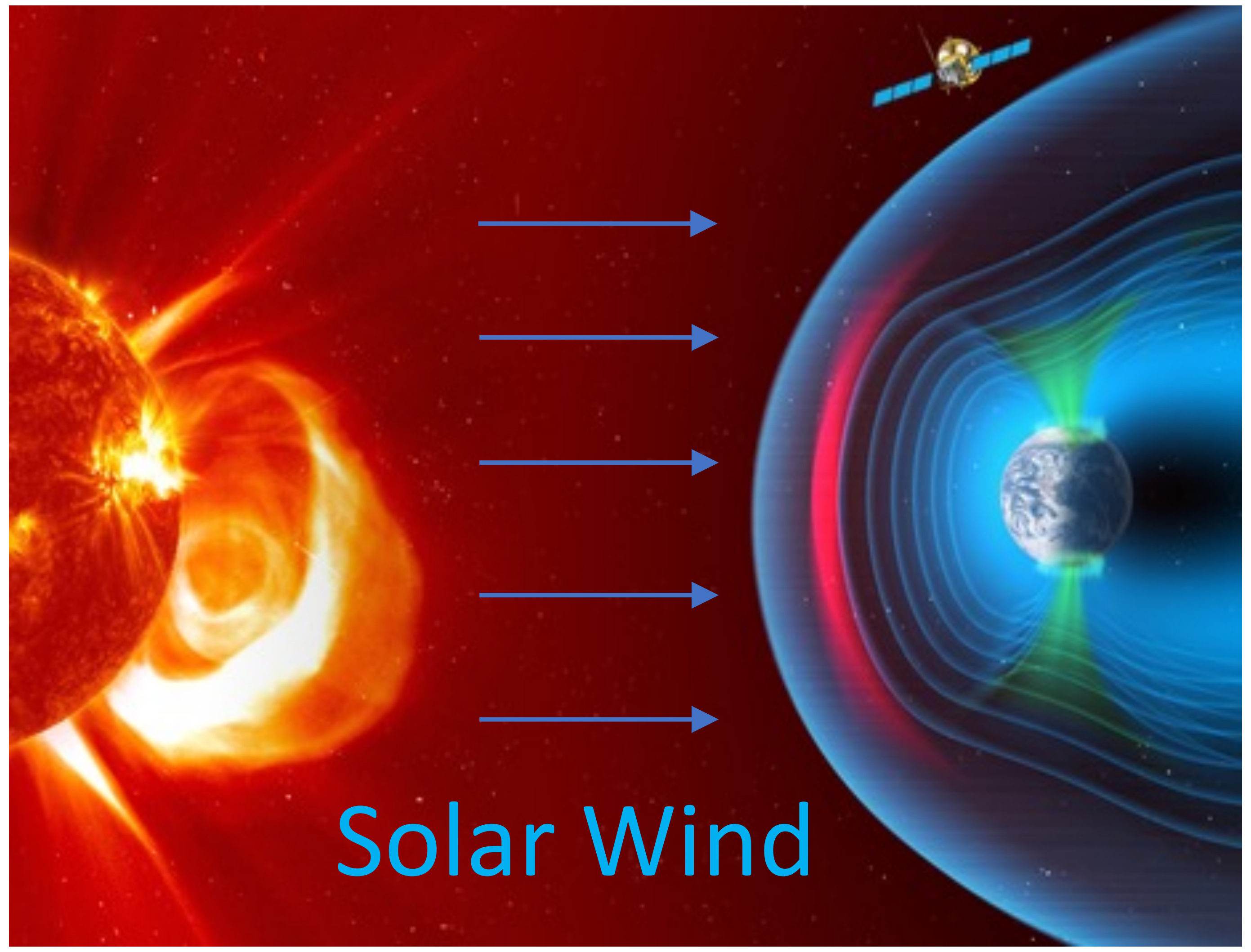
Magnetometer (MAG)
PI: Lei Li (NSSC, China)

Launched by ESA on Vega-C

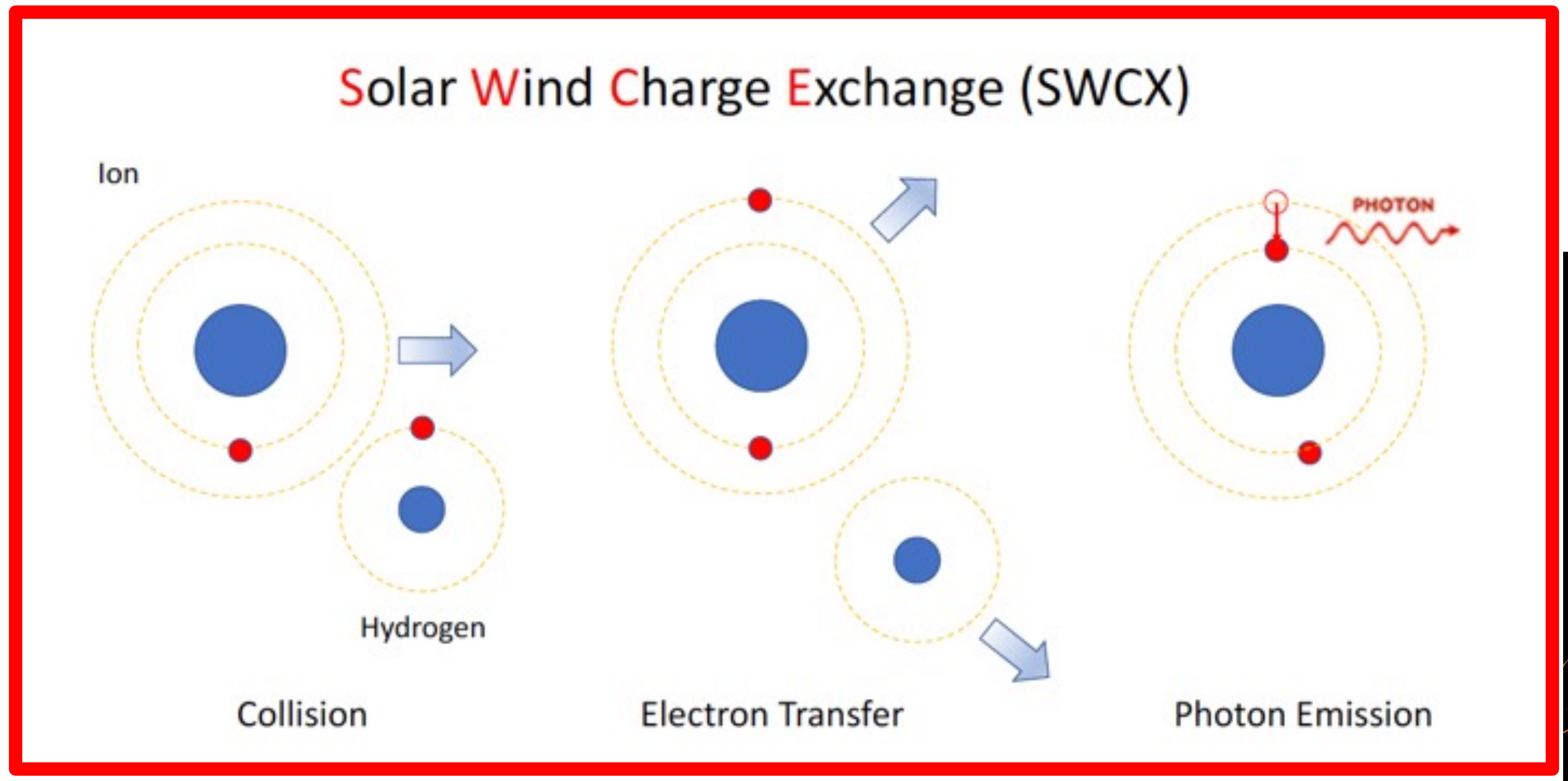
NSSC: National Space Sciences Centre, Beijing (http://english.nssc.cas.cn)

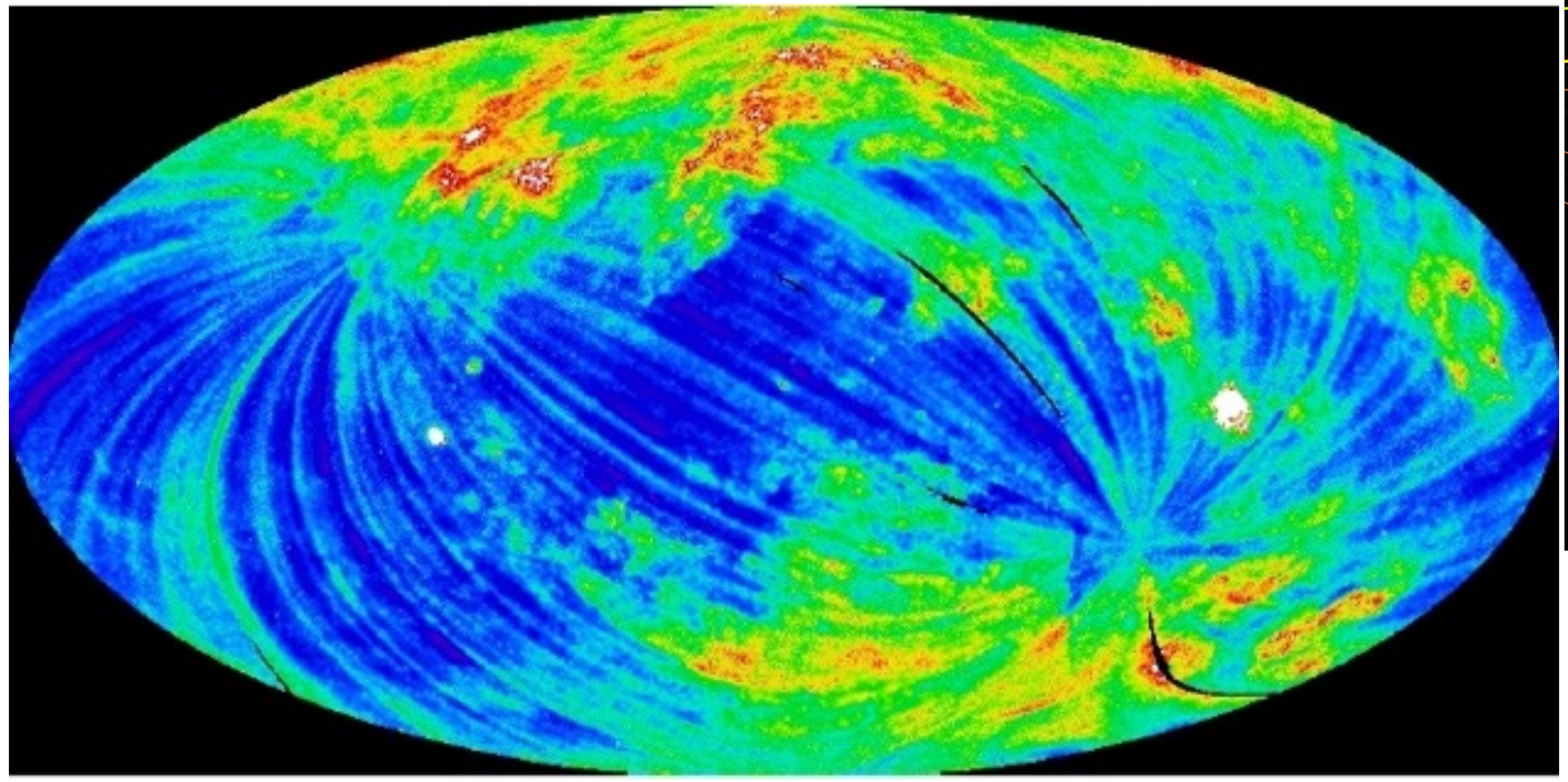
Global imaging using Solar Wind Charge Exchange (SWCX)

SWCX: High charge state solar wind ions in collision with hydrogen in the Earth's exosphere to produce photons at X-ray energies



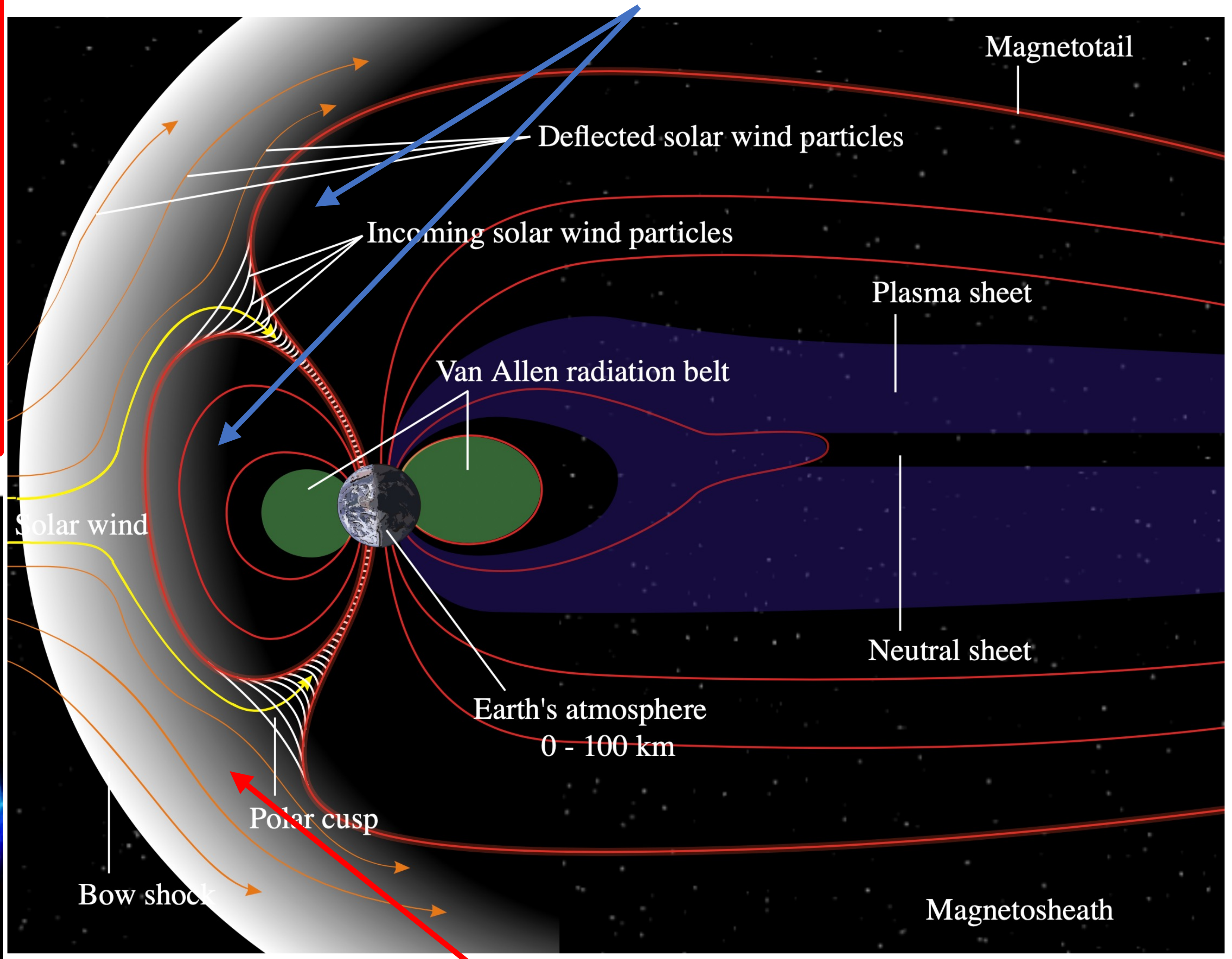
Solar Wind: electrons & protons with some (~2%) heavy ions such as carbon, nitrogen and oxygen embedded in the Sun's magnetic field





ROSAT All-Sky Survey in 1990 (Scanning observations)
SWCX Can be brighter than X-ray background

No Solar Wind in these regions therefore no SWCX X-rays

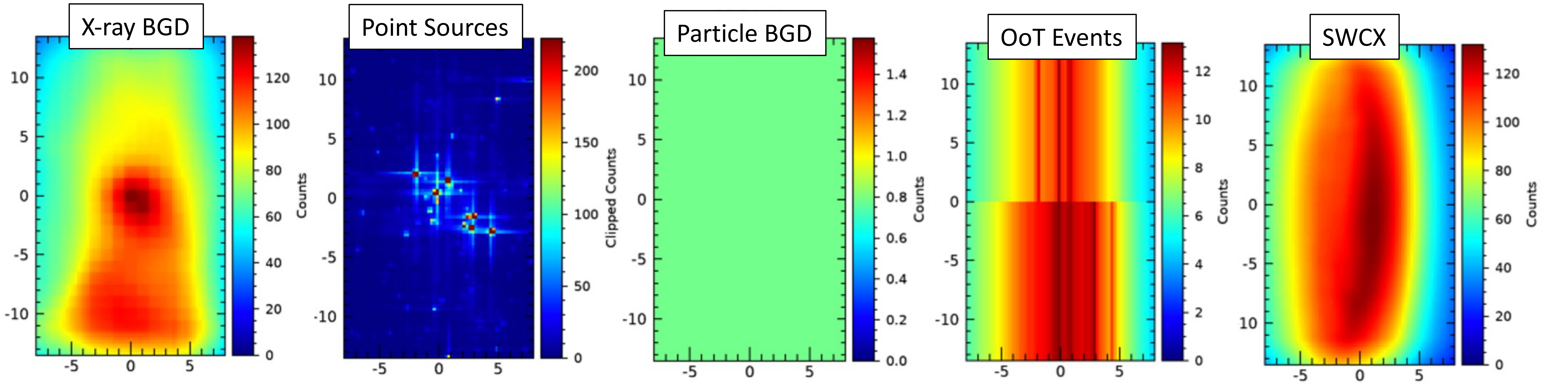


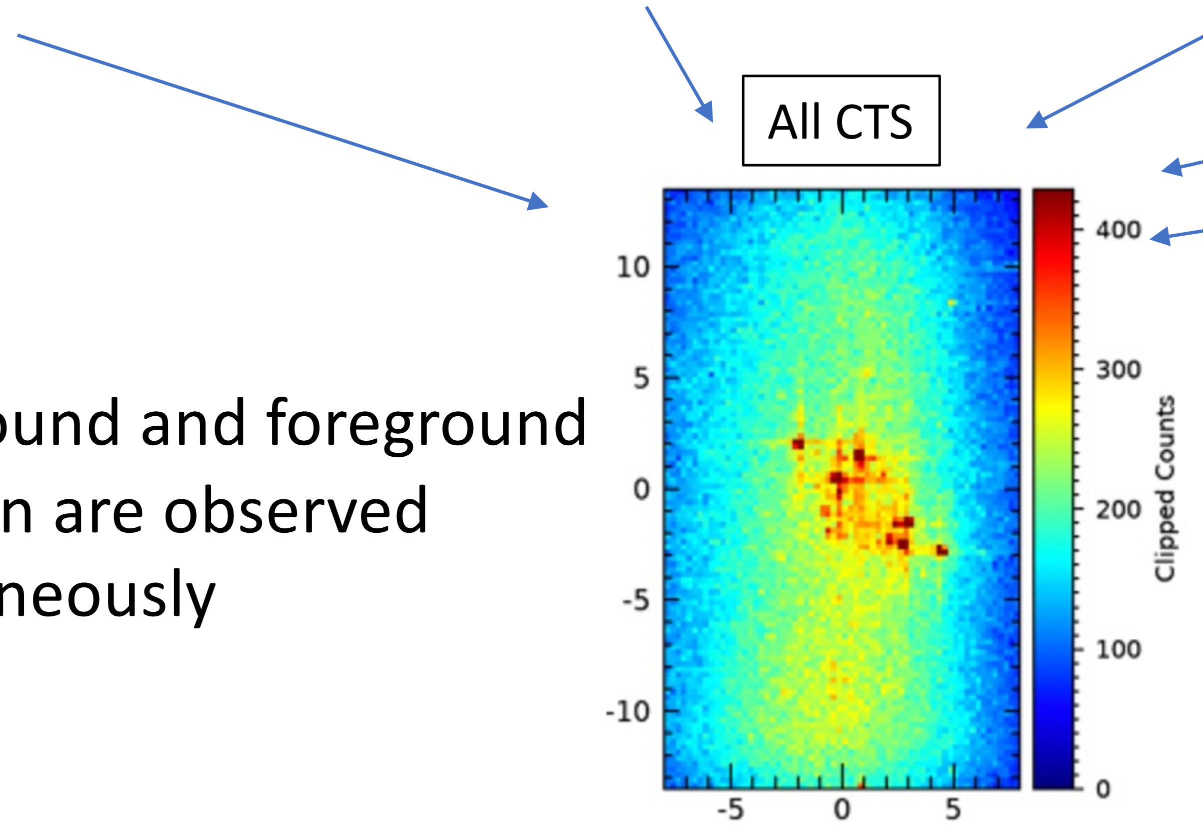
Solar Wind in these regions therefore SWVC X-rays

Hence: magnetopause boundary can be detected using X-ray imaging

SXI observations (simulations)

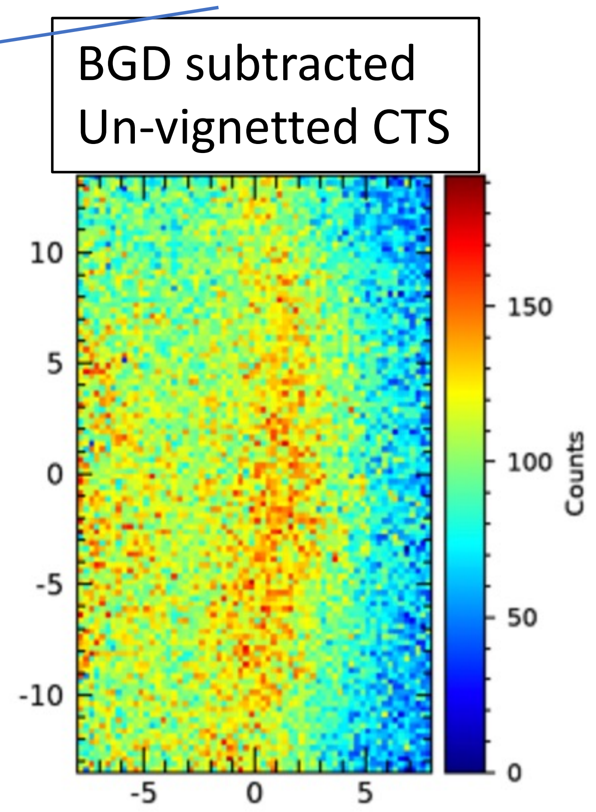
Components within an SXI dataset (simulated)



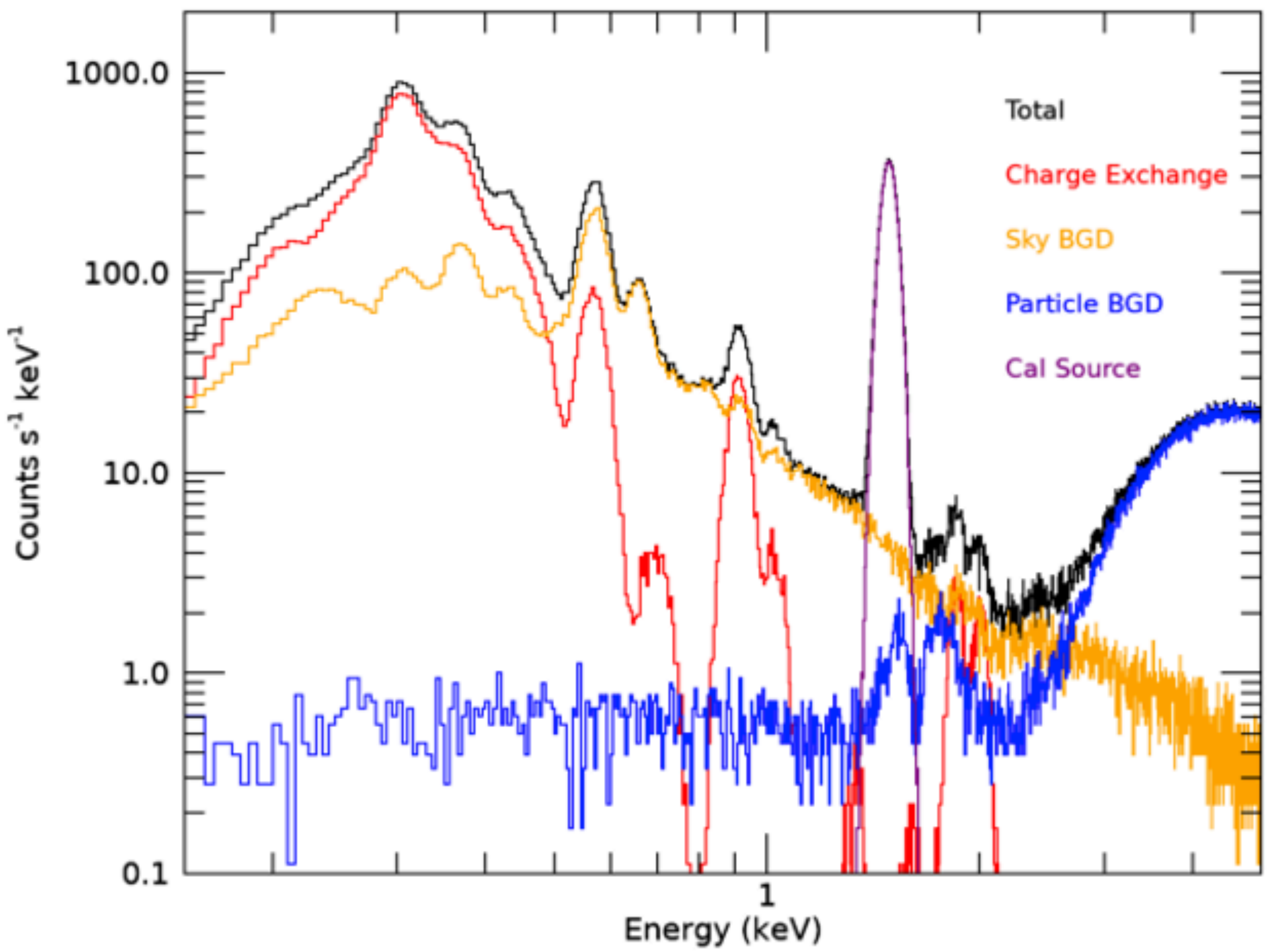


Background and foreground emission are observed simultaneously

Example background subtracted image



Spectral components (simulated, high solar wind case)

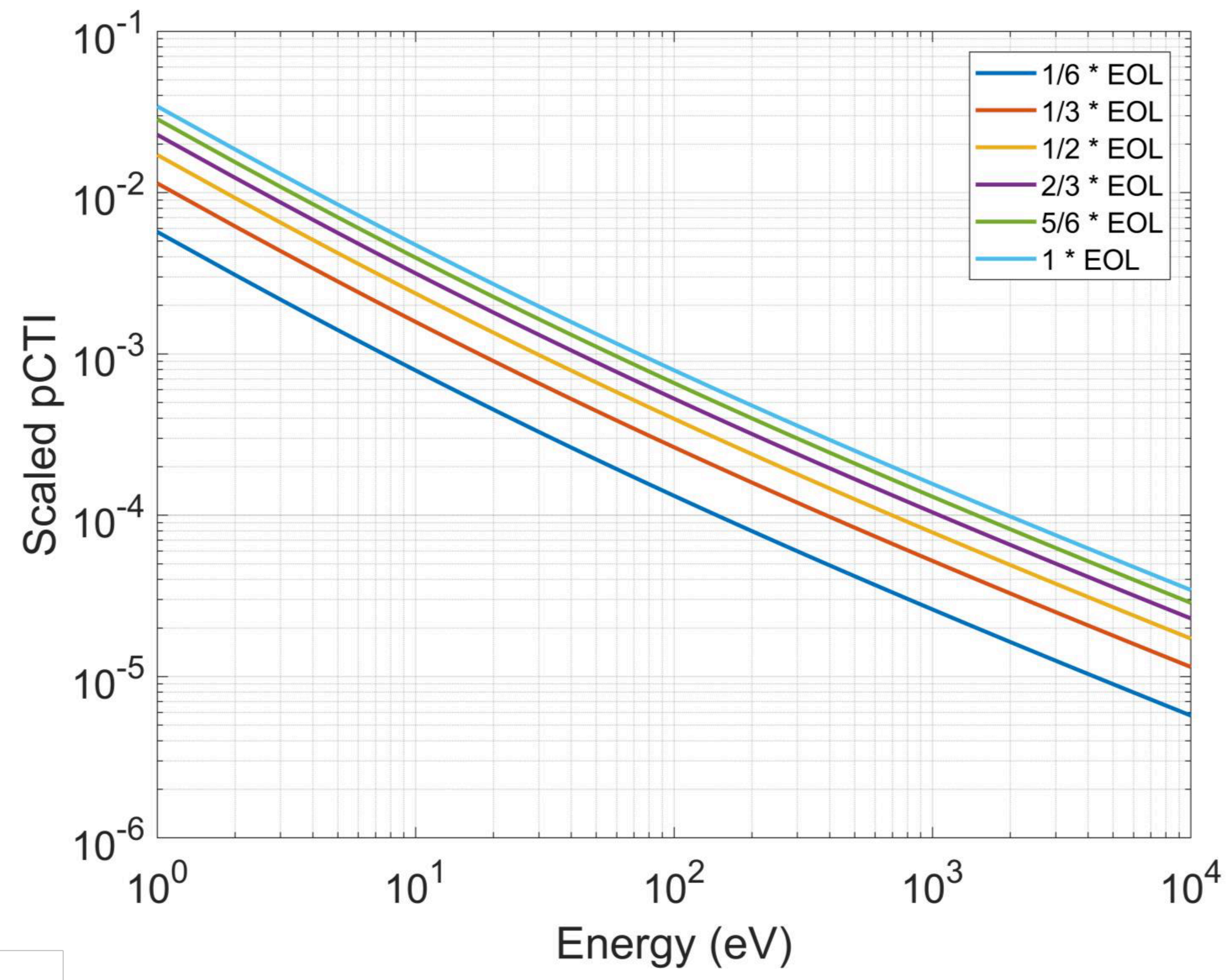


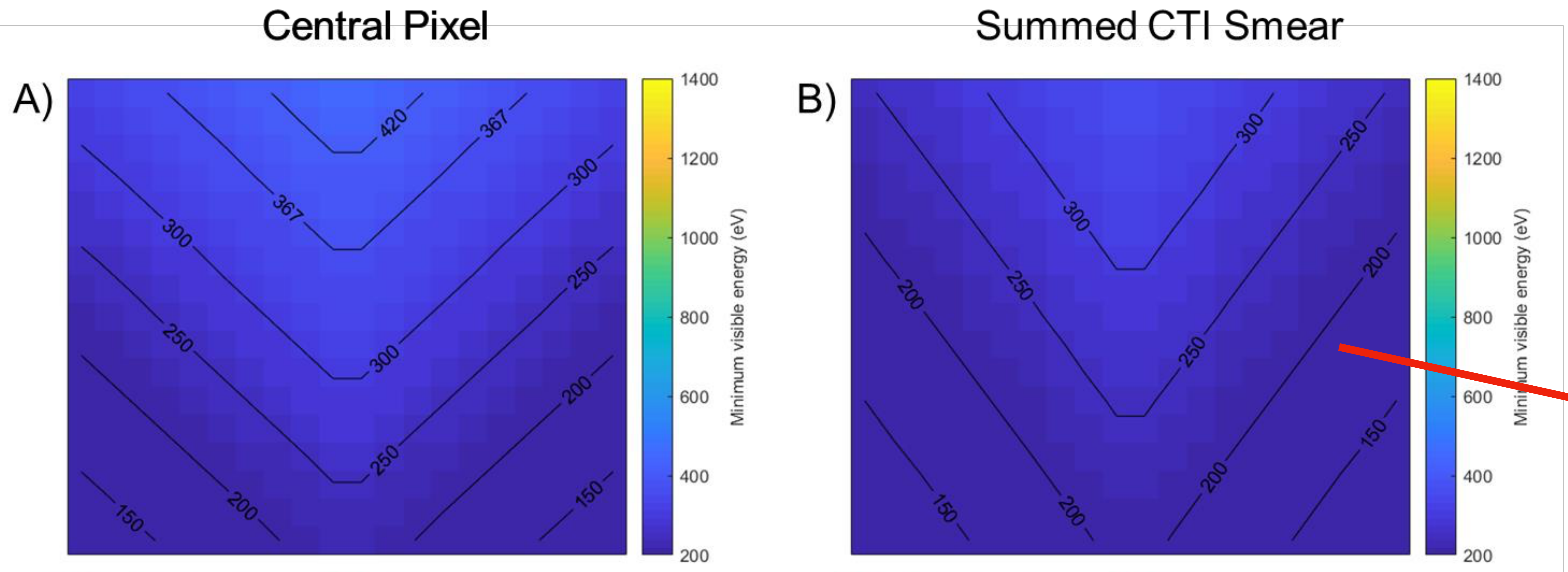
SXI Charge Distortion Model overview

Charge Transfer Inefficiency will be a critical to achieve a successful SXI.

- Preliminary CTI *beginning of life (BOL)* and *end of life (EOL)* estimates are based on PLATO CCD270 operated in SXI-like fashion.
- CTI losses are predicted to be significant, in particular because of the low-energy emission of the primary SXI science

BOL sCTI = 1.5E-06, pCTI = 9.7E-07
EOL sCTI = 1.8E-05, pCTI = 5.6E-05





62% of device detects 300 eV

88% of device detects 300 eV

Areas of the detectors might not be able to detect low energy lines by the end of the mission (3 years).

SXI Charge Distortion Model overview

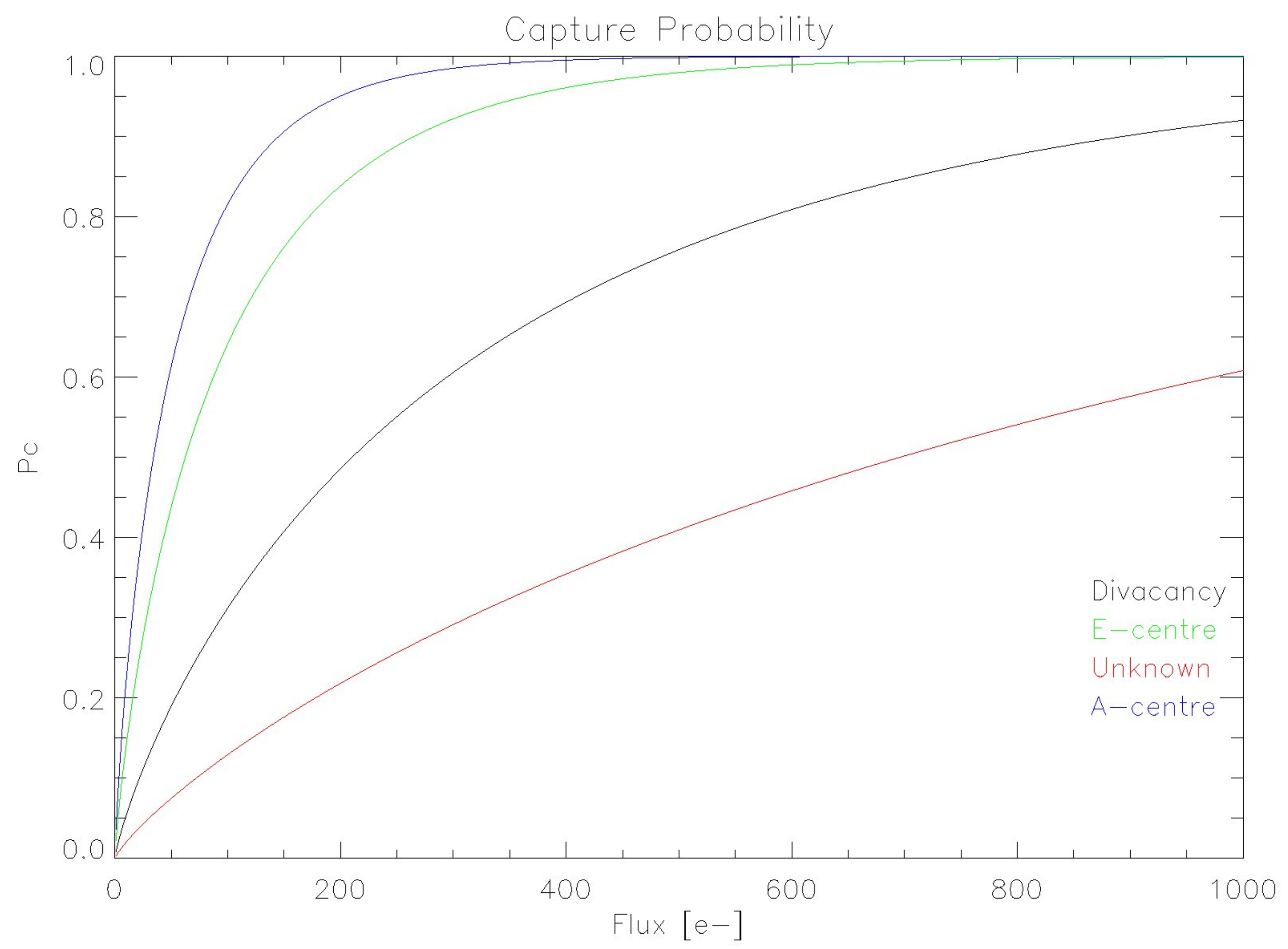
The **SXI CHARGE DISTORTION MODEL (CDM)**

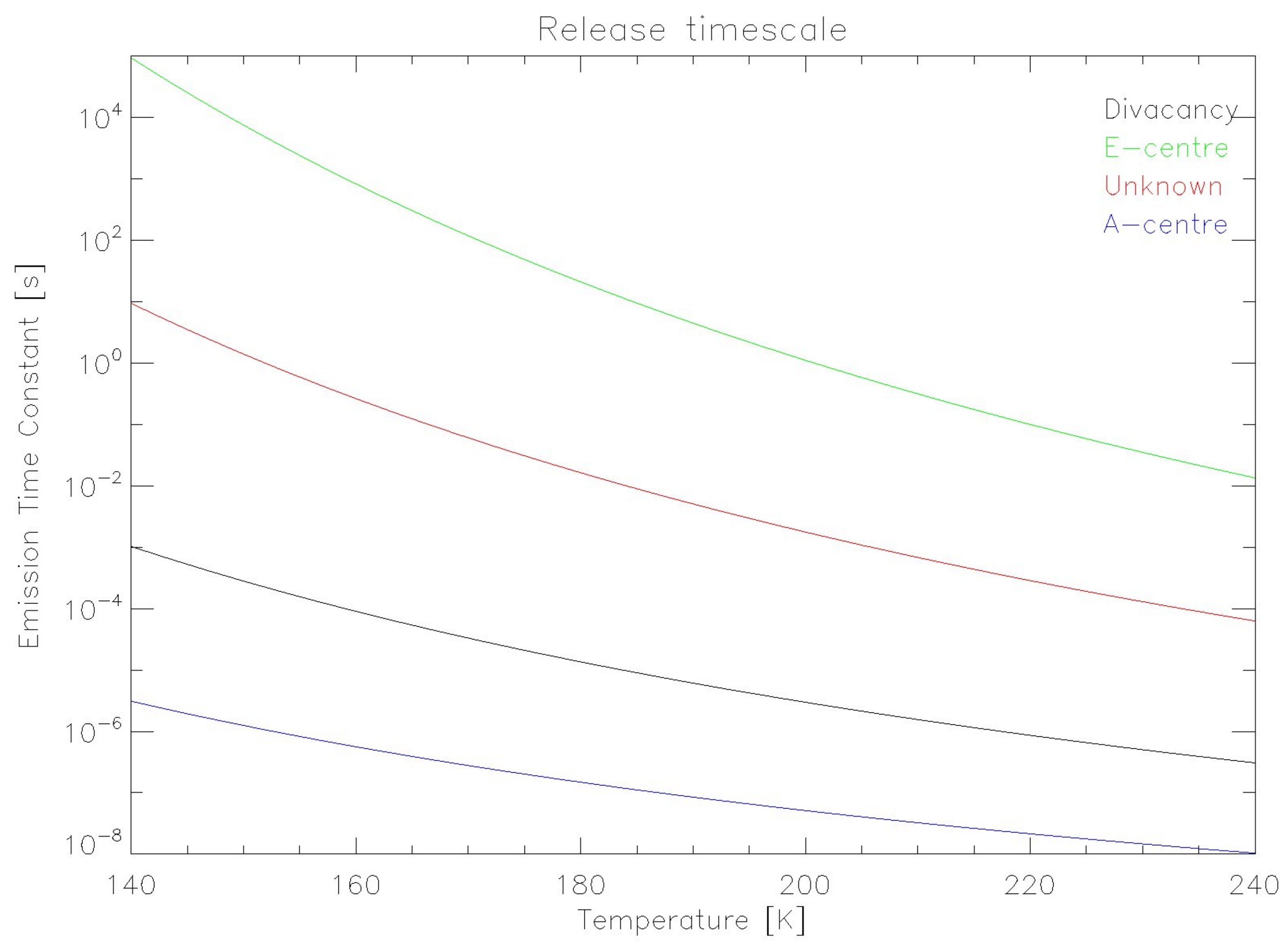
- Physical model, based on the standard **Shockley-Read-Hall** traps theory

- Charge traps are defects in the CCD silicon lattice. Common defects are the E-centre (Phosphorous-Vacancy), the A-centre (Oxygen-Vacancy), the Divacancy (2 vacancies), each with a specific energy level E_t and a capture cross section σ
- The capture and the release of an electron by a trap are stochastic processes, described by a capture probability $P_c(\sigma_t, N_e)$ and a trap release probability $P_r(E_t, T)$

$$P_c(N_e) = 1 - \mathrm{e}^{-\alpha N_e^{1-\beta}} \qquad \text{where} \qquad \alpha = \frac{t\sigma v_{th} FWC^{\beta}}{2V_g}$$

$$P_r = 1 - e^{-\frac{t}{\tau_e(T, E_t)}} \qquad \text{where} \qquad \tau_e = \frac{e^{E_t/kT}}{X_n \sigma_n v_{th} N_C}$$





SXI Charge Distortion Model overview

- SXI CDM pixel based

  Losses: $L = N_{free} P_c$

  Release: $N_r = N_0 \left(1 - e^{-\frac{t}{\tau_r}}\right)$

  Flux update: $F(N) = F(N-1) - L + N_r$

  Trap species occupancy update.

- Includes SXI CCD specific features

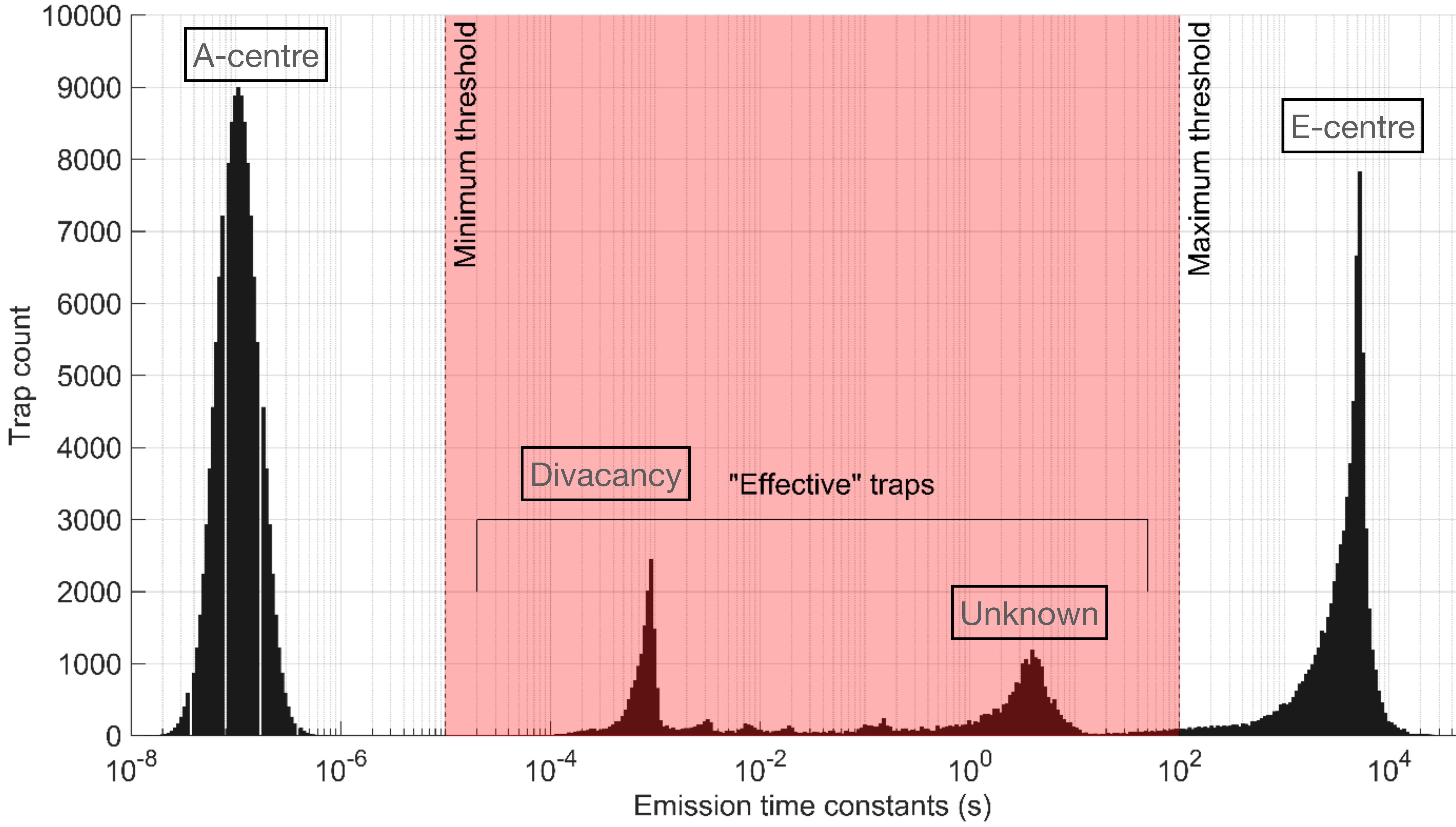
  Charge injection lines, Pixel Binning (6x6 default), 2-nodes output.

- Trap parameters

  Four trap species

  Trap densities based on measurements from cryogenic CCD280 with EOL irradiation of approximately 3.43x10^9 protons/cm^2 (10 MeV equivalent).

Open University trap-pumping measurements



Release timescale (T = 153K)

Specie 1, Divacancy ~ 2E-4 s

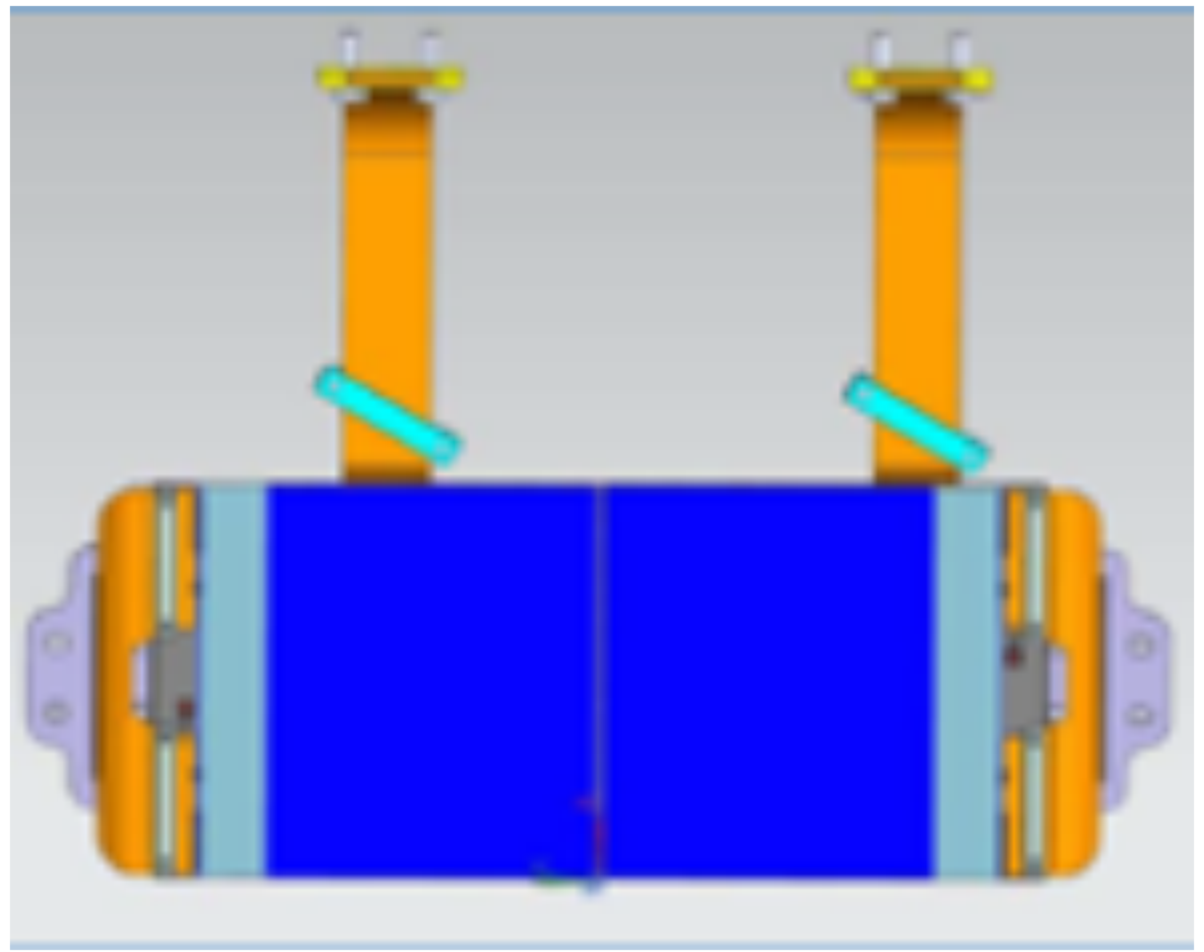
Specie 2, E-centre ~ 3.7E+3 s

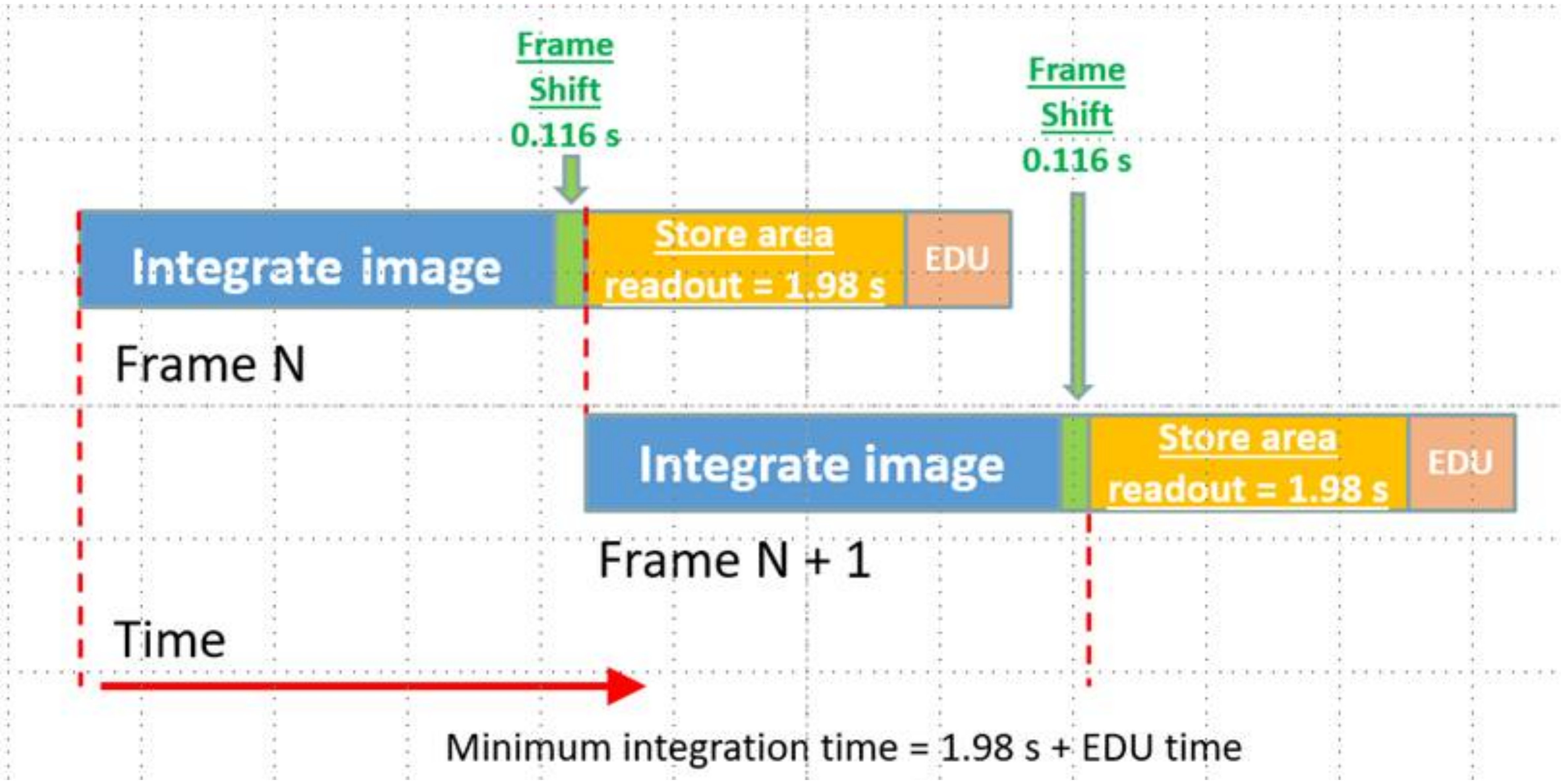
Specie 3, Unknown ~ 0.8 s

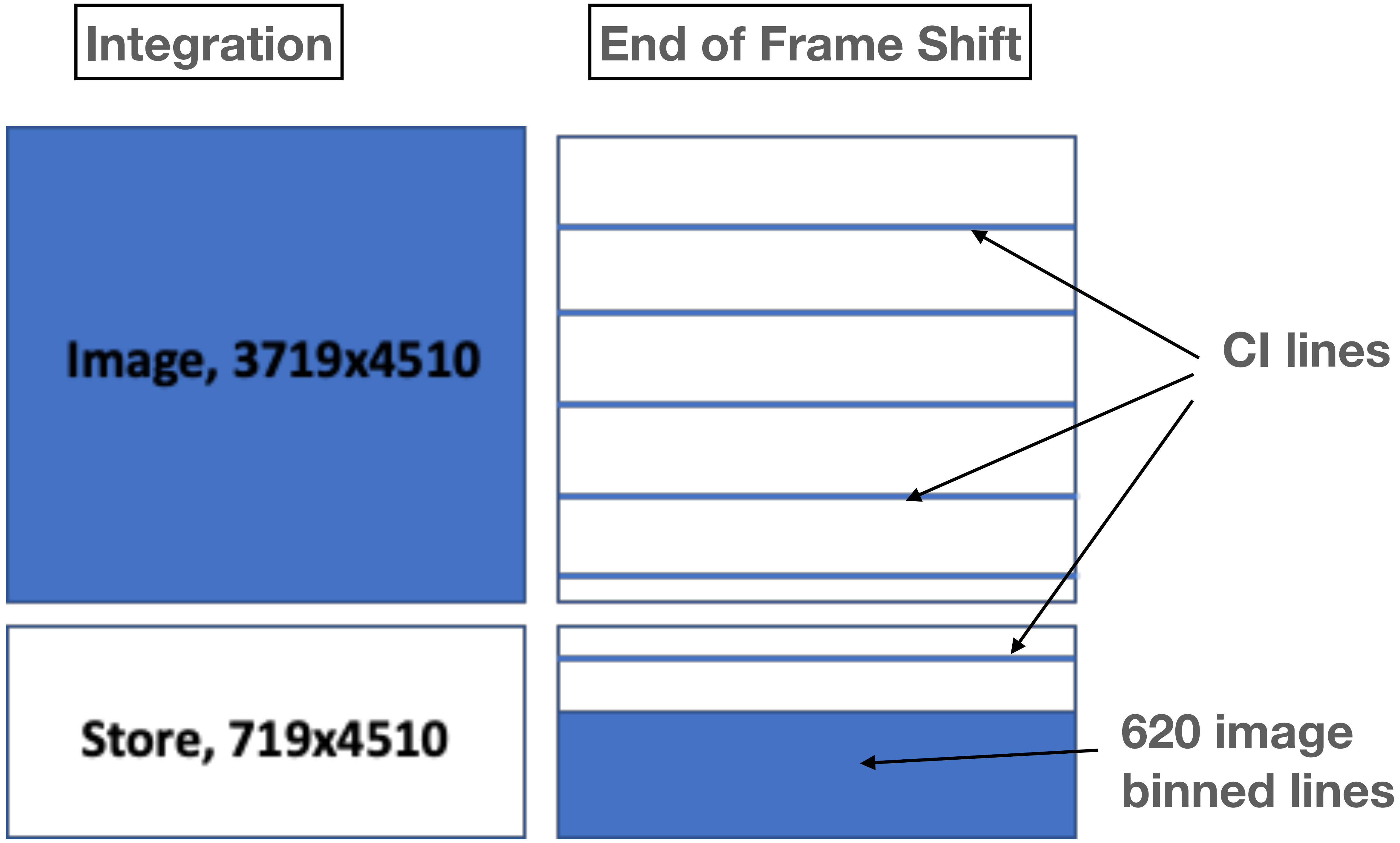
Specie 4, O-centre: ~ 1E-6 s

SXI detectors readout timescales

- SXI with 2 large area, back-illuminated Te2v CCD-370.
- Image (3791 rows) and Store (719 rows) sections.
- 2-node output + charge Injection from top of image.
- Range of signal readout times, resulting in different trap species affecting specific areas of the detector:
  - Image exposure: 2.5 s
  - Parallel transfer in image section: 2.7E-5 s
  - Parallel transfer in store section: 1.6E-4 s & 2.7E-3 s
  - Serial transfer: 1.19E-6 s







CDM code applications, so far..

- Use of **astrophysical sources** to monitor and calibrate gain and CTI on-board.
- Predict CTI losses and spectral distortion (energy losses, line broadening) as a function of **epoch, CCD temperature, charge injection signal.**
- CDM in SXI **CTI correction algorithm**.
- Trap parameters determination accuracy to achieve the desired calibration performance.
- Analyse the effects of a **diffuse optical background** in SXI images.
- Evaluate the **"sacrificial charge"** effect.

SXI CDM - Supernova remnants for CTI measurements

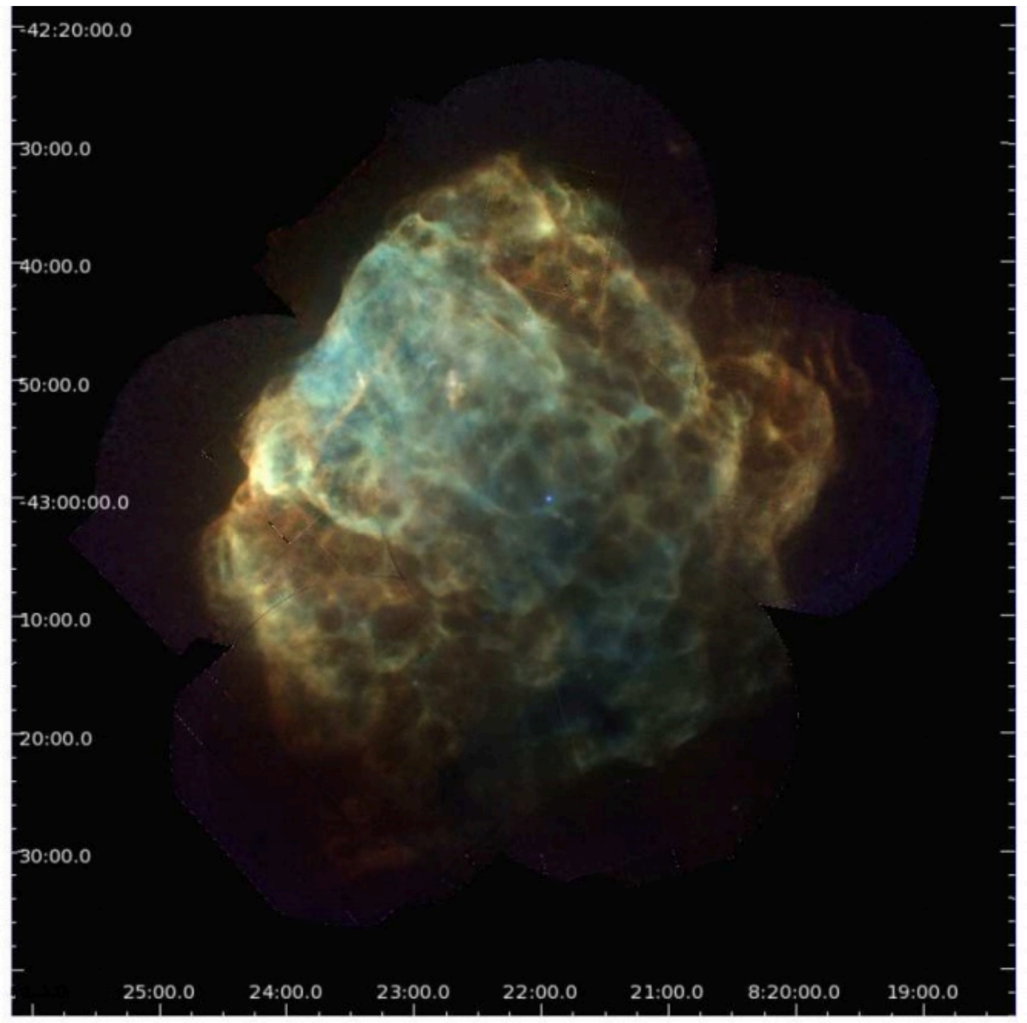
SXI CTI monitoring/calibration on board:

The SXI will observe SNRs serendipitously during a SMILE orbit at various epochs during the mission, with the sources drifting over the detector at various angles/directions.

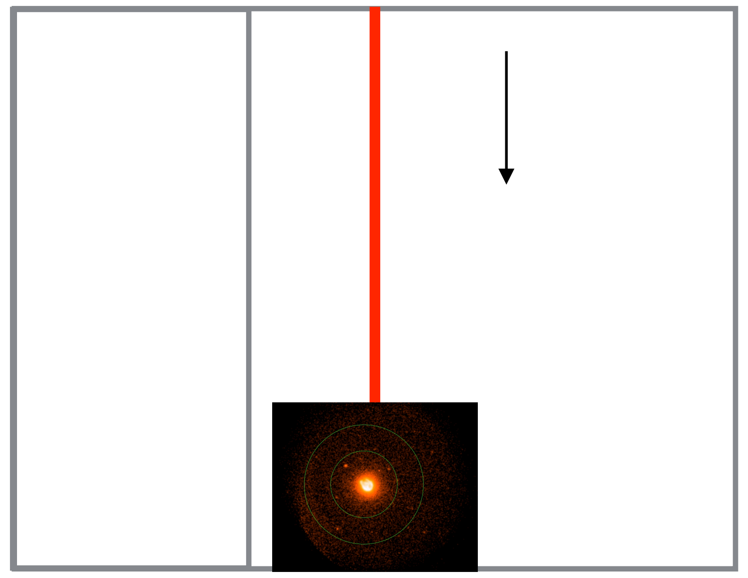
Procedure to investigate the use of supernova remnants to measure SXI CTI in orbit:

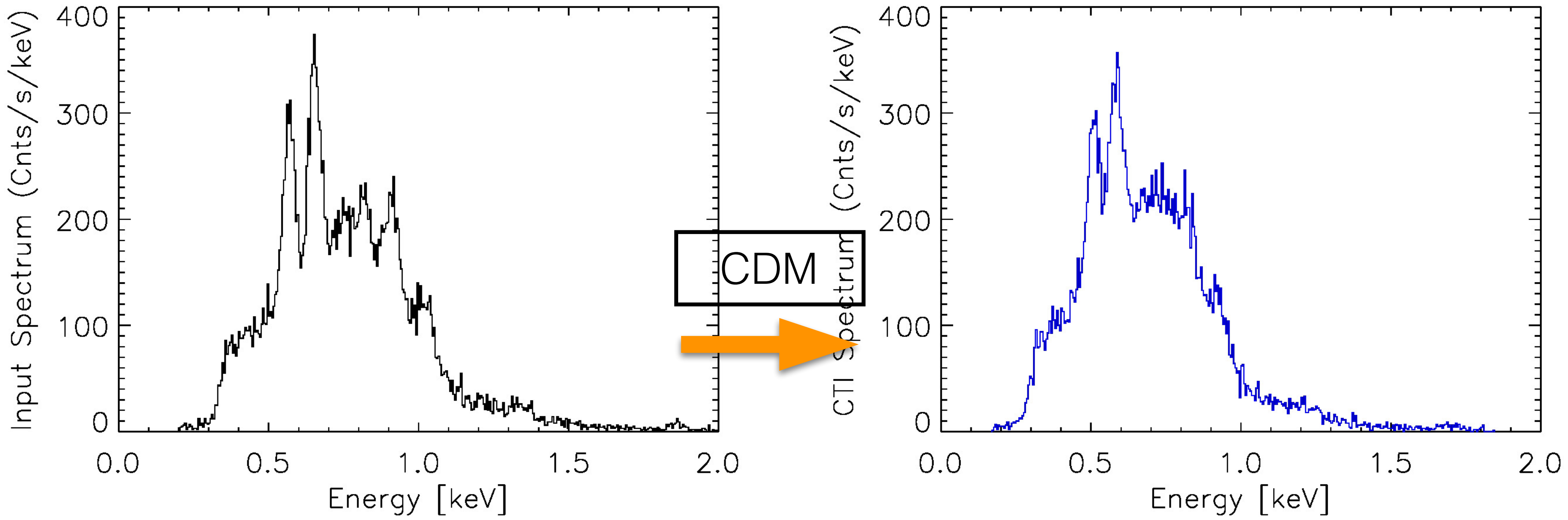
- XSPEC simulated SXI spectra with IACHEC reference model (eg, 1E 0102, N132D) or best fit model of other X-ray missions (eg, Puppis A).
- Process spectra with CDM + special line fitting

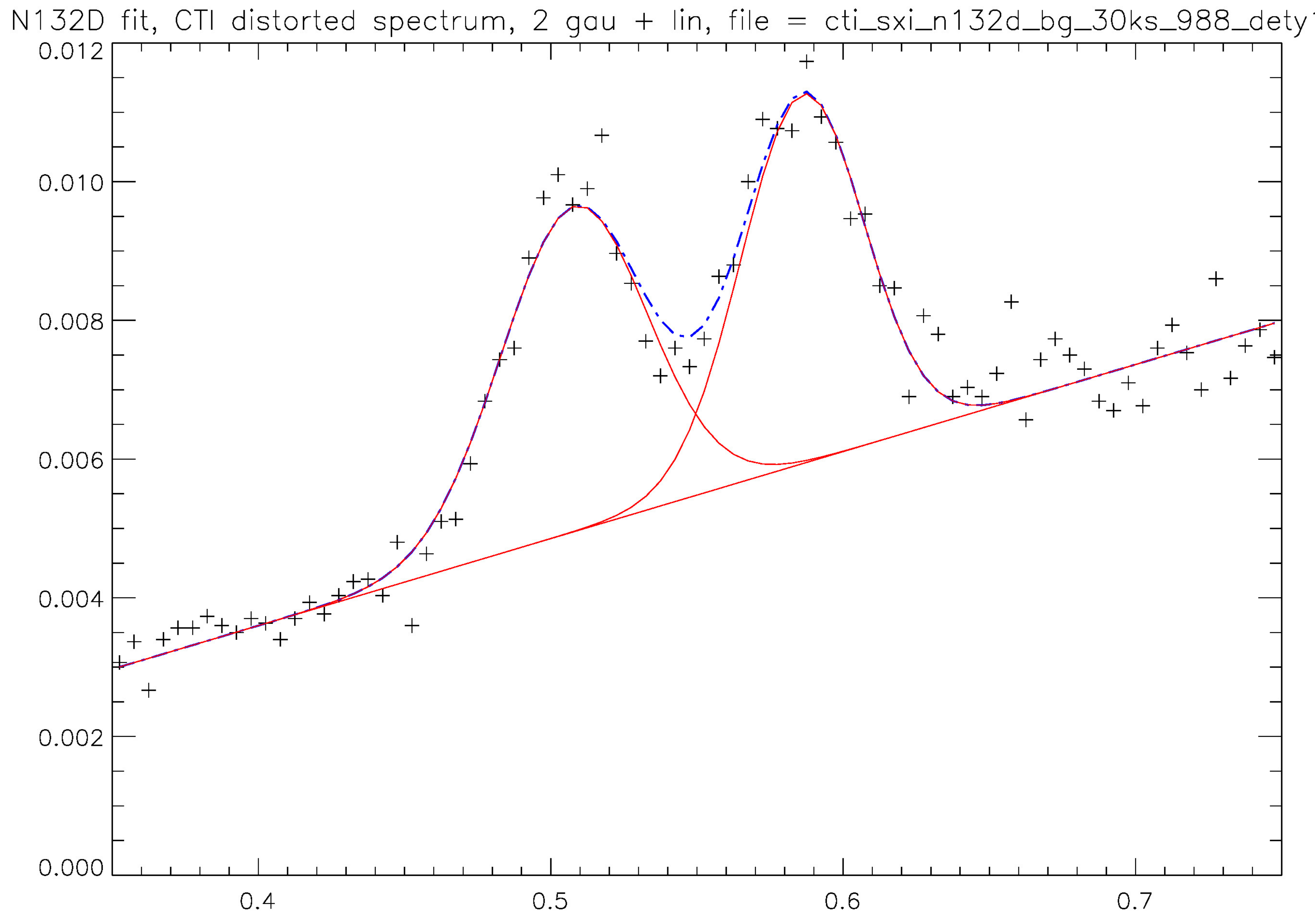
Puppis A (Dubner et al. 2013), mosaic of XMM/Chandra images



EXAMPLE: N132D







Conclusions

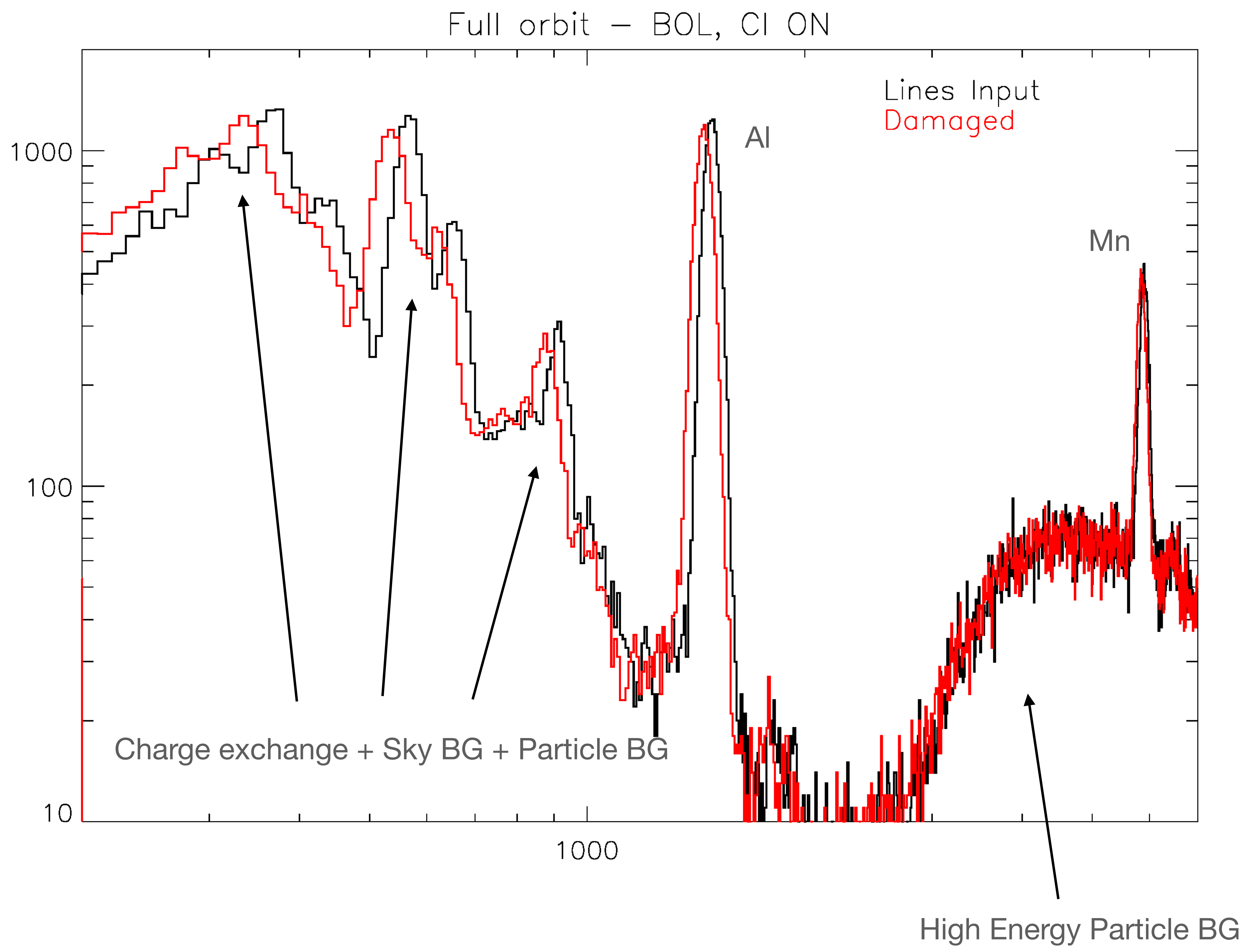
- N132D good candidate to verify energy scale after launch and possibly for CTI estimates early on in the mission.
- Puppis A good for monitoring global CTI evolution during the mission, but likely not bright enough to measure the energy scale of single columns.

SXI CDM - SXI distorted spectra

SXI CTI damage analysis

Run CDM over one full orbit of simulated SXI observations under different trap parameters and CCD operational configurations to investigate:

- Temperature dependence
- Charge Injection effect
- Time evolution
- Influence of the different trap species



Include the CDM in an algorithm to derive the observed spectra

Idea: replicate for SXI Chandra's forward-modelling, iterative approach.

- CDM is run multiple times with incremental refinements to the estimated X-ray events input energies to reproduce the measured energy when an event is processed by the CDM

O = Observed (true) energy
M = Measured energy
C = Corrected energy
D = CDM damaged energy

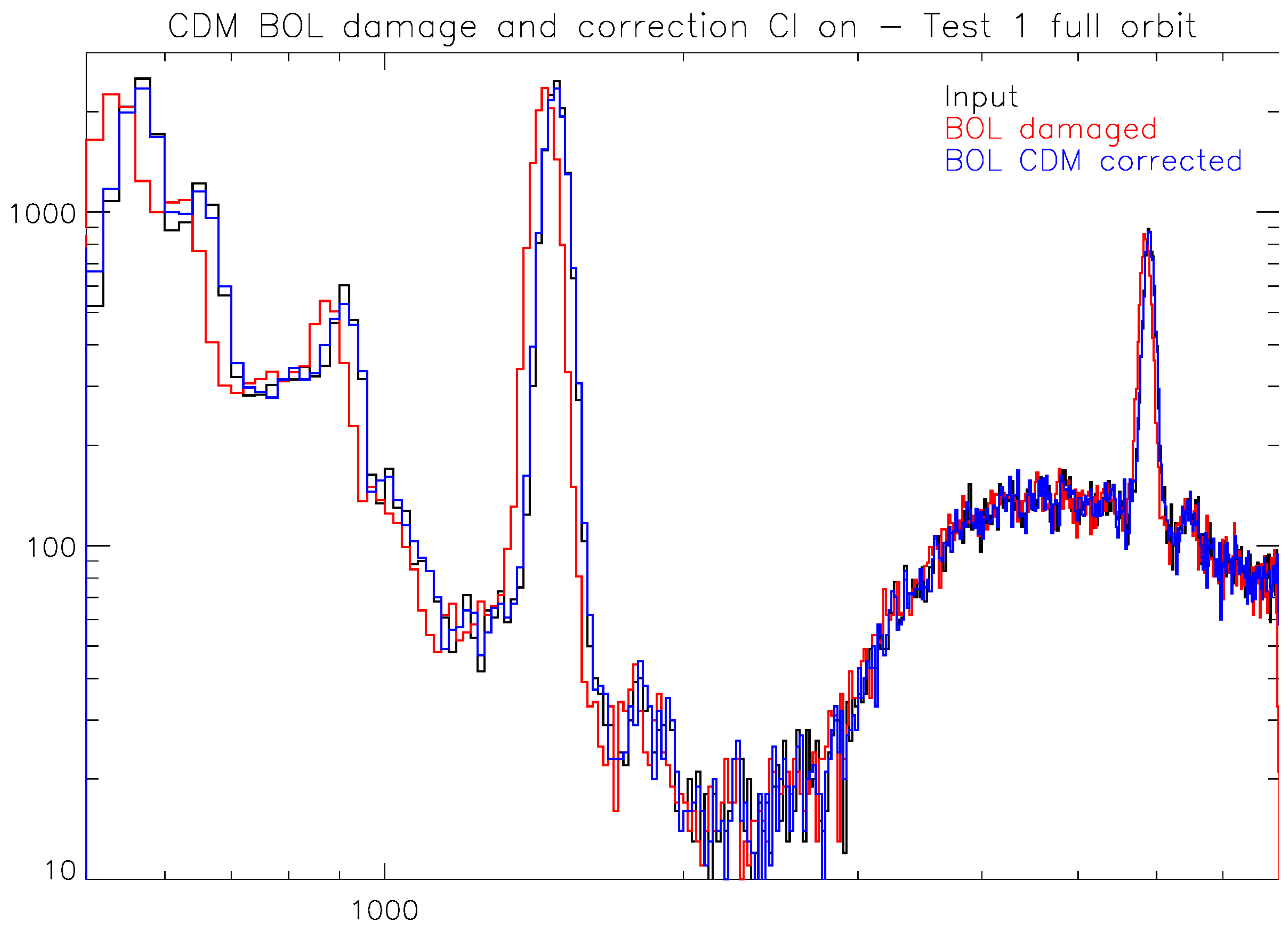
$\boxed{\text{Iterative algorithm}}$

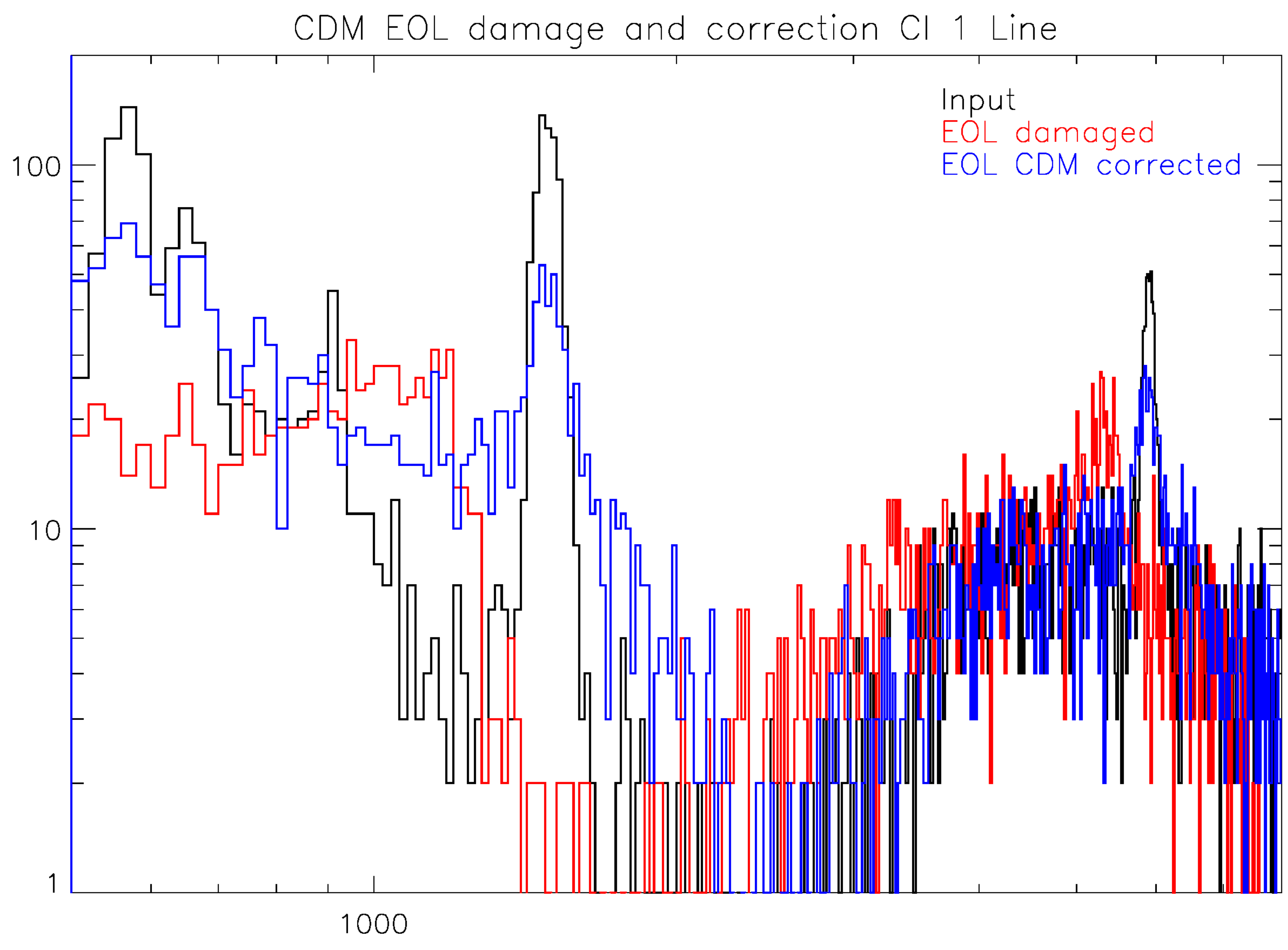
$C_n \xrightarrow{\text{CDM}} D_m$, with $C_0 = M$

Repeat until

$C_n \xrightarrow{\text{CDM}} M$, within a threshold

SXI CDM - CTI corrections





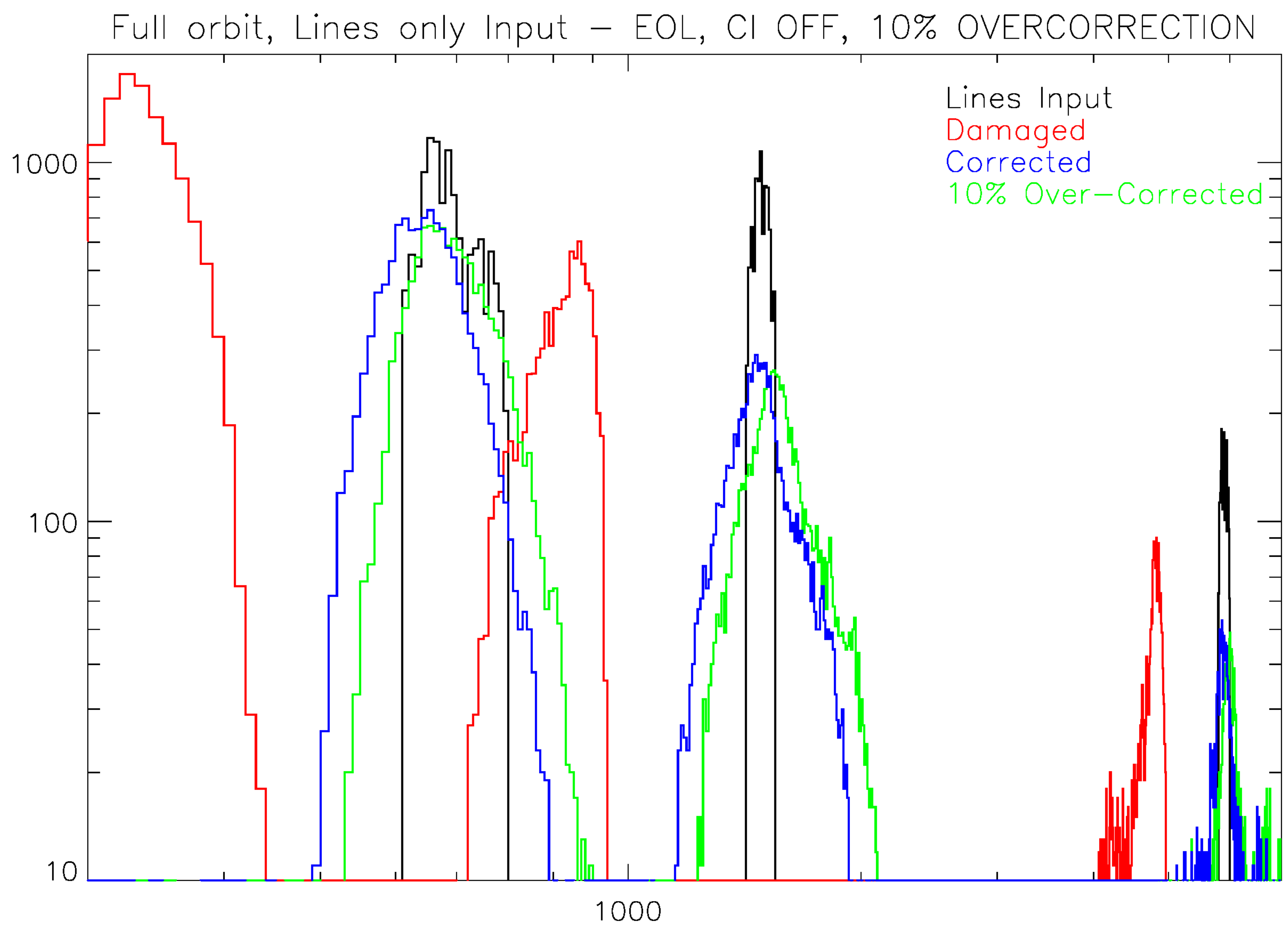
Results:

- BOL corrections work well, line energies recovered nicely
- EOL corrections more of a struggle. At low energies events end up below the detection threshold.
- Main limitation: information loss in the 6x6 pixel binning.

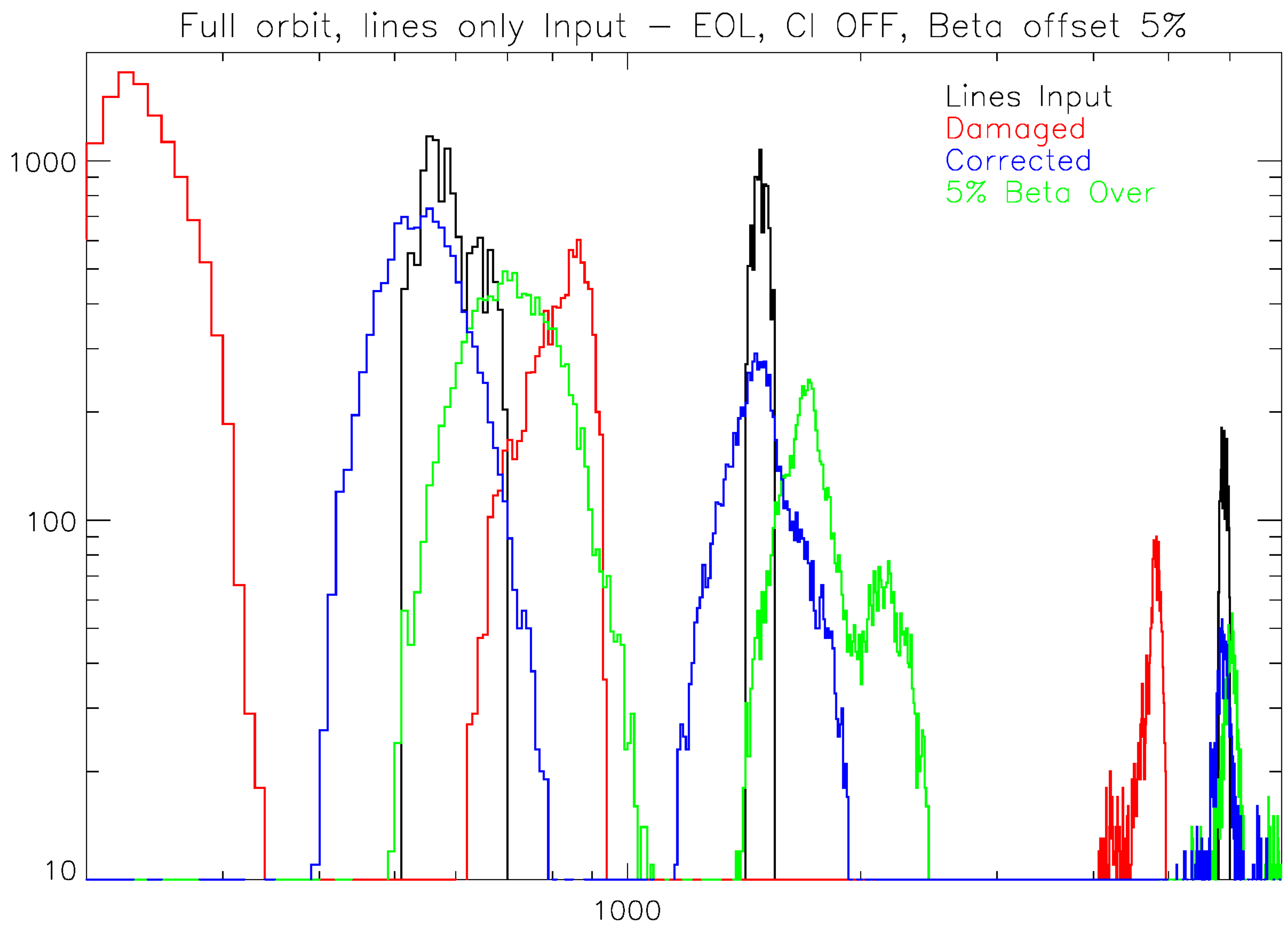
SXI CDM - Trap parameters accuracy

With what accuracy do we need to measure the trap parameters?
=> Run CDM CTI correction algorithm offsetting input trap parameters.

Example case - 10% trap density over-estimation



Example case - 5% volume coefficient over-estimation.



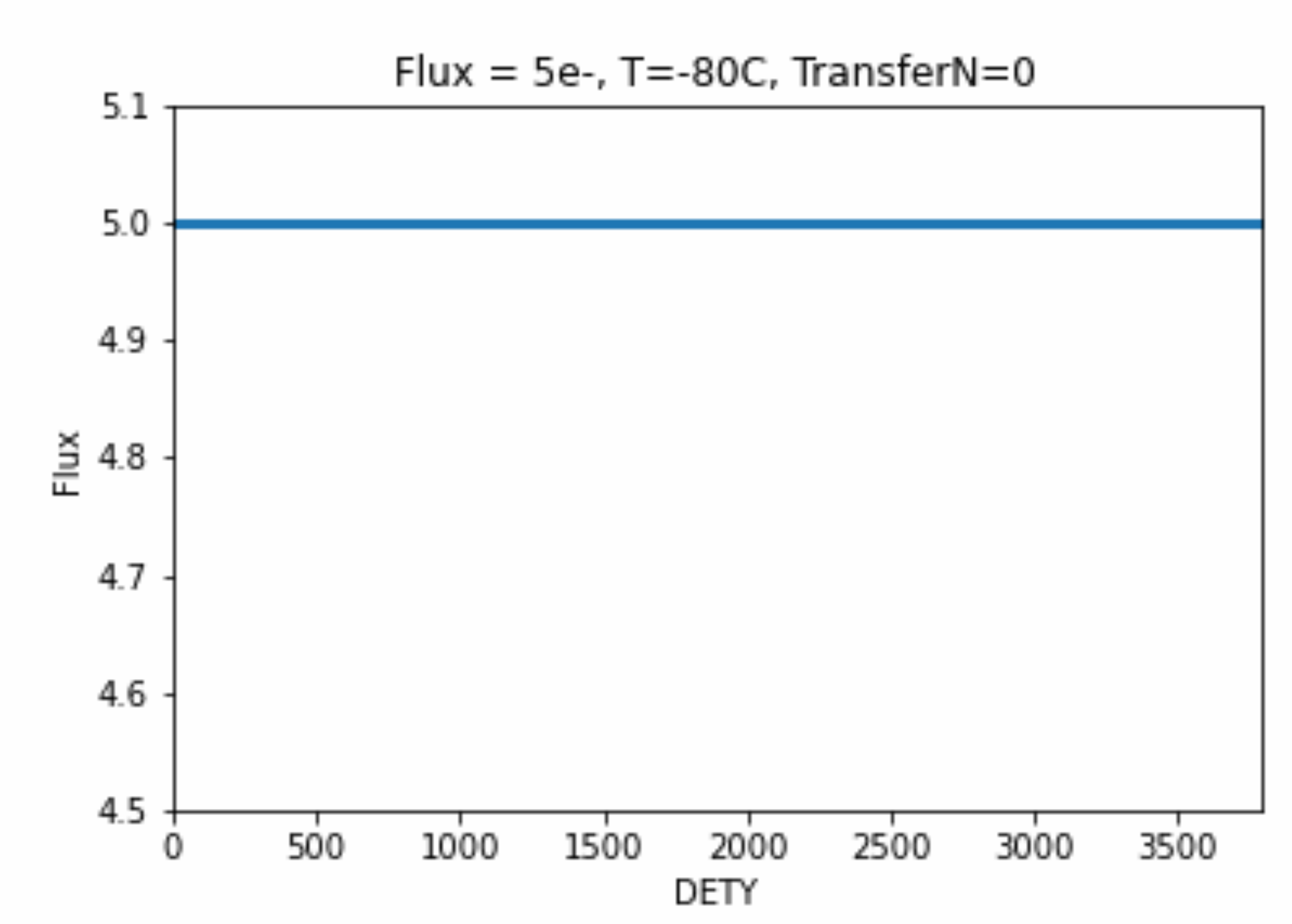
Conclusions:

- Corrections least affected by traps release timescale inaccuracy
- Corrections very sensitive to beta (the charge volume coefficient parameter, that constrains the CTI energy dependence)

The CDM has been used to investigate how different effects can impact CTI, by exploring trap parameters range and various SXI CCD operational settings

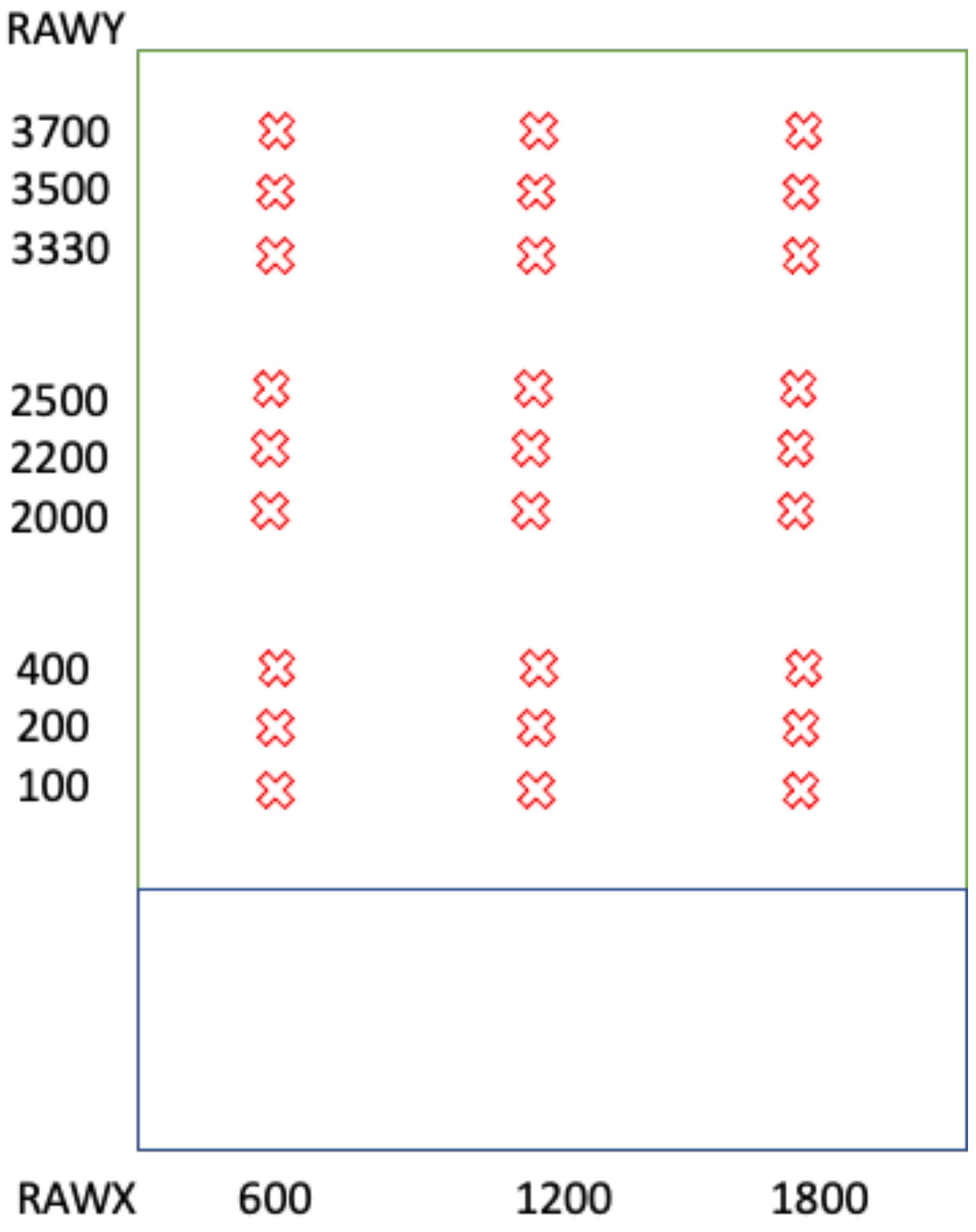
- Charge Injection ON/OFF
- CCD temperature
- Diffuse optical background
- Sacrificial charge effect

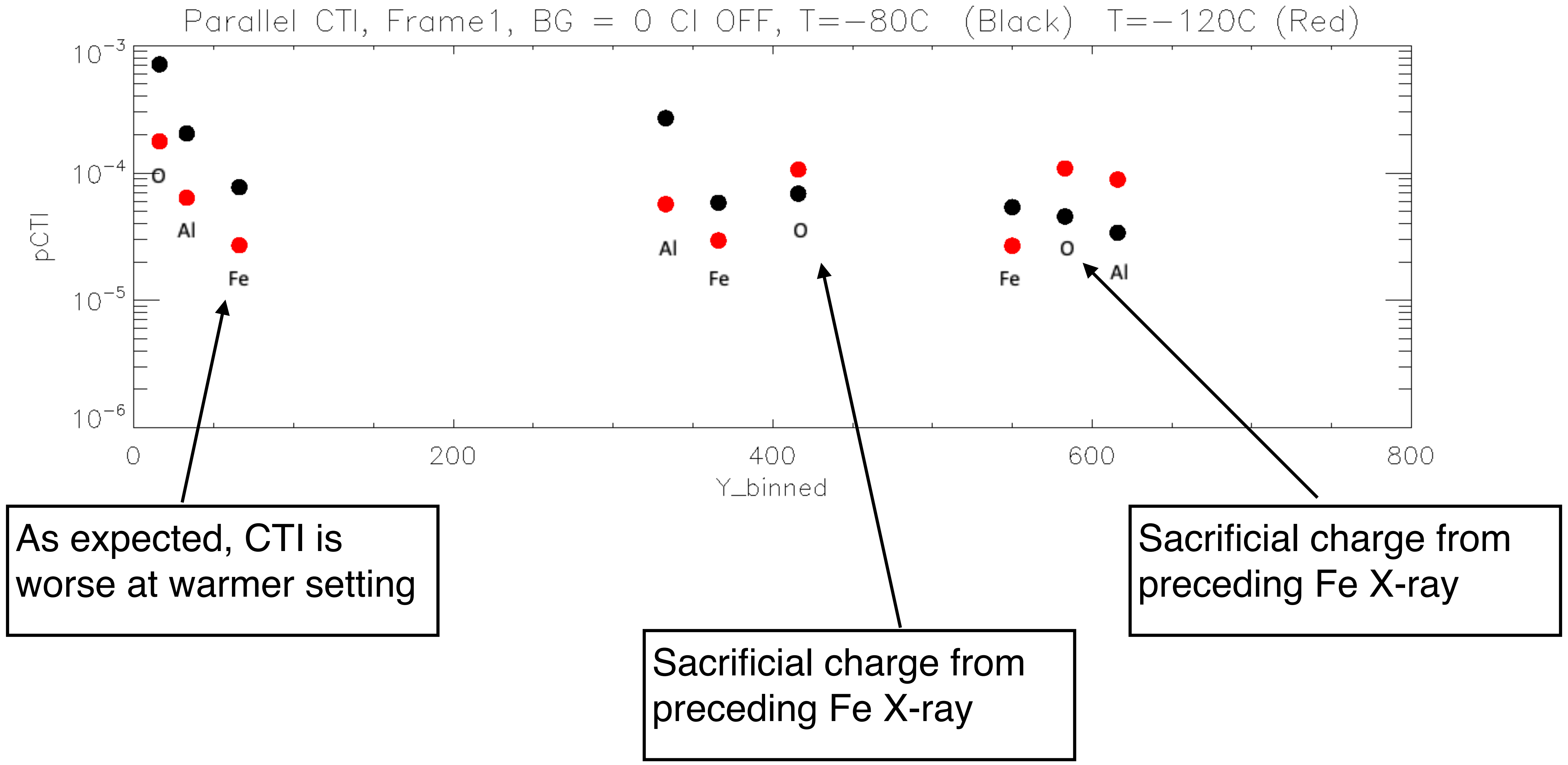
Diffuse background



SXI CDM - Temperature, diffuse background, sacrificial charge effects

Temperature + Sacrificial charge effects





Summary:

- The SXI CDM has been used to model and predict a number of CTI-related effects.
- These analysis will be repeated after irradiation of an SMILE CCD370 and a calibration campaign by the Open University to study CTI and determine more accurate trap parameters.

Current limitations:

- Pixel based implementation is very slow (~8hrs to process SXI observations over a full orbit)
- Cryogenic irradiation of a PLATO CCD280 shows the emergence of a continuum of defects, without well determined emission timescales. This is a concern for the CDM, and it would require a modification of the code, or the introduction of multiple ad-hoc trap species, slowing the CDM down even more.

Conclusions:

- The CDM is a useful tool to model CTI and study the effects of different configurations/CCD operations.
- CDM might not turn out to be the best/practical tool to "correct" CTI effects on board.
- An alternative, more light-weight, functional approach might eventually be needed in the SXI pipeline.