# Exospheric solar wind charge exchange emission: XMM-Newton observations, and modelling

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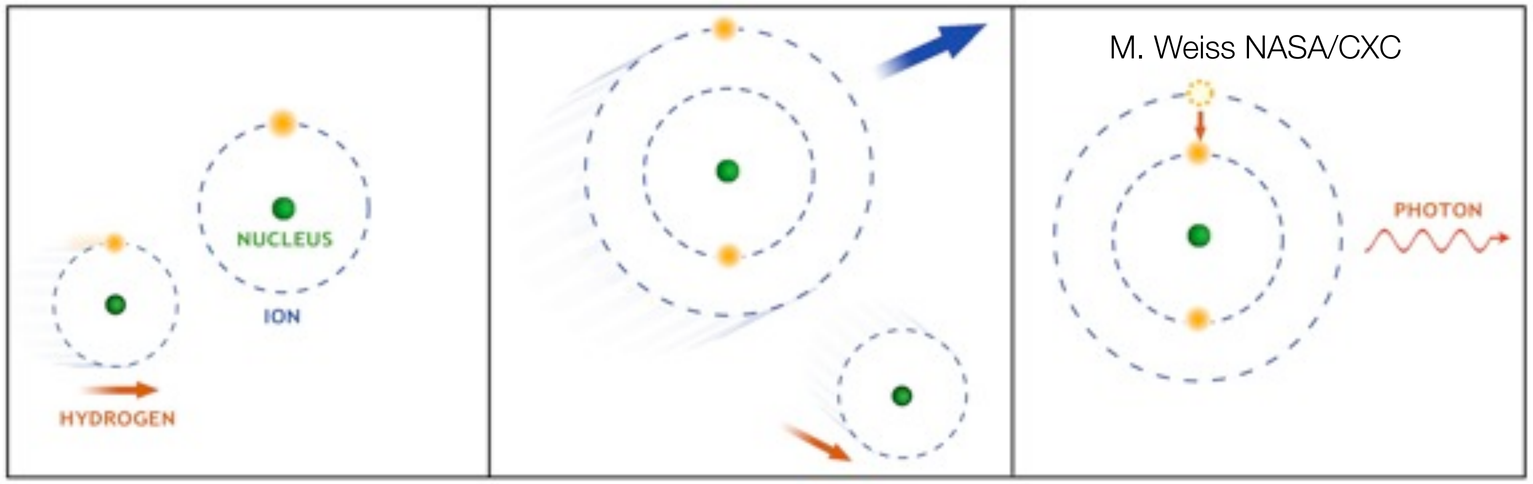
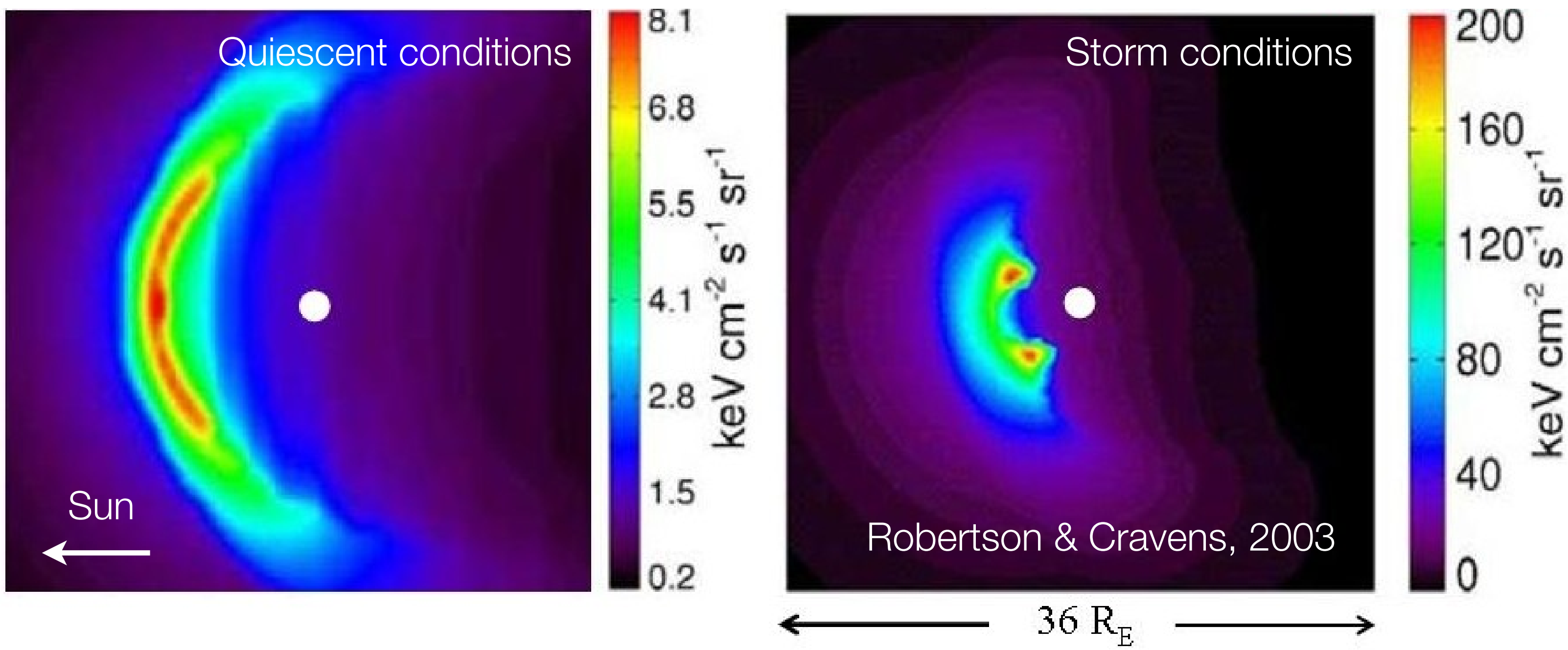
# Talk outline

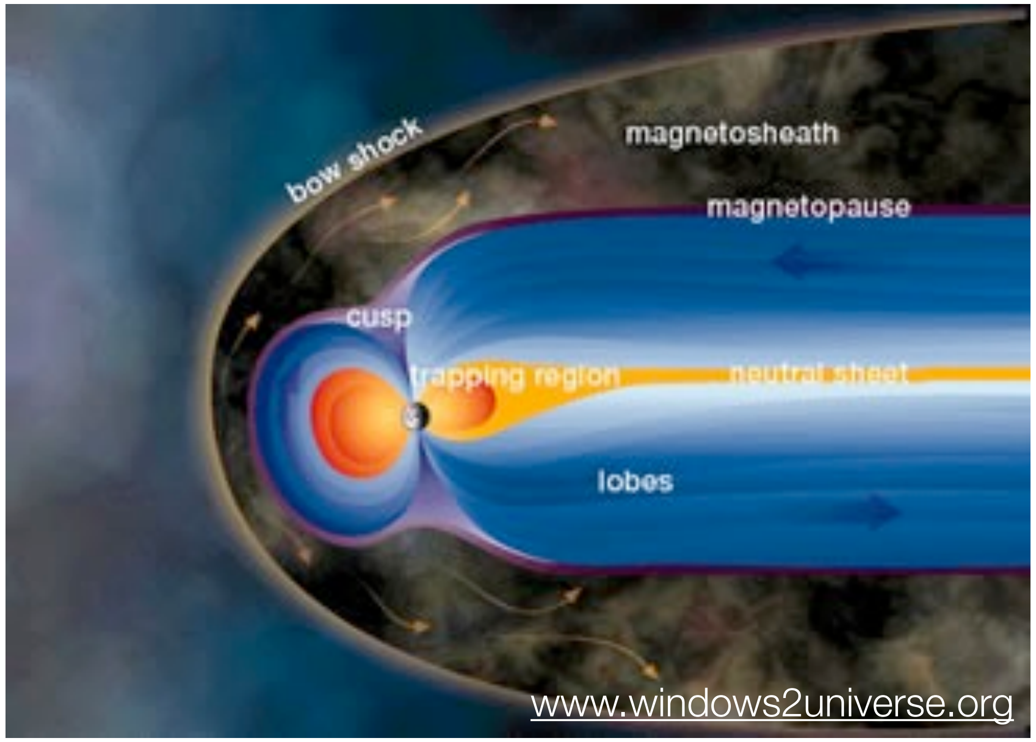
- Charge exchange in the solar wind - locations and signatures
- Observing exospheric solar wind charge exchange (SWCX) with XMM-Newton
  - Original motivation of project: a characterisation of ‘background’ emission for astronomers
- General results of project - characterisation of exospheric SWCX emission as seen by XMM-Newton
  - Relationship with solar cycle and solar wind flux
  - Spectral characteristics
- Modelling of SWCX using GUMICS-4 code
  - This modelling to replace previous empirical modelling (my thesis)
  - Initial results on test observations

# Charge exchange and the solar wind

- Solar wind: velocities ~ 200-1000 km $s^{-1}$, densities ~ 7-40 $cm^{-3}$
- 1% heavy ions
- 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 ~$10^{-16}$ $cm^{-2}$

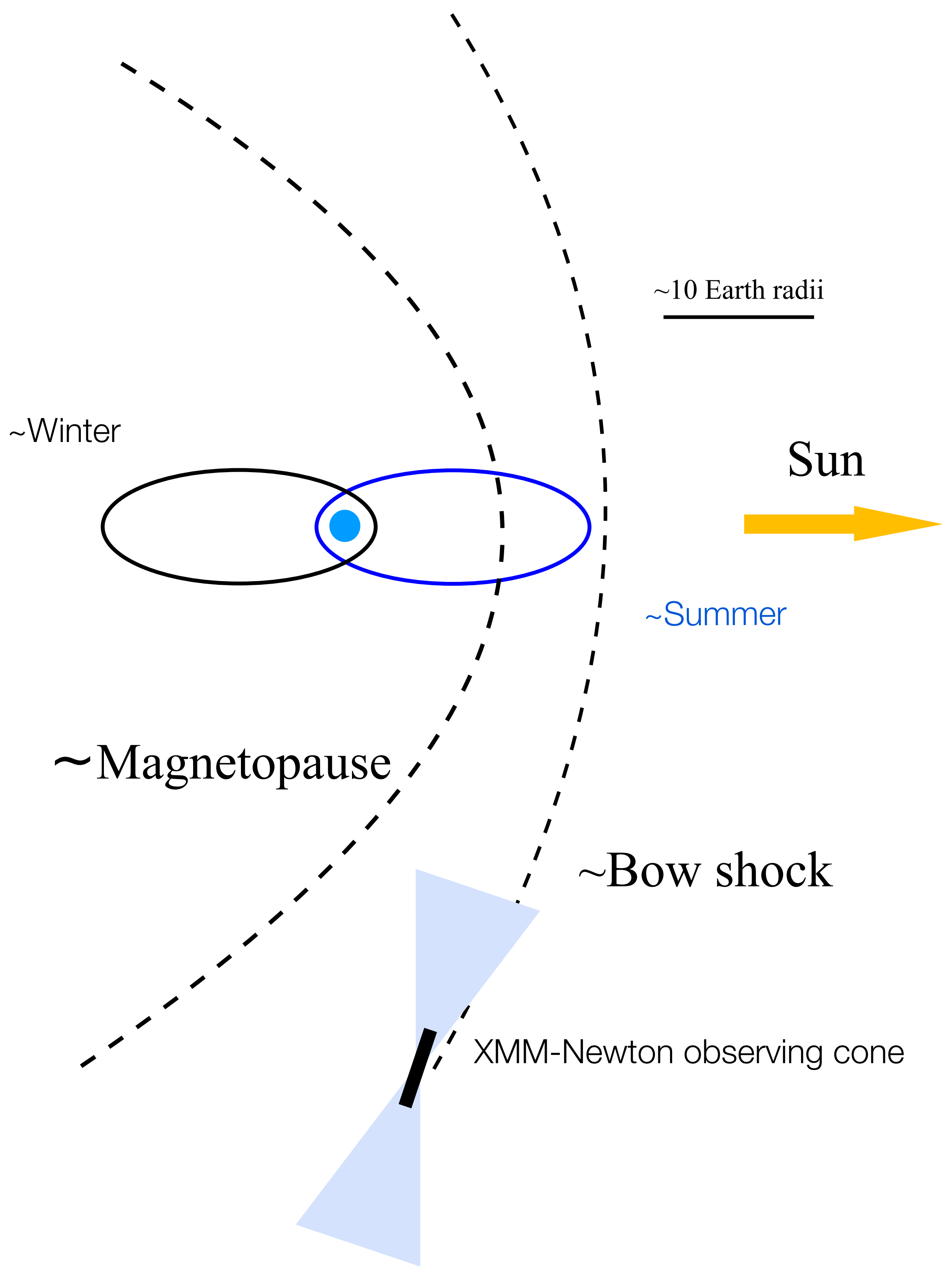



- SWCX emission modelled in Earth's exosphere
- Solar wind storms cause large increases in expected flux
- ...important consequences for XMM-Newton

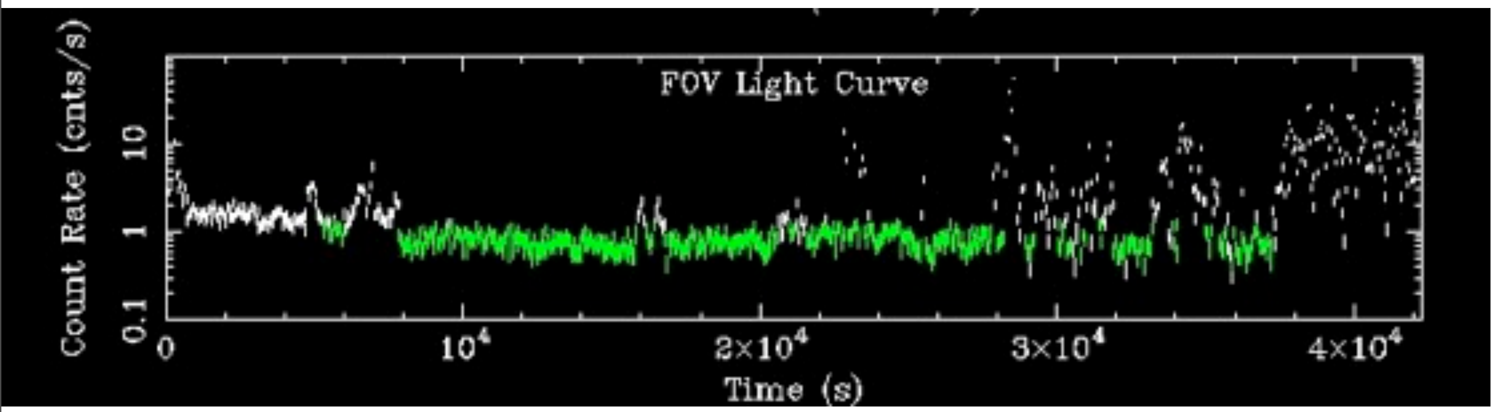
# XMM-Newton’s orbit and viewing angles

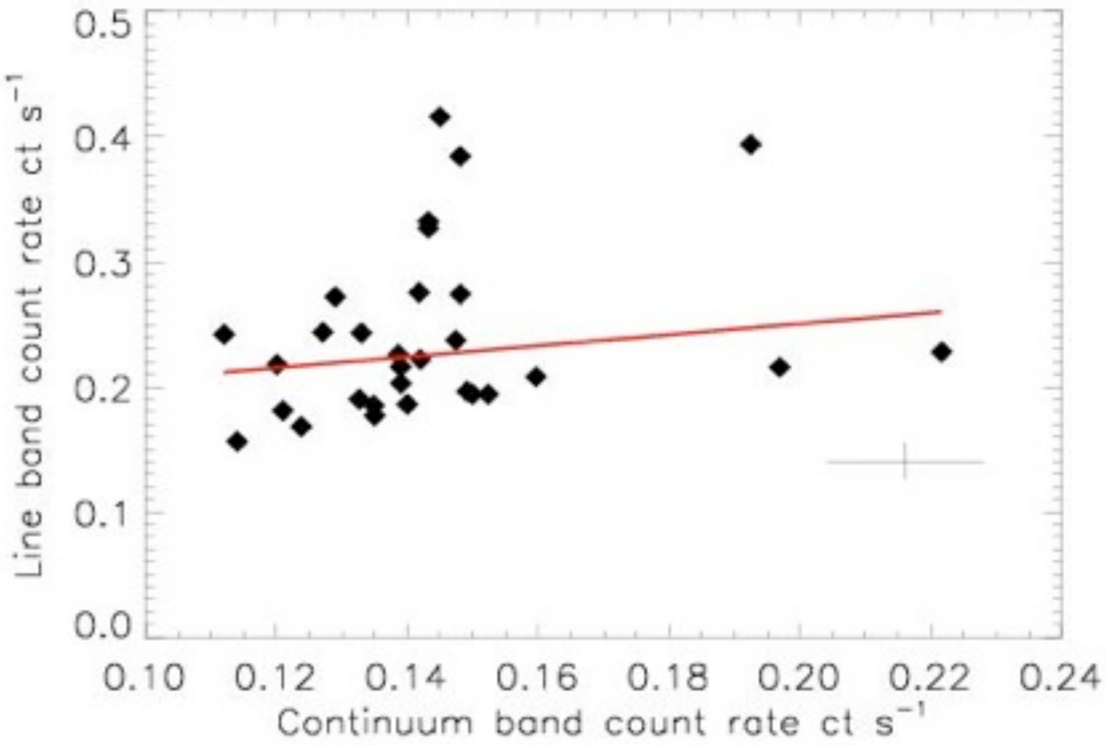



- XMM-Newton: X-ray observatory in highly elliptical orbit
- Seasonal effects expected
- Rough winter/summer split
- Dynamic magnetosheath, responds to solar wind pressure
- **In summer, XMM-Newton can observe SWCX when line-of-sight passes through the dayside magnetosheath**
- Original motivation of project (from an astronomy perspective): how many XMM-Newton observations are affected and the characterisation of these cases (3 imaging cameras on board, but concentrate on 2 EPIC-MOS instruments)

# Searching for XMM-Newton observations affected by SWCX

- Using the imaging EPIC-MOS cameras combined, in full-frame mode
- **No. obs., 3012,** up to revn. 1781 (February 2000 - August 2009).
    1. Cleaned observations for flare periods & all sources
    2. Looked for short timescale variability - indicative of **variable SWCX** near Earth
    3. Create two lightcurves; 0.5 - 0.7 keV & 2.5 - 5.0 keV (SWCX, continuum)
    4. **Scatter plot between lightcurves, statistics of line fit, judge if variable SWCX seen**

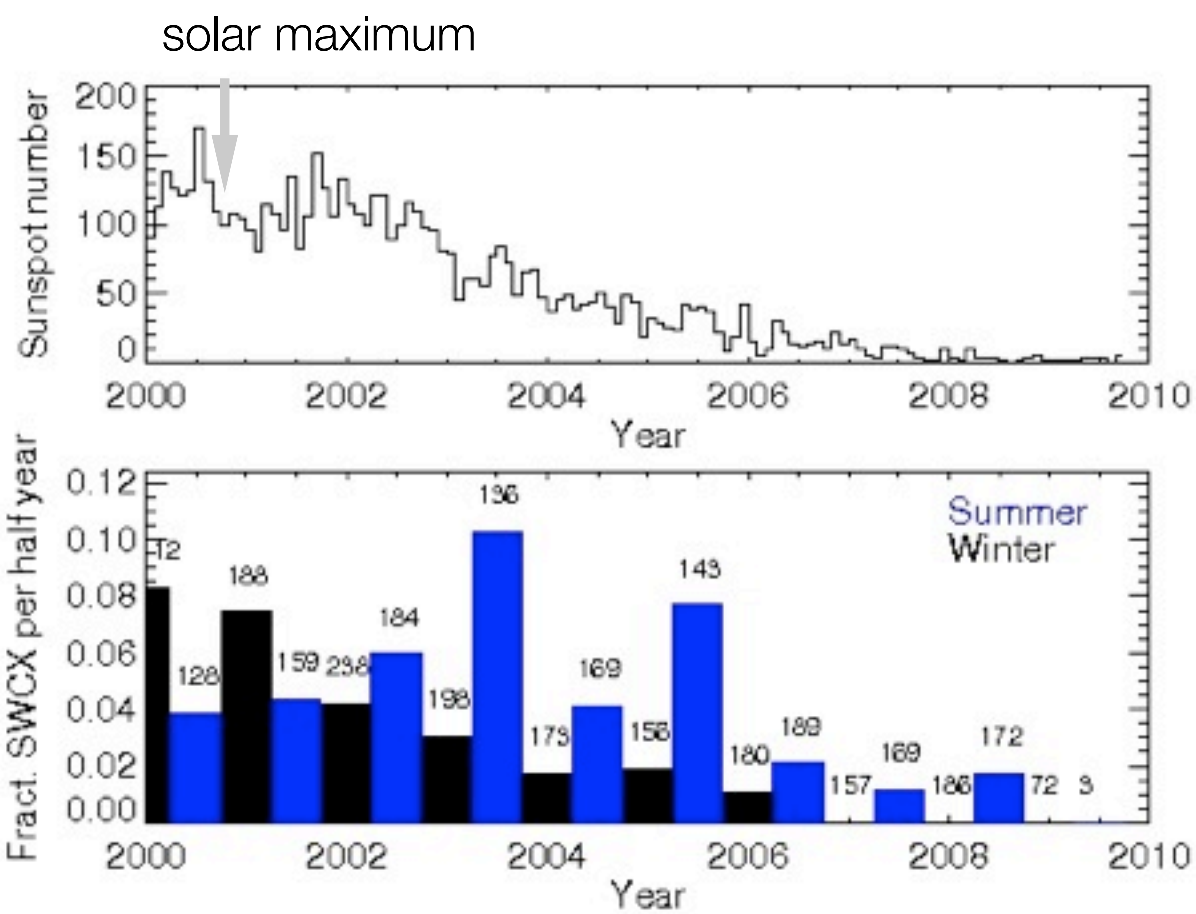


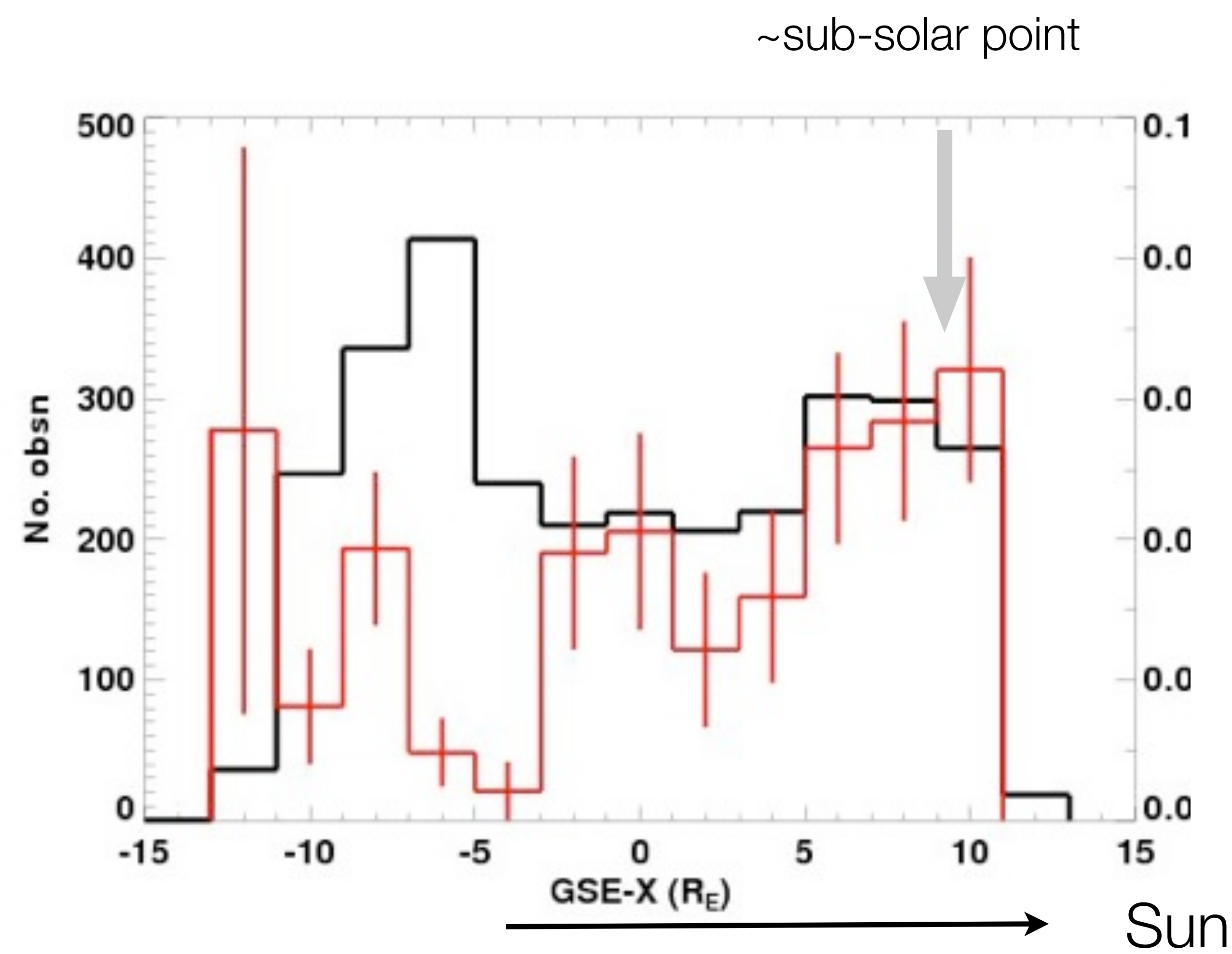

- **103 cases (~3.4% of set) of variable SWCX found** (Carter, Sembay & Read, 2011)

# 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 **sub-solar point** (sunward magnetosheath)



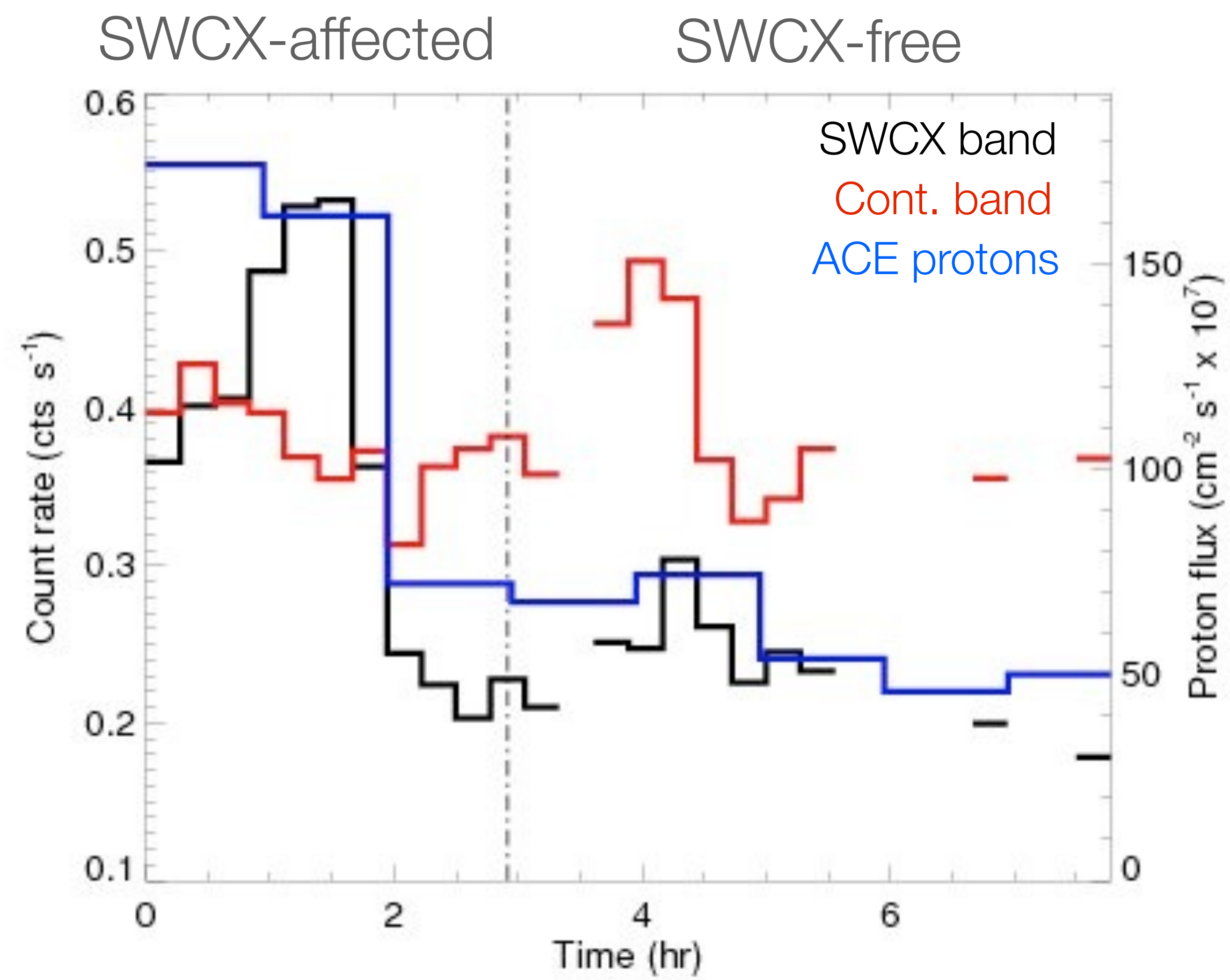

Very few observations with exospheric SWCX signatures towards solar minimum



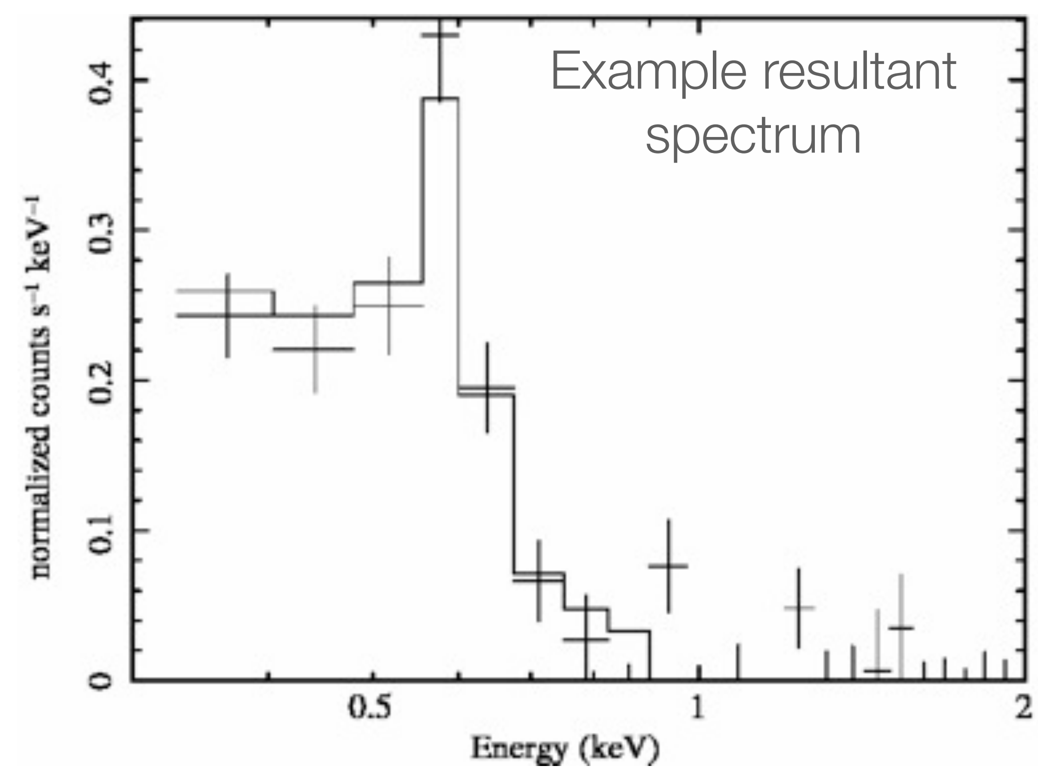

Fraction of all cases affected by SWCX in red

# Spectral modelling

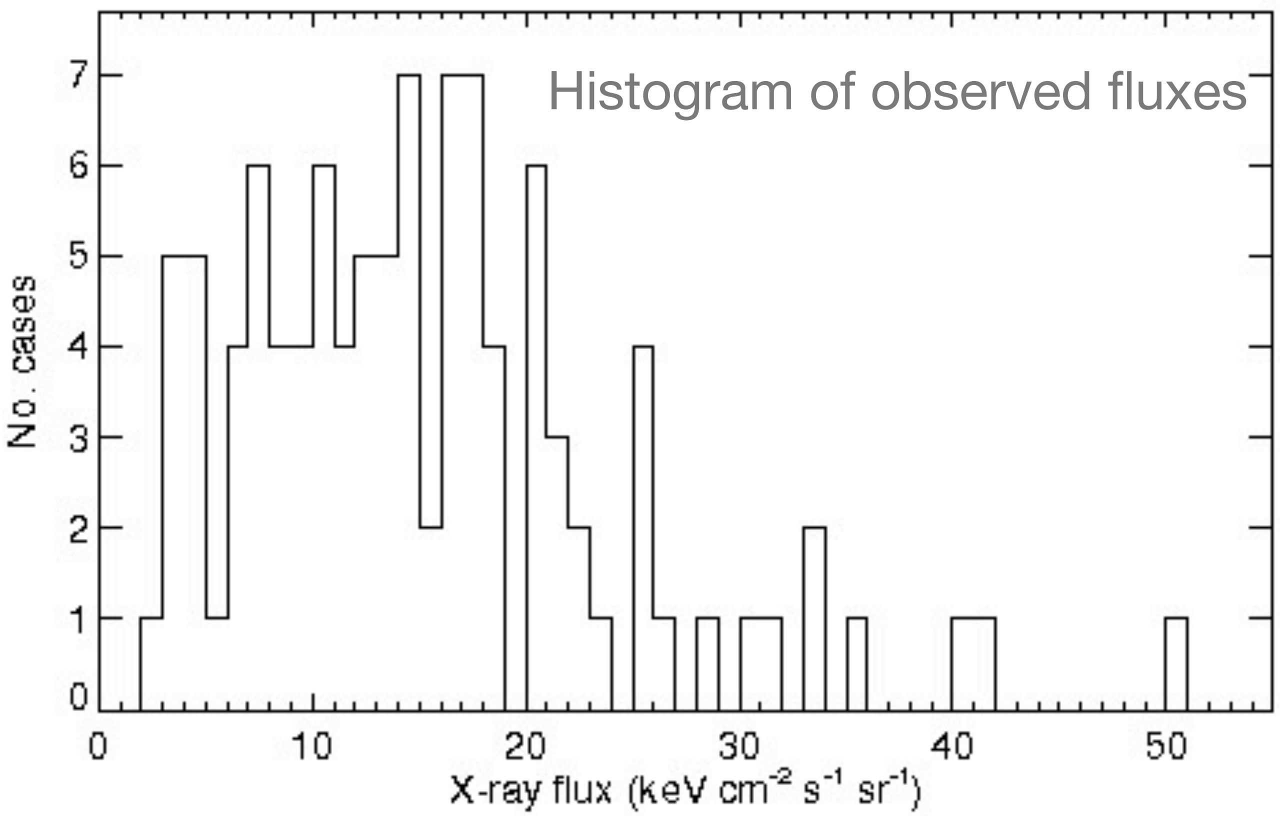
- Defined SWCX-affected and SWCX-free periods for each lightcurve
- Created spectra for each period
- **Created resultant spectra (affected - free period)**
- Modelled each resultant spectrum using 38 Gaussian lines
- Relative normalisations based on the cross-sections of Bodewits 2007 (0.2 - 1 keV)
- **Calculate flux 0.25 - 2.5 keV and also fluxes from individual lines**



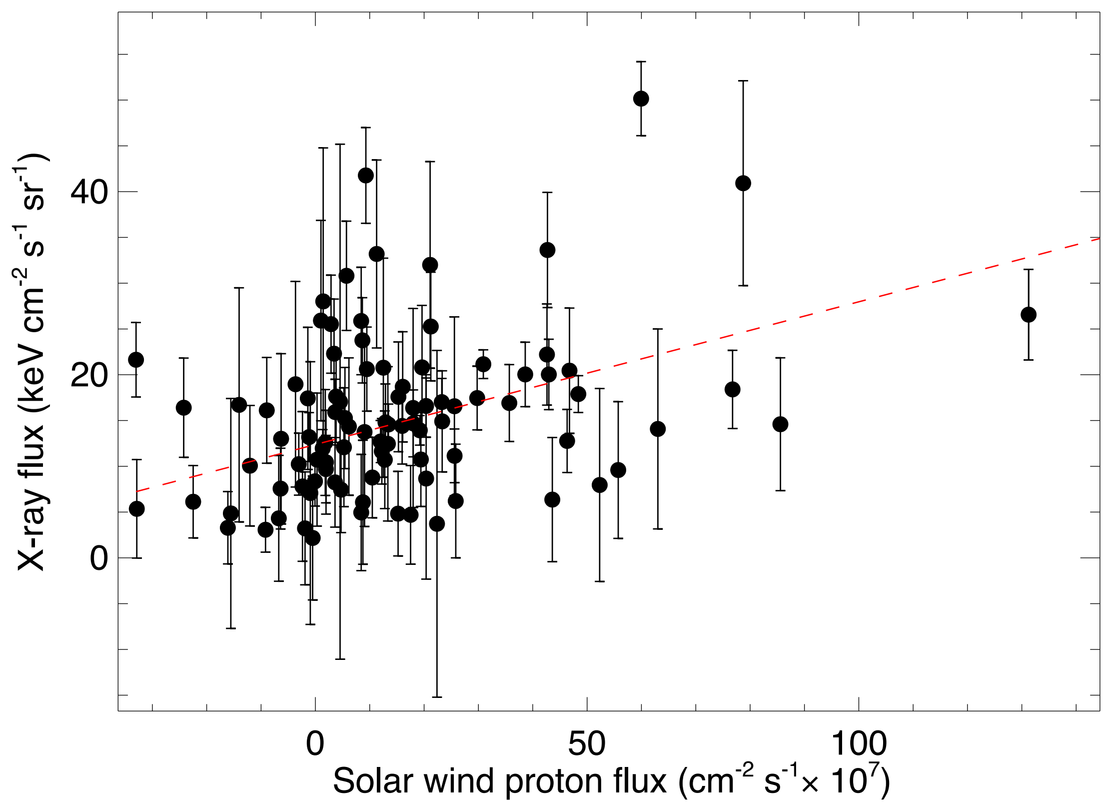

| Ion | Energy (keV) |
|---|---|
| CV | 0.299 |
| CVI | 0.367 |
| NVI | 0.420 |
| NVII | 0.500 |
| OVII | 0.561 |
| OVIII | 0.653 |
| NeX | 1.022 |
| MgXI | 1.330 |
| SiXIV | 2.000 |



# Observed SWCX fluxes, 0.25 - 2.5 keV



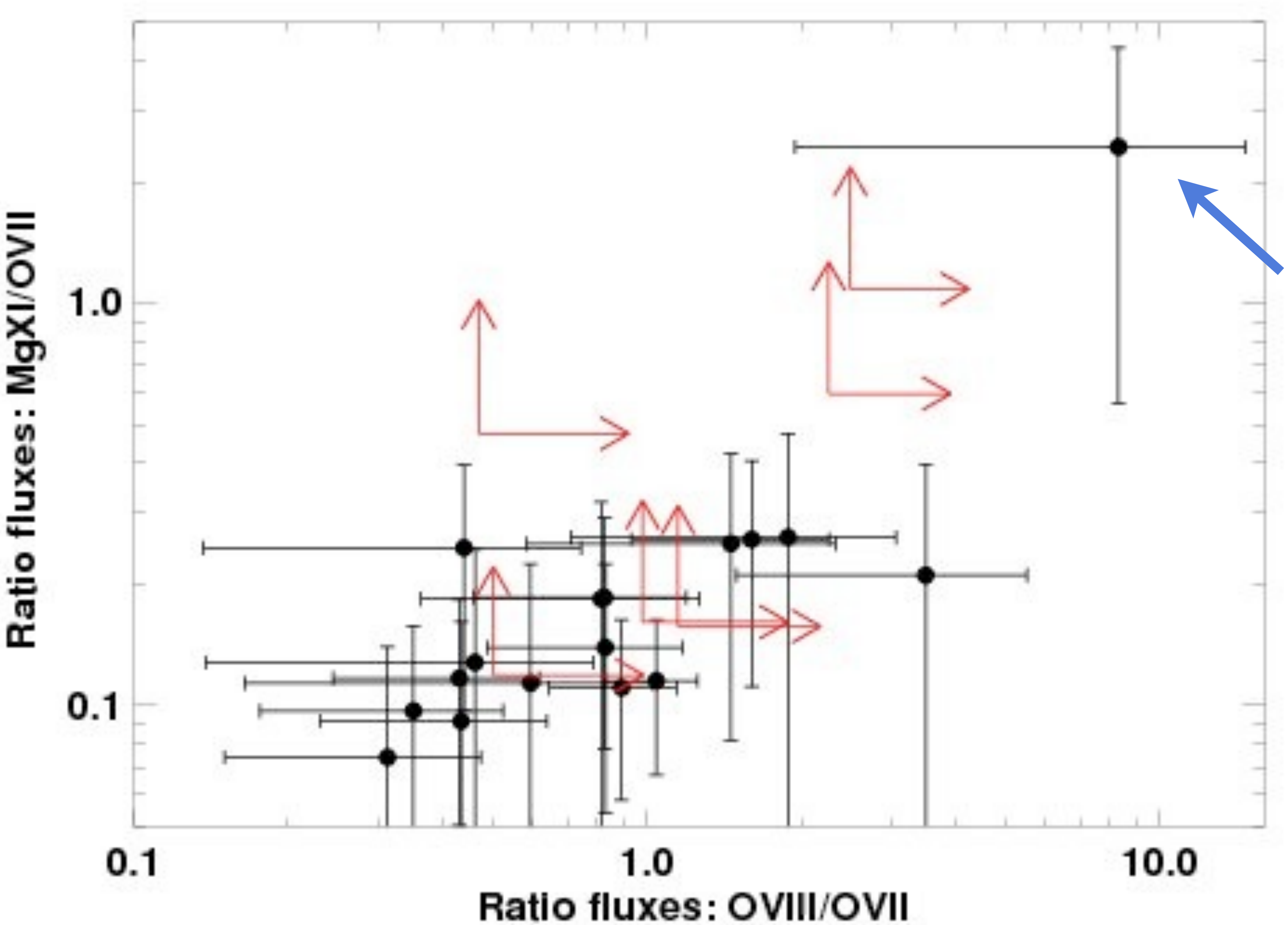

Observed flux versus mean solar wind proton flux difference between SWCX-affected and SWCX-free period as selected from X-ray lightcurve




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

- However, no simple linear relationship
- Positive/negative 'resultant' proton flux: 73/12 i.e. not random
- Considerable scatter, but SW can have large compositional differences: slow, fast, Coronal Mass Ejection

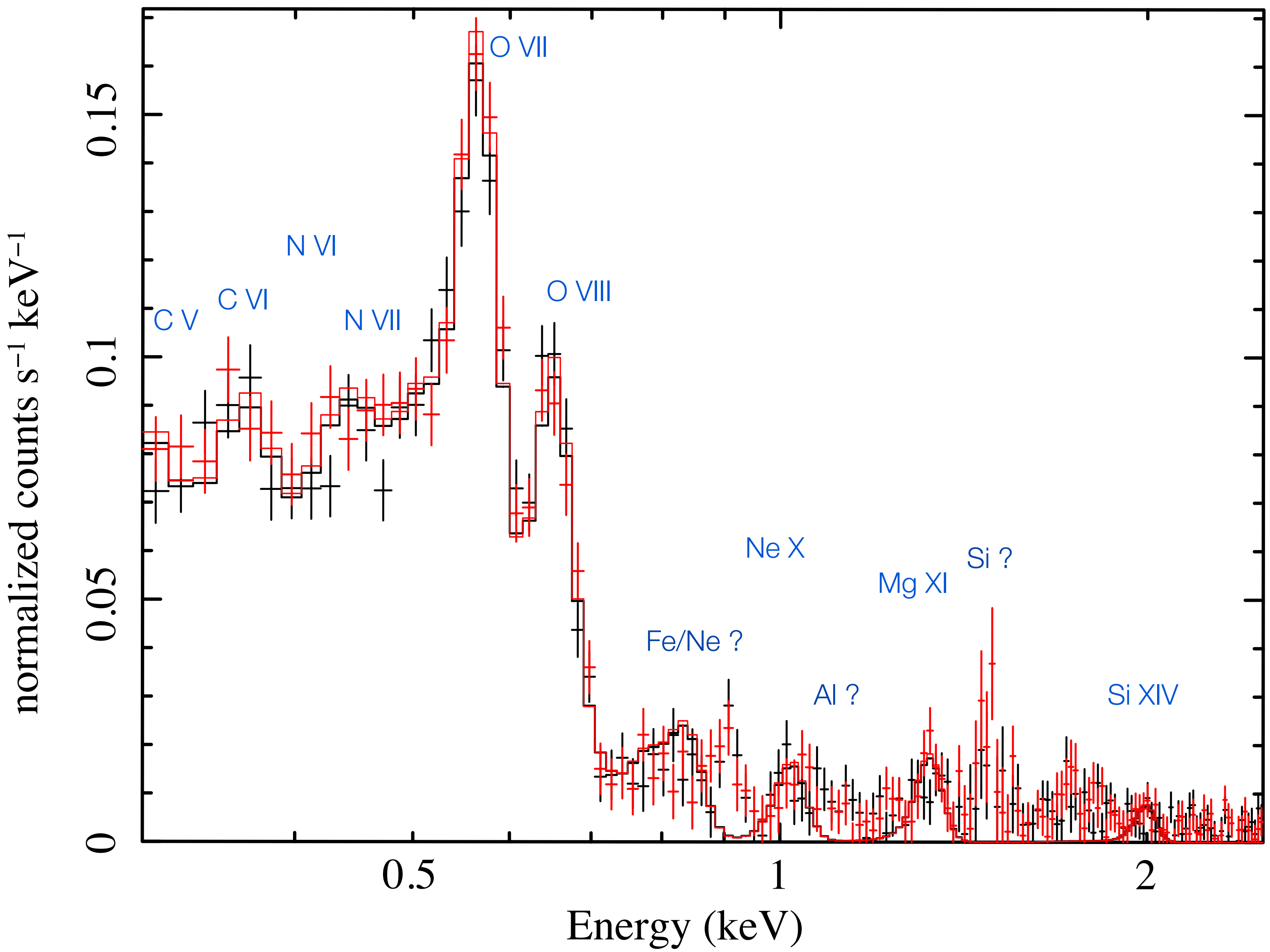
# Line strengths - diagnostics of solar wind type?




Coronal Mass Ejection,
Carter, Sembay & Read 2010

# Stacked SWCX spectra for all exospheric cases

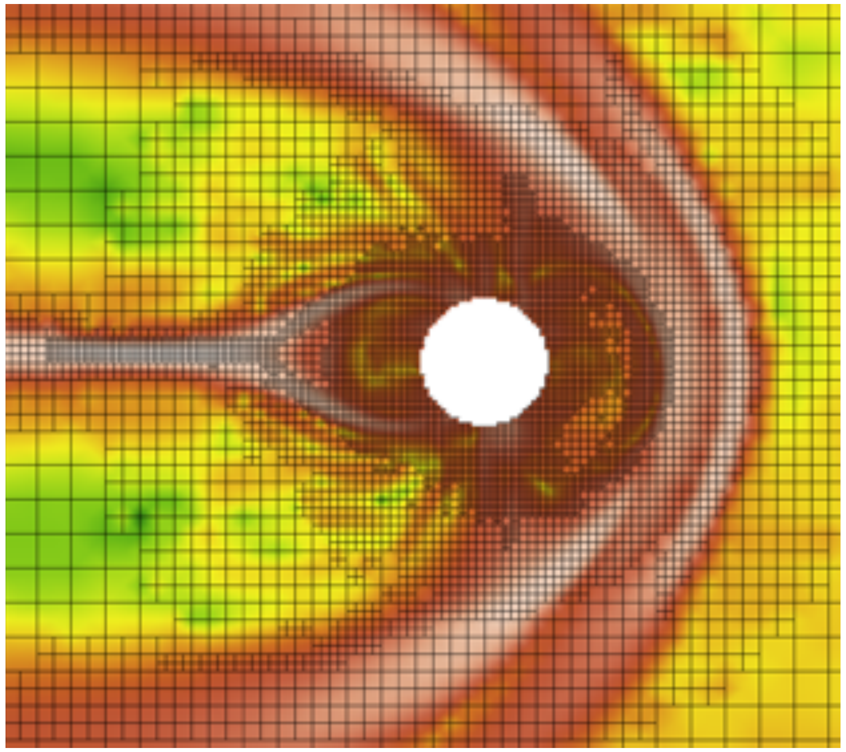
- For MOS1 (black) and MOS2 (red), 103 cases
- Spectral resolution of EPIC-MOS cameras: moderate, E/ΔE ~ 20 at 1 keV

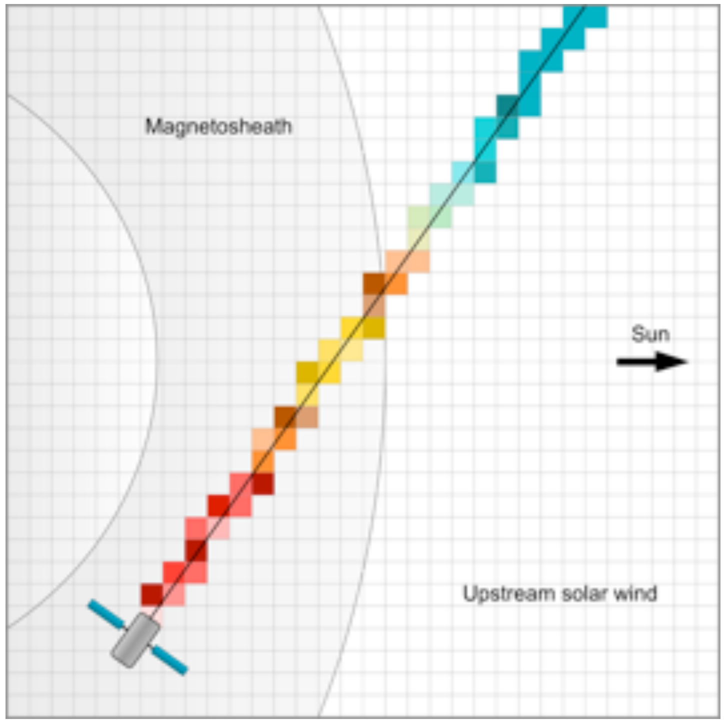



- OVII triplet: 7.6 +/- 0.3 photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$
- OVIII line: 3.0 +/- 0.1 photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$
- But, $O^{8+}$ can charge exchange to $O^{7+}$ along line of sight, so ratio does not accurately represent SW composition
- OVII triplet: forbidden line normalisation stronger than resonance line as expected for charge exchange

# GUMICS-4 and modelling efforts

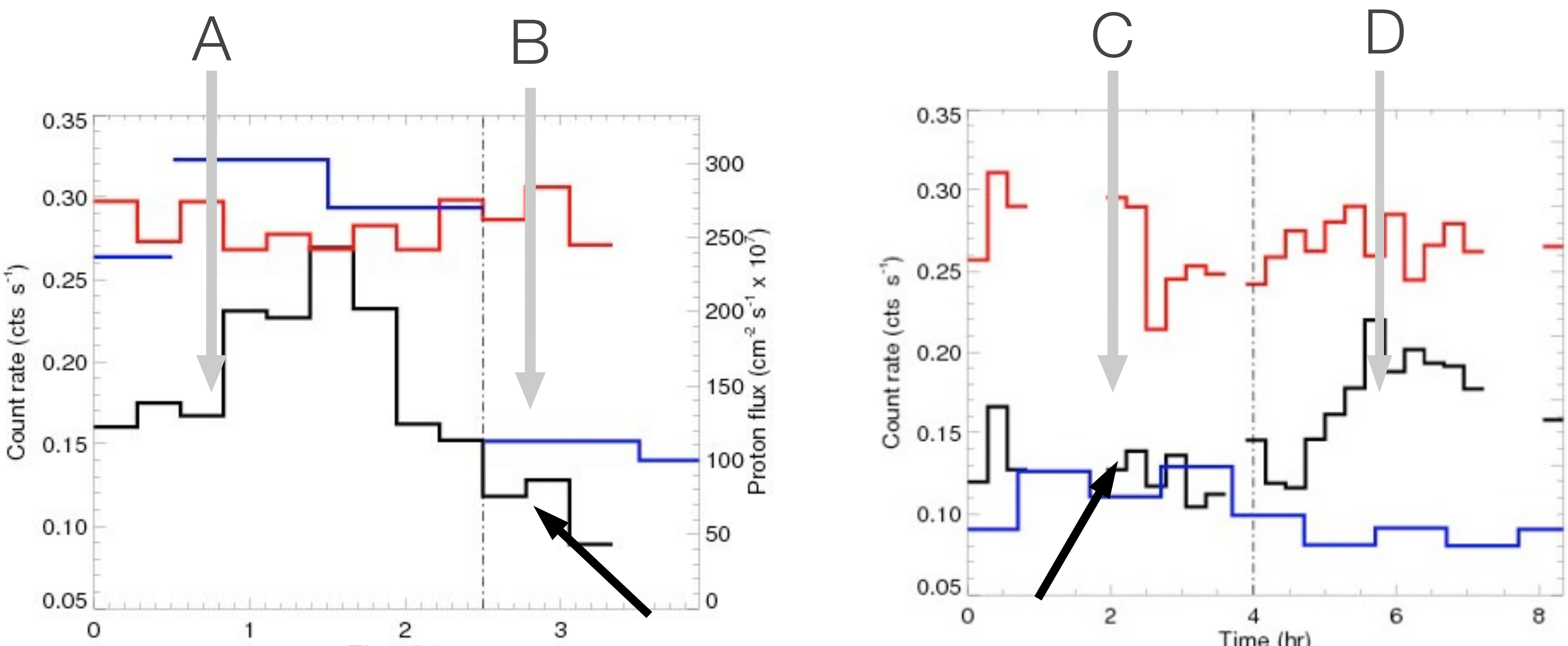
- Grand Unified Magnetosphere Ionosphere Coupling Simulation, version 4 (developed at FMI)
- GUMICS-4 outputs; e.g. plasma density in a box around the Earth
- Build a SWCX emissivity model:
    - $P_{X\text{-ray}} = \alpha \mu_{sw} n_{sw} n_H$ (Robertson & Cravens, 2003)
    - model of neutral hydrogen target density about the Earth
    - CX efficiency factor, $\alpha$
    - integrate along line of sight from observer
- **Compare to fluxes seen by XMM-Newton**
- Similar efforts with BATS-R-US (K. Kuntz, John Hopkins University, STORM consortium)





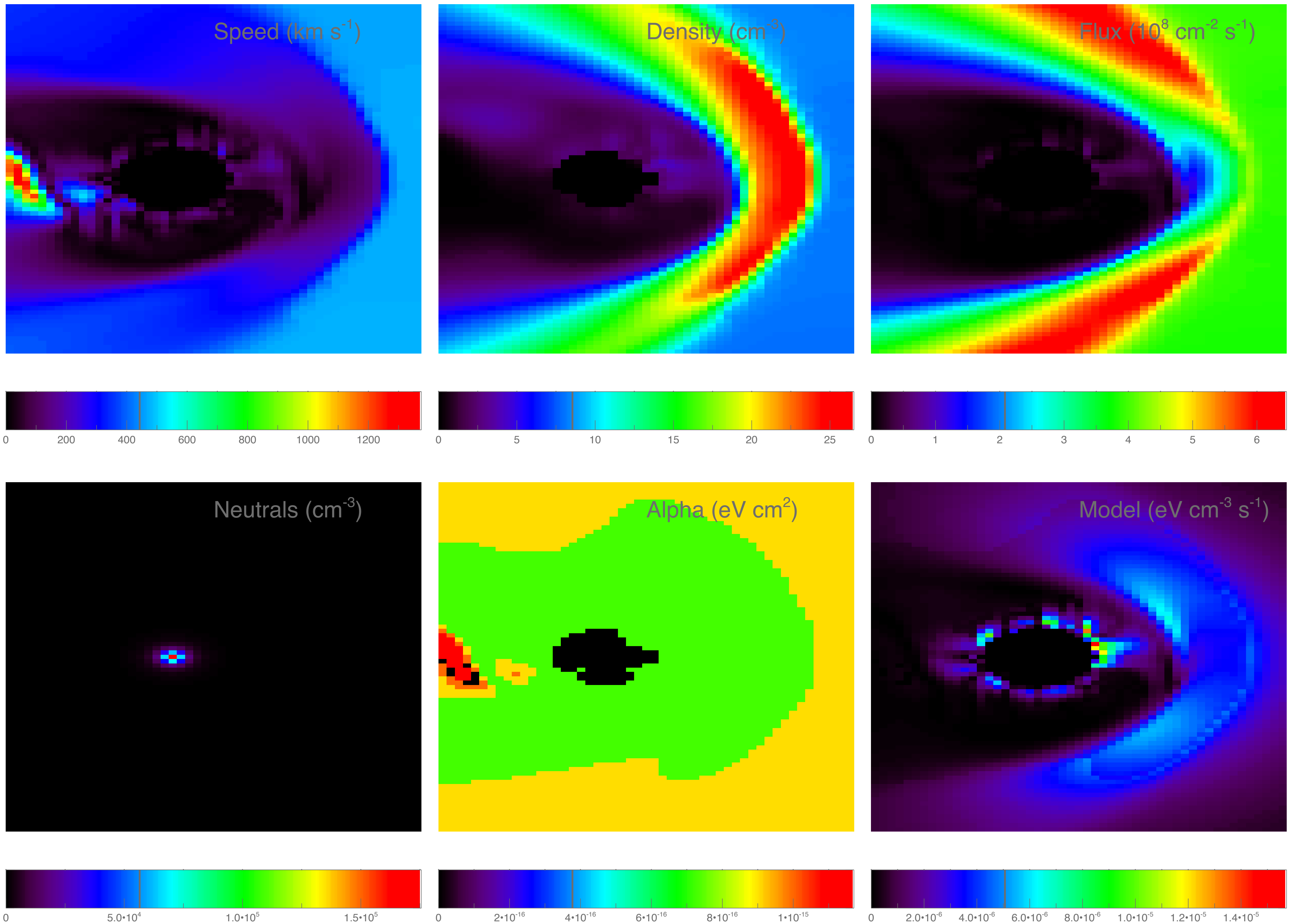
# Initial modelling

- Testing on a crude model grid, 0.5 $R_E$
- Test against two XMM-Newton example 0.5 - 0.7 keV lightcurves
- XMM-Newton field of view of 0.5 degrees diameter
- Take two snap shots for each observation: peak and trough periods
- Compare model A vs B and D vs C




0.5 - 0.7 keV lightcurves (black)

# Model component snap shots (C), $GSE_Y = 0$



# Summary of results

| Case | X-ray period | Upstream solar wind speed, GUMICS input mean (km $s^{-1}$) | Upstream solar wind density, GUMICS input mean ($cm^{-3}$) | Bx (nT) | XMM-Newton count rate (SWCX + sky) 0.5 - 0.7 keV (ct $s^{-1}$) | Model integrated flux (eV $cm^{-2}$ $s^{-1}$) | Model count rate (no background) 0.5 - 0.7 keV (ct $s^{-1}$) | Modelled background subtracted rate | **Observed to modelled ratio** |
|---|---|---|---|---|---|---|---|---|---|
| **A** | Peak | 362 | 65 | -3.0 | 0.175 ± 0.01 | 1.21 | 0.026 | 0.01 | **2.3** |
| **B** | Trough | 375 | 31 | 4.8 | 0.152 ± 0.01 | 0.85 | 0.016 | - | |
| **C** | Trough | 468 | 5 | -0.5 | 0.155 ± 0.02 | 0.29 | 0.015 | - | **flat model** |
| **D** | Peak | 468 | 5 | -0.5 | 0.220 ± 0.02 | 0.29 | 0.015 | 0.0 | |

- A vs B: variability modelled, D vs C: variability not modelled

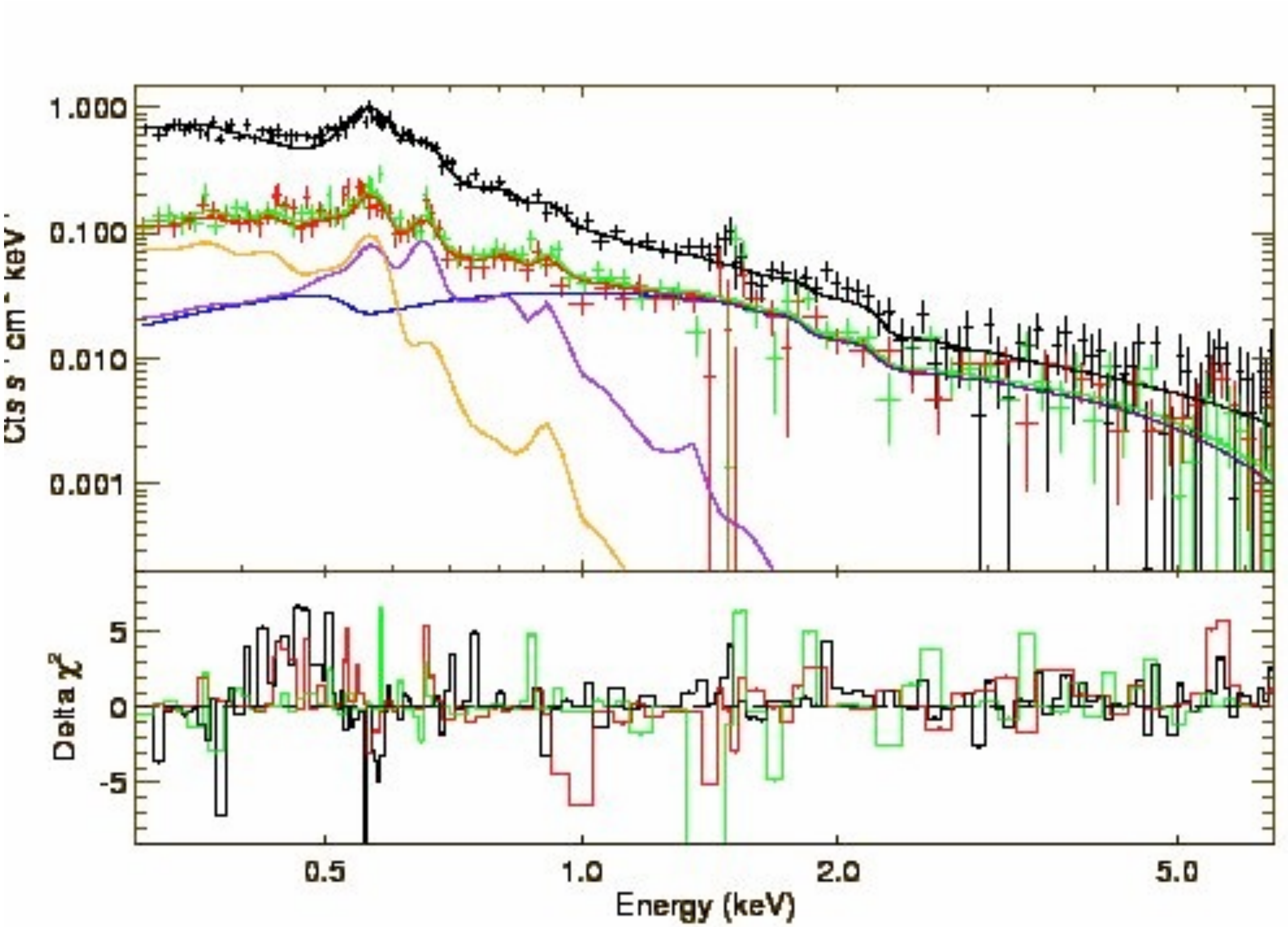
# Summary

- 3.4% of XMM-Newton observations, over one solar cycle, contain a detectable level of temporally variable SWCX
- A coronal mass ejection has been observed by XMM-Newton, with distinct spectral characteristics (e.g. Mg/O ratios)
- 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 minor-ion composition of the solar wind
- Initial modelling efforts show reasonable order of magnitude rates, but in one test fail to show the variability seen by XMM-Newton: what is causing this variability: neutral target model, minor ion abundances in solar wind (vs protons), CX efficiencies.....?
- **Could use SWCX to image the Earth's magnetosheath with wide field optics: AXIOM/AXIOM-C/STORM (see J. Eastwood's talk)**

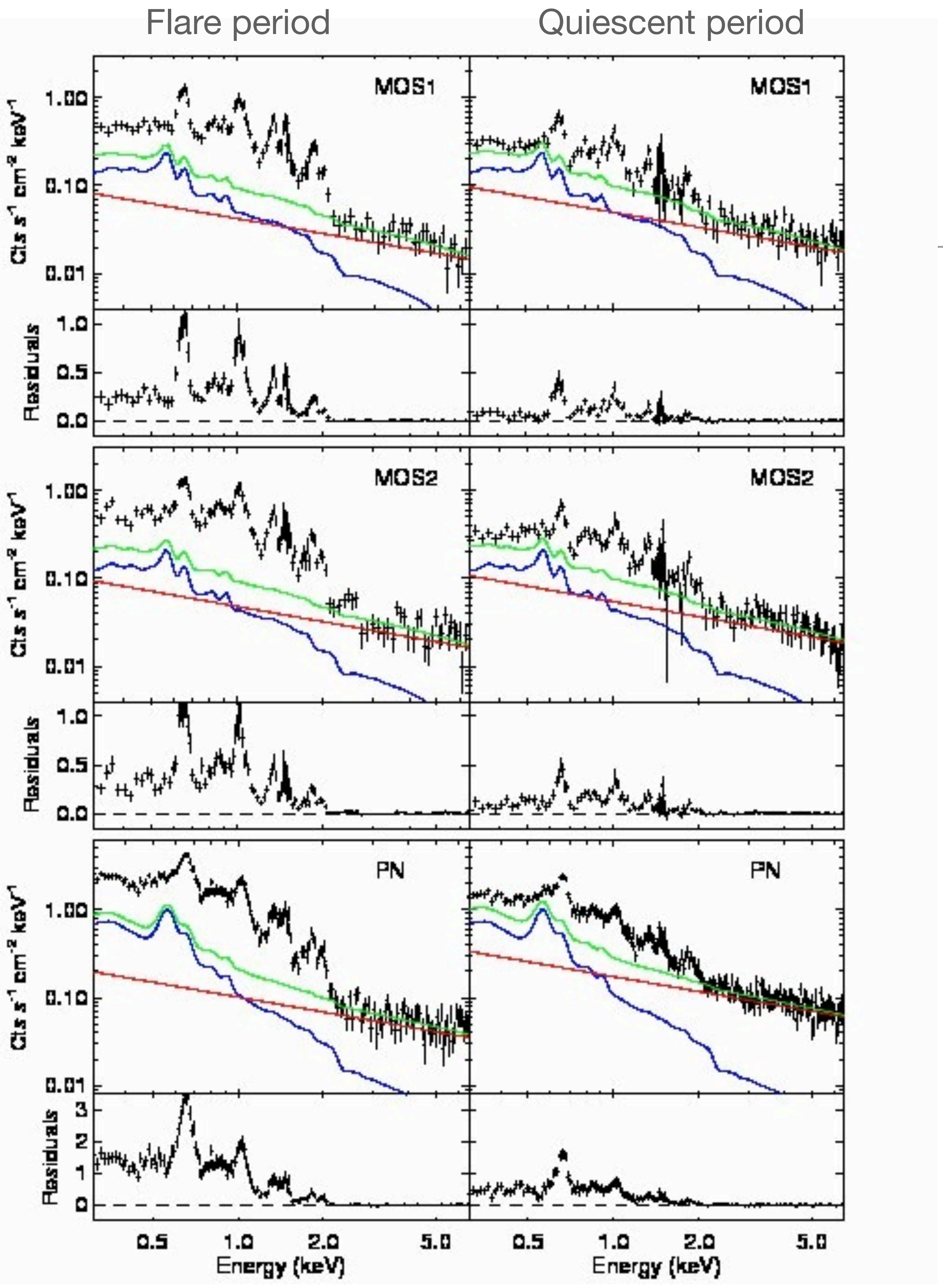
- THANK YOU

# Additional slides

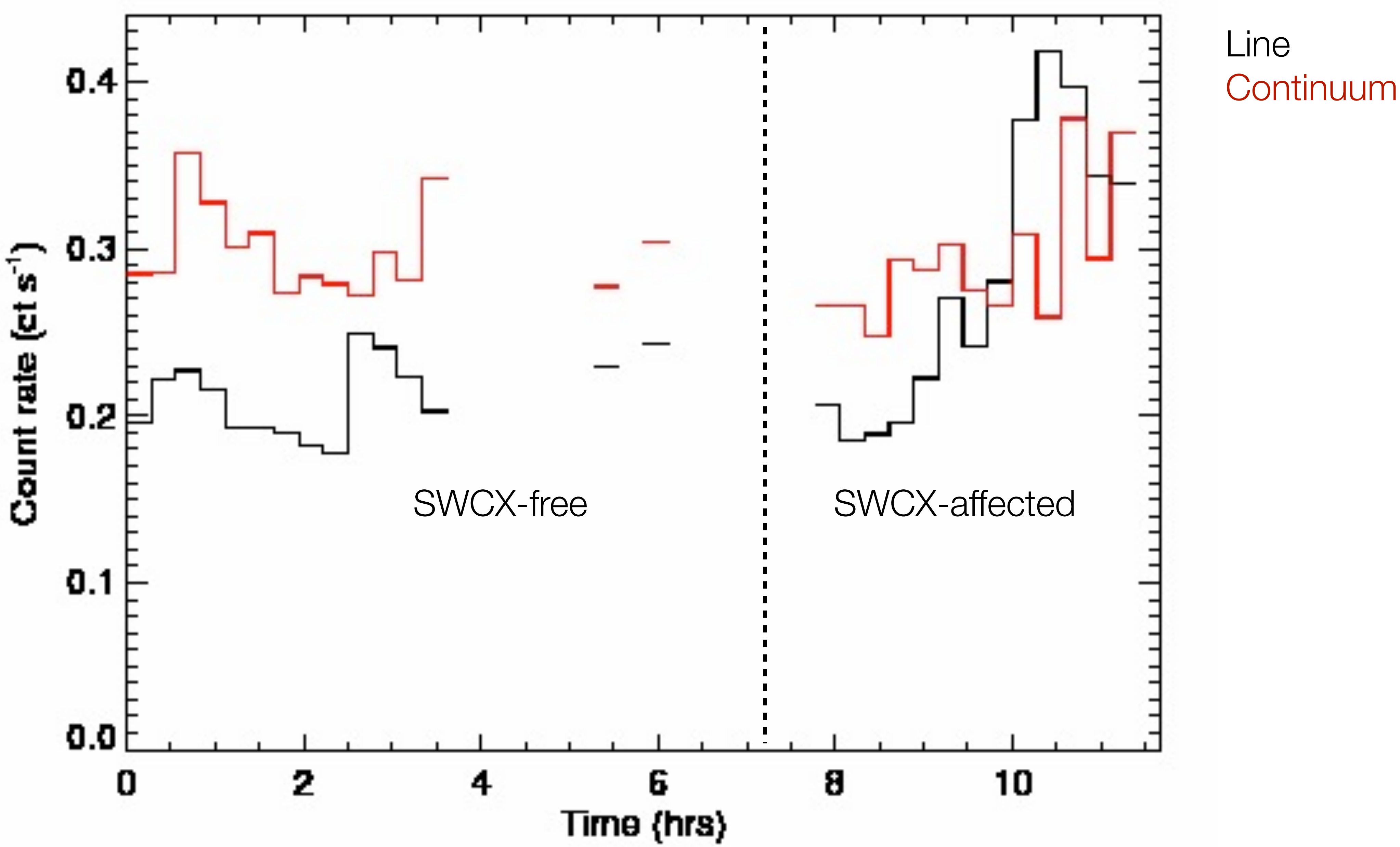
# Background subtraction for CME case



* CME split into flare and quiescent periods

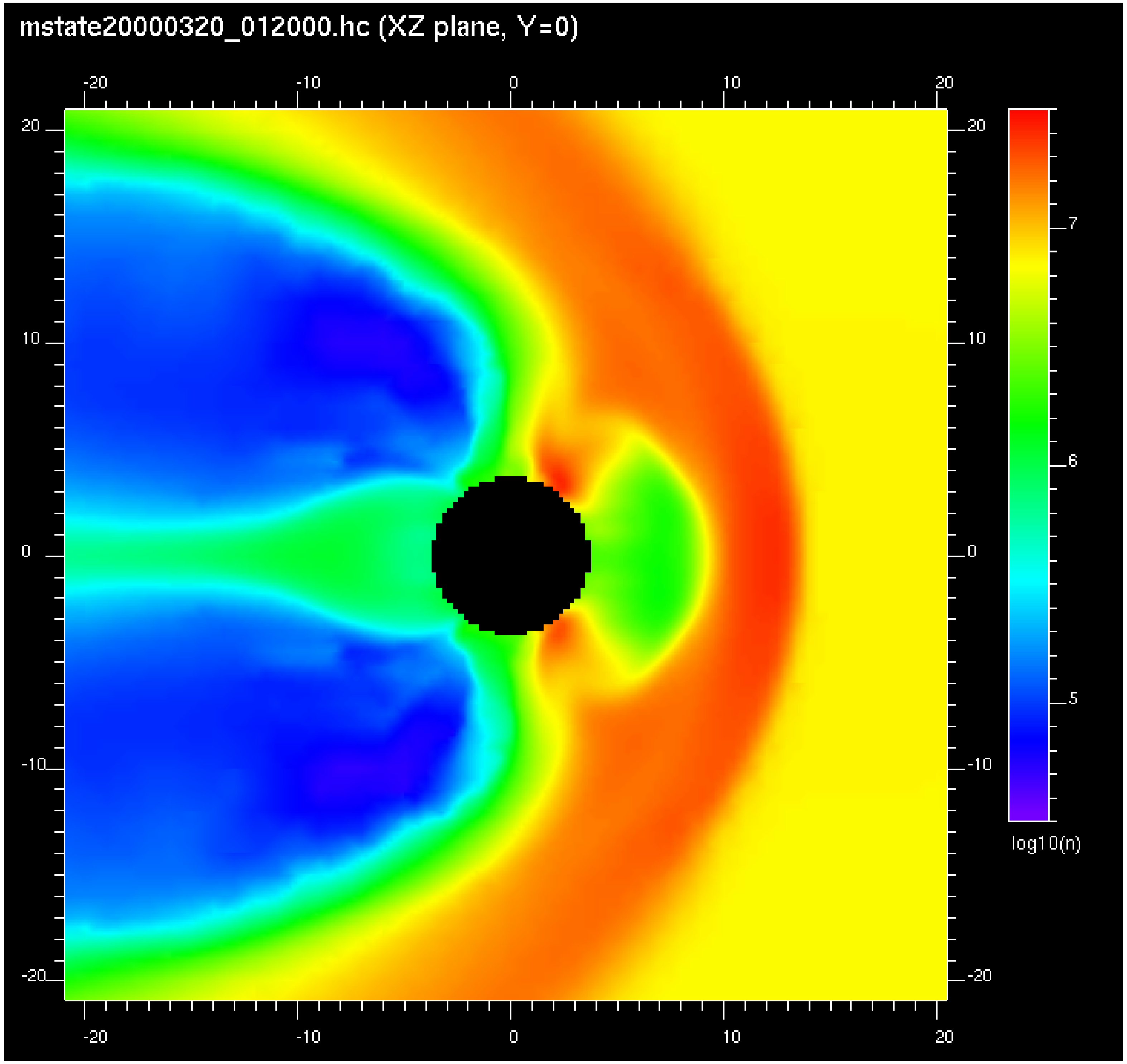


# Alternative standard lightcurves



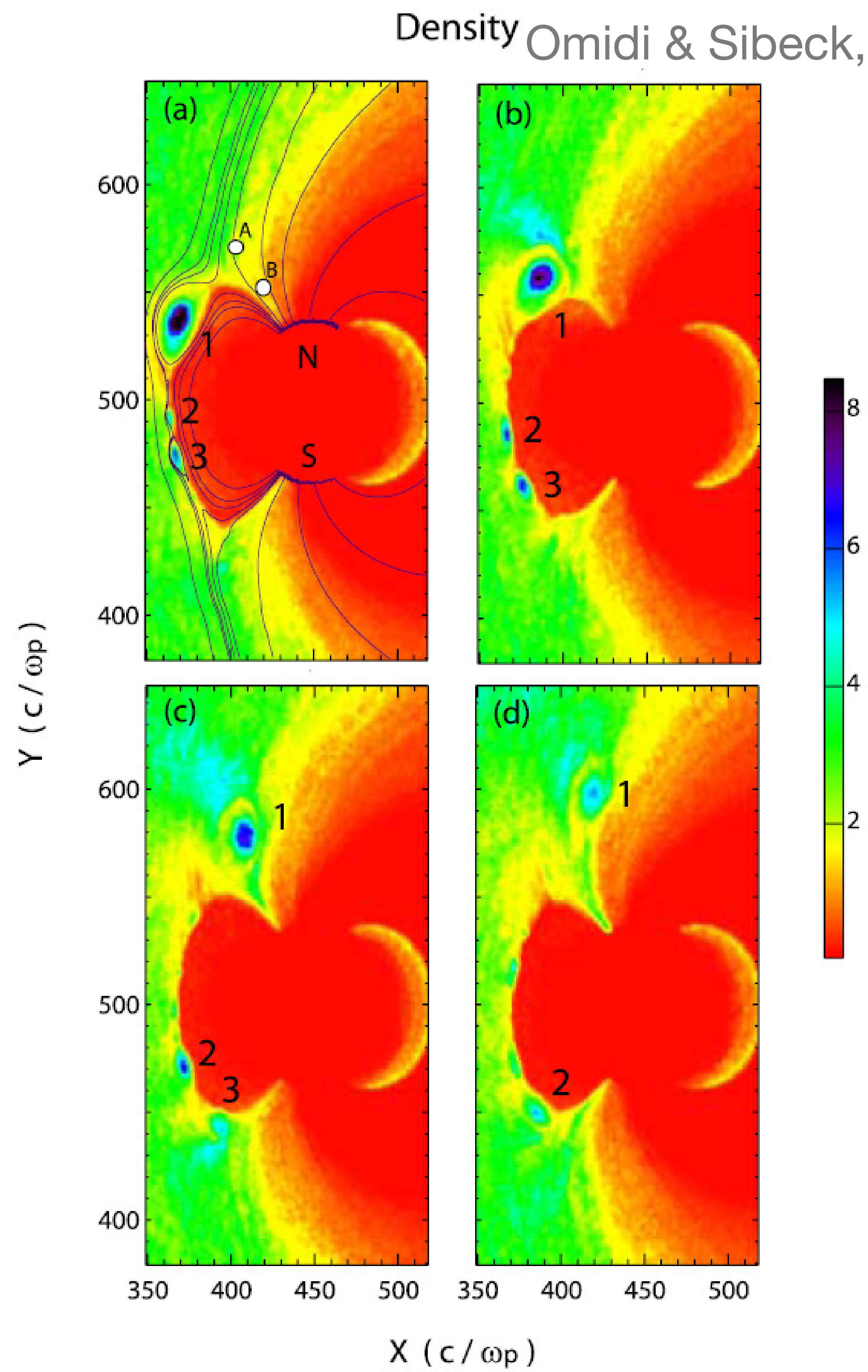
# Minna Palmroth GUMICS, MHD simulation

- Plasma density

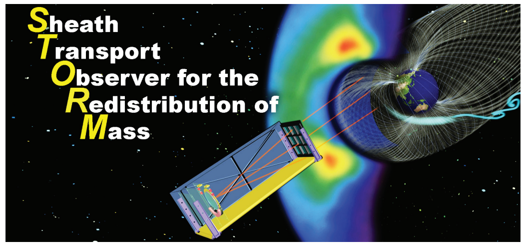


# Using CX to image the magnetosheath

- Charge-exchange could be used to **image large areas** of the magnetosheath
- Various transient phenomena could be observed, for example ‘flux-transfer events’ or boundary events at the magnetopause
- Use **very large field of view** optics
- X-ray imaging using microchannel plates, and a CCD or MCP detector at the focal plane
- Several mission proposals have been submitted, in Europe and the US
- **AXIOM, AXIOM-C and STORM**
- Sounding rocket experiment in late 2012

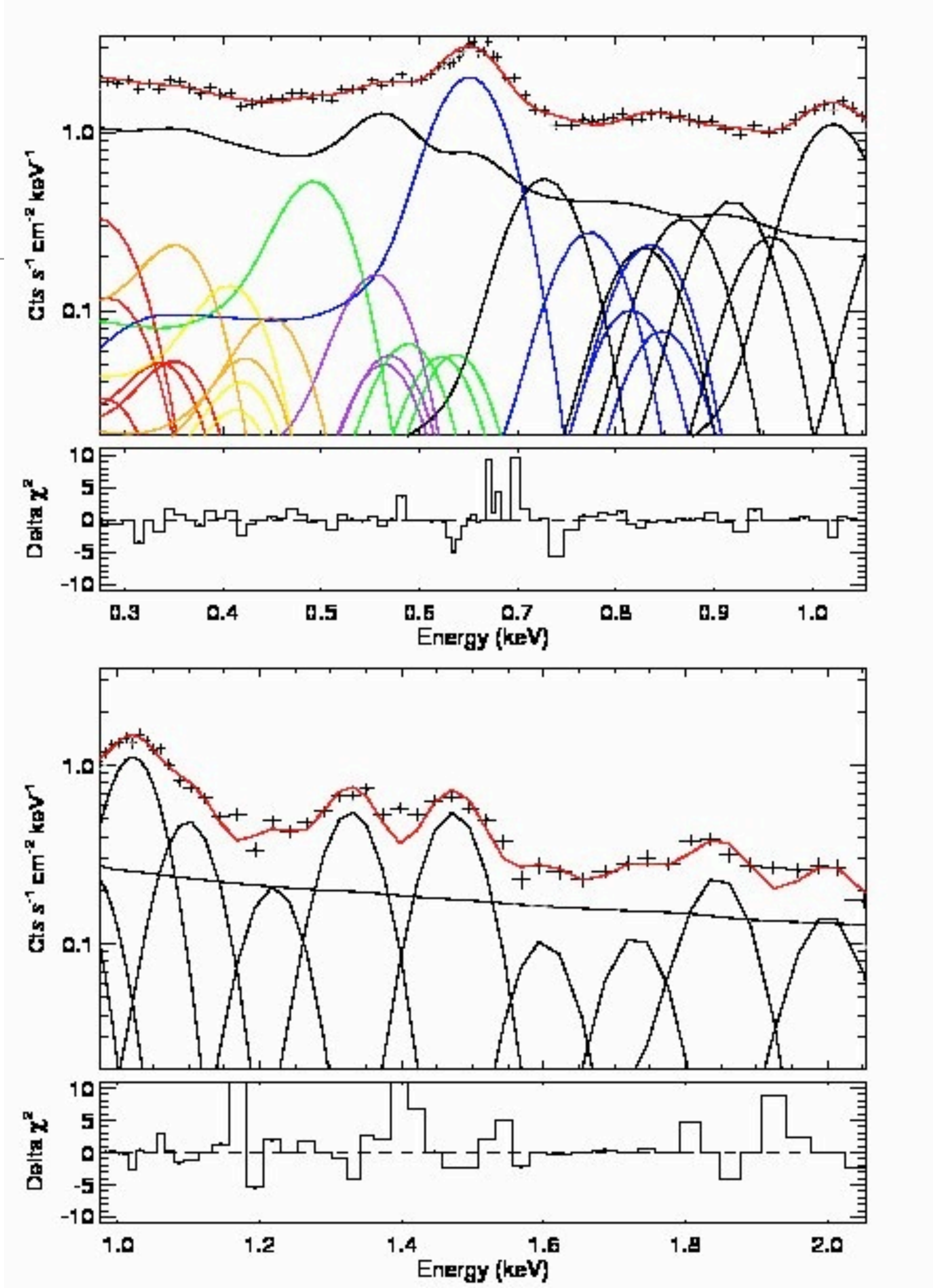



Omidi & Sibeck, 2007

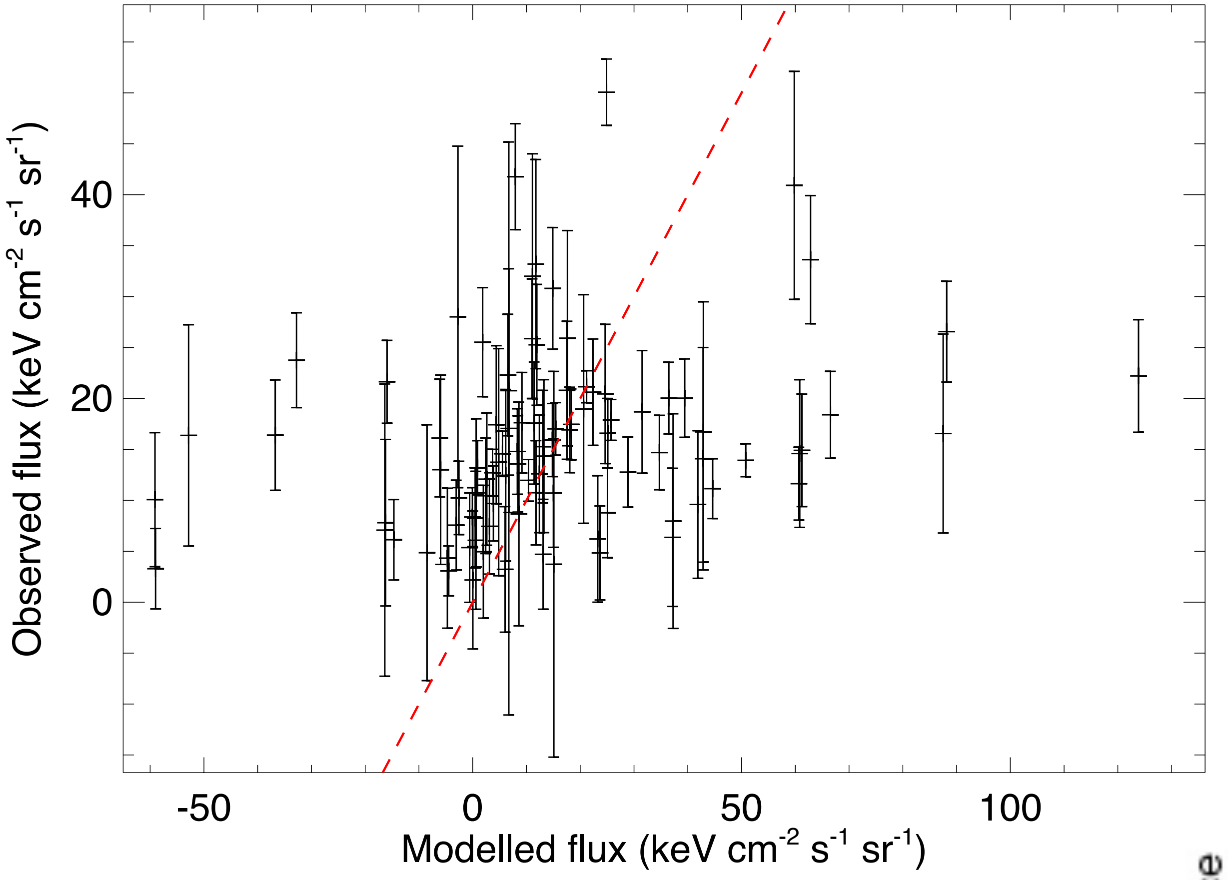


# A standout case

- 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
- Anything left over is (mainly/assumed) SWCX
- Looked at data from all three X-ray imaging detectors on XMM-Newton
- Very strong OVIII and upstream Coronal Mass Ejection detected by solar wind monitors
- Lots of other high-energy lines



# Modelled flux (old model) - compared to observed flux

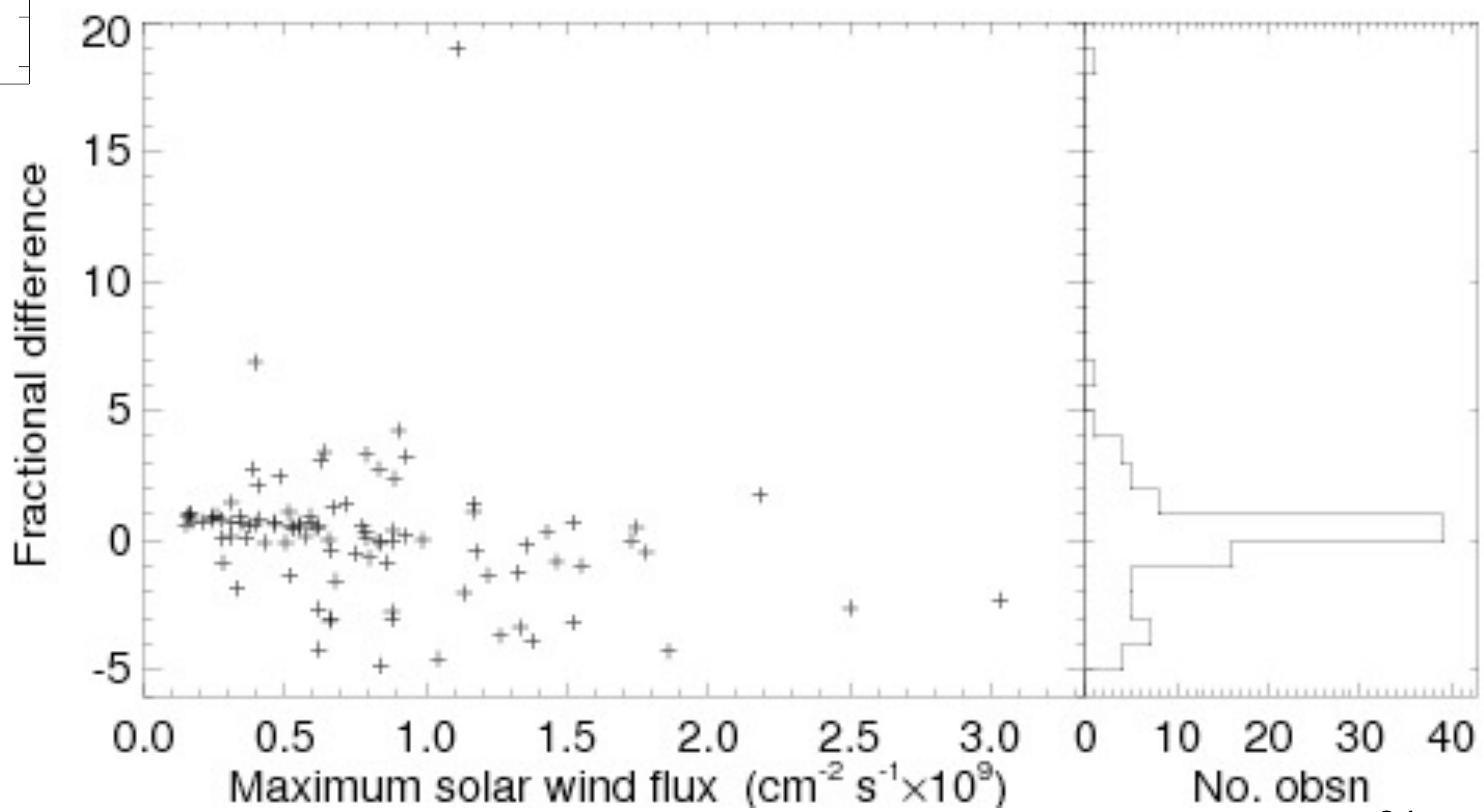



Modelled X-ray emission typically to same order of magnitude as the observed emission

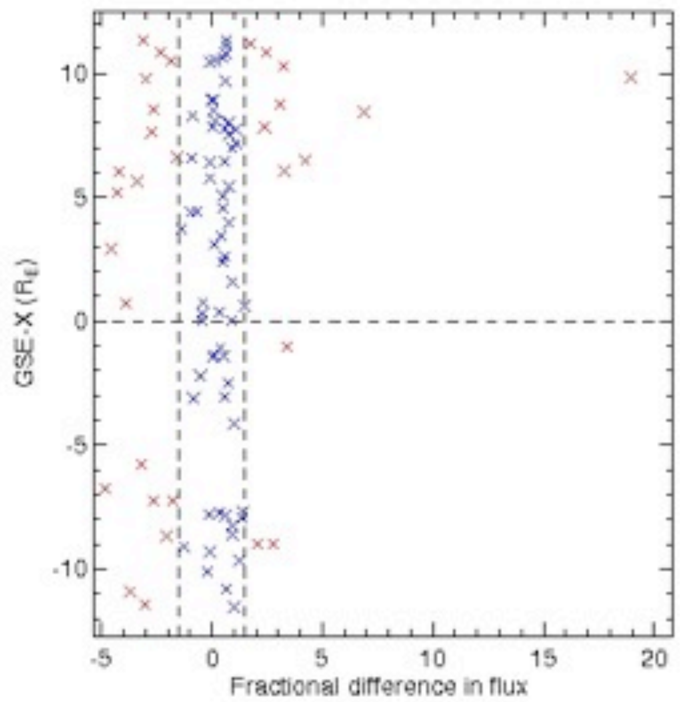
Would have liked to have seen a strong, linear relationship between the observed and modelled flux

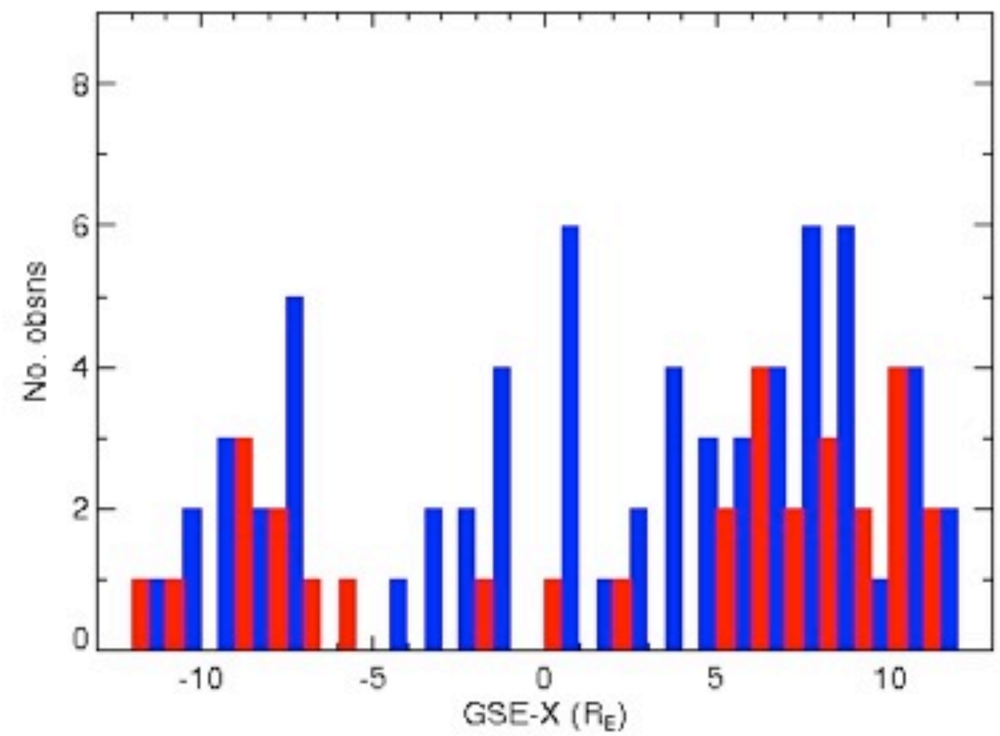
The model is currently too simple to describe the phenomena fully

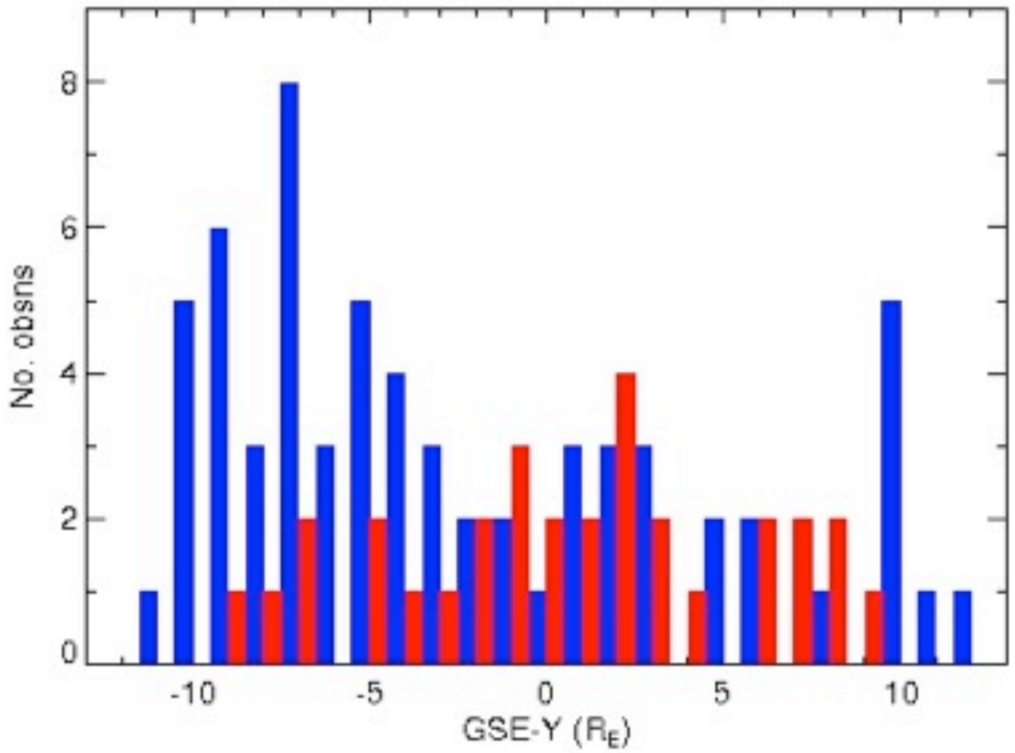
Fractional difference defined as:
(observed - modelled) / observed flux

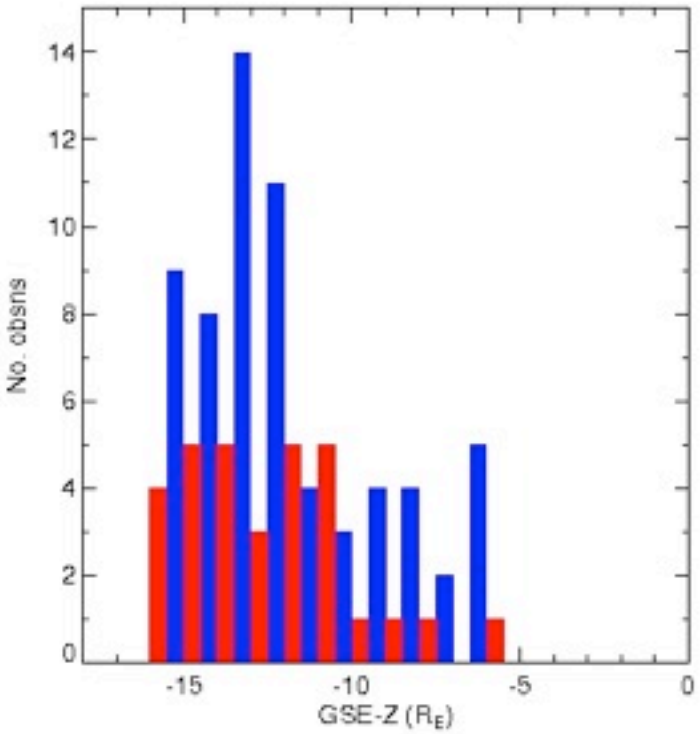


# Previous modelling vs observed flux, with position




Good, Bad (fractional difference)