STIX Meeting
November 7-9, 2023

A multi-thermal analysis of M-class flare observed in common by STIX and XSM

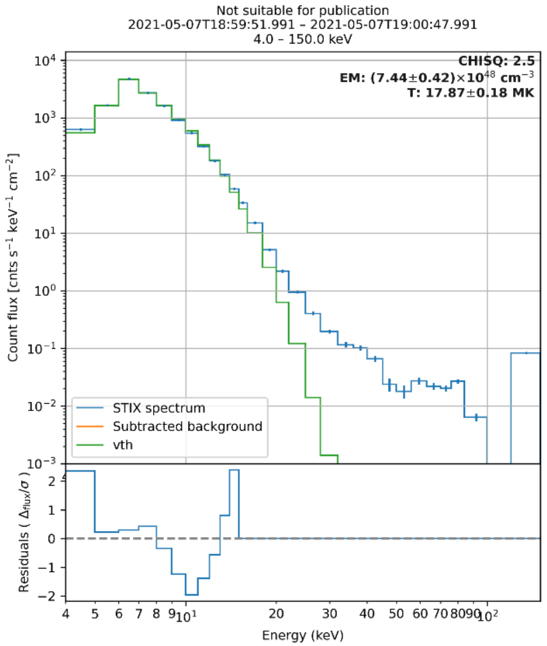
Anna Kępa, Marek Siarkowski, Arun Kumar Awasthi,
Janusz Sylwester, Barbara Sylwester

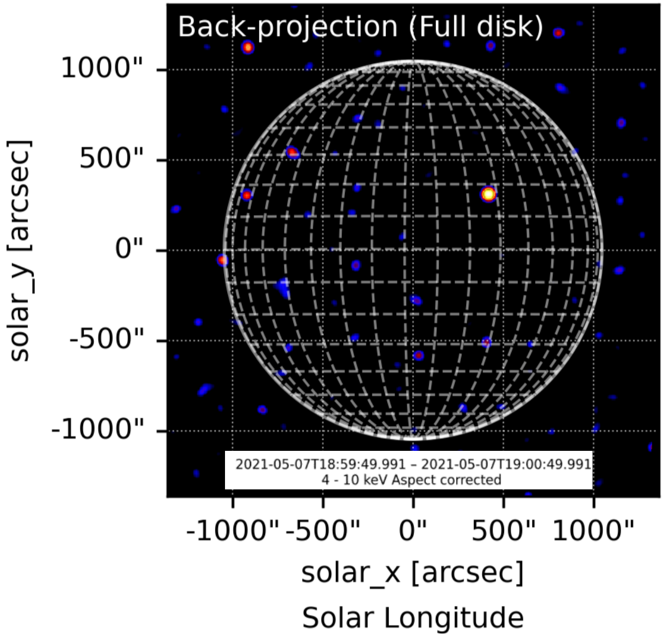
Space Research Centre of Polish Academy of Sciences, 00-716 Warsaw, Bartrycka 18a
Solar Physics Division, ul. Kopernika 11, 51-622 Wrocław, Poland

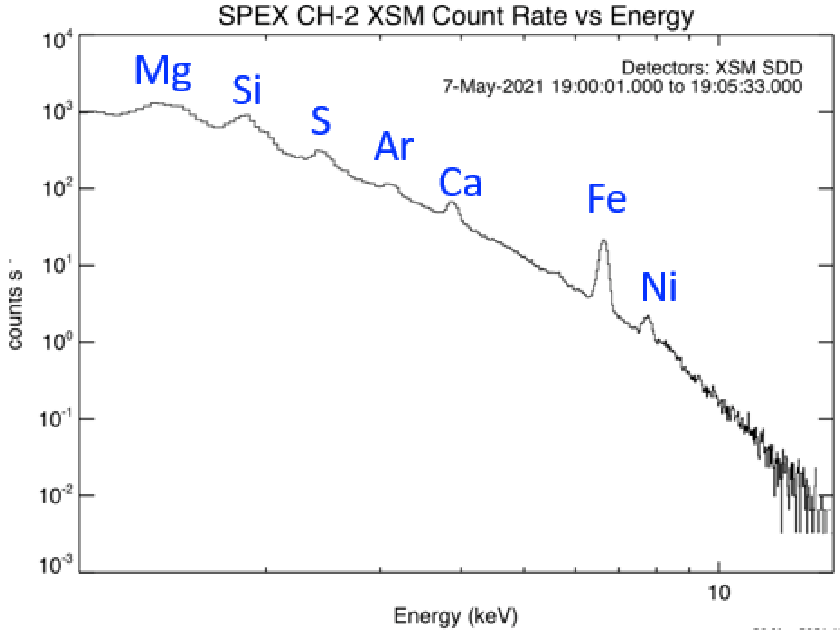
This work was supported by the National Science Centre, Poland grant number 2020/39/B/ST9/01591.

STIX & XSM

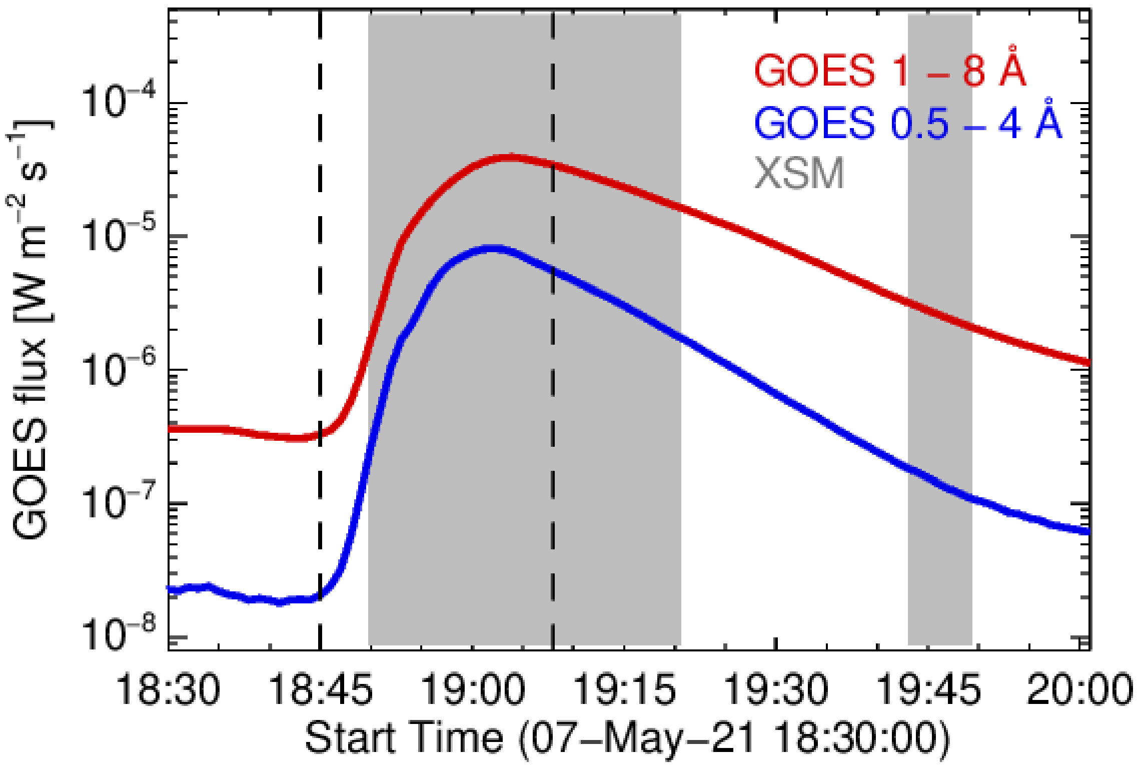
Instrument:	**STIX** (the Spectrometer/Telescope for Imaging X-rays)	**XSM** (the Solar X-ray Monitor)
On -board:	Solar Orbiter	Chandrayaan-2
Energy range:	4 – 150 keV	1 - 15 keV
Energy resolution:	1 – 15 keV (energy dependent)	~180 eV at 5.9 keV
Effective area:	6 cm^2	0.00384 cm^2
Angular resolution:	7 arcsec	-
Field of view:	2 degree	±40 degree
Time resolution:	> 0.1 s (statistics limited)	1 s



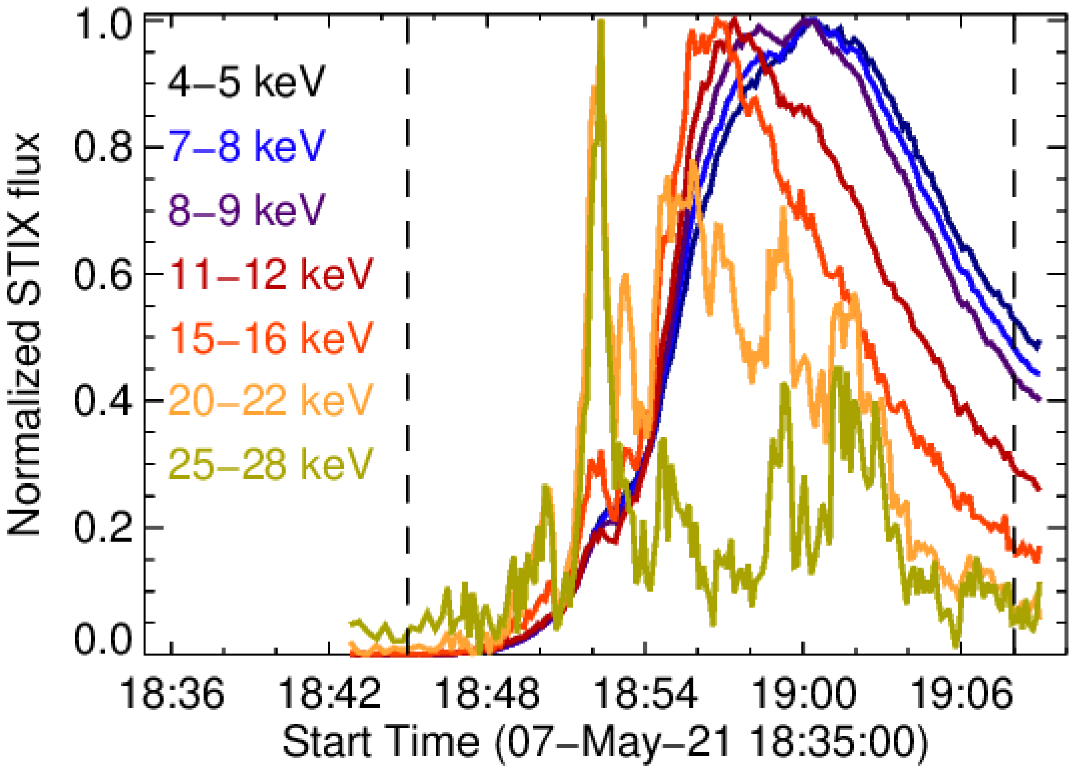




7 May 2021 flare, GOES class: M3.9, max ~ 19:04 UT



GOES (in red and blue) light curves for the 7 May 2021 flare. The time intervals in which the XSM observations were investigated are marked in grey.

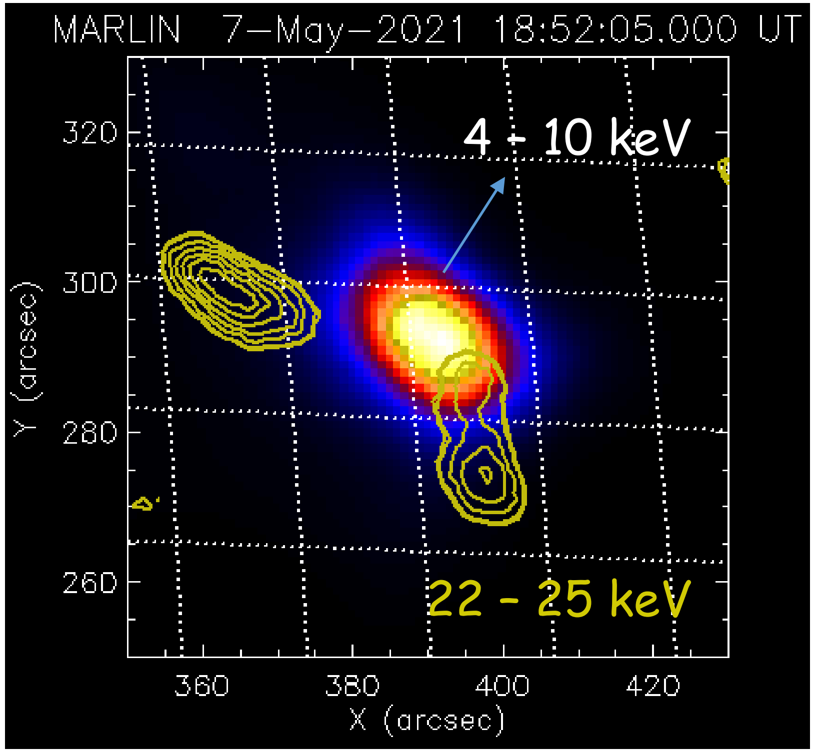


Normalized STIX light curves in seven selected energy bands. The time scale corresponds to the dashed vertical lines from the left plot.

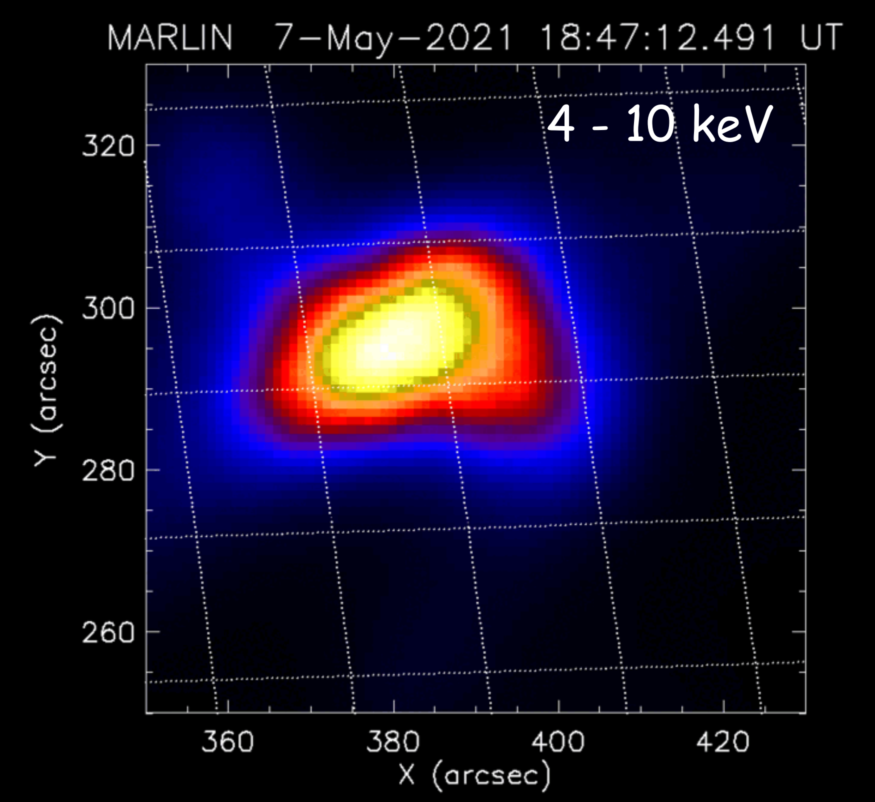
The STIX light curves in lower energy have rather smooth profiles while a lot of pulsations are observed in higher energy channels.

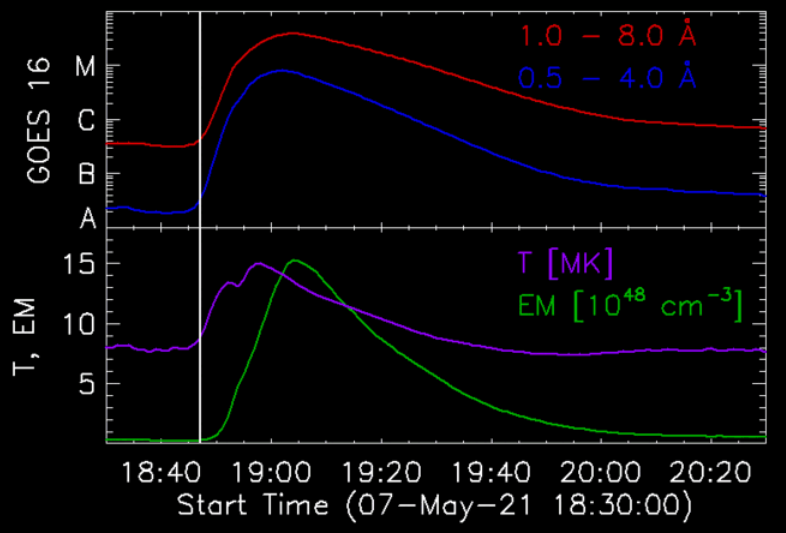
STIX images, 7 May 2021 flare

- Images were reconstructed using MARLIN algorithm (Siarkowski et al., 2020).
- The MARLIN is based on the Richardson-Lucy method.
- The algorithm uses single-pixel-response maps and it is fully independent of the visibilities.
- The most updated STIX transmission functions were used.

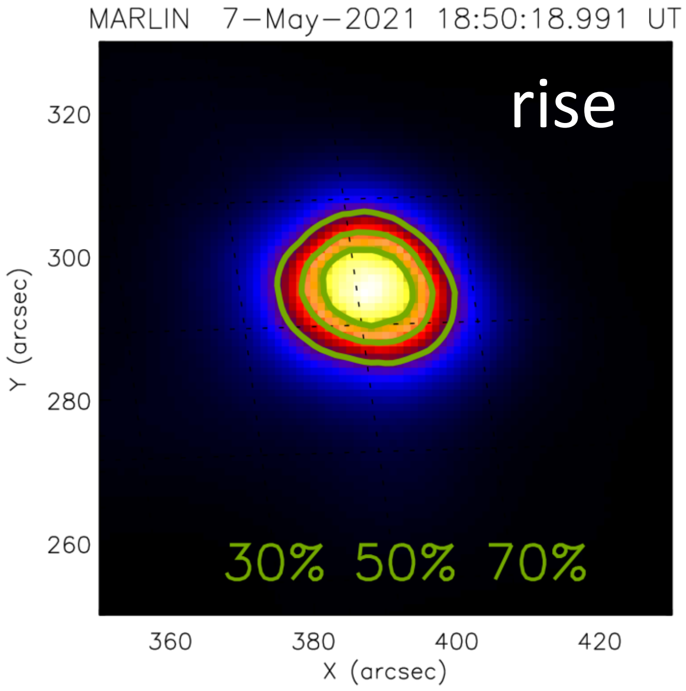


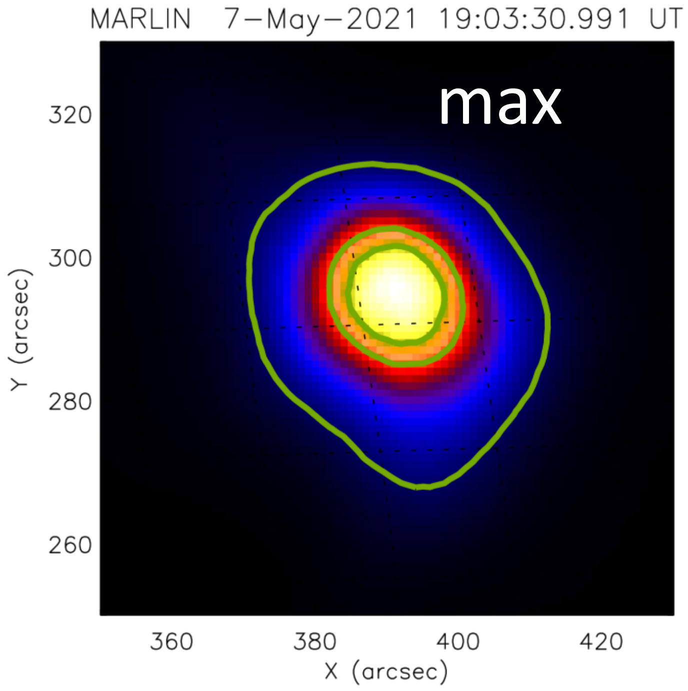
The synthesized X-ray images represent a typical flare geometry of a loop system emitting in the SXR energy bands while the foot-points are imaged in higher energy X-ray emission.

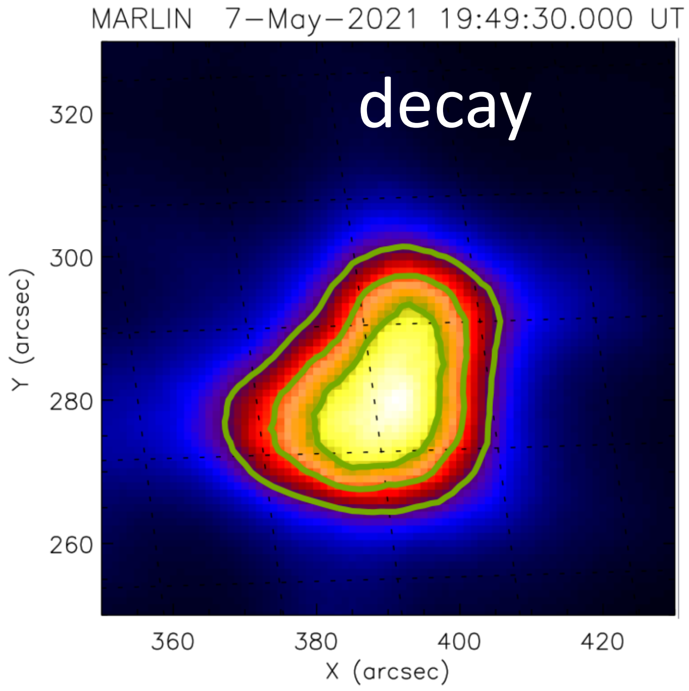




STIX images, 7 May 2021 flare

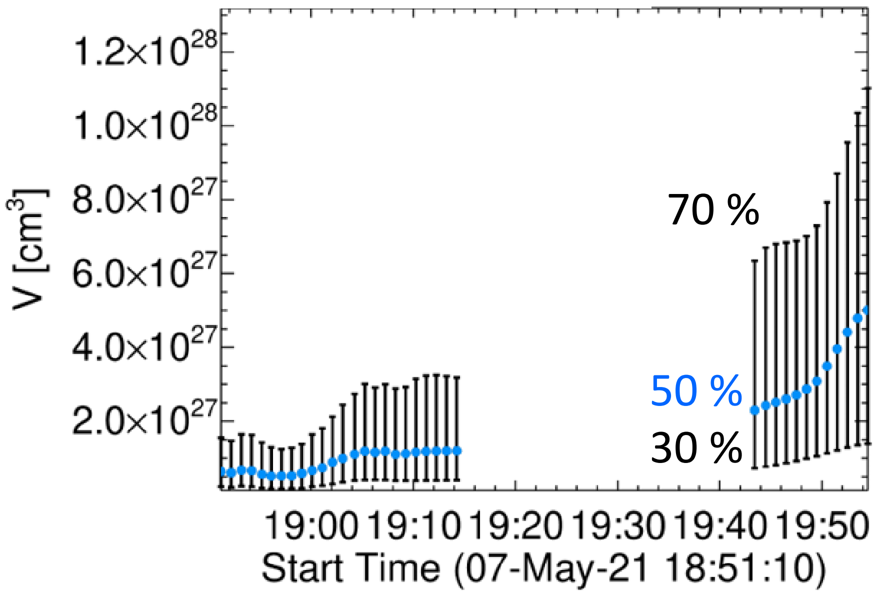






These sequence of STIX images in the energy range 4 – 10 keV were used for estimations of flaring volumes: contours 50%, spherical symmetry assumed, filling factor = 1.

The 30% and 70% contours were used in order to estimate of uncertainties in the volume estimation.



The estimated range of volume variations are between 1.4 and 4.2×10^{27} cm^3.

DEM & abundances

$$\varphi(T_\mathrm{e}) = N_\mathrm{e}^2 \frac{\mathrm{d}V}{\mathrm{d}T_\mathrm{e}}$$

N_e - electron density

V - plasma volume

T_e - temperature

A_i - assumed abundance of an element

$f_i(T_\mathrm{e})$ - emission function

N - number of spectral bands

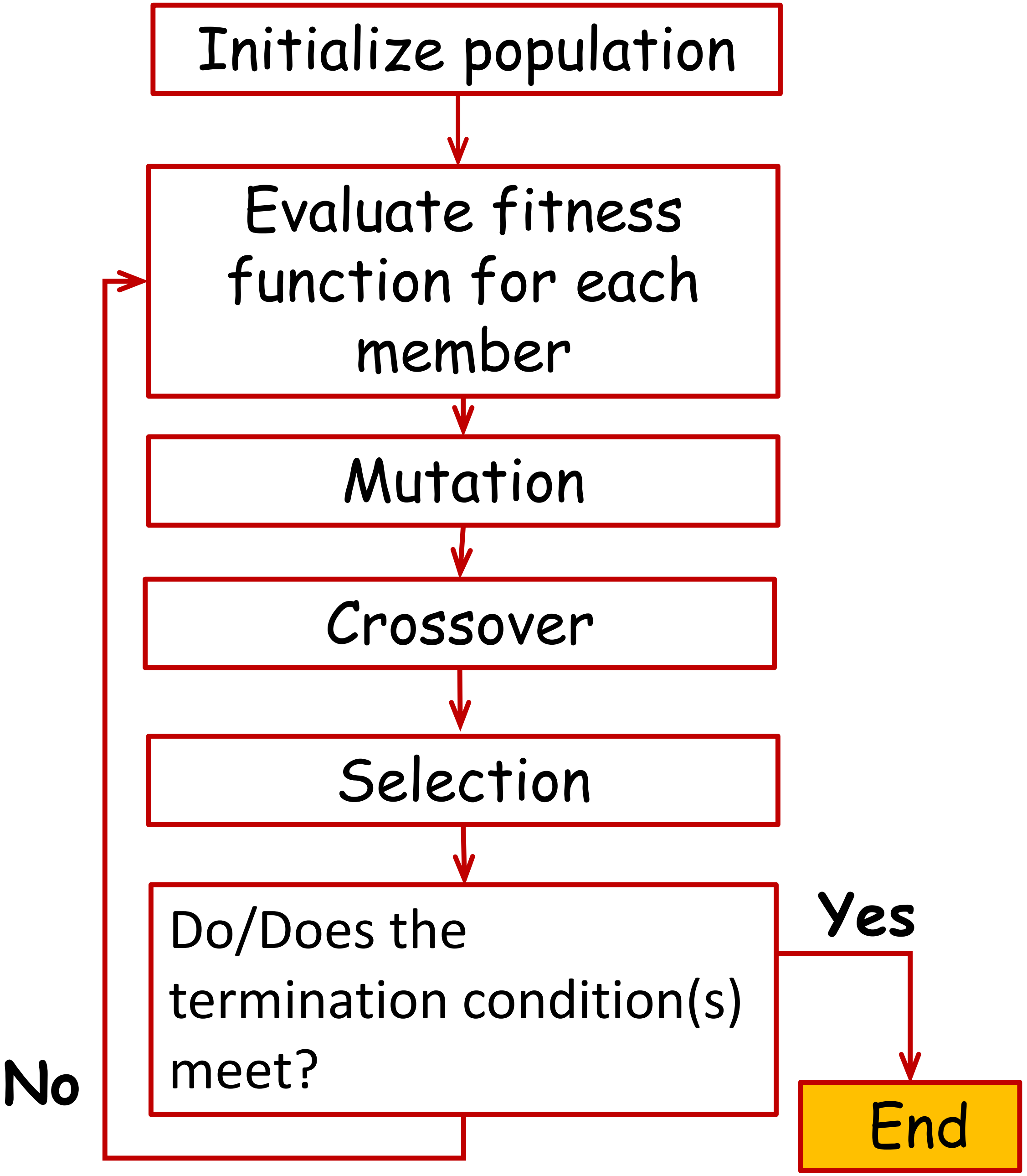
Flux

$$F_i = A_i \int_0^\infty f_i(T_\mathrm{e})\varphi(T_\mathrm{e})\,\mathrm{d}T_\mathrm{e} \quad i = 1, 2, \ldots N$$

Abundances	DEM

Differential evolution method

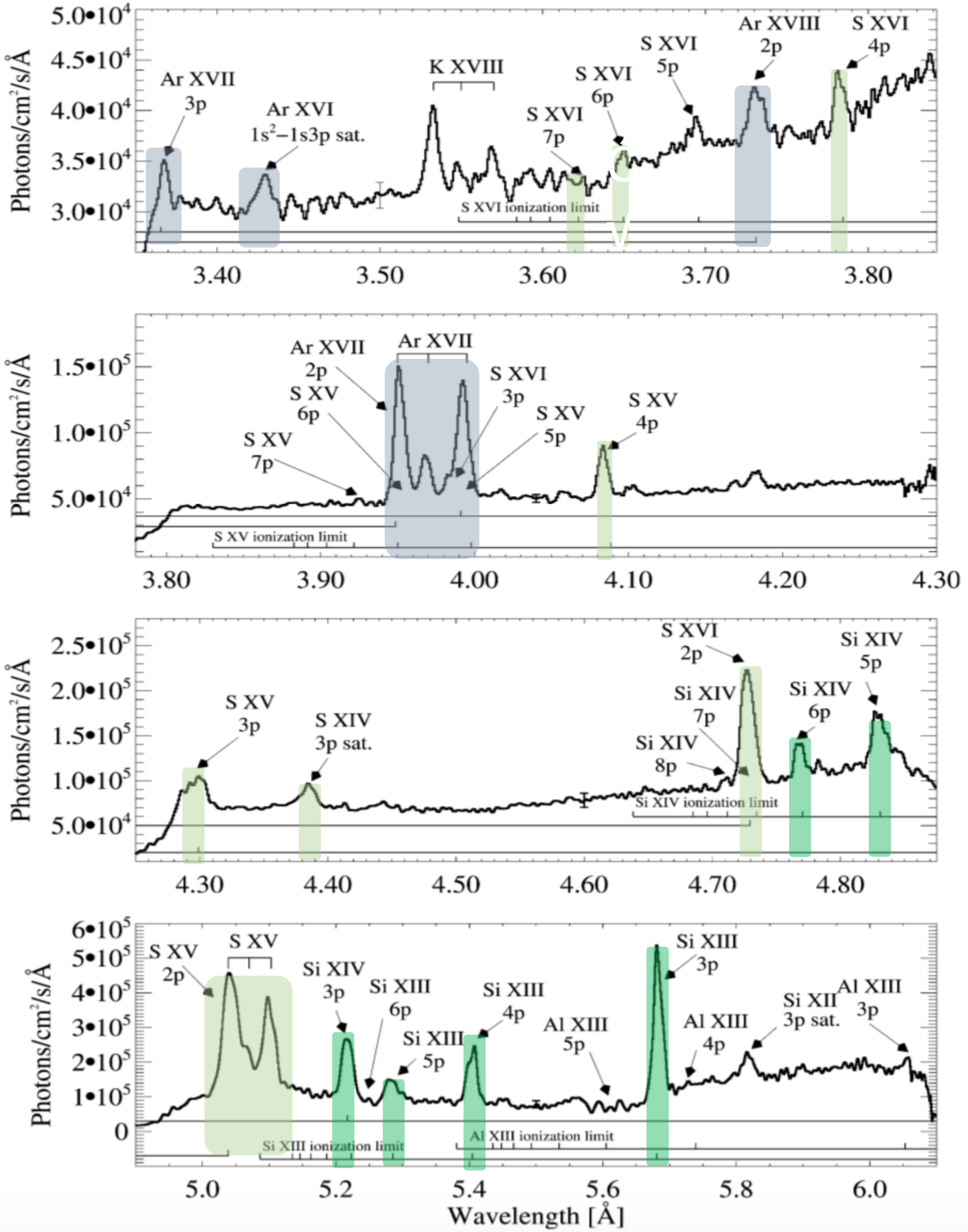
- Proposed by Price and Storn in 1995.
- The method solves optimization problem with real-valued parameters by iteratively trying to improve a candidate solution with regard to a given measure of quality.
- Stochastic, population-based optimization algorithm for solving nonlinear optimization problem.
- Very powerful algorithm for black-box optimization (also called derivative-free optimization).



RESIK spectrometer

Mission : CORONAS-F
Operated: 2001 – 2003
Spectral range: 3.3 – 6.1 Å

REntgenovsky **S**pektrometr s **I**zognutymi **K**ristalami (RESIK) designed to observe solar active region and flare plasmas.



Models

1T

A_{Si}	A_S	A_{Ar}	A_K	T_1	$\varphi(T_1)$

2T

A_{Si}	A_S	A_{Ar}	A_K	T_1	$\varphi(T_1)$	T_2	$\varphi(T_2)$

30T

A_{Si}	A_S	A_{Ar}	A_K	$\varphi(T_1)$	$\varphi(T_2)$	$\varphi(T_3)$	...	$\varphi(T_2)$	$\varphi(T_N)$
				1 MK	2 MK	3 MK			30MK

The ranges of values in which parameters could change

T = 1–30

log EM = 40–50

A_{Si} = 7–9

A_S = 6–8

A_K = 5–7

A_{Ar} = 5–7

Theoretical spectra have been calculated using the CHIANTI 8.0.7 spectral code,

Ionization equilibrium based on Bryans et al. 2009,

Unit elemental abundances for Si, S, Ar, and K.

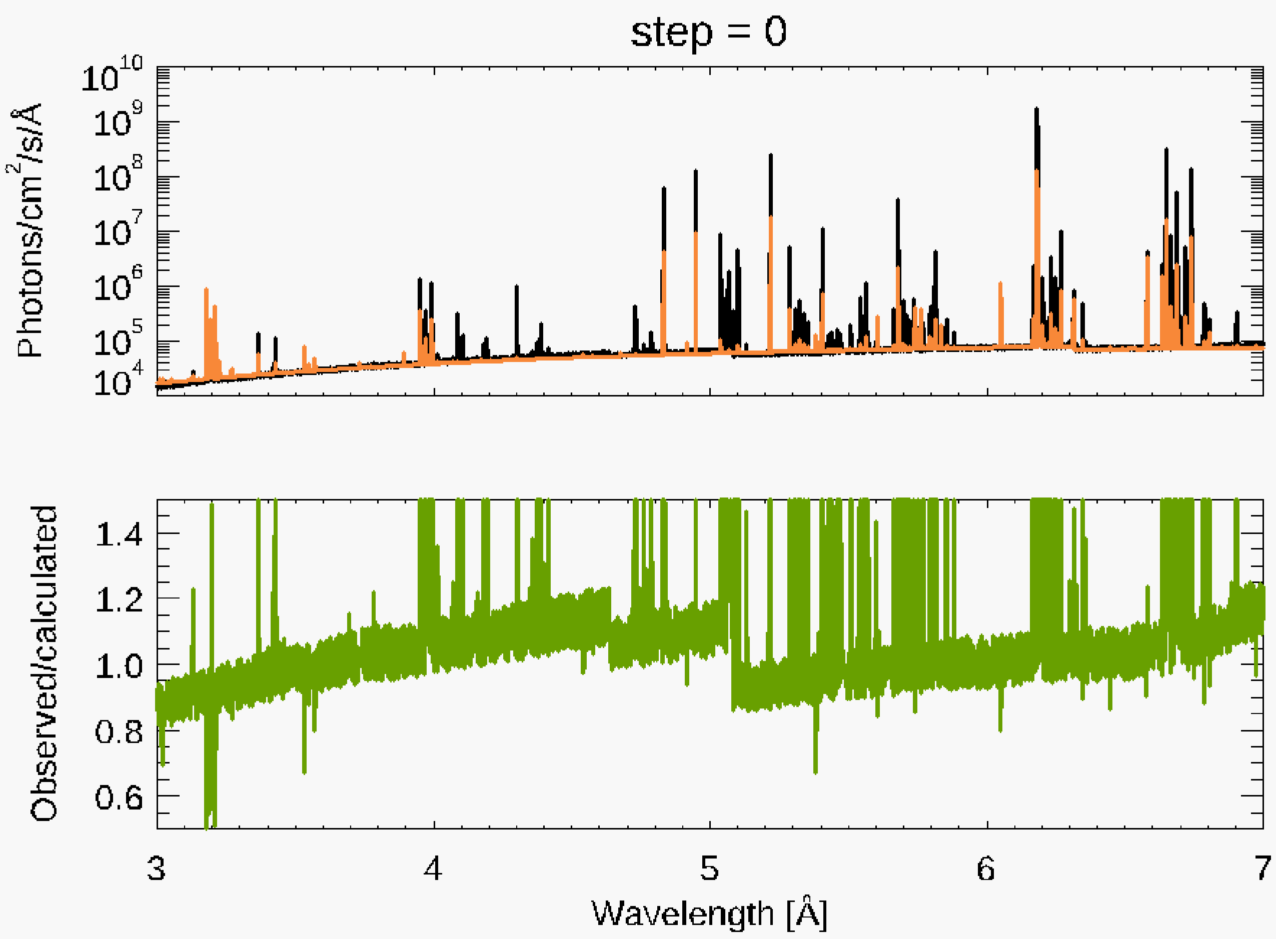
For other elements we used coronal abundances (Feldman et al. 1992).

Test - model 1T

We calculated spectra for assumed values of temperature and emission measure and different abundances for silicon, potassium, argon, and sulfur.

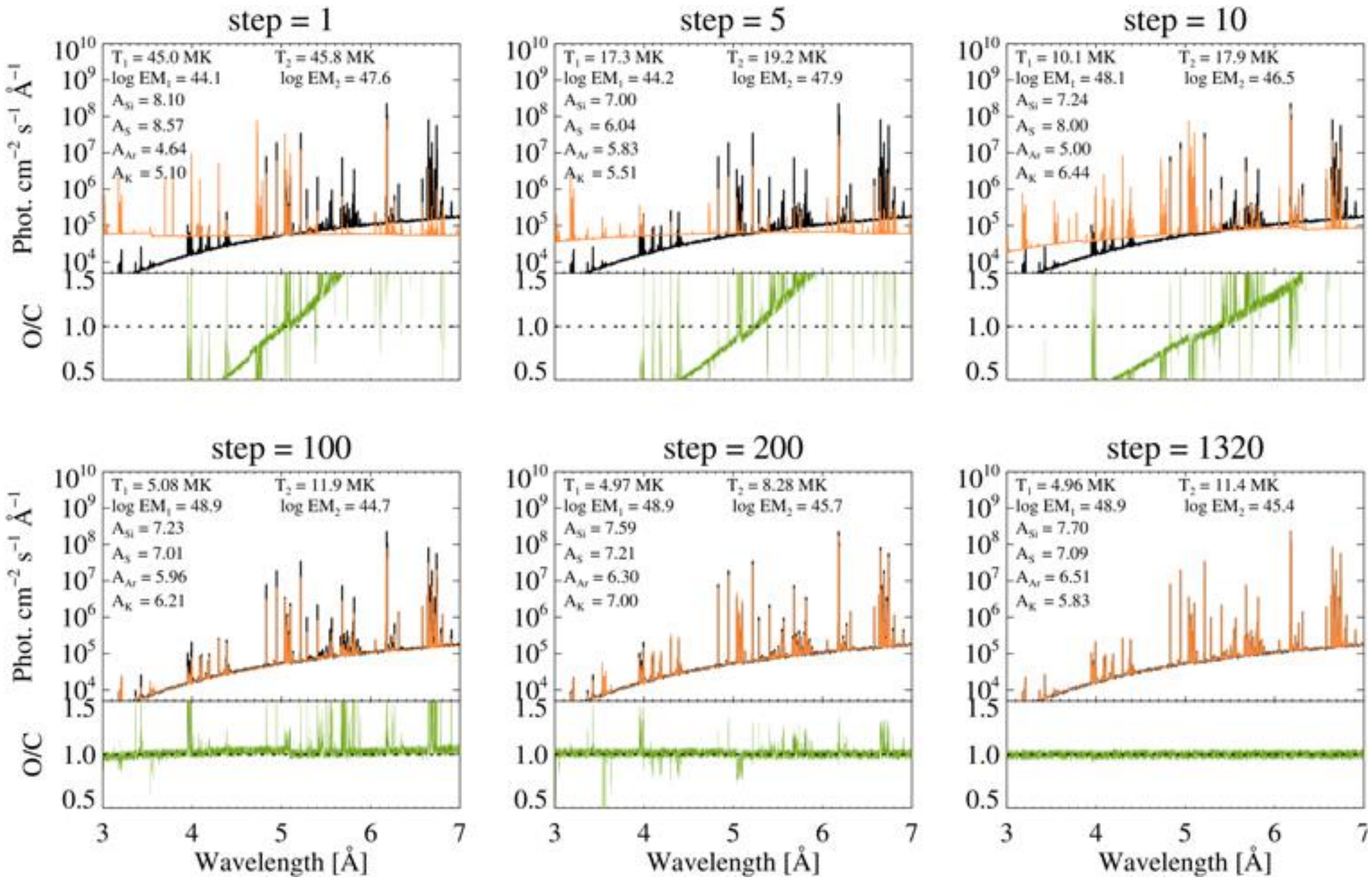
The generated X-ray spectra were perturbed within limits given by errors coming from expected count statistics.

Next, these spectra have been treated as observations, which we should reconstruct using the DE method.



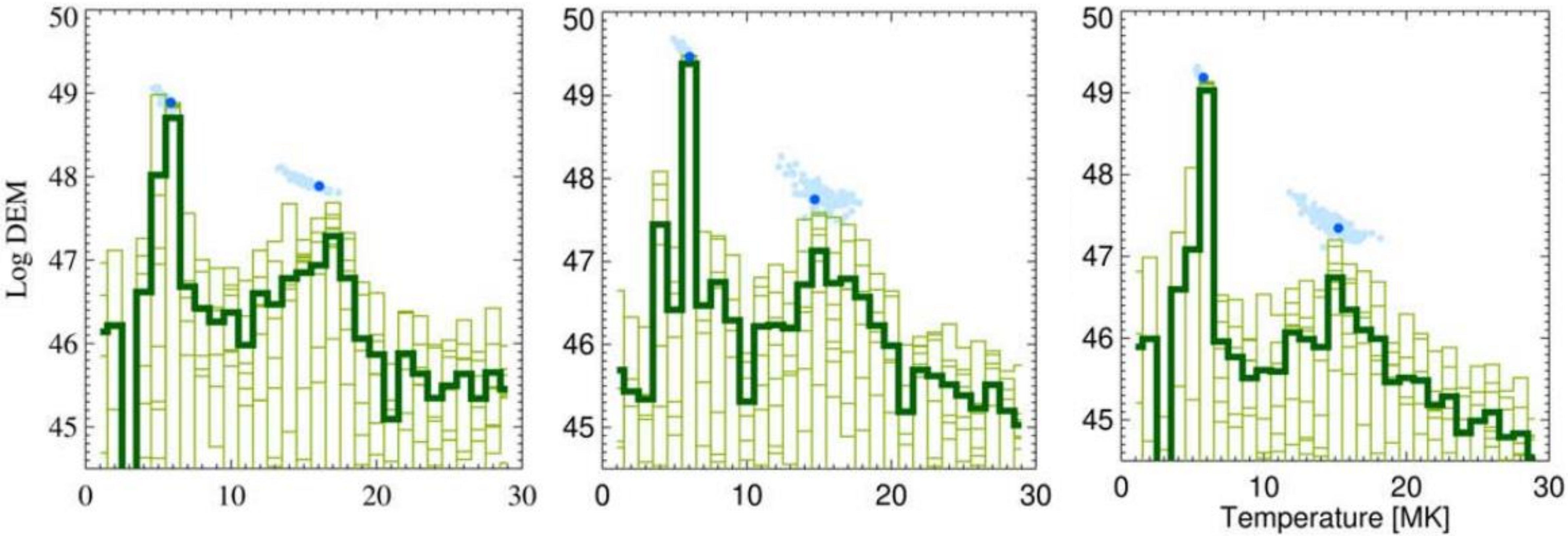
Observed	Calculated
Abu Si = 8.30	Abu Si = 7.13
Abu S = 7.12	Abu S = 4.79
Abu Ar = 6.82	Abu Ar = 6.00
Abu K = 5.41	Abu K = 5.42
T [MK] = 9.0	T [MK] = 10.9
log EM = 48.30	log EM = 48.16

Test – 2T model



„Observed”	Calculated (for 1320 step)
A_{Si} = 7.70	A_{Si} = 7.70
A_S = 7.10	A_S = 7.09
A_K = 5.91	A_K = 5.85
A_{Ar} = 6.50	A_{Ar} = 6.51
T_1 = 5 MK	T_1 = 4.96 MK
EM_1 = 49.0	EM_1 = 48.9
T_2 = 12 MK	T_2 = 11.4 MK
EM_2 = 45.3	EM_2 = 45.4

Test – 30T model



Conclusions:

- ✓ The analysis of presented test and many other performed tests reveals that the DE method satisfactorily reconstructs the assumed plasma parameters.
- ✓ The obtained results are stable and do not change if the iterations continue.
- ✓ A more complex model requires more iterations.

Tests: two- temperature plasma (T, EM) & 8 "unknown" abundances

Approach used when applying Differential Evolution to interpretation of Chandrayan-2 XSM spectra

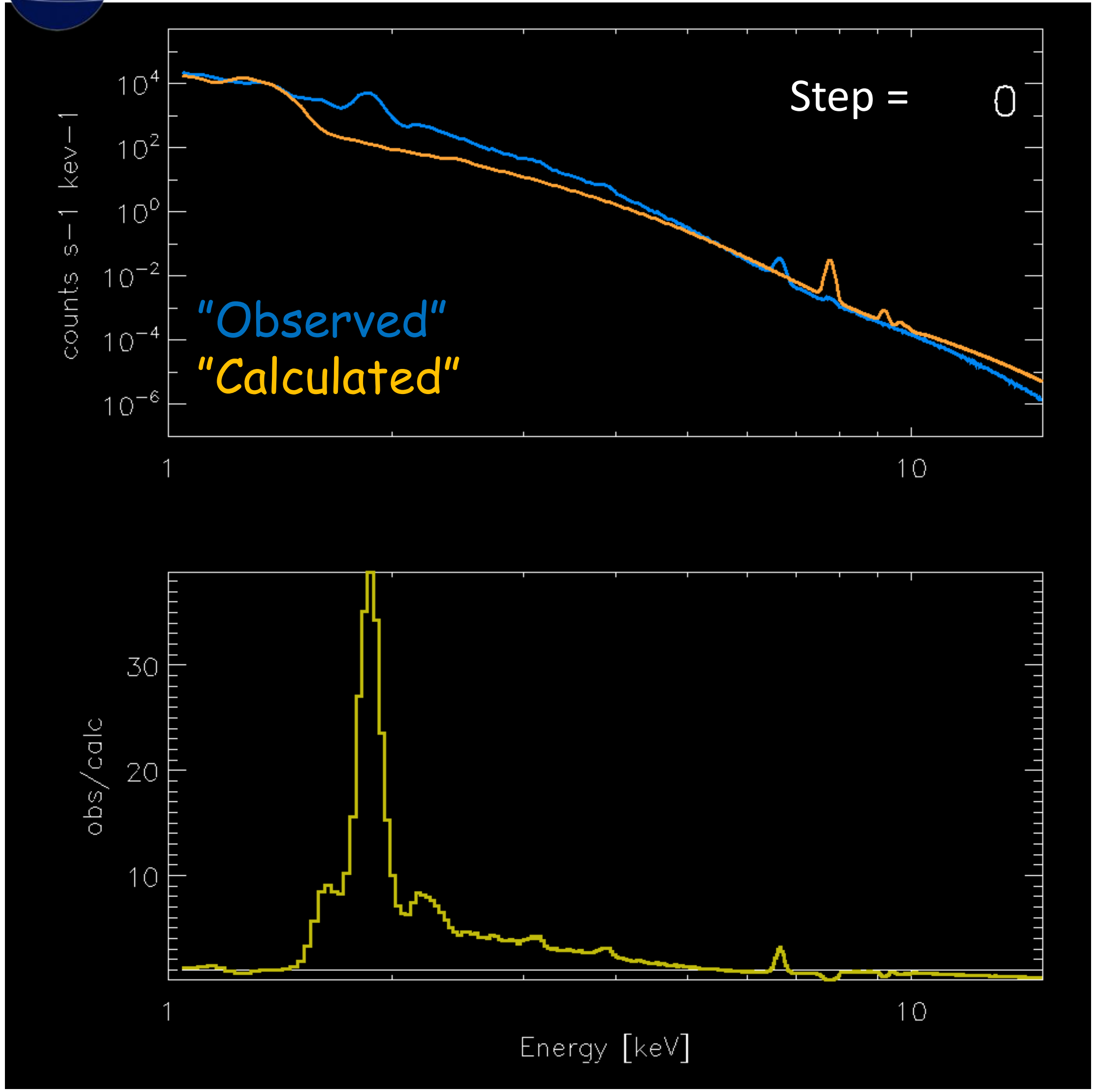
A_{Mg}	A_{Al}	A_{Si}	A_{S}	A_{Ar}	A_{Ca}	A_{Fe}	A_{Ni}	T_1	$\varphi(T_1)$	T_2	$\varphi(T_2)$

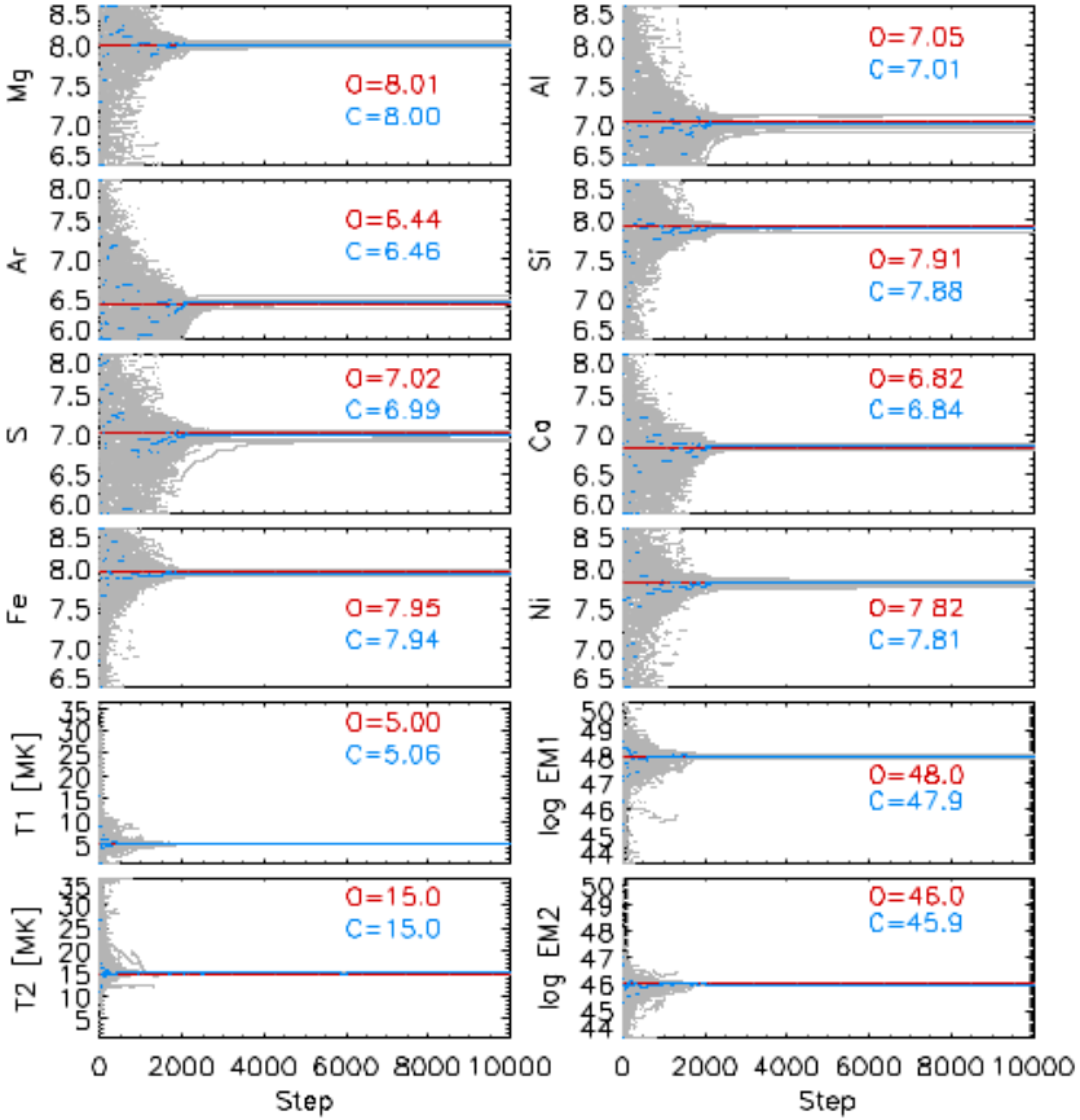
element abundances — A_{Mg} … A_{Ni}

differential emission measure distribution — T_1, $\varphi(T_1)$, T_2, $\varphi(T_2)$

- Theoretical spectra have been calculated using the CHIANTI 10.0.1 spectral code,
- Ionization equilibrium based on Bryans et al. 2009,
- Unit elemental abundances for Mg, Al, Si, S, Ar, Ca, Fe and Ni,
- For other elements in calculations we fixed the abundances to Feldman 1992 values.

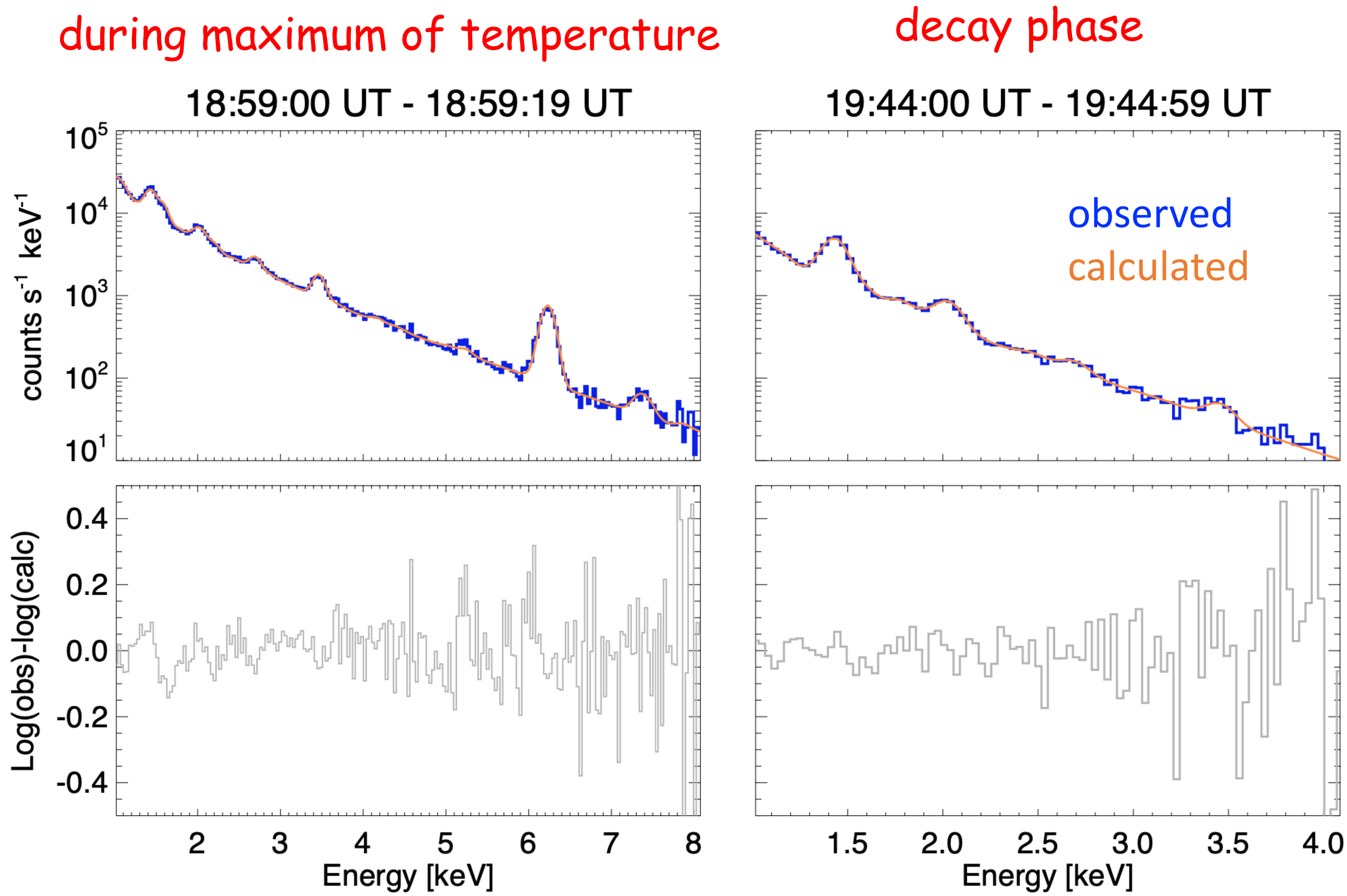
Tests: two- temperature plasma (T, EM) & 8 “unknown” abundances



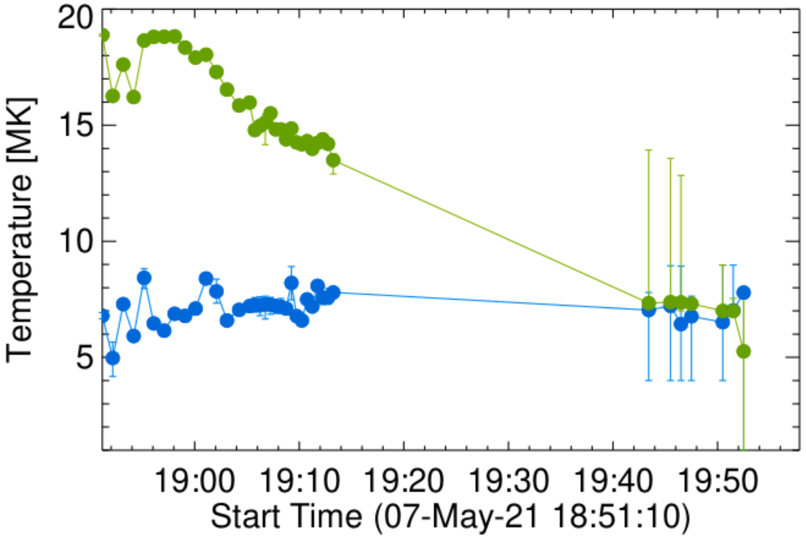


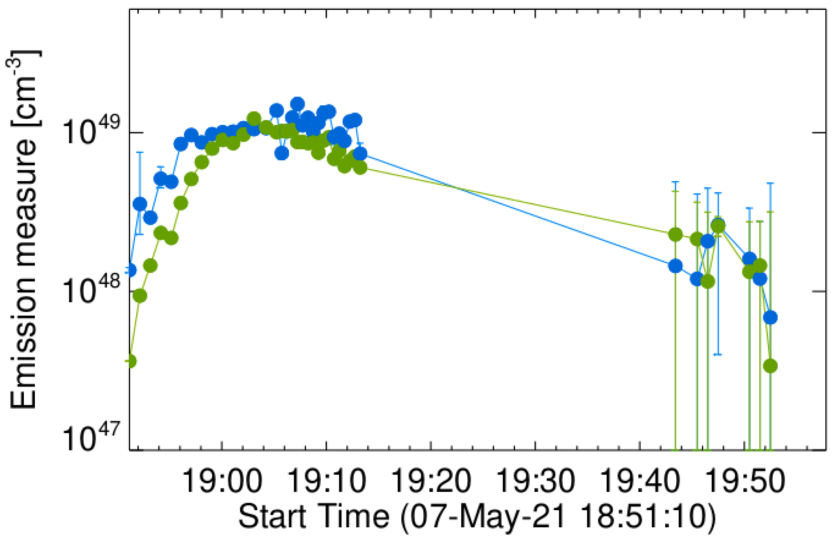
This approach is able to reconstruct observations from XSM/Chandrayaan2

Real spectra modeling



Results: temperature & emission measure

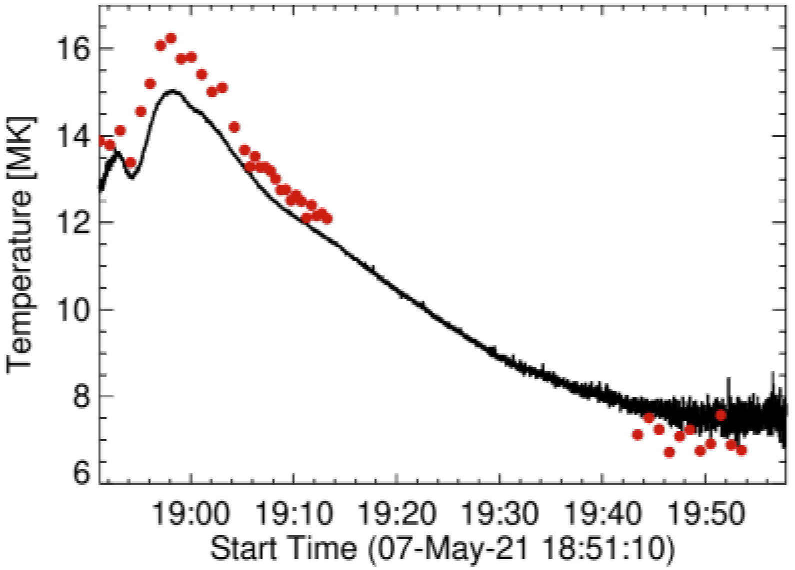


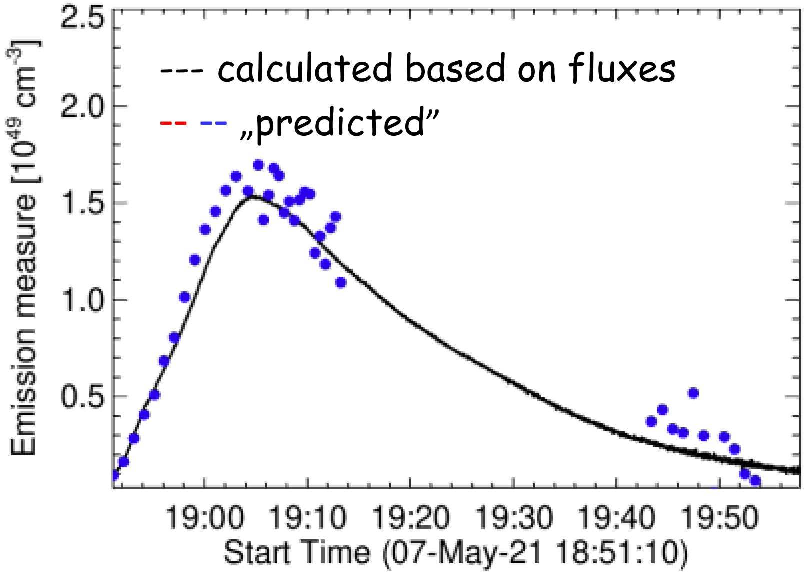


The temperature of the cooler plasma component seems **not** to change and is about 7 MK.

For the hotter component, the values of the temperature are between 12 MK and 20 MK

Emission measure values corresponding to both components vary in a similar manner during flare evolution.

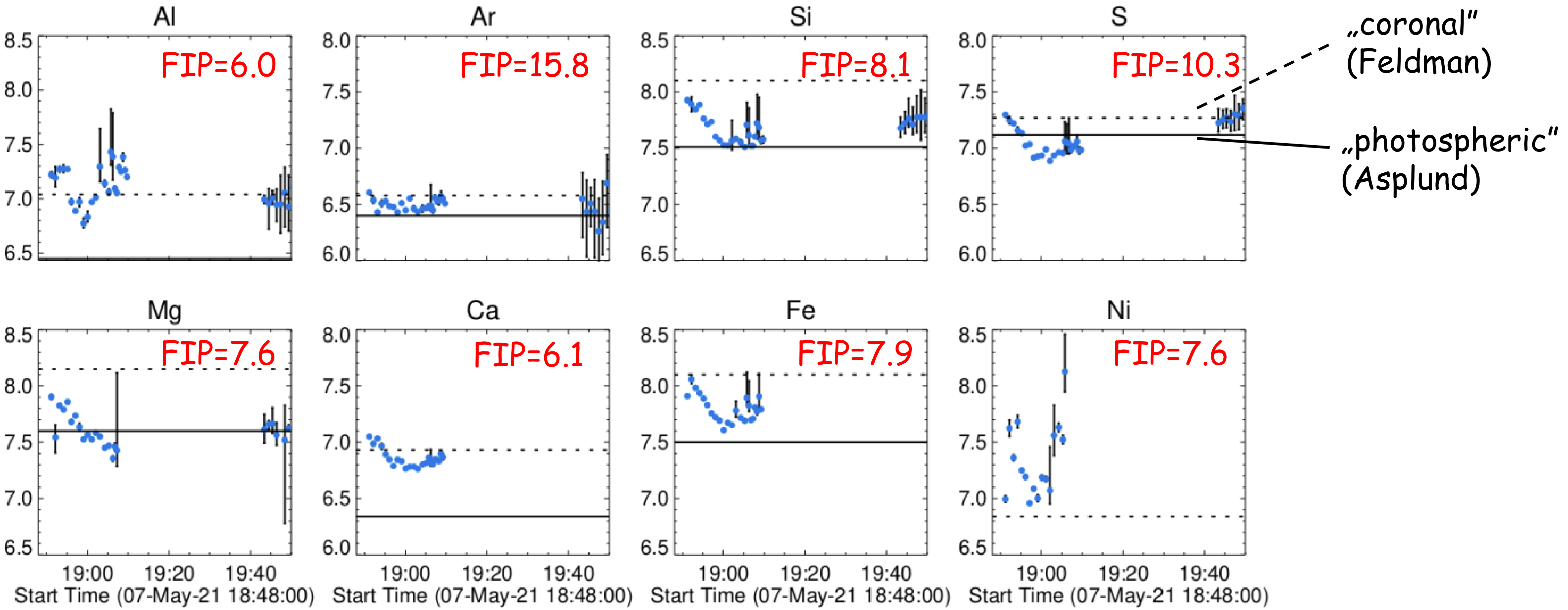




Comparison with GOES 16 observations

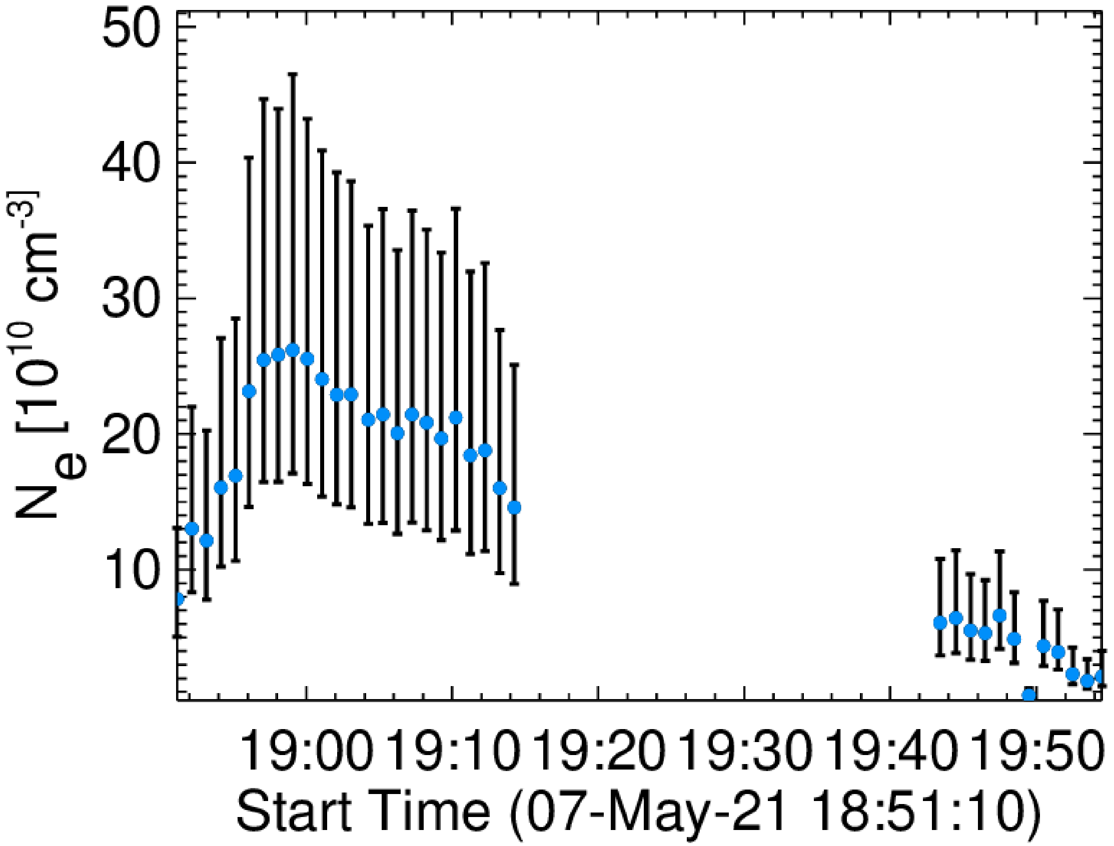
The "predicted" values of temperature are about 1.5 MK higher than those from GOES observations, while emission measure values are in agreement with GOES.

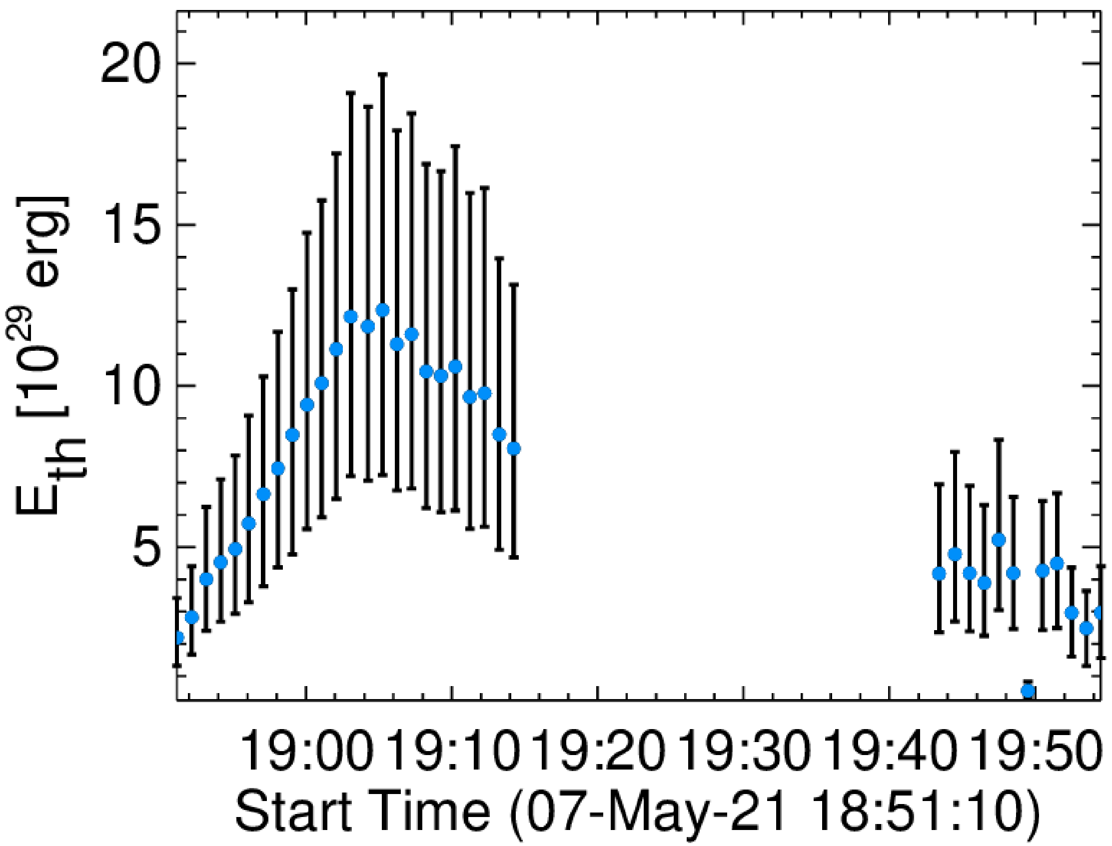
Results: abundances



- The values of aluminium abundances are close to "coronal", the abundances of magnesium are changing during flare evolution, but they are close to photospheric values.
- The abundances of Si, Ca, and Fe are changing between coronal and photospheric, while S abundance is below photospheric for the most of time.
- It was possible to calculate Ni abundance values, however, they are subject to large errors. The obtained values of Ni abundances are above "coronal" ones.

Results: flaring plasma density & thermal energy





The N_e values of the plasma are ranging between **1×10^{10} cm^{-3}** and **26×10^{10} cm^{-3}**.

The estimated thermal energy values are varying from **1.5×10^{29} erg** to **13×10^{29} erg**.

Thank you for your attention!