Using flare data to calibrate the Hinode/EIS instrument and derive element abundances

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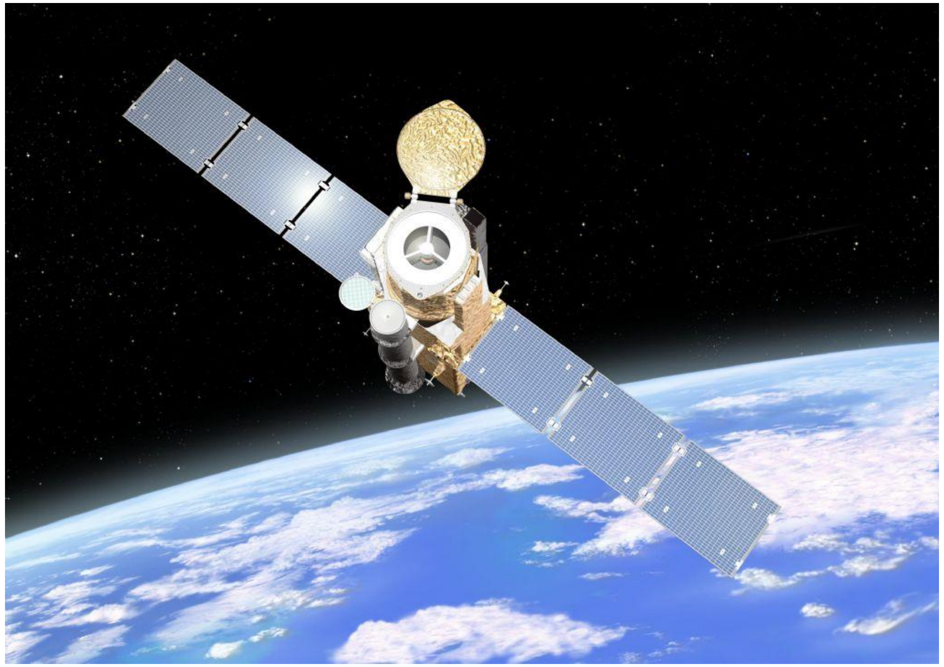
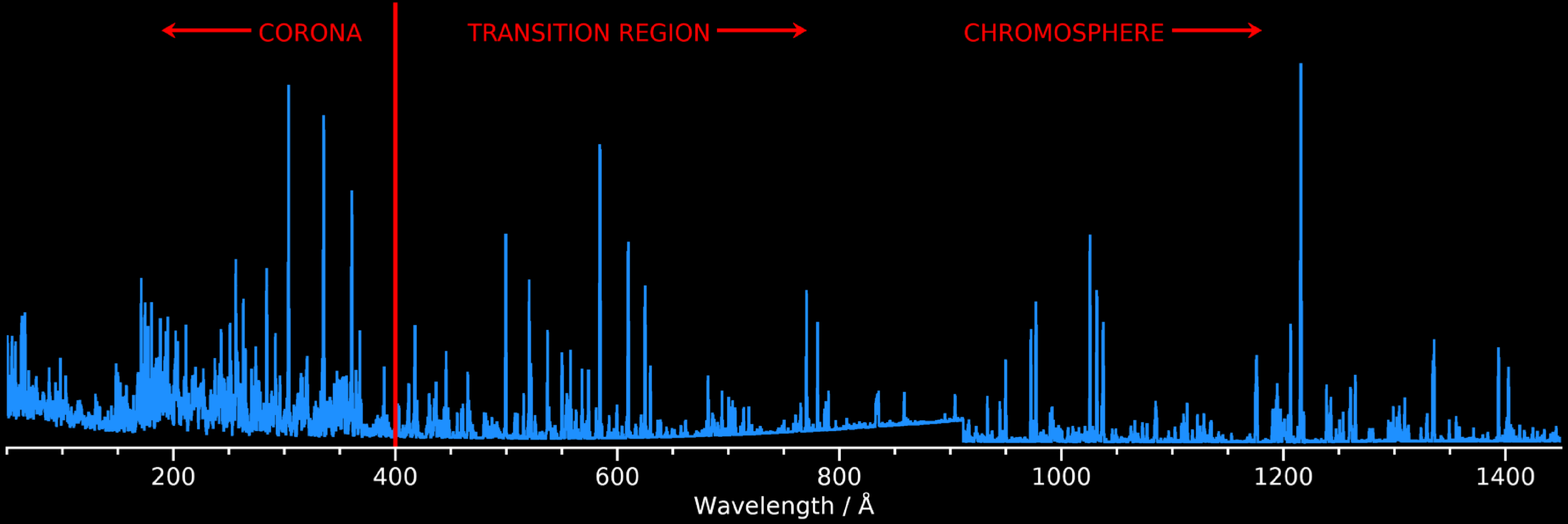
Hinode (Solar-B)

- Launched in Sep 2006
- Three instruments:
  - Solar Optical Telescope (SOT)
  - X-ray Telescope (XRT)
  - EUV Imaging Spectrometer (EIS)
- Mission goal:
  - *Study the connections between fine magnetic field elements in the photosphere and the structure and dynamics of the entire solar atmosphere.*



The EUV is the best region for studying the solar atmosphere

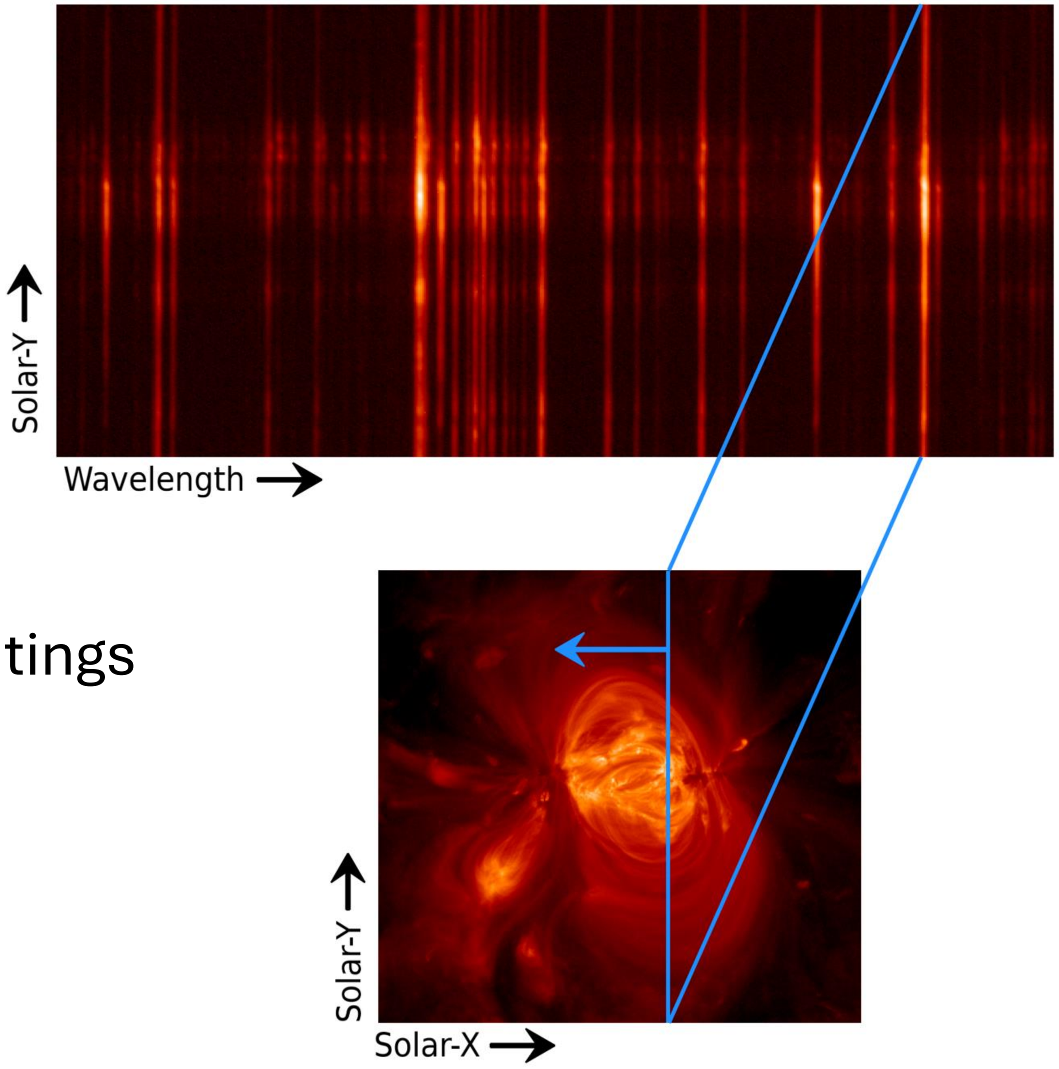


- EUV contains thousands of emission lines, diagnosing the transition region and corona

EIS: a scanning slit spectrometer

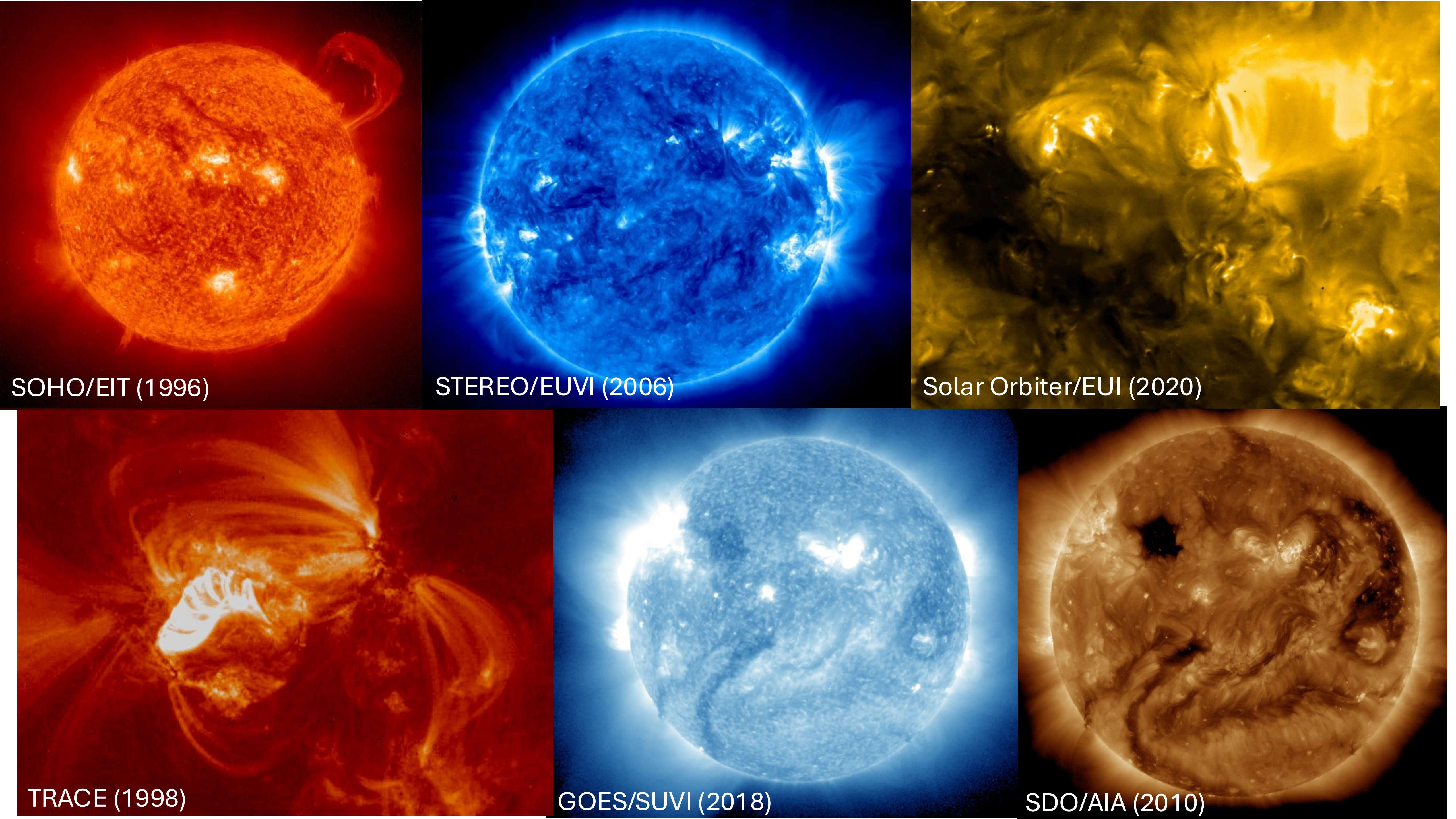
- Two wavelength bands
  - 171-212 Å and 246-292 Å
- Spatial resolution: 3 arcsec
- Images built up by *rastering*

- <u>Innovation</u>: first spacecraft EUV spectrometer to use multilayer coatings



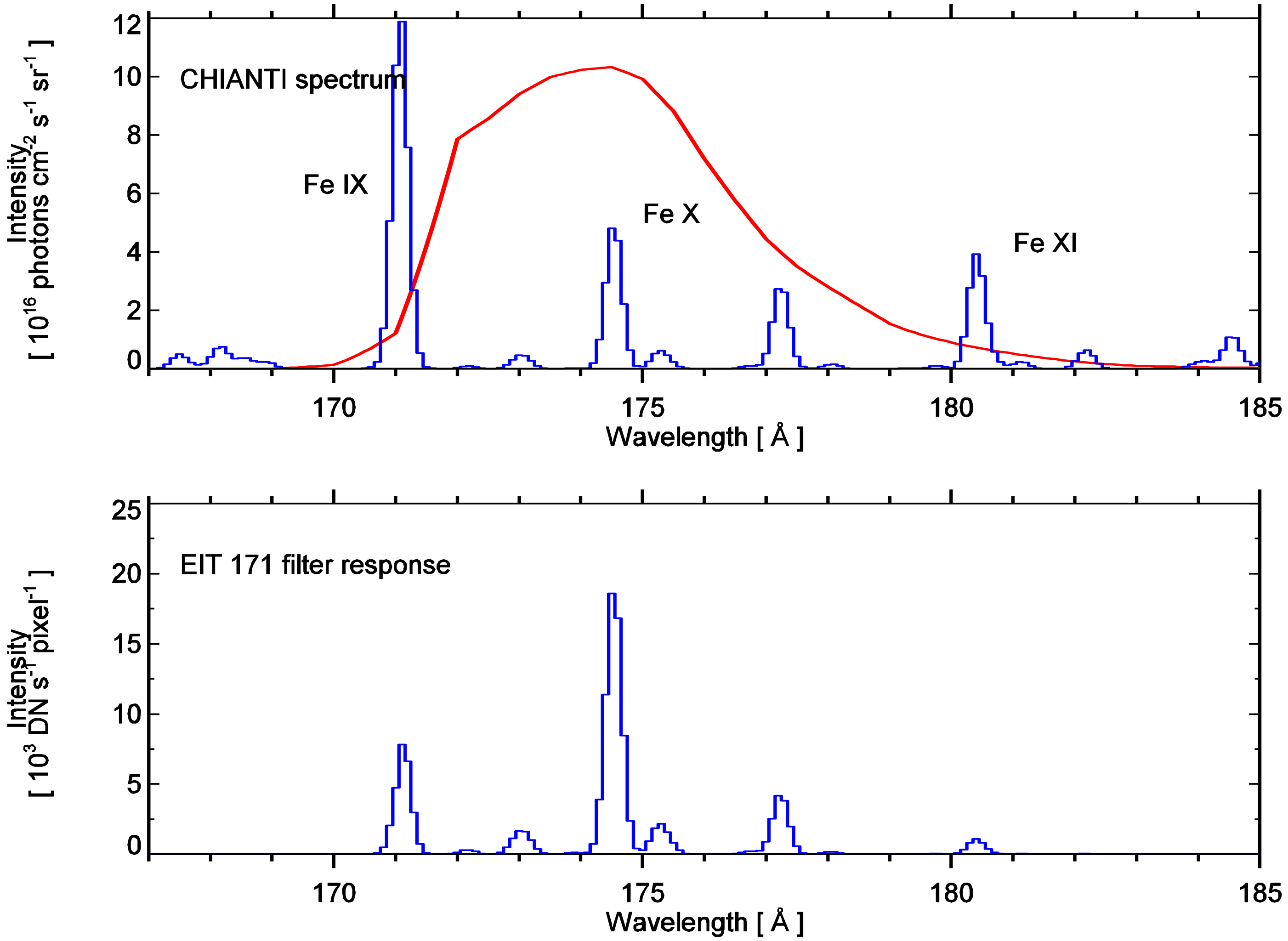
Multilayer coatings

- Standard optical surface coatings do not reflect EUV radiation.
- Early EUV instruments used *grazing incidence* optics.
- Multilayer coatings consist of alternating layers of a light and heavy element (e.g., Mo and Si).
- Used for solar observations in the 1980's (Underwood et al. 1987).
- Began the EUV imaging revolution!


SOHO/EIT (1996)
STEREO/EUVI (2006)
Solar Orbiter/EUI (2020)
TRACE (1998)
GOES/SUVI (2018)
SDO/AIA (2010)

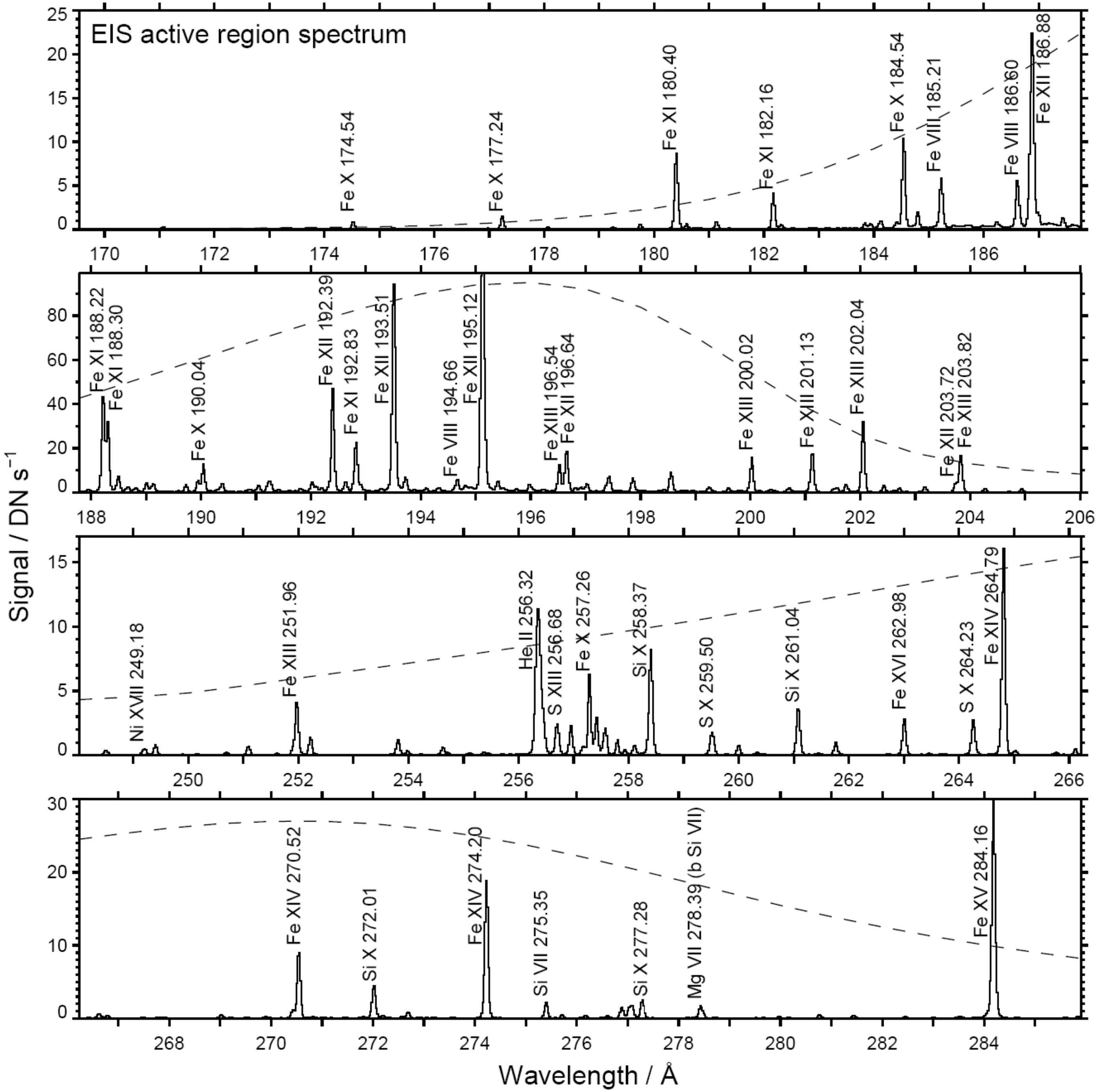
Multilayer coatings

- Multilayer coating enhances reflectivity *only over a narrow wavelength band*.
- Coating can be "tuned" to specific spectral features.



EIS multilayers

- EIS uses two multilayer coatings (applied to mirror and grating) for the two wavelength bands.
- Sensitivity varies with wavelength, particularly for short wavelength band.



Calibrating an EUV spectrometer

- Pre-launch: perform end-to-end calibration in lab.
- Perform regular checks in orbit:
  - Compare with other spacecraft instruments (e.g., EVE, AIA).
  - Cross-calibrate with rocket spectrometer (e.g., EUNIS).
  - Self-calibrate using EIS spectra.

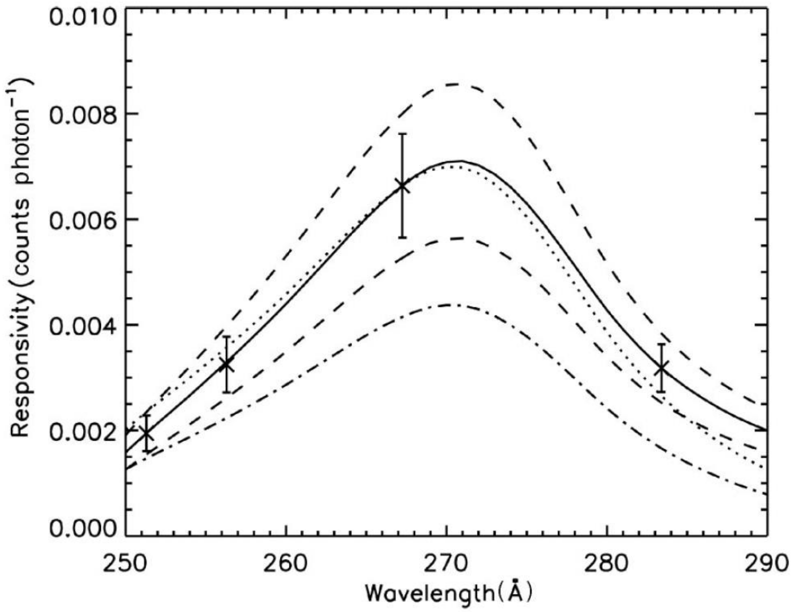
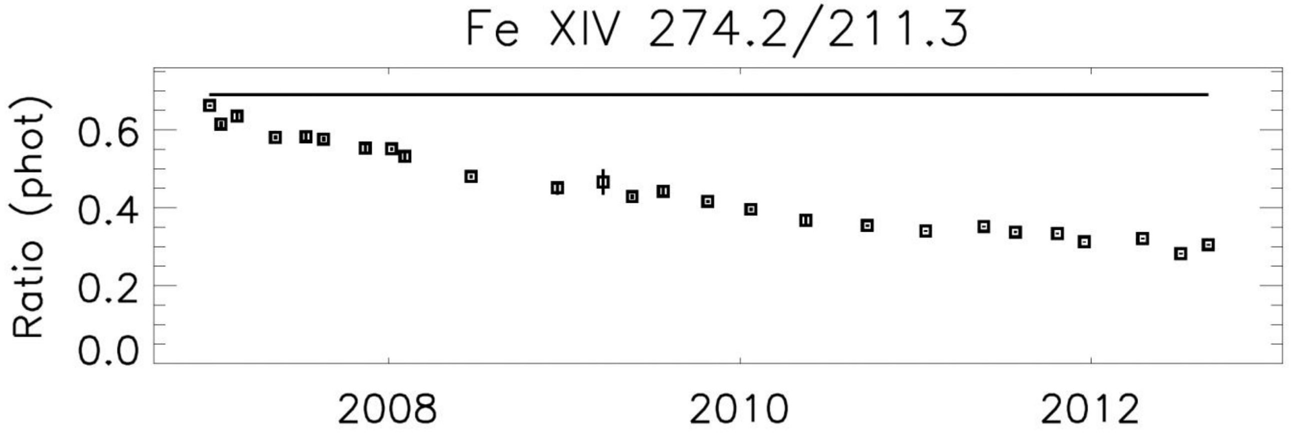


Fig. 15. LW band responsivity for the laboratory setup. The points and curves are as designated in the text.

Pre-launch calibration
(Lang et al. 2006)

Self-calibrating EIS

- Some emission line ratios are <u>insensitive</u> to plasma conditions.
  - Allow degradation to be tracked with time.
  - Check if the shape of the effective area curves are changing.
- Quiet Sun intensities are constant over solar cycle (“standard candle”).
- Quiet Sun at limb is almost isothermal.

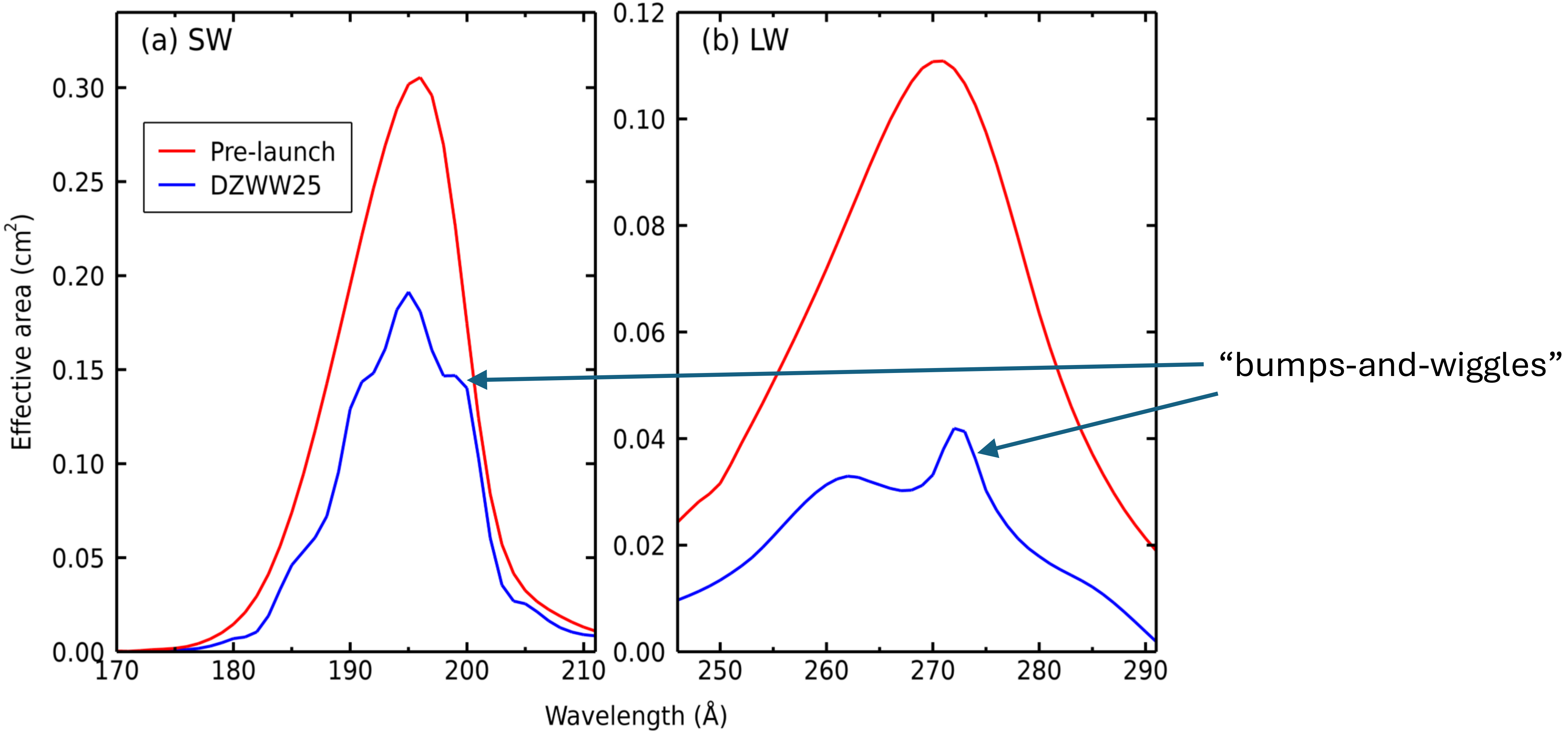


Del Zanna (2013)

EIS calibration history

- Lang et al. (2006) pre-launch calibration.
- T. Wang et al. (2011) cross-calibrated against 2007 EUNIS flight.
- Mariska (2013) found exponential decay with time.
- Del Zanna (2013) found LW channel decayed faster than SW channel.
- Warren et al. (2014) confirmed this result and obtained absolute calibration using SDO/EVE.
- Del Zanna et al. (2025): definitive new calibration over 2007-2022 period.

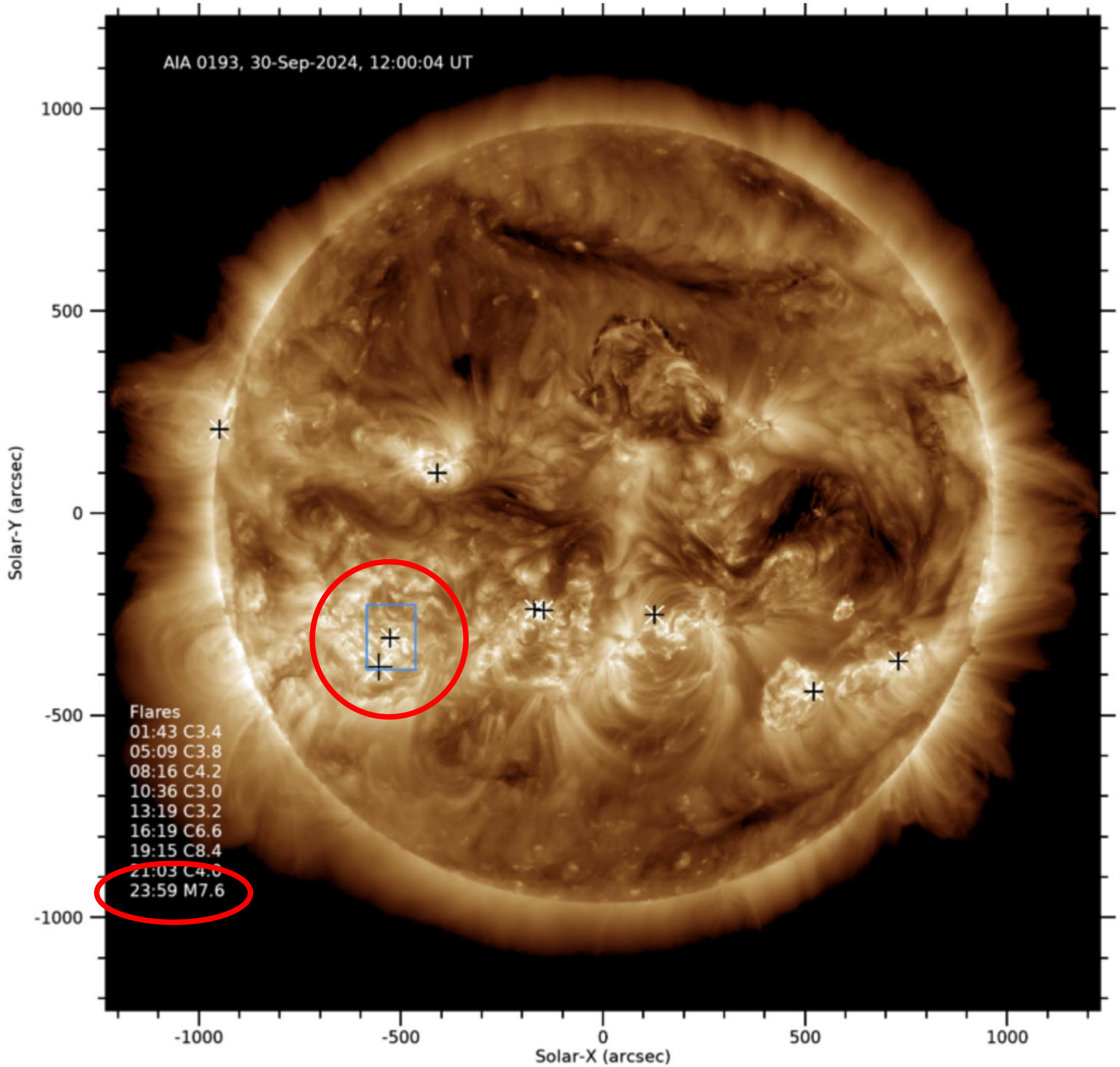
EIS calibration comparison



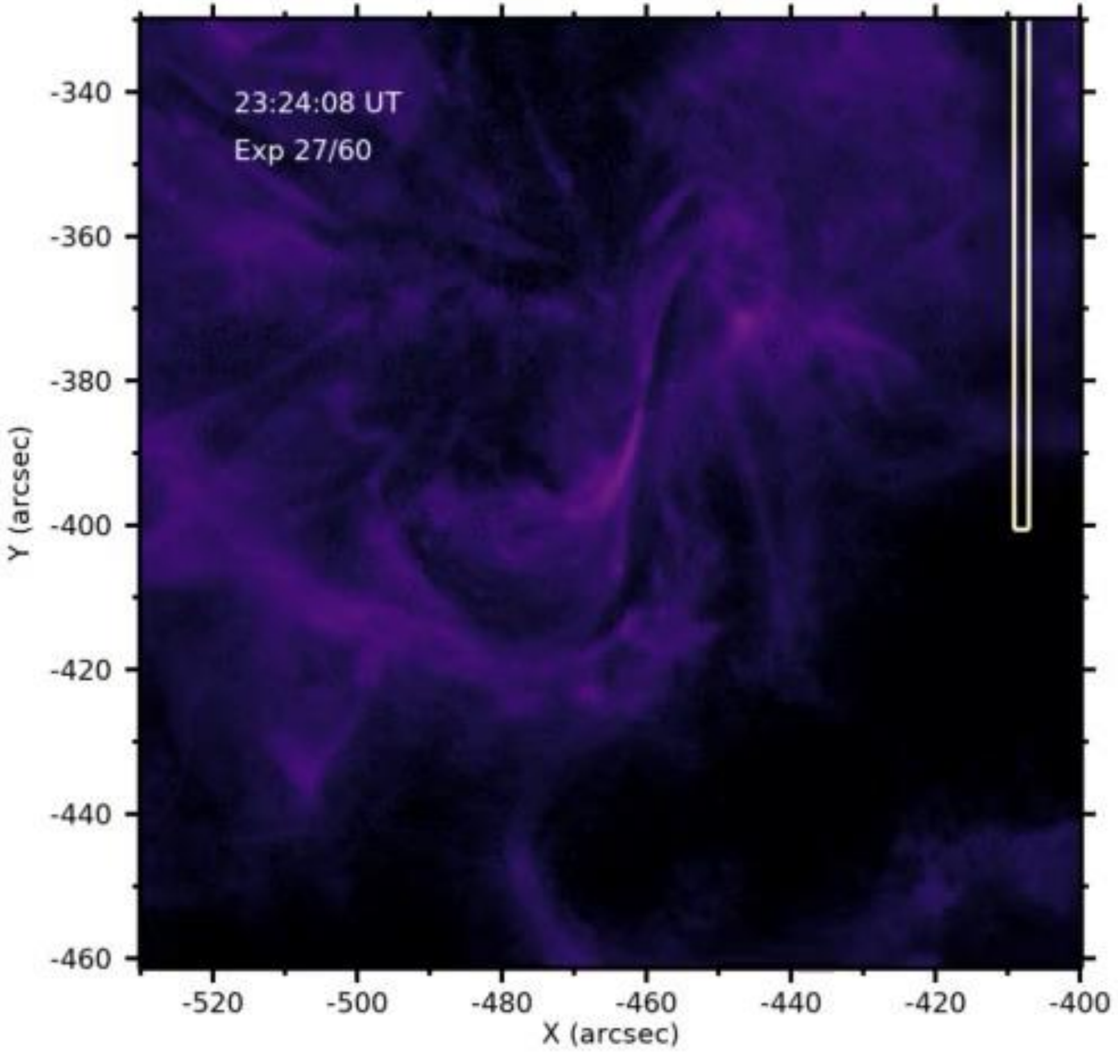
DZWW25 curves for 1-Jan-2022

Stroke of luck!

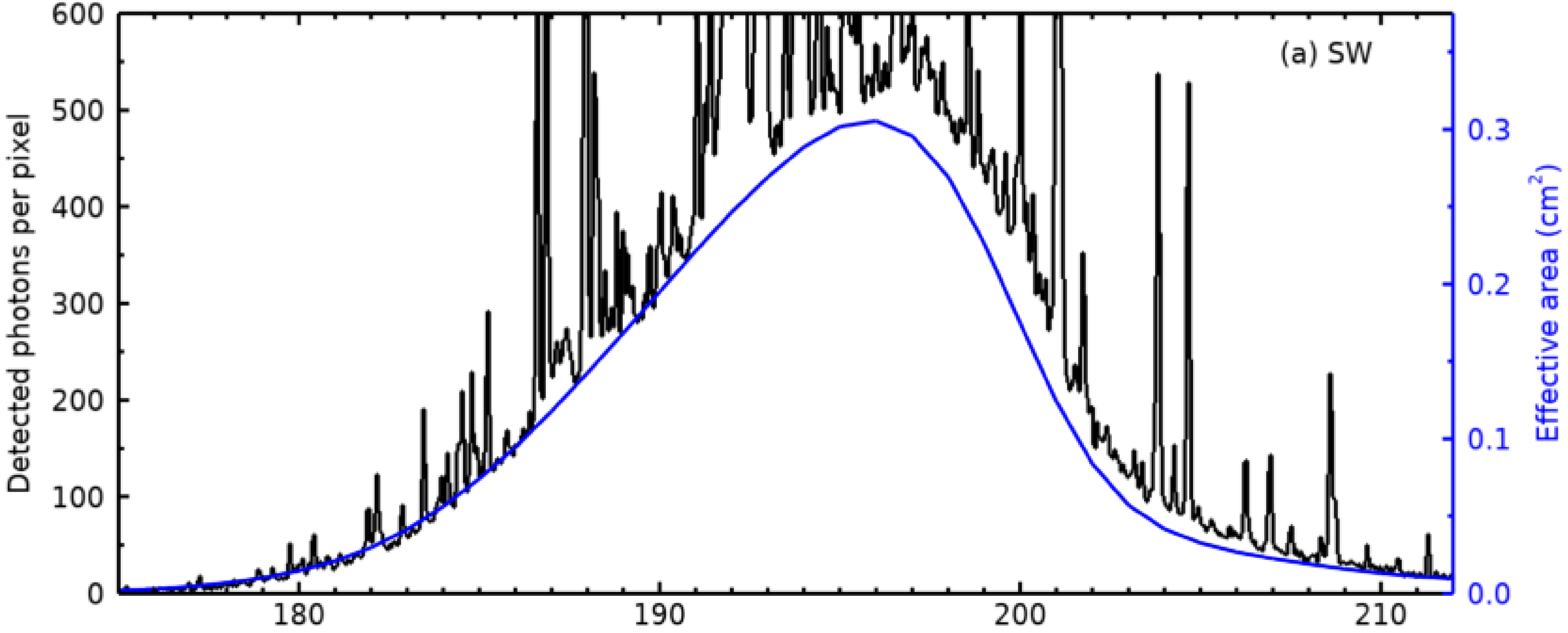
- EIS caught a big flare with a long-duration “spectral atlas” study.
- M8 flare on 30-Sep-2024.



Context movie: AIA 131 Å

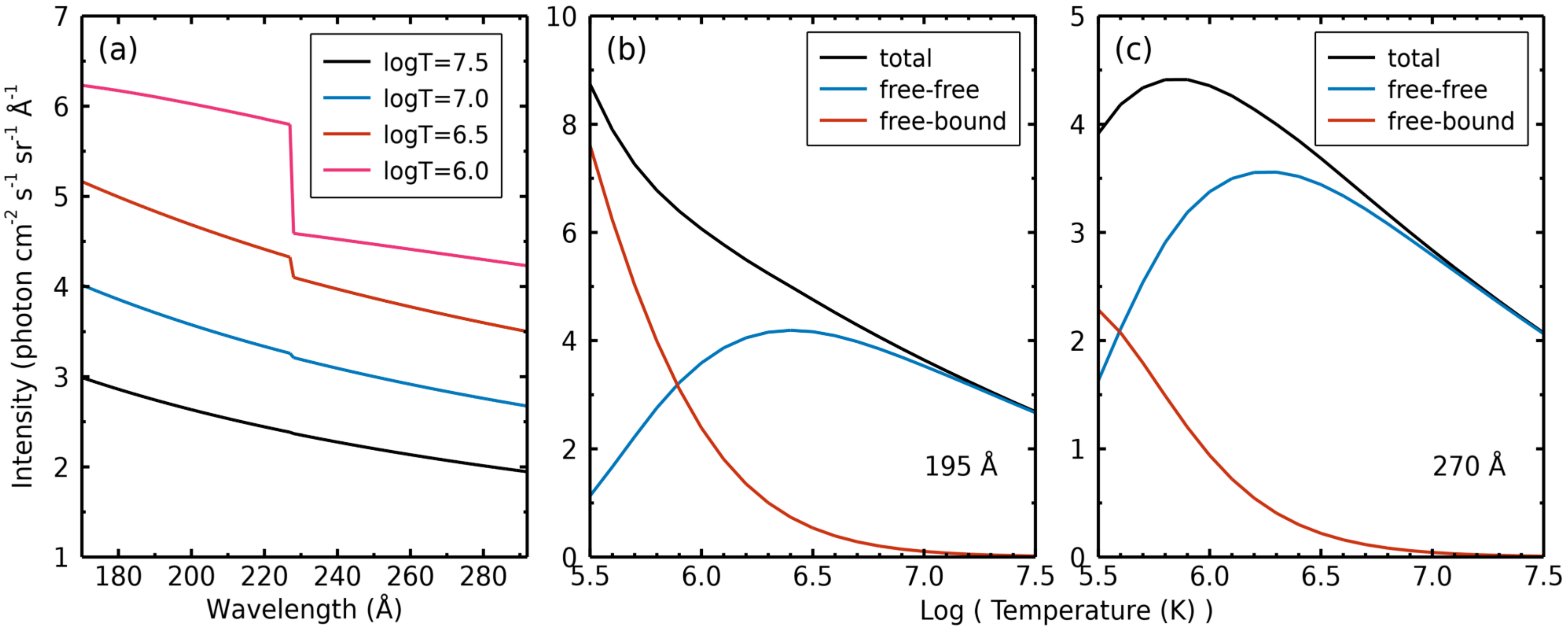


Flare continuum is very strong



- Shape of continuum curve quite similar to pre-launch effective area curve

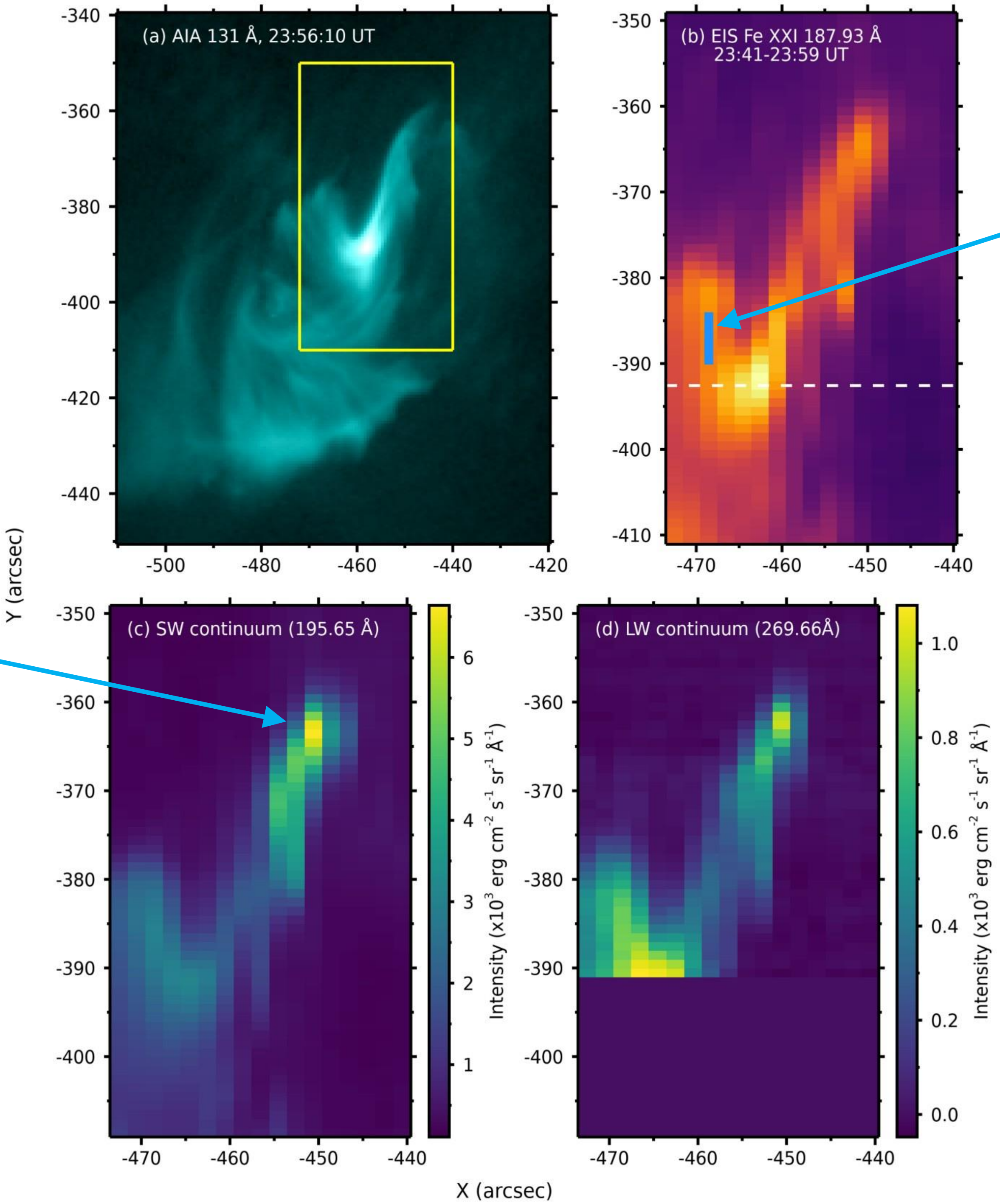
What should continuum look like?



- Curves calculated with CHIANTI software (ch_continuum).
- At flare temperatures (10 MK), continuum dominated by free-free (bremsstrahlung).
- Need to know temperature structure to model continuum.

- Right footpoint is brighter in SW continuum
- Free-bound continuum is significant (strong transition region emission)

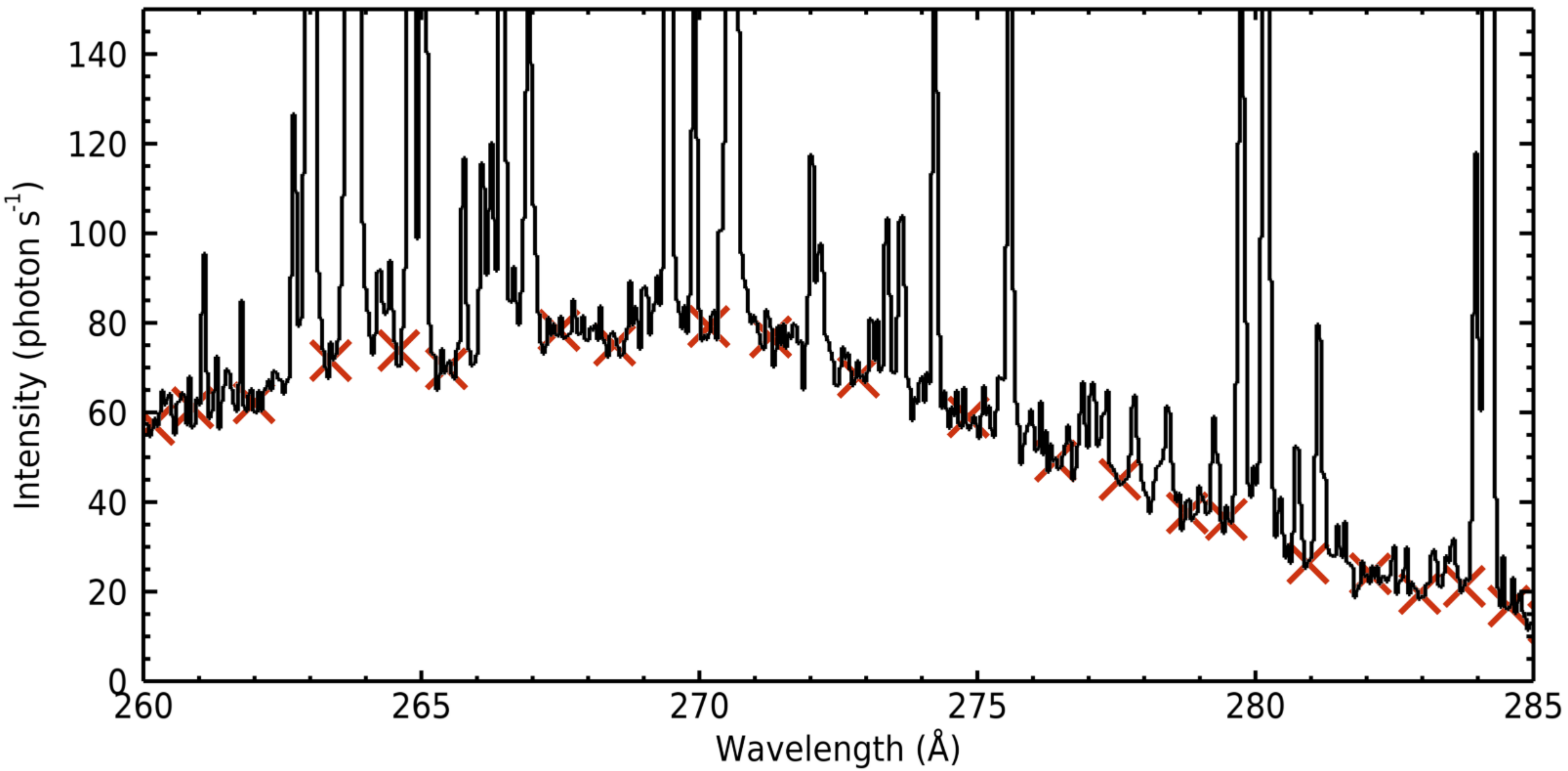
Study continuum from here



Procedure

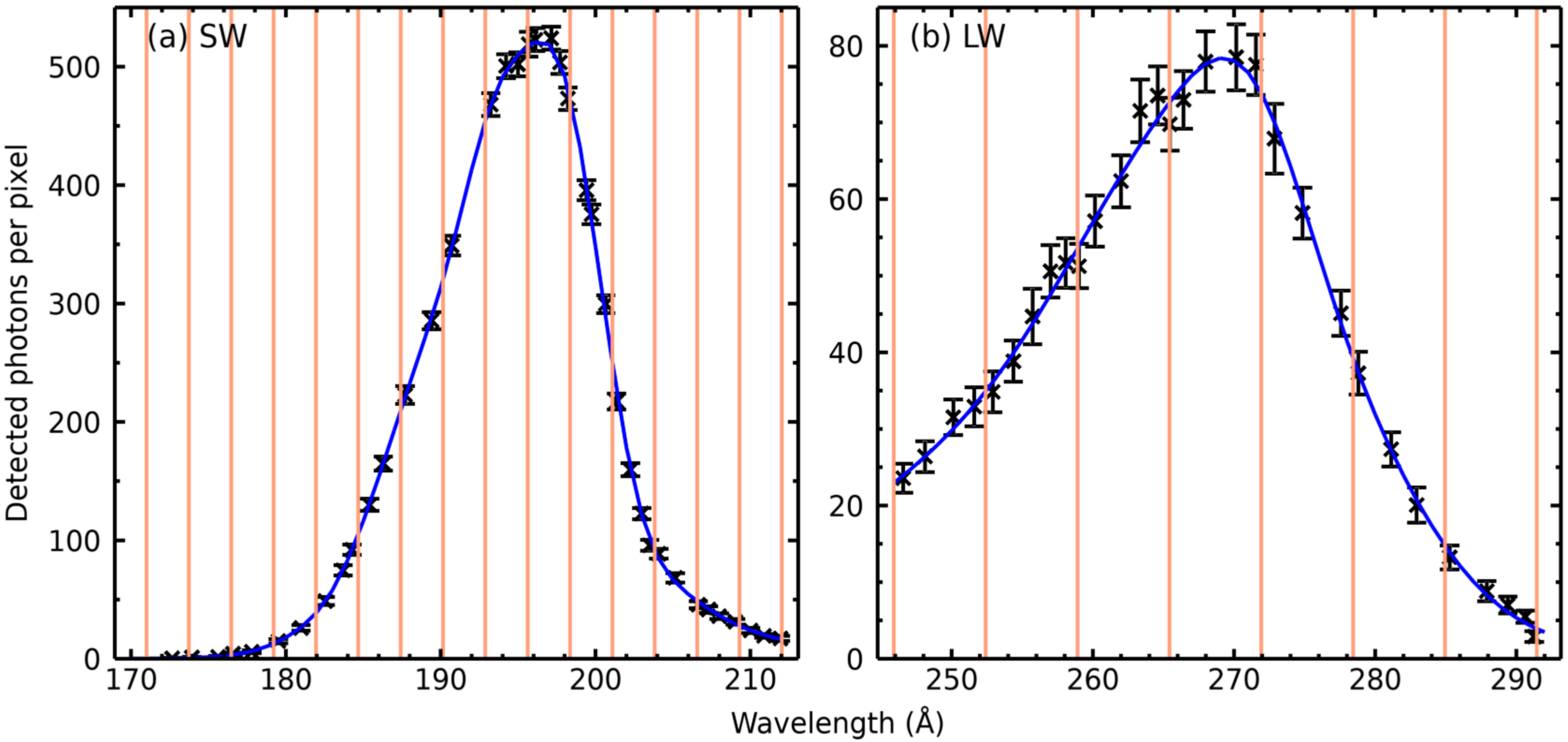
1. Measure continuum intensities from the photon spectrum at sets of wavelengths across both wavelength channels.
2. Measure a set of emission line intensities from the LW calibrated spectrum.
3. Perform a DEM analysis using the LW emission line intensities.
4. From the DEM, create a model for the continuum emission in both the SW and LW channels.
5. Derive updated SW and LW effective area curves by comparing the continuum intensities with the continuum model.
6. With the modified effective area curves, adjust the LW emission linem intensities, and repeat steps (3) to (5).

Step 1a: continuum measurement



- Choose local minima in the spectra.

Step 1b: perform spline fit to continuum intensities



- Orange lines are locations of spline nodes.

Step 2: emission lines for DEM analysis

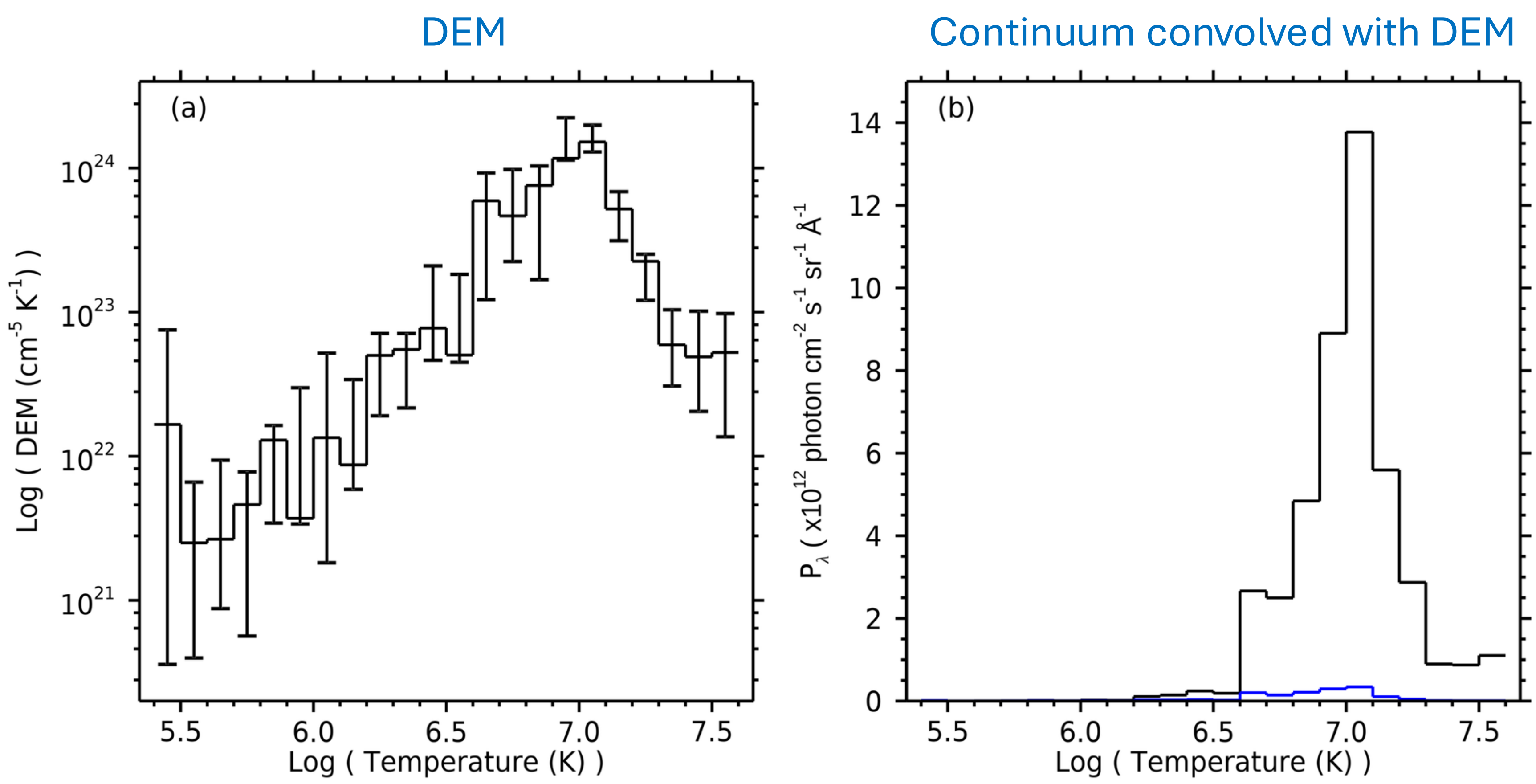
Table 1. Emission lines used for the DEM analysis.

Ion	Wavelength (Å) CHIANTI	Wavelength (Å) Measured	Intensity ($erg\ cm^{-2}\ s^{-1}\ sr^{-1}$) Observed	Intensity ($erg\ cm^{-2}\ s^{-1}\ sr^{-1}$) Model	Ratio[a]	$\log T_{max}$	$\log T_{eff}$
Si VII	275.368	275.405	108.9 ± 21.3	112.3	1.03 ± 0.20	5.75	5.85
Si X	258.374	258.399	1125.0 ± 170.2	1145.7	1.02 ± 0.15	6.15	6.15
Fe XIV	264.788	264.814	4437.5 ± 666.5	4133.2	0.93 ± 0.14	6.25	6.35
Fe XIV	274.203	274.226	2304.6 ± 346.5	1537.6	0.67 ± 0.10	6.25	6.35
Fe XV	284.163	284.190	35848.0 ± 5380.3	41903.4	1.17 ± 0.18	6.35	6.65
Fe XVI	262.976	263.010	13241.0 ± 1987.0	9849.4	0.74 ± 0.11	6.45	6.65
Fe XVII	269.420	269.443	1162.7 ± 175.5	1228.0	1.06 ± 0.16	6.75	6.85
Ti XX	259.272	259.307	610.1 ± 93.7	507.5	0.83 ± 0.13	6.95	7.05
Fe XXI	270.546	270.614	1272.9 ± 207.2	1333.1	1.05 ± 0.17	7.05	7.05
Fe XXII	247.188	247.234	2599.6 ± 393.6	2931.1	1.13 ± 0.17	7.15	7.05
Fe XXIII	263.765	263.783	9534.7 ± 1431.5	8064.0	0.85 ± 0.13	7.15	7.15
Fe XXIV	255.113	255.134	19973.0 ± 2997.5	22214.3	1.11 ± 0.17	7.25	7.15

[a] Ratio of model to observed intensity.

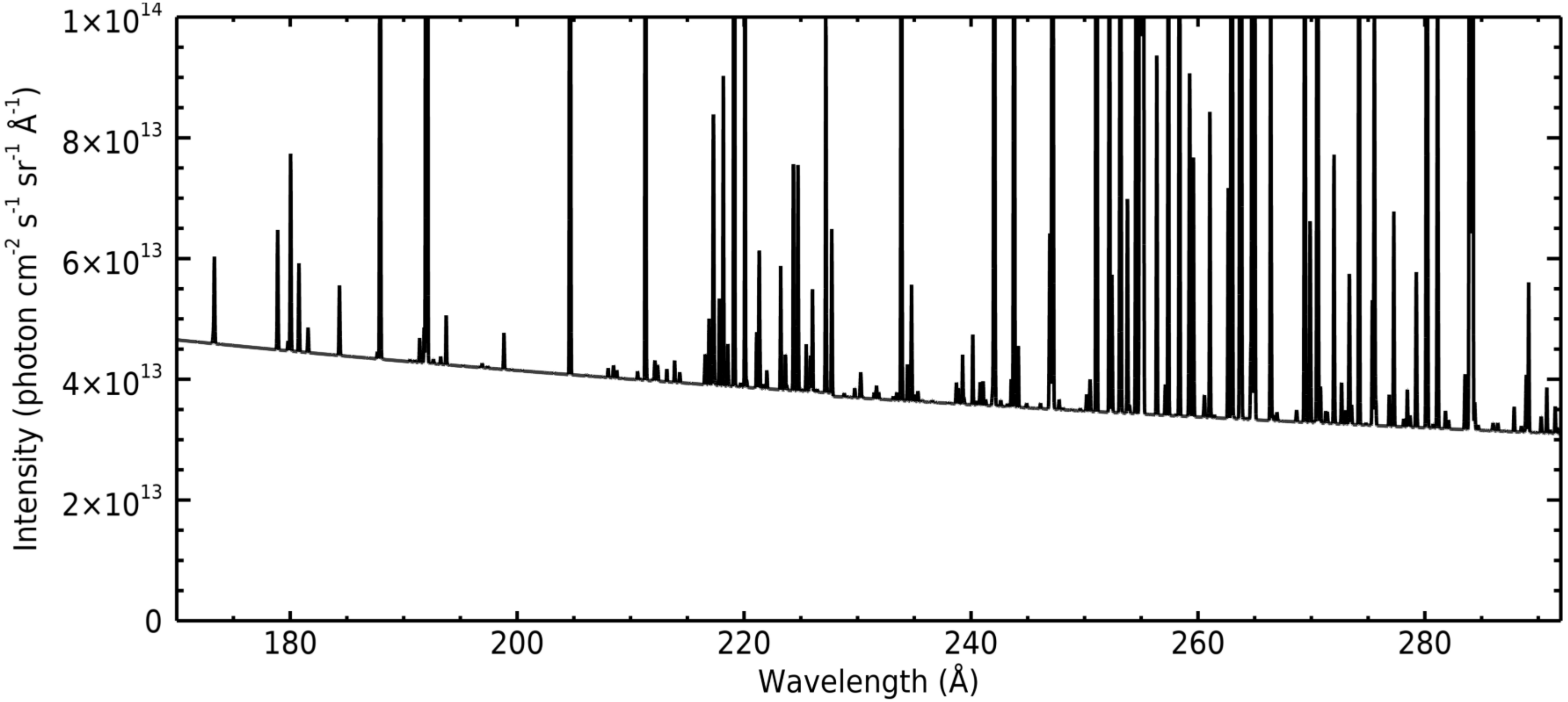
- Good coverage of hot plasma (Ti XX; Fe XXI-XXIV)
- Lines fit with Gaussian function

Step 3: emission lines for DEM analysis



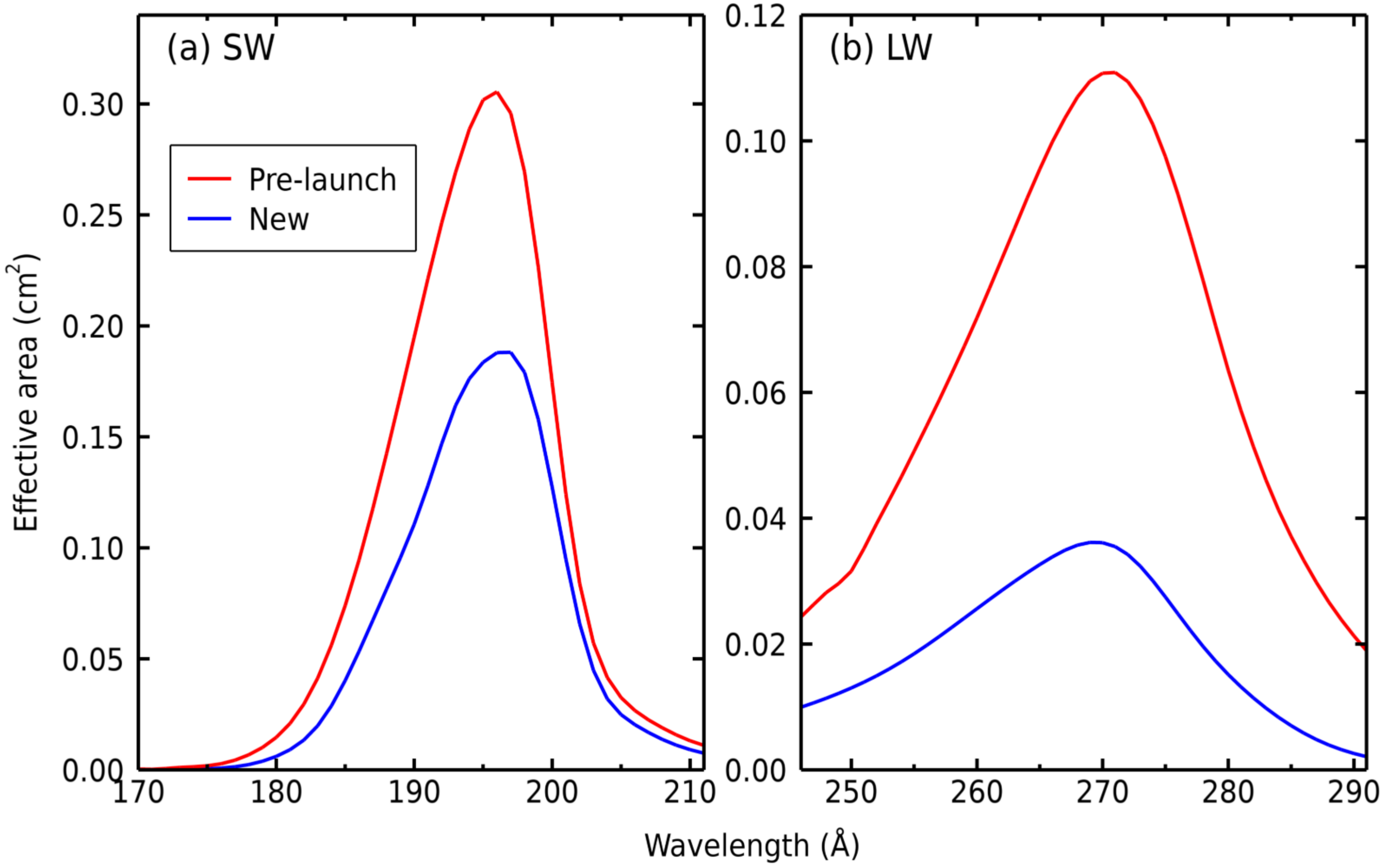
- Used the MCMC DEM method from PINTofALE software.

Step 4: calculate synthetic spectrum



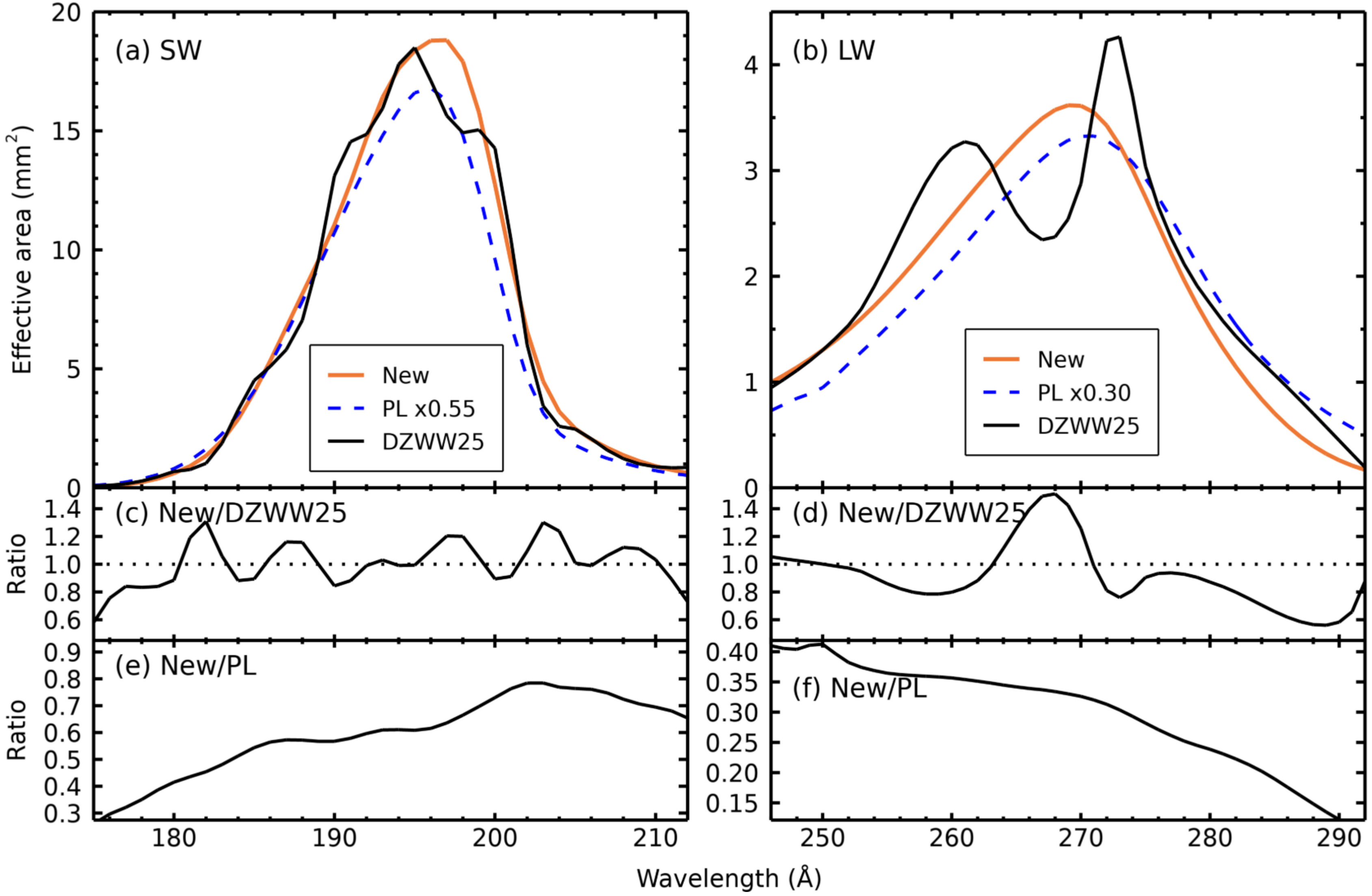
- Use CHIANTI to calculate synthetic spectrum from DEM
- Note continuum is relatively flat over EIS ranges.

Step 5: derive effective area curves



- Shapes similar to pre-launch curves.
- No evidence for the “bumps-and-wiggles”.

Comparison with Del Zanna et al. (2025)



Summary

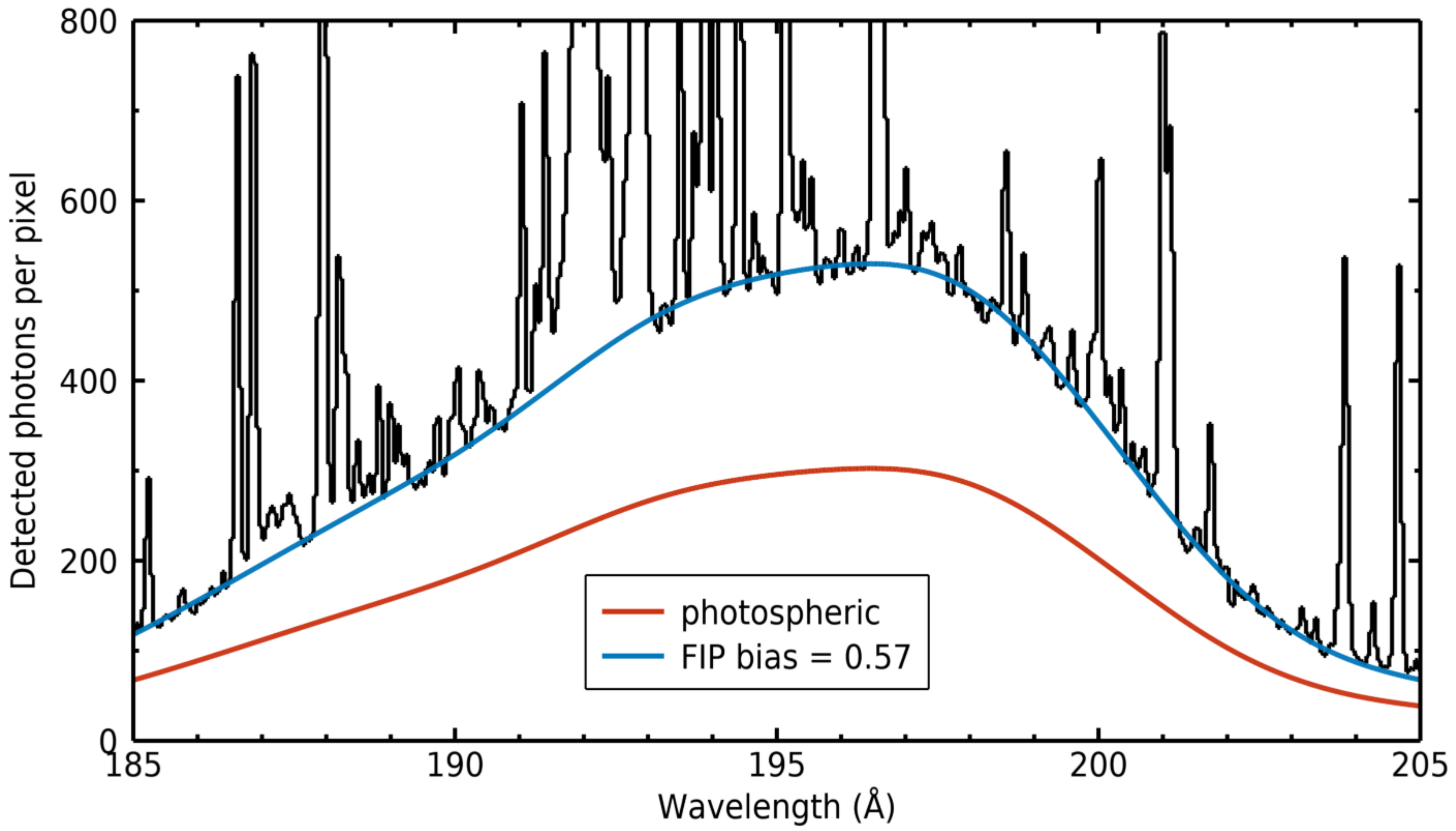
- New curves agree quite well with Del Zanna et al. (2025) – within 30% at most wavelengths.
- New curves do not show the complex structure of Del Zanna et al.

- Unique dataset that does not apply to earlier times in mission.
- However, can be used for 2022-present period
- Continuum method should be useful for MUSE and EUVST.

Element composition

- DEM is dominated by plasma at 10 MK.
- DEM shape is driven by iron ions (Fe XXI-XXIV).
- The DEM predicts the strength of the continuum but depends on choice of element abundances.
- Continuum is dominated by hydrogen: collisions of protons with free electrons.
- Allows the Fe/H relative abundance to be measured.

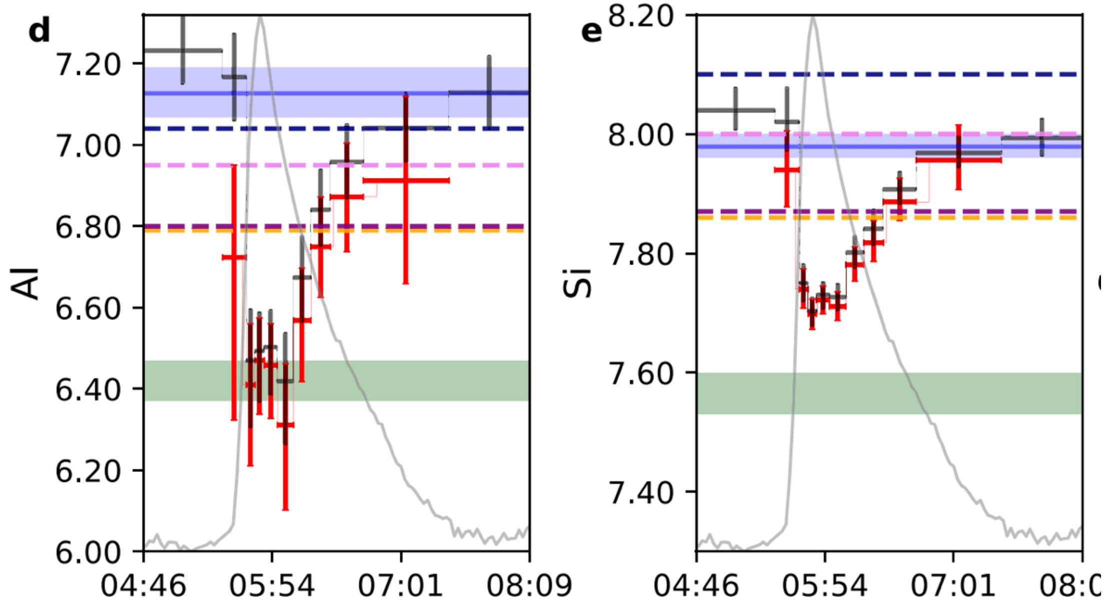
Adjust abundances to match observed continuum level



FIP bias of 0.57 (i.e., “inverse FIP effect”) gives best match

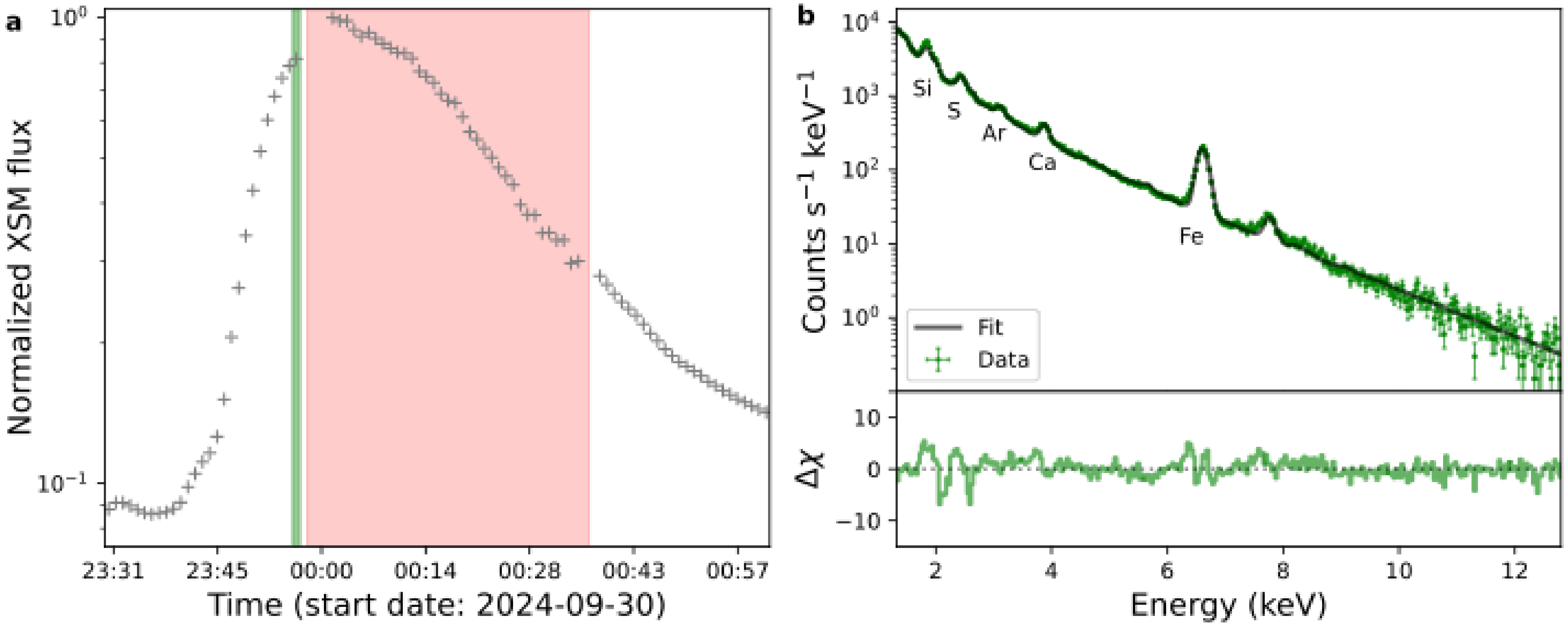
Validating abundance results

- Line-to-continuum ratios are routinely used for FIP bias measurements at X-ray wavelengths.
- The X-ray Solar Monitor (XSM) on Chandrayaan-2 measures the full-Sun solar X-ray spectrum at high time cadence.



Variation of Al and Si abundances with time for a B-class flare (Mondal et al., 2021, ApJ)

XSM results for 30-Sep-2024 flare



- Derived Fe/H ratio is 0.55, compared to 0.57 from EIS

Final summary

- First study of the EUV flare continuum using EIS data.
- Enables EIS effective area curves to be derived.
- Generally good agreement with Del Zanna et al. (2025).
- DEM analysis of lines and continuum yields Fe/H FIP bias of 0.57.
- Analysis of simultaneous X-ray data gives Fe/H FIP bias of 0.55.