George Fraser

The X-ray signature of the solar axion flux observed by XMM-Newton

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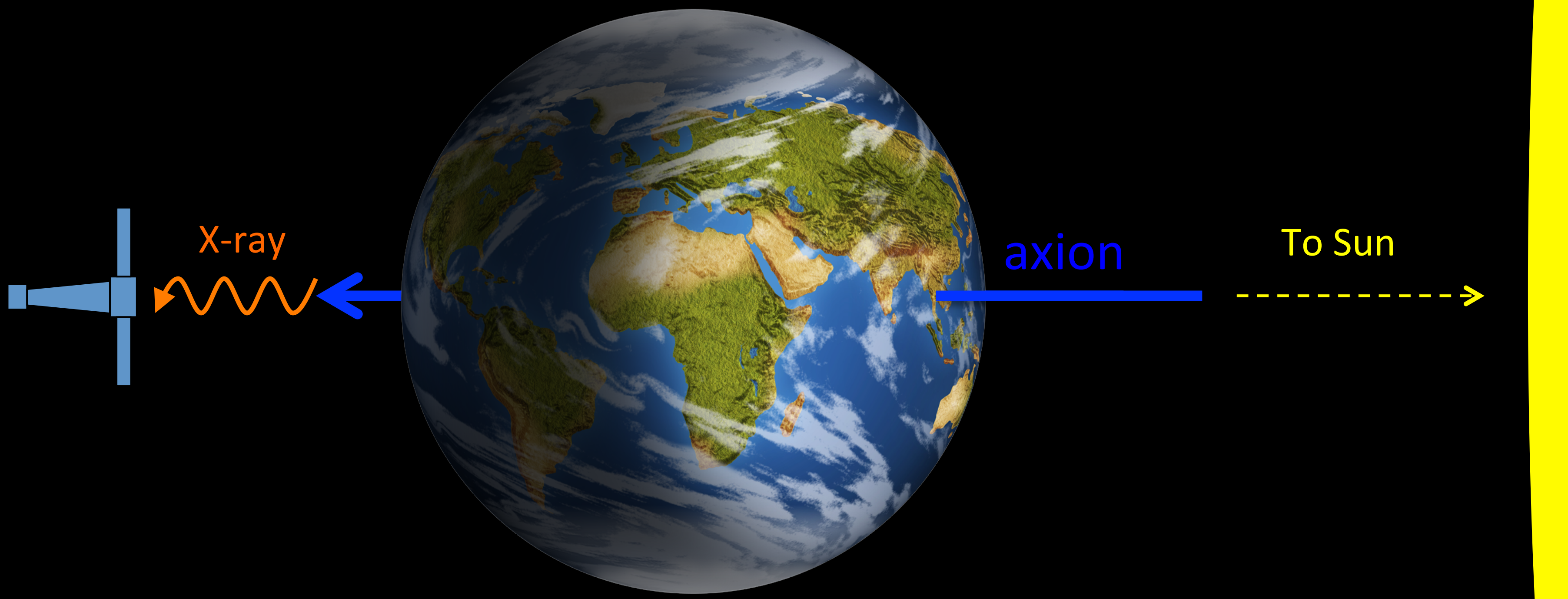
Introduction

- Direct detection of dark matter (DM) has preoccupied physics for 30+ years.
- Of current candidate DM particles : axions
  - weakly-interacting, light, neutral, spin-zero bosons
  - solar axions produced in core by $\gamma\gamma \rightarrow a$ and $\gamma Z \rightarrow aZ$
  - may be observable via their mixing with photons in an external electromagnetic field.
- Development of observing strategies - GECOSAX : GEomagnetic Conversion Of Solar Axions into X-rays (Davoudiasl & Huber [DH] 2006,2008) – based on fact that Earth is a large magnet

GECOSAX (Low Earth Orbit)



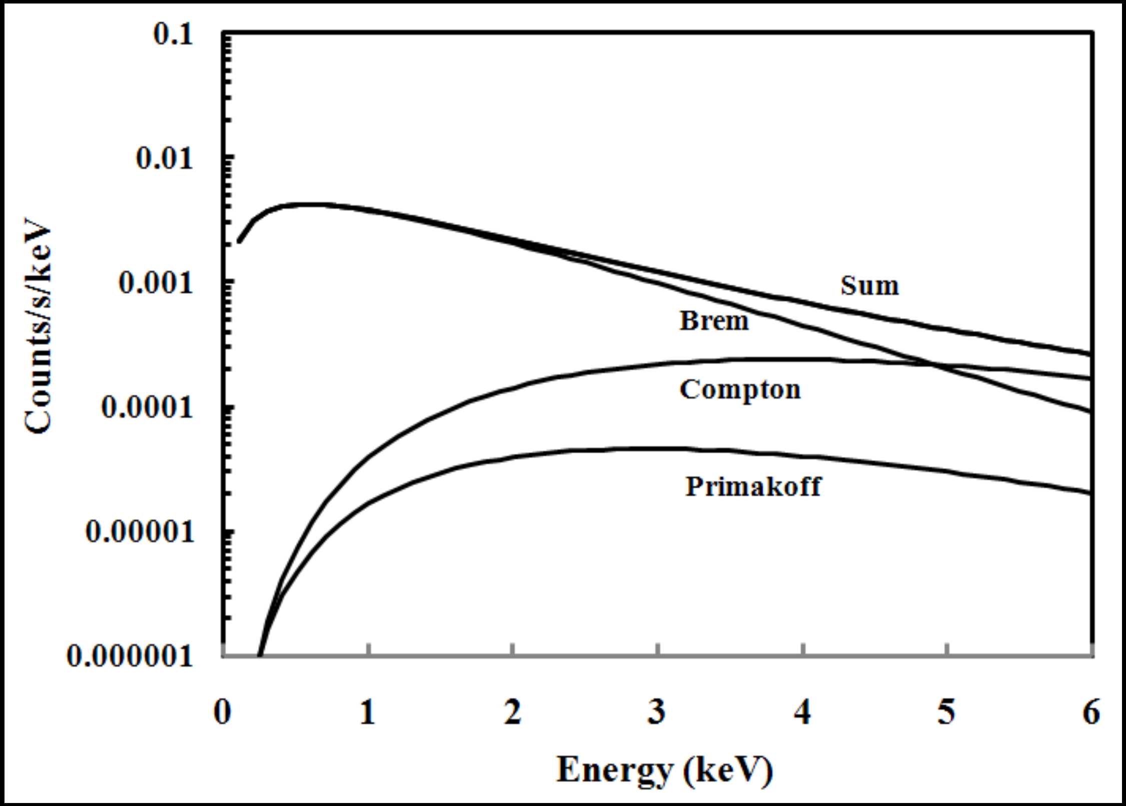
- Excludes X-ray bright Solar disk, and CXB – high sensitivity
- Conversion probability for axion into photon depends on :
  - $L^2 B_T^2$ – both small (for LEO, L~ 600km, B_T=30μT)
  - axion-electron/photon coupling constants g_{ae} , $g_{a\gamma}$

CAST – CERN Axion Solar Telescope

- Nothing seen from CAST – the X-ray point source at Sun-centre not observed
- Nothing seen from any GECOSAX-type experiments: Suzaku, RHESSI, Smart-1 (less sensitive than CAST)
- X-ray spectrum of quiet Sun does not follow original predicted axion spectrum [DH], but keeps rising below 1keV
- Calls into question basic (Primakoff) model - Adjustments to theory…

Predicted Axion Spectrum

- Axion production rates inside Sun :
- In addition to original Primakoff mechanism, two more pathways – Compton and Bremsstrahlung - both dependent on axion-electron coupling constant rather than axion-photon coupling constant. (Derbin+ 2011, 2012, 2013)

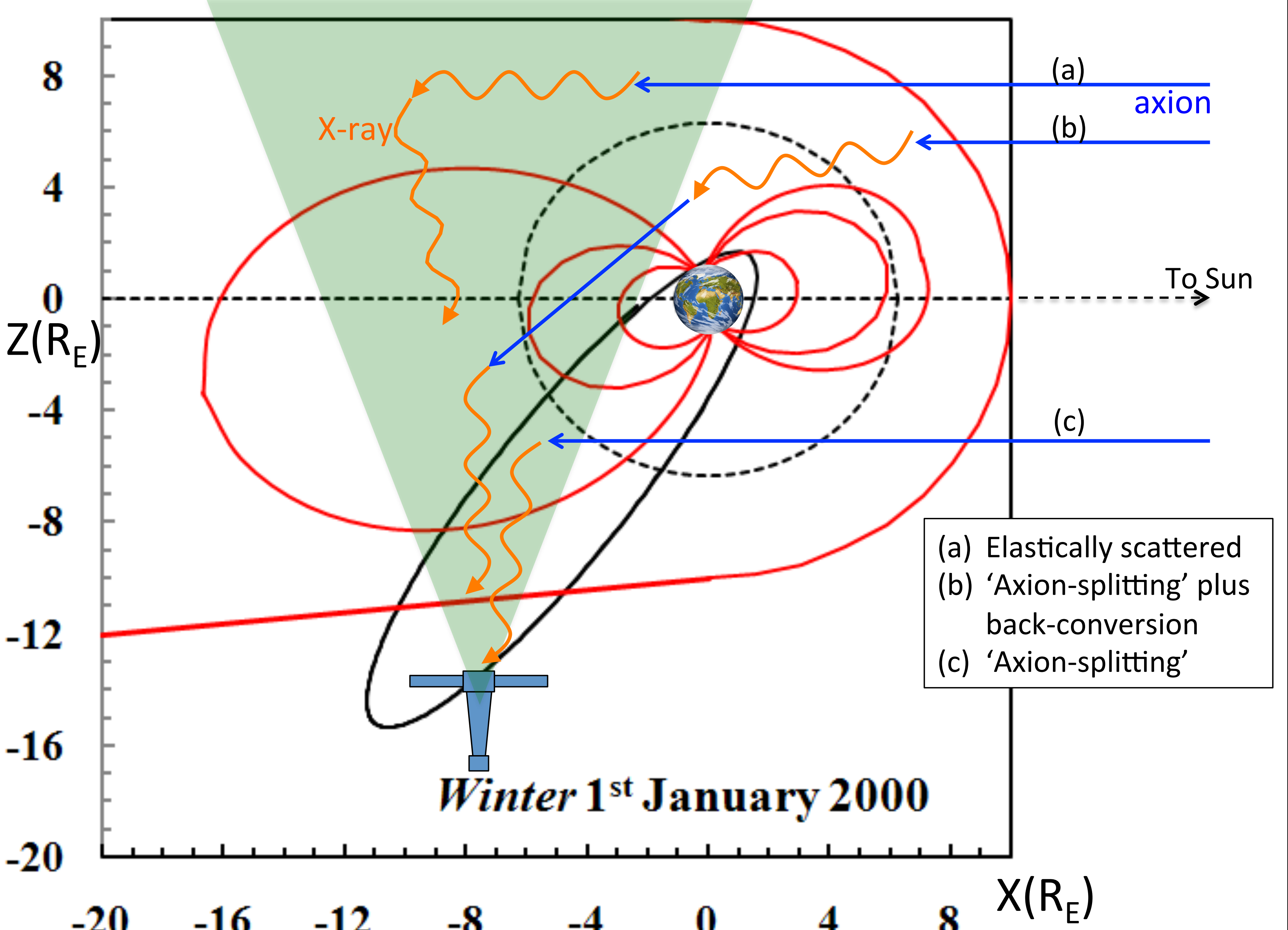


- Spectra calculated for parameters consistent with current experiments ($g_{10}= g_{11}= 1$)
- Compton and Bremsstrahlung dominate over Primakoff, i.e. axion-electron coupling dominates over axion-photon coupling
- Axion signal is broad, with 'peak' below 1 keV.
- Models appear robust compared with spectra of quiet Sun (Zioutas+ 2009)

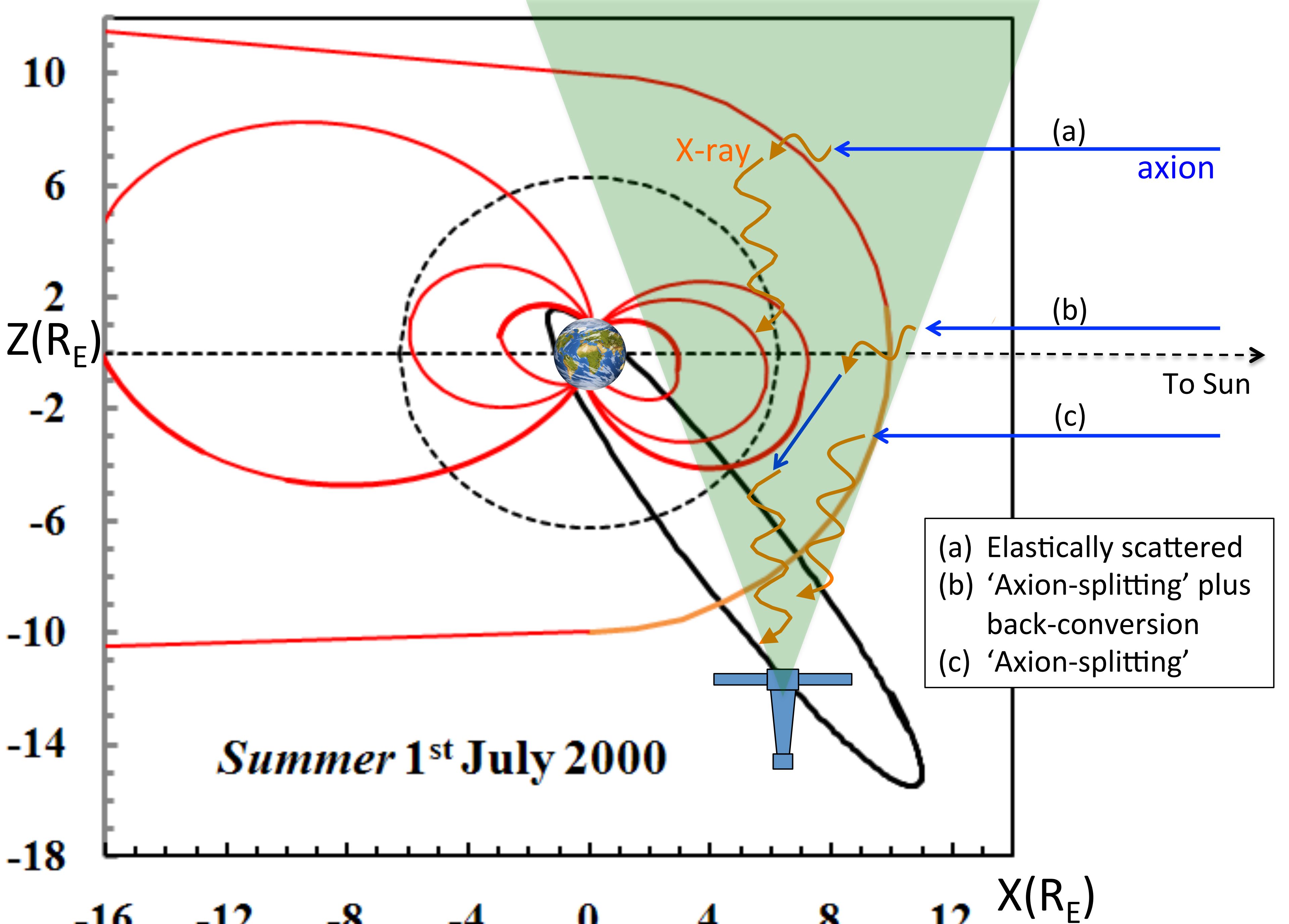
XMM-Newton

- EPIC on XMM-Newton provides largest product of effective area & observing time for potential detection of axion conversion X-rays.
- Area-time-FOV ‘triple product’ unlikely to be exceeded for many years.
- XMM points on average perpendicular to Sun-Earth line – If conversion X-rays propagate in direction of original axions, unlikely that XMM can provide information on the solar axion observables.
- However…

- …can detect those X-ray photons, converted in Earth's magnetic field, which subsequently find their way into the XMM FOV.
- Various mechanisms :
- Elastic scattering
  - Increase in magnetic conversion volume is huge compared to original LEO GECOSAX geometry.
  - Huge magnetic volume increase only partly compensates the inefficiency of elastic scattering process.
- Motion of axions and their conversion X-rays, however, do not need to be co-linear in inhomogeneous magnetic fields (Guendelman(+) 2008, 2010, 2012) – 'axion splitting'.
- Inverse Compton effect ($e^- + a \rightarrow \gamma + e^-$) should also be considered as potential conversion mechanism, alongside the (inverse) Primakoff effect.
- Photon-to-axion back conversion (Primakoff) in Earth's magnetic field – mix of (not necessarily co-aligned) axions and photons.



(a)
axion
(b)
X-ray
(c)
To Sun
Z(R_E)
X(R_E)
8
4
0
-4
-8
-12
-16
-20
-20
-16
-12
-8
-4
0
4
8
(a) Elastically scattered
(b) 'Axion-splitting' plus back-conversion
(c) 'Axion-splitting'
Winter 1st January 2000

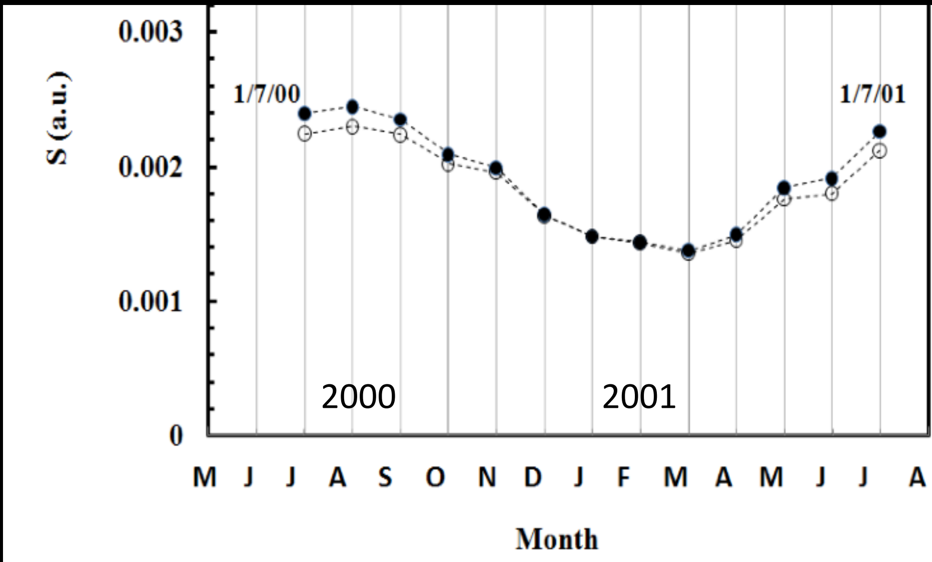

Z(R_E)
X(R_E)
10
6
2
-2
-6
-10
-14
-18
-16
-12
-8
-4
0
4
8
12
X-ray
(a)
axion
(b)
To Sun
(c)
(a) Elastically scattered
(b) 'Axion-splitting' plus back-conversion
(c) 'Axion-splitting'
Summer 1st July 2000

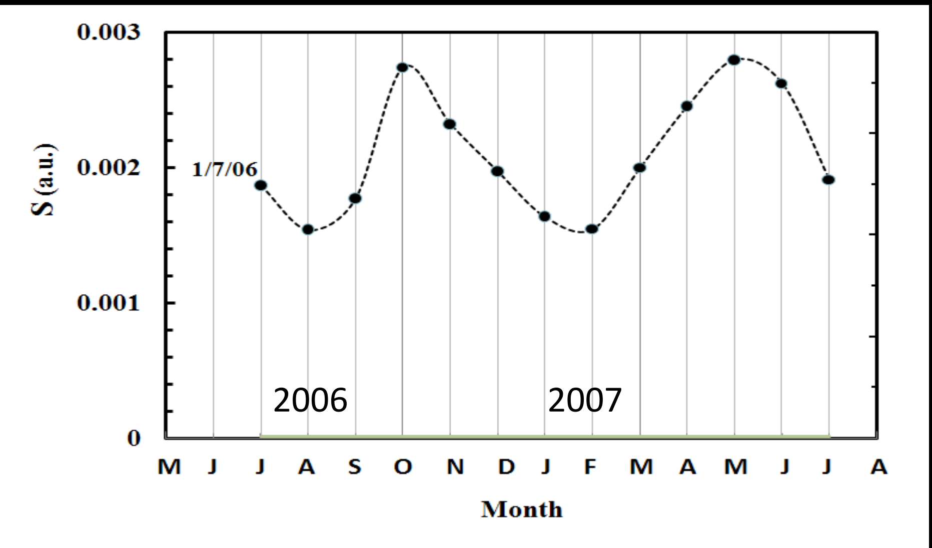
XMM – 'Orthogonal' GECOSAX

- One disadvantage and one advantage:
- Disadvantage : Need to detect faint extended source filling FOV rather than Sun-centred point source.
- Advantage : For XMM-Newton in elliptical HEO, conversion X-ray intensity is seasonally modulated (period ~1yr) by virtue of the changing visibility of the sunward magnetic field region.
  - Earth's magnetotail always away from Sun
  - satellite orbit 'fixed' in inertial space

Predicted Axion conversion X-ray signal

Analytical model of geomagnetic field plus XMM 2000-2012 orbit ephemeris
- predict seasonal variation of conversion X-ray intensity.



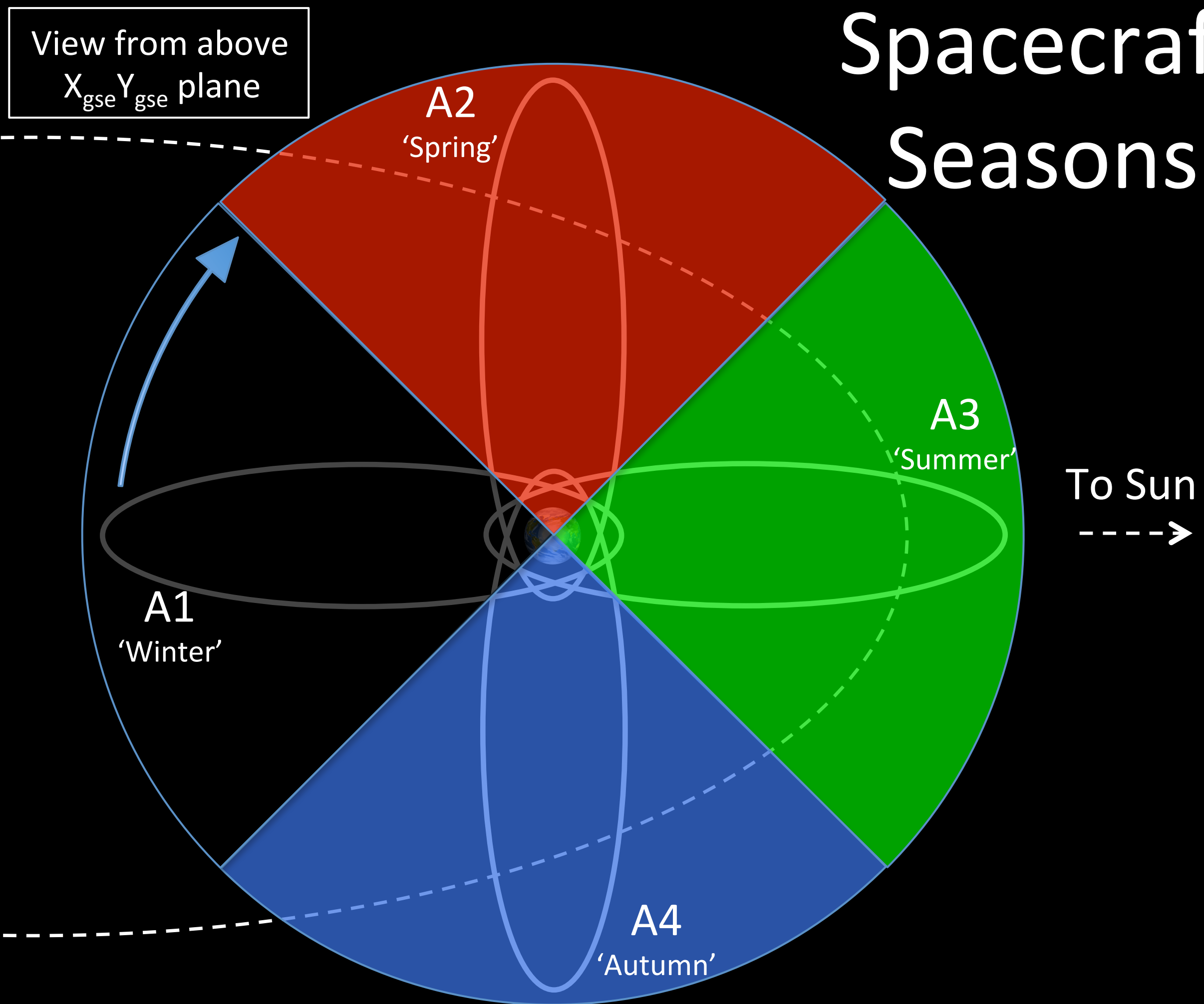


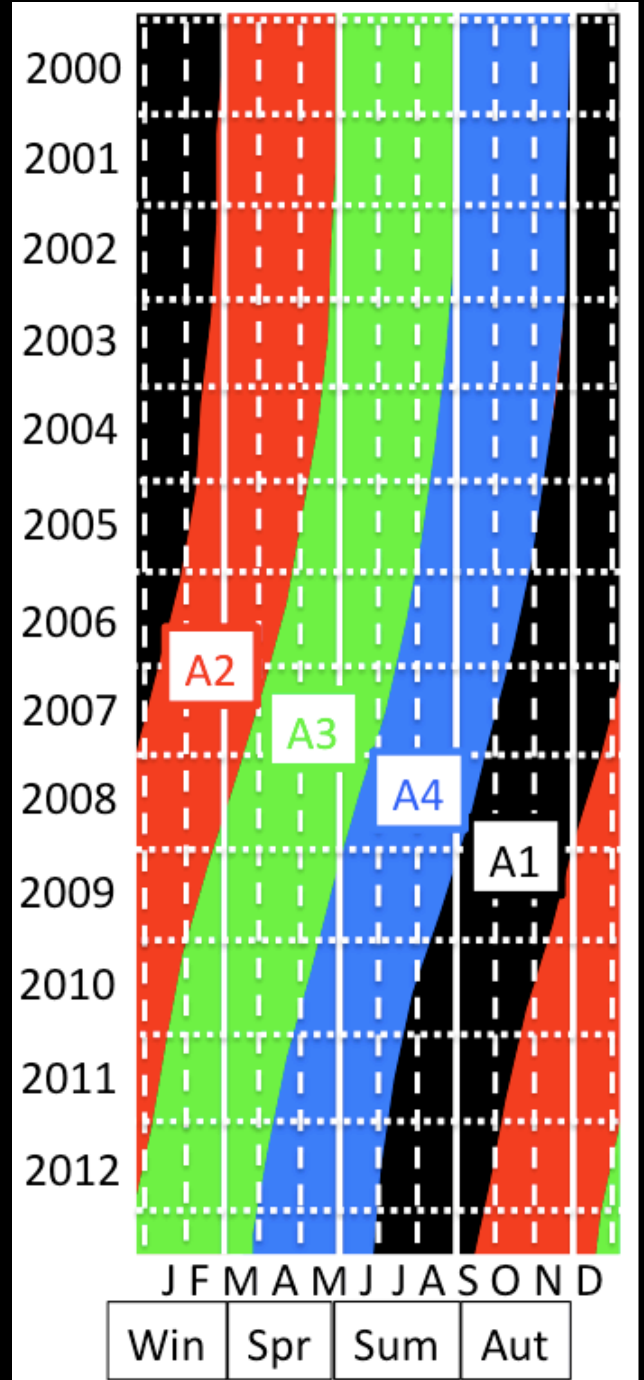
Mission-start: A broad Winter/ Spring minimum is predicted.

Mission-mid: A strong Autumn peak and a Winter minimum is predicted.

- Complex and varying S-profiles, depending on projections of (evolving) orbit
- Generally, axion flux is predicted to be low in winter and high in summer/autumn
- A complication : these seasons 'move'…

Spacecraft Seasons





- Orbit evolution means spacecraft seasons vary from ~1/4 to <1/4 of year, and lag through the year
- Subsequent use of spacecraft seasons A1-A4 in analysis, rather than true seasons, avoids long-term blurring of the geometries and maximises sensitivity to a modulated signal.

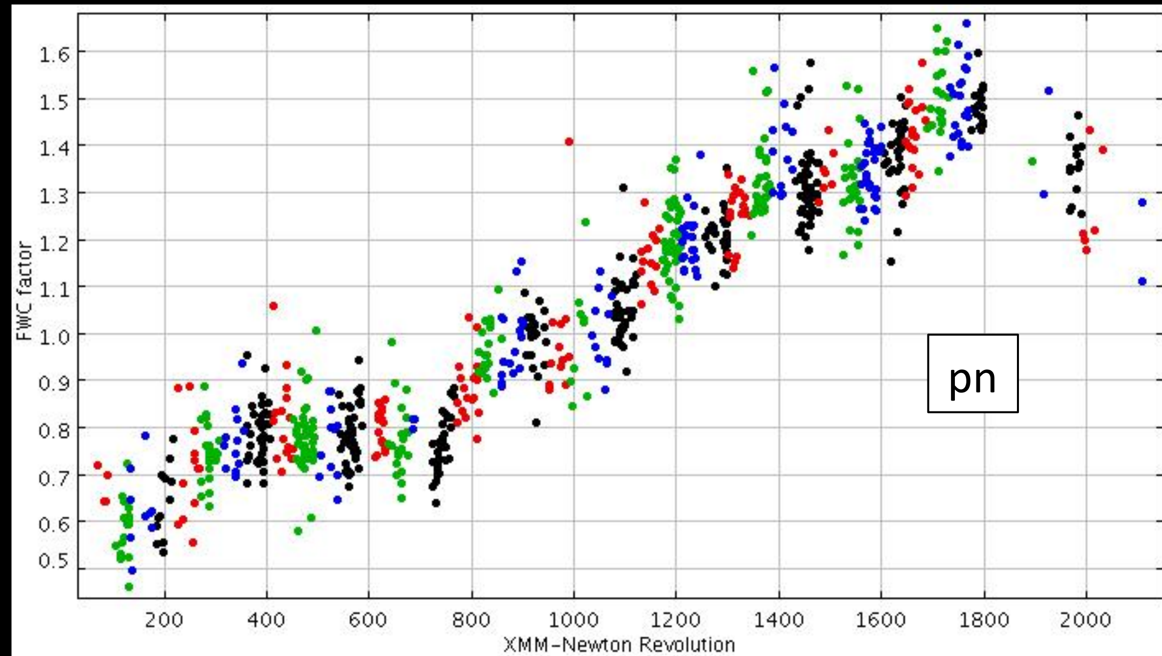
X-ray Analysis (summary)

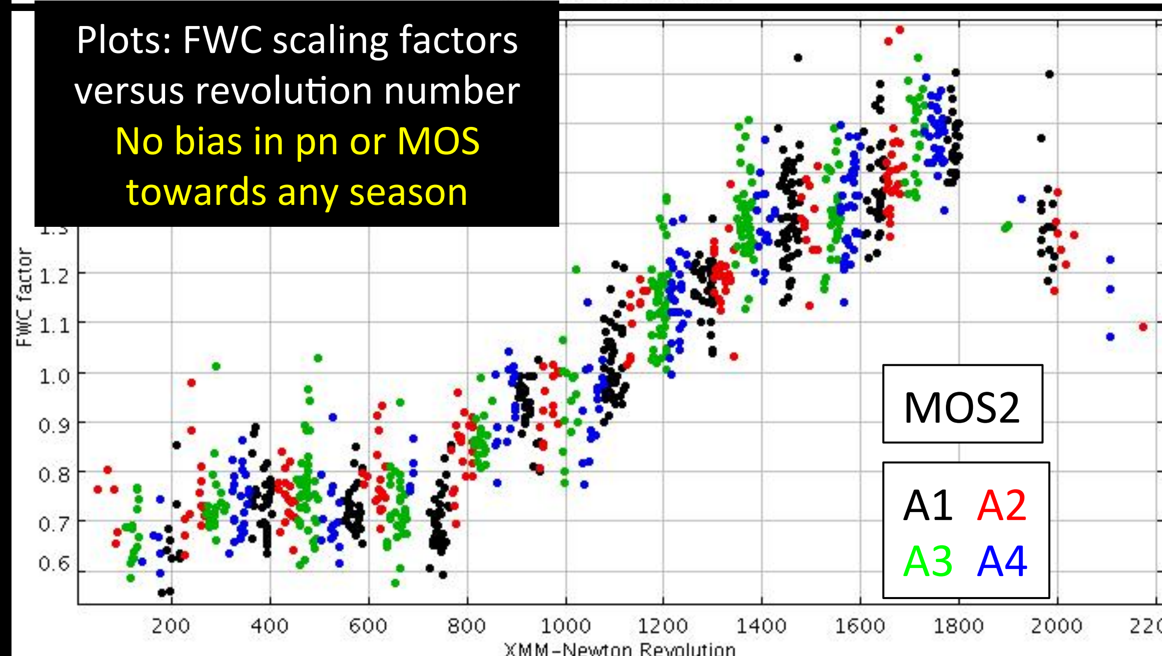
- Entire EPIC pn & MOS database 2000-2012 analysed using Blank Sky (+) protocols of Carter & Read (2007)
- FF mode only, Galactic plane (|b|<10°) excluded
- Primary analysis in 2-6 keV band
  - Allows use of all three filters
  - Effectively excludes sources of soft X-ray diffuse emission - Local Bubble, WHIM , SWCX.
  - Avoids strong instrumental lines in pn and MOS
- Within Blank-Sky analysis:
  - Point sources systematically removed, and holes filled in on an event-by-event basis
  - Each event file filtered to remove periods of high background 'flaring', due to soft protons (SPs)
  - Visual inspection+screening of all files – no contamination (point, diffuse, bright wings, single reflections etc)
- Second, more rigorous removal of residual SP contamination : (2-12 keV full-FOV light curve & Gauss.Clip.)
  - Further visual inspections of all light curves and histograms – all non-clean behaviour removed.
- ~17% of available FF files retained and only ~6% of possible exposure time.
- Final products : Four stacked X-ray spectra, one for each spacecraft season (integrated over 2000-2012)
  - Plus associated with each, a correctly-scaled instrumental BG spectrum
  - Response files created using standard SAS tools.
- pn & MOS2 all revolutions, MOS1 up to rev.961 (March 2005; CCD6 loss – response issues, FWC scaling)
- Apart from final segregation of files into S/C seasons, data reduction methods follow standard procedures.
  - Nothing presumes any feature of the solar axion conversion model
- Can then look at variation of spectra with S/C season A1, A2, A3, A4… First, some diagnostics…

Cosmic-ray induced Background

Calculated by comparing hi-energy (i.e. 9-12 keV [pn] , 10-11.2 keV [MOS]), out-FOV flux with that from Filter Wheel Closed (FWC) files.

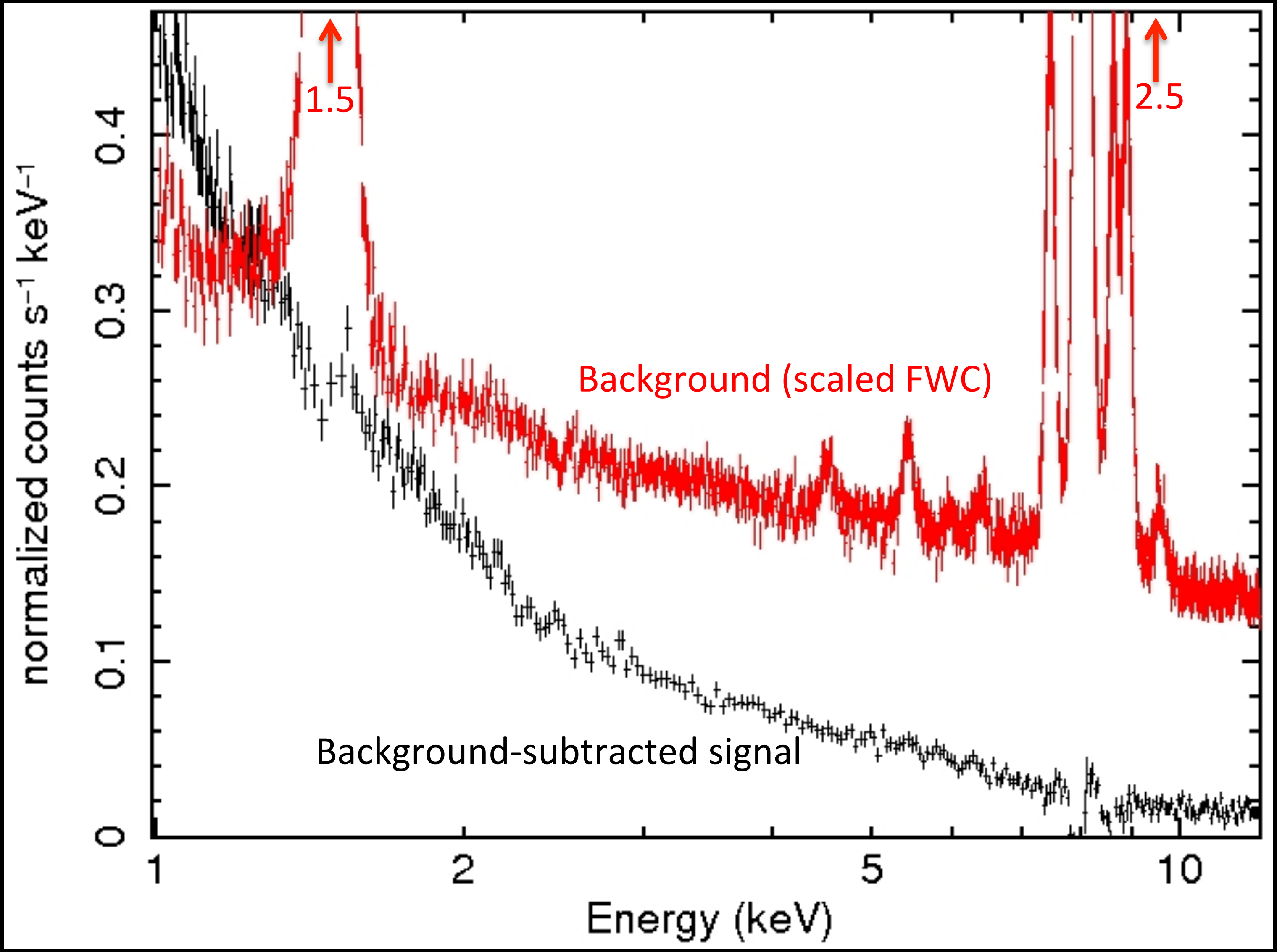
For all cameras, datasets for seasons A1-A4 follow a common curve –
peaks around 2009-2010 solar minimum.





Plots: FWC scaling factors versus revolution number
No bias in pn or MOS towards any season

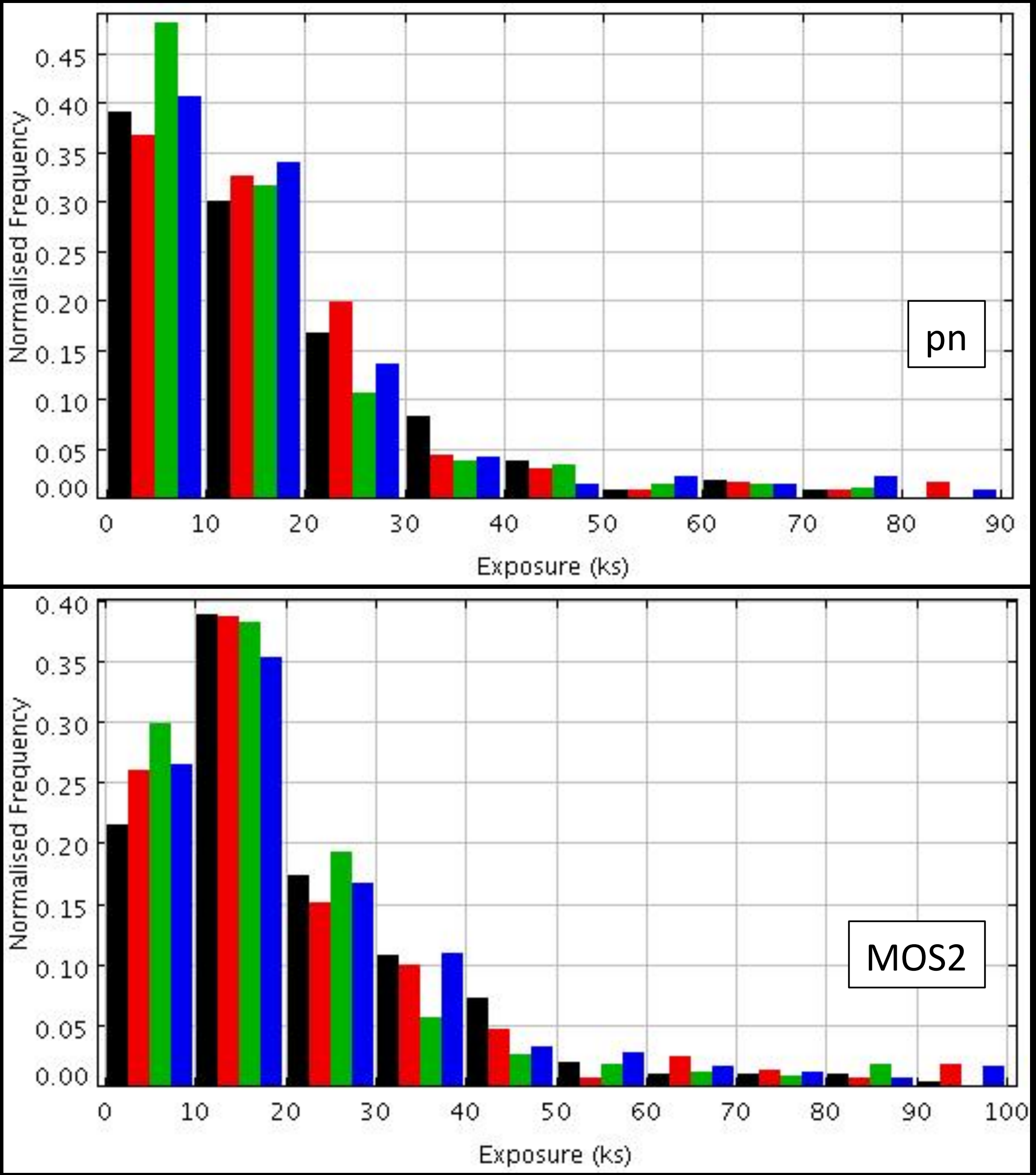
Background Subtraction



Example pn spectra: BG is way in excess of source signal, but BG-subtraction is very good

Exposure Times

Distribution of exposure time for the 4 spacecraft seasons A1-A4 – very consistent across seasons - Implies a seasonally-independent flux distribution for the removed point sources in each camera

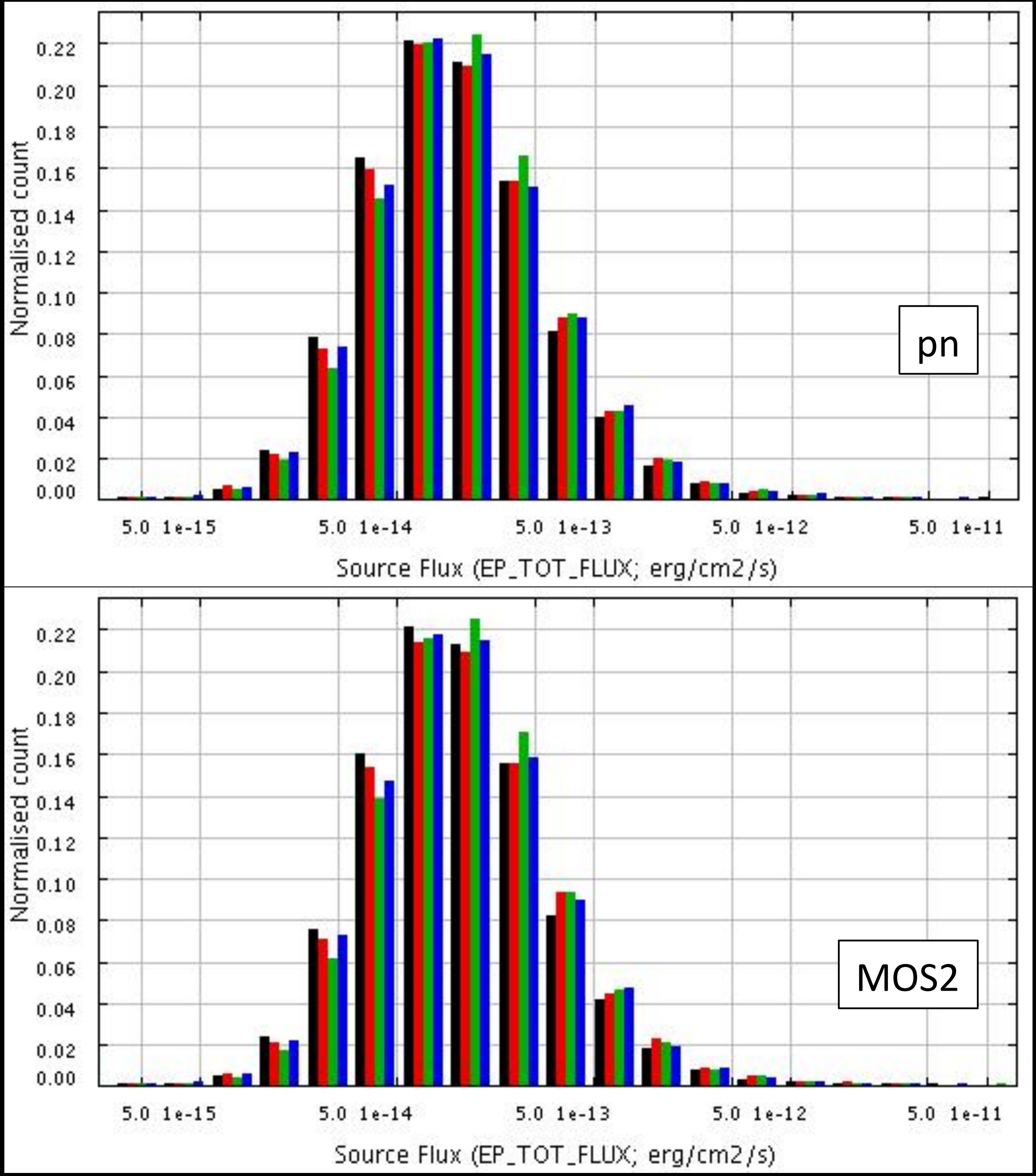


A1 A2
A3 A4

Removed Source Flux

This is seen :

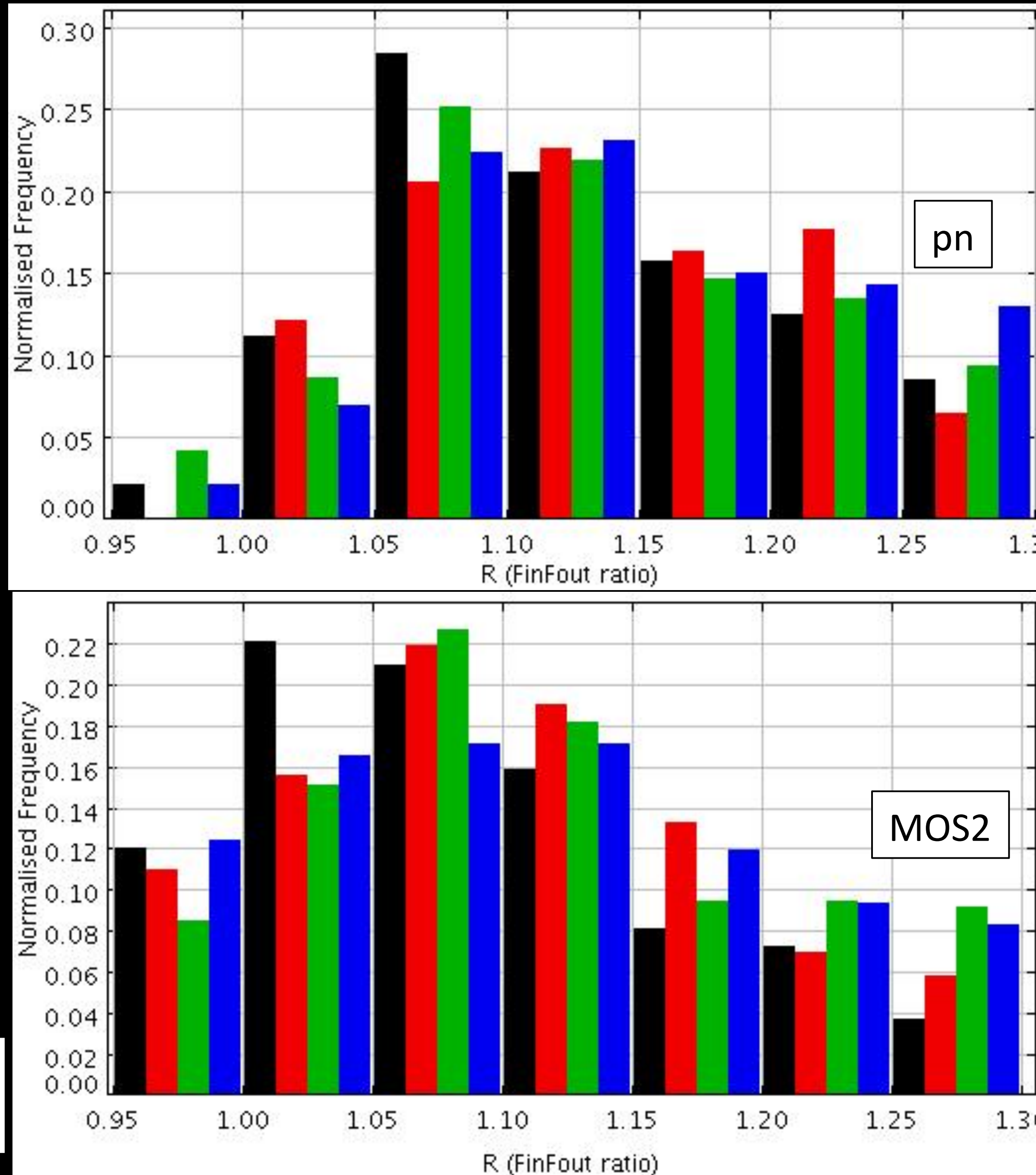
Distribution of removed point source fluxes for the 4 spacecraft seasons A1-A4 – extremely consistent across seasons



A1 A2
A3 A4

Residual Soft Proton Contamination

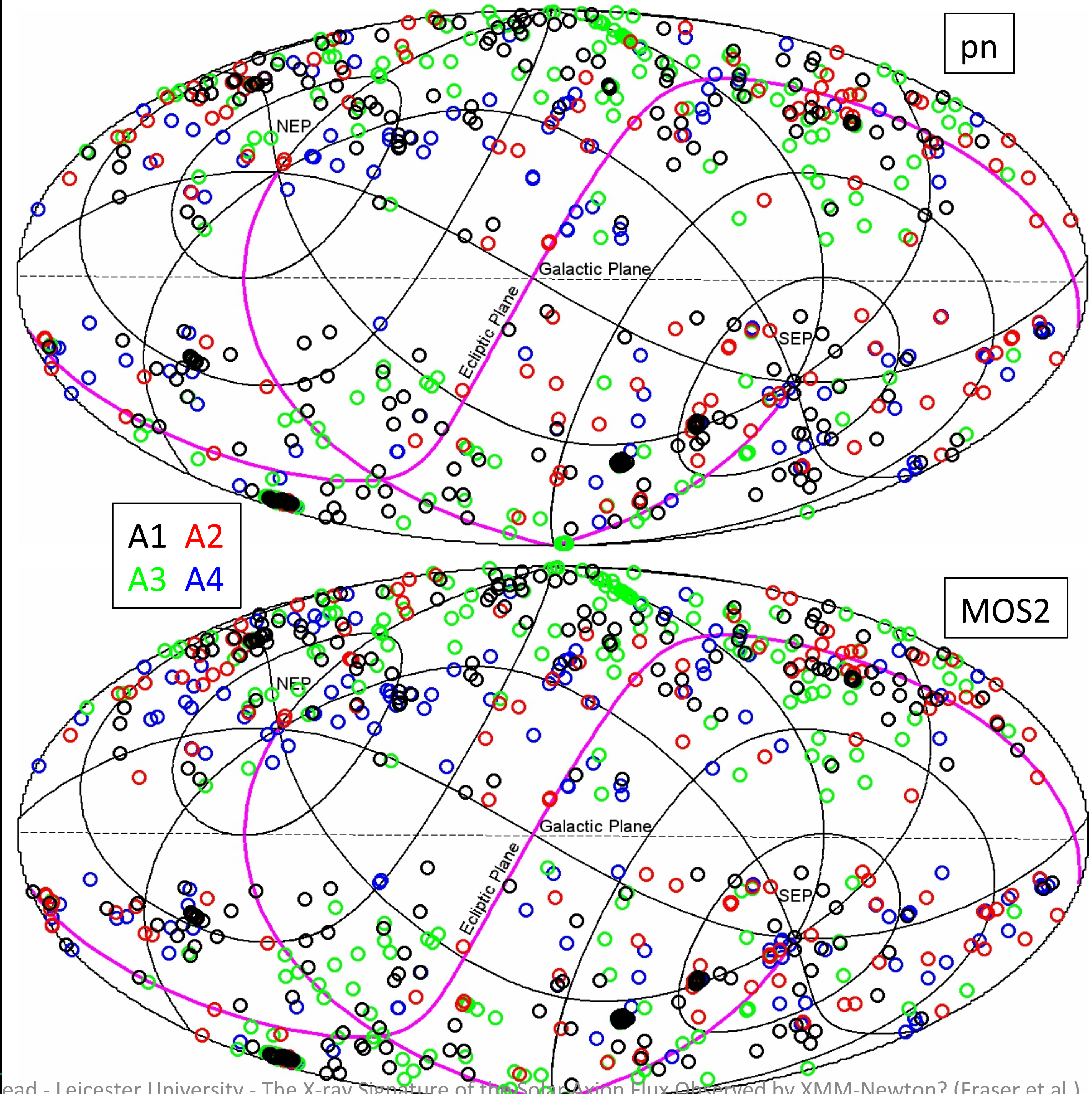
- Degree of residual Soft Proton contamination : Distributions of data files by Flux in – flux out *R* value (de Luca & Molendi 2004).
- *R* <1.3 is regarded as conservative.
- Degree of residual SP contamination is (a) small and (b) consistent across spacecraft seasons A1-A4



A1 A2
A3 A4

Sky Distributions

- Sky distributions of A1-A4 observations.
- No preferential concentration of fields towards galactic plane/poles, or towards any known large-scale massive structures

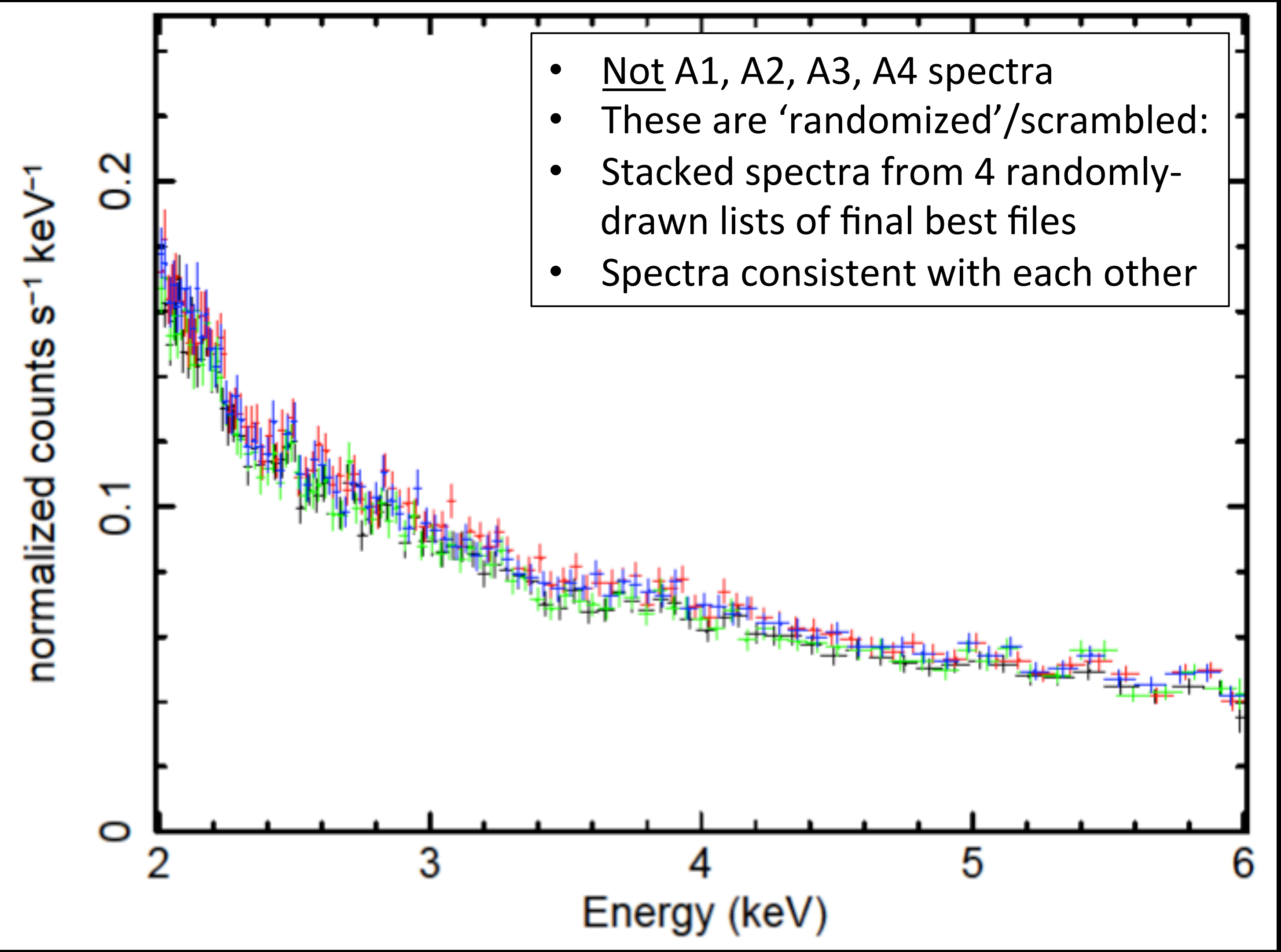


Diagnostics Summary

- Data are very consistent across spacecraft seasons A1-A4

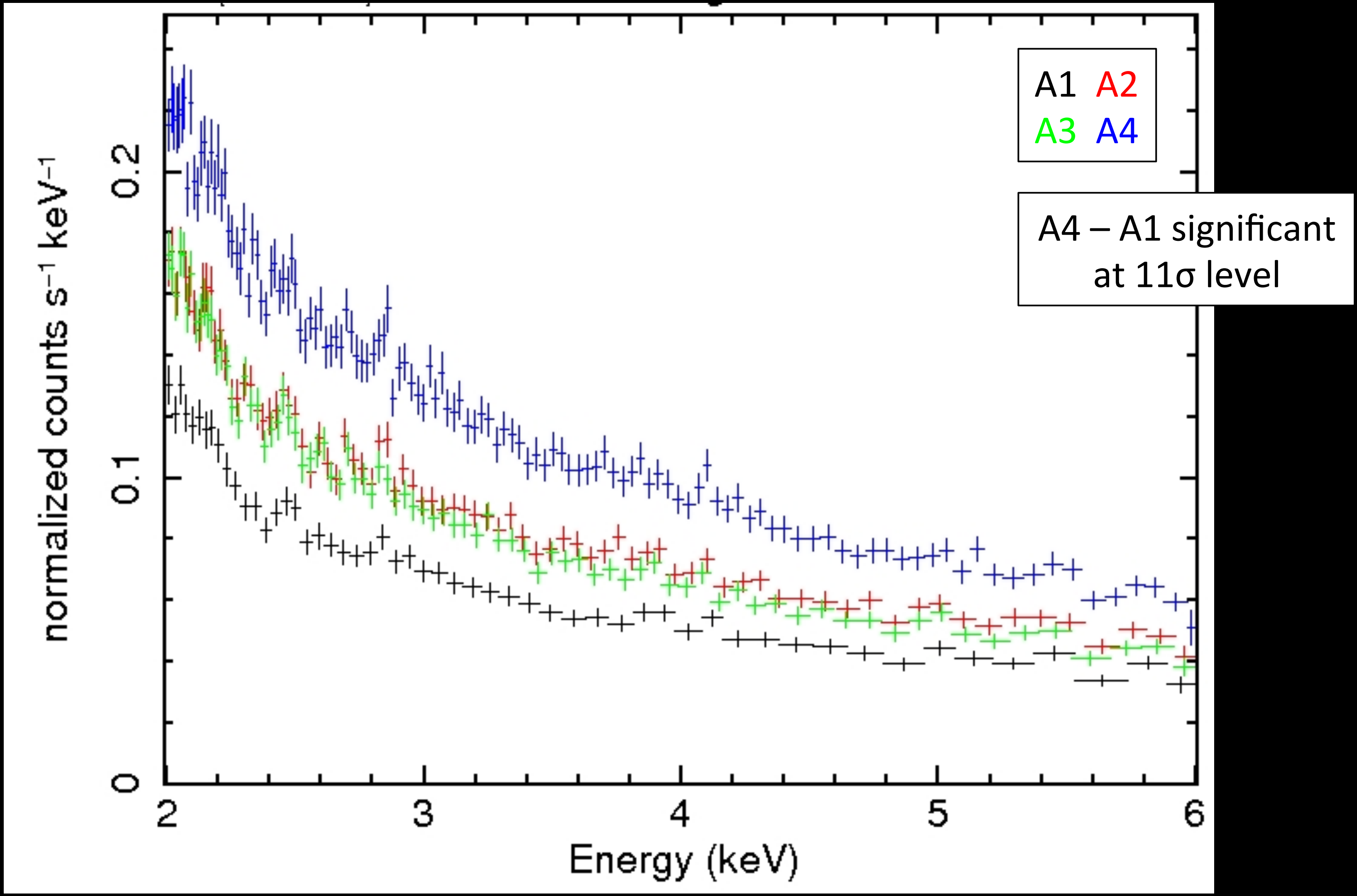
- Cosmic ray induced BG
  - No bias in MOS or pn towards any season
- Exposure times
  - Consistent across seasons
- Removed source flux
  - Consistent across seasons
- Residual soft proton (SP) contamination
  - Small
  - Consistent across seasons
- Sky distributions
  - No preferential concentrations towards planes, poles, large-scale structures

Results – pn



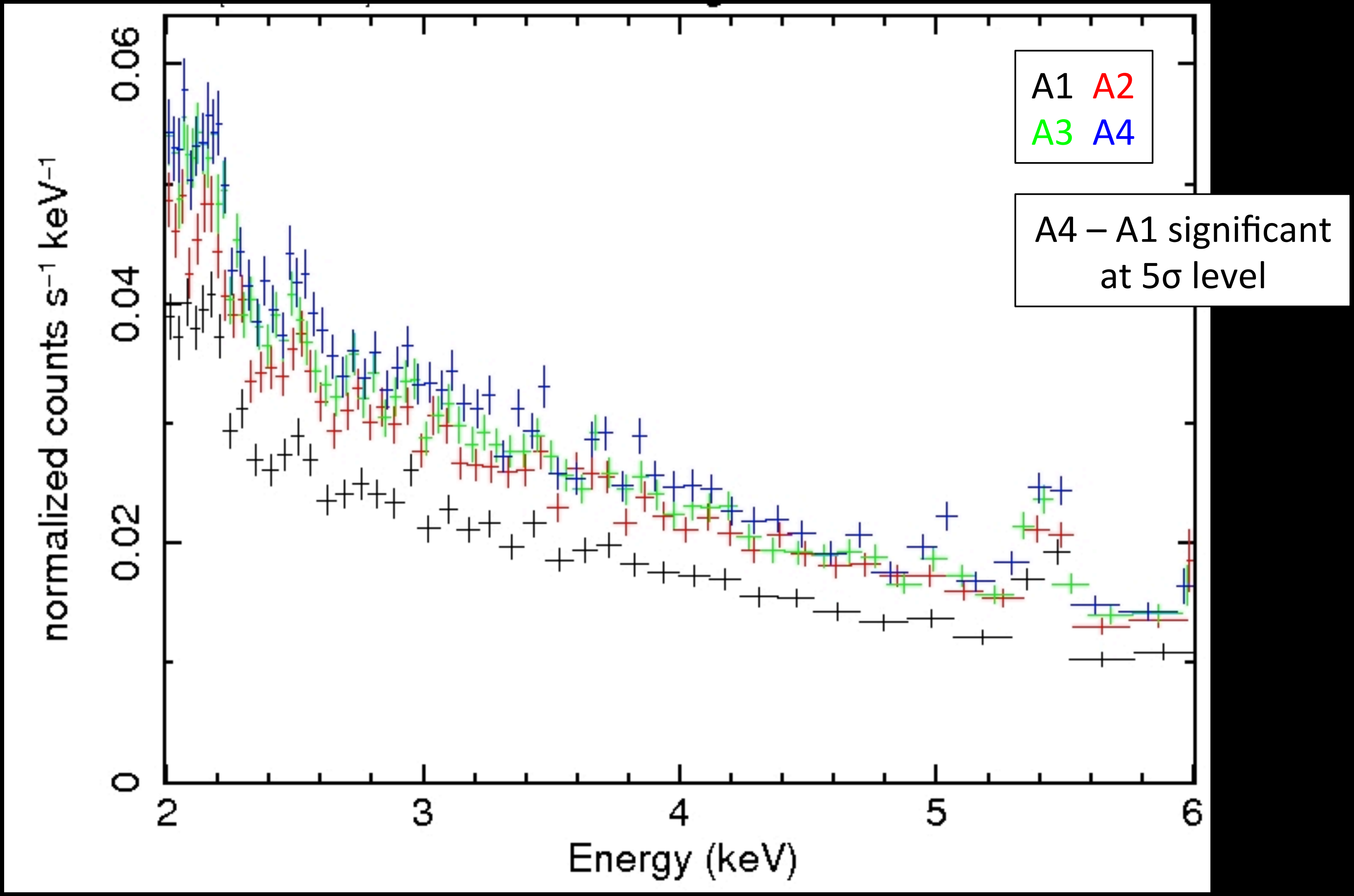
- Not A1, A2, A3, A4 spectra
- These are 'randomized'/scrambled:
- Stacked spectra from 4 randomly-drawn lists of final best files
- Spectra consistent with each other

Results – pn



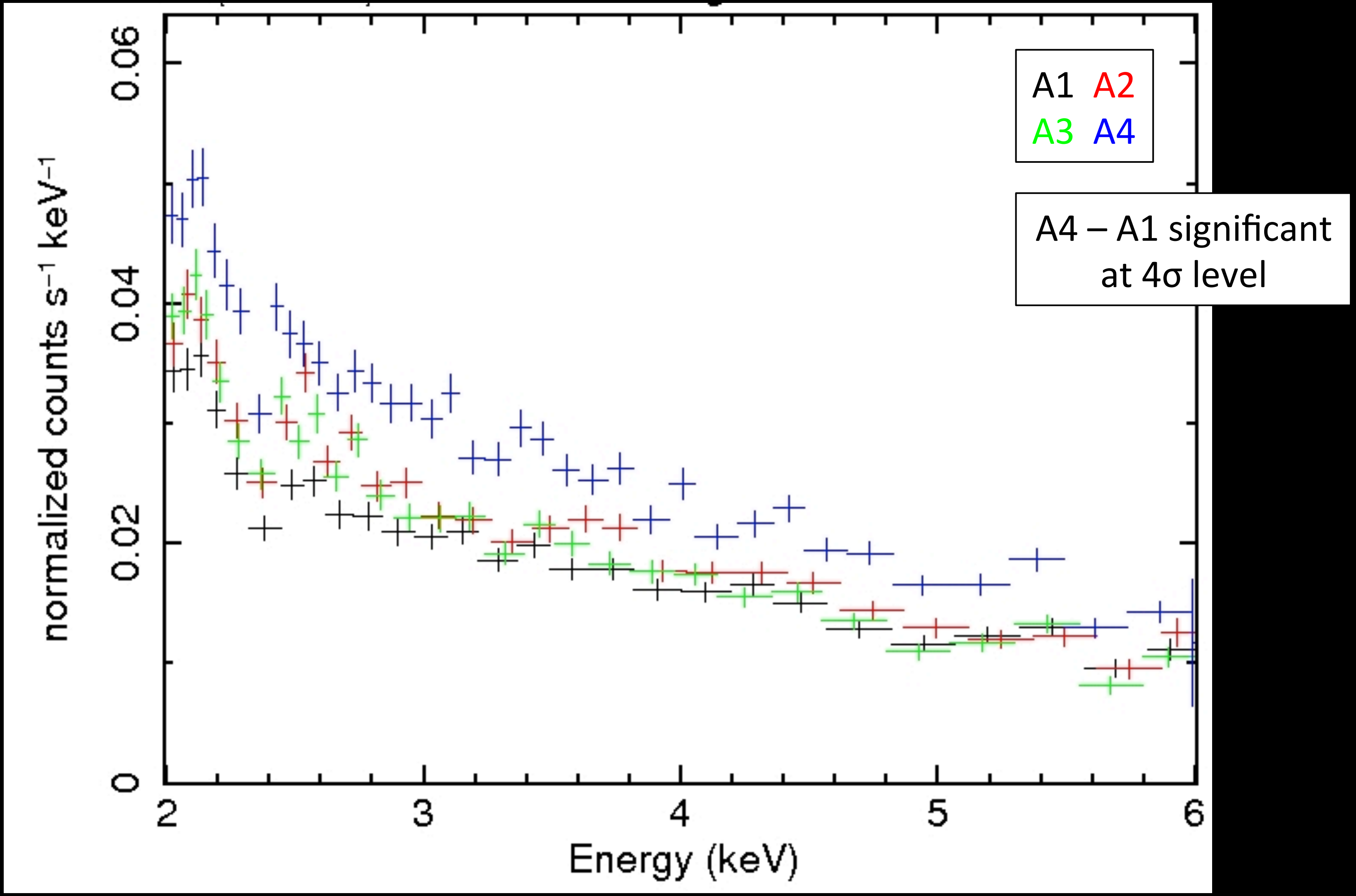
A1 (‘winter’) lies significantly below the others, with A4 (‘autumn’) significanly above.
A4-A1 difference ~4.6 x 10^{-12} erg.$cm^{-2}s^{-1}deg^{-2}$

Results – MOS2



A1 ('winter') lies significantly below the others. A4 ~ highest.
Statistics slightly poorer.

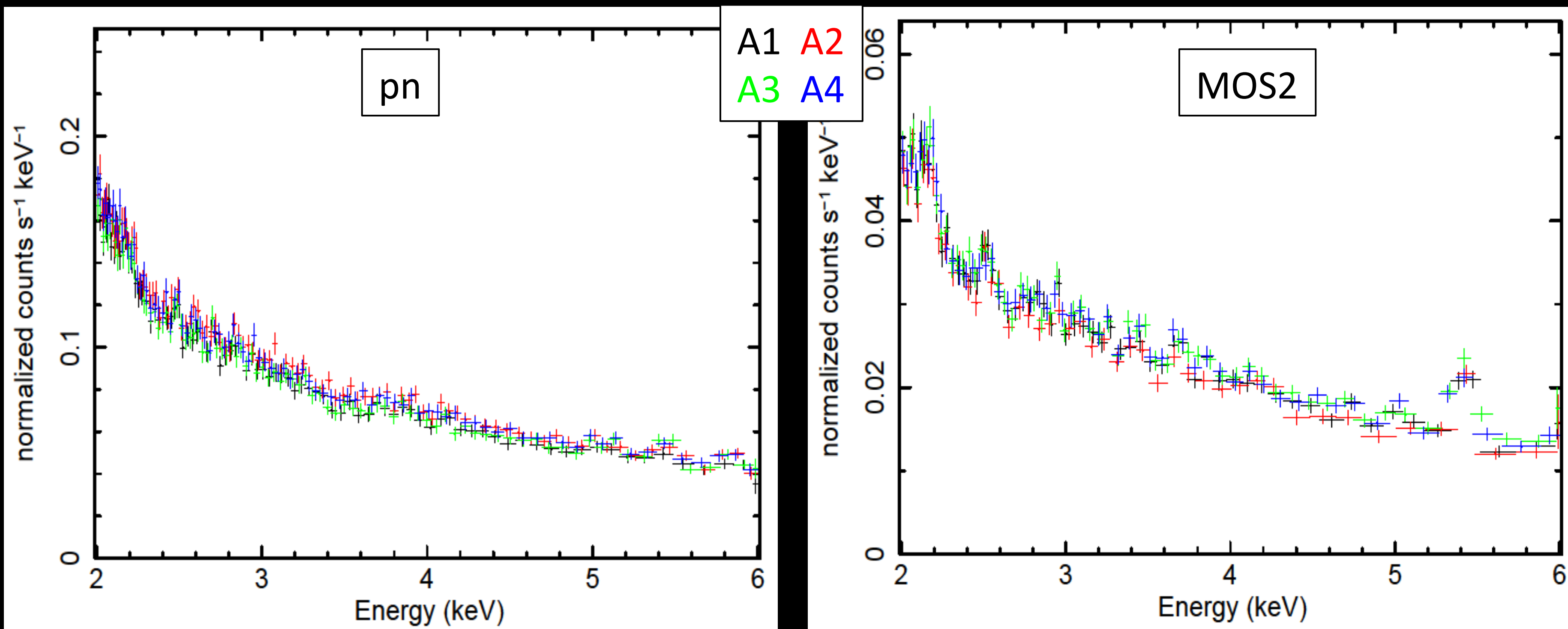
Results – MOS1



A1 ('winter') lies ~below the others, with A4 ('autumn') significanly above.

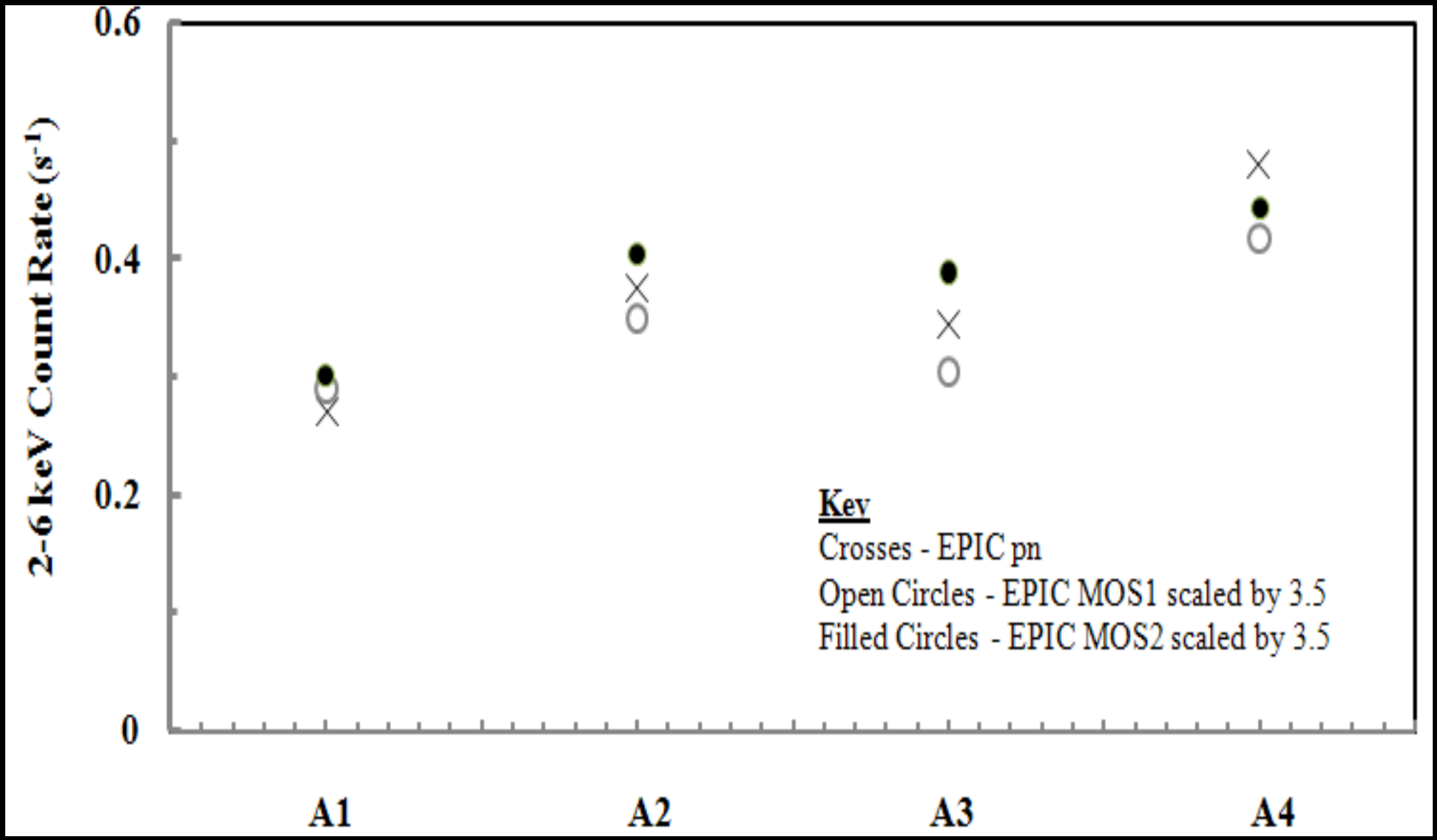
Statistics poorer still. MOS1-MOS2 : Suggestive also of yearly behaviour not repeating exactly.

Results – Randomized Datasets



- Randomly assigning the same observation files in lists A1-A4 to four new lists (A1*-A4*), each containing the same number of files as the original A1–A4
- No differences between the randomized spectra.

Results – All-EPIC

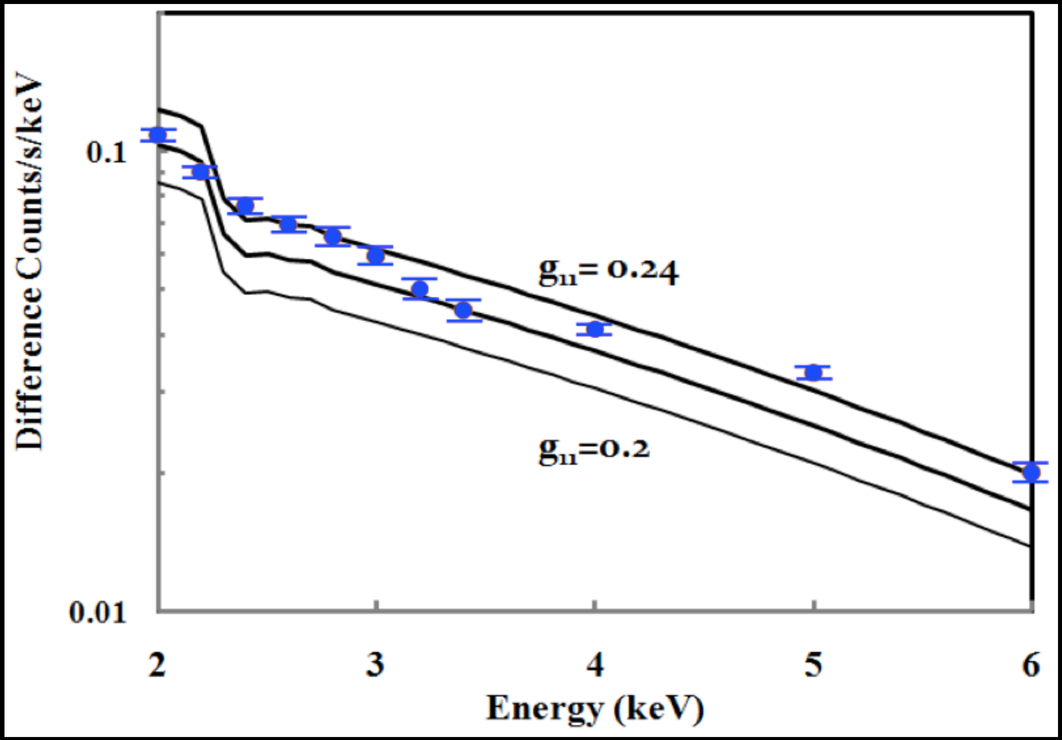


(error bars of order symbol size).

- A scaling factor (3.5:1) applied to MOS1 & MOS2 count rates minimises overall variance between camera/season combinations
- This consistent with the X-ray photon grasps of the EPIC instruments – Supports hypothesis that variable BG arises from external X-ray source that responds to the photon grasp (rather than the proton grasp)

Derived Axion Properties

- Blue symbols : EPIC pn difference spectrum (A4 – A1)
- Lines : axion conversion spectra (Primakoff + Compton + Bremsstrahlung) for different values of axion-electron coupling constant.



- @2keV constrains value of axion-electron coupling constant : $g_{11} \sim 0.22 \pm 0.02$
- If axion-photon coupling constant g_{10} unity (CAST), then product of coupling constants : $g_{ae}\, g_{a\gamma} = 2.2e^{-22}$ GeV^{-1} (within factor ~2 of CAST value; Barth+ 2013)

- Constrain axion mass: maximum sensitivity for $m_a = 2.3e^{-6}$ eV (a lower limit, given inhomogeneity in Earth's field) – at lower end of allowed axion mass range : $10^{-6} – 10^{-3}$ eV ; from ground-based searches and observations of astrophysical objects + Sun (Chelouche+ 2009)

No time here for... :

- Seasonal dependence of CXB normalization in past XMM-Newton surveys (observed)
- North/South asymmetry (predicted & observed)
- Alternative mechanisms, including soft protons (rejected)
- Axionic line features (observed)
- Other X-ray Observatories

Concluding Remarks

- Seasonally-varying component of X-ray background is observed in all three XMM-Newton EPIC instruments; seasonal difference significant at 11σ (pn), 4σ (MOS1), 5σ (MOS2) levels.
- No conventional explanation, but consistent with discovery of the predicted axion – a dark matter particle candidate :
  - Appears plausible that axions are produced in solar core and convert to soft X-rays in magnetic field of Earth, giving rise to a significant, seasonally-variable component of the X-ray BG.
  - This, together with north-south anisotropy and TBC axionic line features would raise the bar against competing explanations.
- Implications not only for our understanding of true CXB, but also for identification of galactic cold dark matter (CDM).
  - An axion mass in 10 μeV range is sufficient, for a non-thermal dark matter axion population, to account for entire galactic CDM density (Raffelt 2007).