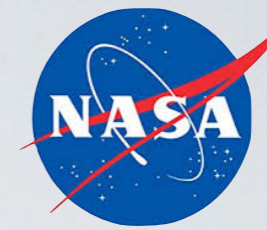




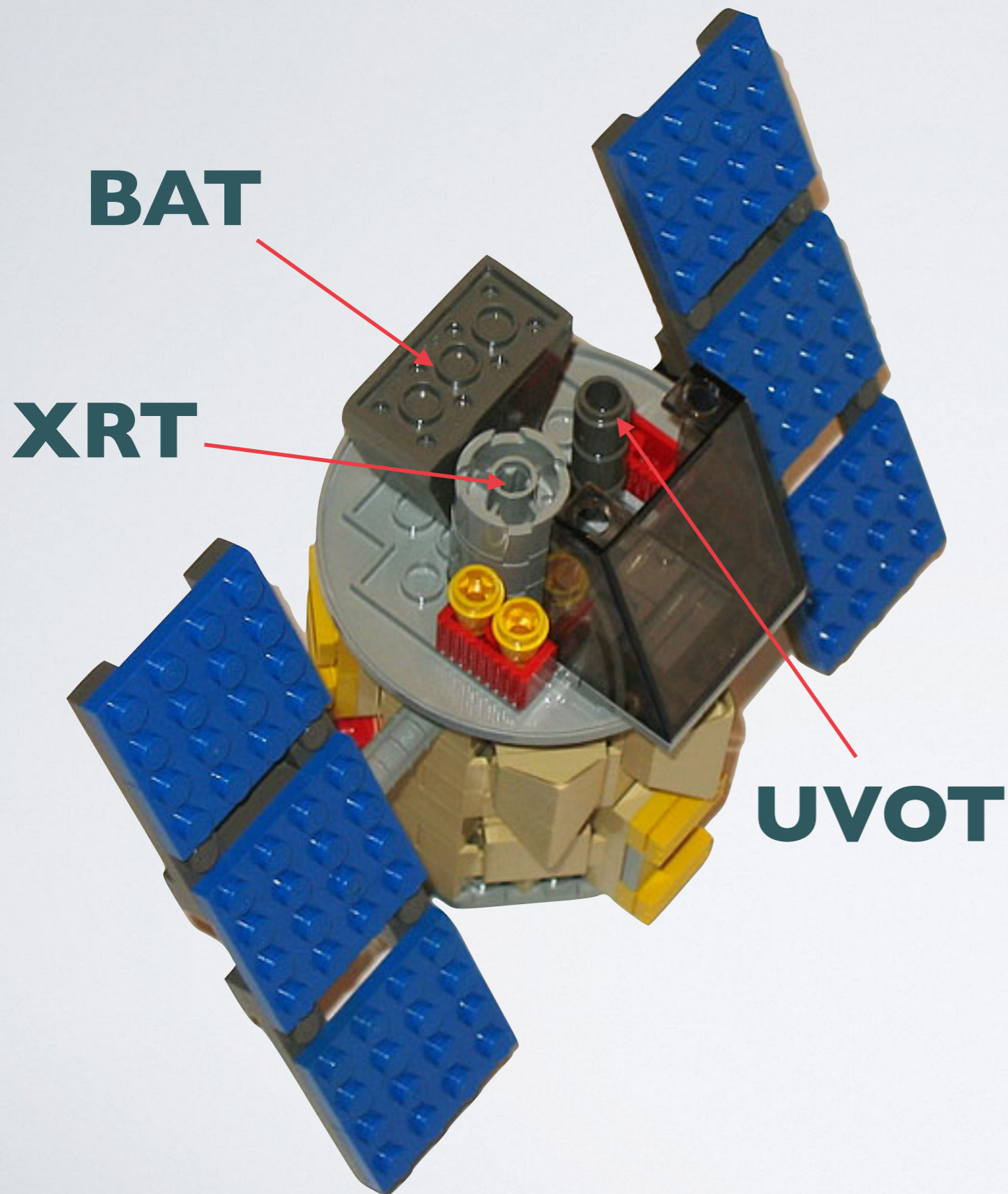
**PennState**  
Eberly College of Science



# **SWIFT X-RAY TELESCOPE - CALIBRATION ISSUES PRIMER**

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NASA Neil Gehrels Swift Observatory**

# NEIL GEHRELS SWIFT OBSERVATORY



- **Burst Alert Telescope (BAT)**

- “Hard X-ray” 15-150 keV
- 2 sr field of view (1/6th of sky)
- CdZnTe detectors
- Detects ~100 GRBs per year

- **X-Ray Telescope (XRT)**

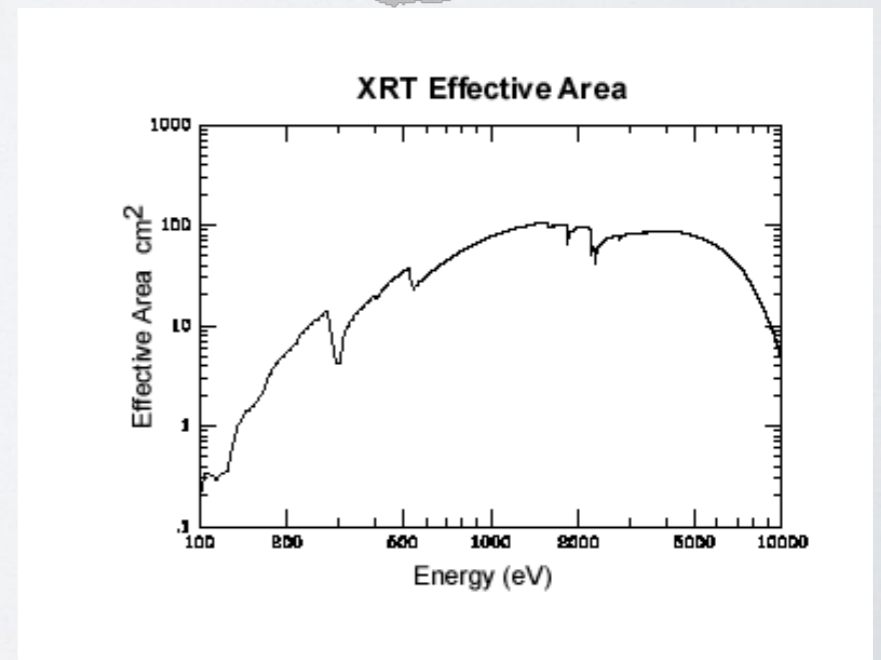
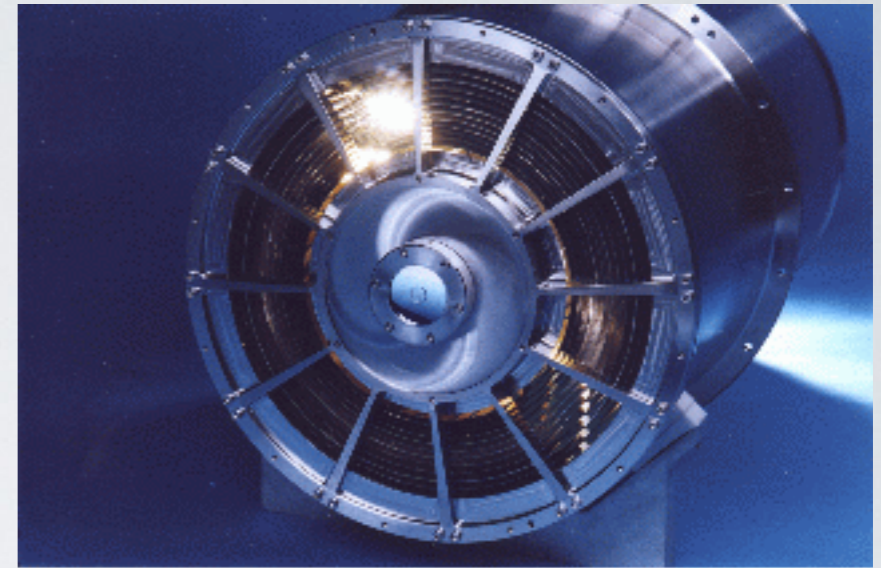
- “Soft X-ray” 0.3-10 keV
- 23.8 arcminute diameter FOV (~0.12 sq degree)
- few arcsecond (as good as 1.8”) positions
- CCD spectroscopy

- **UV/Optical Telescope (UVOT)**

- 170 – 650 nm
- 17 arcminute width square FOV (~0.8 sq degree)
- Sub-arcsecond positions
- Grism spectroscopy
- 6 UV/optical broad-band filters
- 22nd mag sensitivity (filtered)

# SWIFT X-RAY TELESCOPE

- Swift X-ray telescope is a fairly simple device.
  - Wolter Type-I grazing incidence mirrors effective area of  $110\text{cm}^2$
  - EEV CCD-22 600x600 pixel detector (same as XMM EPIC-MOC detectors)
  - PSF 18 arc-second HPD (similar to XMM)
  - Thin filter in front of CCD to block optical light.
- Main read out modes:
  - Photon Counting (PC):
    - 2.5s exposure time.
    - Full Frame 2D imaging.
    - Event recognition gives position, energy, time of each X-ray.
  - Windowed Timing:
    - 1.7ms timing resolution
    - Readout only 200x600 (central 1/3rd of detector)
    - Event recognition gives x-position only, time and energy.
- Other modes:
  - Photodiode modes - non imaging fast readout modes that have not worked since 2005.
  - Image Mode - simple integrated image with no event recognition - used for GRB localization only.
  - Engineering modes (RAW frames, bias maps etc).



# CALIBRATION ISSUES

- In this talk I will discuss various issues that can cause calibration problems with XRT data, if not properly handled. A short list of these problems are:
  - Correcting for hot pixels and hot columns
  - Background subtraction in WT
  - Optical Loading
  - Pile-up
  - Age-related issues (e.g. evolving bias, traps, trailing charge etc)
  - Proper grade selection

# XRT BEST PRACTICES

- Best practices for performing XRT data analysis and making sure calibration of data is correct:
  - Always ensure you have latest CALDB. Latest release for XRT was August 2020.
  - Always ensure you have latest HEAsoft. XRT analysis software is being actively updated to deal with issues.
  - Always reprocess data from SDC using `xrtpipeline` giving RA/Dec of source of interest. e.g.:
    - `xrtpipeline extractproducts=no indir=009543040002 outdir=009543040002_out steminputs=sw009543040002 srcra=130.1718 srcdec=-35.2738 clobber=yes createexpomap=yes`
  - When extracting events, use region file RA/Dec derived from XRT data (i.e. centroiding position using `ds9`).
    - Don't assume Simbad position is correct or consistent with what XRT sees (star tracker errors could make error 1-2 pixels for example)
    - All examples in this talk assume 20 pixel radius extraction region for sources.
- Always check work against Leicester Automatic Analysis Page (later slide)

# EVENT GRADES

- PC mode.

- PC mode Event recognition is performed on a 3x3 grid, as sometimes charge from X-ray is split between pixels.

- Grade 0 is a “single pixel event”, i.e. all charge concentrated in one pixel
- Grades 1-12 are “split events”, with charge distributed over 2 (grades 1-3) to 3 (grades 5-8) or 4 pixels (grades 9-12).

- Higher grades are considered unlikely to be real.

- For PC standard is to use grades 0-12. Using grade 0 will be more accurate but will loose ~10-15% of all X-ray events.

- RMFs exist for grade 0, grades 0-4 and grade 0-12.

- WT mode

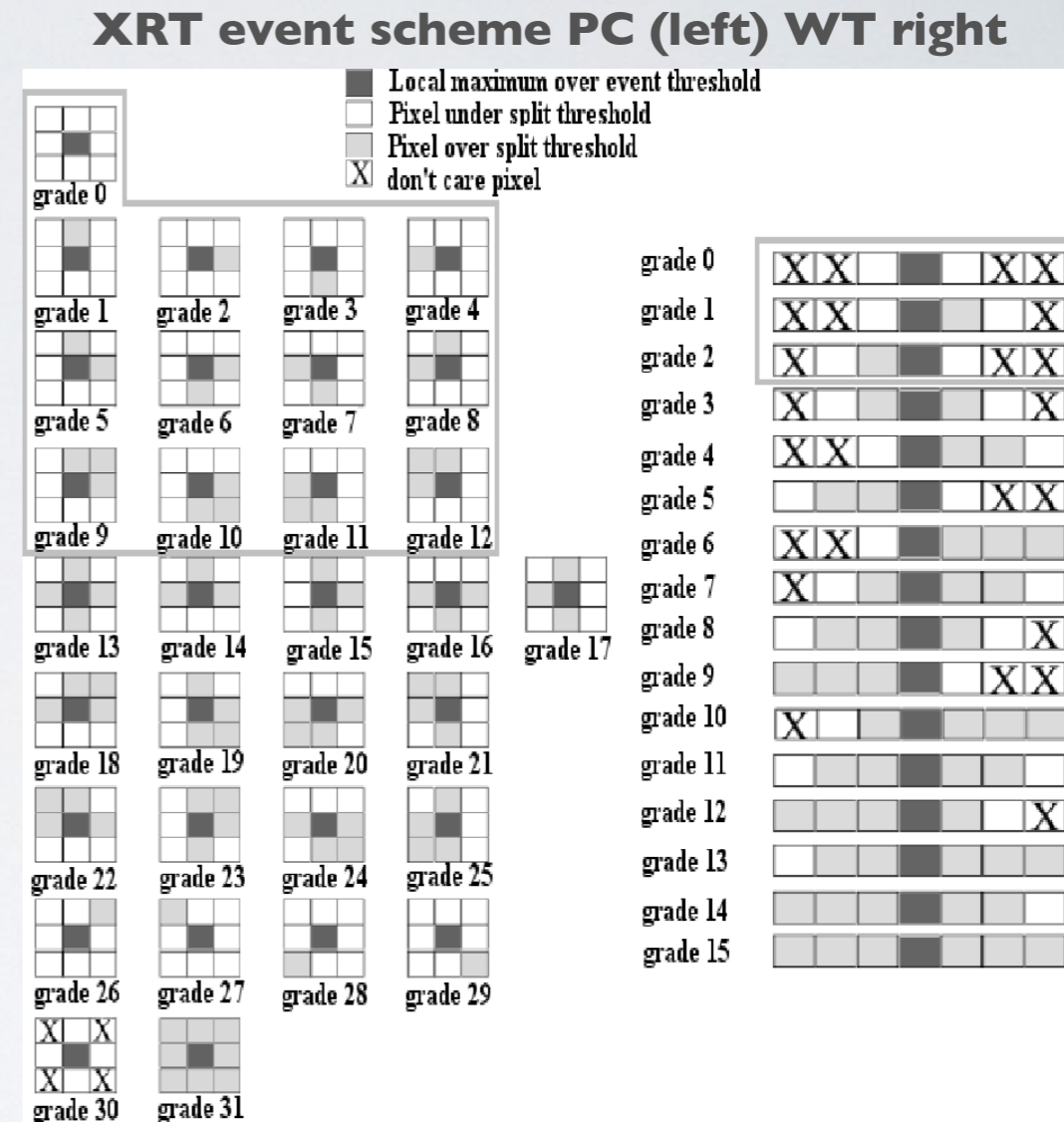
- Events are graded on a 1D 7 pixel strip.

- Grade 0 is single pixel. Grade 1-2 are split across 2 pixels.
- High grades are considered spurious.

- Use grade 0-2 for most cases where pile-up isn't an issue.

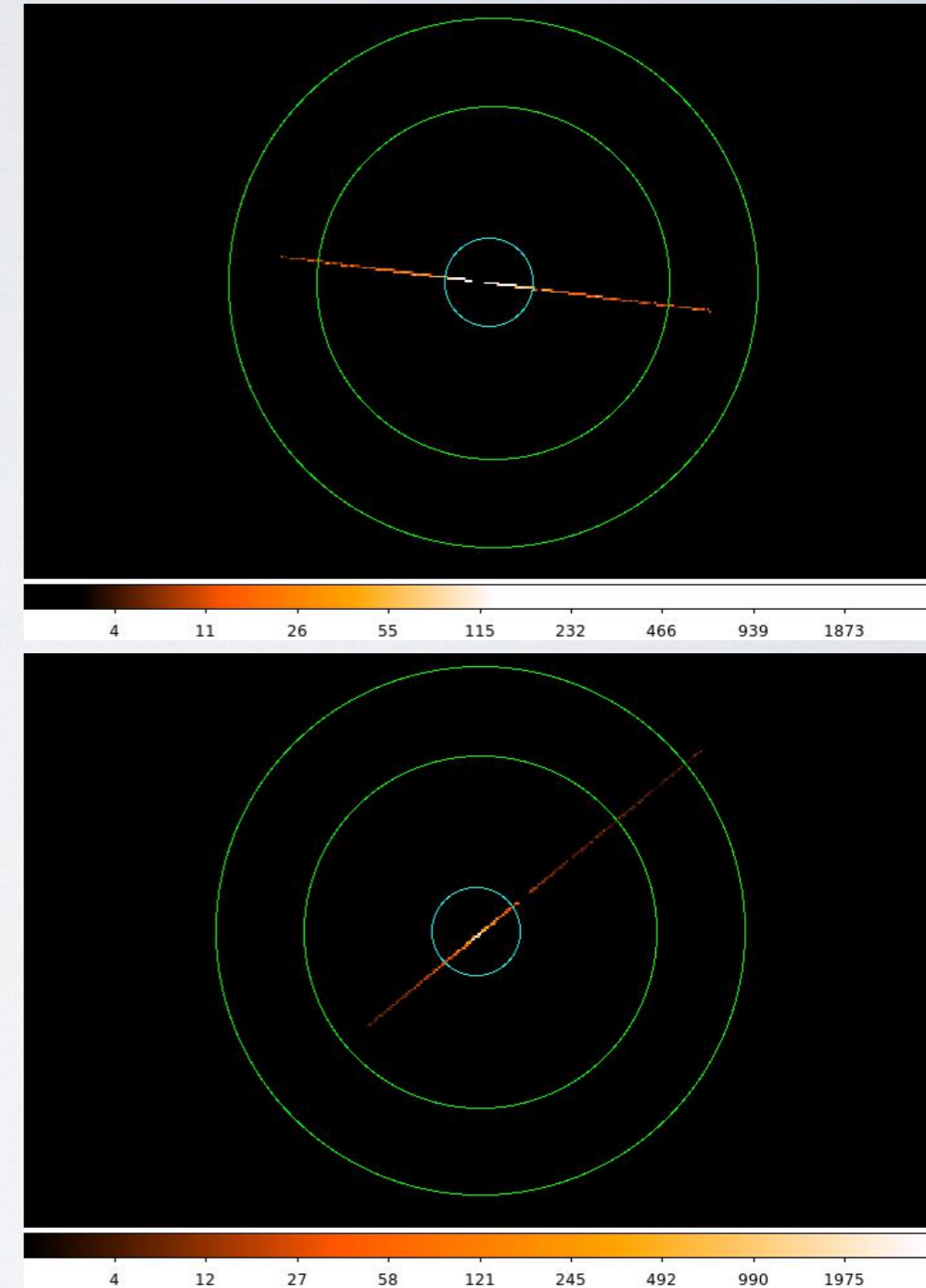
- Using grade 0 only in WT can fix some issues with pile-up and other bad events, so for bright sources is “best practice”.

- Less piled-up grade 0-2 spectra show hardening from pile-up before grade 0
- Avoids low-E redistribution features seen in spectra from heavily absorbed sources”



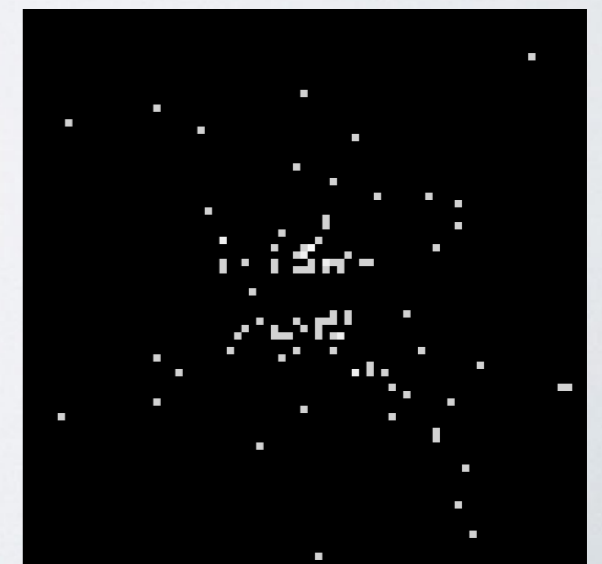
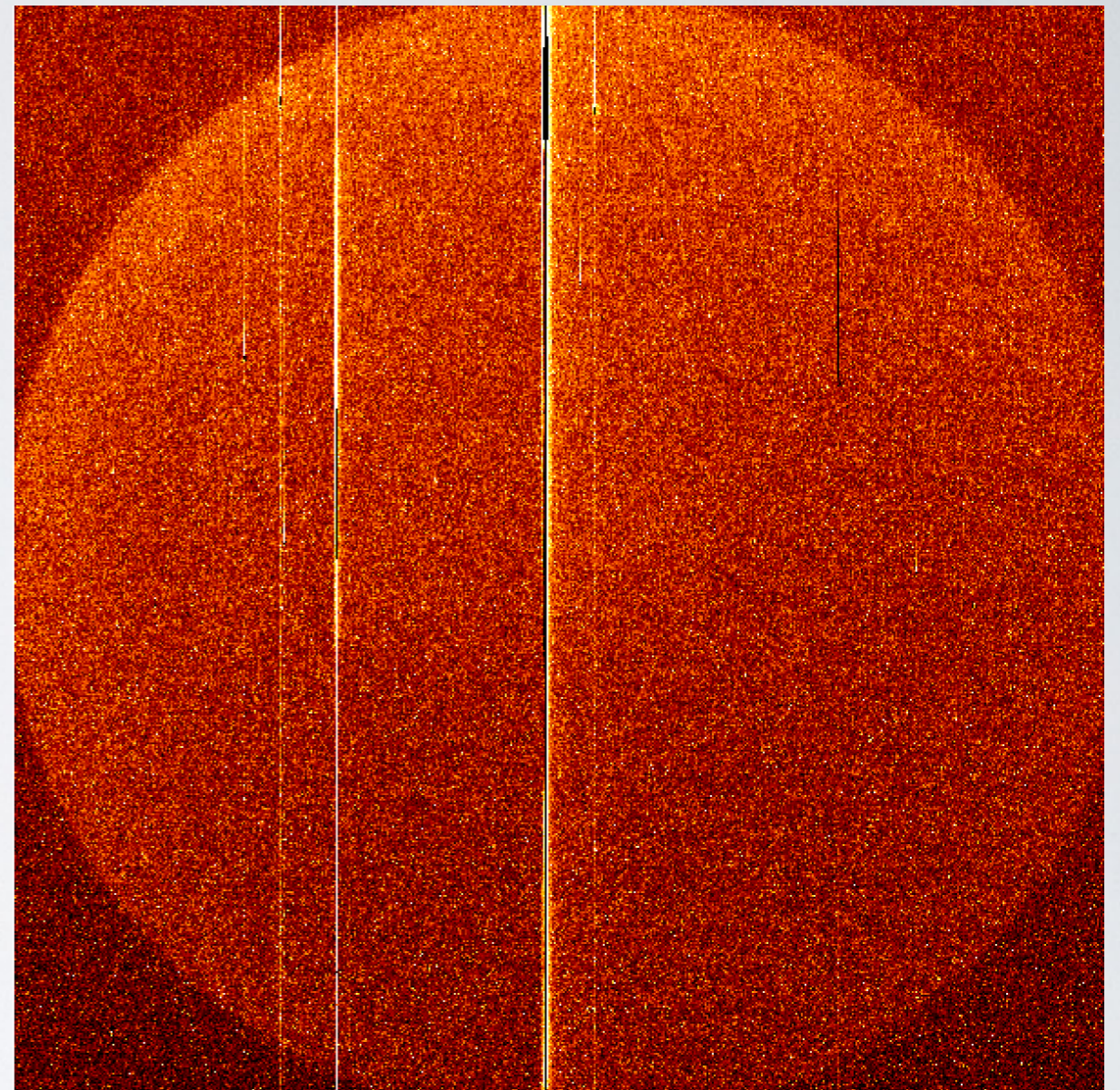
# CORRECT BACKGROUND IN WT MODE

- In WT mode, it's best to use a background that is far away from the point source.
- However, as window is narrow (200 pix), this means using edge.
- As pointing changes between snapshot, edge of window can change.
- Best practice Use an annulus for background, with inner/outer radii 80 / 120 pixels.
  - This ensures the same amount of background included regardless of shifting pointing.
  - Also ensures as little contamination from wings of PSF as possible.
- However - big issue with this - BACKSCAL keyword used by Xspec and others, will be wrong.
  - It assumes size of background area is area of the annulus, whereas because WT data is 1D, it is actually a rectangle (as is the circular extraction region!
  - Need to correct BACKSCAL keyword manually to fix this issue.
- Note for very bright sources, background subtraction is unnecessary as background will be dominated by the PSF wings, rather than actual background.



# HOT PIX/COLUMNS AND EXPOSURE MAPS

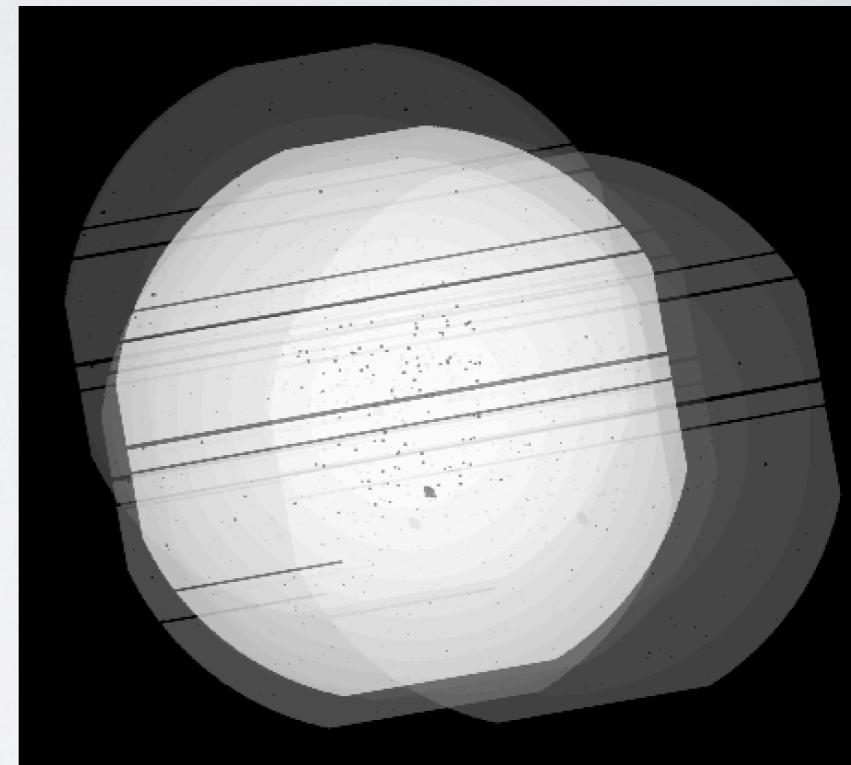
- In May 2005, XRT was hit by a micrometeorite, which caused hot columns to form.
- 5 hot columns of varying strengths. Most important / annoying are the two in the middle of the detector.
- Hot pixels spread all over detector need to be masked out. Hot columns masked out.
- This is why it's important to make exposure maps!
- Note that exposure map correction is sensitive to correct RA/Dec given for source, based on XRT position.
  - Accuracy of correction is only good to  $\sim 15\%$  if the source extraction region is not centered on XRT source.





# EXPOSURE MAPS AND ARFS

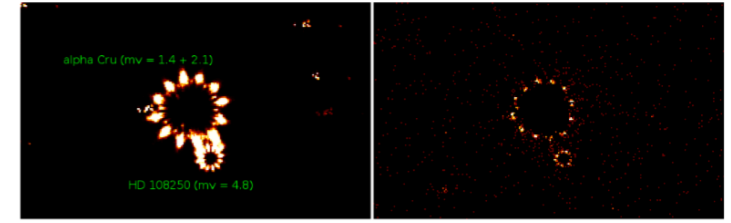
- Swift is in LEO and has a typical maximum exposure of 1.8ks.
  - If observation is longer than 1.8ks, it will be made up of multiple exposures.
  - Swift is not very accurate at pointing (within 3' 90% of time), so source will land on different part of detector in each "snapshot".
- Important to create an exposure map to deal with this issue, and use this when creating a ARF for your spectrum.
  - `xrtmkarf expofile=sw00954304002xpcw3po_ex.img`
- When creating lightcurves, you have to correct for hot columns for each snapshot.
- For best / most accurate results, process each snapshot separately and create an ARF for each snapshot, then combine using `mathpha/addarf`.
  - This addresses an issue where sometimes `xrtmkarf` can get vignetting correction wrong, if offaxis angles between snapshots differ by a lot (e.g. like in image to right).



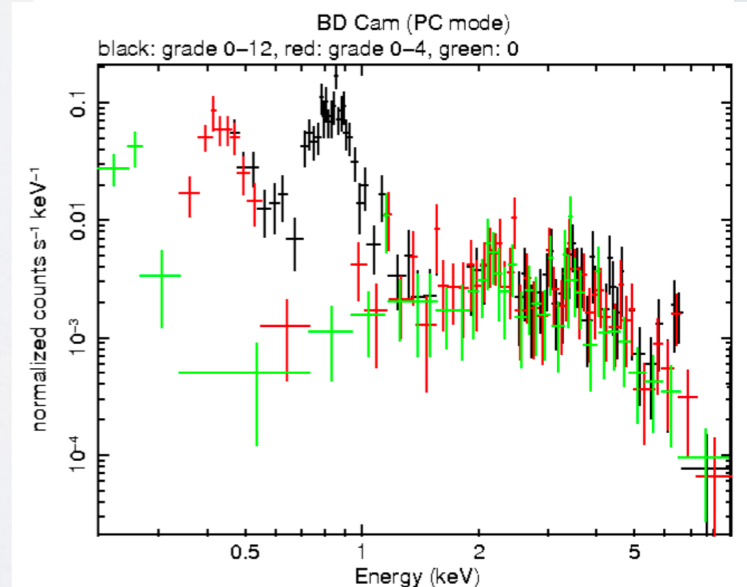
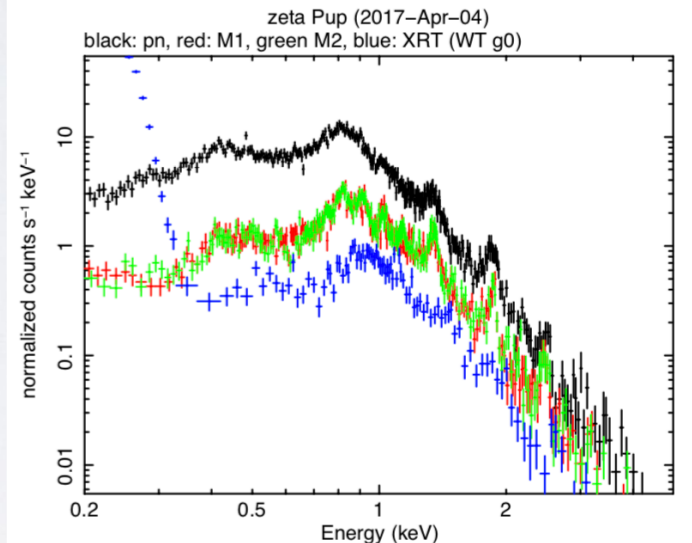
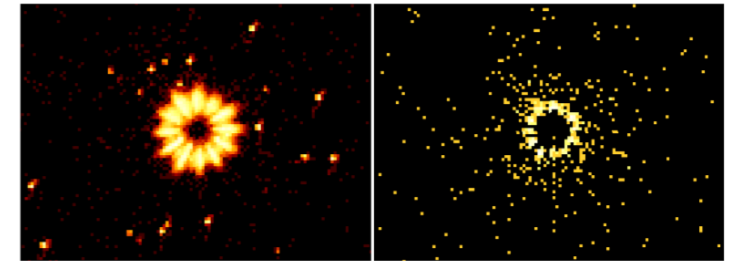
# OPTICAL LOADING

- What is “Optical Loading”?
  - XRT detector is a CCD. Therefore it will detect optical photons as well as X-rays.
  - To mitigate this a filter is placed in front of the CCD to reflect optical light, but transmit X-rays. Unlike other telescopes, XRT only has one such filter, comparable to XMM’s thin filter.
  - Although this filter attenuates light, very bright / red star photons can leak through. If enough optical photons leak through, these can be seen as “fake” X-rays.
  - Optical Loading is usually only an issue for very bright stars when in PC mode.
  - Optical loading events often have high event grades, so examining unfiltered vs filtered event files makes them quite obvious (see image in top right of slide).
- Effect of optical loading:
  - Spectra can be contaminated at low energies (see Figure bottom right)
  - “False” X-ray sources - double check they aren’t bright stars.

$\alpha$  Cru ( $m_V = 1.4 + 2.1$ ) & HD108250 ( $m_V = 4.8$ )

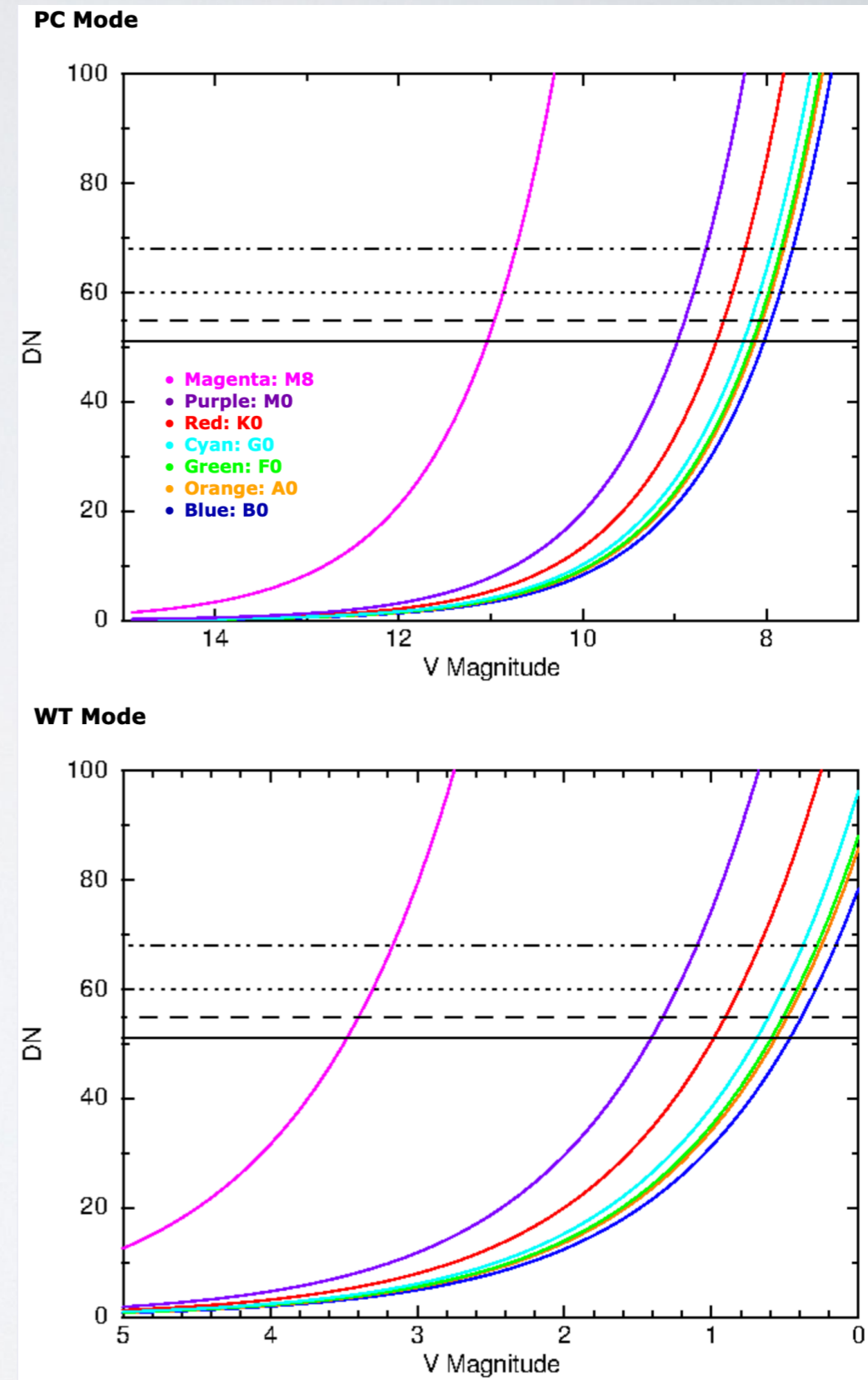


BD Cam ( $m_V = 5.1$ )



# OPTICAL LOADING (2)

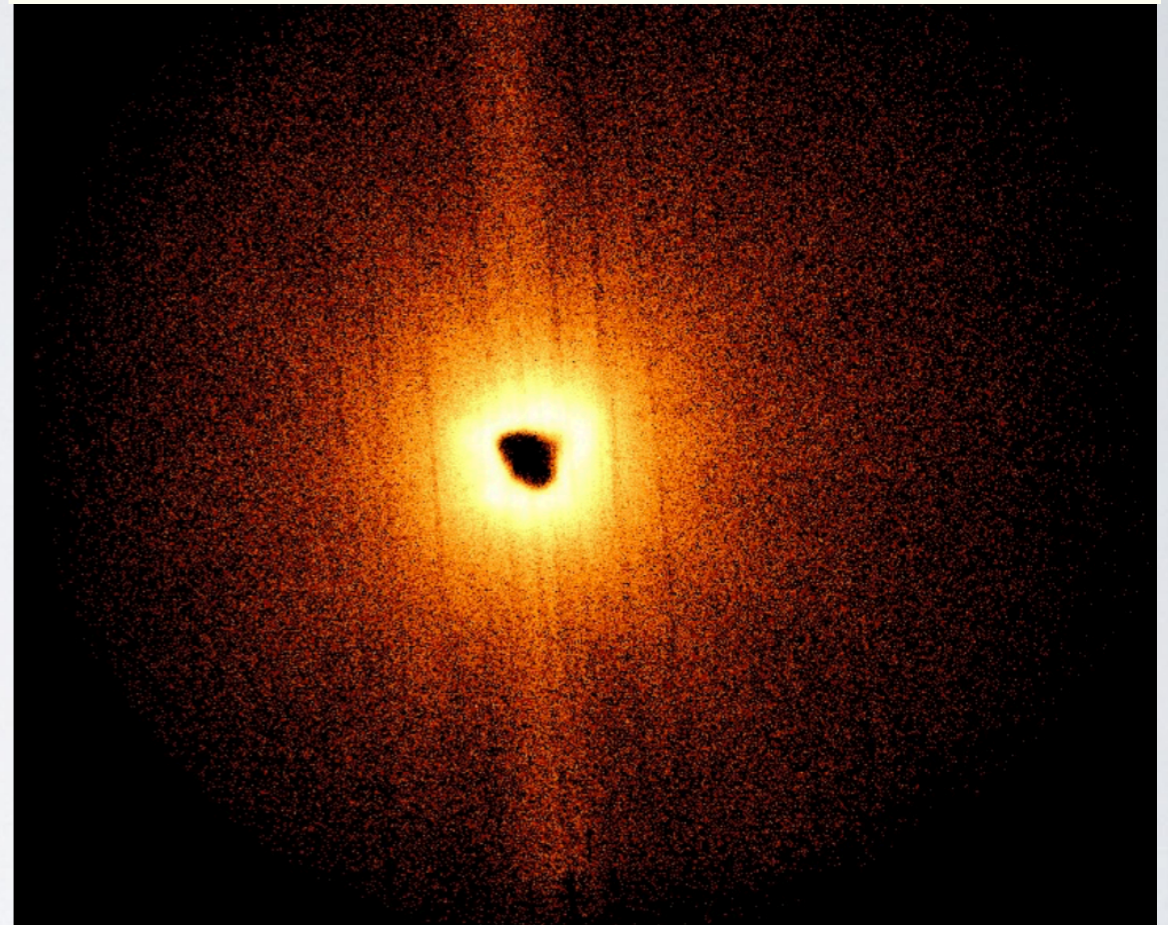
- How to avoid optical loading:
  - Check for bright stars when submitting Swift TOO / GI proposal
  - If star is brighter than  $V=8$ , optical loading will be an issue in PC mode, predictions are given for PC mode in top right plot.
  - Selecting WT mode for optically bright sources mitigates most issues relating to optical loading for all but the brightest stars.
- Read up on Optical Loading here:
  - [https://www.swift.ac.uk/analysis/xrt/optical\\_loading.php](https://www.swift.ac.uk/analysis/xrt/optical_loading.php)



# PILE-UP

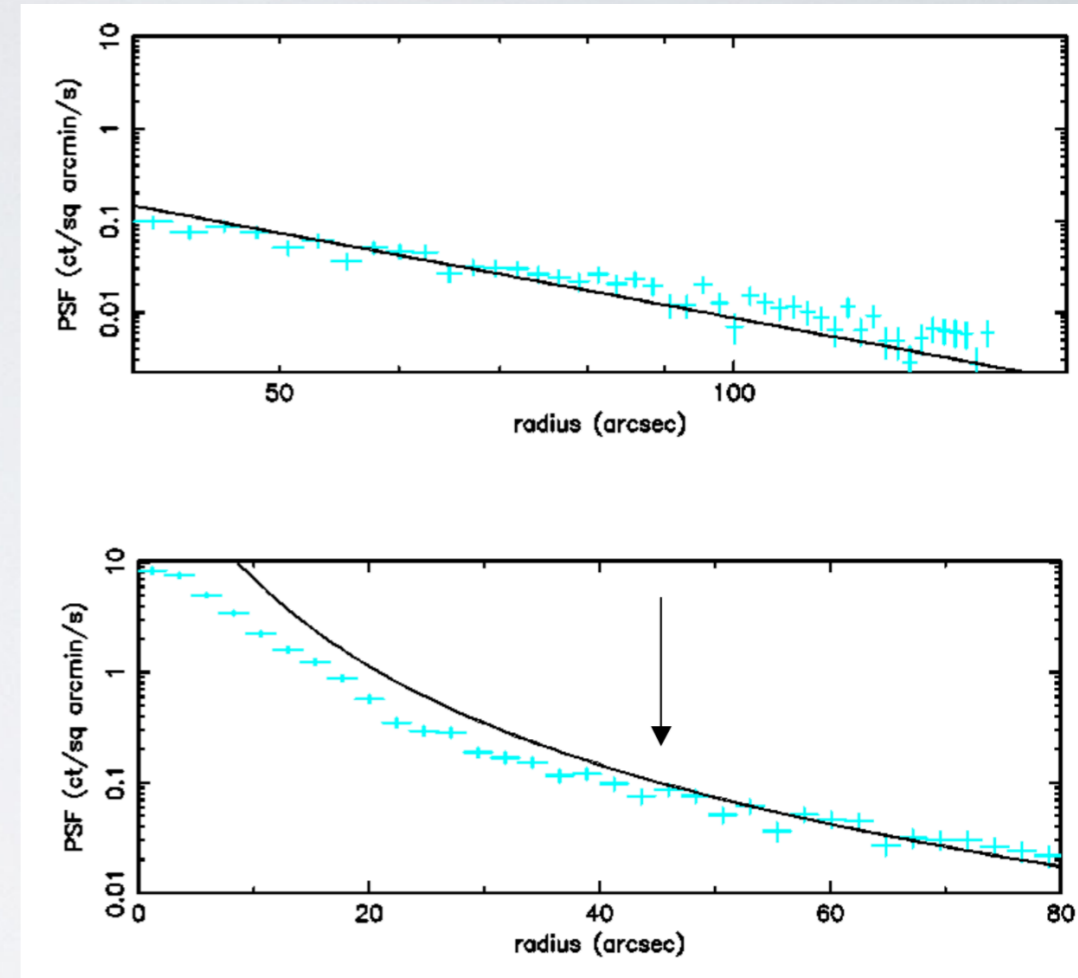
- Pile-up occurs when X-rays hit the same or adjacent pixels in a single exposure frame.
- For PC mode, exposure frame is 2.5s, which means pile-up becomes an issue for sources where count rate is  $>0.5$  c/s. WT mode experiences pile-up at  $>100$ c/s.
- Pile-up at worse case causes event recognition to fail, and events to have high grade values, so for very bright sources, it shows up as a hole in the source (see PC mode Crab image on right).
- For lighter pile-up, look for deformations in the PSF. Ximage can be used to see if PSF model is correct.

**Crab Nebula PC mode exposure**



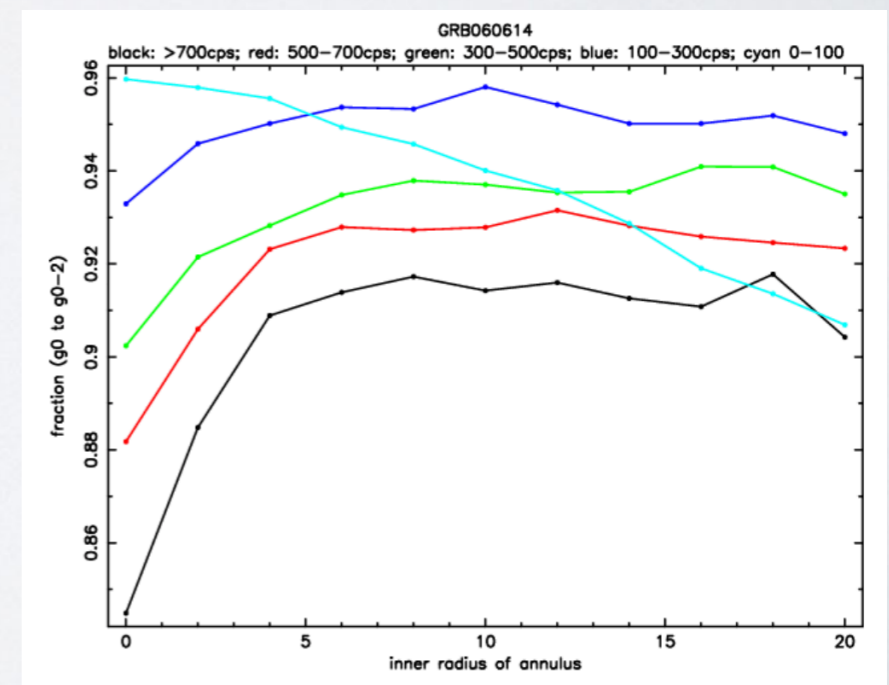
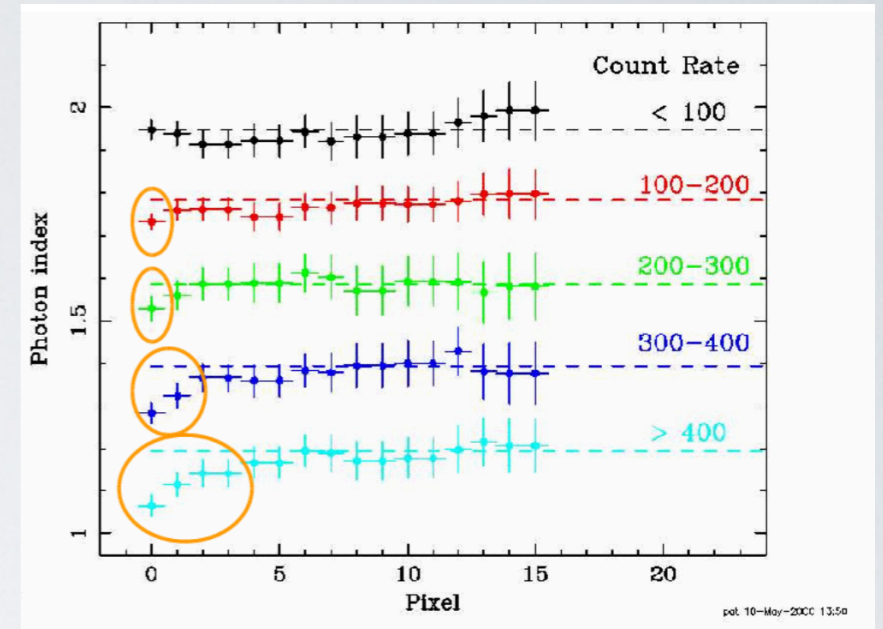
# PILE-UP (2)

- XRT PSF is fit by model:
  - $\text{PSF}(r) = [1 + (r/r_c)^2]^{-\beta}$  where, for Swift,  $r_c \sim 5.50$  and  $\beta \sim 1.524$
- Extract PSF radial shape in Ximage and fit PSF King model to wings of PSF.
- See how this fit works of the core of the PSF. For pile-up, the core should be over-estimated by the fit (as pile-up suppresses count rate).
- See also <http://www.swift.ac.uk/pileup.shtml>



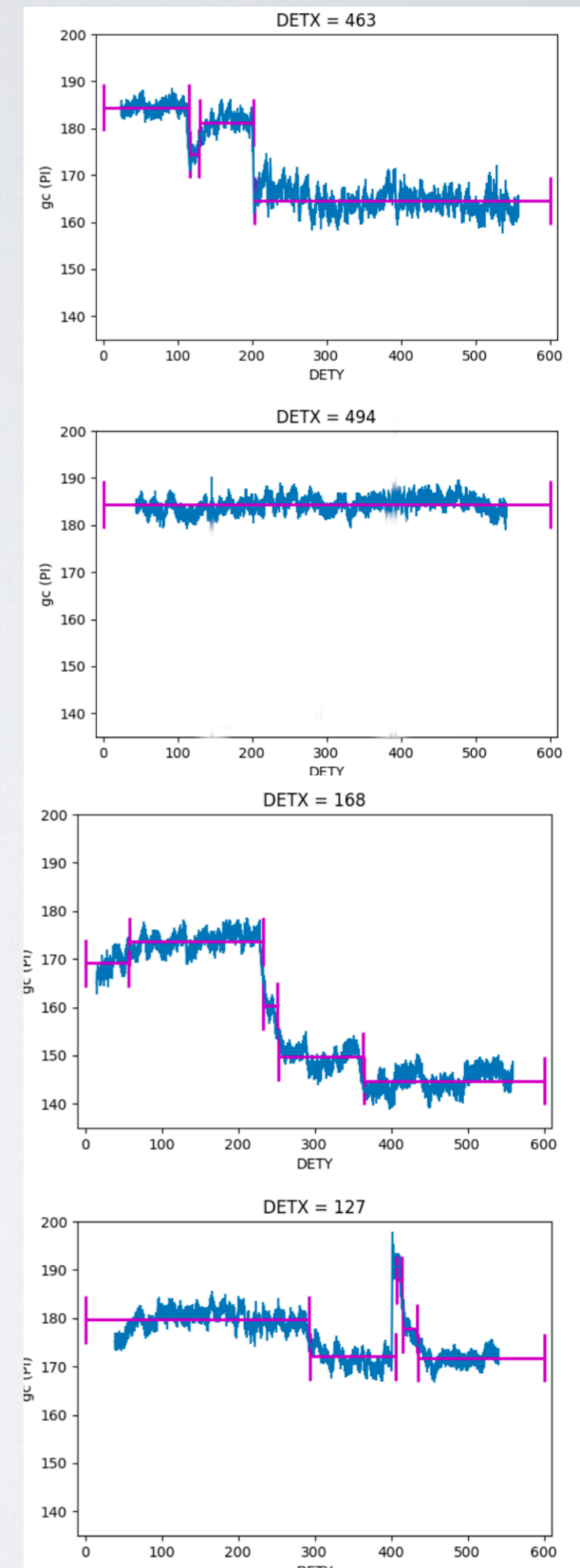
# PILE-UP HOW TO FIX

- To fix pile-up simply remove the core of the PSF when extracting it.
  - Use ds9 annulus to remove core of PSF.
- PSF fit before can be used to figure out size of core to remove.
- Alternatively, simply try increasing the exclusion radius, and see how the spectrum looks.
  - Pile-up makes a spectrum harder, so as core is increased, spectral fit will become softer.
  - When spectral fit no longer changes with increasing core radius, you've removed the correct amount.
- Another method, which works well in WT mode, is to look at the distribution of event grades.
  - Fraction of single pixel events should flat or higher in center of PSF.
  - For piled up sources, single pixel events fraction is lower in core.



# GAIN ISSUES

- Swift has been in orbit for 16 years so CCD heavily radiation damaged causing deep charge traps (e.g. attached plot).
  - Charge traps remove charge from pixels when read out, and can cause broadening of spectral response.
- Also, CCD was supposed to operate at -100C but loss of cooling system early in the mission, this can vary between -50C to -70C.
  - To fix this gain file coeffs and trap corrections are CCD Temp dependent.
  - However, most calibration performed at -60C (rarely outside -65C to -55C.).
  - Rising bias level cause traps to be filled when CCD is hot so can cause (positive) energy scale shifts.
- Gain offset issues are most obvious in WT mode (due to statistics).
  - They appear as residuals around the O, Si and Au instrumental edges. Because gain is off, the measured and modelled instrumental edges are not aligned causing "W" or "M" shaped residuals.
- Although gain file is updated often, the gain is changing over time, so by the end of the gain year (so before a new gain file release) the WT gain could be off by 30-50eV.
  - Xspec allows for gain to be fit or adjusted, so if large residuals around edges are seen, try "gain fit", with linear term fixed (at 1.0), allowing the constant term to vary (by ~20-50eV)
  - **Do not just mask out these residuals - your fit will be wrong.**

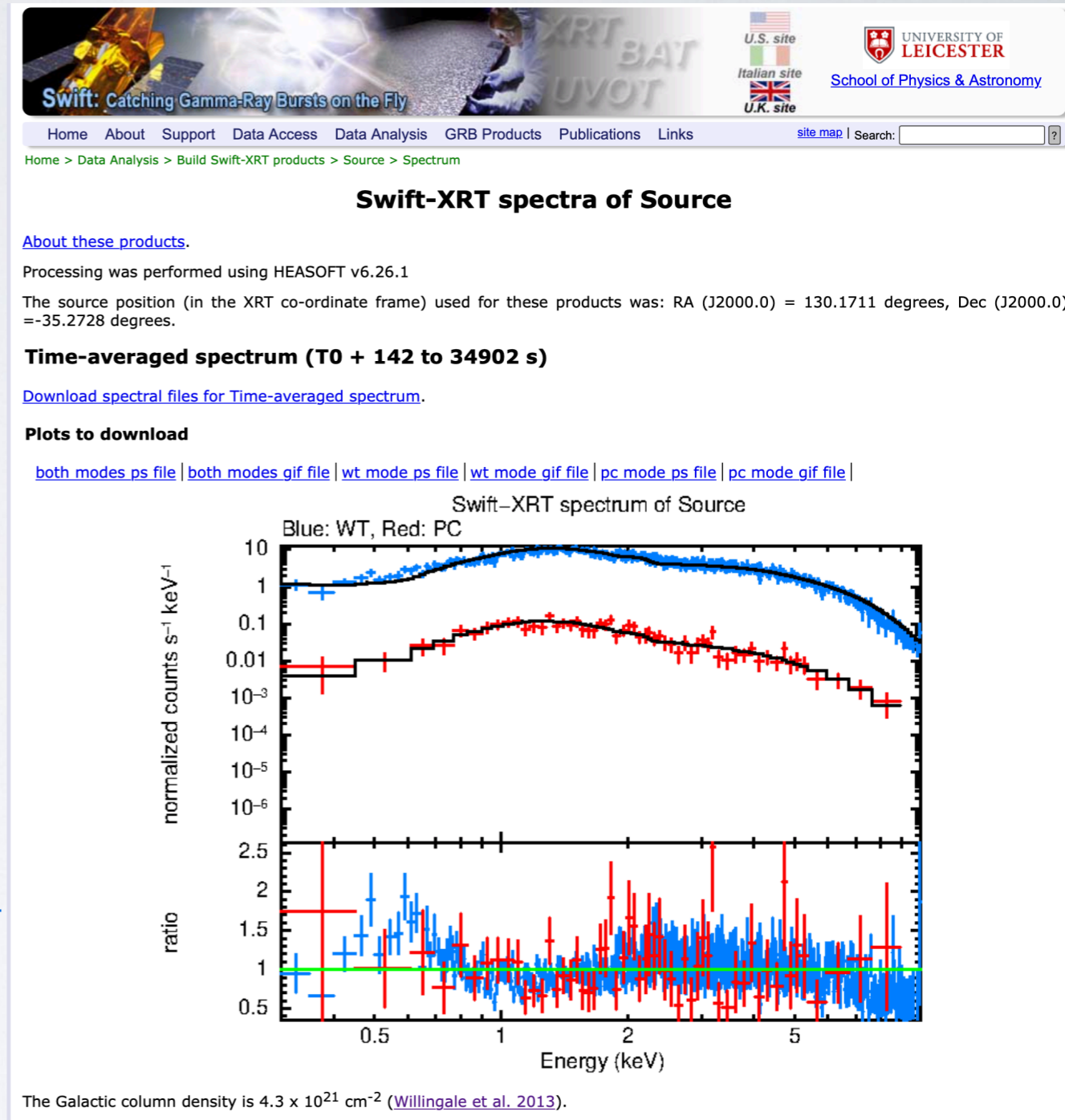


# CHECK YOUR WORK

- University of Leicester provides a page to automatically generate positions, spectra and lightcurves of XRT data (new: source detection in fields!).
- All corrections needed are performed.
- Use this page to double check your results!

[https://www.swift.ac.uk/user\\_objects/](https://www.swift.ac.uk/user_objects/)

- Note that also a Python API for submitting batch jobs to this program - new as of 2020.





# FINAL SLIDE

- Read up on XRT analysis issues at this page:
  - [https://www.swift.ac.uk/analysis/xrt/digest\\_cal.php](https://www.swift.ac.uk/analysis/xrt/digest_cal.php)
- Use XRT “User Objects” page to check your work!
  - [https://www.swift.ac.uk/user\\_objects/](https://www.swift.ac.uk/user_objects/)
- Make sure your CALDB is up-to-date:
  - <https://heasarc.gsfc.nasa.gov/docs/heasarc/caldb/swift/>
- Use the latest HEASoft!
  - <https://heasarc.gsfc.nasa.gov/docs/software/lheasoft/download.html>
- Make sure you check for issues with pile-up, gain, optical loading, background subtraction, as discussed.