Exospheric solar wind charge exchange emission as viewed by XMM-Newton

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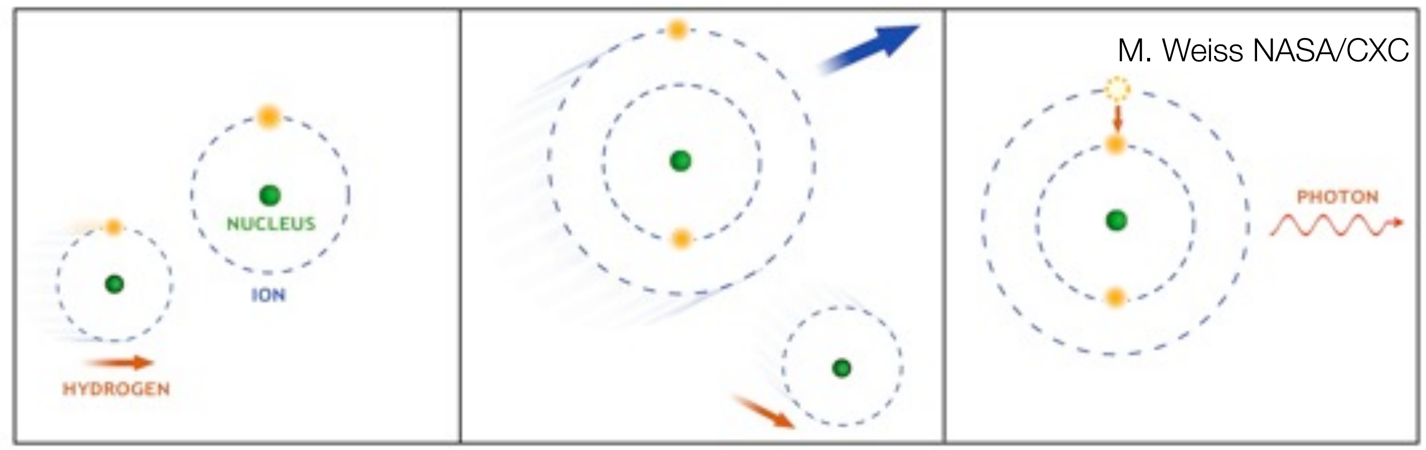
X-ray Universe 2011

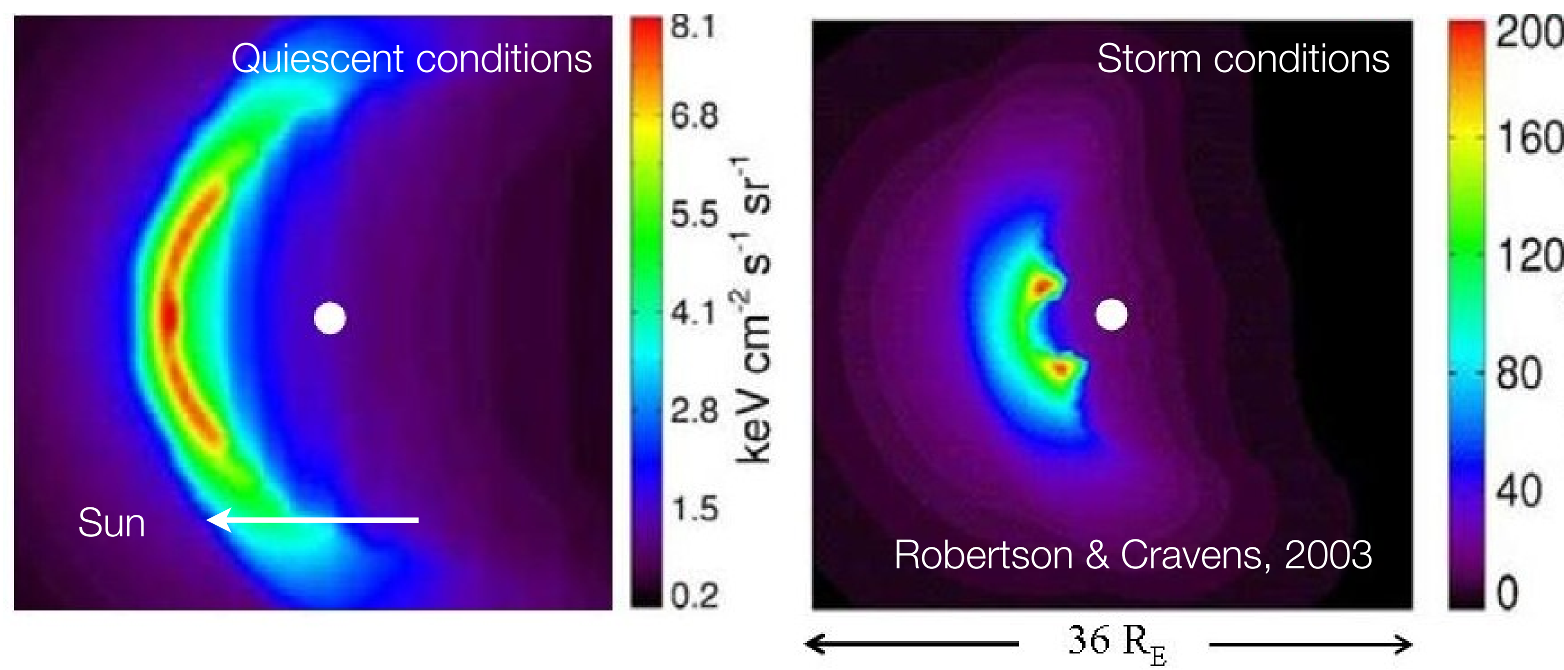
Talk outline

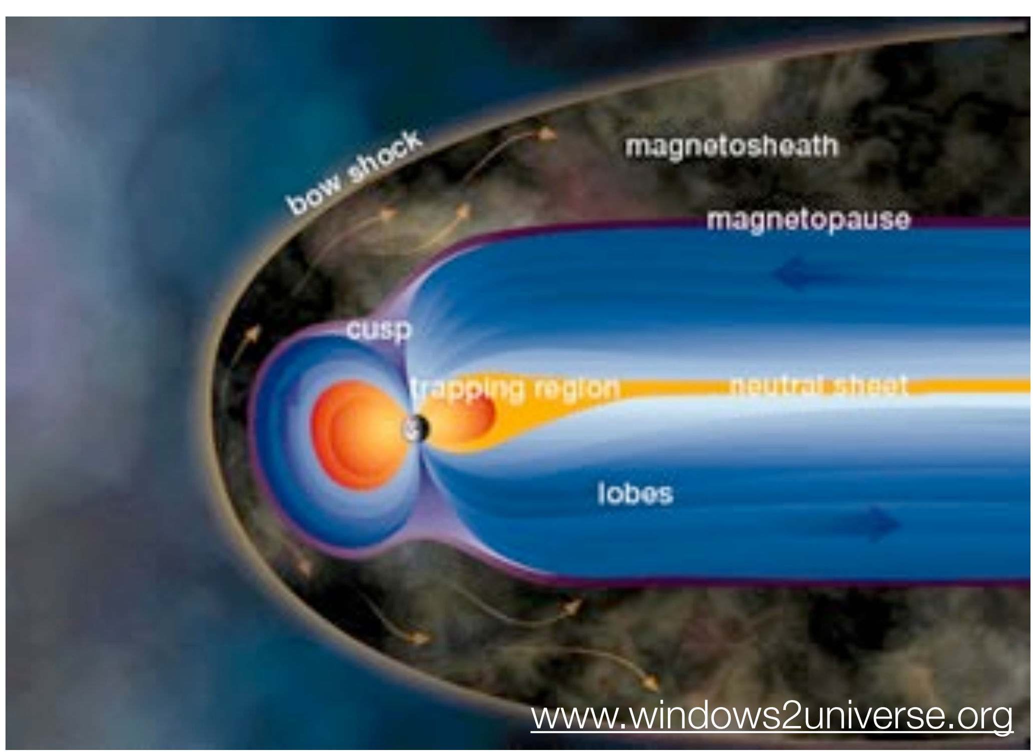
- Observing exospheric solar wind charge exchange (SWCX) with XMM-Newton
- General results of project - characterisation of exospheric SWCX emission as seen by XMM-Newton
    - Level of ‘contamination/enhancement’ (depends on perspective) within archive
    - Relationship with solar cycle
    - Spectral characteristics
- A particular case of interest; viewing a Coronal Mass Ejection
- Modelling the expected SWCX X-ray flux seen by XMM-Newton

Charge exchange and the solar wind

- Solar wind: velocities ~ 200-1000 km s^{-1}, densities ~ 7-40 cm^{-3}
- Solar wind charge exchange (SWCX): charge exchange between a solar wind ion and a neutral in the Solar System
- Cross-sections for charge exchange are high ~10^{-16} cm^{-2}

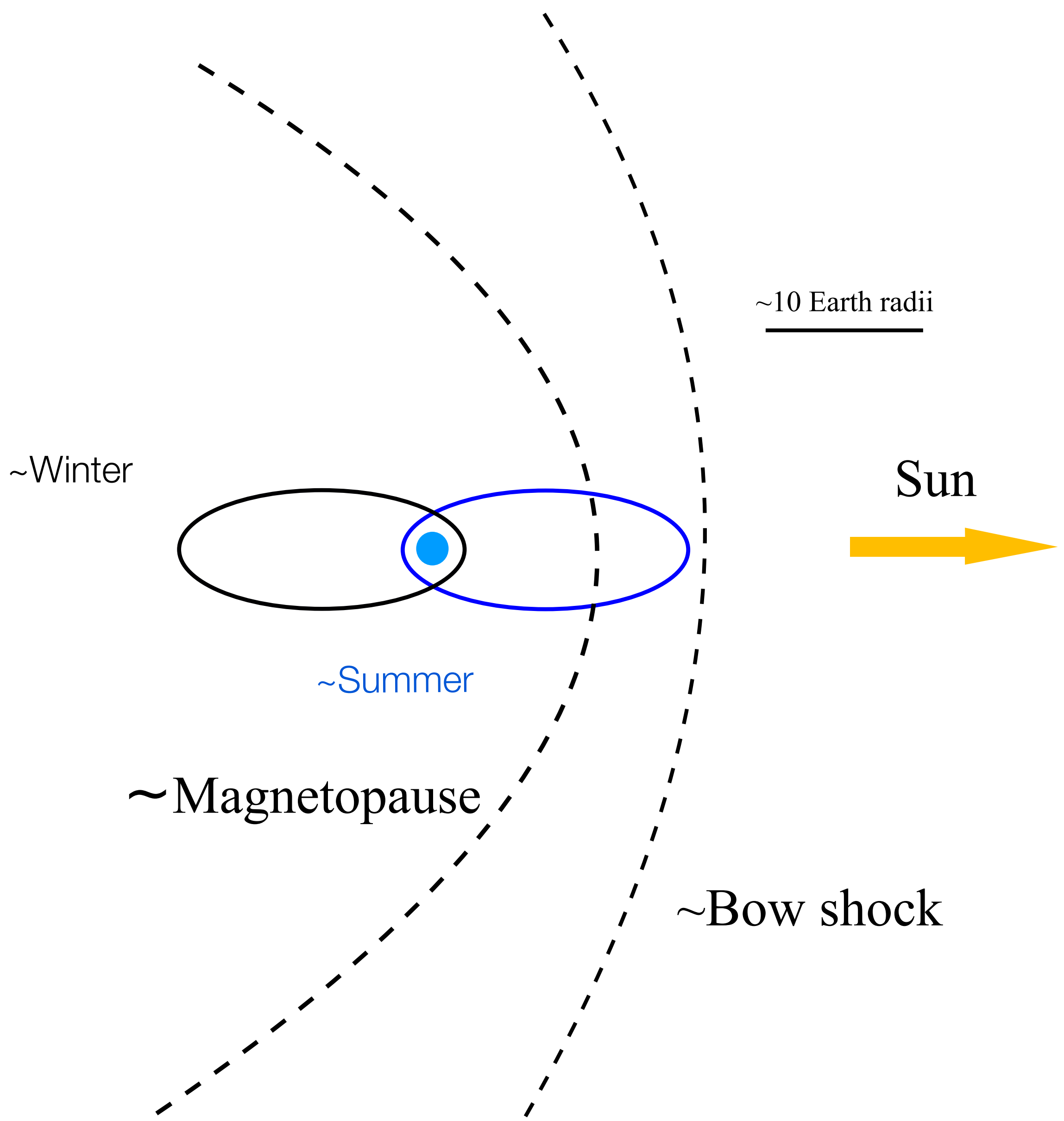






- SWCX emission modelled in Earth's exosphere
- Solar wind storms cause large increases in expected flux
- ...important consequences for XMM-Newton

XMM-Newton’s orbit and viewing angles



- Seasonal effects expected
- Rough winter/summer split
- Dynamic magnetosheath, responds to solar wind pressure
- In summer, XMM-Newton can observe SWCX when line-of-sight passes through the magnetosheath
- Motivation of project: how many XMM-Newton observations are affected and the characterisation of these cases

Searching for XMM-Newton observations affected by SWCX

- Using the EPIC-MOS cameras in full-frame mode. No. obs., 3012, up to revn. 1781 (February 2000 - August 2009).

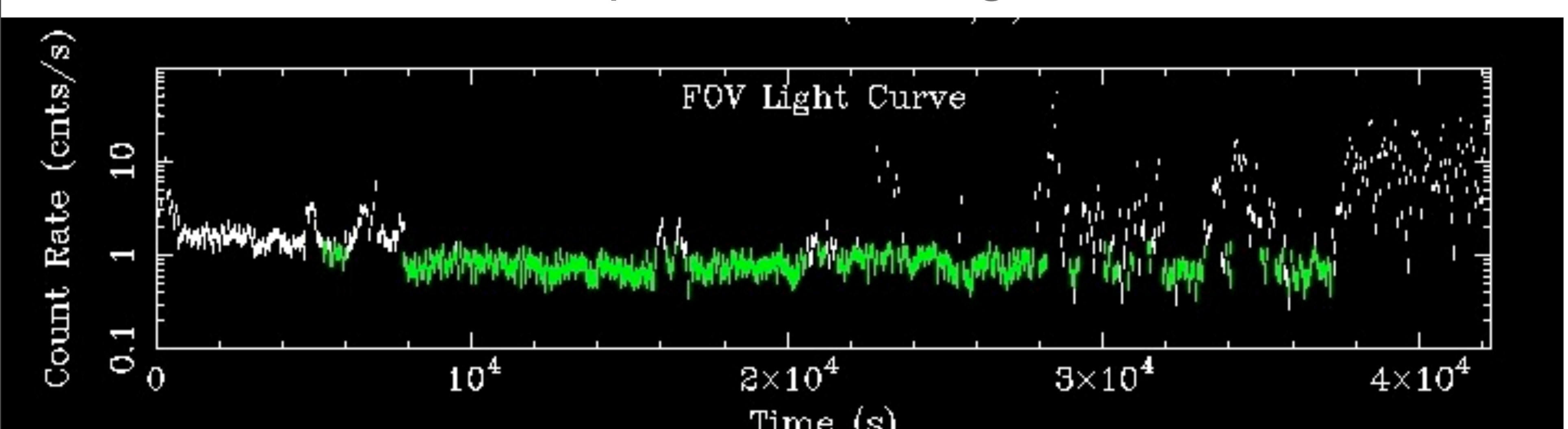
1. Cleaned observations for flare periods (soft protons), ESAS software - residual soft proton contamination can and does occur

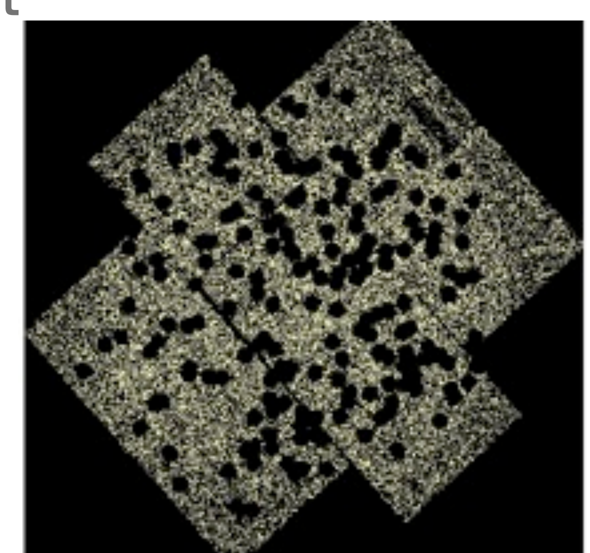
2. Removed resolved point sources, using 2XMM source lists

3. Looked for short timescale variability - indicative of variable SWCX near Earth

4. Create two lightcurves; one for a SWCX energy band (0.5 - 0.7 keV), the other for a supposedly non-varying band (2.5 - 5.0 keV)

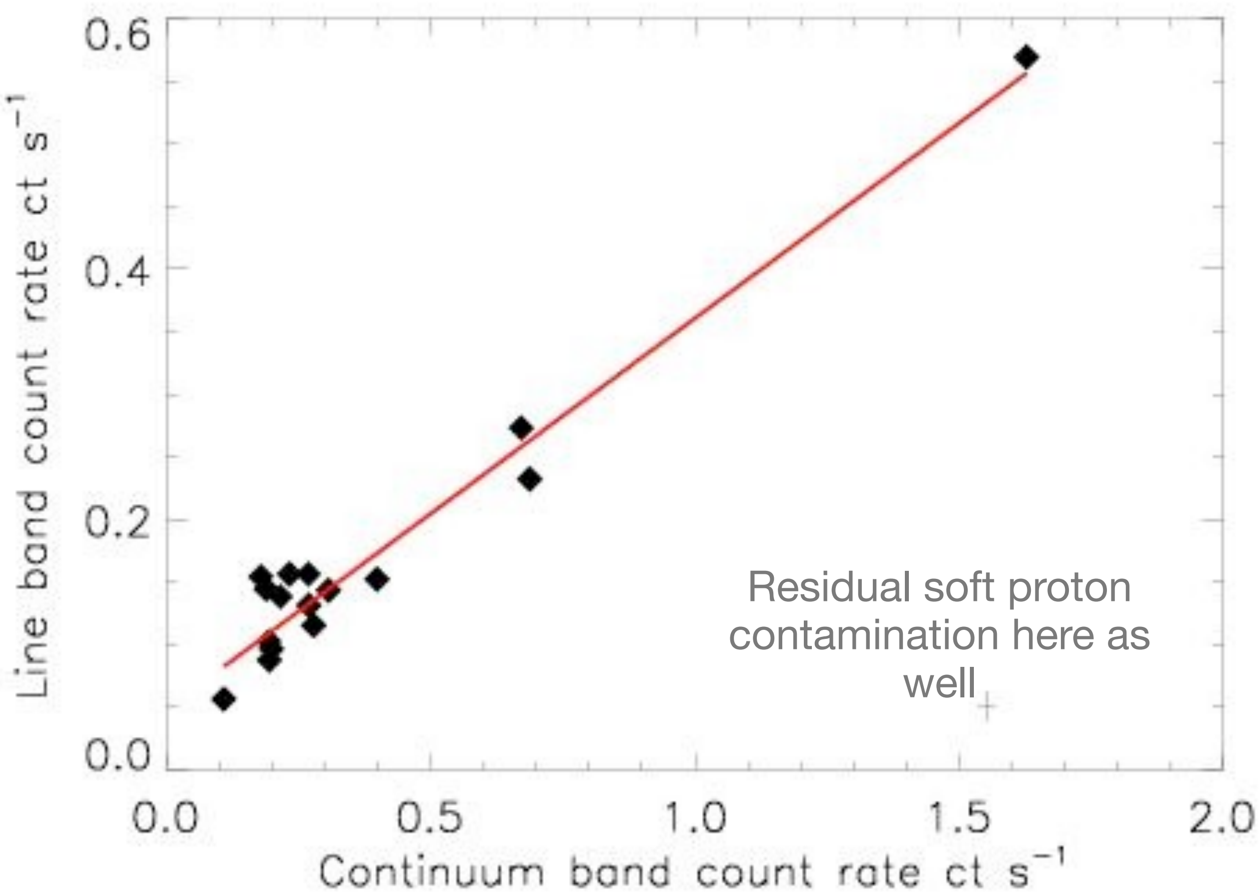
5. Line fit to scatter plot between lightcurves, statistics of fit



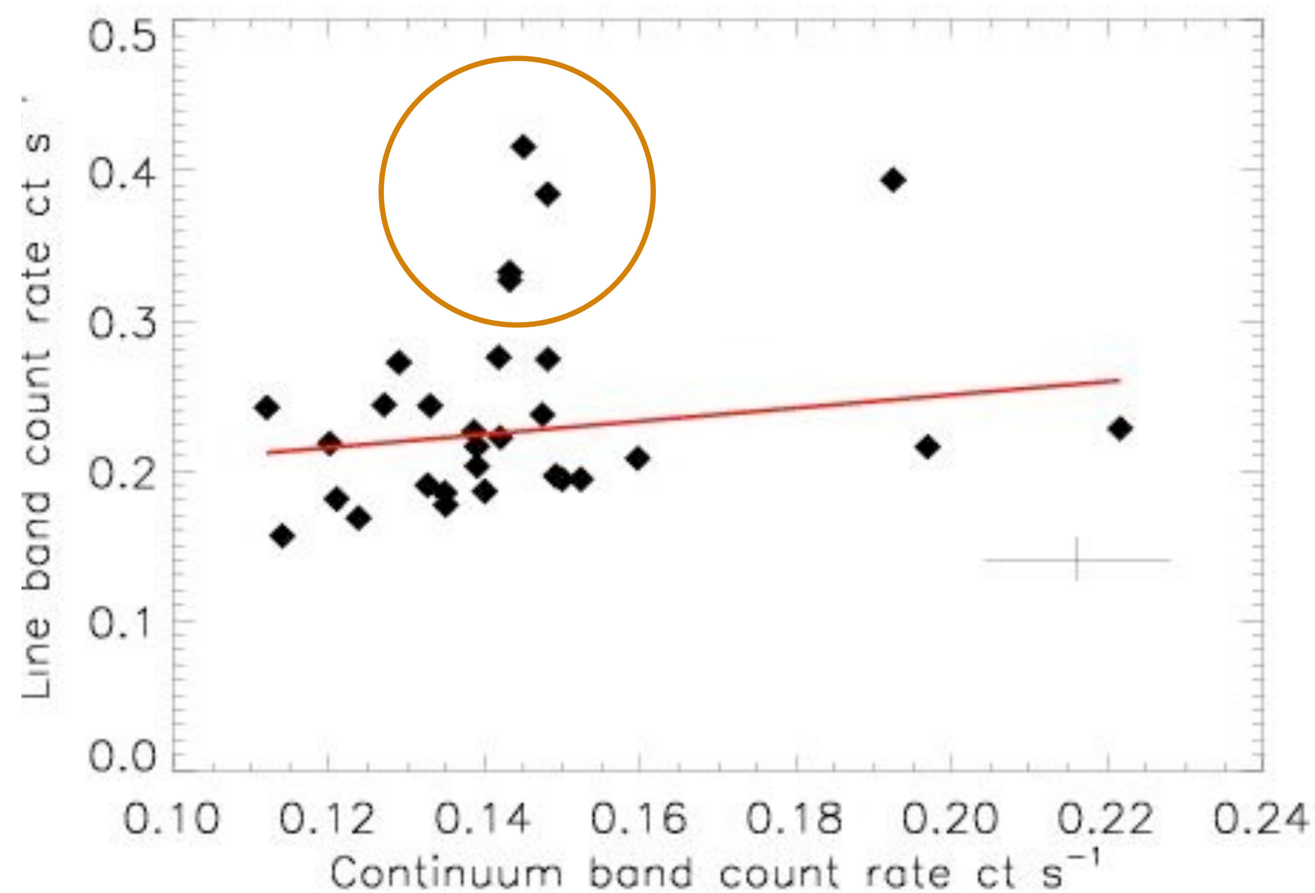


Example line fits

Low chi-squared



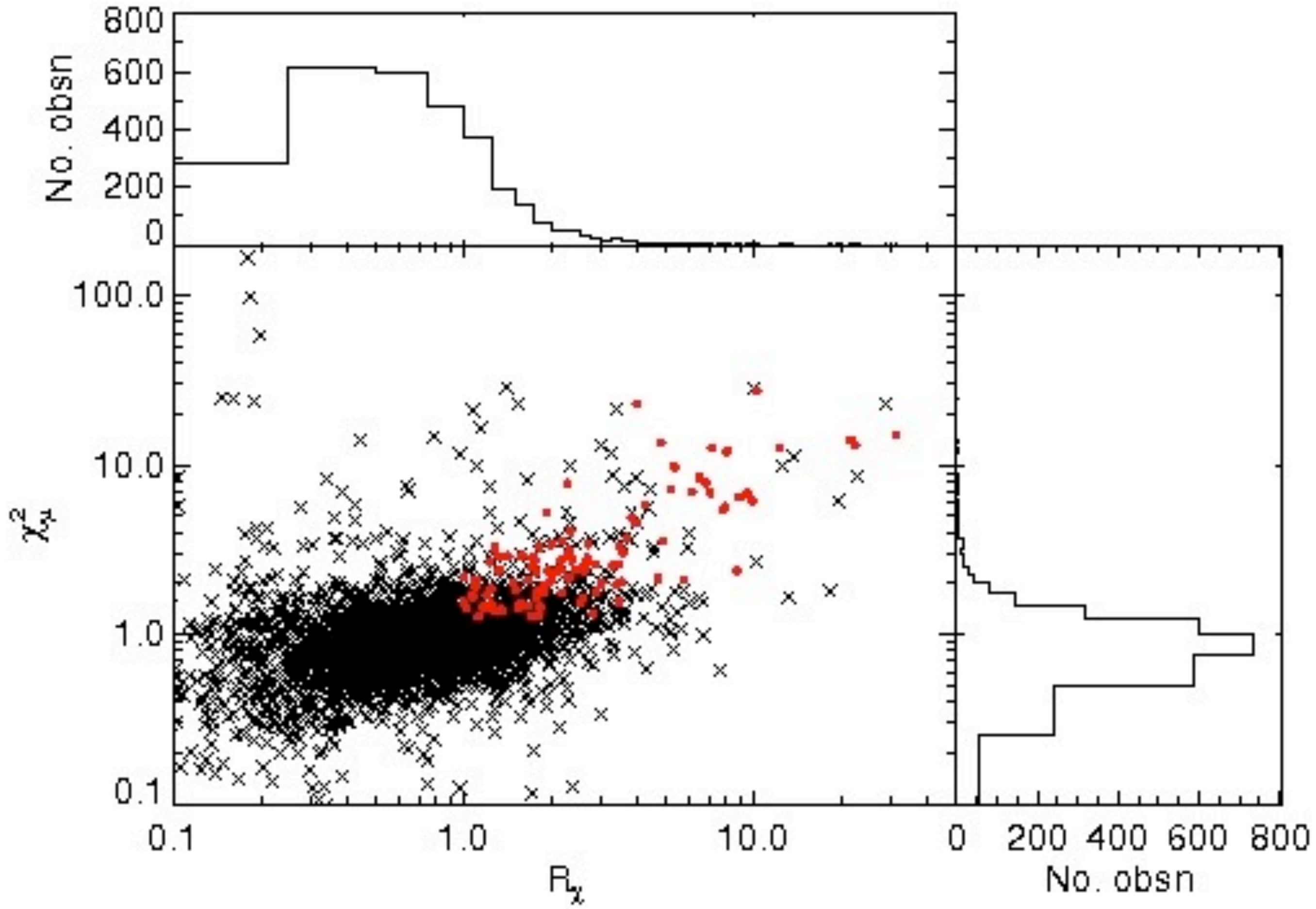
High chi-squared



- Find chi-squared for each linear fit, $X^2\mu$
- Find variability in each lightcurve and calculate the ratio of these variabilities, $R\chi$
- Test all observations in set, rank according to $X^2\mu$ and $R\chi$

Summary of SWCX affected observations

- Red cases those with temporarily-variable SWCX (new or known, published)
- Those with highest $X^2\mu$ were comets, next highest CME (Carter, Sembay & Read, 2010)
- 103 cases identified with SWCX (Carter, Sembay & Read, 2011)

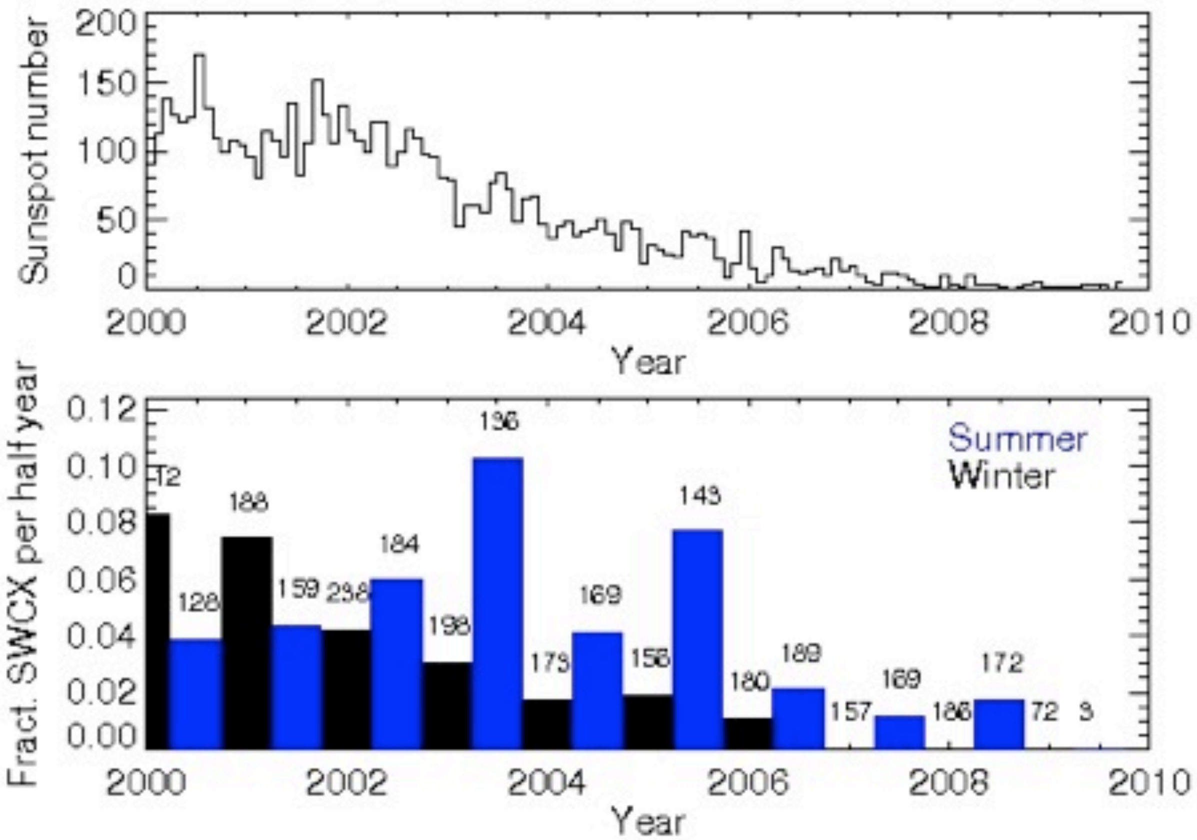


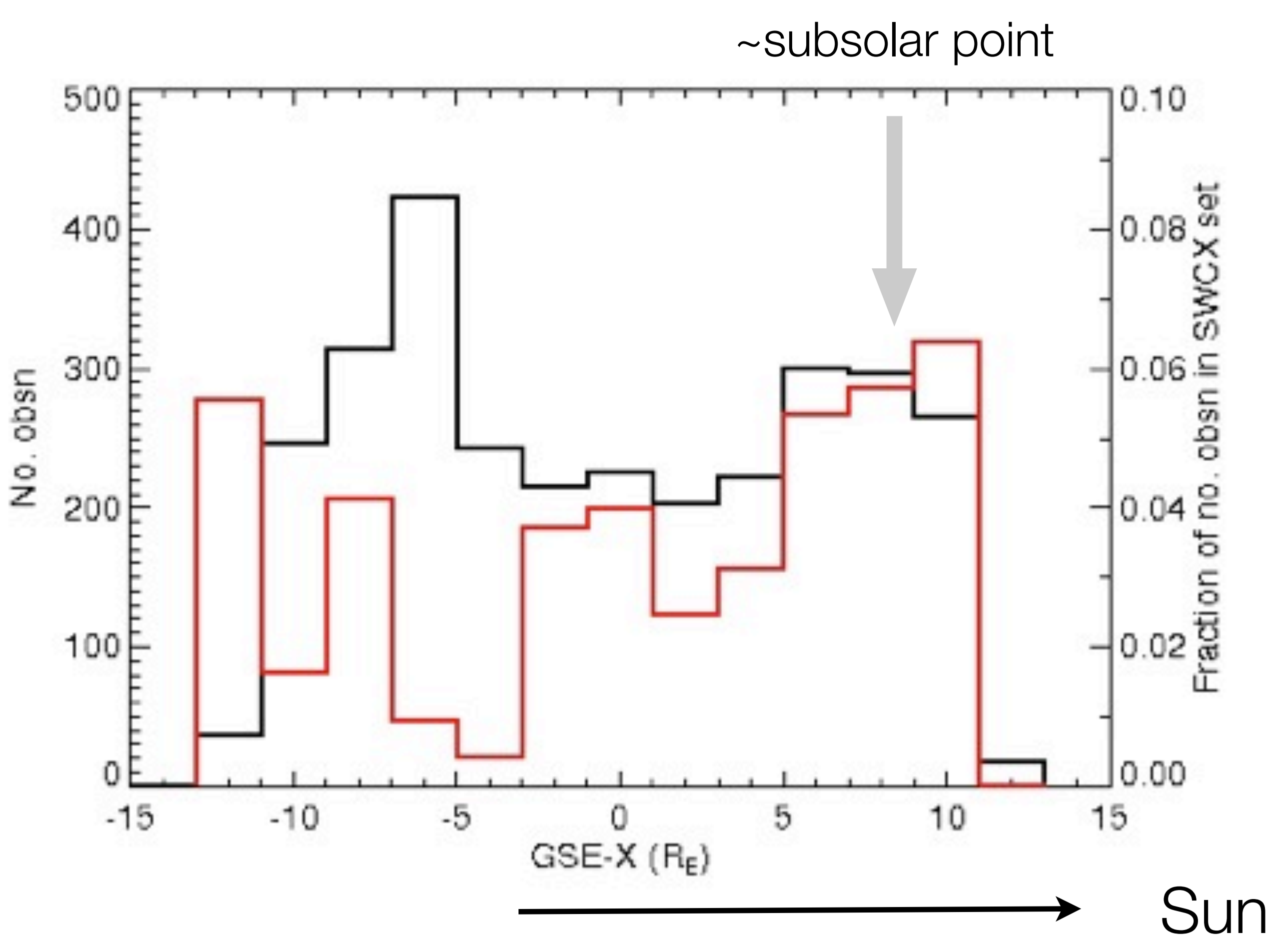
Comets excluded from inclusion in red set as also sites of SWCX emission

Considerable no. observations with Rx < 1.0: soft-proton affected

SWCX cases with respect to solar activity and XMM-Newton orbital position

- Cases preferentially detected in summer, as expected (summer/winter - 64/39)
- Cases preferentially detected about the subsolar point (sunward magnetosheath)



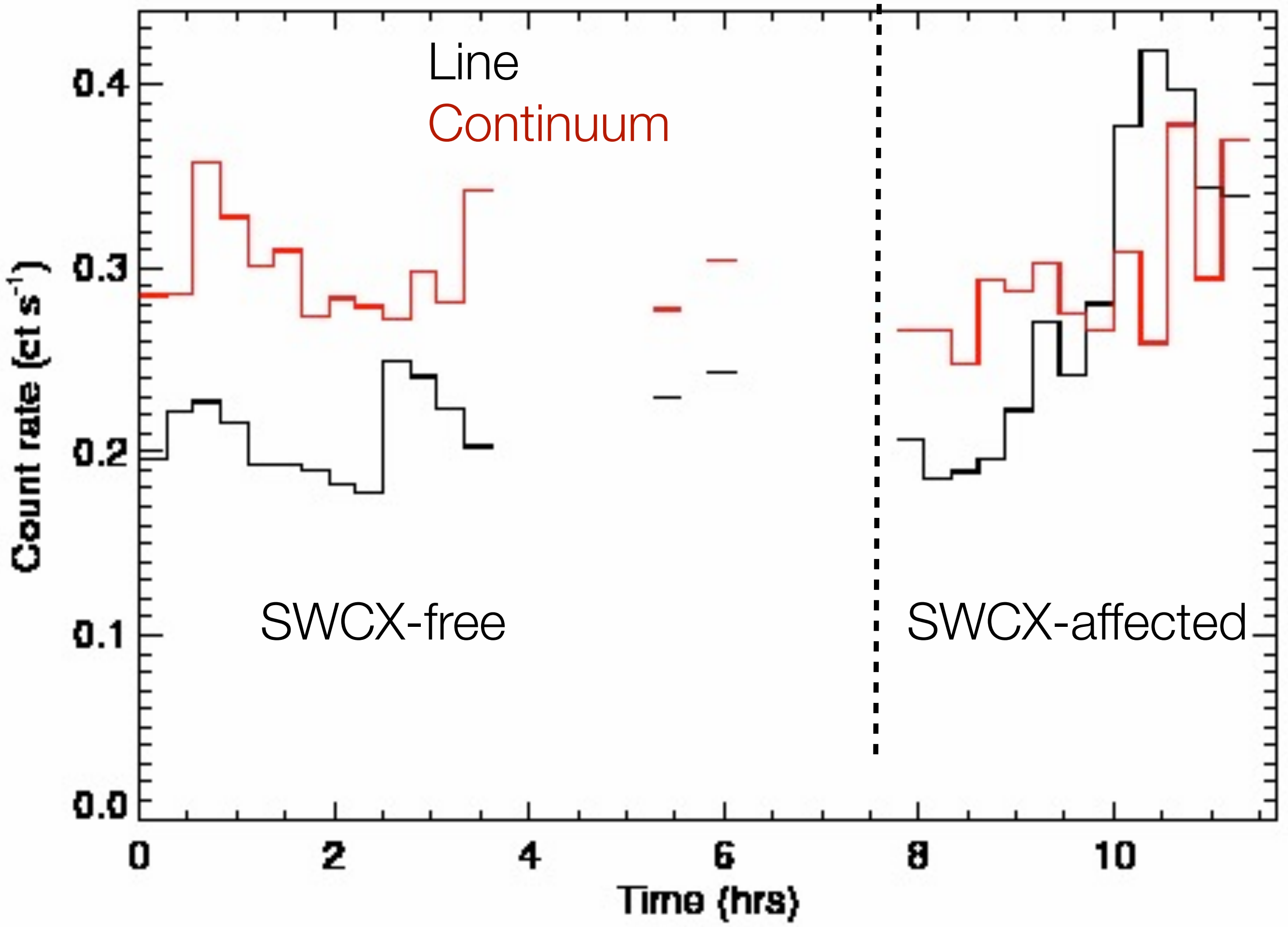


Very few observations with exospheric SWCX signatures towards solar minimum

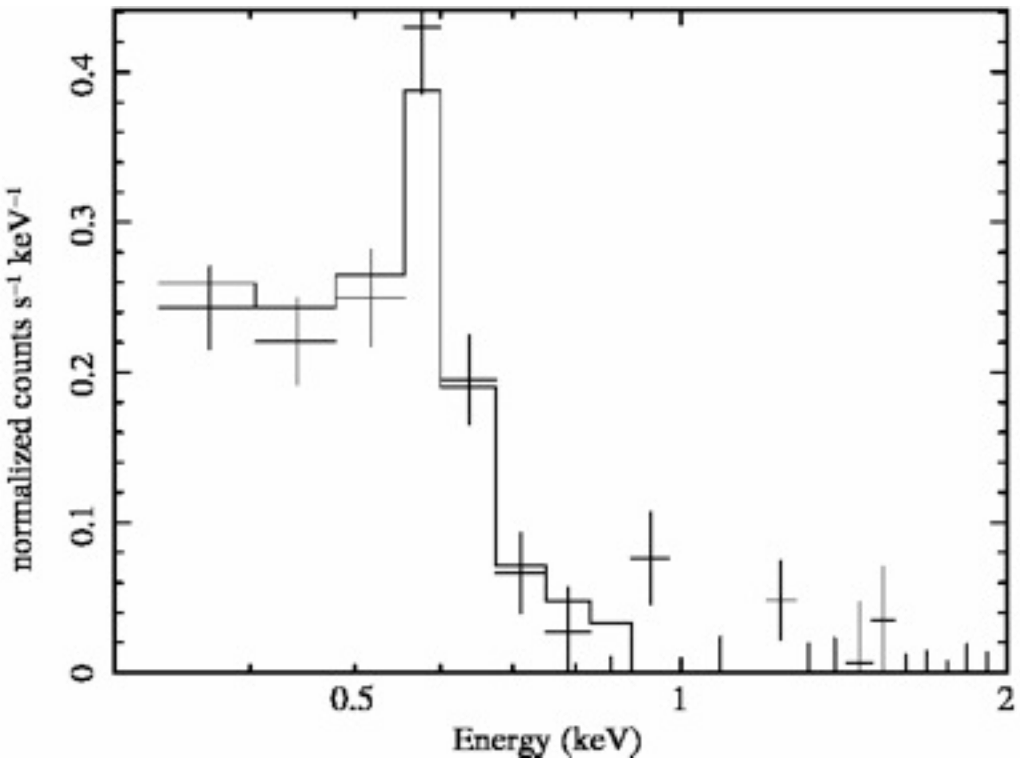
Fraction of all cases affected by SWCX in red

Spectral modelling

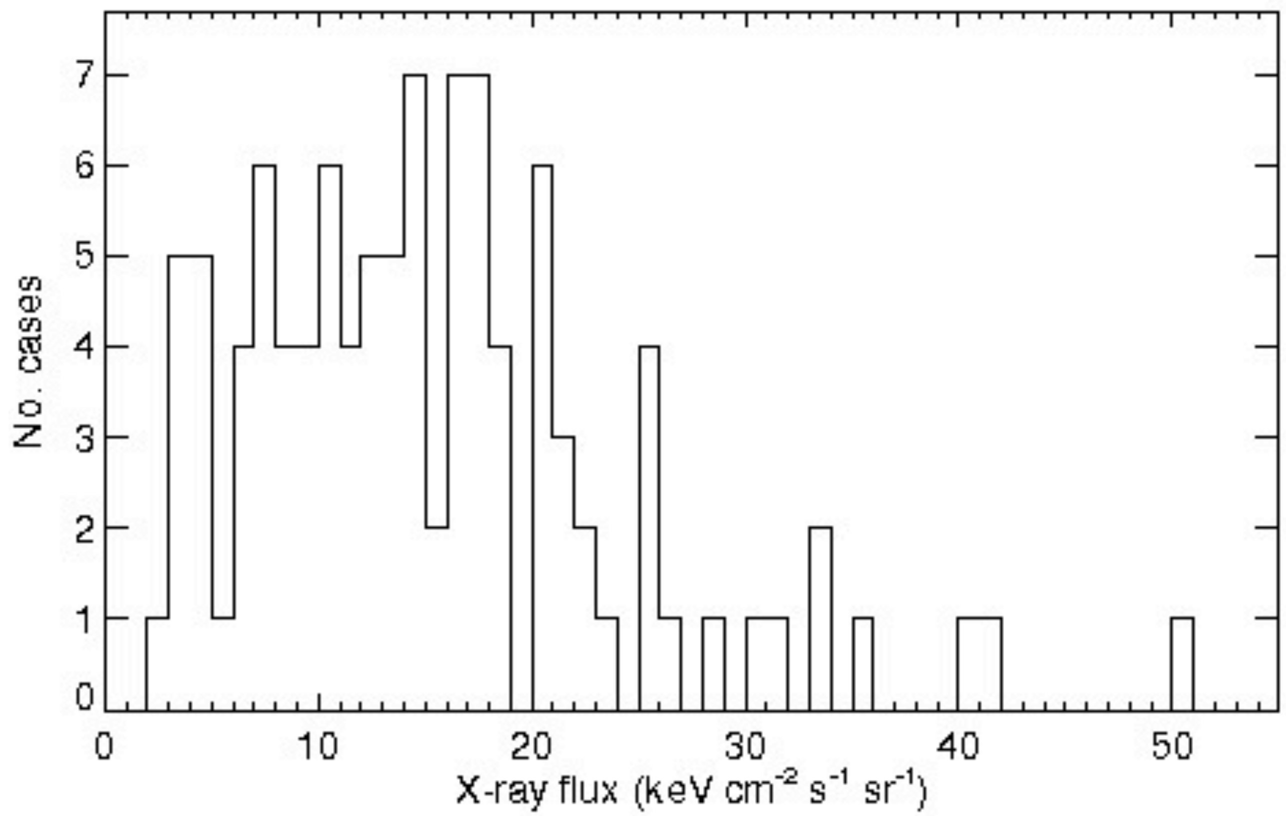
- Defined SWCX-affected and SWCX-free periods for each lightcurve
- Created spectra for each period
- Modelled a SWCX spectrum to each ‘resultant’ spectrum
- Model consisted of 38 Gaussian lines
- Relative normalisations based on the cross-sections of Bodewits 2007 (0.2 - 1 keV)
- MOS1 and MOS2 spectra fitted separately, converted to per steradian values and error-weighted average flux calculated
- Calculate flux 0.25 - 2.5 keV and also fluxes from individual lines



Ion	Energy (keV)
CV	0.299
CVI	0.367
NVI	0.420
NVII	0.500
OVII	0.561
OVIII	0.653
NeX	1.022
MgXI	1.330
SiXIV	2.000

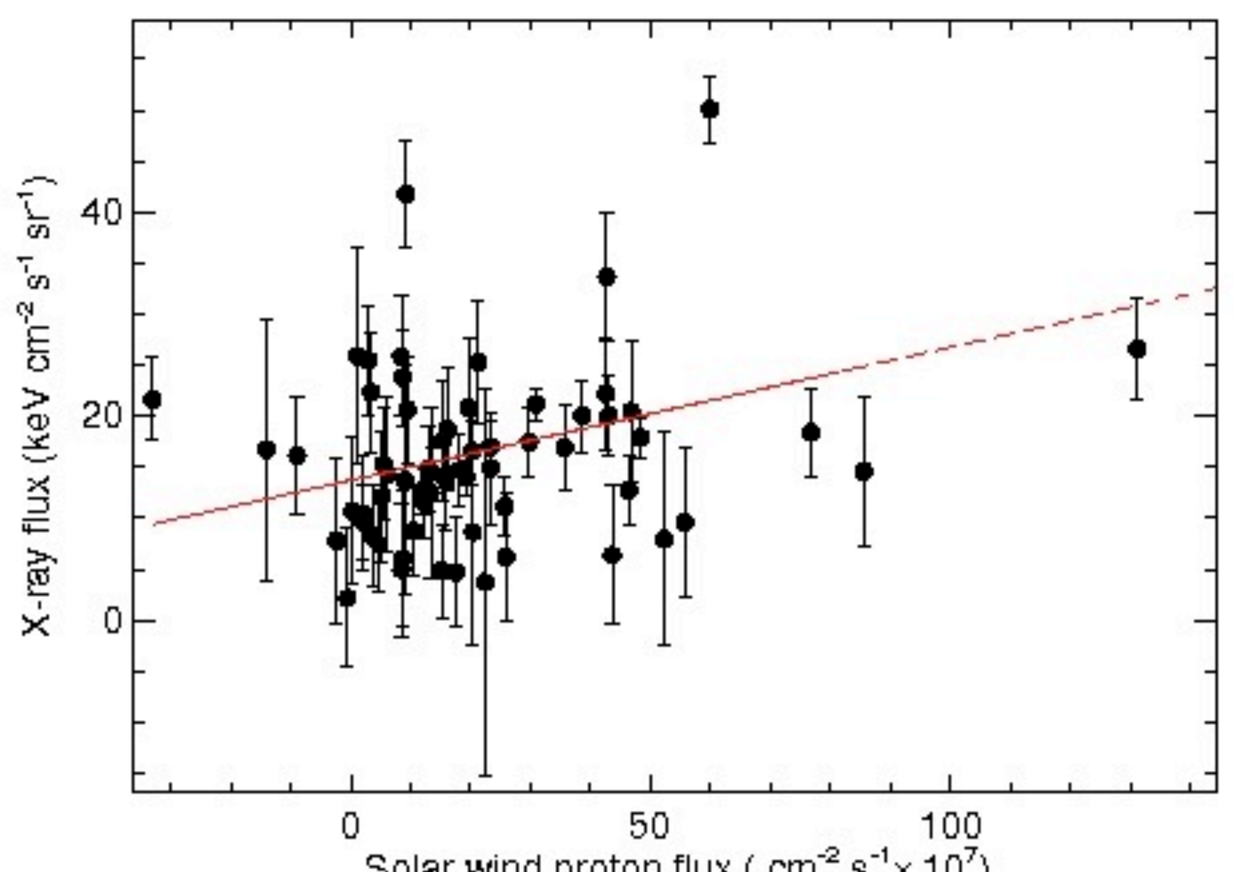


Observed SWCX fluxes, 0.25 - 2.5 keV



Histogram of observed fluxes

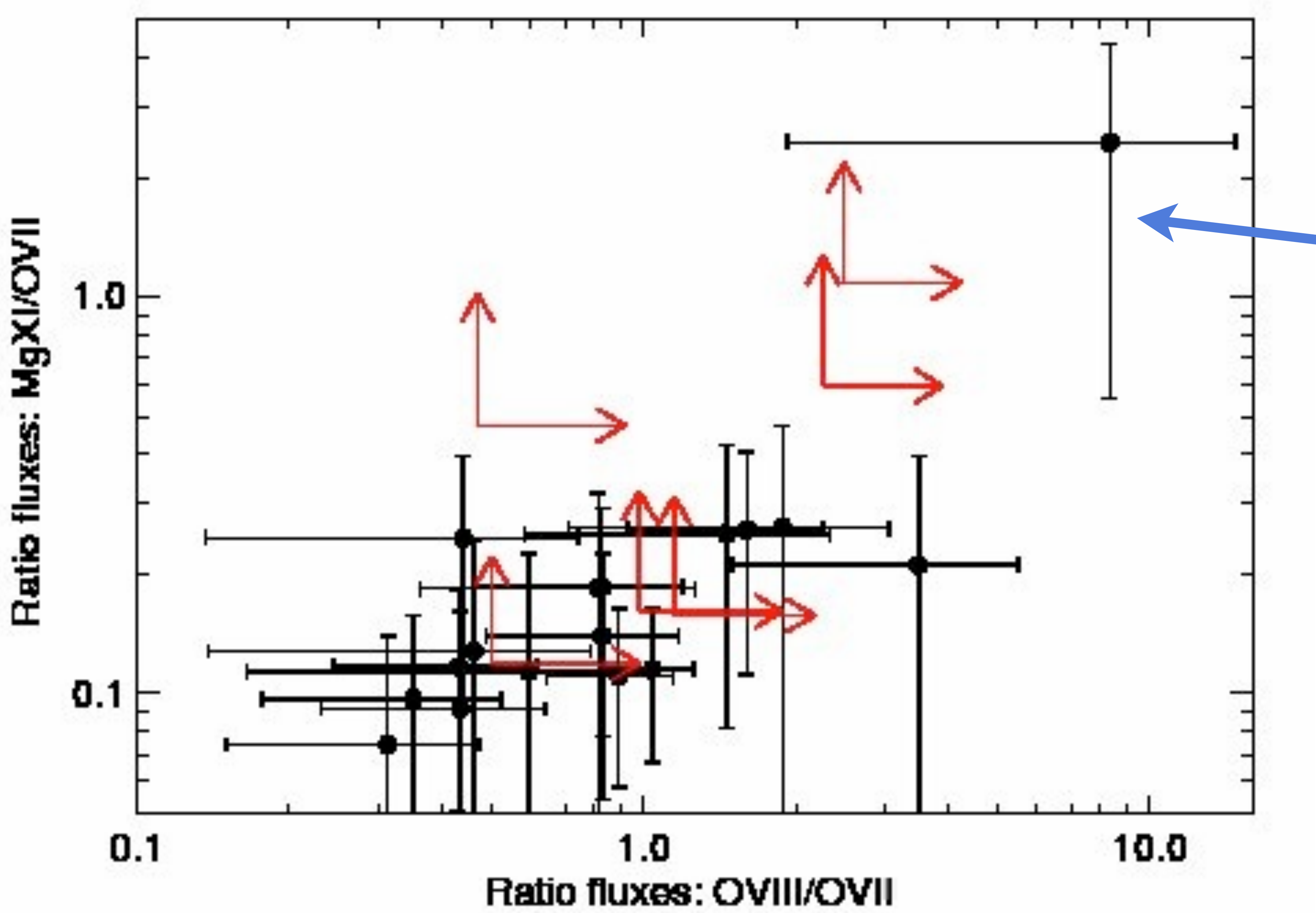
Observed flux versus mean solar wind proton flux difference between SWCX-affected and SWCX-free period as selected from X-ray lightcurve



High solar wind proton flux ⇒ high SWCX X-ray flux

- However, no simple linear relationship

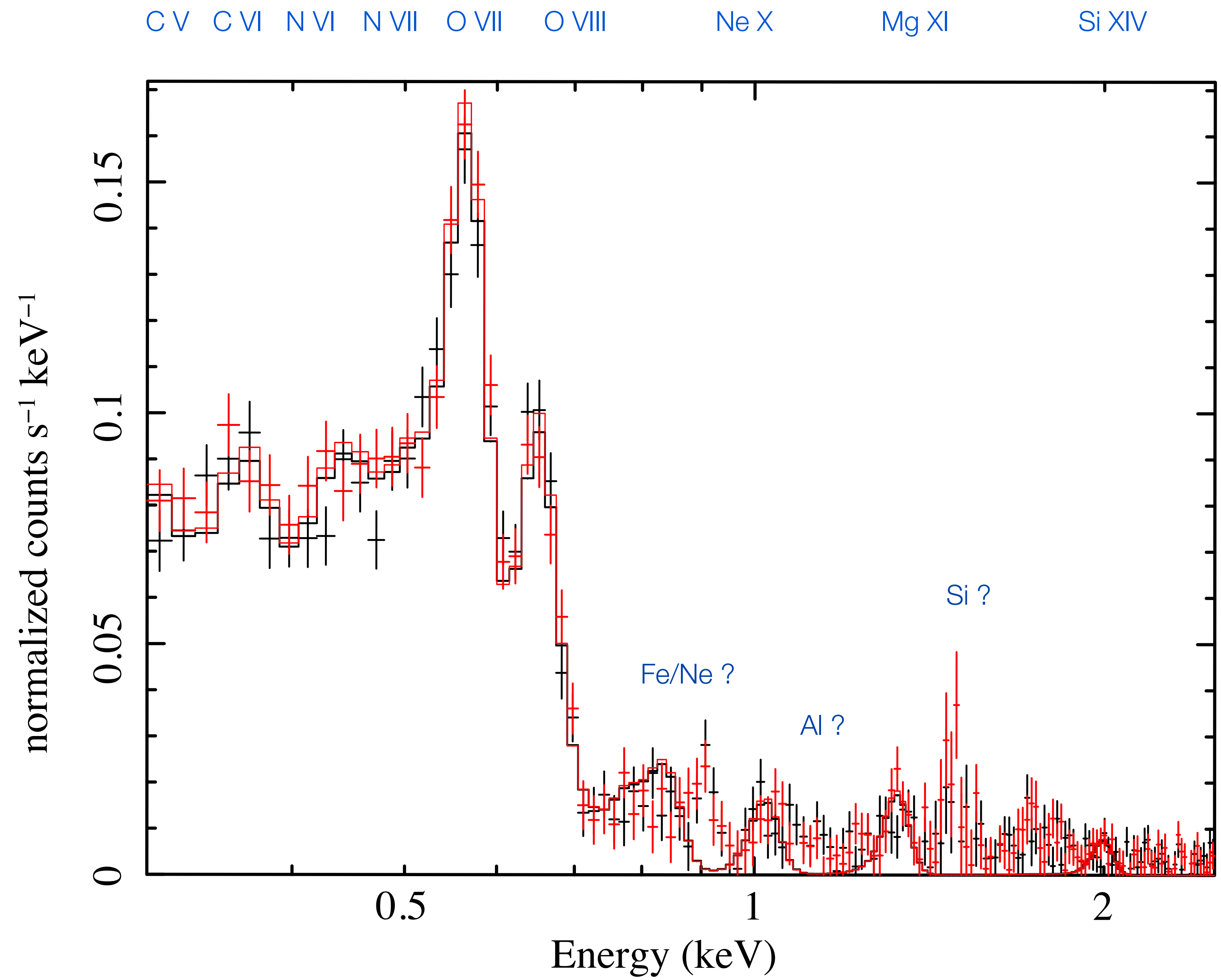
Line strengths - diagnostics of solar wind type?



Coronal Mass Ejection, Carter, Sembay & Read 2010 - later in the talk

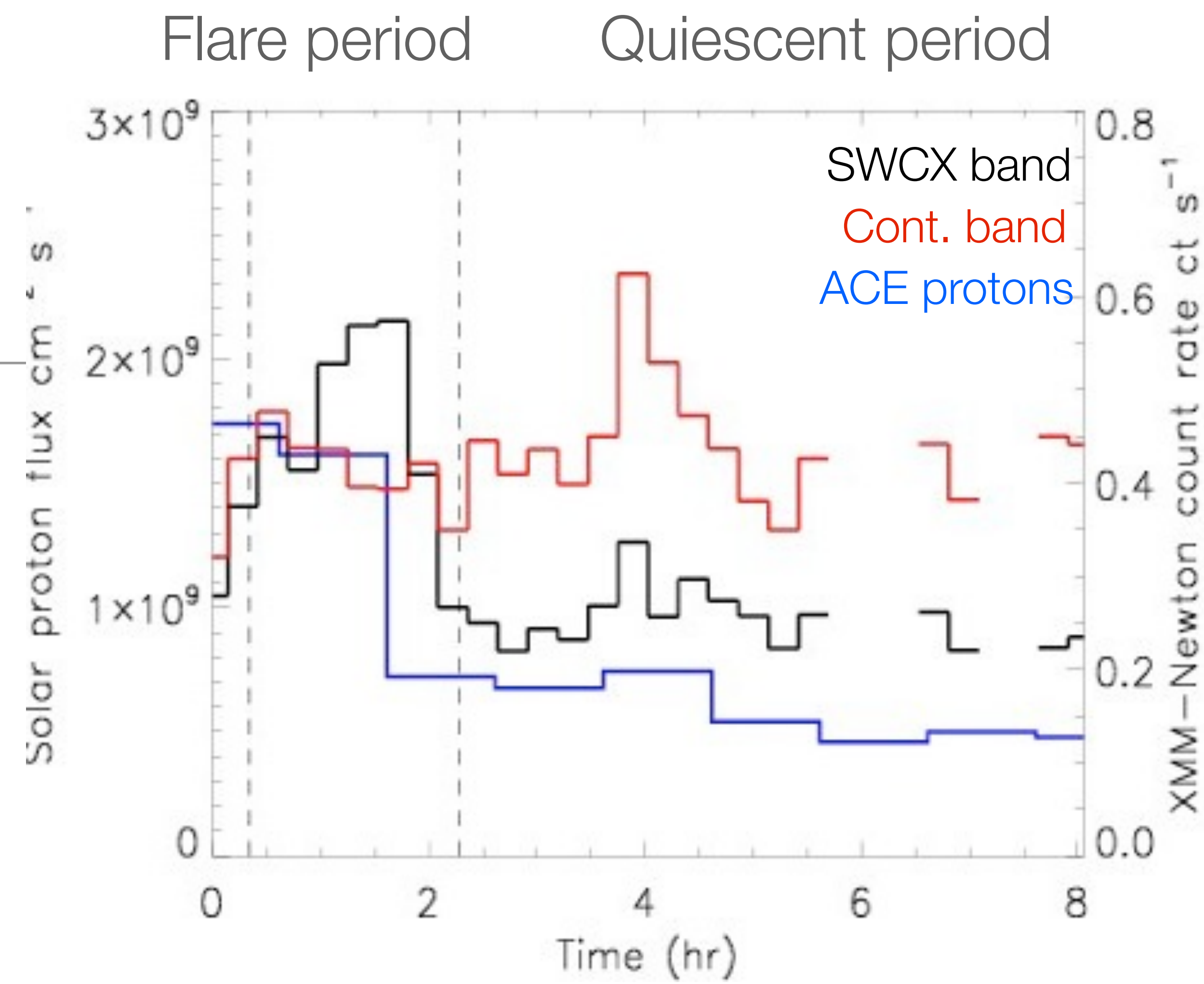
Stacked SWCX spectra

- For MOS1 (black) and MOS2 (red), 103 cases
- OVII triplet: forbidden line stronger than intercombination line

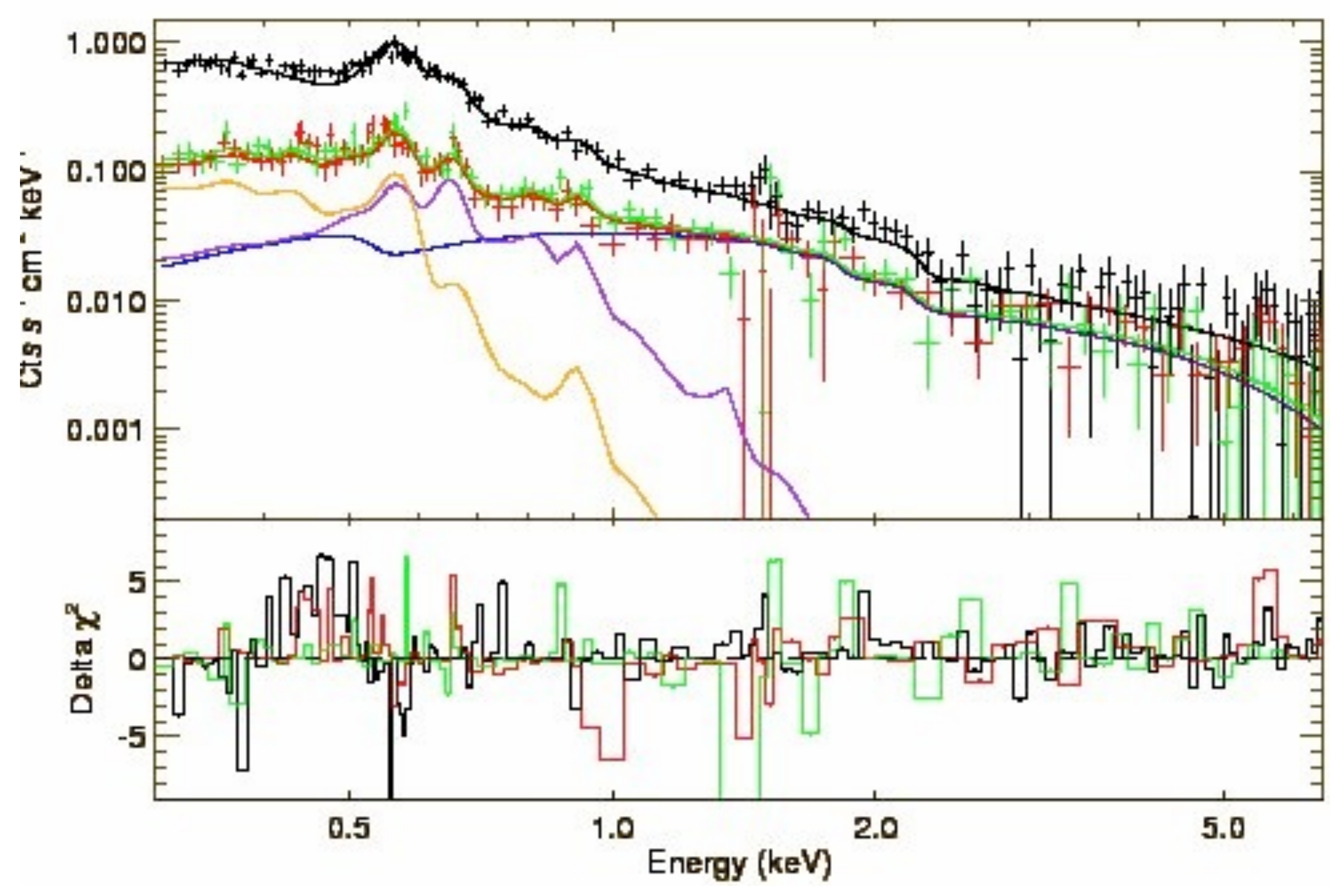


A standout case

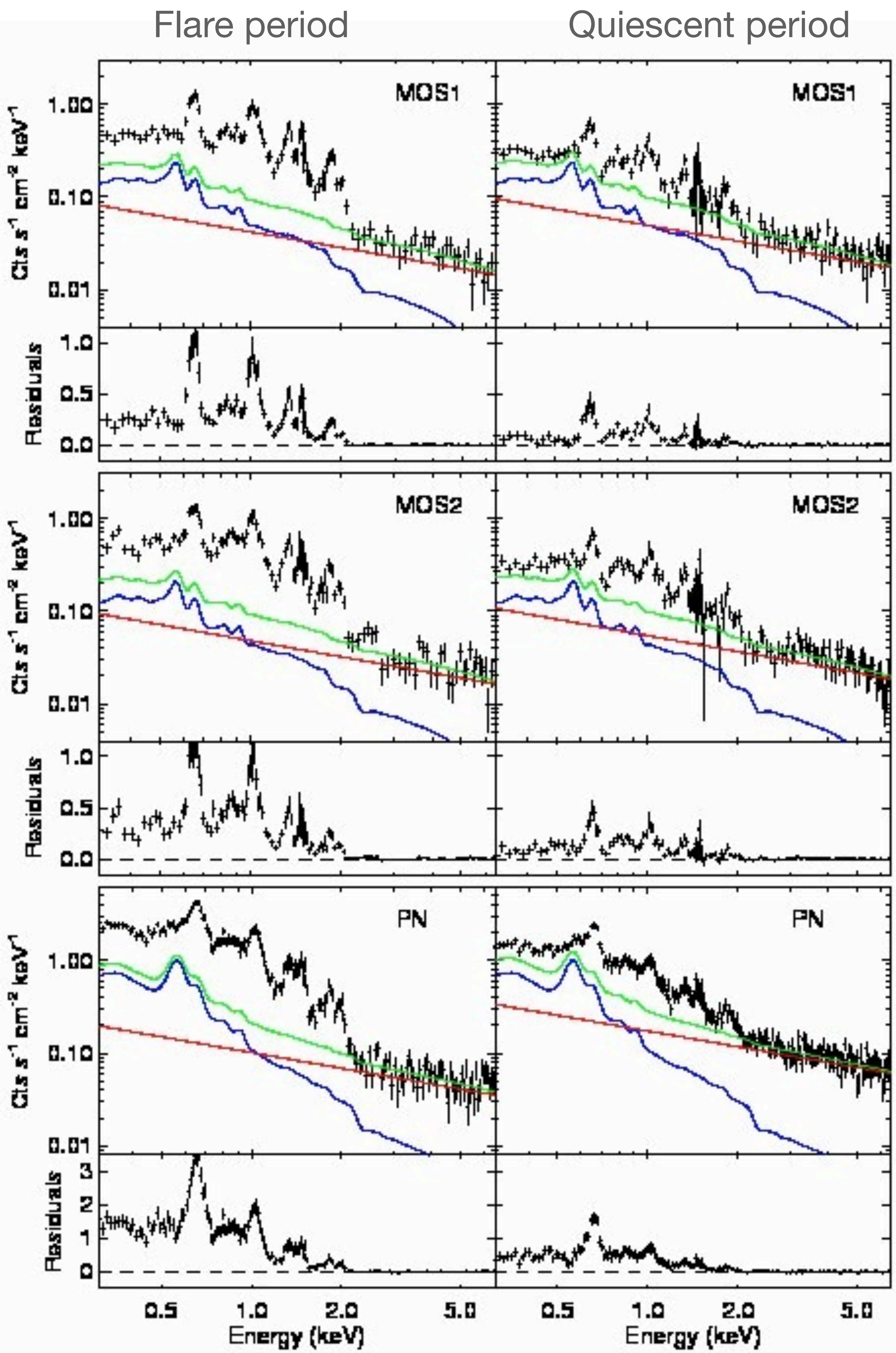
- Case warranted particular extra study - strongest case (Carter, Sembay & Read 2010)
- Two other observations, same sky target - helpful to extract the sky background and concentrate on the SWCX signatures
- Modelled the sky background: unresolved point sources (e.g. AGN) + Milky Way halo + Local Bubble + residual soft protons (that originate from the Sun)
- Anything left over is (mainly/assumed) SWCX
- Very strong O VIII and upstream CME detected by solar wind monitors

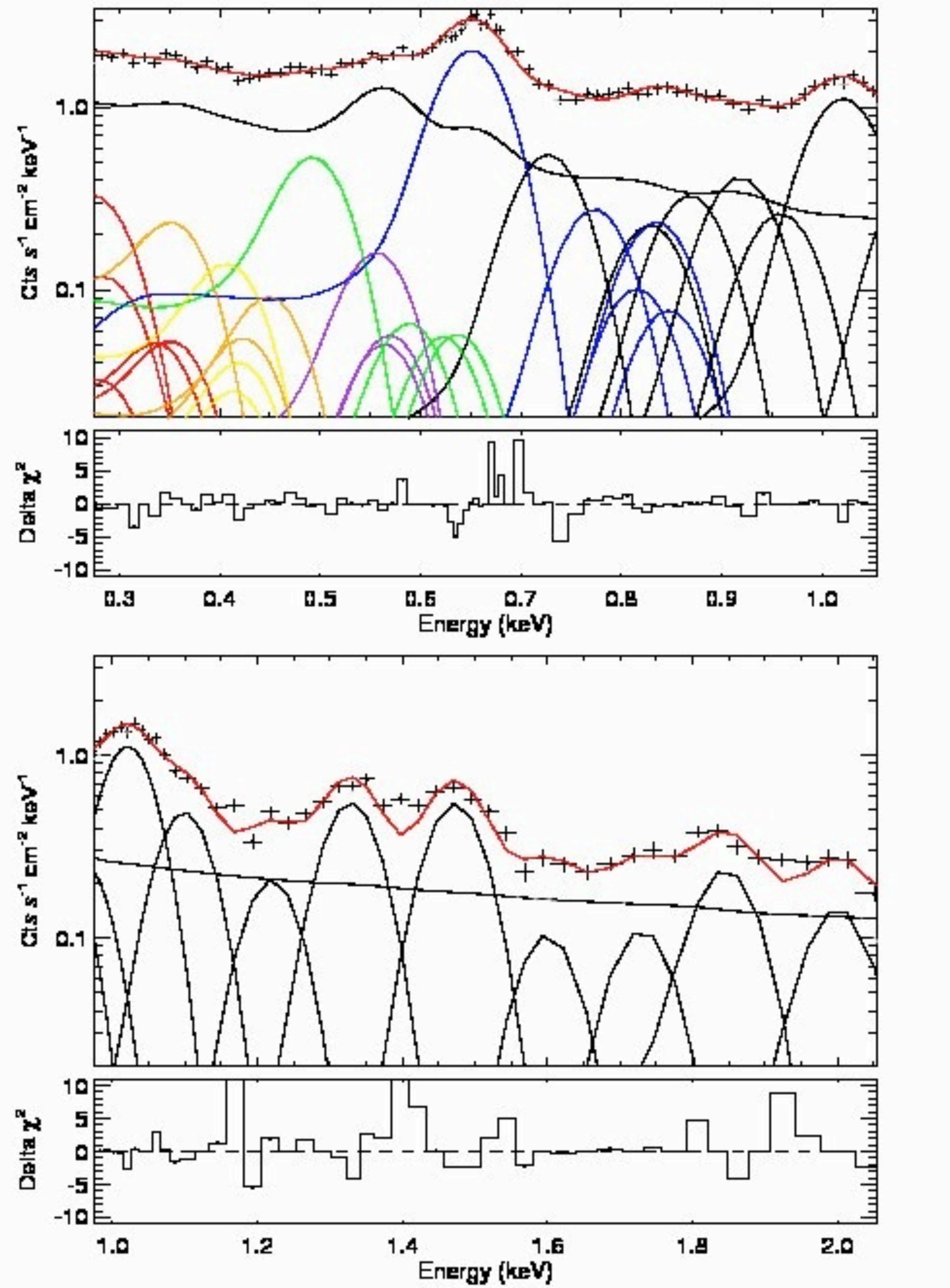


Previous observation - non-SWCX affected



SWCX-affected observation example; a CME



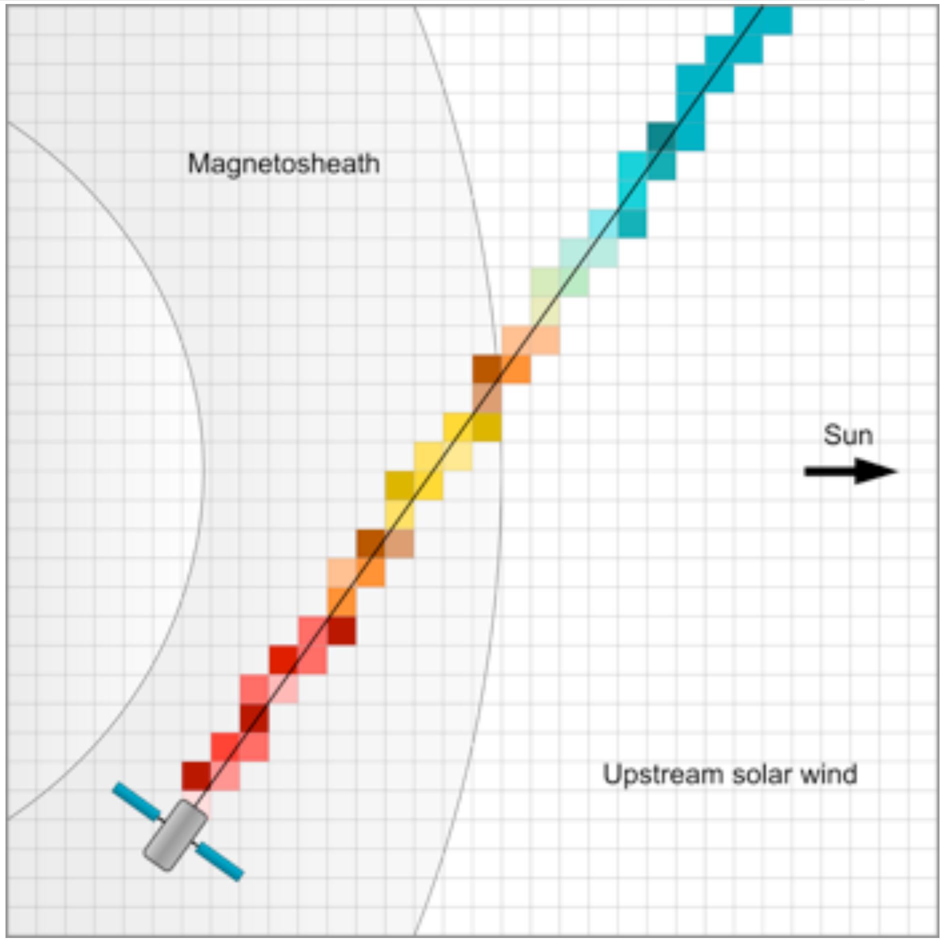


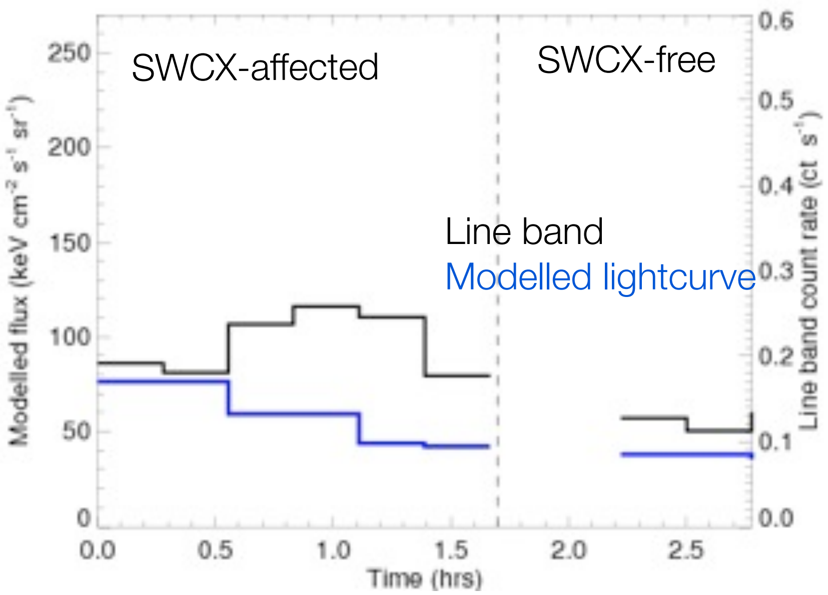
Modelling the expected emissivity

- Calculate the expected flux due to SWCX occurring in the vicinity of the Earth:

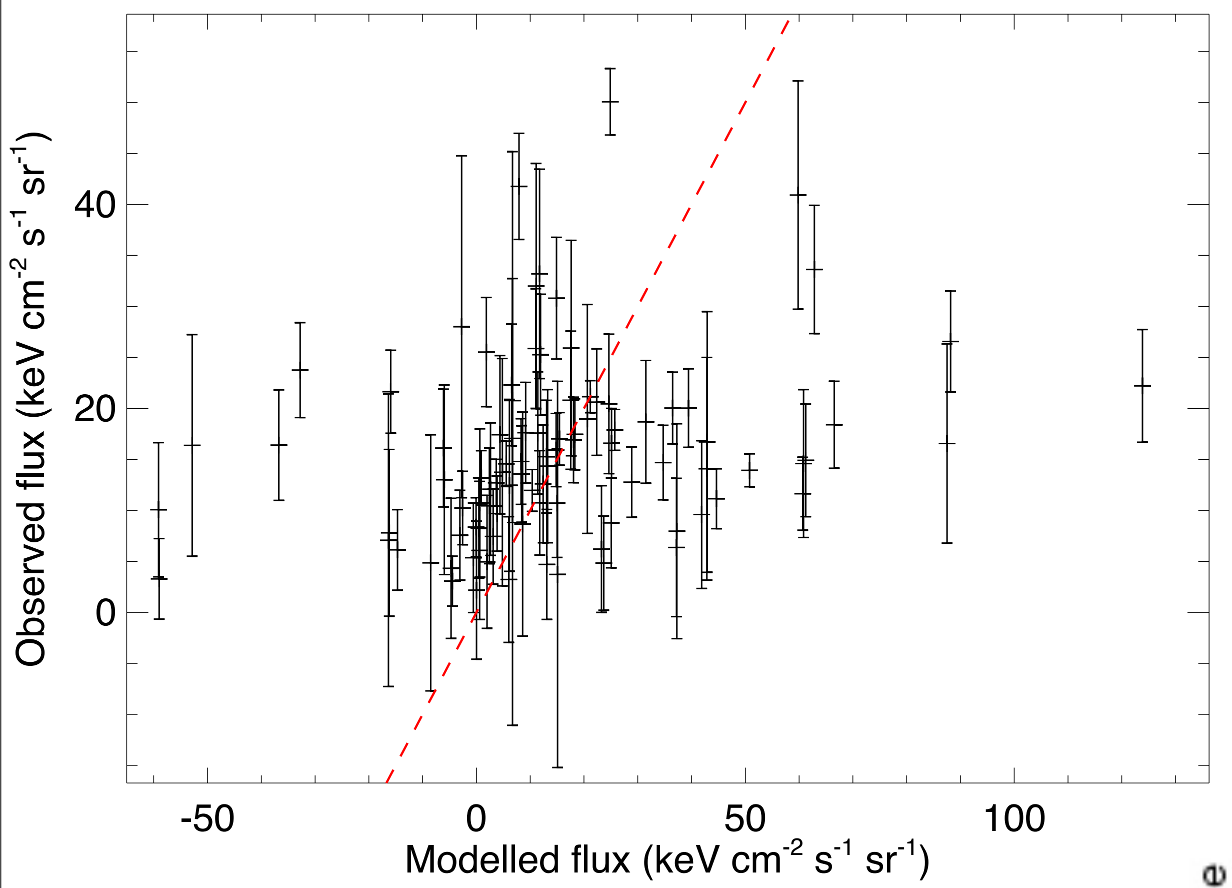
  $P_{X\text{-}ray} = \alpha \mu_{sw} n_{sw} n_H$ (Robertson & Cravens, 2003)

- Take the solar wind conditions at ACE (at L1), apply a delay
- Perturb the solar wind in the magnetosheath (Spreiter 1966)
- Use the XMM-Newton orbit files to find the line-of-sight through the magnetosheath
- Take values from a model of exospheric hydrogen Østgaard (2003) in the line-of-sight
- Calculate the total flux seen in the line-of-sight
- Repeat the calculation for each time step
- Apply model to all observations with quality ACE data





Modelled flux - compared to observed flux



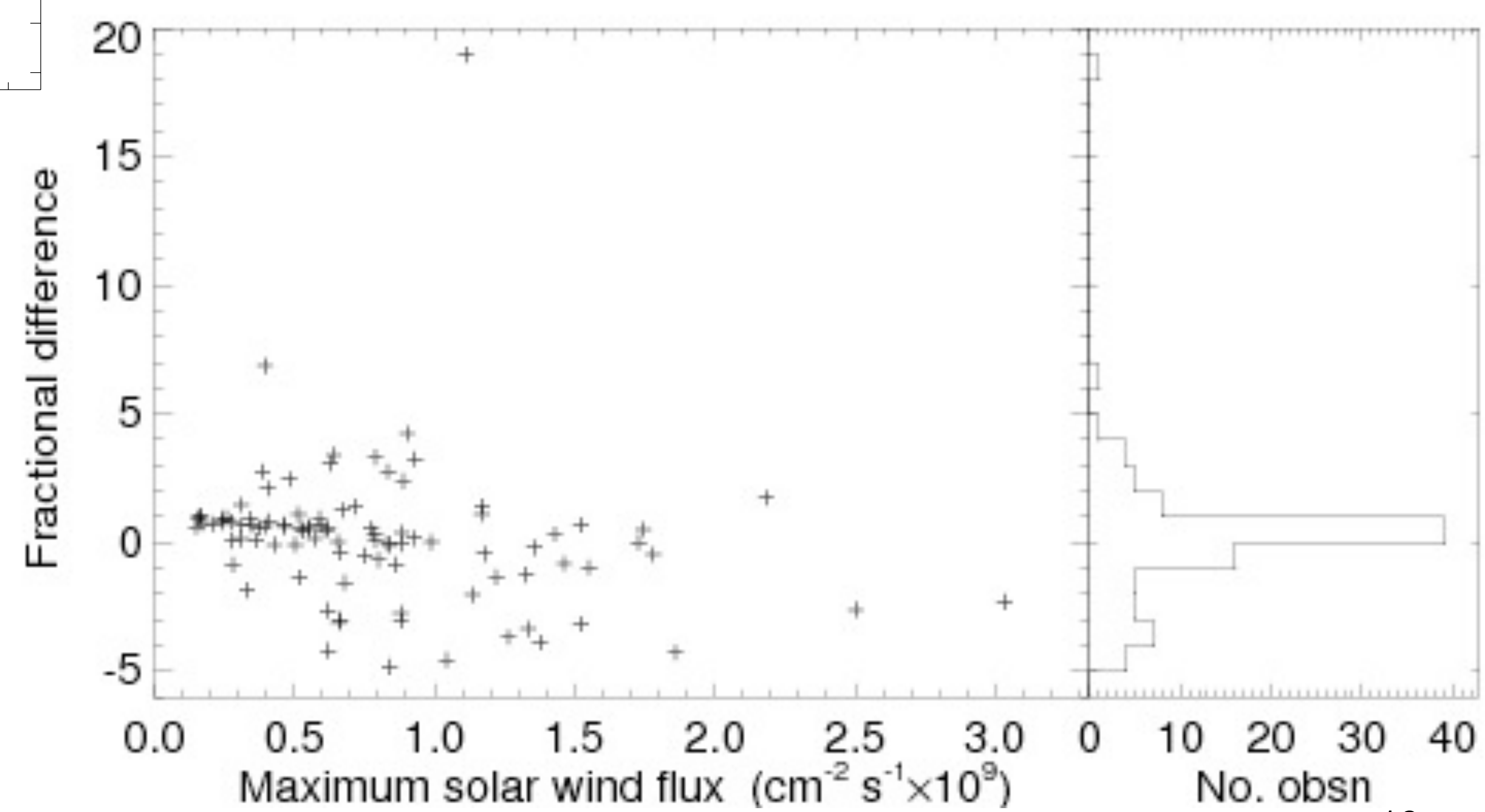
Modelled X-ray emission typically to same order of magnitude as the observed emission

Would have liked to have seen a strong, linear relationship between the observed and modelled flux

The model is currently too simple to describe the phenomena fully

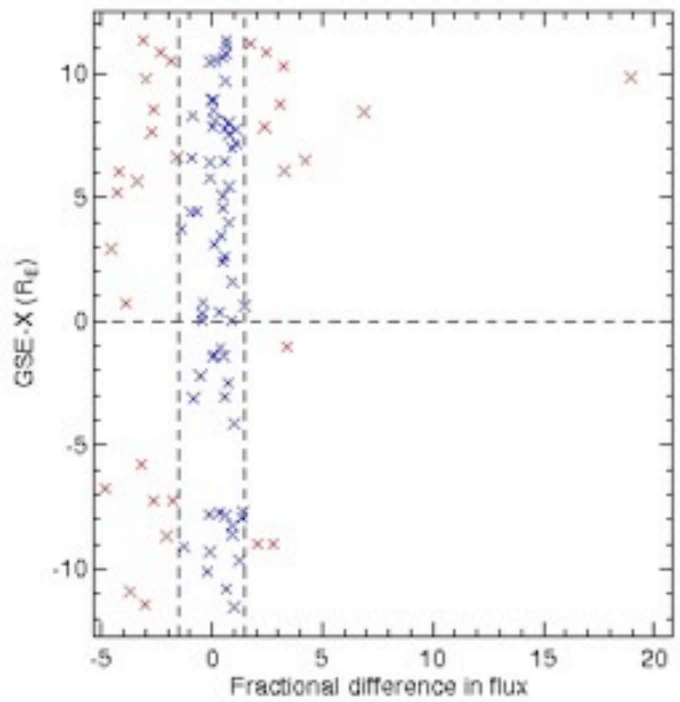
Fractional difference defined as:

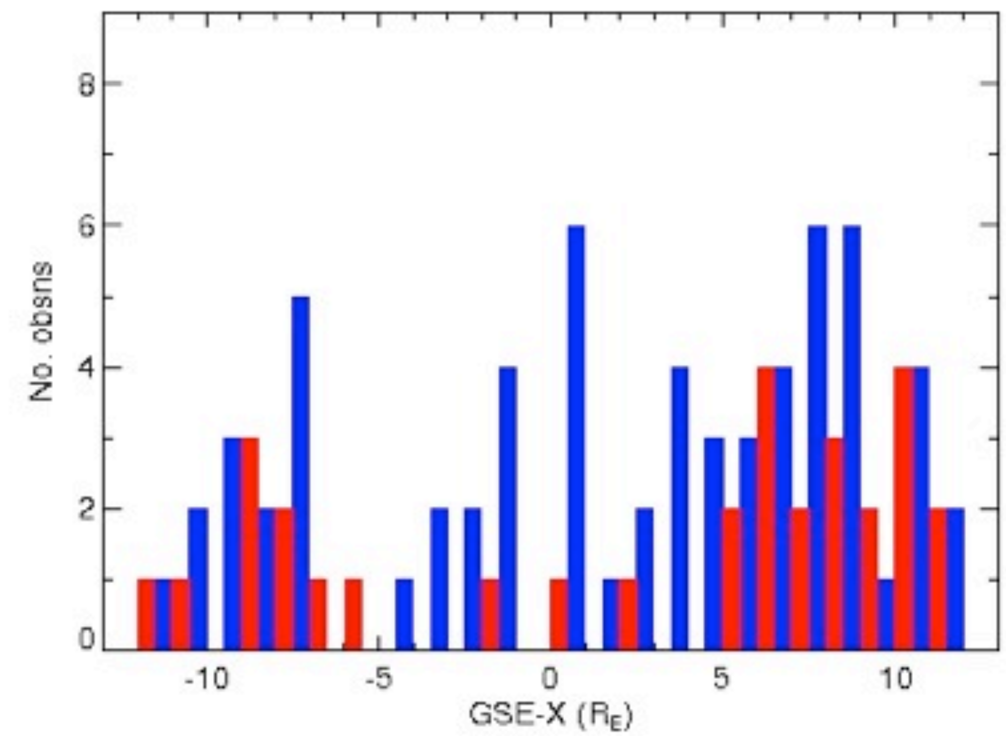
(observed - modelled) / observed flux

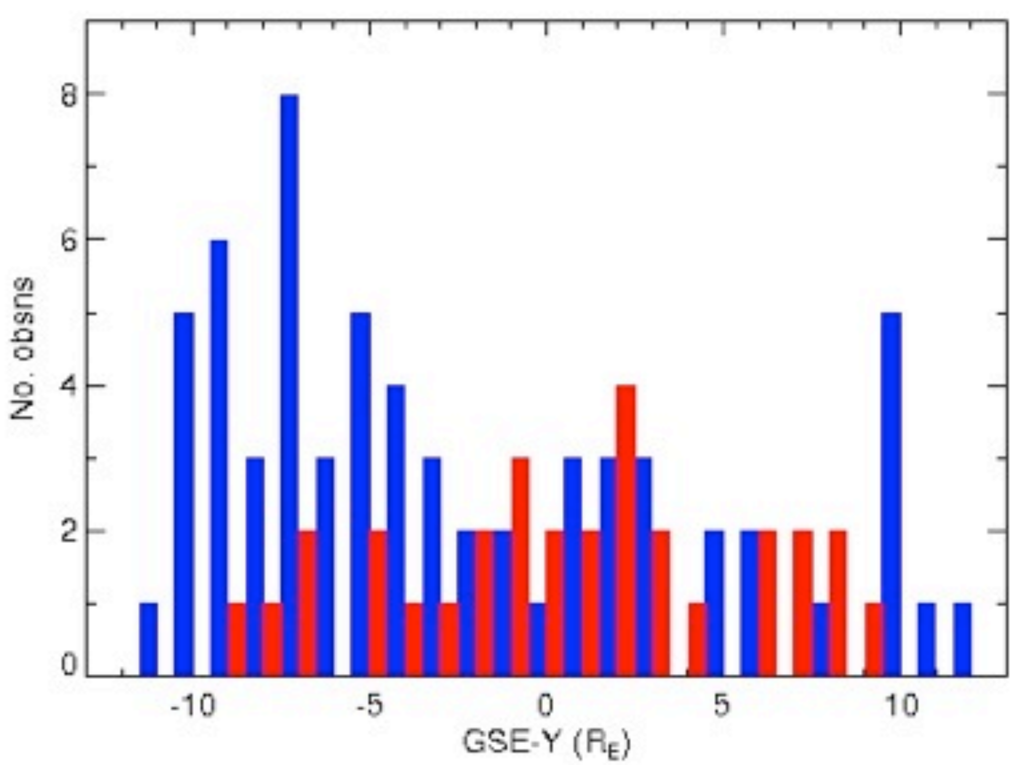


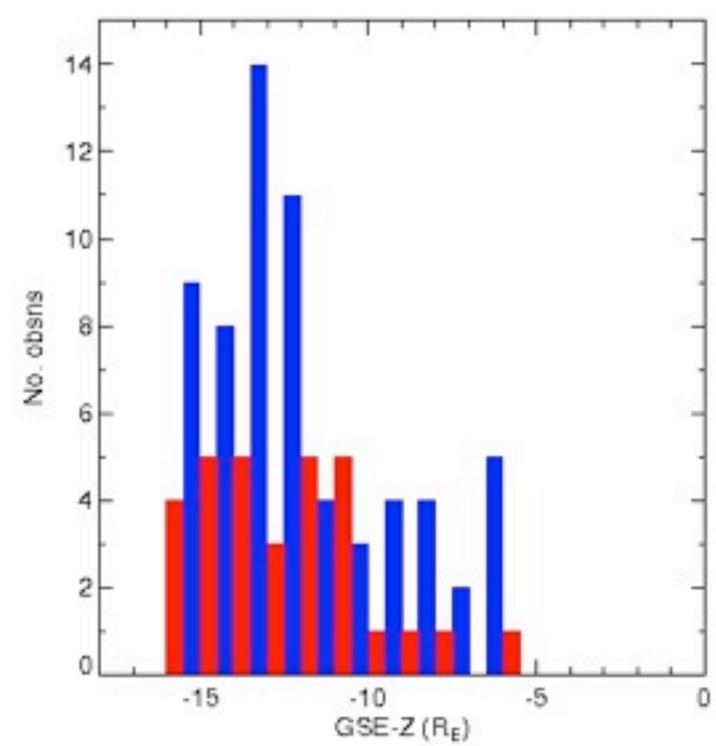
Modelling vs observed flux, with position

Good, Bad









Summary

- 3.4% of XMM-Newton observations contain a detectable level of temporally variable SWCX
- Lower limit to the number of observations affected (SWCX at heliopause, slowly varying cases etc. not detected by this method)
- Users of XMM-Newton should be aware of possible SWCX contamination
- Model of expected emissivity provides a rough estimate of X-ray flux observed, although larger discrepancies are seen in the positive GSE-Y directions (dusk side, towards the incoming Parker spiral)
- Temporal and spatial information from SWCX occurring in the vicinity of the Earth can be used to understand how the Sun and Earth plasmas interact and provide information about the heavy-ion composition of the solar wind
- **See subsequent talk by G. Branduardi-Raymont: AXIOM, using SWCX to image the Earth's magnetosheath**

- THANK YOU