ASI Symposium 003 - Cosmic Vision 2047:
Solar and Planetary Dynamics through Observations and AI/ML

JECRC University Jaipur

Confined vs. Eruptive Solar Flares: A Thermal and Compositional Diagnostic Study with Aditya-L1/SoLEXS

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Outline of the Talk

- Introduction
- Instrument Specification and Data products
- Event Selection and Description
- Methodology
- Results
- Summary

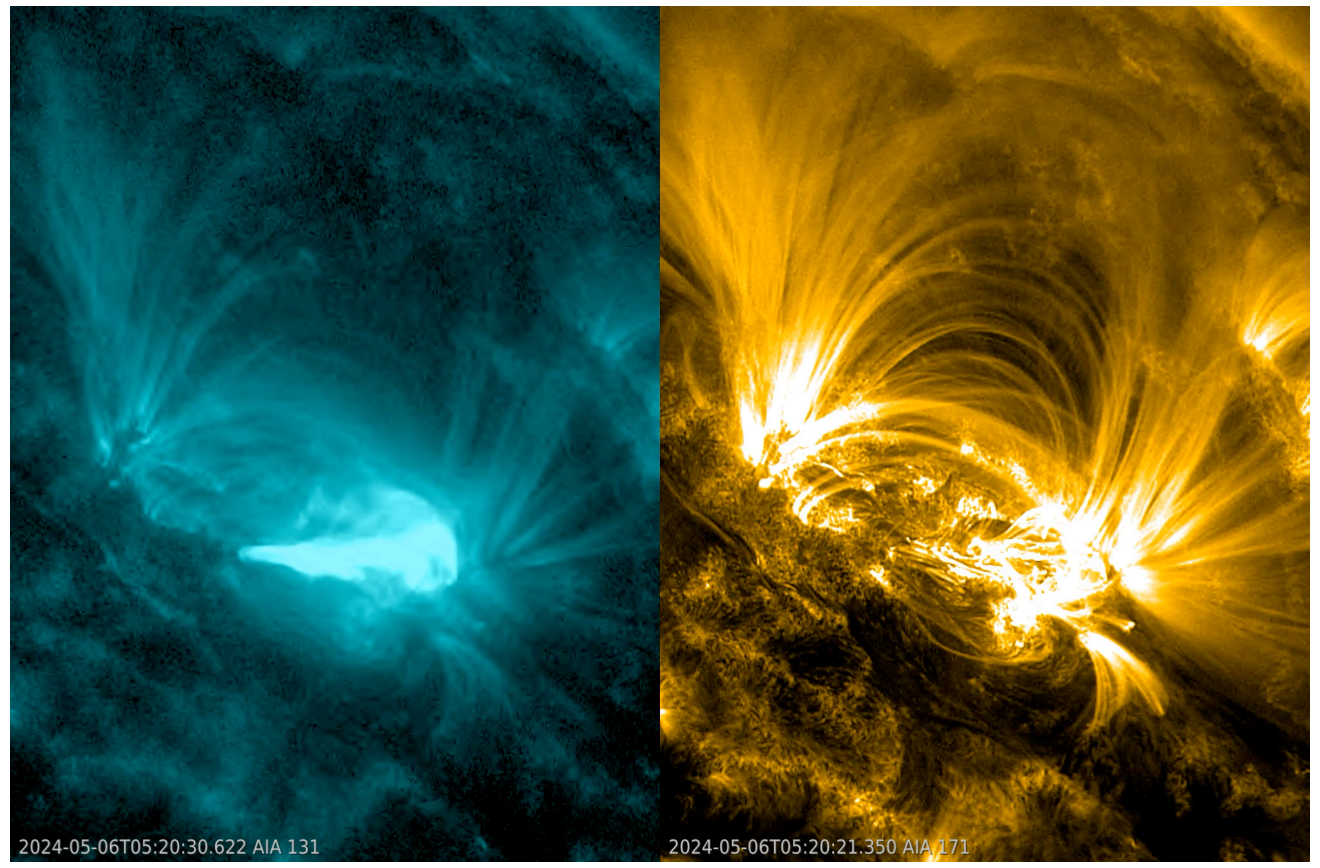
Solar Flares

A solar flare is a **sudden, intense burst of radiation** coming from the release of magnetic energy in the Sun's atmosphere.

Classification

Confined

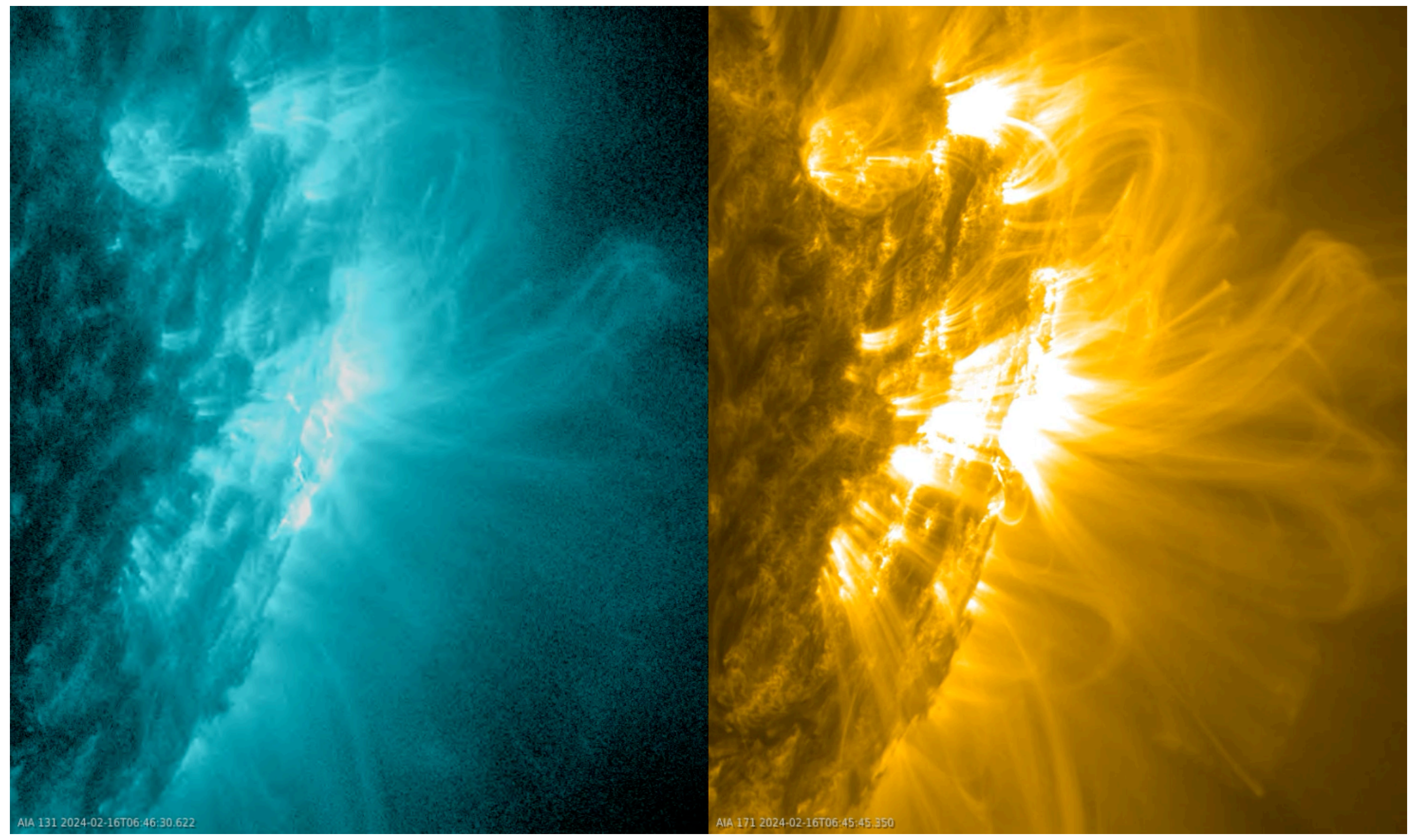
Magnetic structure remains intact and no significant plasma is ejected into interplanetary space **(No CME)**



Solar Flare on 6 May 2024 in two different AIA channels 131Å and 171Å. *Credit: Jhelioviewer*

Eruptive

Where large amounts of plasma and magnetic flux are expelled from the Sun **(CME Associated)**



Solar Flare on 16 February 2024 in two different AIA channels 131Å and 171Å. *Credit: Jhelioviewer*

Flare Class	Associated X-ray Flux (W/m^2)
A	$< 10^{-7}$
B	10^{-7} - 10^{-6}
C	10^{-6} - 10^{-5}
M	10^{-5} - 10^{-4}
X	$> 10^{-4}$

A Class Flare - Weakest

X Class Flare - Strongest

Instrument

SoLEXS Specification

Solar Low Energy X-ray Spectrometer

Table 1: Specifications of SoLEXS

Parameter	Specification
Energy Range	2 – 22 keV (2.8 – 22 keV for spectral fitting)[1]
Energy Resolution	∼ 170 eV @ 5.9 keV
Time Cadence	Spectral Channel: 1 second Temporal Channel: 1 second
Detector	
Type Number Active Area Thickness Entrance Window	Silicon Drift Detector (SDD) 2 (named SDD1 & SDD2) 30 mm^2 450 ± 20 μm 8 μm thick Be
Aperture Area	SDD1: 7.106 mm^2 SDD2: 0.106 mm^2
Field of View	SDD1: ± 1.8° SDD2: ± 1.3°
Calibration Source	Fe-55 with Ti foil
Digital Pulse Processing parameters	
Pulse peaking time (triangular pulse)	Spectral Channel: 2 μs Temporal Channel: 0.35 μs
Number of channels in the spectrum	340
Channel Width	1 - 168 channel: ∼ 47.6 eV 169 - 340 channel: ∼ 95.2 eV

Solar Minima

Solar Maxima

- Sun as a Star Spectrometer
- Energy Range - **2 - 22 KeV**
- Uses **Silicon Drift Detector (SDD)** for precise X-ray energy detection.

Image Credit: ISRO

SoLEXS

Data Products

1. **Good Time Intervals (.gti) Files:** Time periods when the detector was operational and collecting good data.

2. **Light Curve (.lc) Files:** 1-second-cadence count rates (2–22 keV) over a day.

3. **Pulse Invariant (.pi) Files:** Calibrated energy spectra recorded every second over a day.

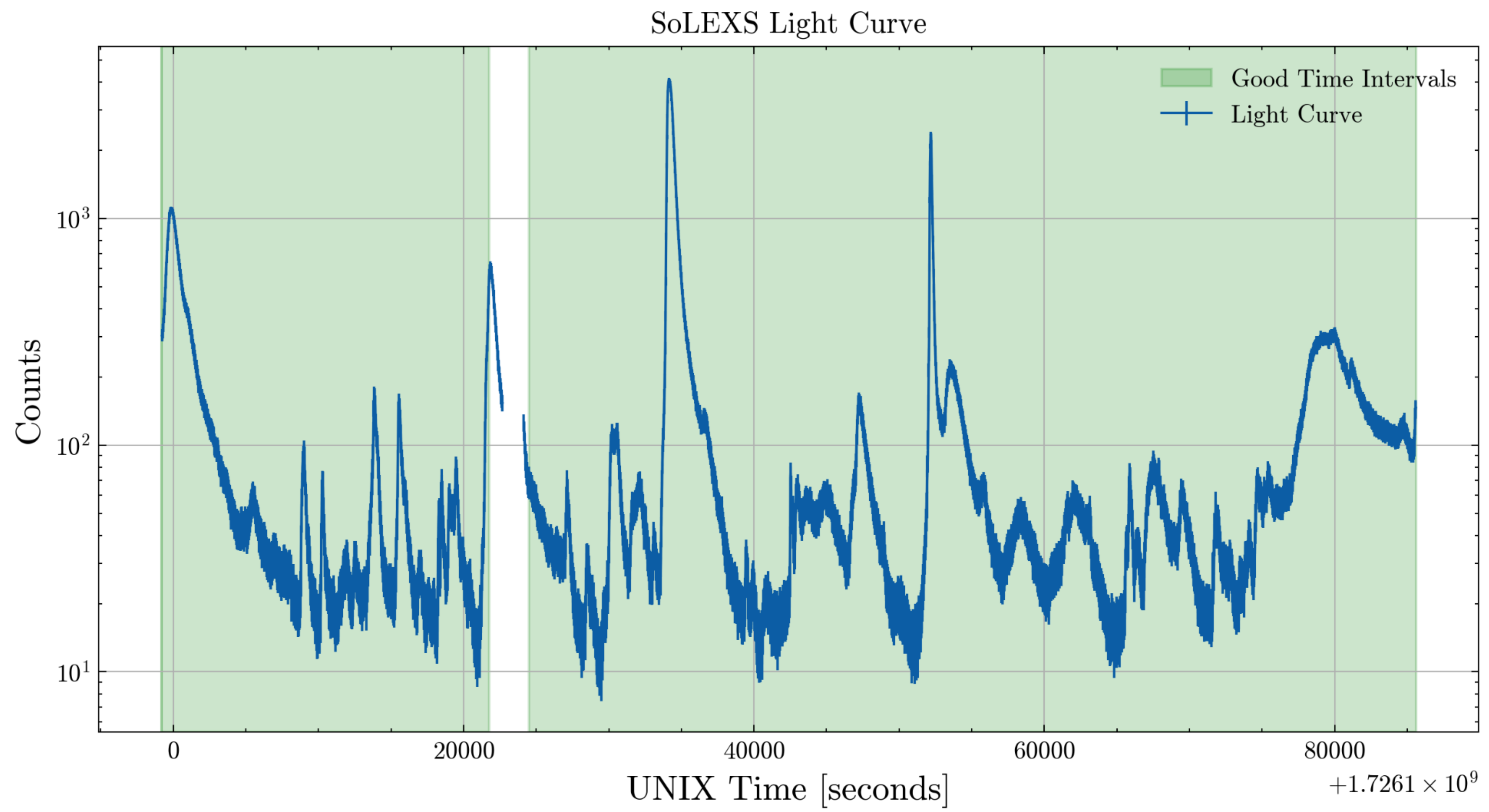


Figure 1: GTIs identified in SoLEXS observations for a single day.

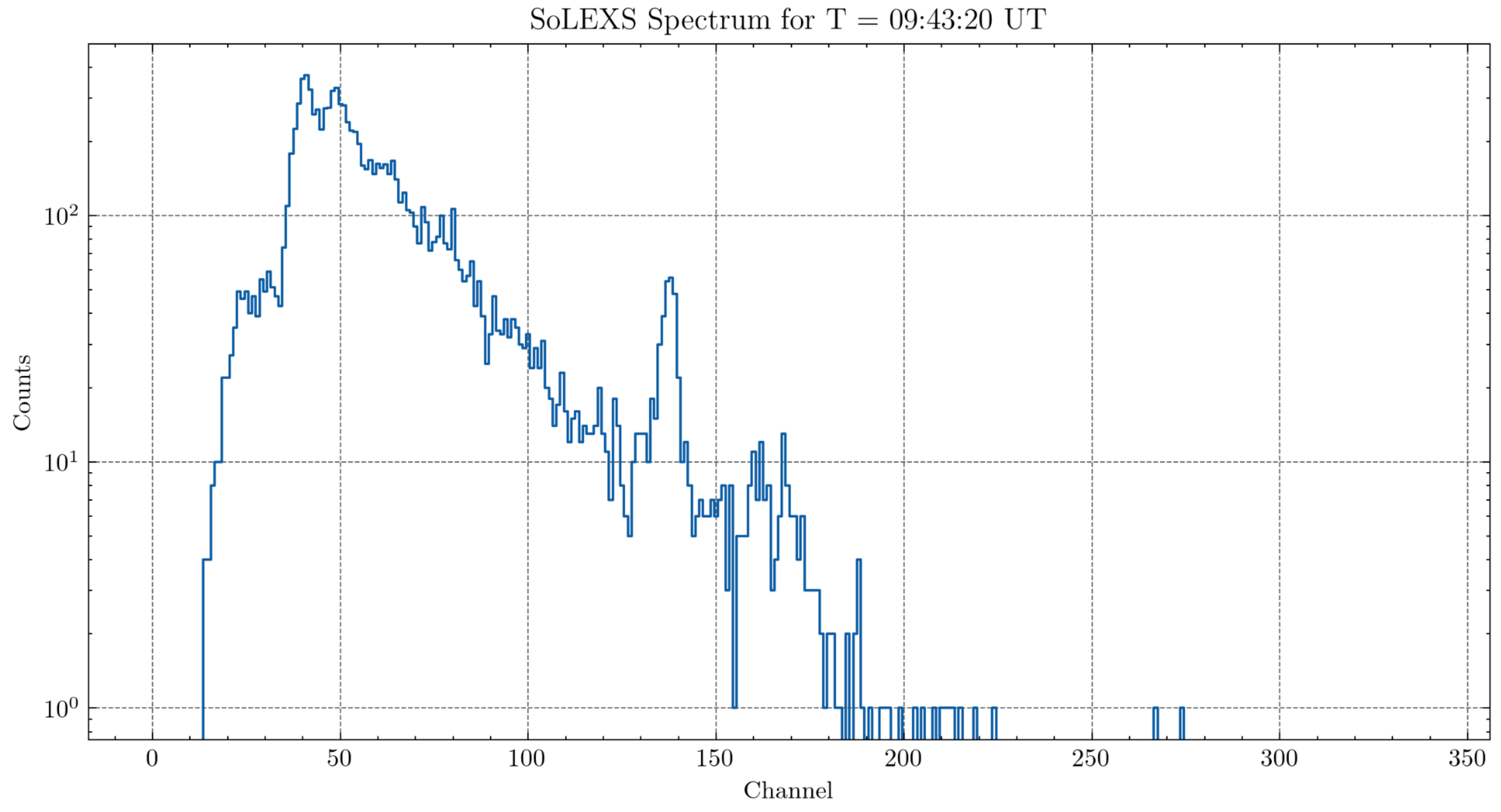


Figure 2: Spectrum at a selected time from SoLEXS data.

Aim of the Study

Primary Goal: To conduct a comparative X-ray analysis of solar flares across different classes (C, M, and X) to identify and quantify their distinct physical characteristics.

- Derive fundamental plasma parameters for each Flare event:
  1. **Plasma Temperature (T)**
  2. **Emission Measure (EM)**
  3. **Elemental Abundance (A_x)**
- Analyze **temporal evolution** of these parameters across the flares.
- To investigate the physical differences between **confined (no CME)** and **eruptive (with CME) solar flares**.
- Draw conclusions about different Flare Class events using SoLEXS data.

Dataset
Event Selection and Description

Event Selection Criteria -

- **Flare identification**
  - Selected events from the **GOES Flare Catalog**
  - Time period: **1 July 2024 – 31 July 2025**
- **Verification**
  - Cross-checked with **SoLEXS X-ray light curves**
- **CME association**
  - Identified using the **SOHO/LASCO CME catalog**

Total Flares analyzed: 43 (July 2024 – July 2025)

Flare Class	Eruptive	Confined	Total
C-class	4	4	8
M-class	16	8	24
X-class	10	1	11
Total	**30**	**13**	**43**

Most X-class Flares are Eruptive (CME-associated) !!

Methodology

- ## Data Processing:

Used **SoLEXS_Tools** to create light curves and define flare phases (rise, peak, decay)

- ## Spectral Extraction:

Spectral File were generated for each Flare using **solexs-genmultispec**. Time bin intervals were optimized ensure a high signal-to-noise ratio and goodness of fit.

- ## Spectral Fitting:

Spectra were fitted within **PyXSPEC** using Chianti Isothermal Model (**chisoth**). The analysis was restricted to the **2.8–15 keV** energy range to maximize spectral feature sensitivity.

- ## Free Parameters:

Temperature, Emission Measure, and **Abundances** of **Ar, Ca, Fe, Ni** are left free during fitting to capture plasma composition and thermodynamics.

Chisoth Model

Model takes - Log(T),
Elemental Abundances (A_x) (Z=2 to 30)
Emission Measure (EM)

Model par	Model comp	Component	Parameter	Unit	Value	
1	1	chisoth	logT	K	6.39000	+/- 0.0
2	1	chisoth	He		10.9000	frozen
3	1	chisoth	Li		1.64000	frozen
4	1	chisoth	Be		1.94000	frozen
5	1	chisoth	B		3.09000	frozen
6	1	chisoth	C		8.59000	frozen
7	1	chisoth	N		8.00000	frozen
8	1	chisoth	O		8.89000	frozen
9	1	chisoth	F		4.56000	frozen
10	1	chisoth	Ne		8.08000	frozen
11	1	chisoth	Na		6.93000	frozen
12	1	chisoth	Mg		8.15000	frozen
13	1	chisoth	Al		7.04000	frozen
14	1	chisoth	Si		8.10000	frozen
15	1	chisoth	P		5.45000	frozen
16	1	chisoth	S		7.27000	frozen
17	1	chisoth	Cl		5.50000	frozen
18	1	chisoth	Ar		6.58000	frozen
19	1	chisoth	K		5.67000	frozen
20	1	chisoth	Ca		6.93000	frozen
21	1	chisoth	Sc		3.71000	frozen
22	1	chisoth	Ti		5.56000	frozen
23	1	chisoth	V		4.54000	frozen
24	1	chisoth	Cr		6.21000	frozen
25	1	chisoth	Mn		5.93000	frozen
26	1	chisoth	Fe		8.10000	frozen
27	1	chisoth	Co		5.46000	frozen
28	1	chisoth	Ni		6.84000	frozen
29	1	chisoth	Cu		4.75000	frozen
30	1	chisoth	Zn		5.14000	frozen
31	1	chisoth	norm		1.00000	+/- 0.0

Parameters of the chisoth model parameters

After Fitting

Model par	Model comp	Component	Parameter	Unit	Value	
1	1	chisoth	logT	K	7.13396	+/- 4.02007E-03
2	1	chisoth	He		10.9000	frozen
3	1	chisoth	Li		1.64000	frozen
4	1	chisoth	Be		1.94000	frozen
5	1	chisoth	B		3.09000	frozen
6	1	chisoth	C		8.59000	frozen
7	1	chisoth	N		8.00000	frozen
8	1	chisoth	O		8.89000	frozen
9	1	chisoth	F		4.56000	frozen
10	1	chisoth	Ne		8.08000	frozen
11	1	chisoth	Na		6.93000	frozen
12	1	chisoth	Mg		8.15000	frozen
13	1	chisoth	Al		7.04000	frozen
14	1	chisoth	Si		8.10000	frozen
15	1	chisoth	P		5.45000	frozen
16	1	chisoth	S		7.27000	frozen
17	1	chisoth	Cl		5.50000	frozen
18	1	chisoth	Ar		6.46480	+/- 8.20094E-02
19	1	chisoth	K		5.67000	frozen
20	1	chisoth	Ca		6.68036	+/- 7.18484E-02
21	1	chisoth	Sc		3.71000	frozen
22	1	chisoth	Ti		5.56000	frozen
23	1	chisoth	V		4.54000	frozen
24	1	chisoth	Cr		6.21000	frozen
25	1	chisoth	Mn		5.93000	frozen
26	1	chisoth	Fe		7.95718	+/- 9.06158E-02
27	1	chisoth	Co		5.46000	frozen
28	1	chisoth	Ni		8.38875	+/- 0.288261
29	1	chisoth	Cu		4.75000	frozen
30	1	chisoth	Zn		5.14000	frozen
31	1	chisoth	norm		1443.05	+/- 200.068

Parameters of the chisoth model parameters after fitting and unfreezing abundances

Spectral Fitting

Using XSPEC and Chisoth Model

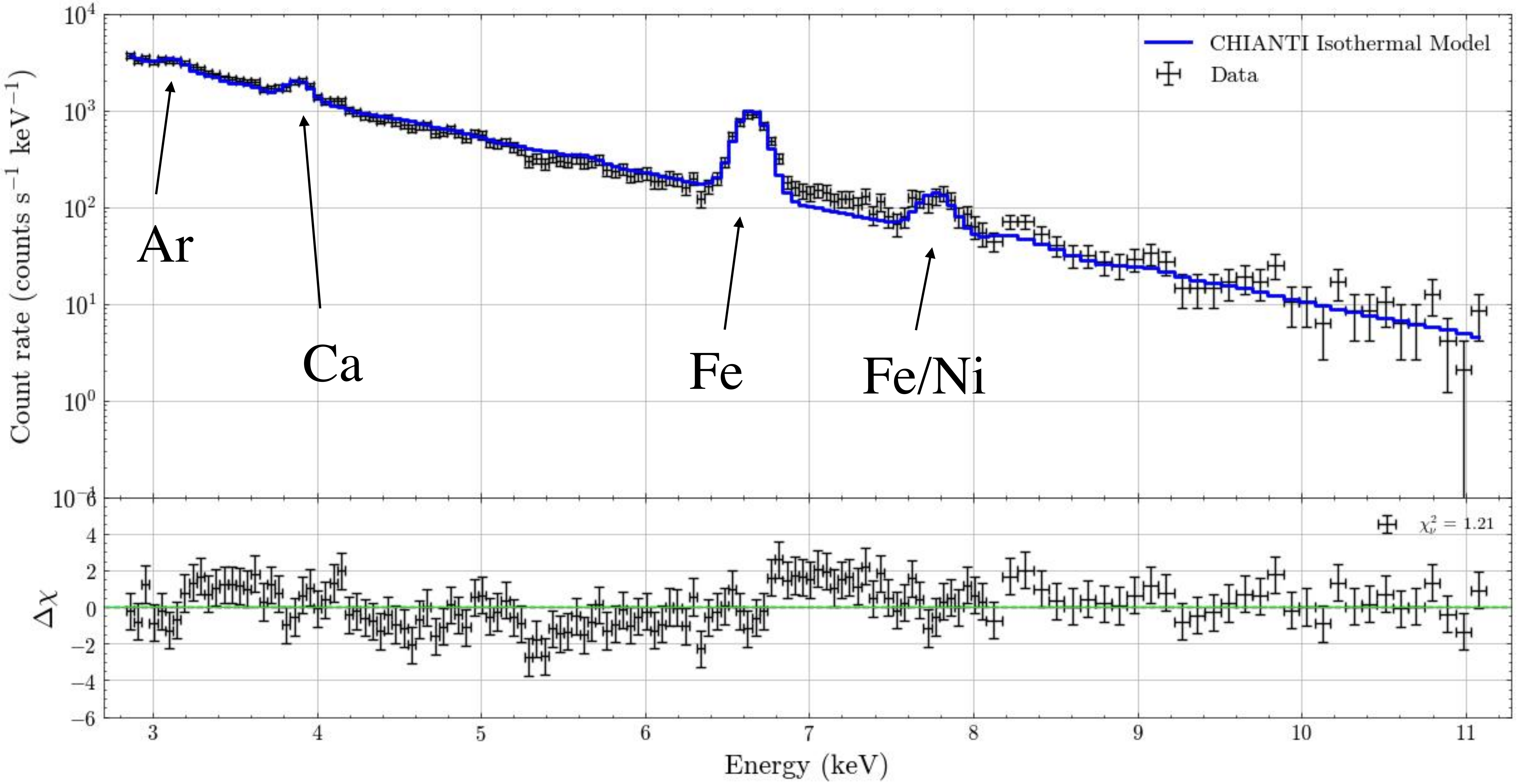


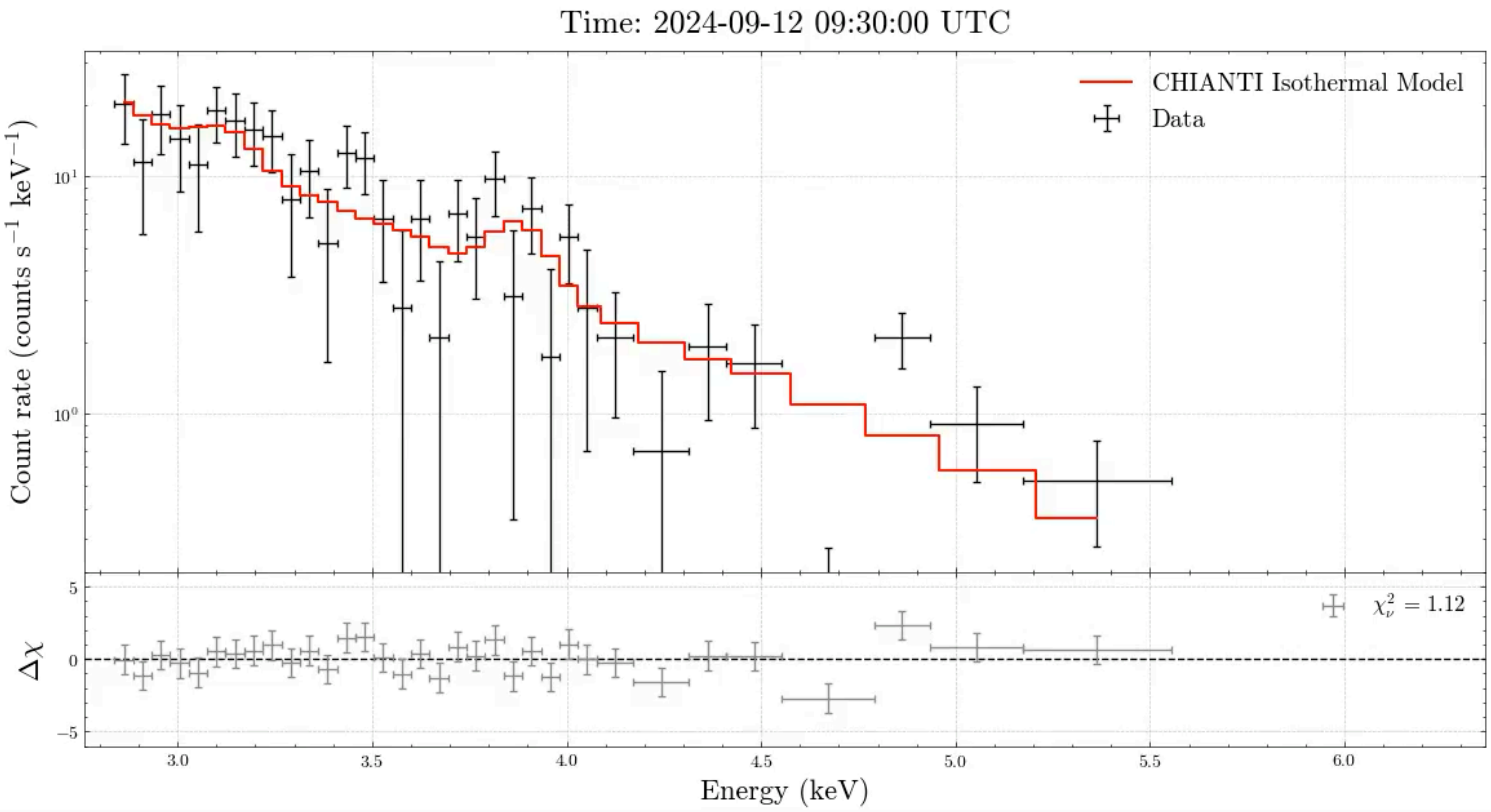
Fig - SoLEXS spectrum of the X1.3 flare peak fitted with the CHIANTI 1T model.
Lower panel shows the reduced chi-square. Blue line: best fit.

Spectral Fitting

Using XSPEC and Chisoth Model

(Arnaud et al. 1996) (Biswajit et al. 2021)

Energy Range used for Fitting - **2.8 - 15 KeV**



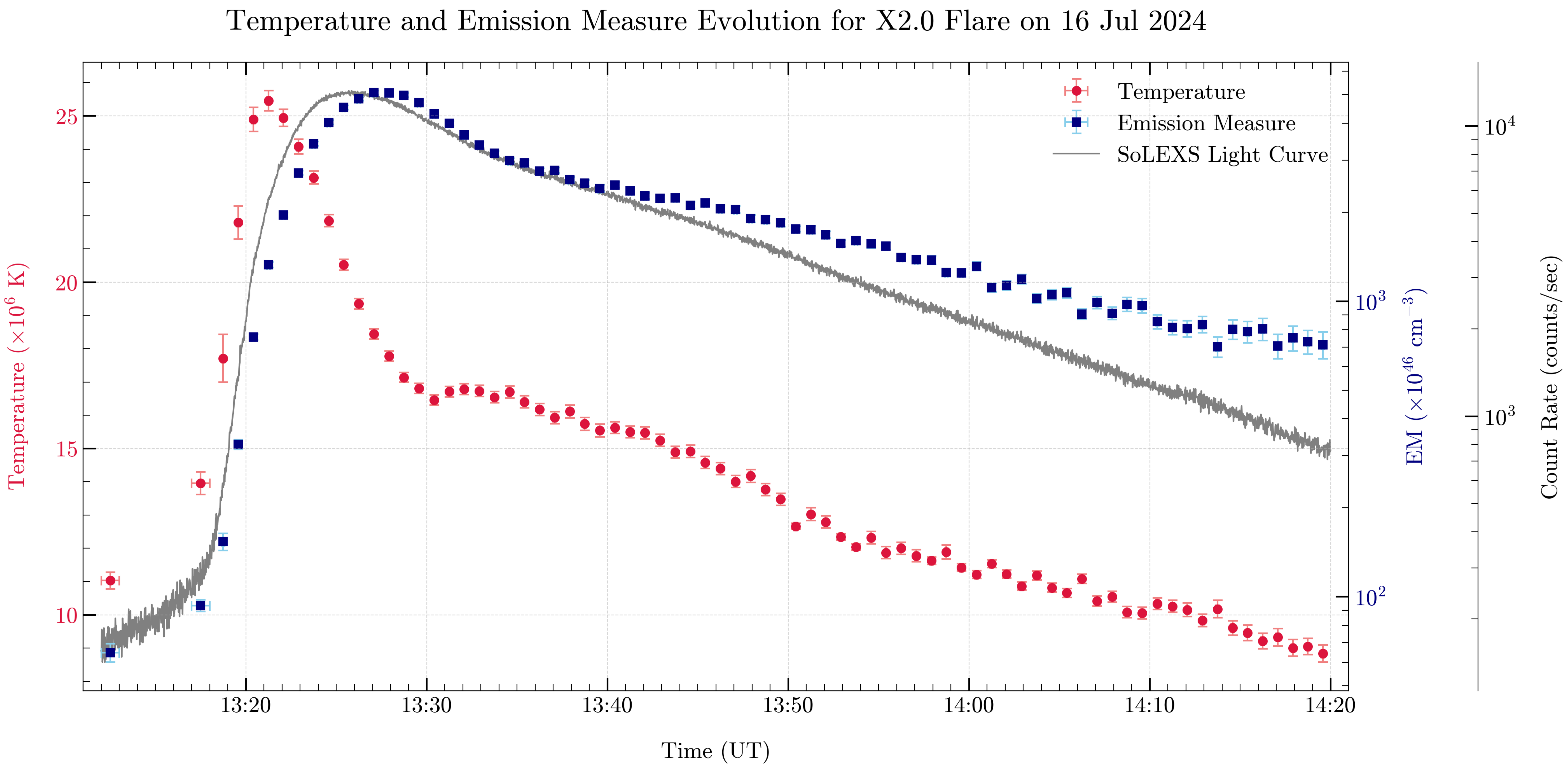
Results

Temperature and Emission Measure Evolution During a Flare

Temperature peaks

X-ray light curve peaks

Emission Measure peaks



Observe with All Flares Analyzed !!

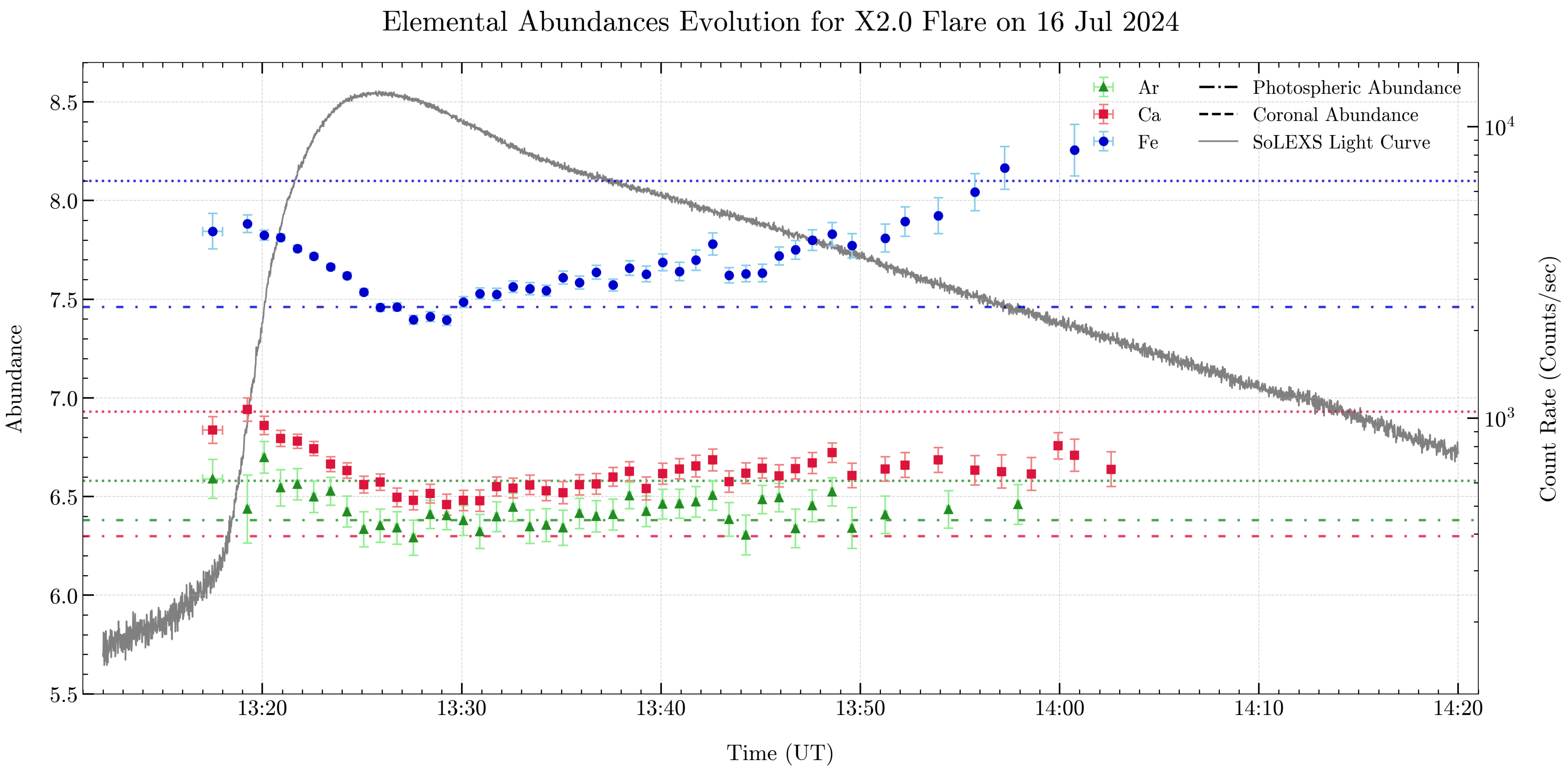
This is consistent with Standard Flare Model !!

- Photospheric Abundances from - Asplund 2021
- Coronal Abundances from - Feldman 1992

Results

Elemental Abundances Evolution During a Flare

- Observed **depletion** of elemental abundances during **flare peak**.
- Abundances drop toward **photospheric values**, indicating **chromospheric material injection.**
- Recovery to **coronal levels** post-flare.

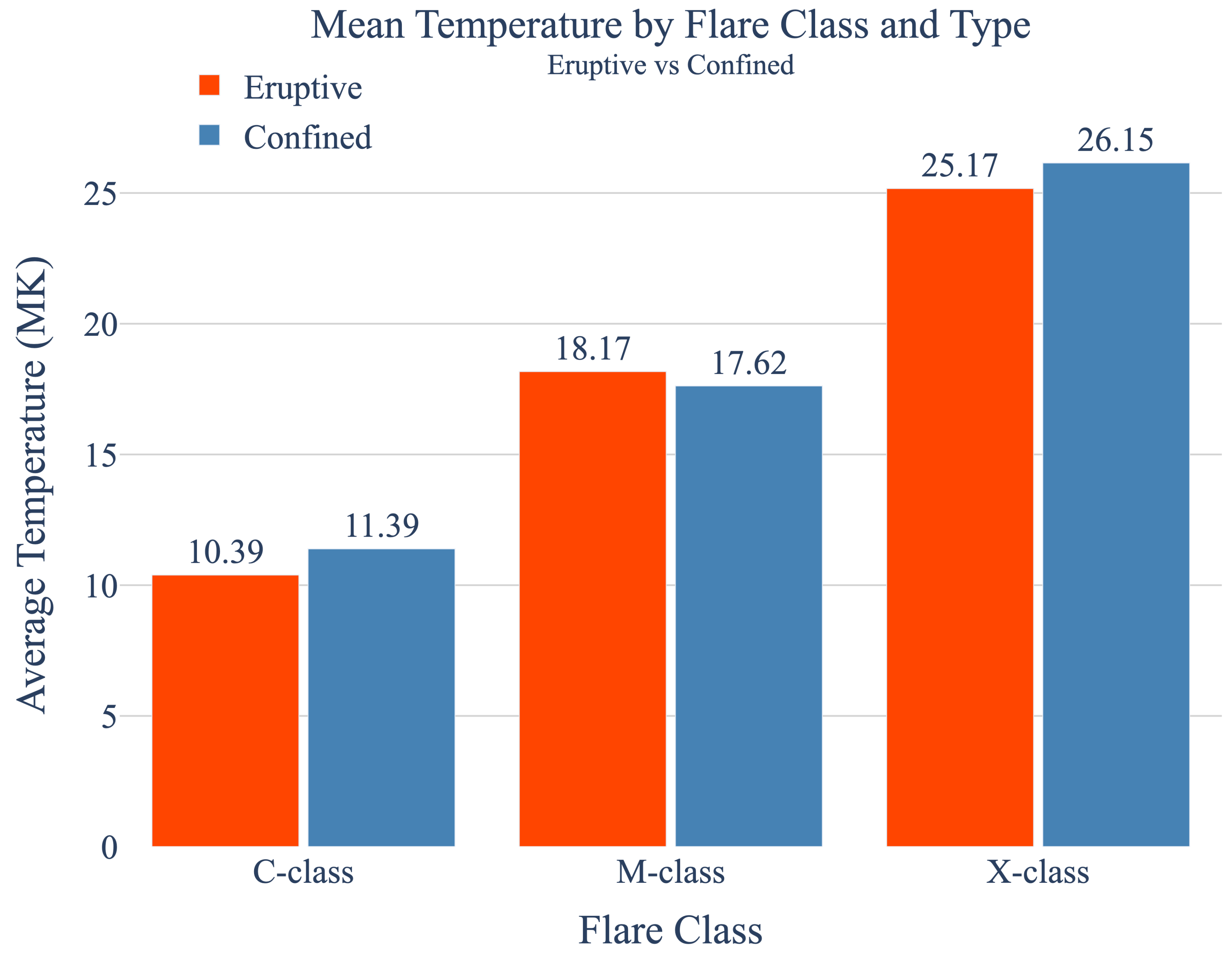


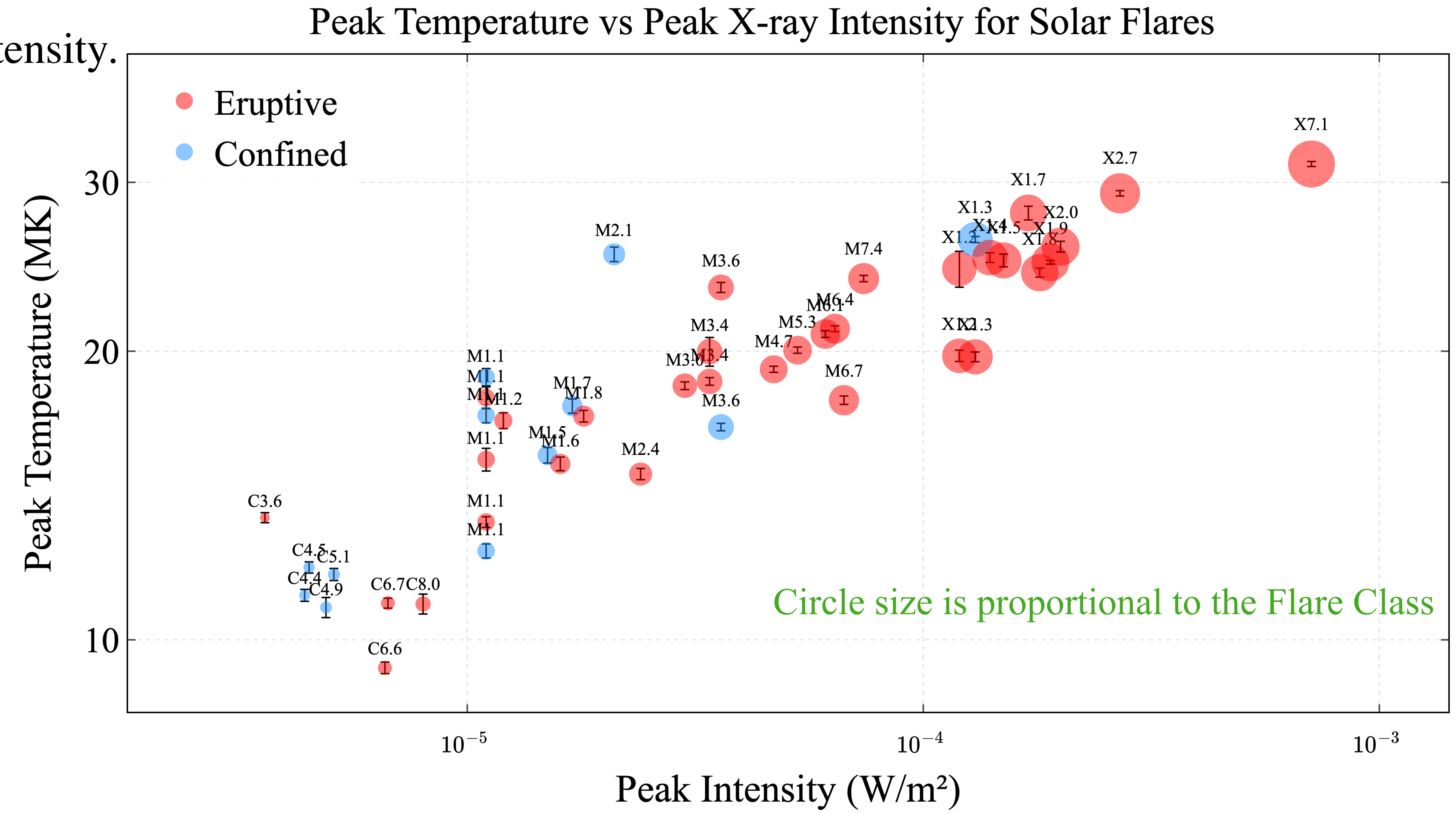
Ca and **Fe** **(low-FIP):** Min Abundance is **higher** in confined flares → more coronal-like.
Ar **(high-FIP):** Similar between eruptive and confined.

Results

Peak Temperature and Peak Intensity

- Peak Temperature **increases** with Peak Intensity.
  - **C-class:** ~11 MK
  - **M-class:** ~18 MK
  - **X-class:** ~25 MK

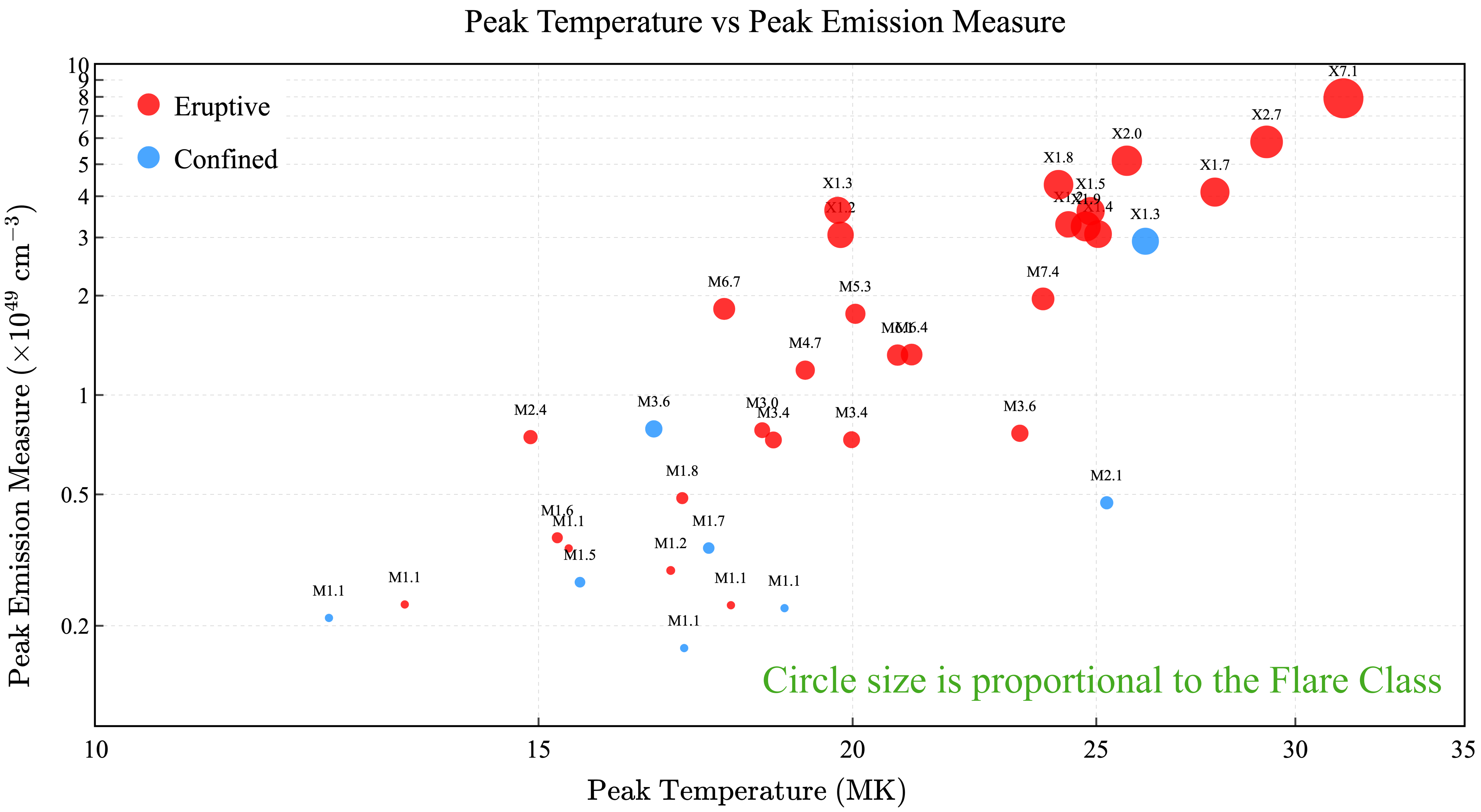


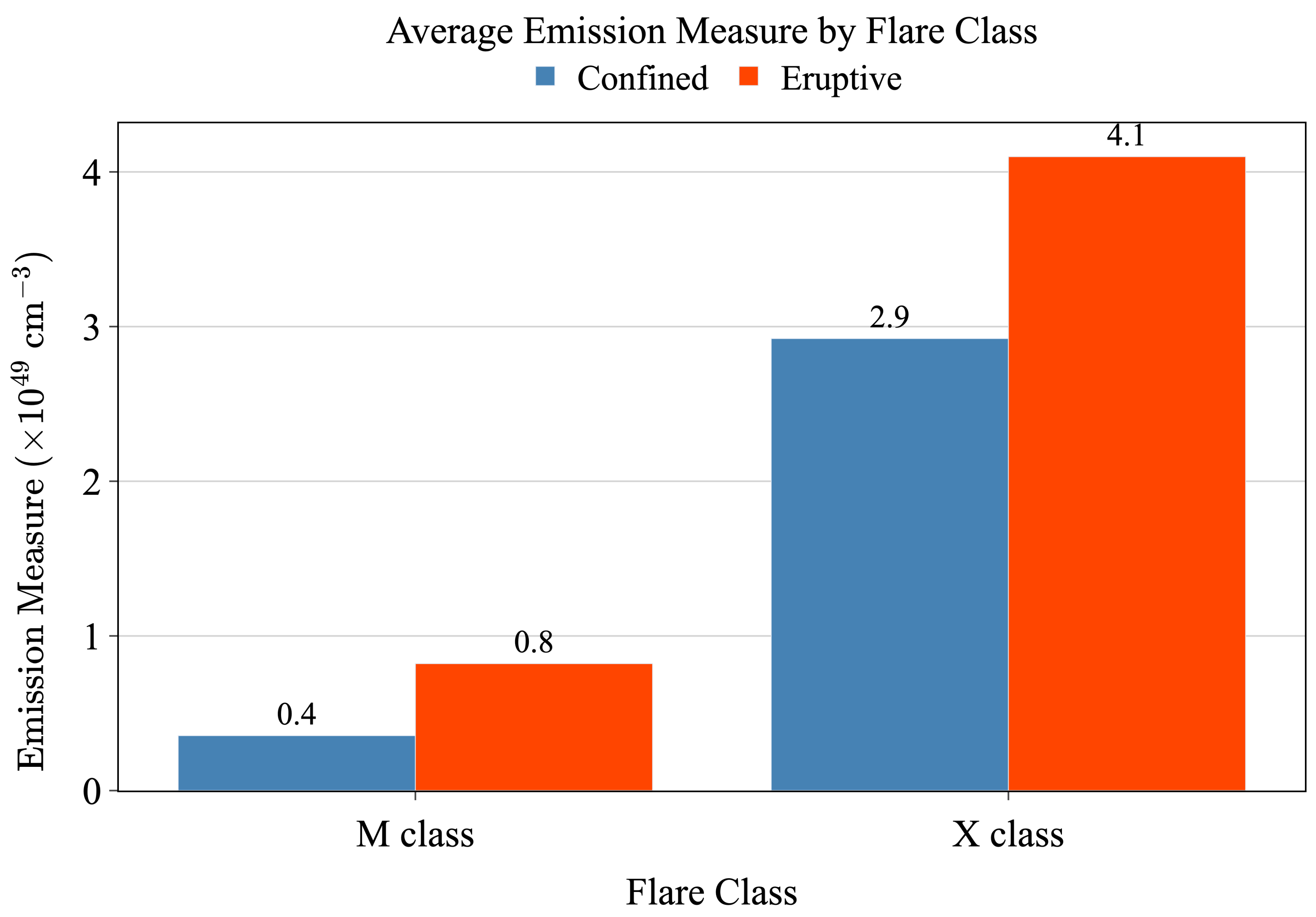


- **C-Class & X-Class:** **Confined flares** show **higher peak temperatures** than **Eruptive**.
- **M-class flares: Mixed behavior** — some **confined flares** are hotter, others not.

Results

Peak Emission Measure and Peak Temperature





- Peak Emission Measure **increases** with Peak Intensity (Flare Class).
- **Eruptive Flares** have significantly **higher Emission Measure** than **Confined Flares**.

Summary

- Significant **Time lag** between **Peak Temperature**, **Peak Xray Flux** and **Peak Emission Measure**.
- **Peak Temperature and Peak Emission** Measure **increases** with Peak Intensity.
- **Confined Flares** exhibit **higher peak temperatures** than **Eruptive Flares**
- **Eruptive Flares have** a **higher EM** than **Confined Flares**
- **Confined Flares** show a **stronger FIP effect**.

References

1. Del Zanna, G., 2021. ***CHIANTI—An Atomic Database for Emission Lines*. XVI. Version 10**, Further Extensions.

2. Arnaud, K.A., 1996. **XSPEC: The First Ten Years. Astronomical Data Analysis Software and Systems V,** eds. Jacoby G. and Barnes J., p17, ASP Conf. Series volume 101.

3. Mithun, N. P. S., Vadawale, S., Zanna, G. D., (2022). **Soft X-Ray Spectral Diagnostics of Multi Thermal Plasma in Solar Flares with Chandrayaan-2 XSM.** *The Astrophysical Journal*, 939:112.

4. Arnold O. Benz, 2008. ***Flare Observations***. Springer Nature Link

5. Mondal, B., Vadavale V. S., 2021. ***Evolution of Elemental Abundances during B-Class Solar Flares: Soft X-Ray Spectral Measurements with Chandrayaan-2 XSM*.**

6. Aditya-L1 Solar Low Energy X-ray Spectrometer (SoLEXS), Data Analysis Guide, SoLEXS PI Team

7. ***Elemental abundances in the upper solar atmosphere*** (Feldman 1992)


Thank You