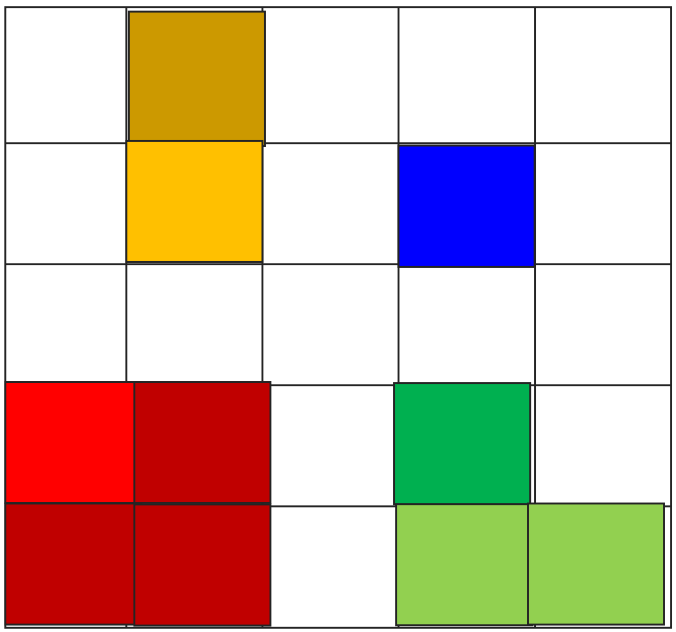
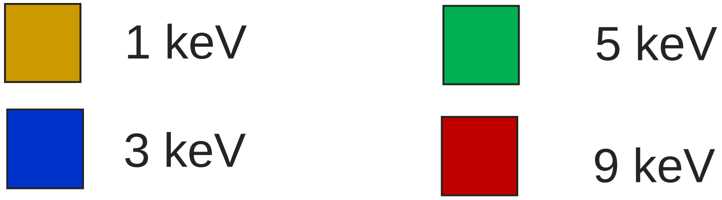
Pile-Up in CCD cameras

CCD events

Frame #1



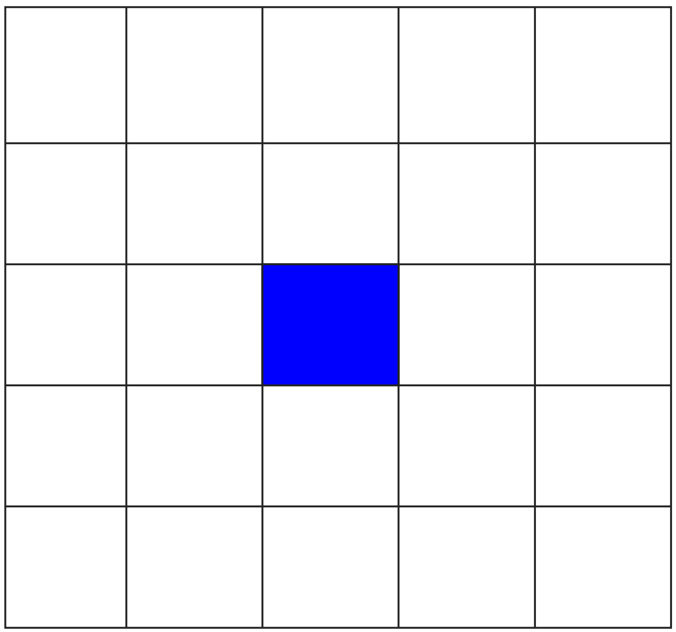
Events which land within a single Frame and don't touch are registered As good events.



"Good" events with different patterns

What is pile-up ?

Frame #1



Pile-up occurs when two or more events fall within the same pixel(s) within a single frame

Energy pile-up

1 keV

3 keV

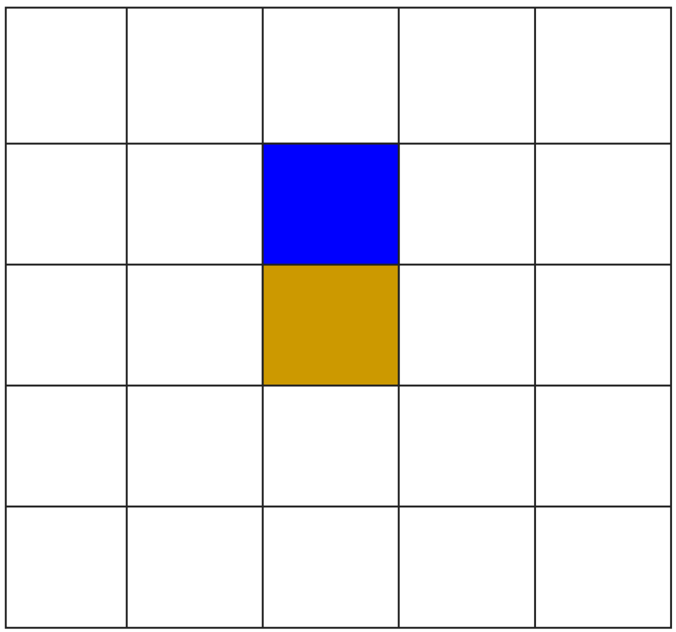
Apparent single pixel event at 4 keV

event 1

event 2

Pattern pile-up

Frame #1



Pattern pile-up occurs when two or more events fall within the same pixel(s) within a single frame

Pattern pile-up / Grade migration

1 keV

3 keV

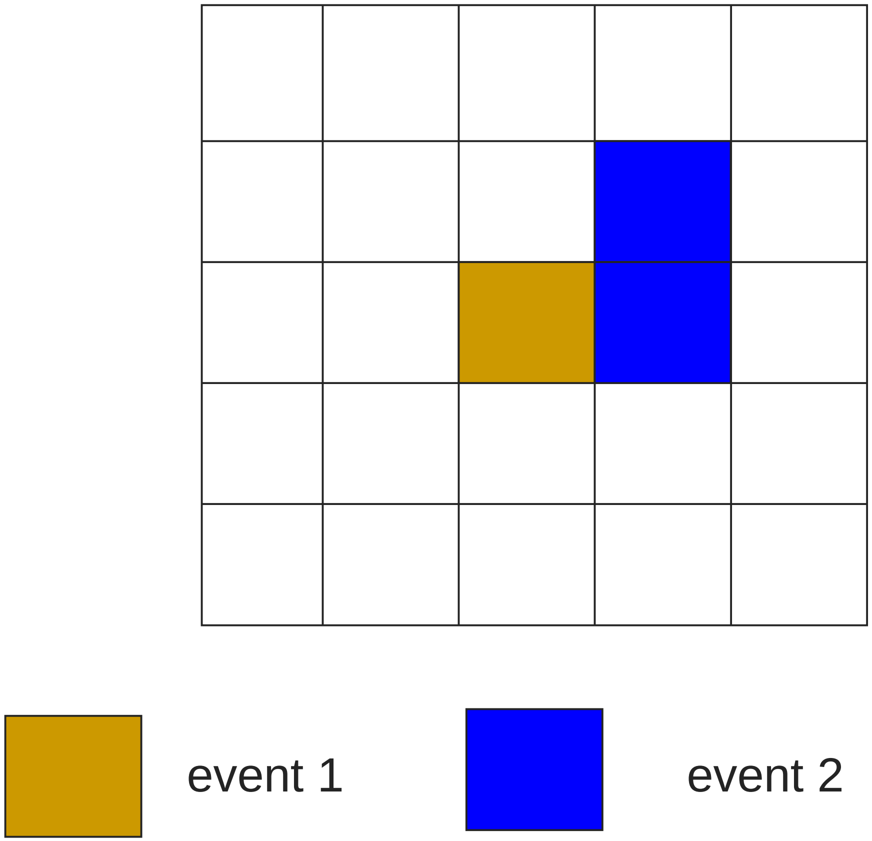
Apparent double pixel event at 4 keV

event 1

event 2

Pattern pile-up - triple

Frame #1



Pile-up occurs when two or more events fall within the same pixel(s) within a single frame

Pattern pile-up / Grade migration

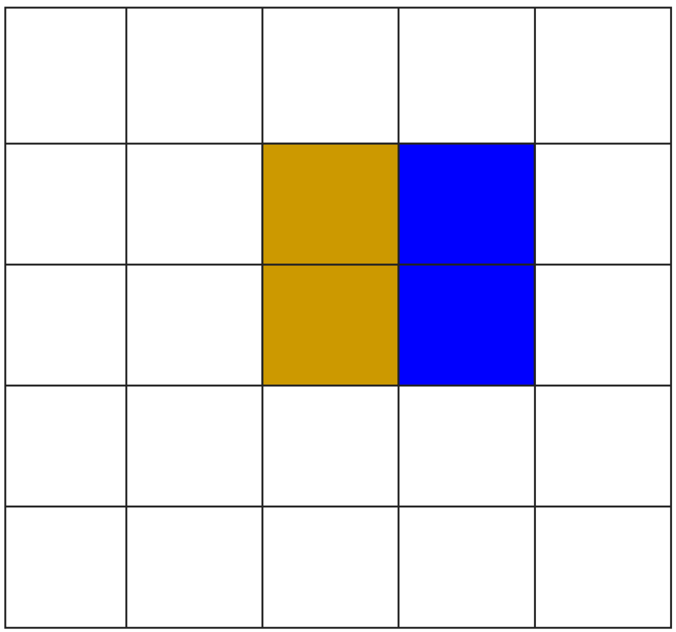
1 keV (single)

3 keV (double)

Apparent triple pixel event at 4 keV

Pattern pile-up - quadruple

Frame #1



Pile-up occurs when two or more events fall within the same pixel(s) within a single frame

Pattern pile-up / Grade migration

1 keV (double)

3 keV (double)

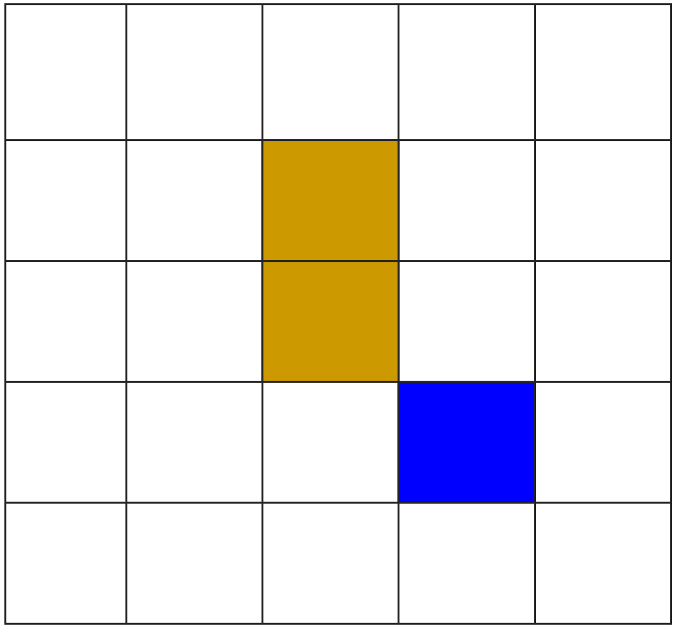
Apparent quad pixel event at 4 keV

event 1

event 2

Event destruction

Frame #1



Event destruction

1 keV (double)

3 keV (double)

Apparent bad (non-valid pattern) event

event 1

event 2

At what flux is it important ?

Pile-up depends on the frame time (Observing mode), the count rate (filter and spectral-model) and the Point Spread Function (PSF) but very roughly in standard mode:

XMM EPIC-pn (0.2-12 keV) > 5×10^{-12} ergs/s/cm^2

XMM EPIC-MOS (0.2-12 keV) > 3×10^{-12} ergs/s/cm^2

Chandra –ACIS (0.2-12 keV) > 5×10^{-12} ergs/s/cm^2

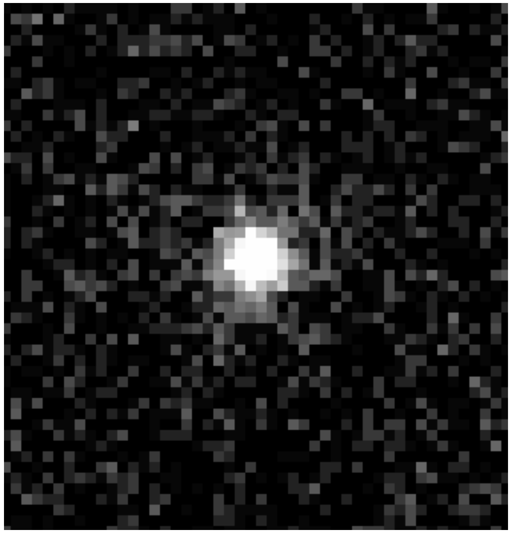
Swift-XRT (0.3-10 keV) > 2×10^{-11} ergs/s/cm^2

NuSTAR – The sun or Sco X-I in flaring states ☺

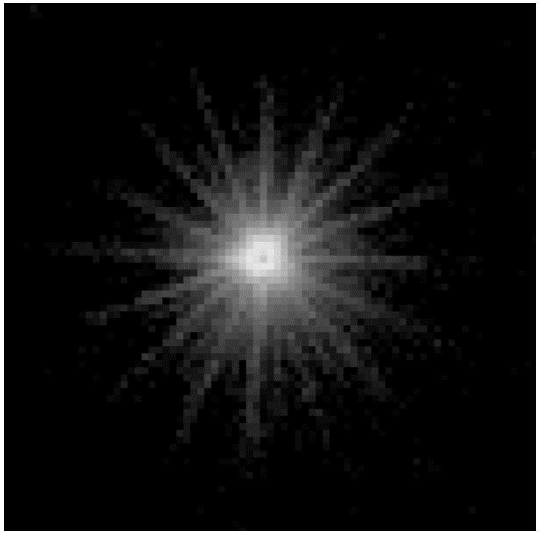
Astrosat-SXT (0.3-10 keV) > 2×10^{-9} ergs/s/cm^2

Suzaku-XIS (0.5-10 keV) > 5×10^{-11} ergs/s/cm^2

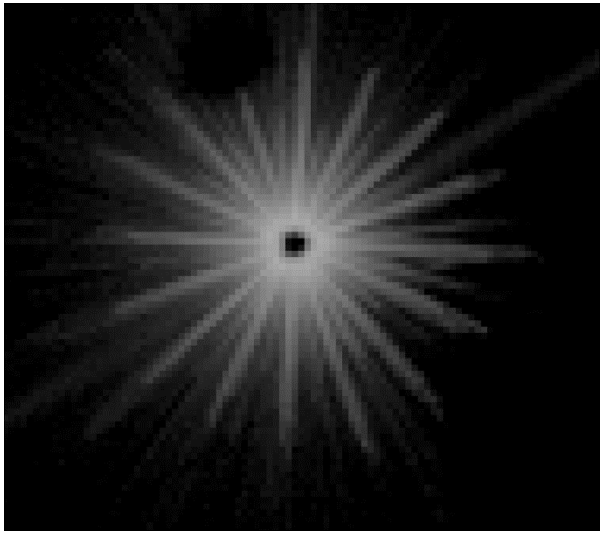
Images – XMM-Newton EPIC-pn



2MASS 1446+68
0.5 c/s



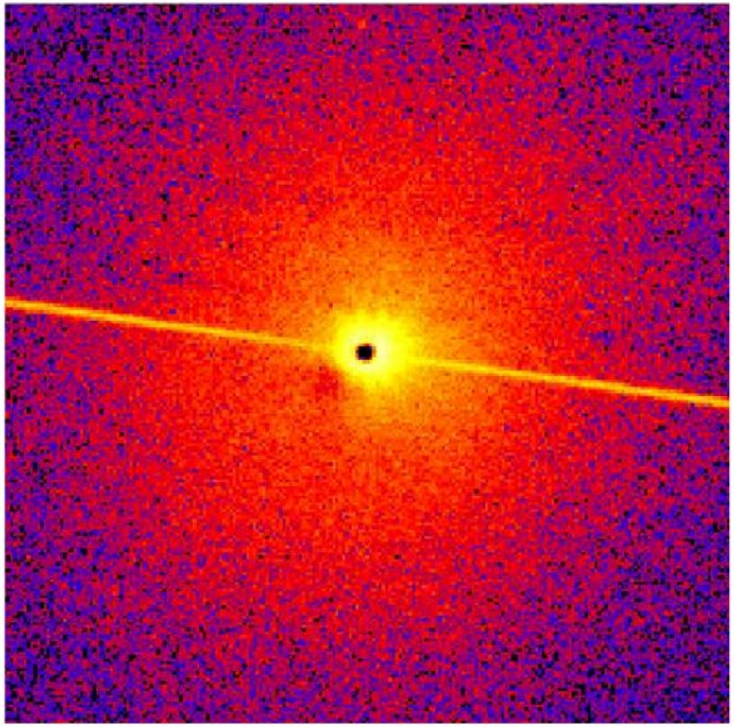
3C273
9.4 c/s



MKN 421
54 c/s

Pile-up destroys events in the centre of the PSF

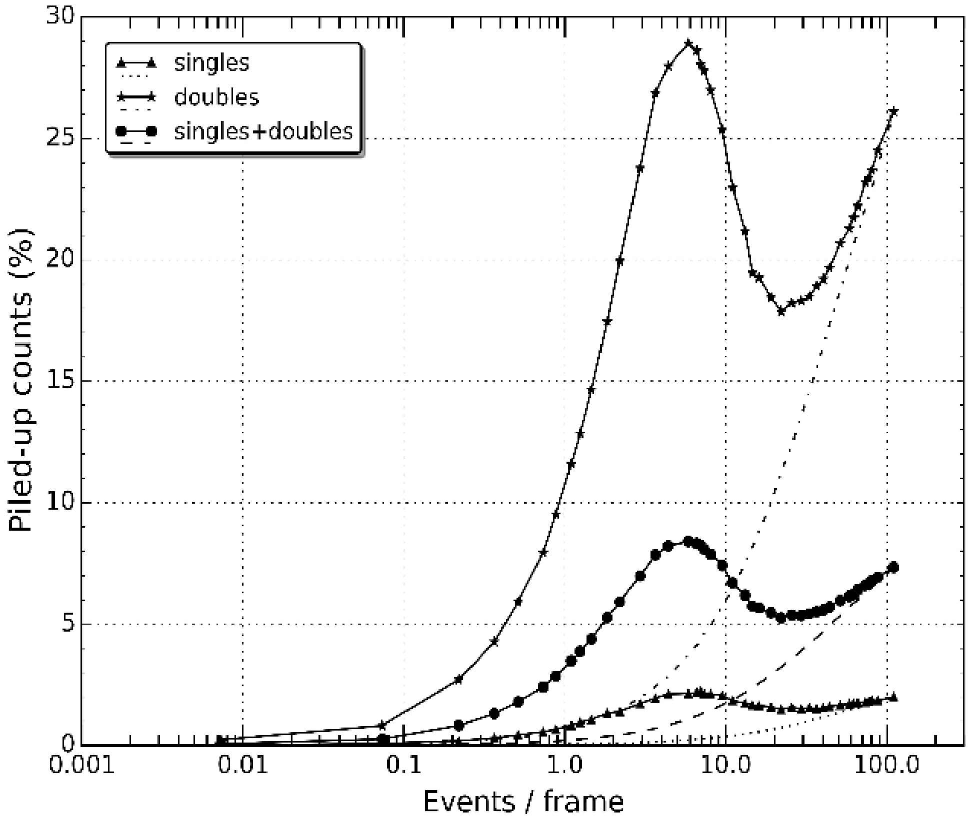
Images – Chandra ACIS-HETG



0th order image from an ACIS-HETG observation of a bright X-ray binary.

From “Chandra_ABC guide to Pile-up”

Piled-up event fractions



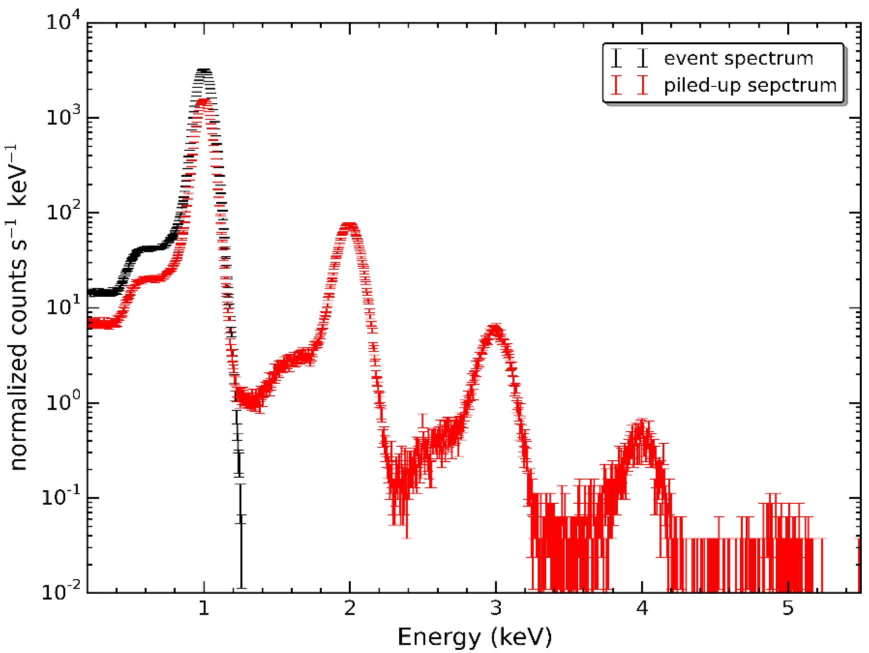
Solid lines = 0-60” circle

Dashed lines = 15-60” annulus

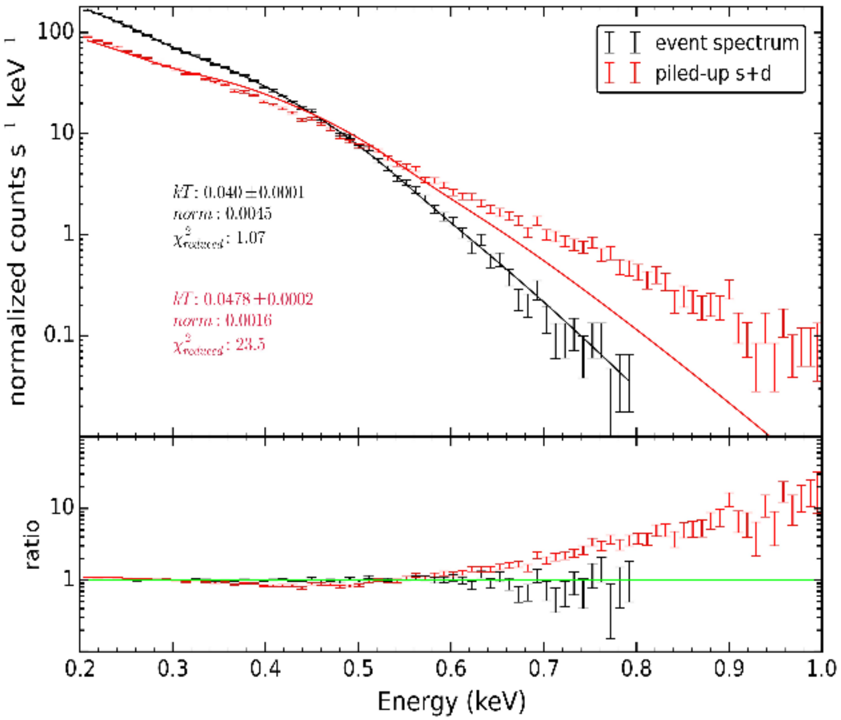
Hump is due to destroyed events

Koch-Mehrin (2016) - CAL-TN-0214-214-1.pdf

Spectral deformation



Piled-up 1 keV gaussian



Piled-up black-body

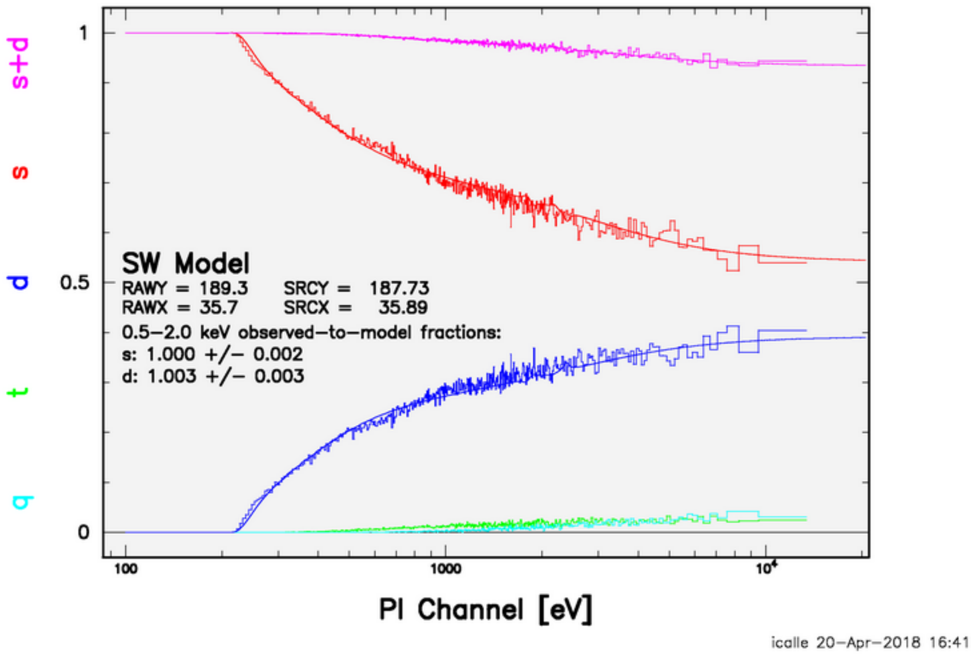
An absorbed power-law appears as a power-law with a different slope

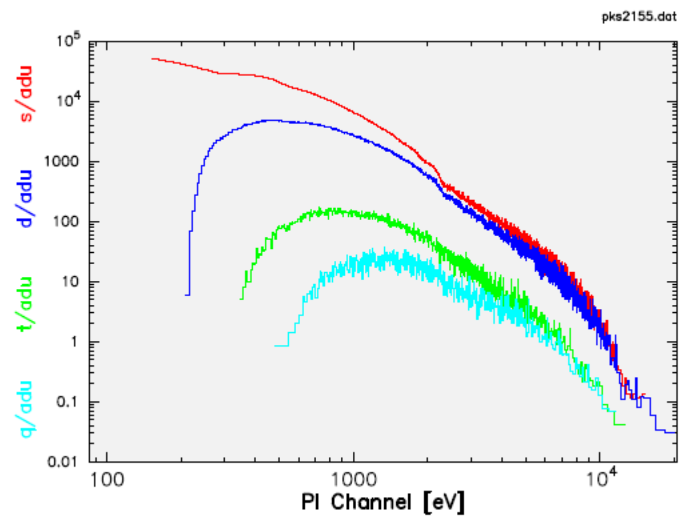
Koch-Mehrin 2016: CAL-TN-0214

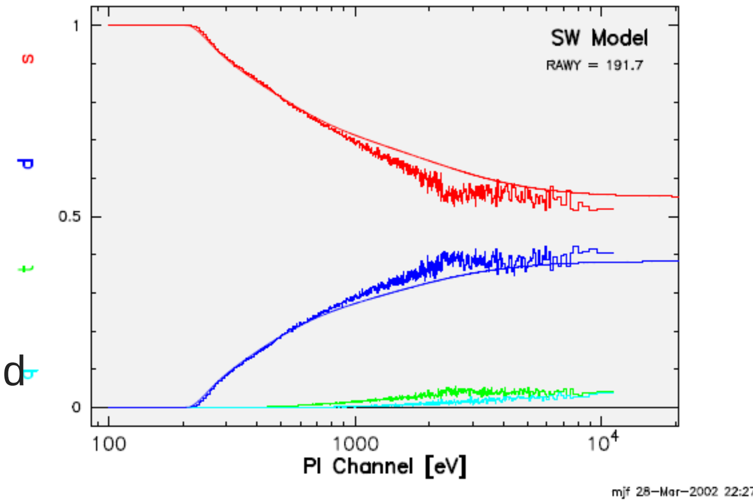
Estimation Methods

- Pattern Fractions – epatplot (XMM)
- Spectral fitting - Chandra fitting in ISIS
- Diagonal event fraction
- Pre-calculated tables

Estimation Methods – pattern fractions







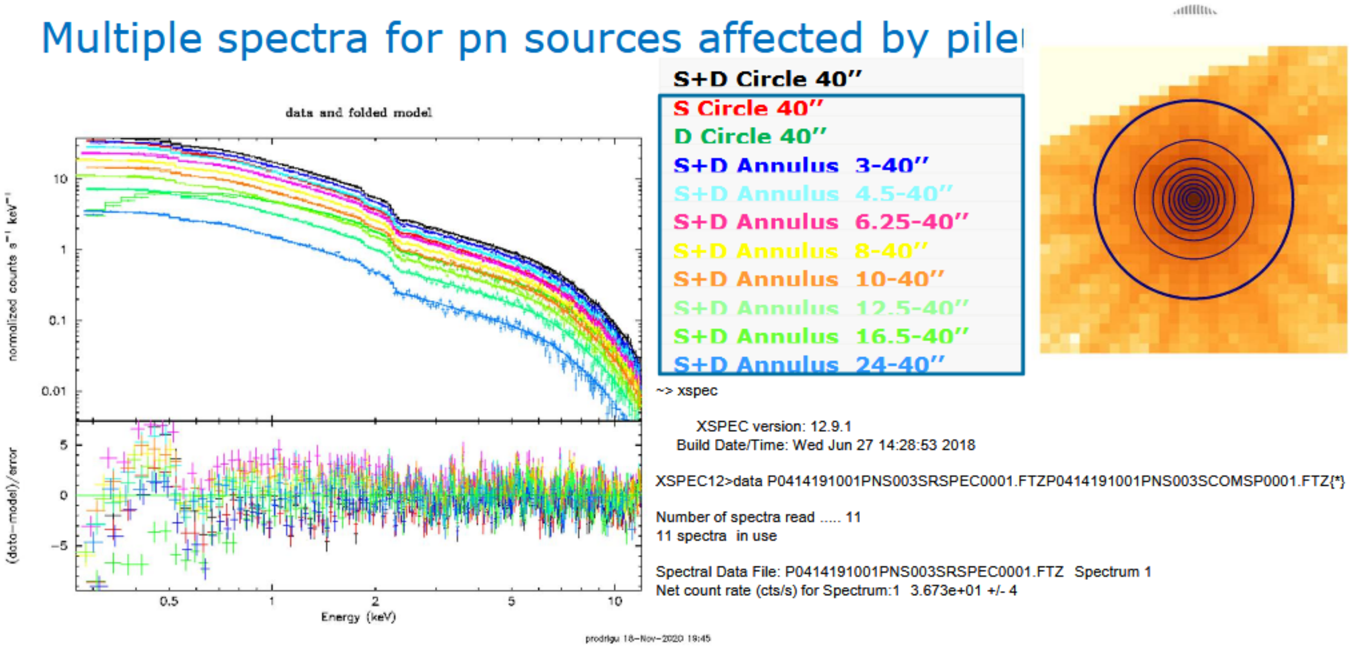
An un-piled source has a ratio of single to double pixel events equal to the ground Cal.

A piled-up source has less single and more double pixel events than standard.

Estimation Methods – model fitting

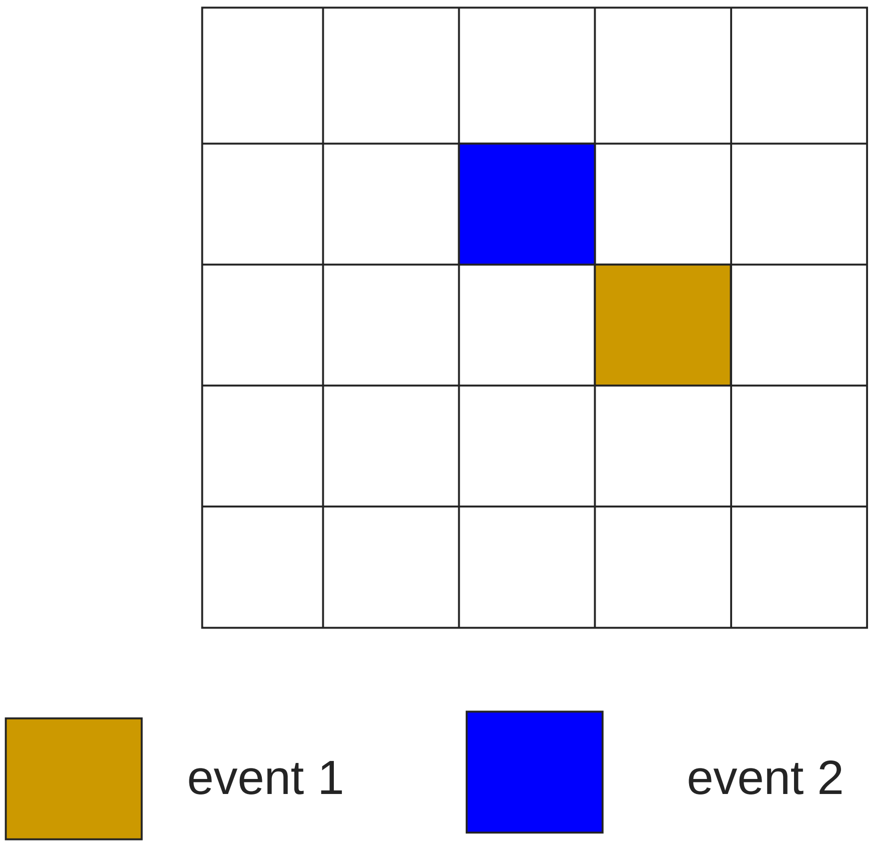
Chandra : estimate pile-up level using a model in ISIS

XMM-Newton : simultaneous fit of spectra extracted at various annuli



Estimation Methods – diagonal events

Frame #1



Two possibilities:

One event with a bad pattern (unlikely)

Two or more events landing in a single frame (pile-up)

The fraction of diagonal to single-pixel events in the PSF core gives an indication of the level of pile-up.

Estimation Methods – tables

XMM-Newton EPIC cameras

Instrument	Mode	Frame time	Conservative [s^{-1}]	Tolerant limit [s^{-1}]
EPIC-pn	Extended Full Frame	199.1 ms	0.7	1.5
	Full Frame	73.4 ms	2	4
	Large Window	47.7 ms	3	6
	Small Window	5.7 ms	25	50
EPIC-MOS	Full Frame	2.6 s	0.5	1
	Large Window	0.9 s	1.5	3
	Small Window	0.3 s	4.5	9

Conservative limit = 2−3% flux loss and <1% spectral distortion
Tolerant limit = 4−6% flux loss and 1−1.5% spectral distortion

Remedies

- Observing Mode / Parameters Selection
- Place source off-axis / Use Thick Filter
- Annular extraction
- Pattern 0 only spectra – pros and cons
- Diagonal pixel correction
- Chandra pile-up model – spectral fitting
- “Add an Event” method

Observing parameters

Instrument	Mode	Frame time	Conservative [s^{-1}]	Tolerant limit [s^{-1}]
EPIC-pn	Extended Full Frame	199.1 ms	0.7	1.5
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	Small Window	5.7 ms	25	50
EPIC-MOS	Full Frame	2.6 s	0.5	1
	Large Window	0.9 s	1.5	3
	Small Window	0.3 s	4.5	9

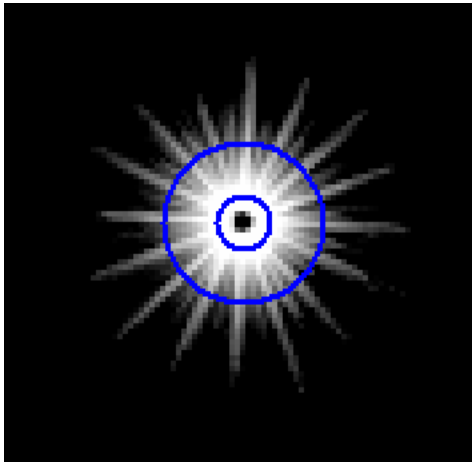
Downside = smaller area, less exposed area to measure background
= higher dead-time fraction, e.g. Burst mode=3% efficiency

Decrease readout time by reading out less chips – 1/8 subarray, Chandra ACIS

Filter – Thin -> Medium -> Thick = reduction in c/s for soft spectra – Lose counts

Off-axis angle = use vignetting to reduce count rate
and in some cameras the PSF is wider - Lose counts + worse cal

Annular Extraction

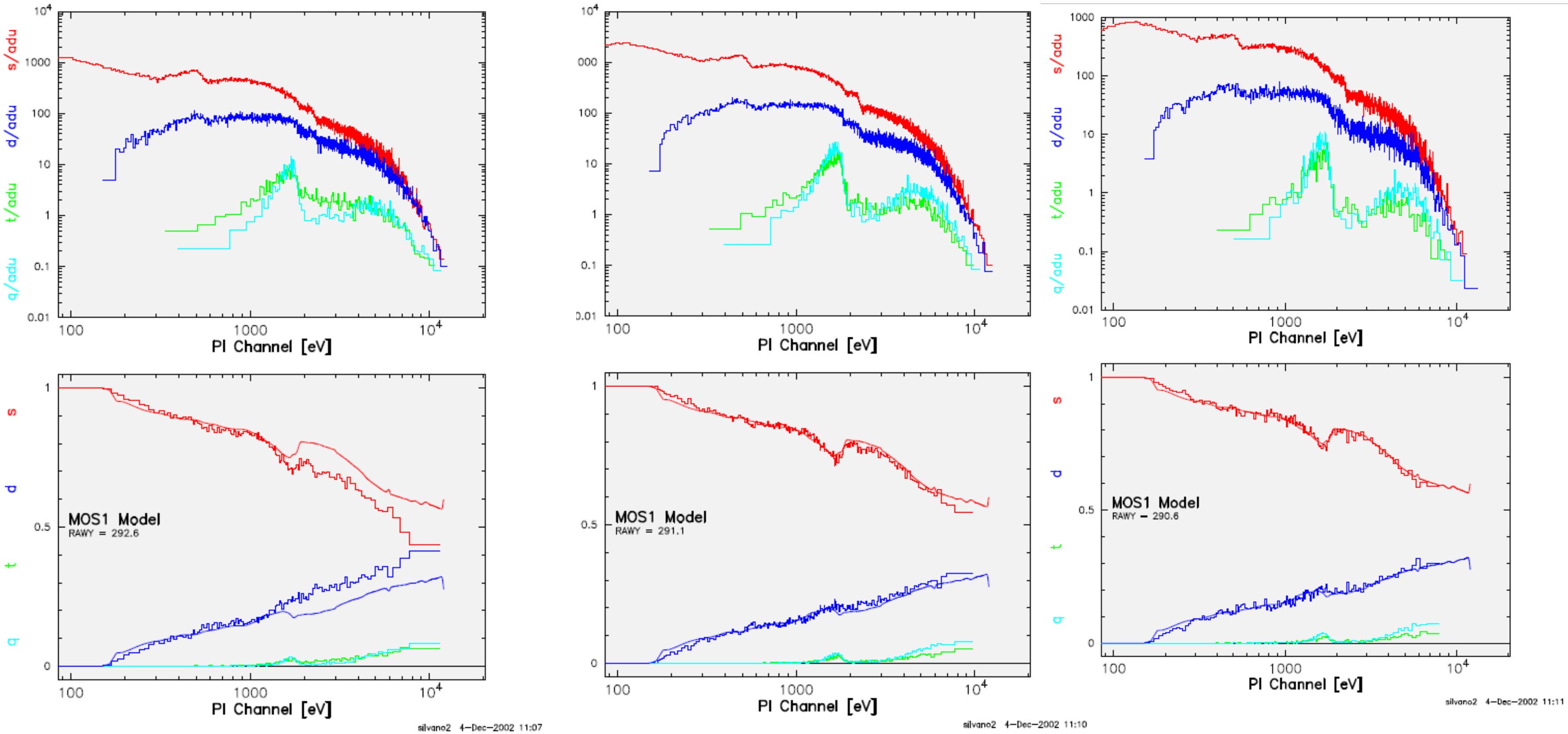


Exclude inner 25” where pile-up is worst

EEF=90+/-1% in 1 arcmin circle
EEF=20+/-2% between 25 and 60 arcsecs

Problem: Lose fraction of counts
Introduce a PSF (encircled energy) energy-dependent, systematic error

Annular Extraction - diagnostics



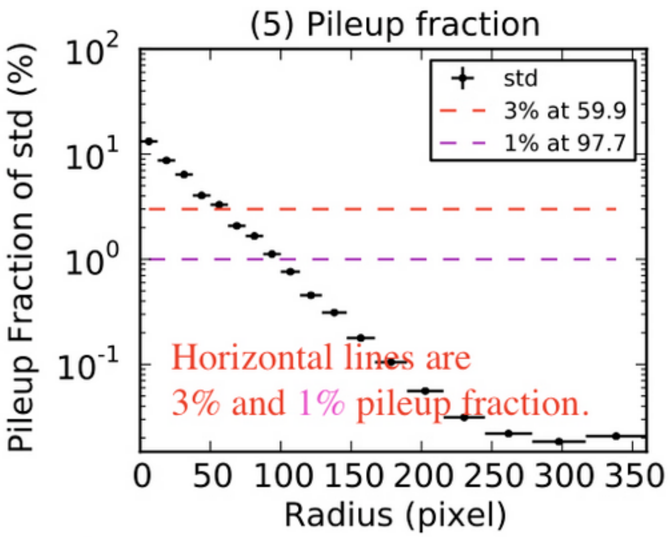
Circular extraction | Annulus, excluding inner 6” | Annulus, excluding inner 15”

Annular Extraction – helper tasks

SUZAKU-XIS (from XIS_PileupDoc_20120220_ver1.1.html)

On Cyg X-1

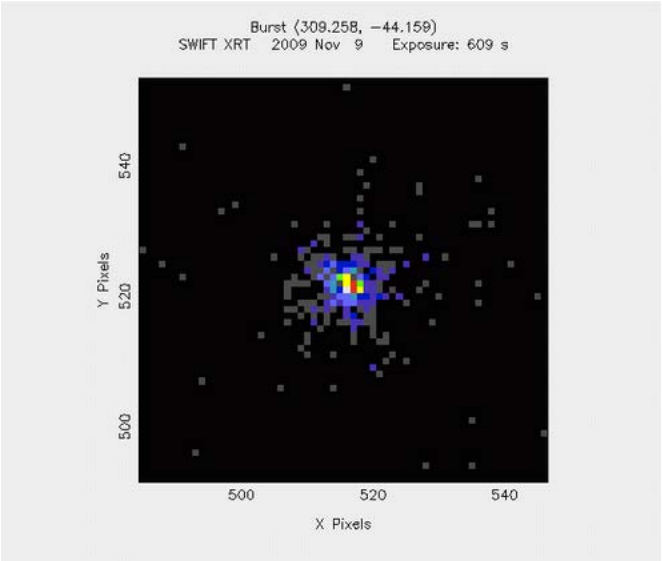
>aepileupcheckup.py ./ 0 -f xi0check.ps -y xi0check.yaml -p region
****
********** aepileupcheckup.py ***************
****
(omit)
koooooooooo Pileup is likely to occur.
koooooooooo 3 % at 59.9 pixel, 1 % at 97.7 pixel (1 pixel ~ 1 arcsec)
.... Creating region files .....

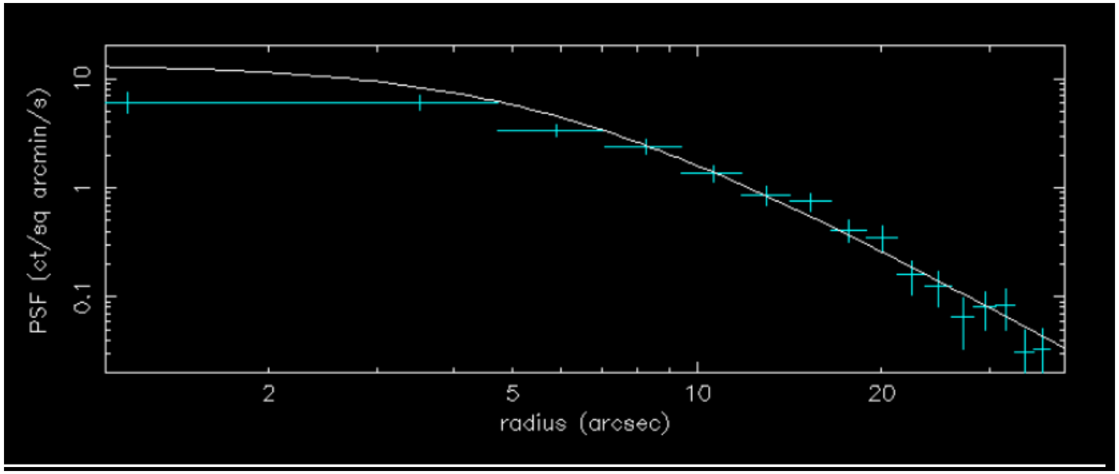


Problem: Lose fraction of counts

Introduces a PSF (encircled energy) systematic error

Annular Extraction – PSF fitting





Extract radial profile

Fit radial profile with the known Point Spread Function

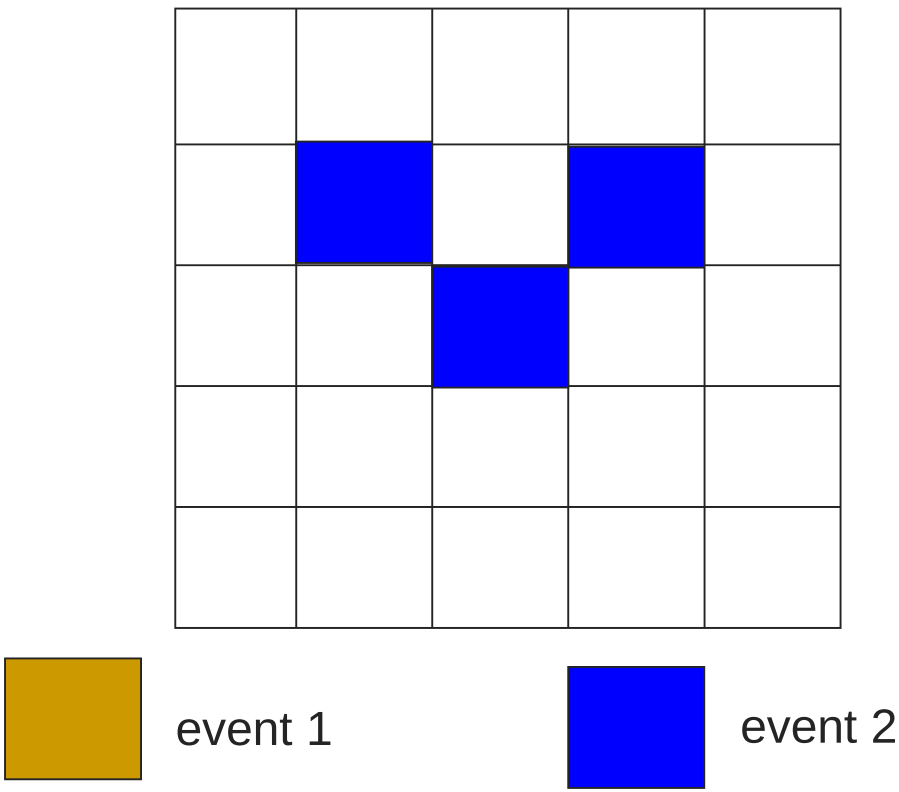
Extract events from annulus of 8-40”

https://www.swift.ac.uk/analysis/xrt/pileup.php

Use Pattern 0 events

Ballet 1999 – Using a spectrum with single-pixel events experience minimises spectral pile-up

Frame #1



1 in 9 chance of energy pile-up

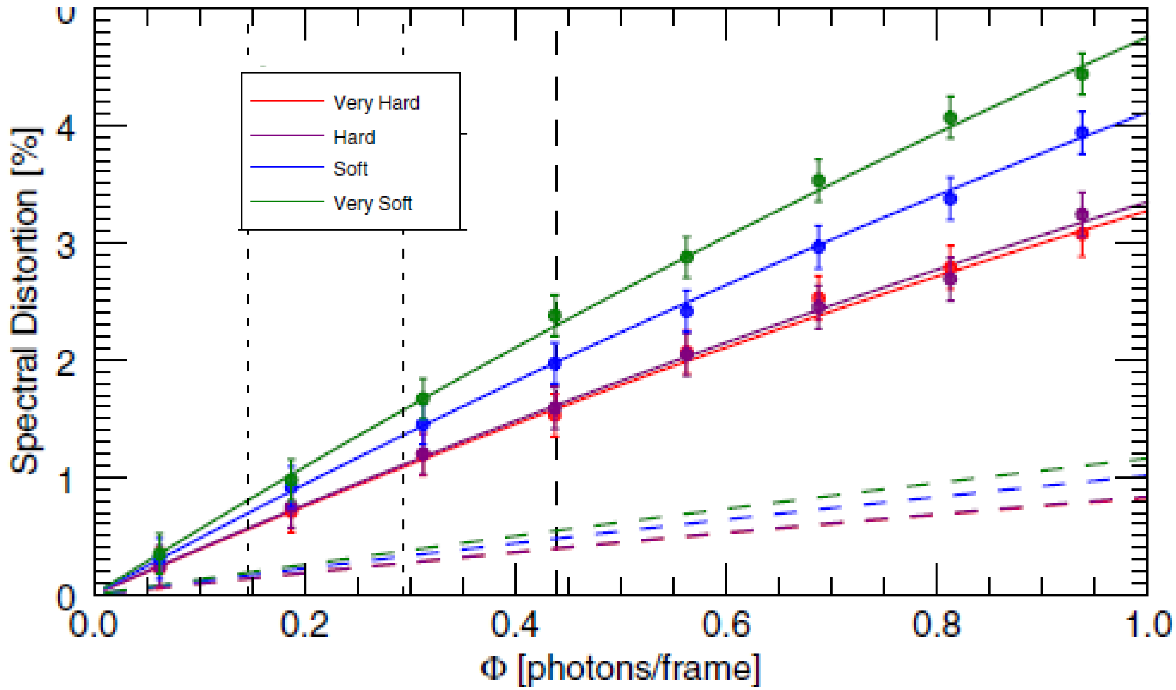
Corner: No good event – 2 events lost =4

Adjacent: Double event – 2 events lost =4

On Top: One wrong energy event = 1

Pattern 0 – Spectral distortion

Ballet 1999 – Single pixel events experience minimum spectral pile-up



Solid = single+dub
Dashed = singles

Jethwa et al. 2015

Spectral distortion = 1 – non-piled Events / Piled events

Scaling by number of diagonal events

$$\bar{S}(E) = \bar{S}_{obs}(E) + \frac{\gamma_1}{4\alpha_1}\bar{S}_{dia\_p0}(E) - \frac{1}{4}\bar{S}_{dia}(E).$$

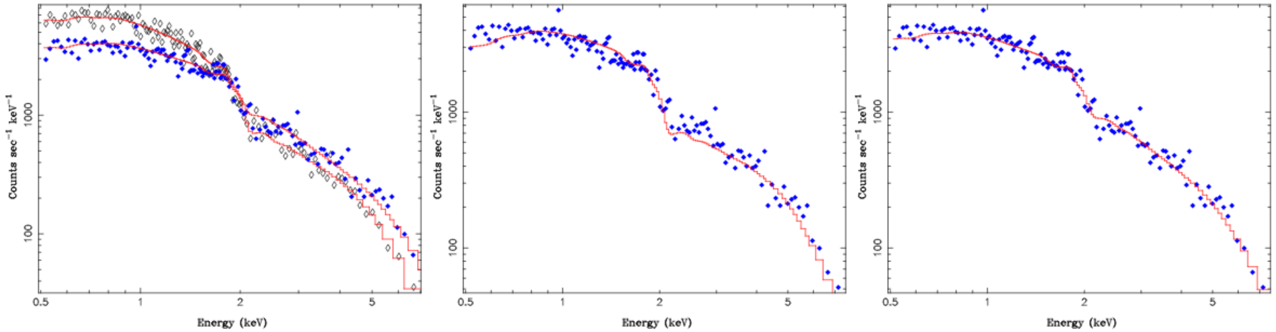
Molendi & Sembay 2003

S = emitted pattern 0 counts(E)
S_{obs} = Observed pattern 0 counts(E)
S_{dia_p0} = Counts(E) obtained by splitting diagonals into two singles
S_{dia} = Counts(E) observed in diagonal events
α_1 = fraction of single-pixel events
y_1 = probability factor for encountering a diagonal (fn of pattern fractions)

Possible if software allows diagonal events to be split into 2 charges.
More useful for cameras where the pixel size is small compared to the PSF.
e.g. XMM-MOS.

Pile-Up Modelling

From Chandra ABC pile-up guide



Simulated piled-up Γ=2 absorbed power-law

Spectral fitting returns a Γ=1.26 power-law

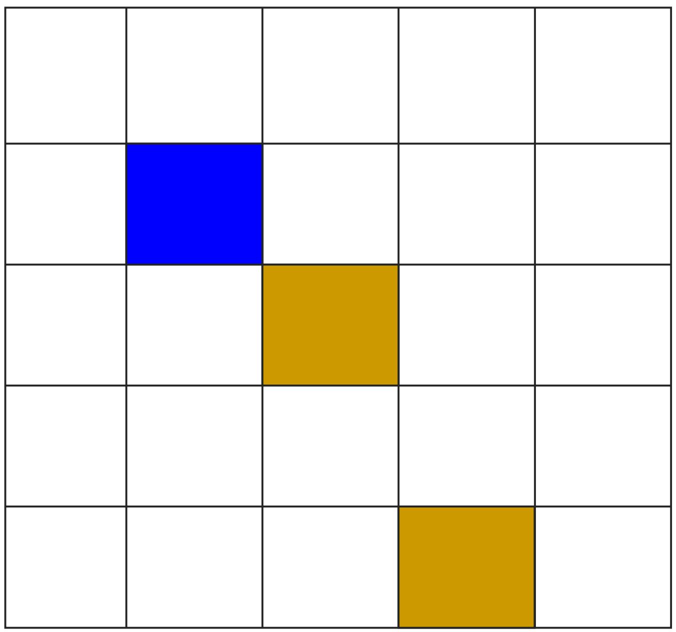
Fitted with pile-up model, Returns Γ=1.82

Models: **pileup** (xspec,isis,Sherpa) - fast pile-up algorithm from Davis 2001.
jdpileup (Sherpa) – Gratings, Novak et al. 2008

With variable parameter, α , the grade migration survival probability

Add event model – XMM-Newton

Frame #1



= event from ODF   = trial event

- Start from an event file

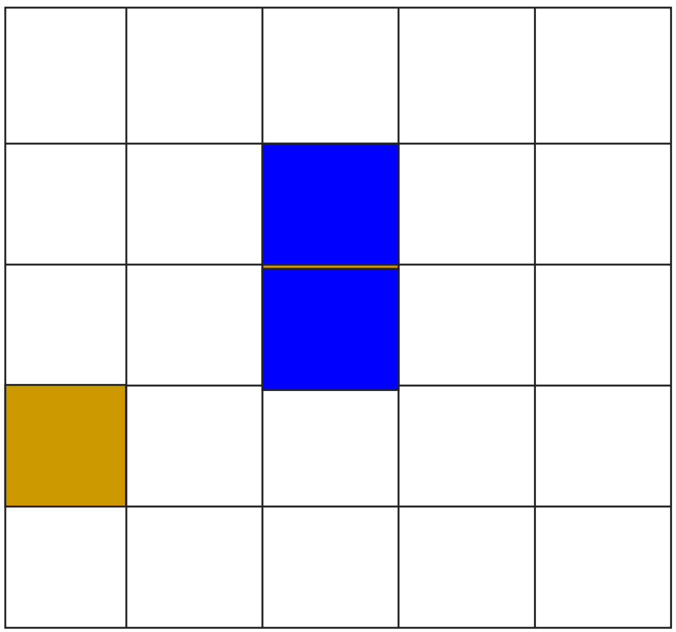
- Add one new event into each frame
  - in psf-weighted pixel
  - with a trial PI channel
  - with pattern chosen from p.f. ratio

- Calculate what happens to the event

- Produce a distribution of the output event PIs for each input PI

Add event at a given energy

Frame #2



- Add one event into each frame
  - in psf-weighted pixel
  - with a trial PI channel
  - with pattern chosen from p.f. ratio

- Calculate what happens to the event

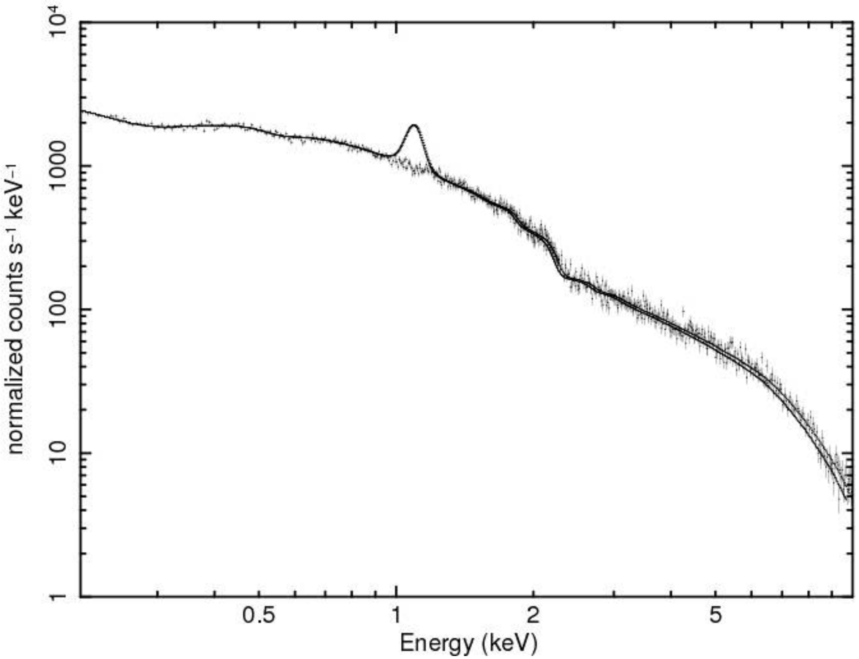
- Produce a distribution of the output event PIs for each input PI

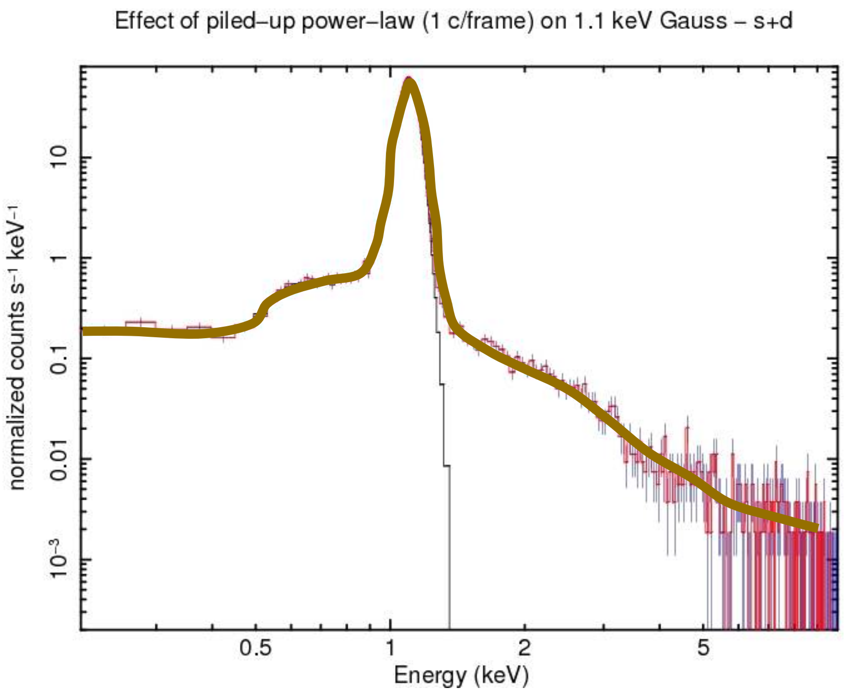
Double event

= event from ODF

= trial event

Output: Piled-up spectrum for 1.1 keV

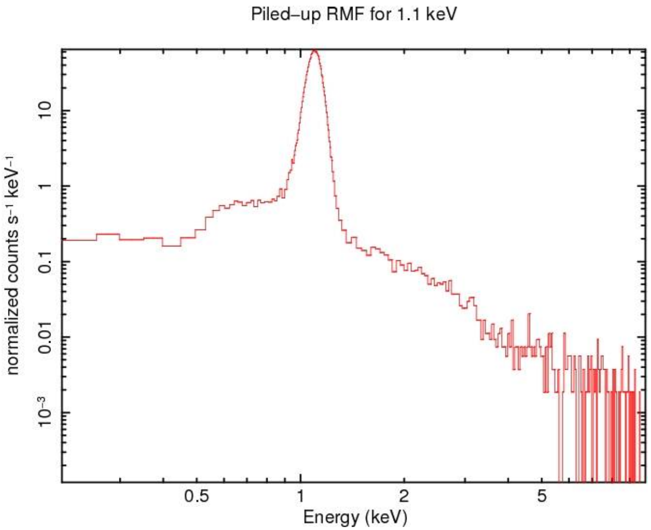




Initial power-law spectrum from observation. Add a 1.1 keV event many times.

Initial (black) and output (brown) RMFs

Result written as a new row in RMF



Convolution > RMF for trial energy

Standard RMF

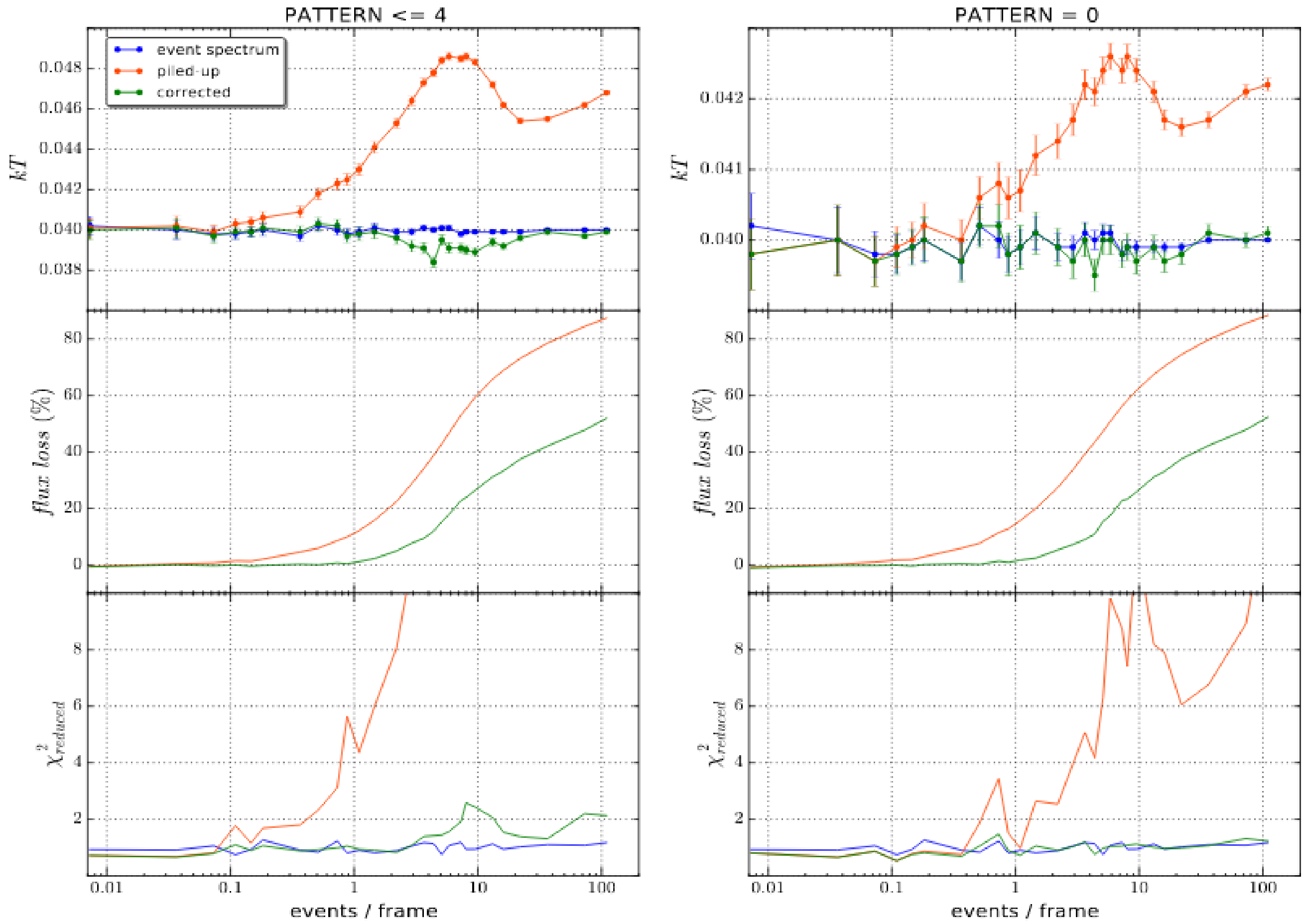
Energy

0.1	**0.1**	**0.2**	**0.2**	**0.1**	**0.07**	**0.04**	**0.0**
0.08	0.08	0.1	0.15	0.1	0.06	0.03	0.02

P.I. channel

Write the piled-up distribution for each energy into the RMF. Produce an RMF which is not normalised to one, hence model the events which produce bad patterns and are lost.

Results – simulation

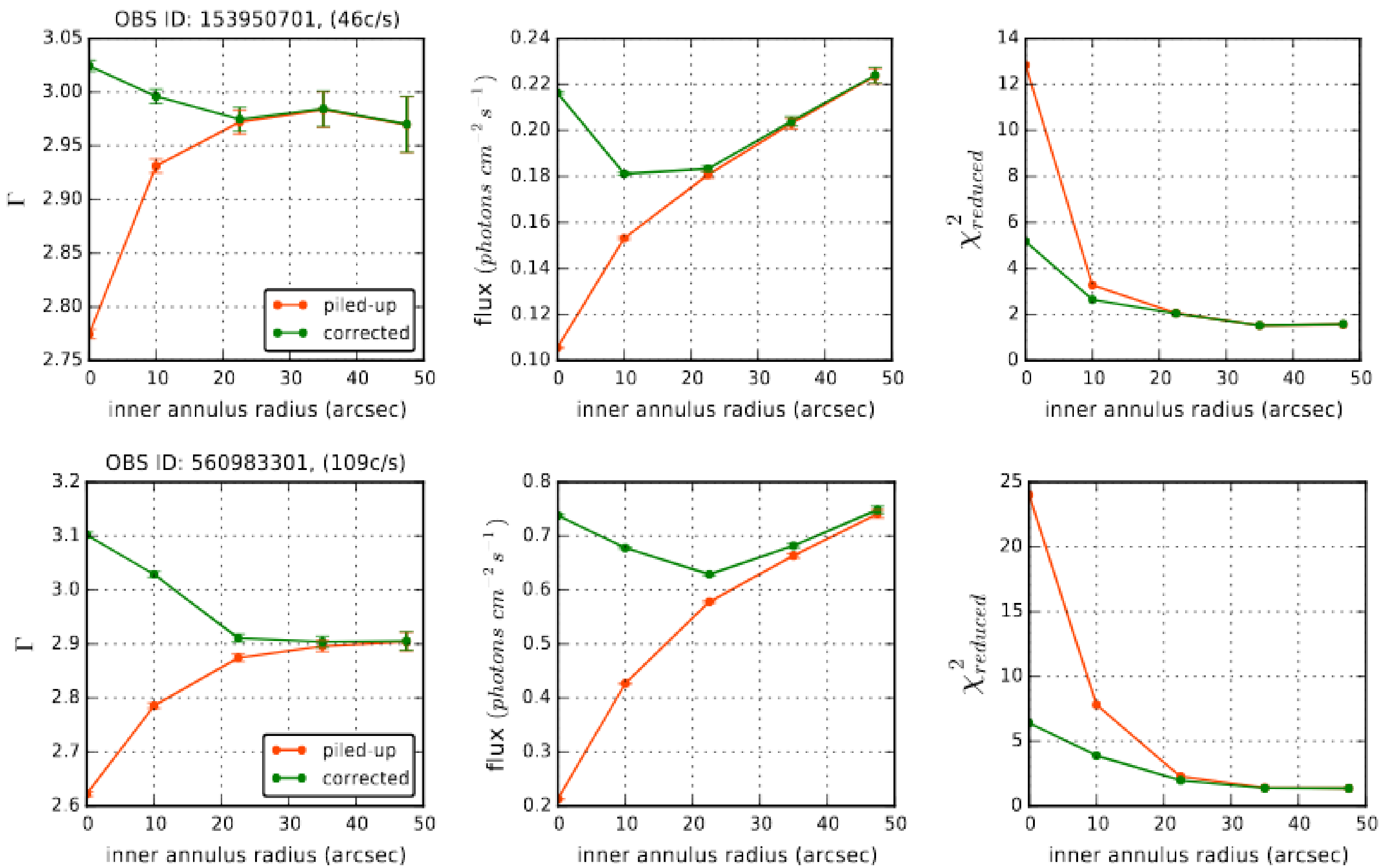


Koch-Mehrin (2016) - CAL-TN-0214

Black-body 40 eV

Works well for sources observed with EPIC-pn in imaging modes with low or moderate pile-up.

Results – MKN 421



Medium pile-up

Heavy pile-up

Koch-Mehrin and Constantino (2016) - CAL-TN-0213-1

Relevant Papers

- Ballet 1999 – Stats of pile-up on CCDs, single-pixel events ok.
- Ballet 2001 – Effects when pixel size is large compared to PSF
- Davis 2001a – Spectral analysis of non-piled up sources
- Davis 2001b – Description of Chandra pile-up model
- Molendi & Sembay 2003 – triangular events as a diagnostic
- Jethwa et al. 2015 – count rate limits for XMM-Newton cameras
- Swift-XRT pile-up – https://www.swift.ac.uk/analysis/xrt/pileup.php
- Chandra ABC Guide to Pileup - https://cxc.harvard.edu/ciao/download/doc/pileup_abc.pdf
- Tomsick et al. 2004 – effect on timing analysis (reduction of noise)
- Yamada et al. 2012 – Pile-up effects on Suzaku-XIS
- CAL-TN-0213 and CAL-TN-0214 XMM-Newton technical notes – testing of “Added event” model
- Nowak et al. (2008) – Chandra gratings pile-up model