Disentangling detector and background effects at soft energies in X-ray CCDs

(a work in progress)

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IACHEC 2022 Spring Workshop

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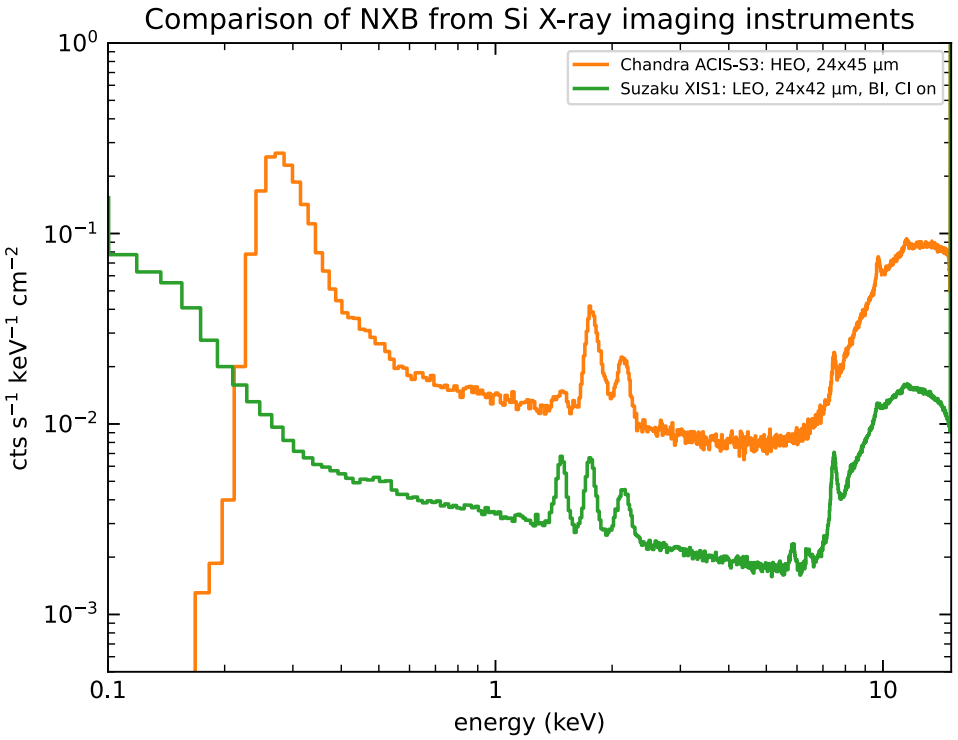
MIT KAVLI INSTITUTE

The problem



- Suzaku and Chandra BI CCDs show a sharp up-turn at soft energies in flight non-X-ray background (NXB) spectra.

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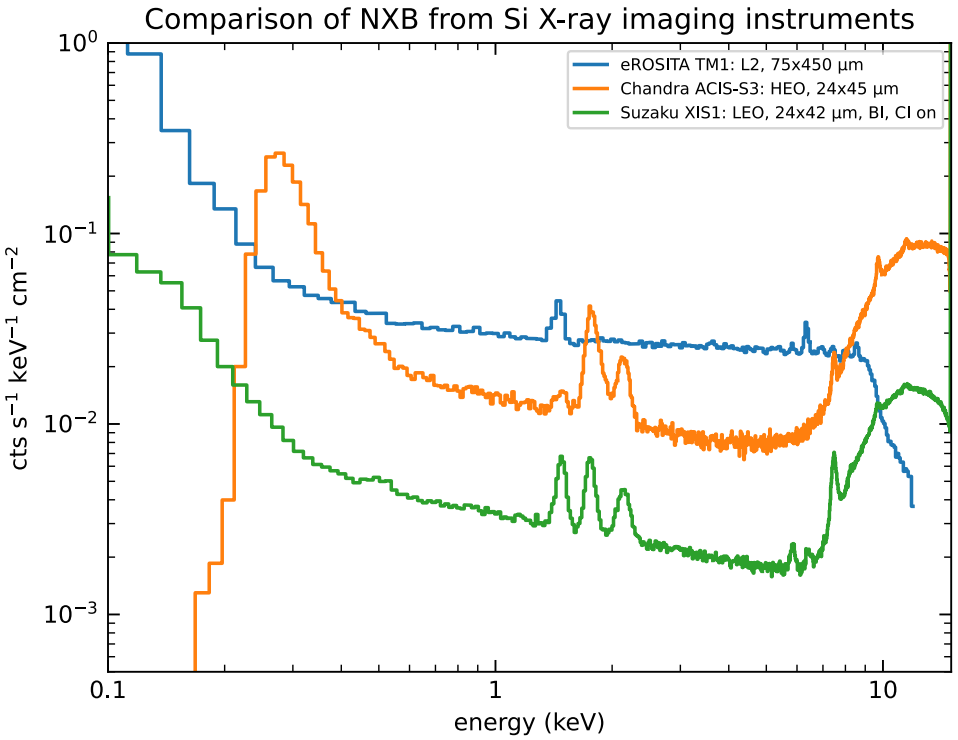

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- eROSITA BI PNCCDs also show this.

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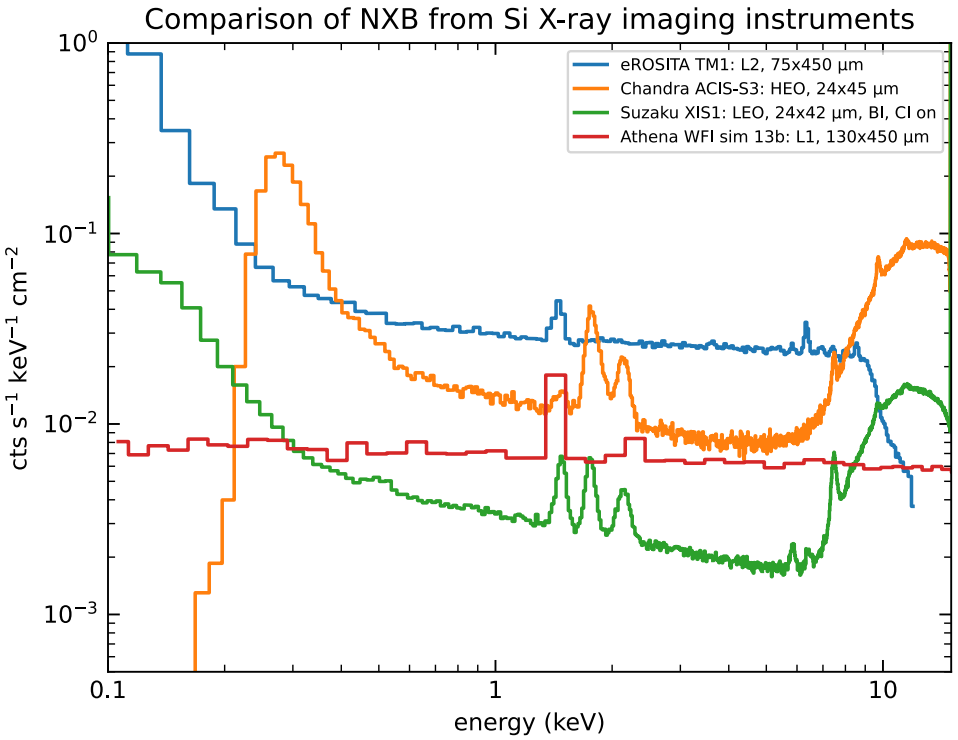

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- eROSITA BI PNCCDs also show this.
- Athena WFI BI DEPFETs do ***not*** show this in Geant4 simulations.

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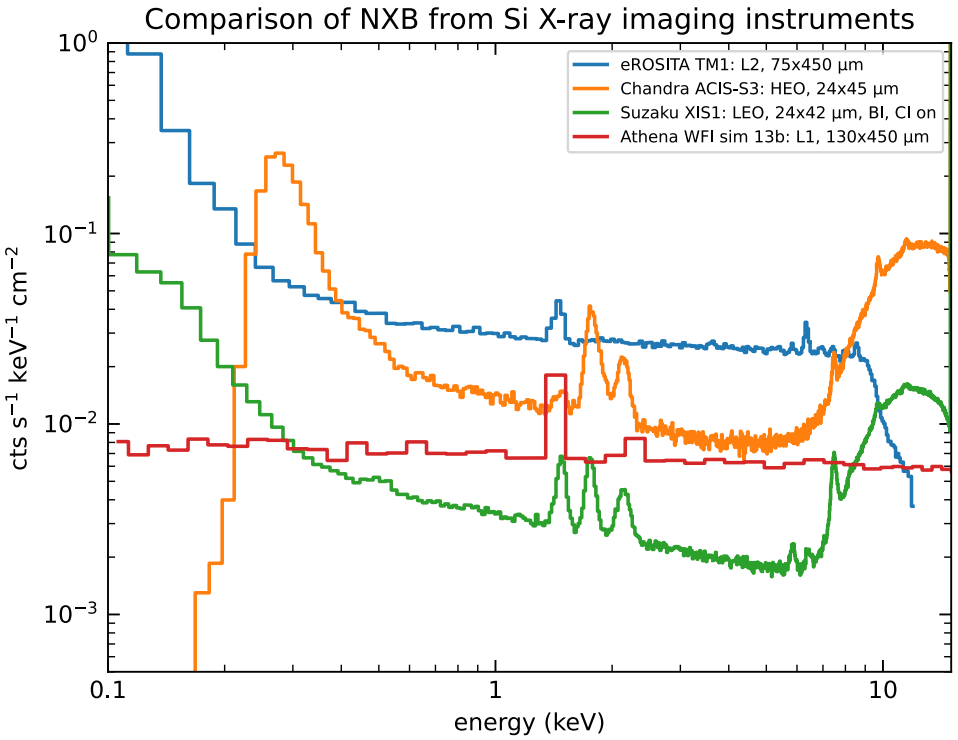

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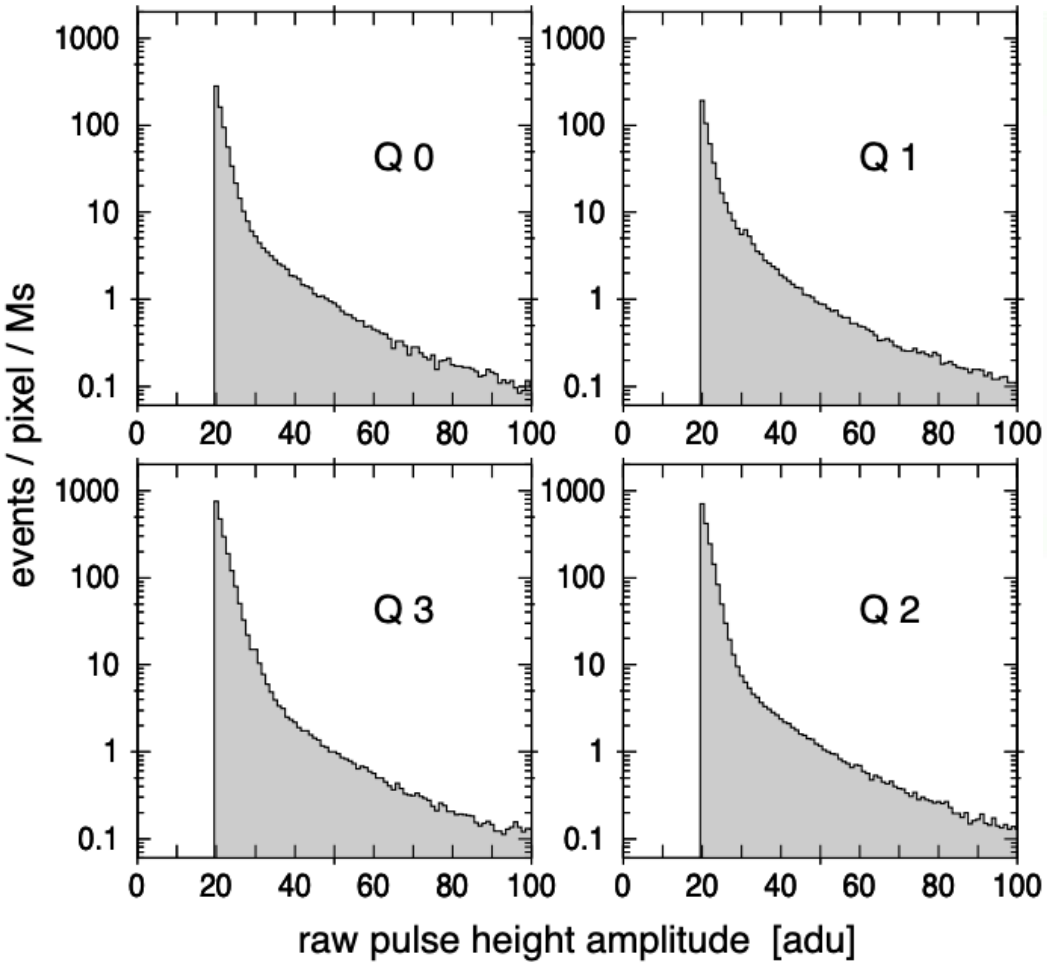
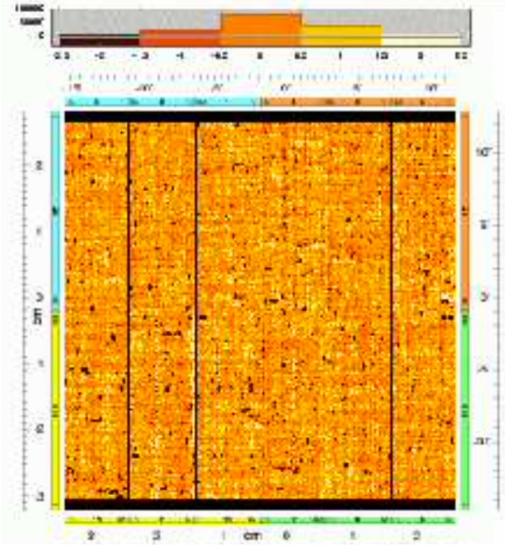
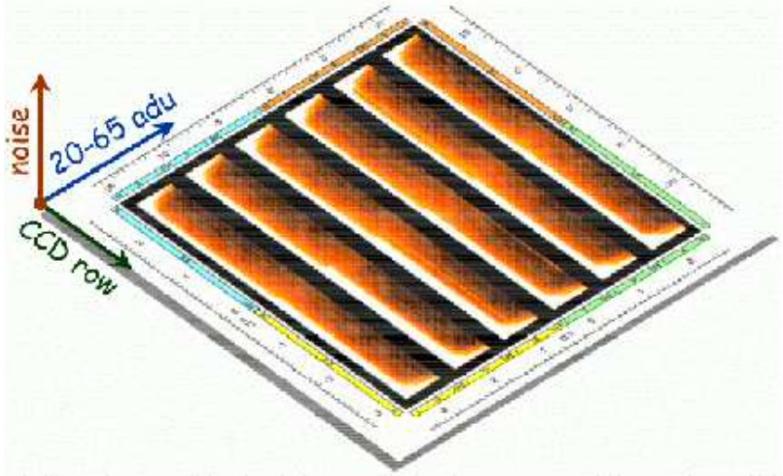
1. What causes this up-turn?
   - Flickering or noisy pixels?
   - Non-Gaussian amplifier noise?
   - Improper bias subtraction?
   - Redistribution/charge loss?
   - Cosmic ray particles/secondary electrons?
2. If GCRs, why is it missing from Geant4 sims?
   - Only detector effect included is pixelization.

Soft up-turn: the XMM-Newton EPIC pn experience

From Dennerl+2004, Proc. SPIE, 5488, 61



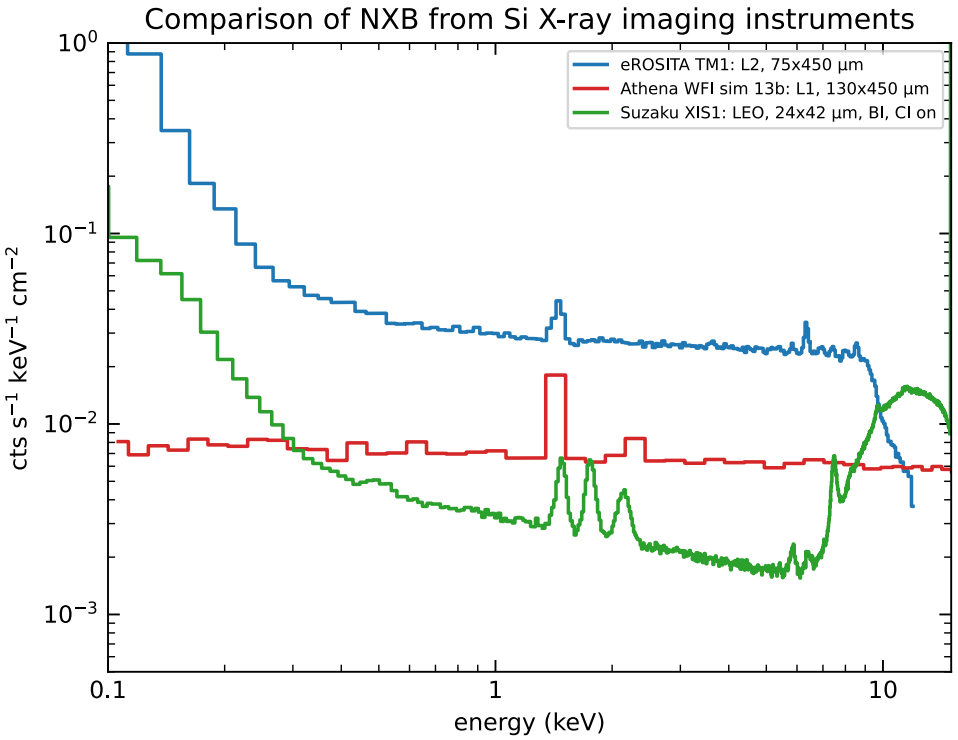




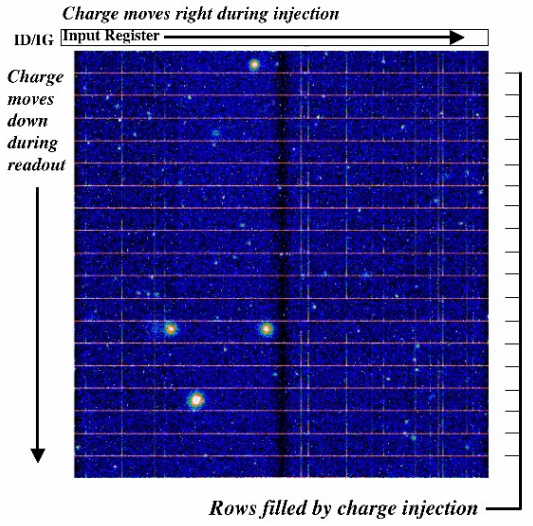
- Dennerl+2004 identify an up-turn from:
  - Particle-induced improper offset/bias/dark correction.
  - Spatially dependent detector noise.

(Thanks to Fabio Gastaldello)

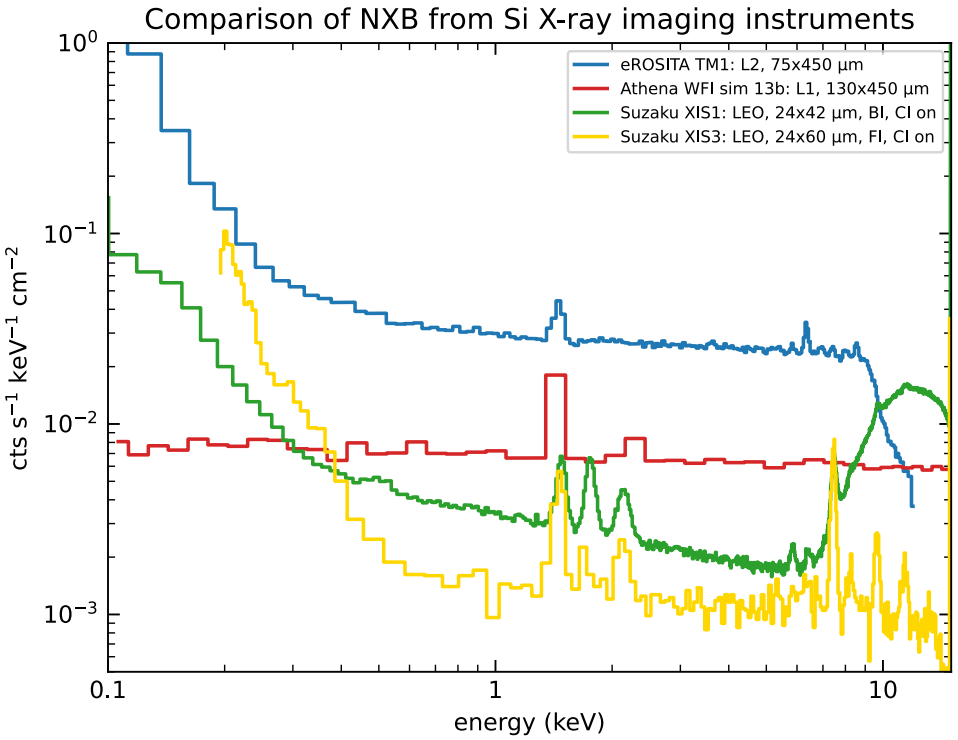
Soft up-turn: flickering or noisy pixels?



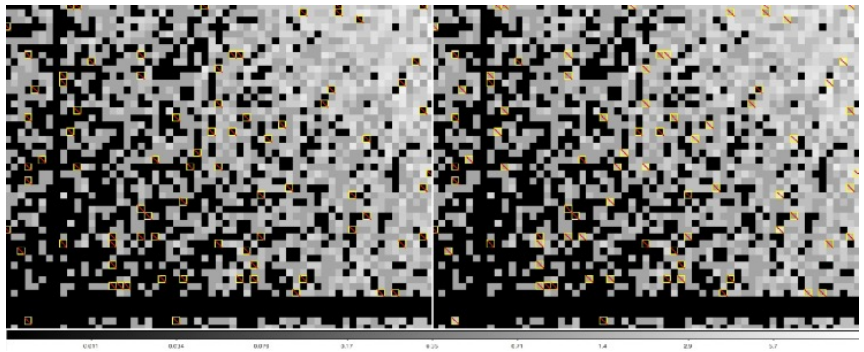
- Suzaku BI NXB spectrum from mission years 2–10
- charge injection on
  - can increase noise and flickering pixels
- default flickering pixel cleaning (cleansis)

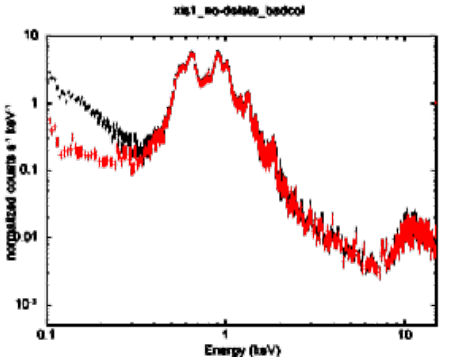


Soft up-turn: flickering or noisy pixels?

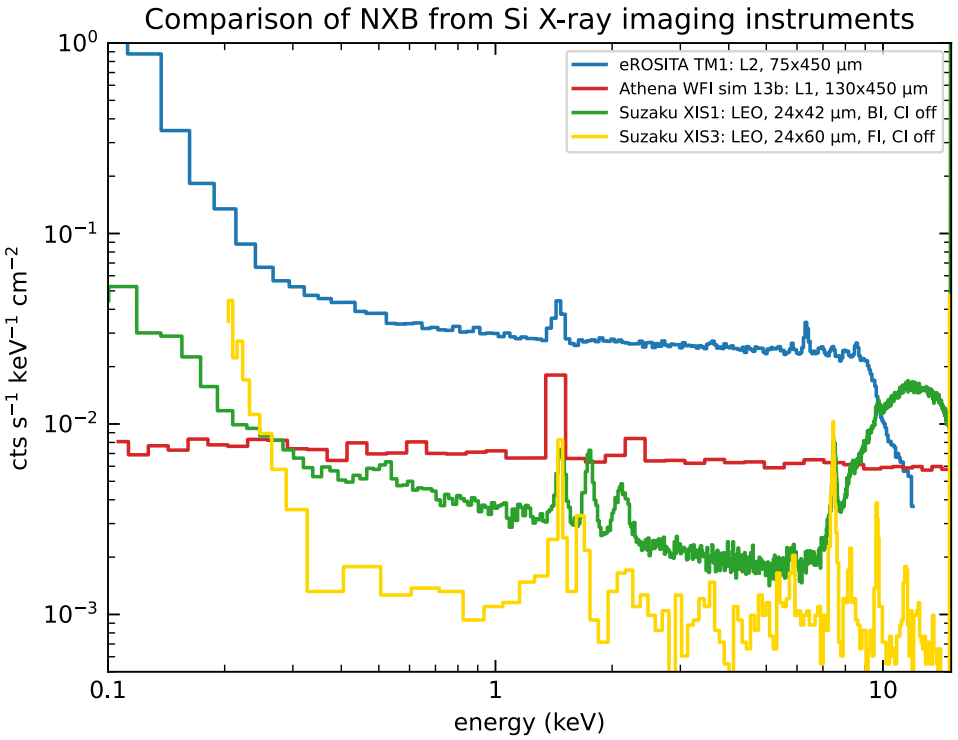


- Suzaku BI and FI NXB spectra from mission years 2–10
- charge injection on
  - can increase noise and flickering pixels
- ‘noisy pixel map’ applied
  - captures all flickering pixels during mission
  - affects short exposures more



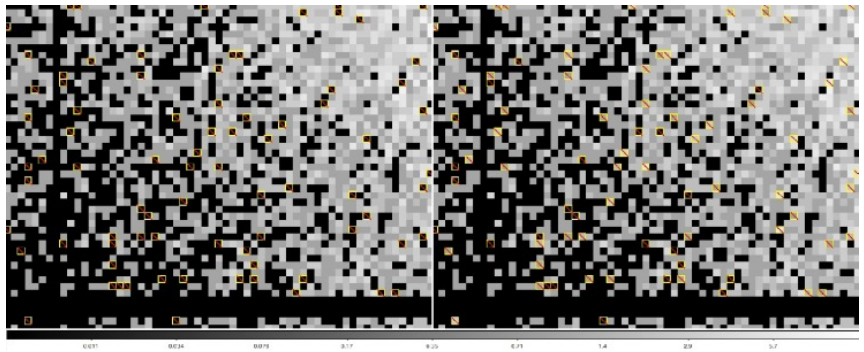


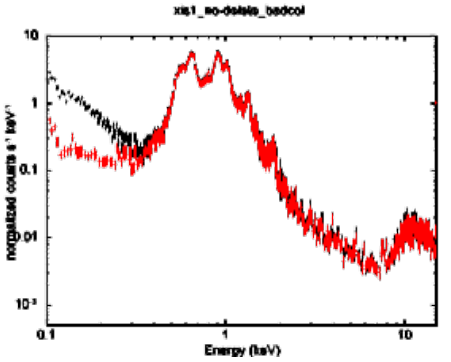
Soft up-turn: flickering or noisy pixels?



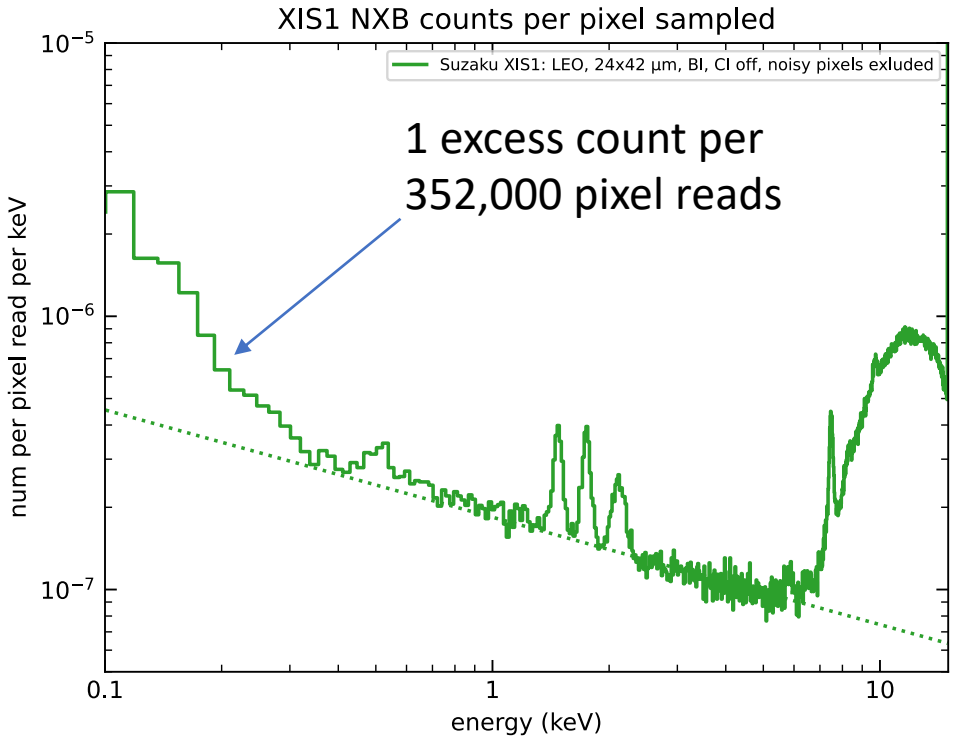
- Suzaku BI and FI NXB spectra from mission year 1
- charge injection of
- ‘noisy pixel map’ applied

- Most pristine data, reduces upturn by ~50%, but it’s still there.



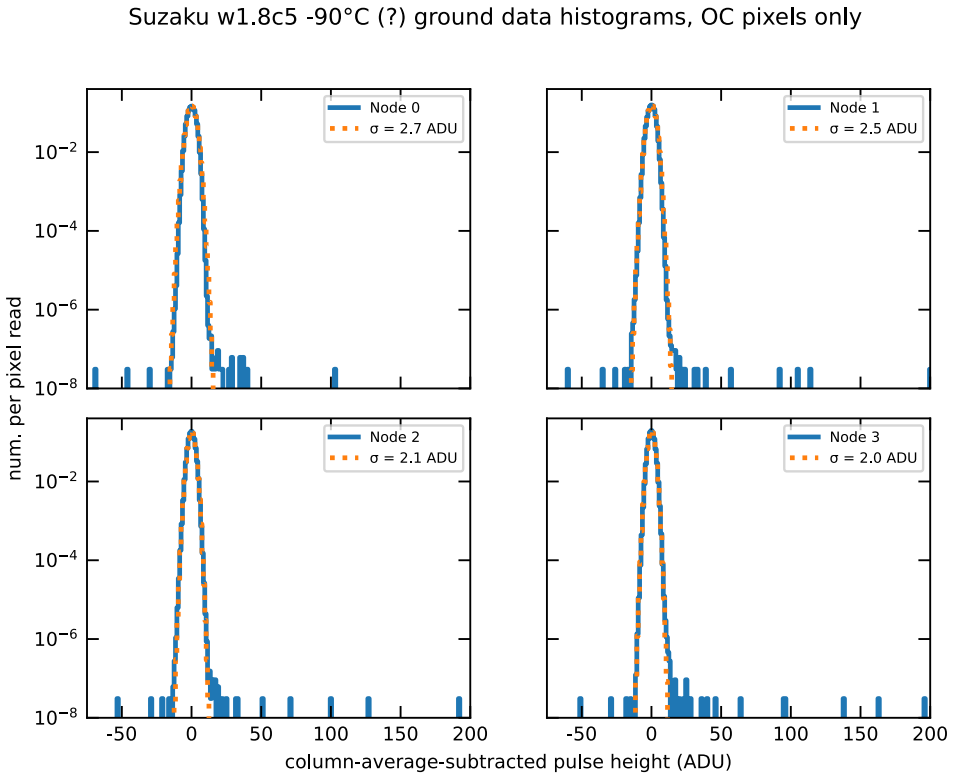


Soft up-turn: non-Gaussian amplifier noise?



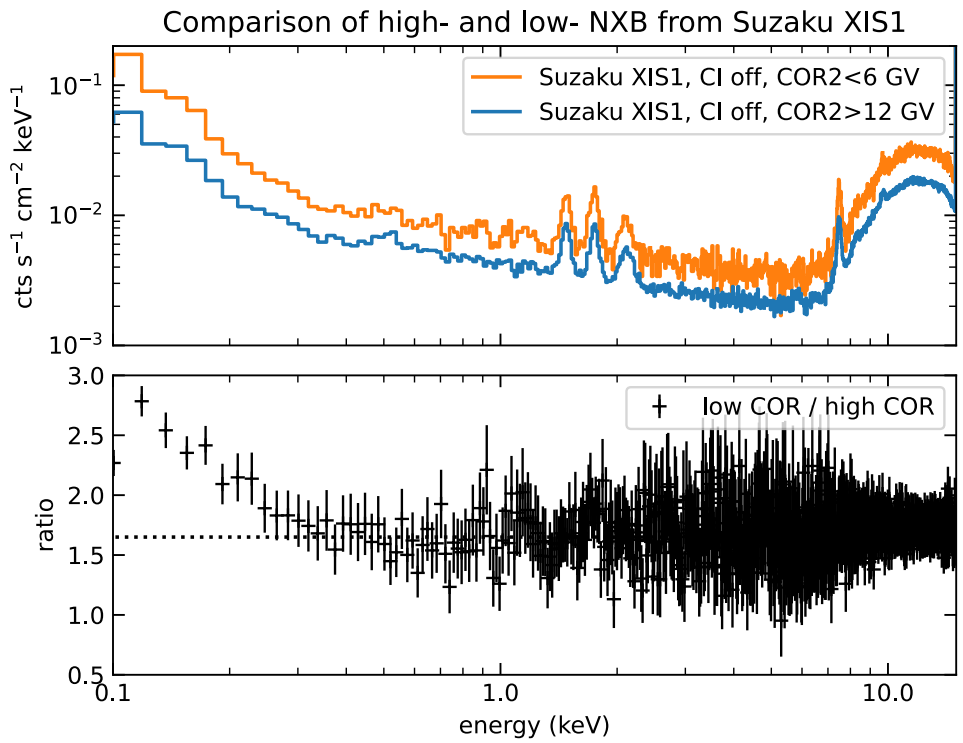
- If we assume it is Gaussian read-out noise with σ = 2.5e-:
  - 100 eV is 10-σ, or 1 every 10^{23} reads.
  - 1 per 33 billion years of observing.
- If we assume it is from a non-Gaussian noise tail:
  - 1 excess count per 350,000 pixel reads at 0.1–0.4 keV.
  - 3 events per XIS frame.

Soft up-turn: non-Gaussian amplifier noise?



- Suzaku BI0 (w1.8c5) ground data with flight electronics.
- 2000 bias and Fe55 frames, overclocks only.
- 1 excess sample > 27 ADU (100 eV) per 2–3 million reads.
- Explains <10% of the up-turn.
- Probably particles in the serial register.
- Analysis of in-flight data underway.

Soft up-turn: particles?

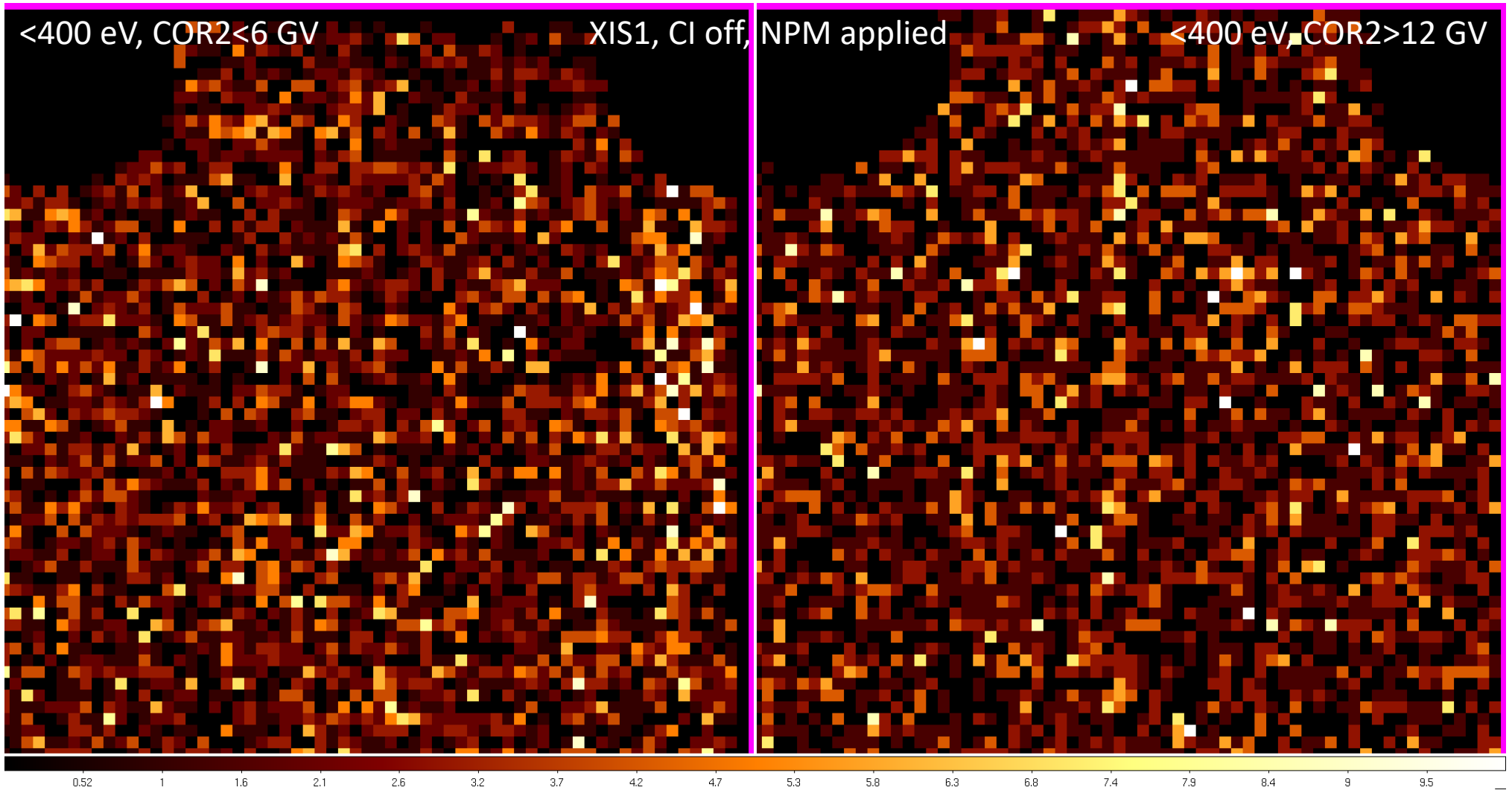


- Suzaku NXB is modulated first by orbit, less by Solar cycle.
  - i = 31° orbit traverses wide distribution of shielding by Earth's magnetic field ('cut-off rigidity' or COR).
  - Data taken only 'outside' SAA.
- Up-turn is higher during times of high background (low COR).
  - Shielding affects GCR protons with E < a few GeV.
- Can compare to HEO/L2, but Solar activity is dominant and correlates with instrumental evolution.

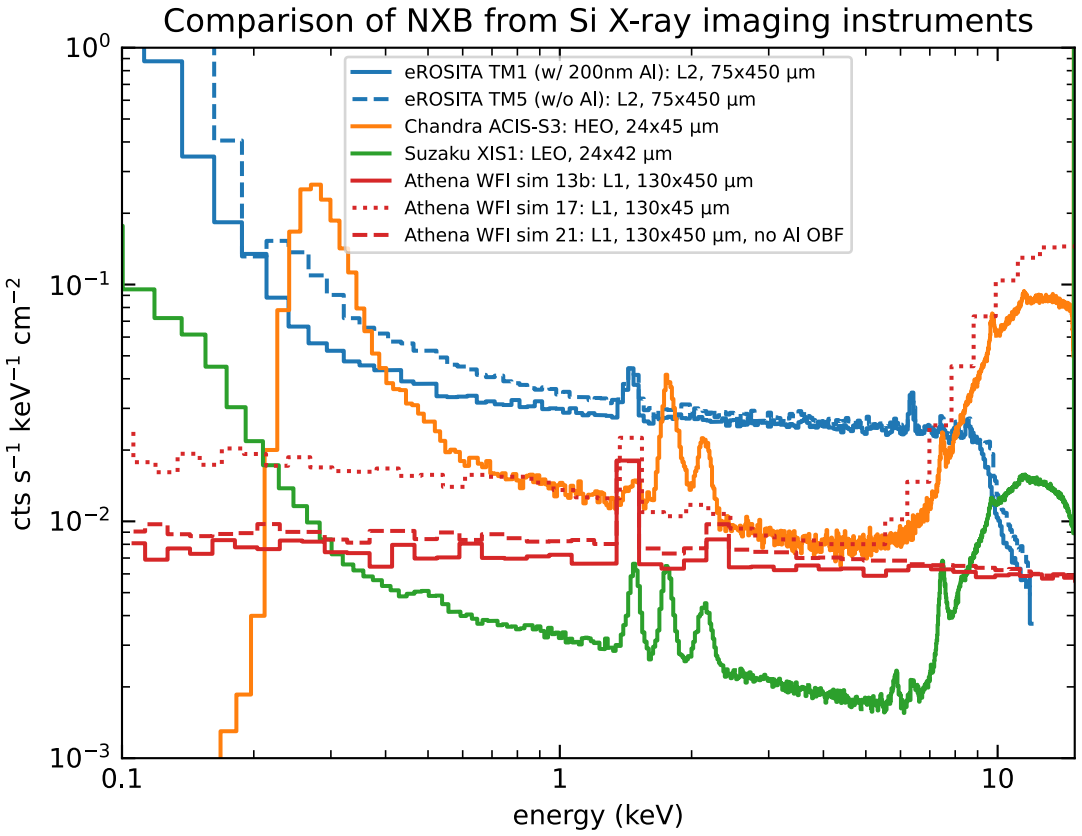
Soft up-turn investigation summary

- What causes this up-turn?
  - Non-Gaussian read-out noise?
    - Probably not. Still need to account for particles in raw frame overclocks.
  - Flickering or noisy pixels?
    - Definitely some, maybe 50%. Maybe more.
  - Improper bias/dark correction?
    - To be determined.
  - Redistribution/charge loss?
    - Unlikely for BI, unless it comes from…
  - Cosmic ray particles/secondary electrons?
    - …the interaction of CR-induced secondaries (e- and ɣ) in BI oxide layer. Can we simulate this?
    - Up-turn enhanced at low COR, so could be GCR-related and something missing in Geant4.
- Future steps
  - Verify energy deposit processes are being captured correctly in Geant4 post-processing.
  - Chat with eROSITA and Athena WFI experts about what they think.
  - *Present to IACHEC and see what they have to say.*

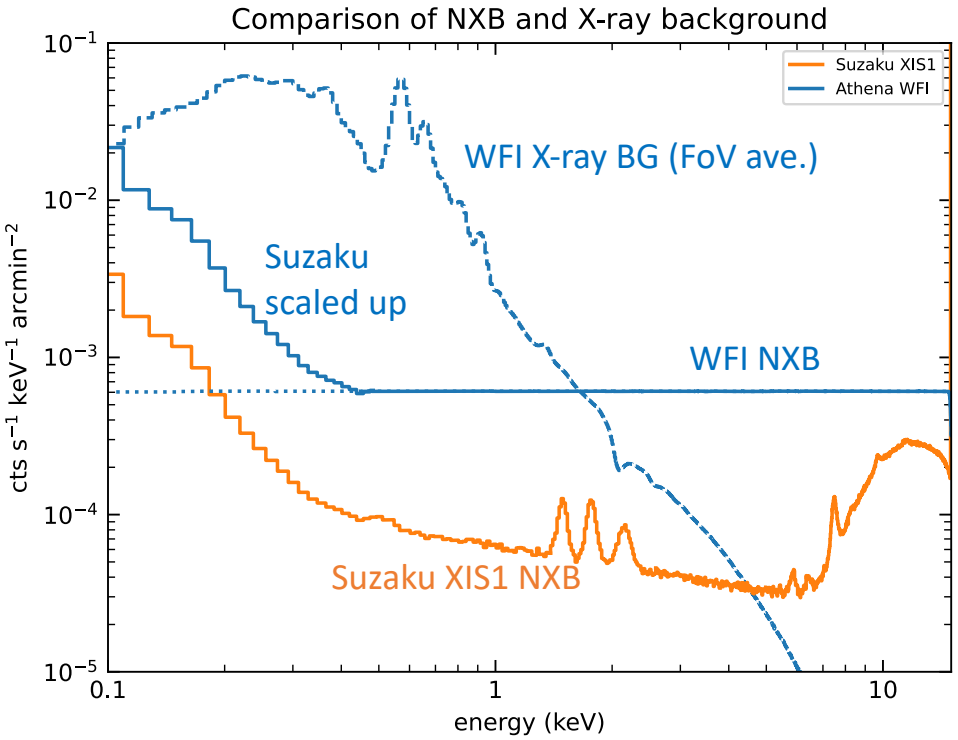
Soft up-turn: noisy pixels?



The problem


Comparison of NXB from Si X-ray imaging instruments
eROSITA TM1 (w/ 200nm Al): L2, 75x450 µm
eROSITA TM5 (w/o Al): L2, 75x450 µm
Chandra ACIS-S3: HEO, 24x45 µm
Suzaku XIS1: LEO, 24x42 µm
Athena WFI sim 13b: L1, 130x450 µm
Athena WFI sim 17: L1, 130x45 µm
Athena WFI sim 21: L1, 130x450 µm, no Al OBF
cts s^{-1} keV^{-1} cm^{-2}
10^{0}
10^{-1}
10^{-2}
10^{-3}
0.1
1
10
energy (keV)

MIT: soft up-turn investigation



- Why do we care about Suzaku for WFI?

1. If WFI has an up-turn similar to Suzaku, it could rival Galactic foreground at soft energies.
2. If it's a Geant4 issue, there could be other unknown but more important issues.
3. Important to understand for future missions.

Soft upturn: redistribution/charge loss?

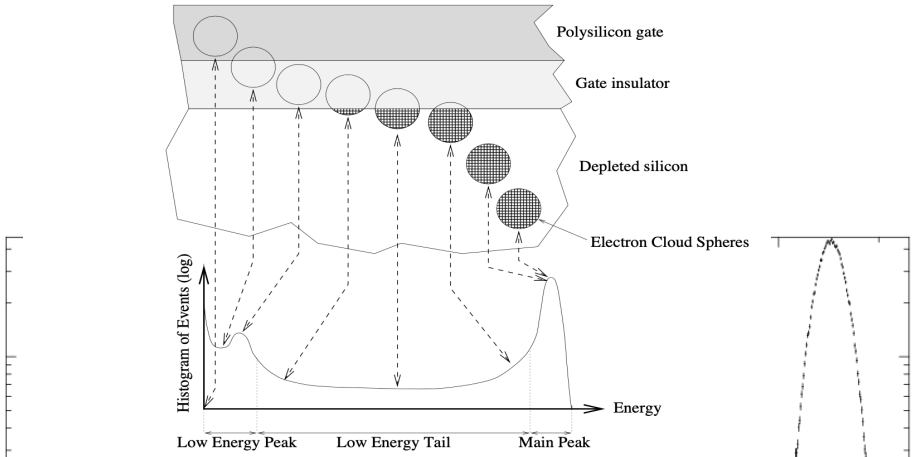
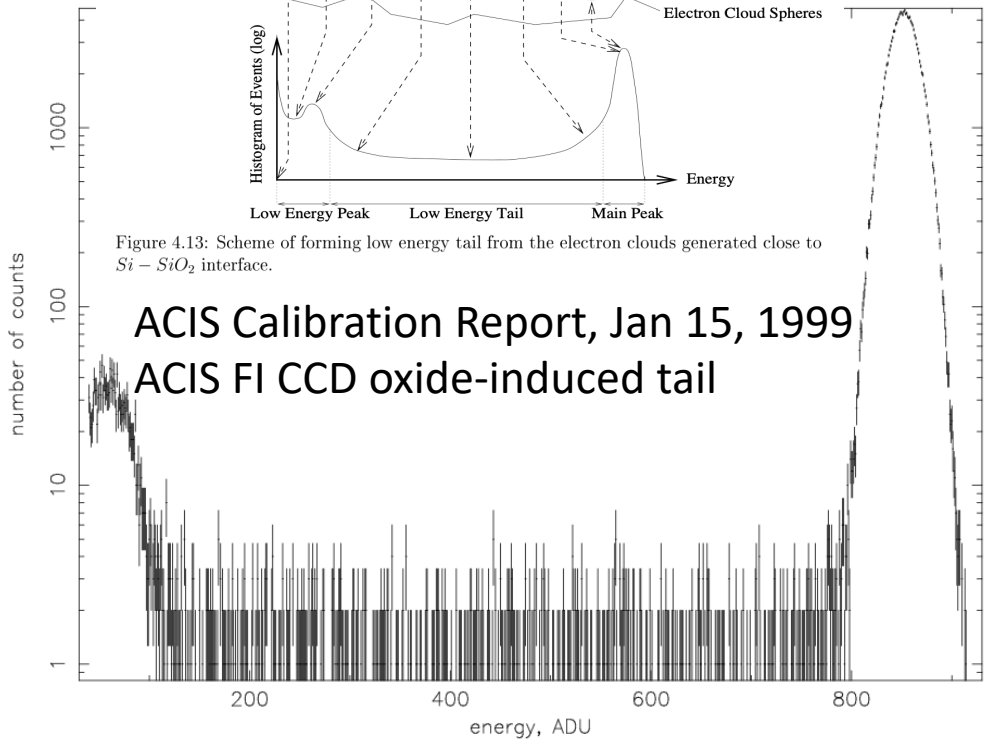
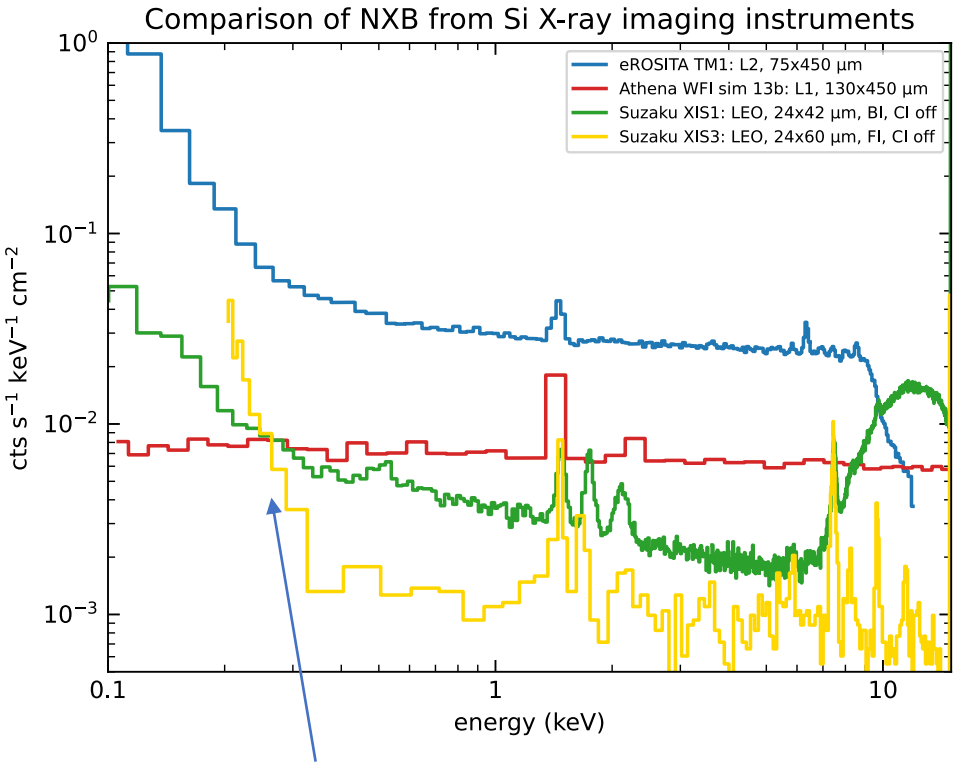


Figure 4.13: Scheme of forming low energy tail from the electron clouds generated close to $Si - SiO_2$ interface.



ACIS Calibration Report, Jan 15, 1999
ACIS FI CCD oxide-induced tail

Figure 4.8: Histogram of the CCD response to 1700 eV X-rays.



Maybe in the FI

Soft upturn: redistribution/charge loss?

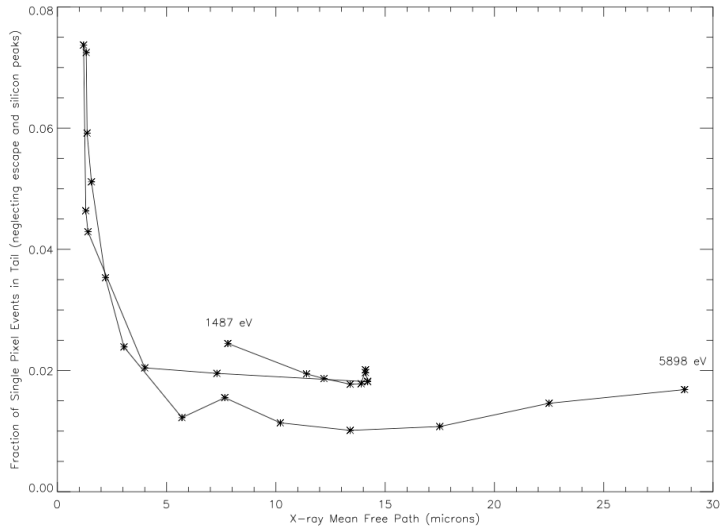
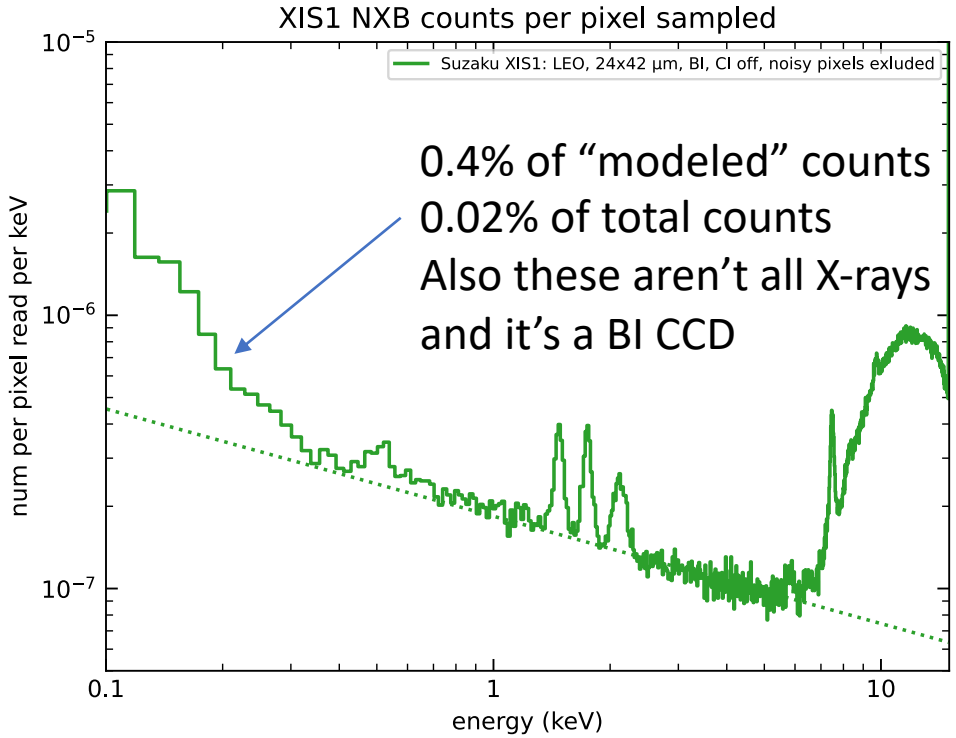


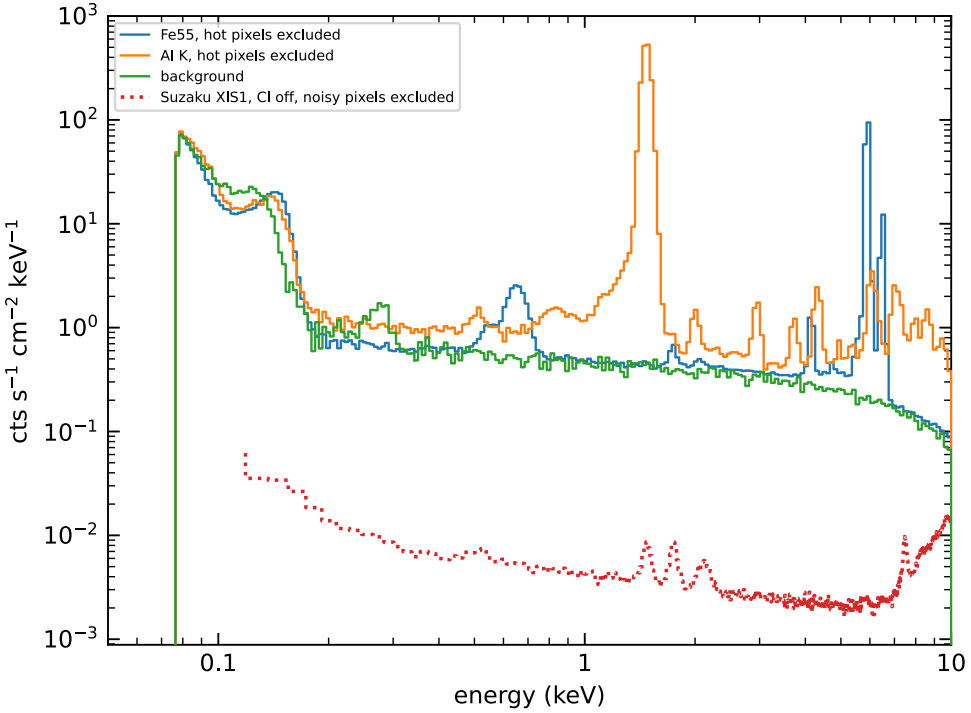
Figure 4.14: Fraction of single pixel events in tail as a function of characteristic absorption length in silicon.

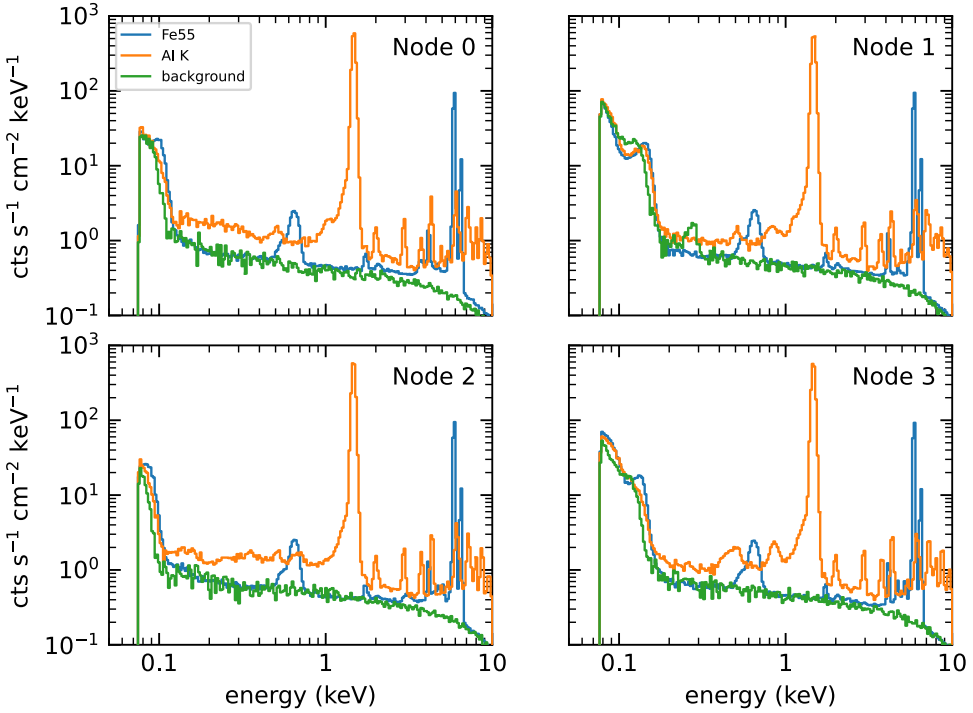


Maybe secondary e- and X-rays generated near and interacting in the BI gate oxide.

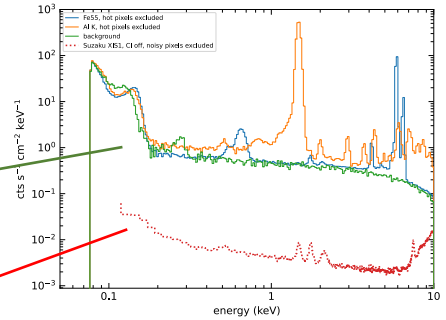
Soft up-turn: non-Gaussian noise?

Suzaku XIS1 ground data shows different upturn.

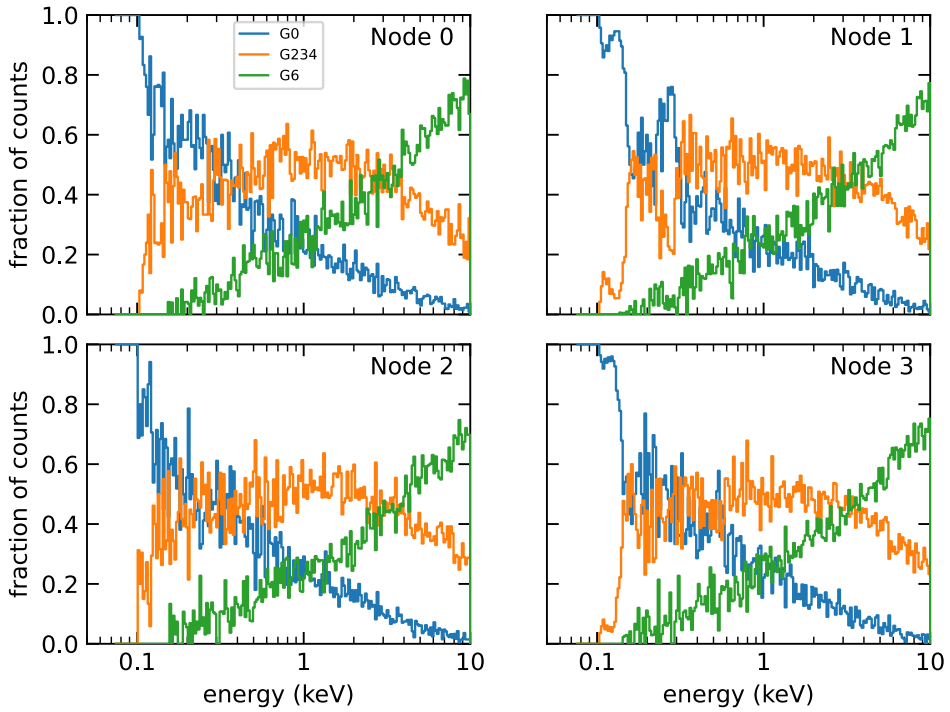




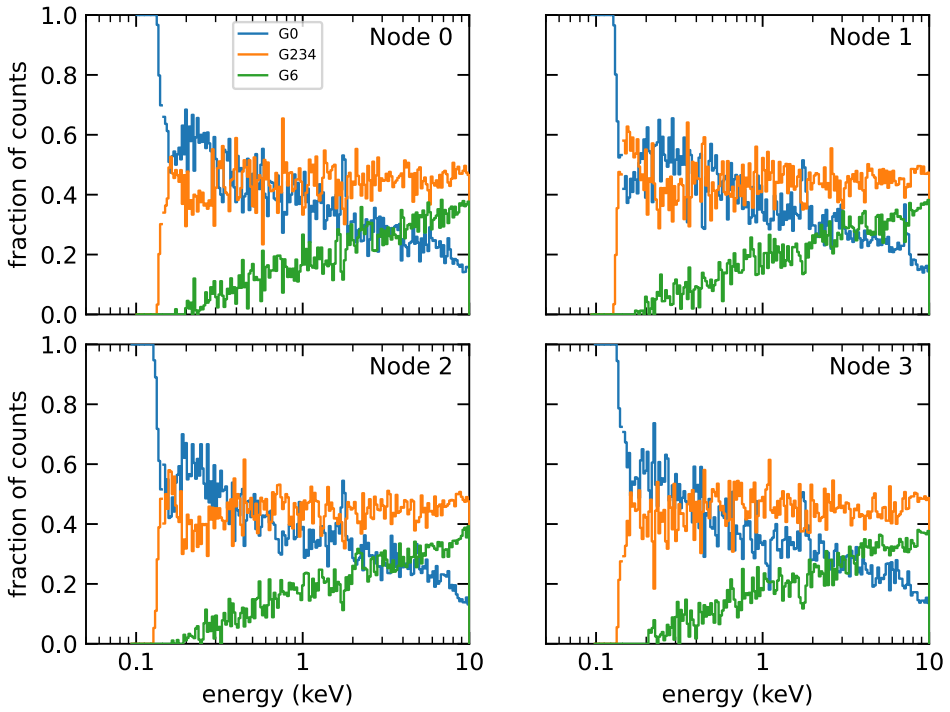
Soft up-turn: non-Gaussian noise?



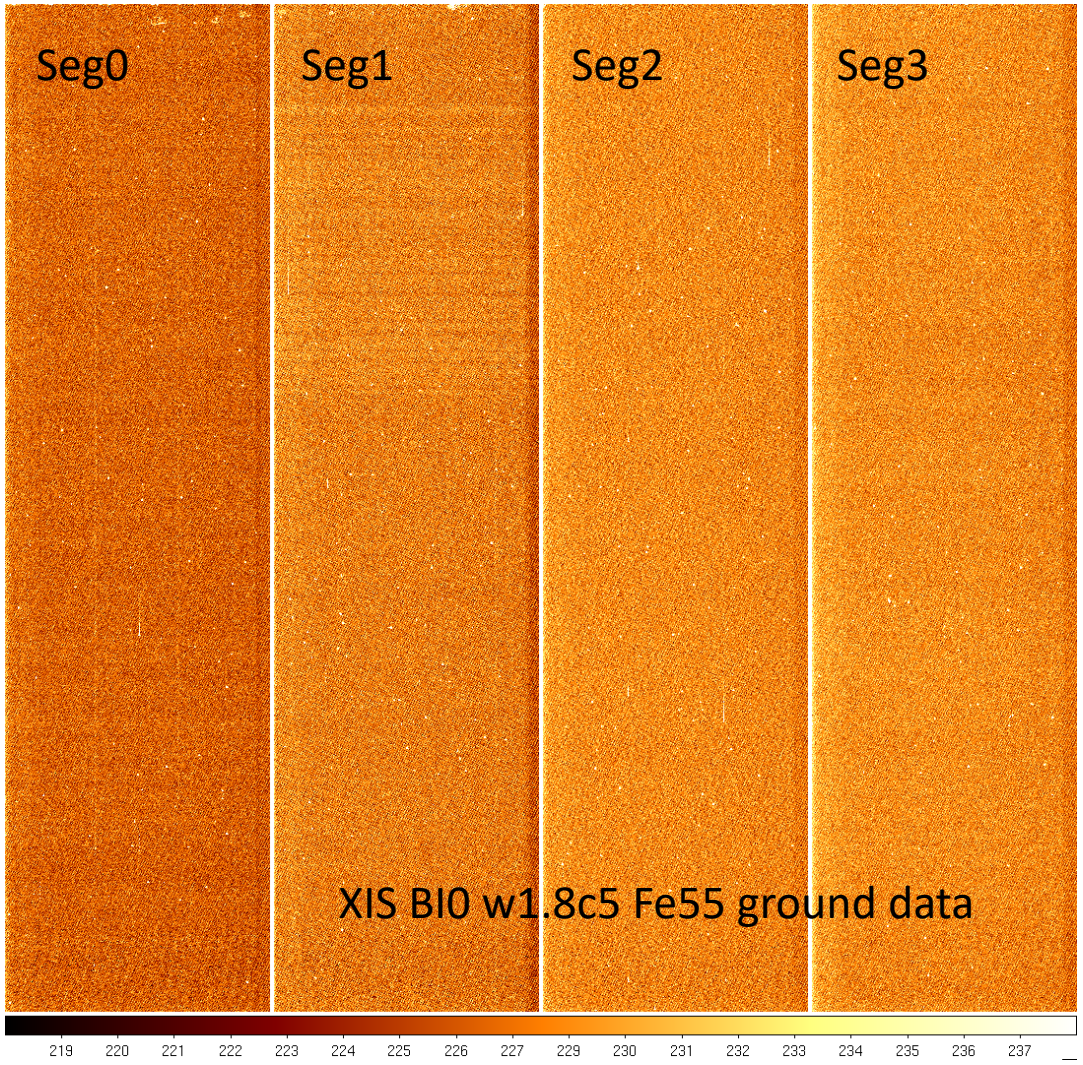
Ground background grade ratios



Flight background grade ratios



Soft up-turn: non-Gaussian noise?



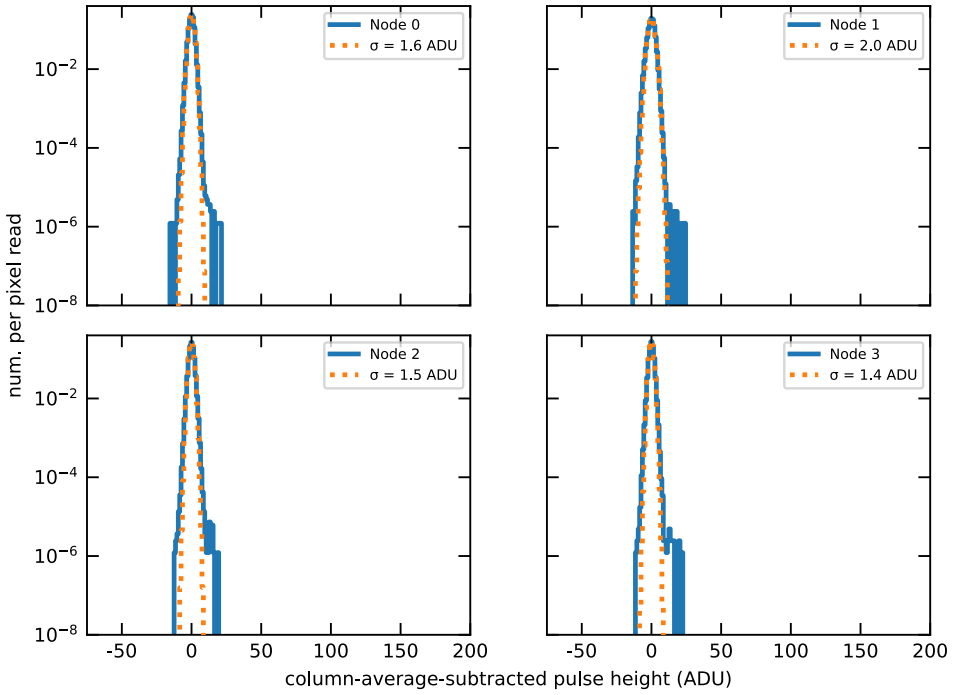
- Accumulate a statistically meaningful sample of signal-free pixel reads.
- Event corner pixels could have signal at this level.
- Ground and flight raw frames have X-rays and particles. But their overclocks don't. (Well, not many.)
- Get ACIS ops to observe with serial clock running backwards?

- Extracted column-mean-subtracted OC regions (1024x16-ish per node per frame)

Soft upturn: non-Gaussian noise?

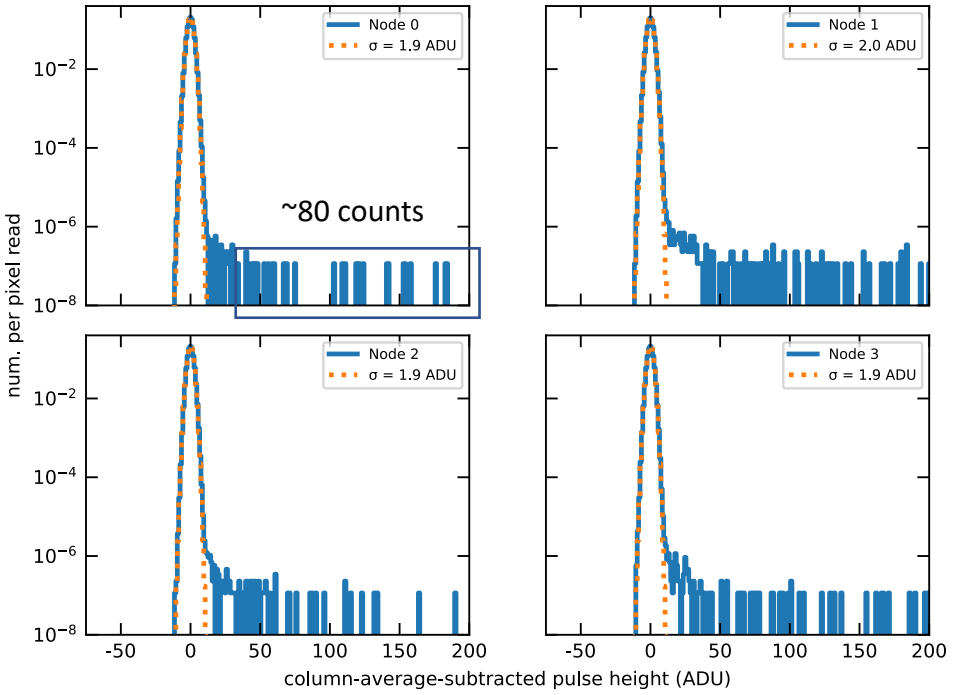
Suzaku and Chandra flight raw frames, over-clocks only—just read from serial register.
There are particle events, however.

Suzaku XIS1 (w1.8c2) -90°C flight raw frame histograms, OC pixels only



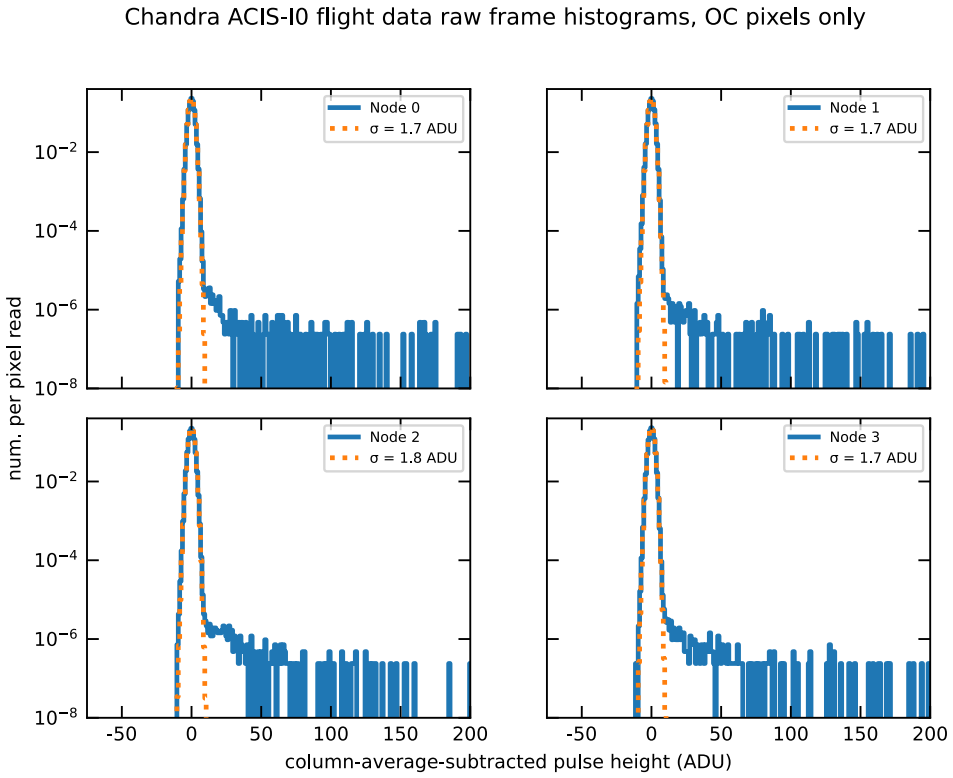
~50 raw frames (0.8M samples)
expect 2 non-Gaussian counts, get 0

Chandra ACIS-S3 flight data raw frame histograms, OC pixels only

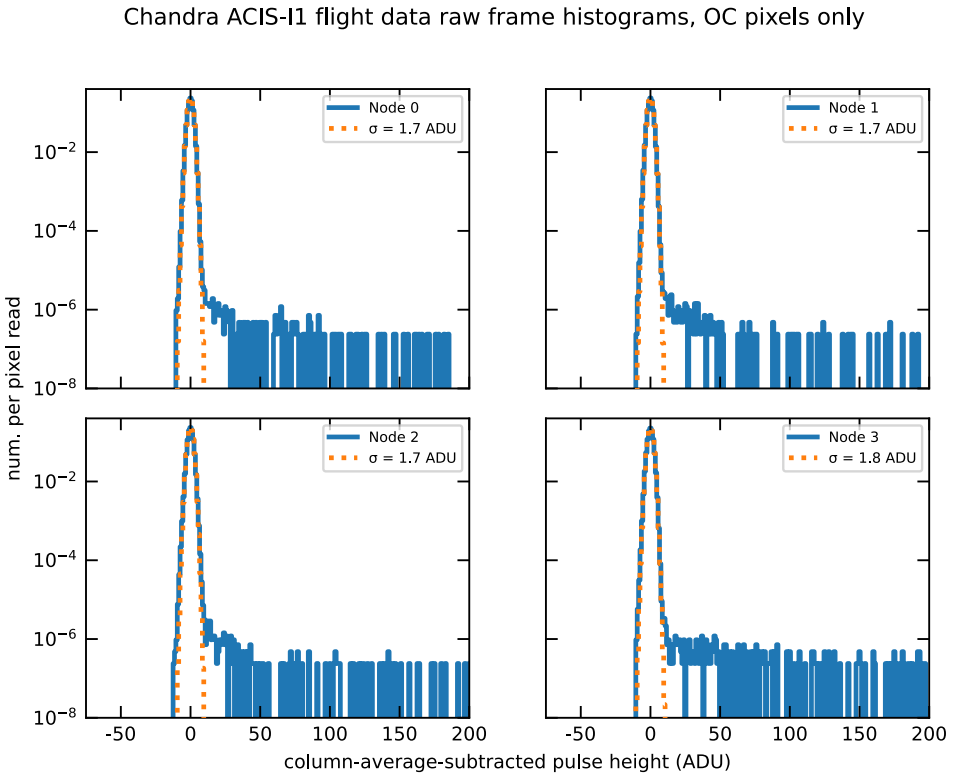


~500 raw frames (8M samples)
expect 20 non-Gaussian counts, get 80

Soft upturn: non-Gaussian noise?

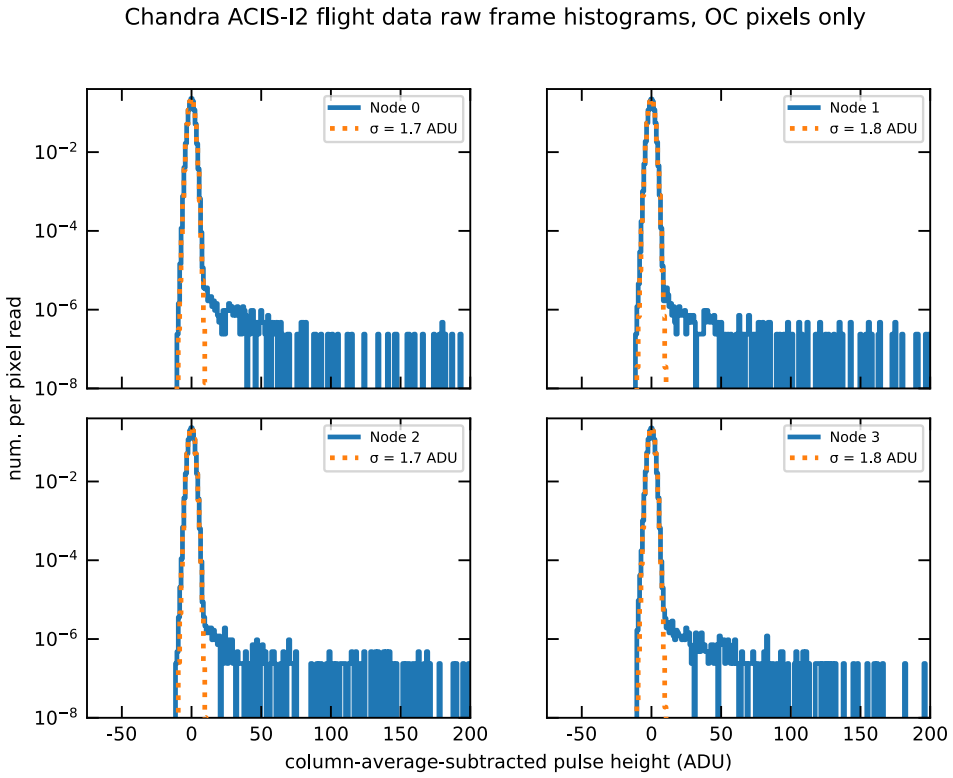


255 frames

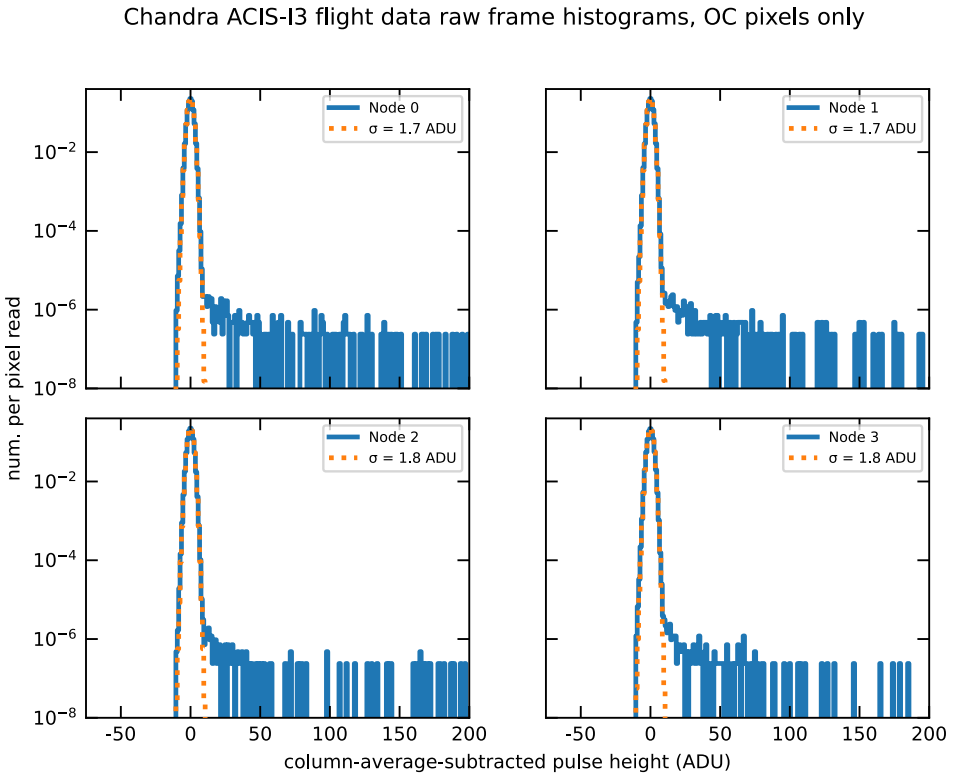


255 frames

Soft upturn: non-Gaussian noise?

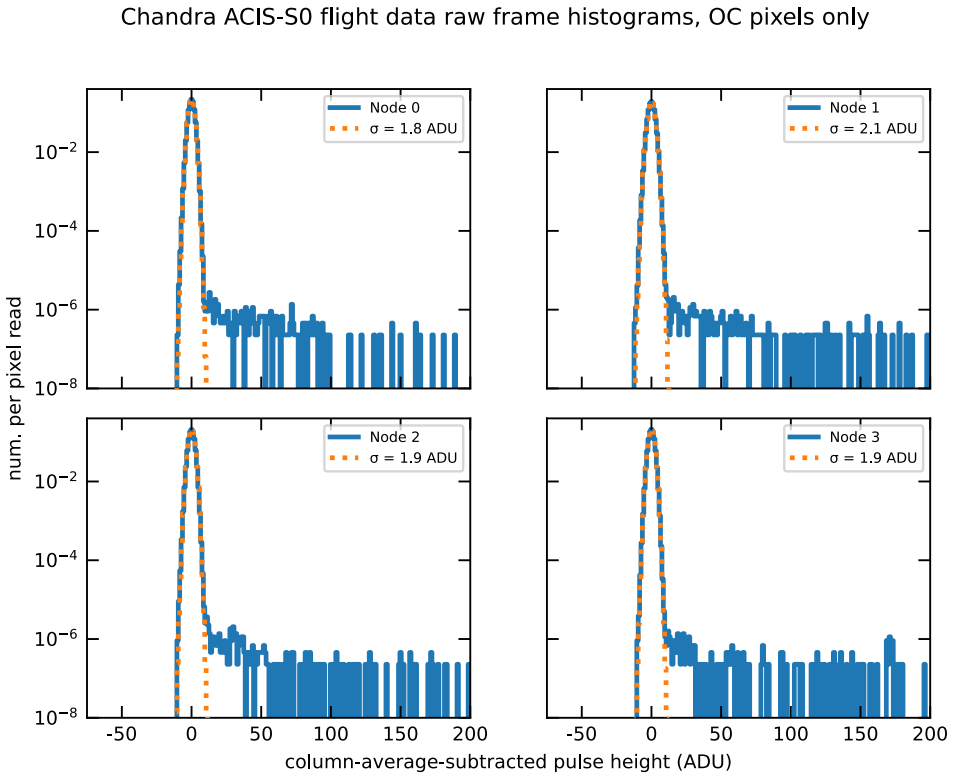


255 frames

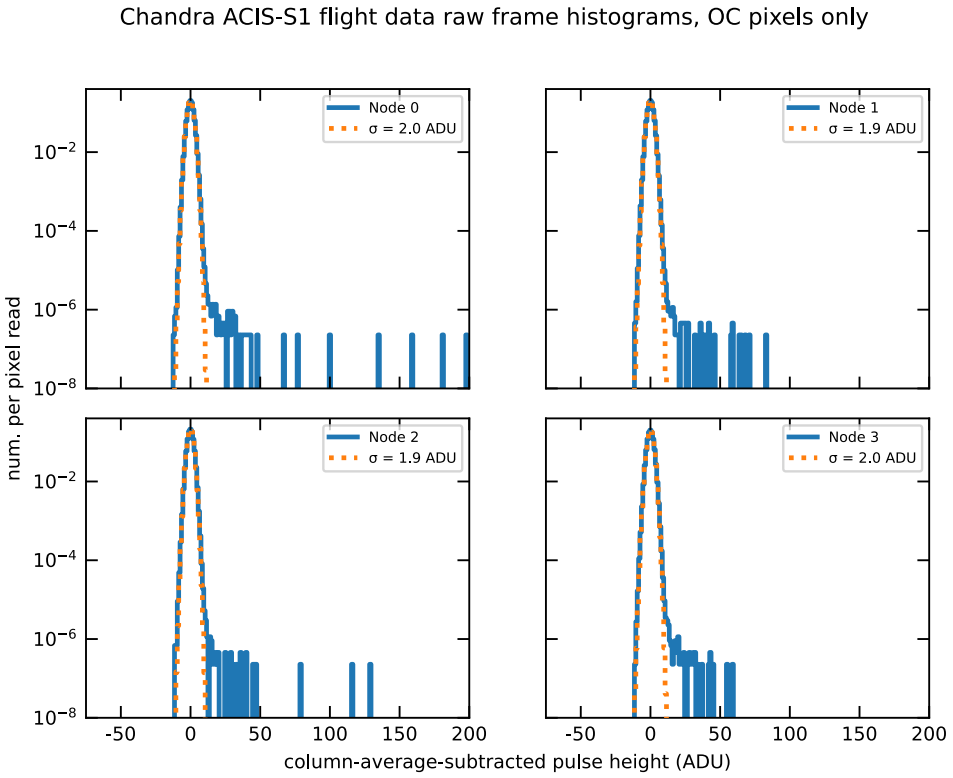


530 frames

Soft upturn: non-Gaussian noise?



255 frames



255 frames

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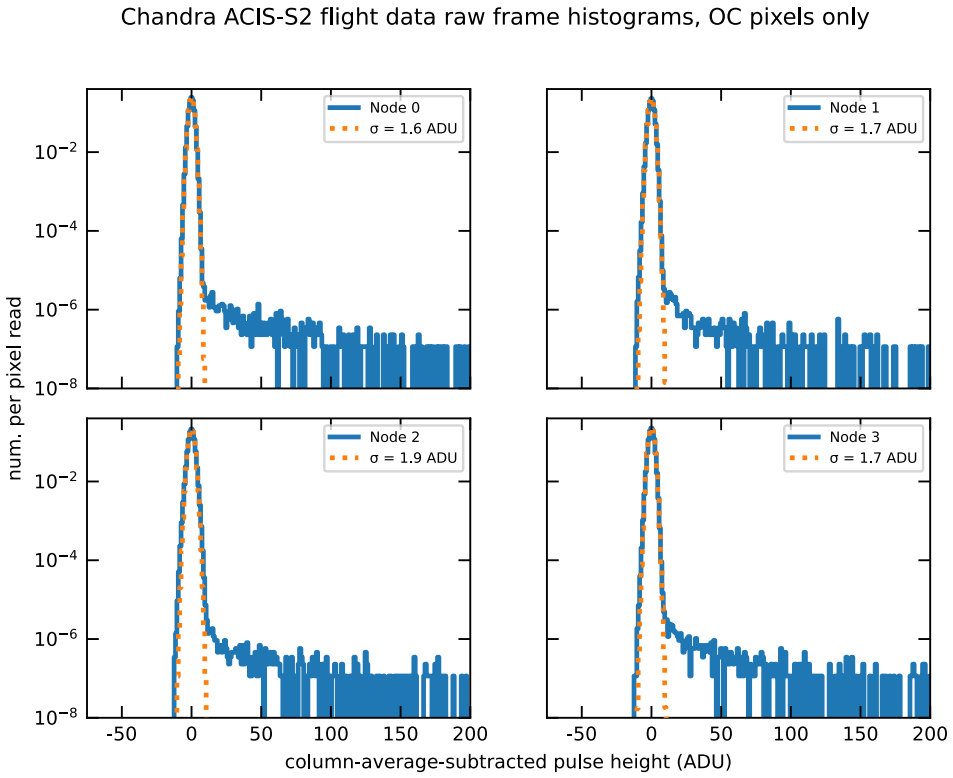
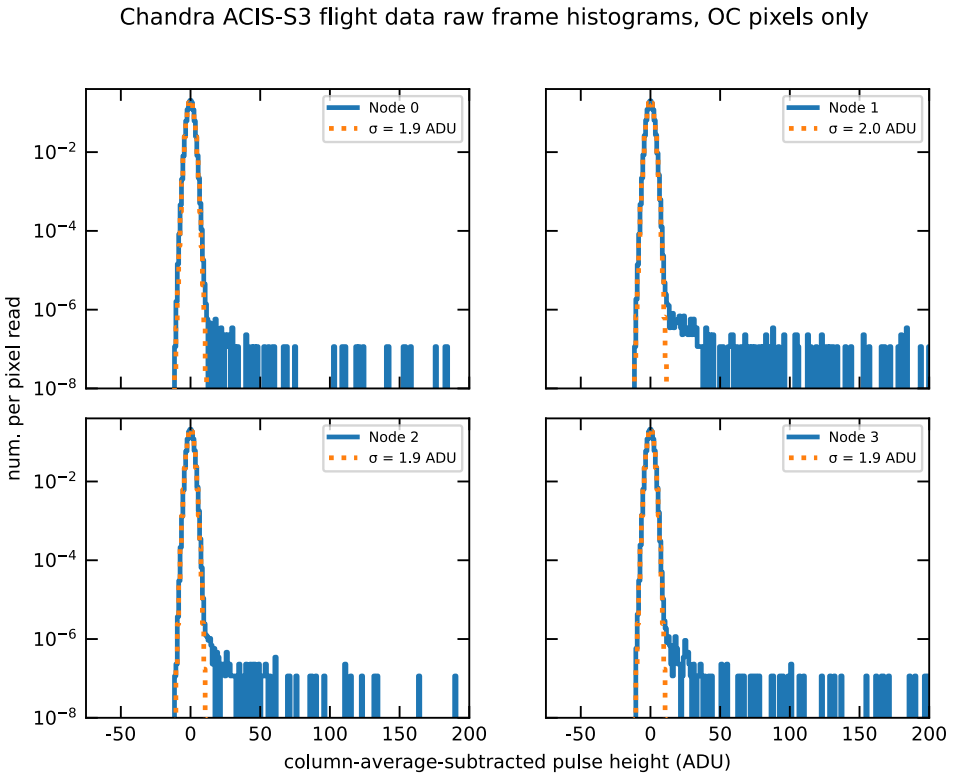


255 frames



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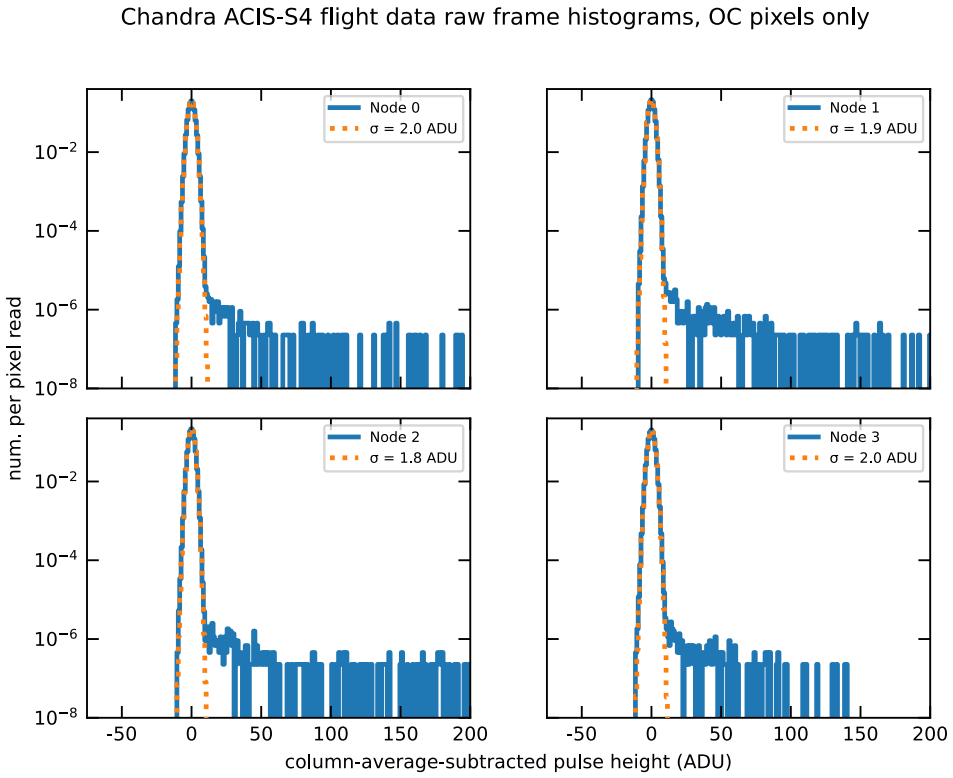
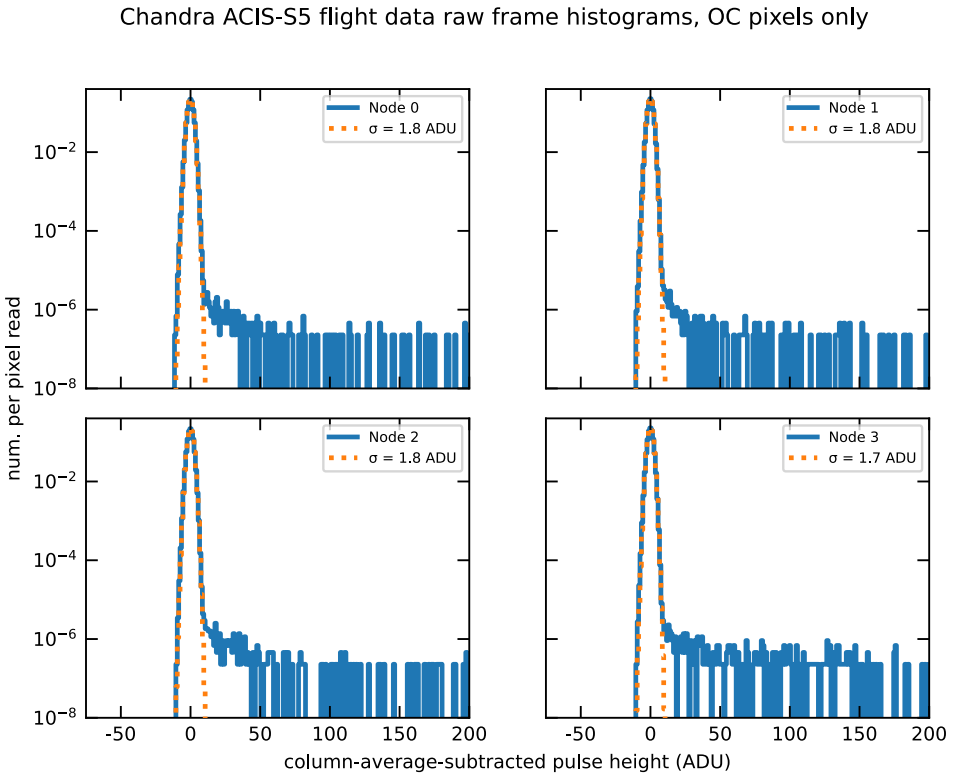
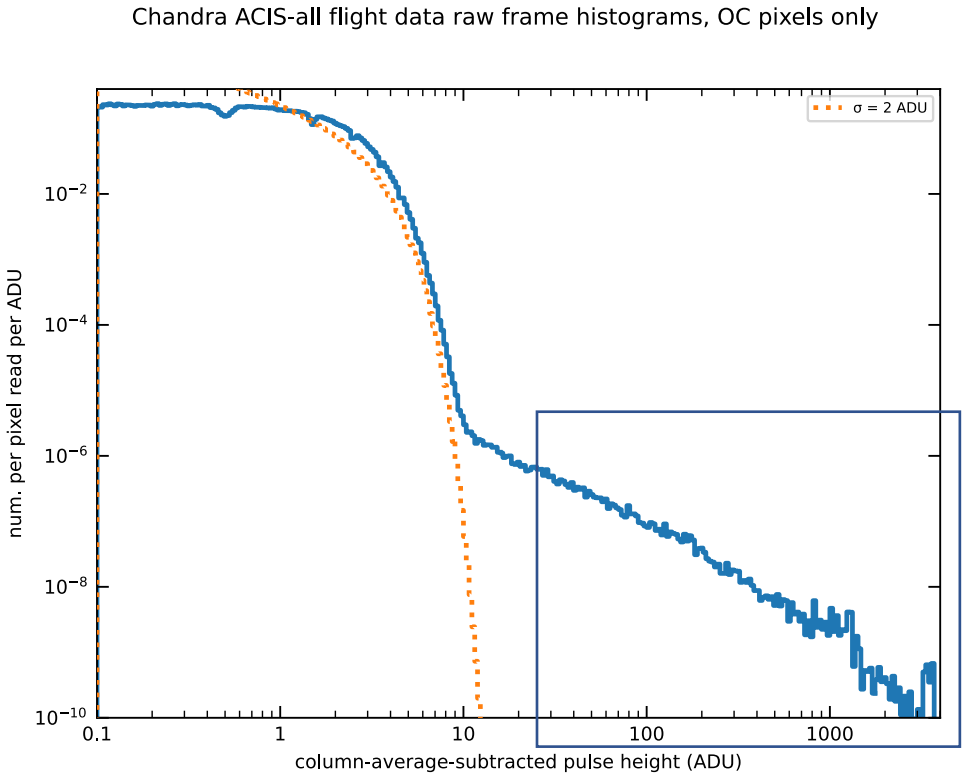


255 frames



255 frames

Soft upturn: non-Gaussian noise?



- 3146 ACIS flight raw frames combined (gasp!) for all CCDs and readout nodes
- Overclocks only
- 1 excess sample > 27 ADU (100 eV) per 35,000 reads
- 10x the up-turn
- Probably particles in the serial register, but we should be able to account for these. (TBD)