Detectors for AXIS

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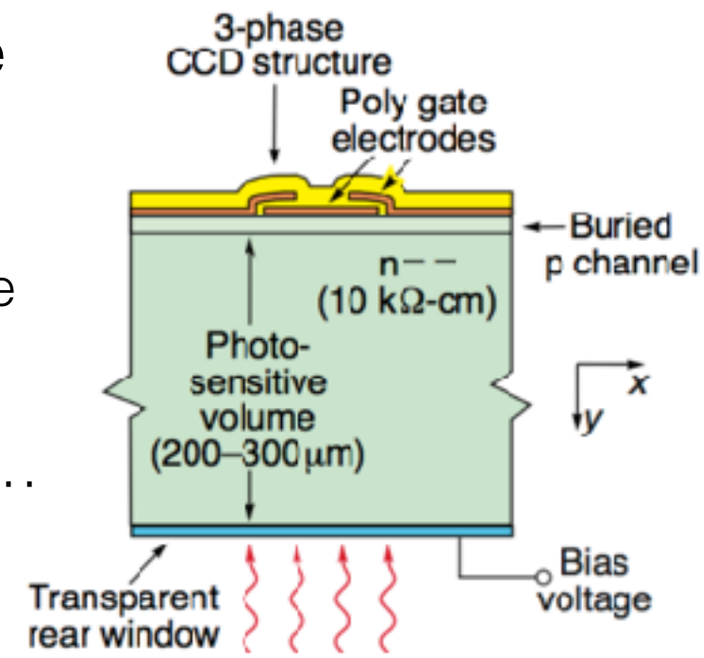
Outline

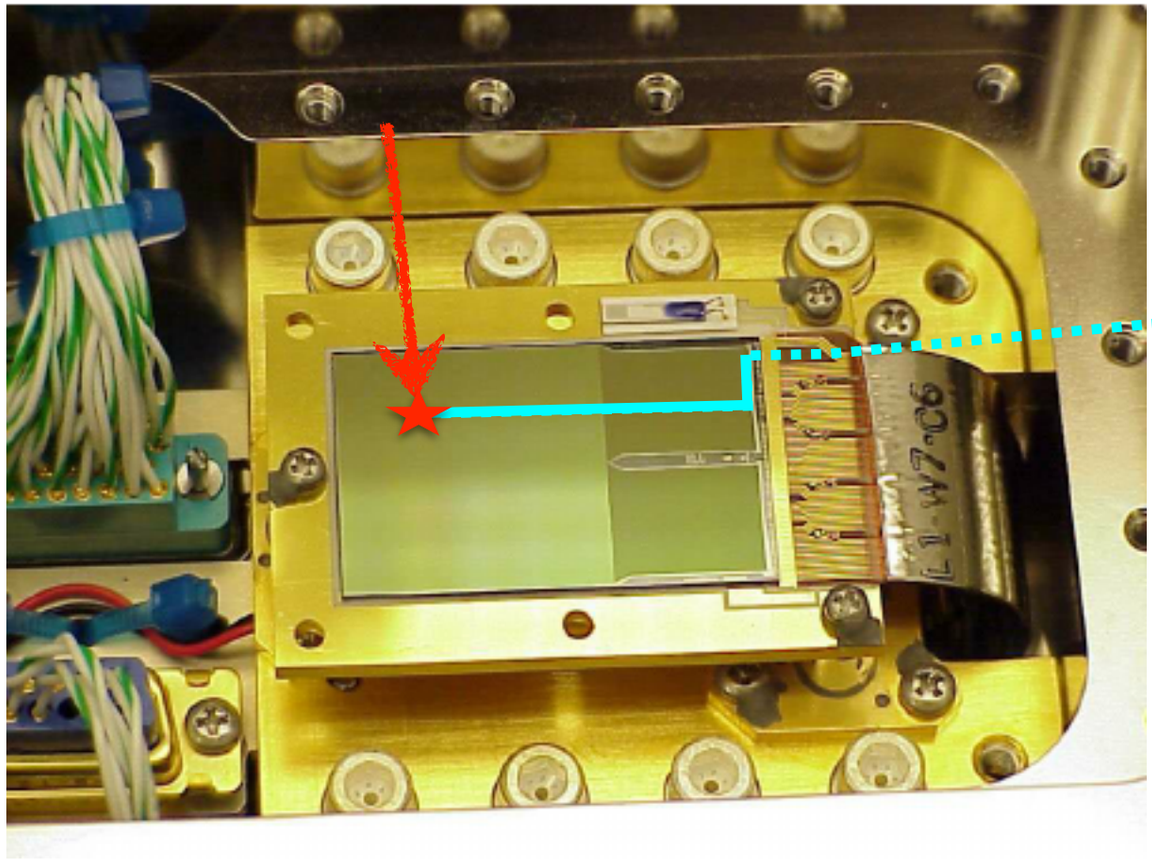
- detector technology and capabilities
  - CCD (charge coupled device)
  - APS (active pixel sensor)
  - notional AXIS detector
- background
  - particle environment vs. orbit
  - damage to detectors
  - limits to science
- cost and schedule

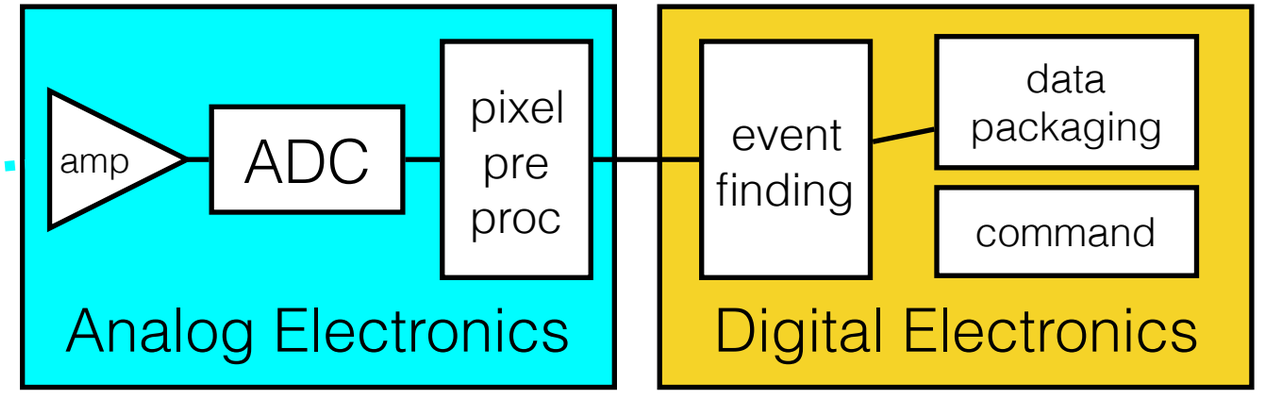
Technology

CCD Detector

- doped, depleted Si substrate converts X-rays to charge
- transfer charge across device to readout
  - integration time ~ seconds; limited by readout from frame store region, amplifier speed, external analog-to-digital converter
- flown on ASCA, Chandra, XMM, Suzaku, Swift, Hitomi, …
- development for *Lynx*, Explorers (MIT/LL)

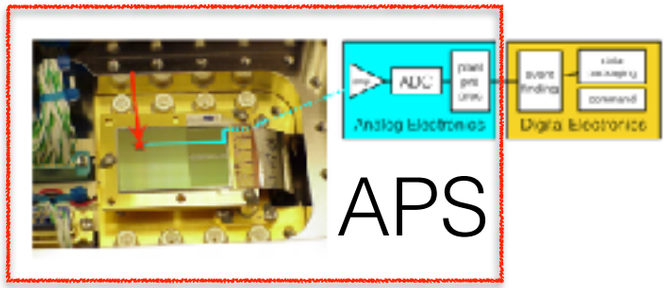




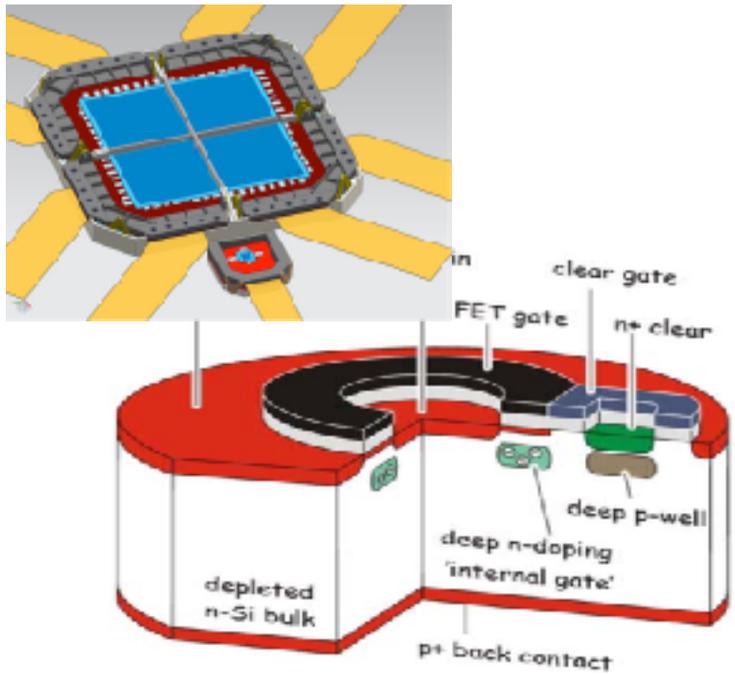


Active Pixel Sensor (APS)

- doped, depleted Si substrate converts X-rays to charge
- each pixel read out “in place” by pixel-based amplifier
- several architectures: CMOS, DEPFET, OTA (sort of)
- planned for Athena (DEPFET = Depleted P-channel Field Effect Transistor)
- development for Lynx and other X-ray applications
  (PSU, SAO/CfA, MIT/LL, others); optical/IR on HST, Wise, JWST

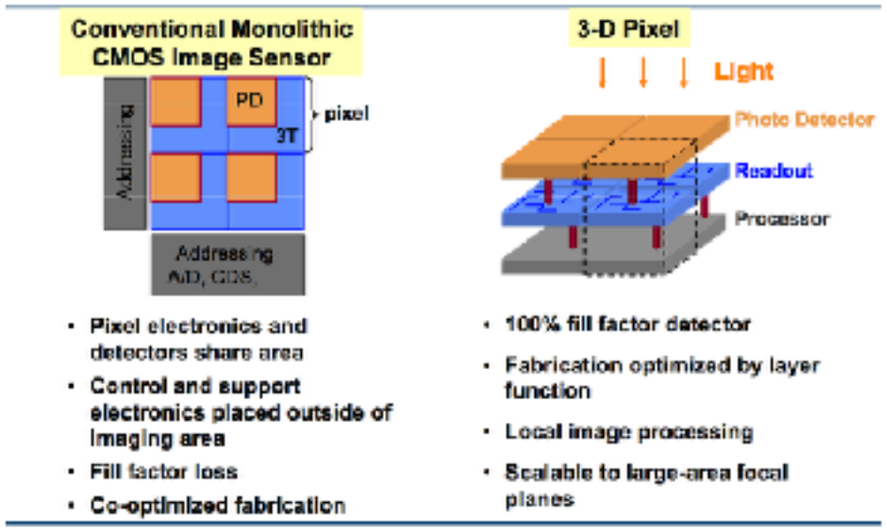


Athena DEPFET (MPE)

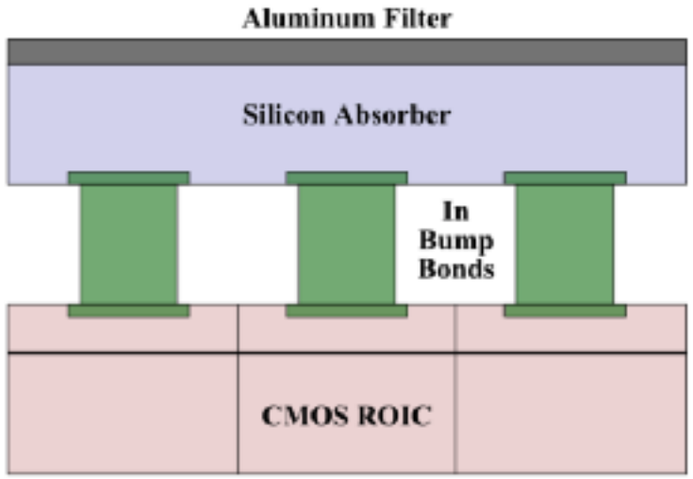


CMOS (MIT/LL)

Monolithic Hybrid



Hybrid CMOS (PSU)



CCD vs. APS Right Now

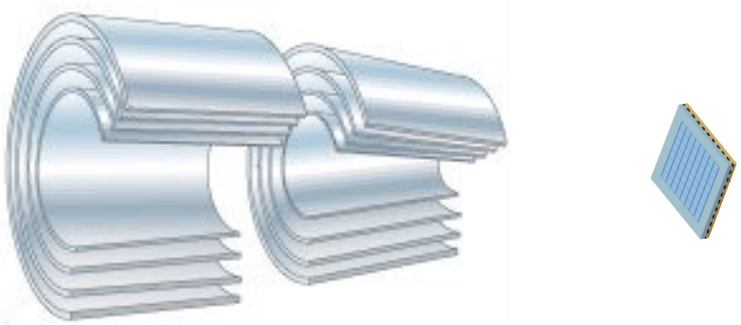
- CCD Advantages
  - Proven CCD spectral resolution (~Fano, low-noise, uniformity)
  - Proven soft X-ray (E < 0.5 keV) response
  - 1000s fewer amplifier gains to calibrate, at lower dynamic range; greatly affects low-energy response
    - split pixels come from different amplifiers on APS, must be *each* be calibrated down to very low threshold
- CCD Disadvantages
  - Radiation susceptibility
  - Lower frame rates
  - Higher power consumption

Detector Comparison (Eric's take)

	APS	CCD
• fast readout		
• why: reduce pile-up, improve dynamic range, timing resolution		
• problems: increased noise, power (Fano limit @ 0.2 keV is 2.5 e^-)	✓	✗
• small pixels		
• why: take advantage of angular resolution, better BG rejection		
• problems: manufacturing, requires faster readout, more digital processing, more split events so very accurate pixel gain calibration required (over high dynamic range for APS)	✗	✓
• deep depletion		
• why: increase hard X-ray sensitivity, better BG rejection		
• problems: complicated by structure of 3-D integrated detector + amplifier (monolithic CMOS)	–	–
• radiation tolerant		
• why: better spectral resolution, lower dark current, fewer bad pixels	✓	✗
• problems: requires cooling, charge injection, optimal orbit		
• flight heritage		
• why: detectors need to work in space	✗	✓
• problems: only CCDs have flown for X-ray detectors		

“Easy” AXIS Detector

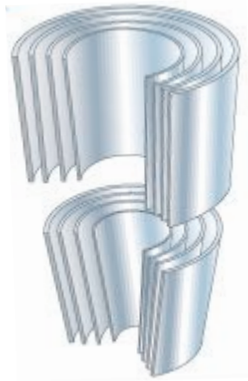
- 1 back-illuminated (BI) CCD, 3 cm (11 arcmin) FOV
- 3450 x 3450 imaging array of 8 μm (0.2″) pixels
- 50–100 μm depletion (0.1–10 keV sensitivity)
- frame-transfer architecture used for almost all X-ray CCD instruments flown to date
- 16 outputs @ 5 MHz
  - 6 frame/sec (20x Chandra)
  - uniform response to split events

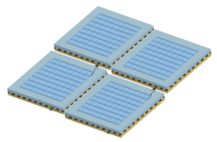


- charge injection to reduce CTI
- QE with OBF: 25% (0.2 keV), 75% (0.5 keV), >90%(>1 keV)

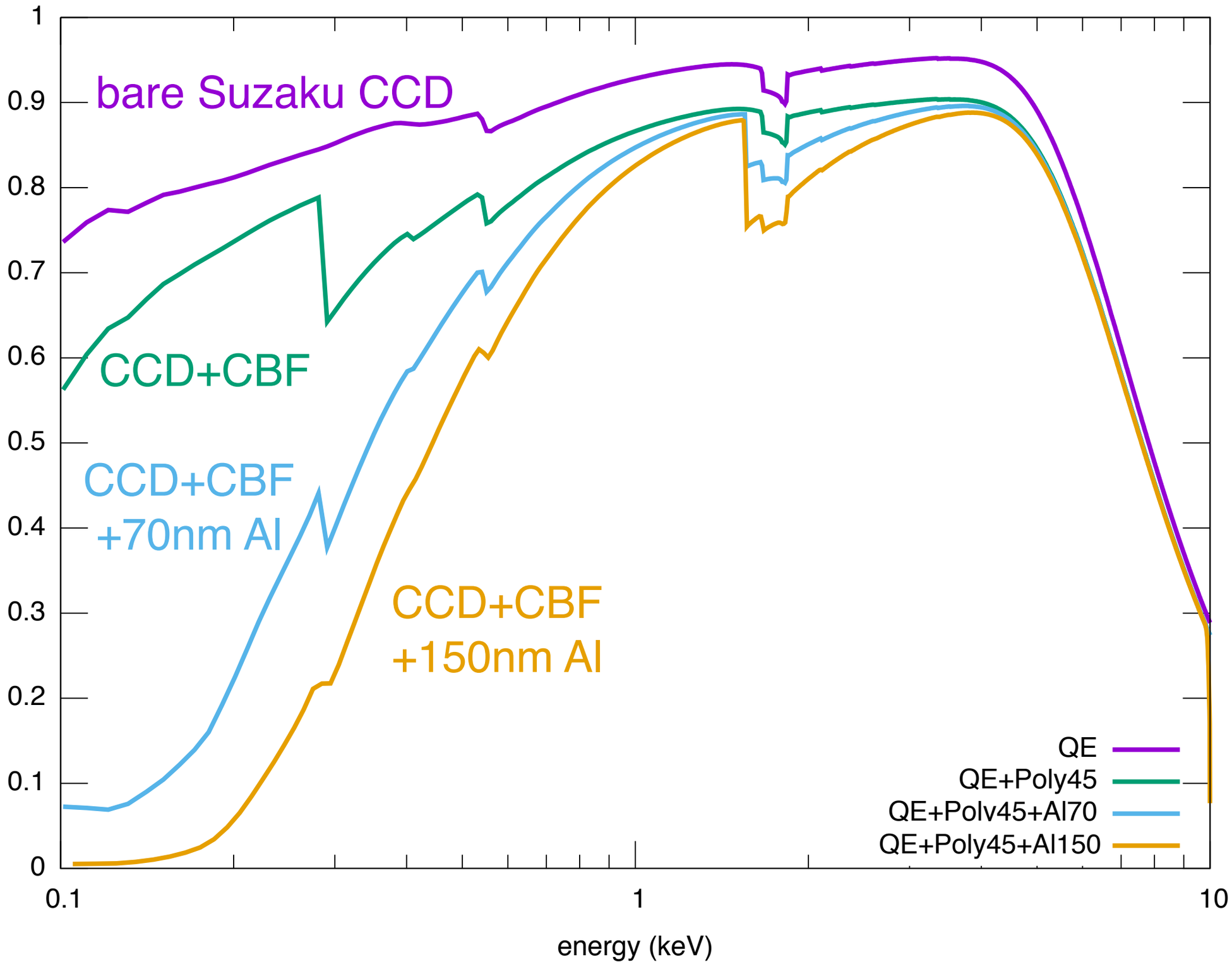
“Hopeful” AXIS Detector

- 4 BI CCDs in 2x2 array, 3.2 cm (12 arcmin) FOV
- each 4096 x 4096 imaging array of 4 μm (0.09″) pixels, with on-chip binning available to 8 μm (0.17″)
- 50–100 μm depletion (0.1–10 keV sensitivity)
- frame-transfer architecture used for almost all X-ray CCD instruments flown to date
- 128 outputs @ 5 MHz
  - 33 frames/sec (100x Chandra) at 0.09″ resolution
  - 122 frames/sec (400x Chandra) binned to 0.17″ resolution
  - high frame rate *and* uniform response to split events
- charge injection to reduce CTI
- QE with OBF: 25% (0.2 keV), 75% (0.5 keV), >90%(>1 keV)





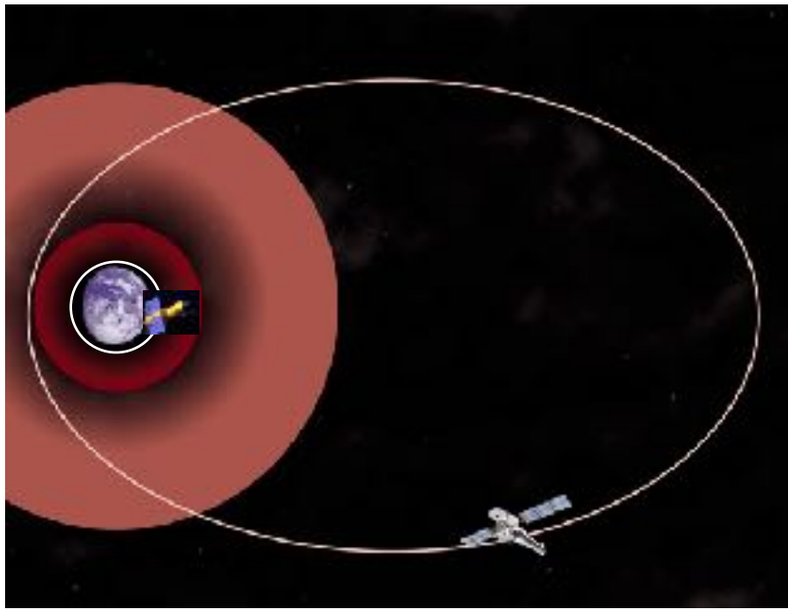
Filters and Quantum Efficiency



Instrumental Background

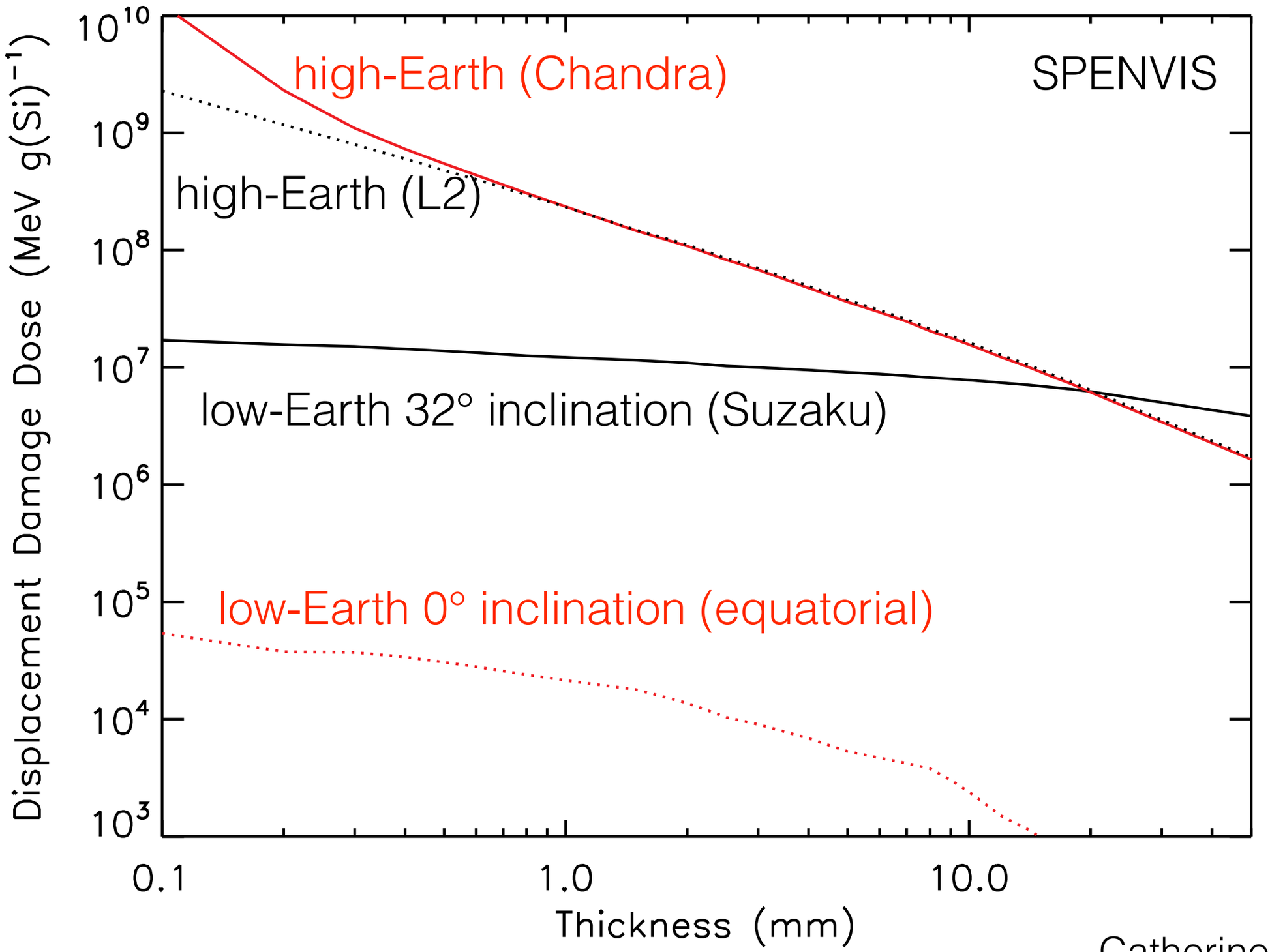
Instrumental Background – Radiation Damage

- non-ionizing radiation causes displacement damage to Si lattice sites, creates charge traps and CTI
- degrades spectral resolution, increases dark current
- cooling (-100 C) improves performance
- effects depend on types of traps, time constants, particle energy and type (Grant, Prigozhin @ MIT)
- compare Chandra and Suzaku (Grant, LaMarr, Miller @ MIT)
  - SPENVIS (SPace ENVironment Information System from ESA) modeling of radiation environment in different orbits
  - some assumptions/unknowns; take models with a grain of salt



(Photo: CXC/M. Weiss)

Instrumental Background – Radiation Damage



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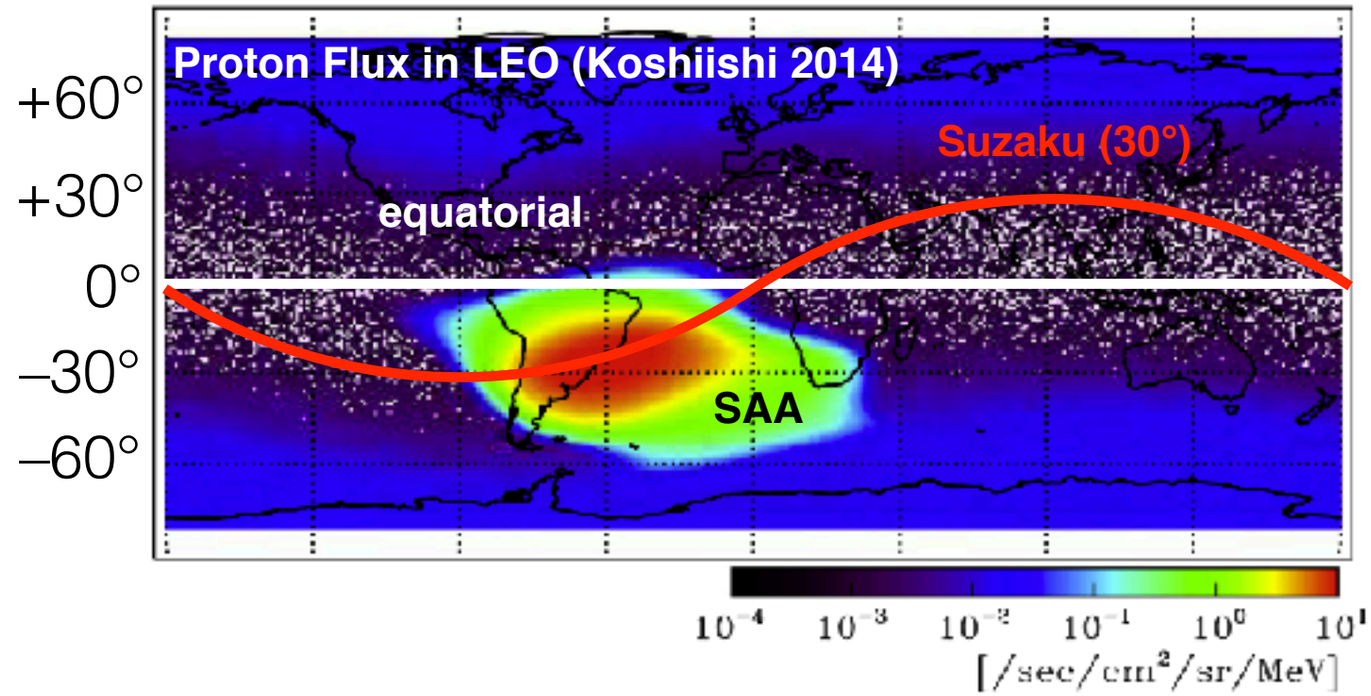
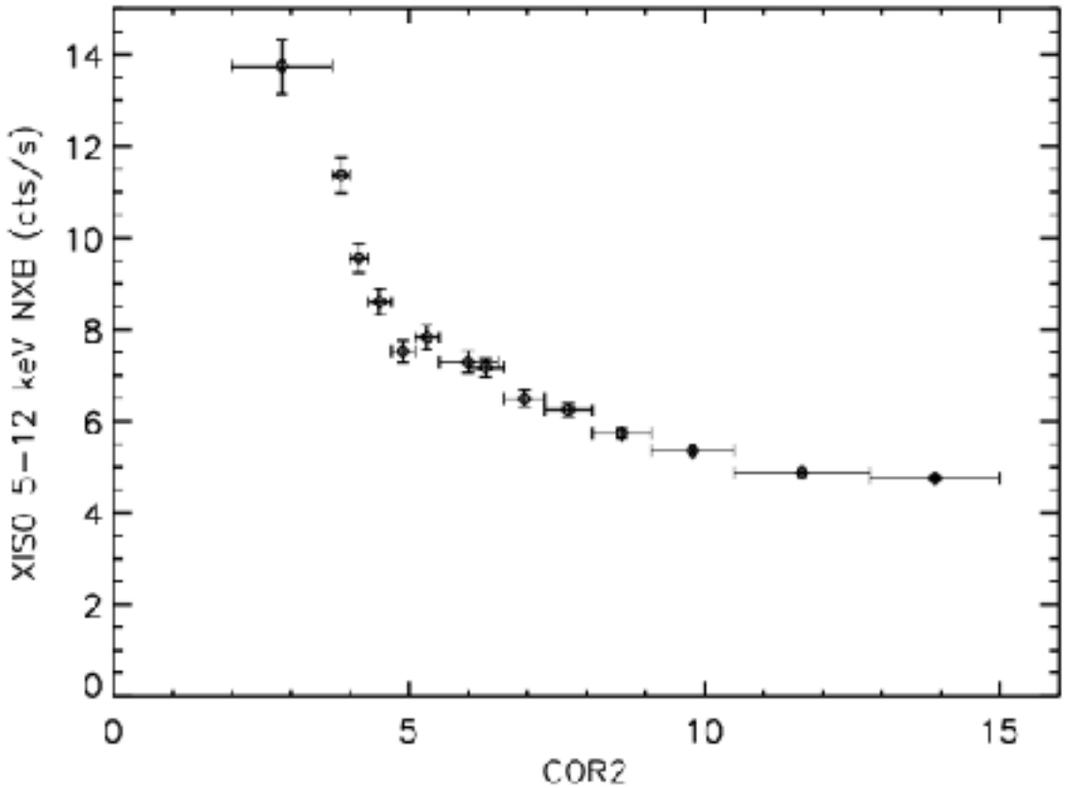
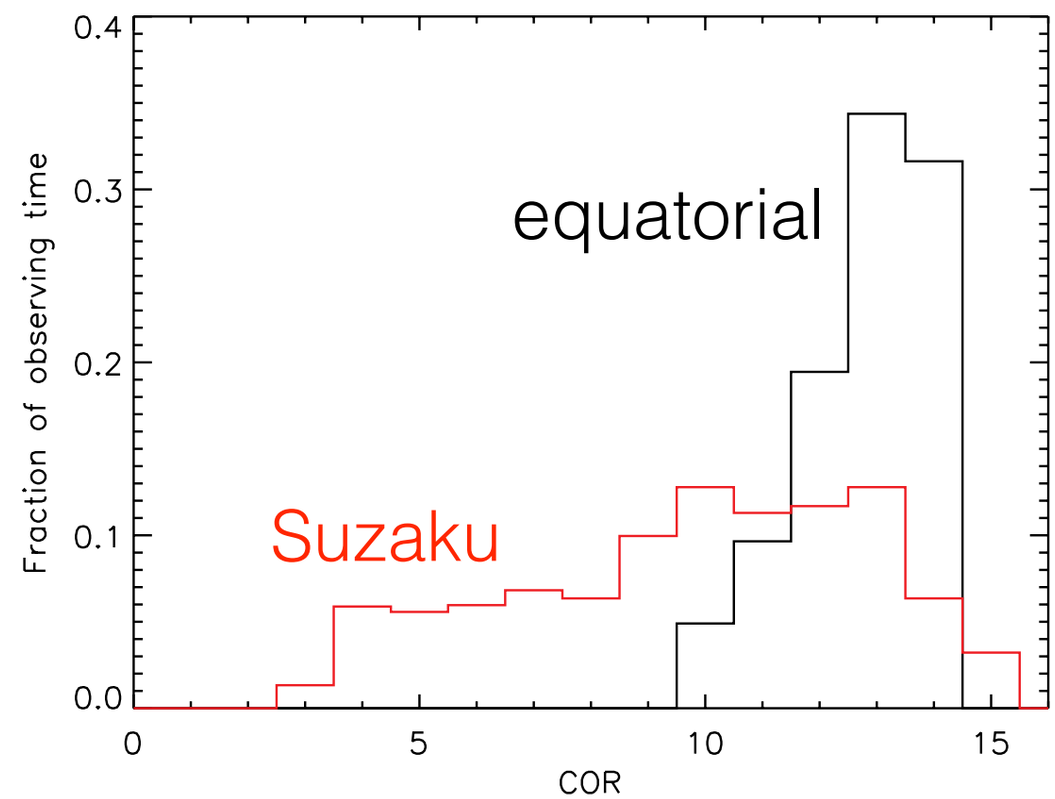
Instrumental Background – Low Earth Orbit

- geomagnetic cut-off rigidity (COR) measures the shielding of the Earth's magnetic field vs. cosmic rays
- it is low (bad) in the SAA







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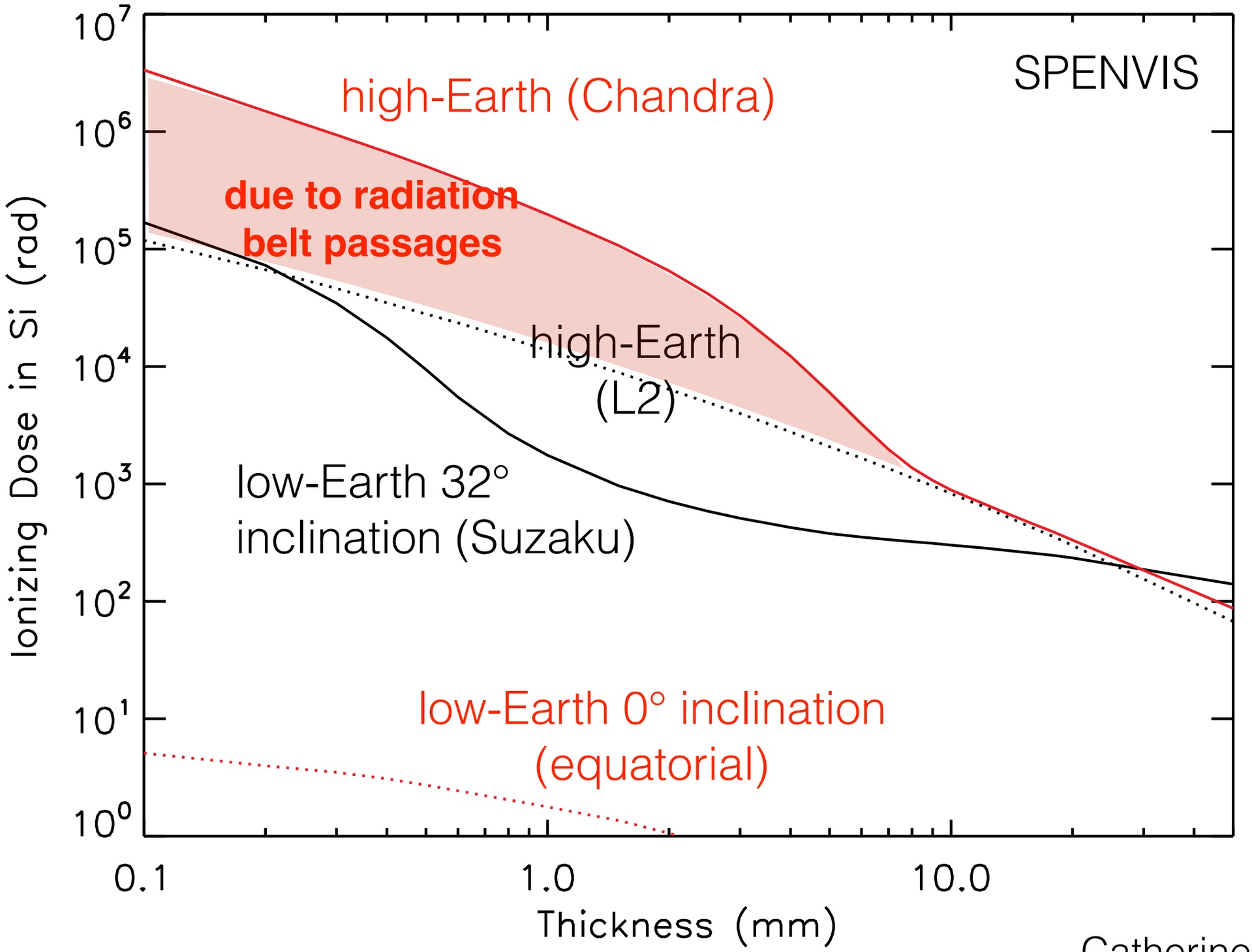
Instrumental Background – Observed

- ionizing radiation produces charge clouds that can mimic X-rays
- event grading, energy filtering can reduce BG
- small pixels help distinguish particle events from X-ray, but…
  - need better understanding of particle and X-ray interactions in detector (Geant4 calls this regime “optical”)
  - many interaction sites along particle track activate many pixels; can we use this? (Grant, Miller, Bautz @ MIT)
- observed background depends on orbit

Instrumental Background (**Orbit-Averaged**)



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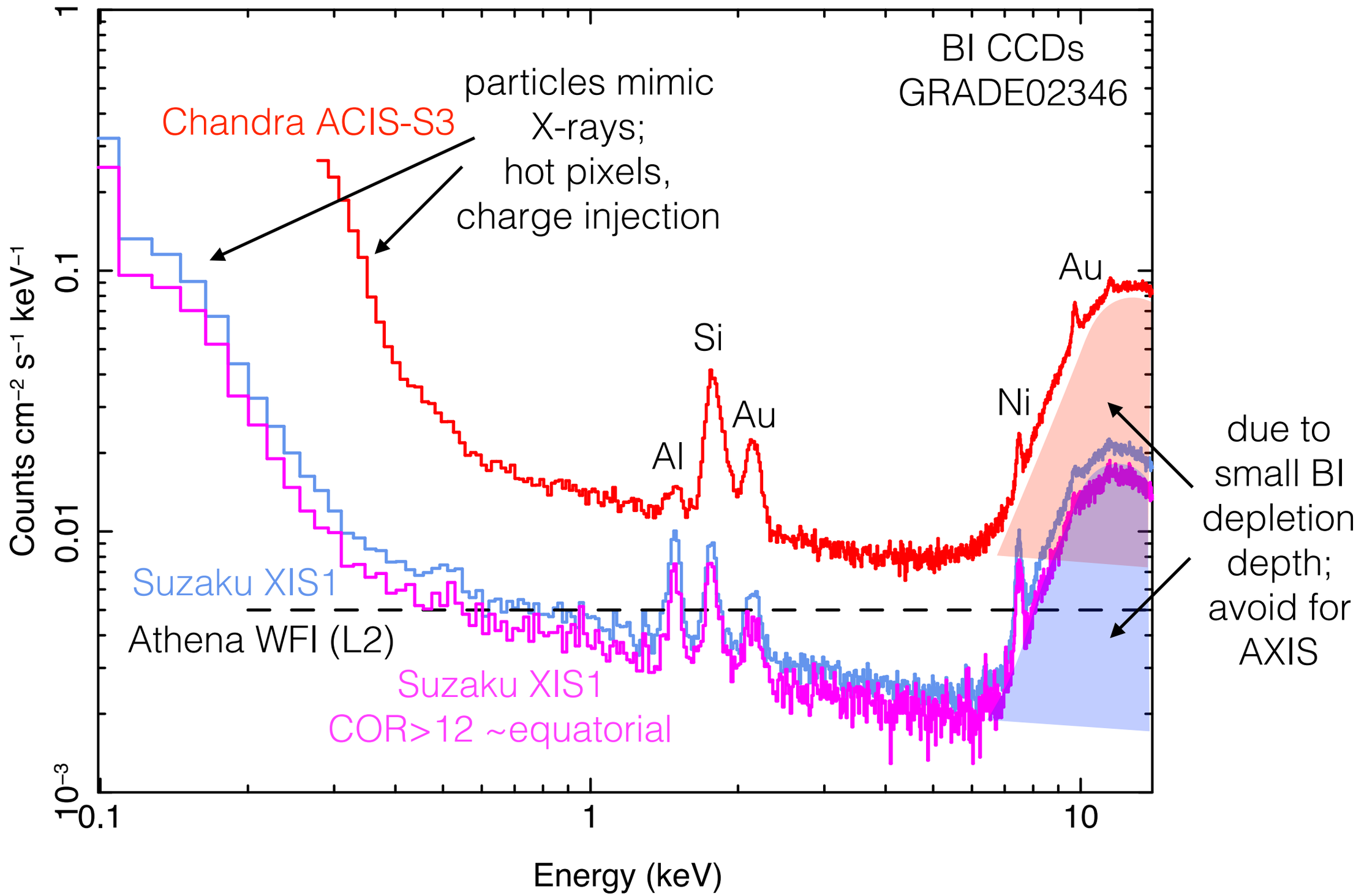
Instrumental Background (Actual)



Programmatics

Cost

- notional focal plane instrument with ~100 cm^2 of active detector area and associated electronics would cost ~ a few $10Ms for a NASA class C mission if started today
  - depending on mission assurance requirements, Probe class instrument might cost more
- 10–15% of focal plane cost is detector, the rest is people (testing, calibration)
  - MIT/LL charges per wafer lot, most vendors do not provide quantity discount
  - some economy of scale in spares; losing 1 of 25 detectors is not as bad as 1 of 4
  - little economy of scale in testing and calibration
    - NICER tested 7–8 devices at once, but very simple 1-pixel devices
    - TESS requires many more people to test 4 flight cameras
    - for advanced instrumentation, # people hours $\propto$ # detectors

Cost

- cost does not include:
  - digital electronics
    - turn image into events, initial filtering, BG rejection to reduce telemetry, package data and HK, some instrument and temperature control
  - thermal control
    - LEO requires thermal control and needs somewhere to dump heat
    - many detectors will require a big plumbing job (lots of power and heat)

Schedule

- both CMOS and DCCDs are likely to be ready for mid-2020s AXIS-type Probe mission if current technology development funding holds (SAT, APRA)
  - Physics of the Cosmos Program Annual Technical Report (PATR) 2016 identifies “Fast, low-noise, megapixel X-ray imaging arrays with moderate spectral resolution” as a top-priority technology development gap
  - “…and High-resolution, lightweight X-ray optics.”
- manufacturing and testing many devices is close to critical path