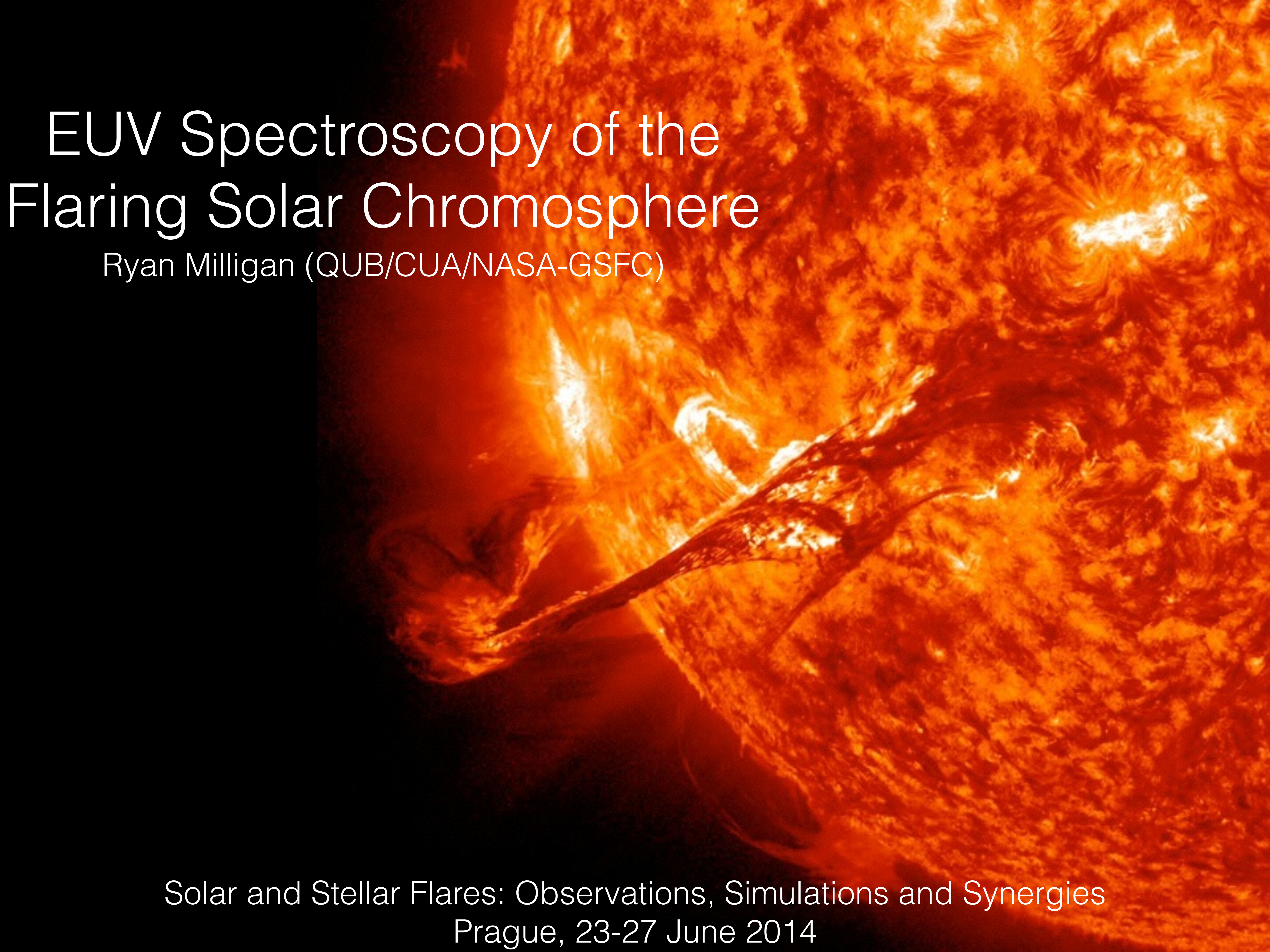
EUV Spectroscopy of the Flaring Solar Chromosphere

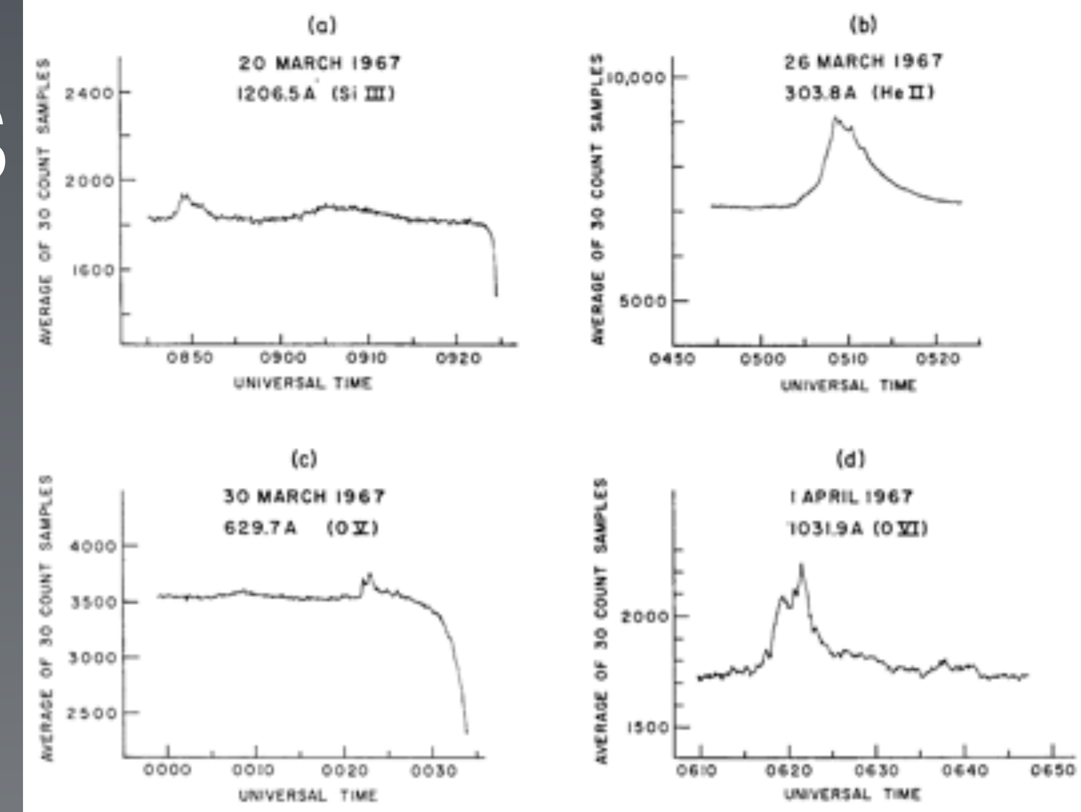
Ryan Milligan (QUB/CUA/NASA-GSFC)



Solar and Stellar Flares: Observations, Simulations and Synergies
Prague, 23-27 June 2014

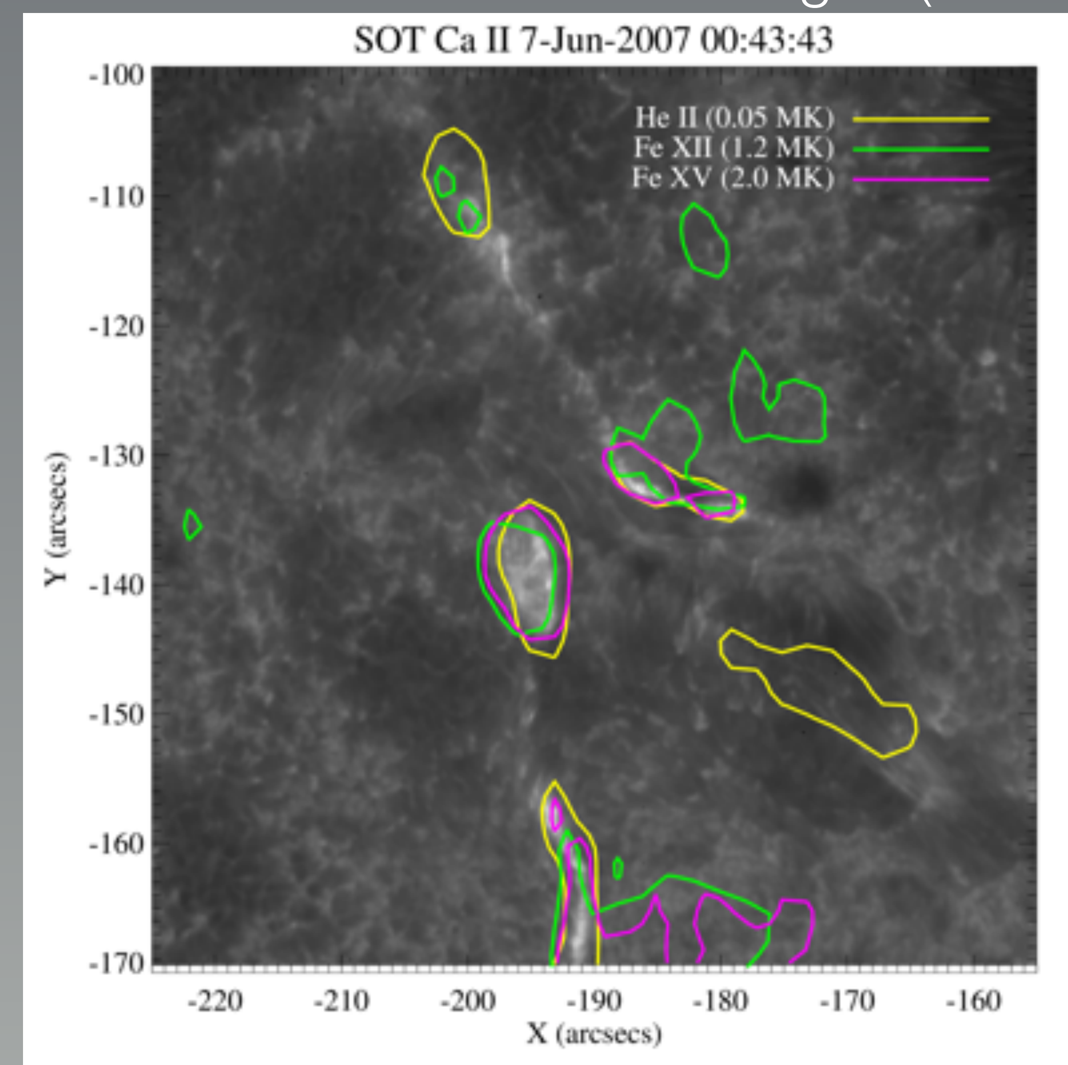
Chromospheric Flares

- The most direct manifestation of flare heating and energy transport
- Origin of coronal material though chromospheric evaporation
- Most of a flare's energy is radiated by chromospheric plasma
- Location of HXR emission; a crucial diagnostic of accelerated electrons
- Source of geoeffective emission, particularly during a flare's impulsive phase



Hall 1971

Milligan (2008)

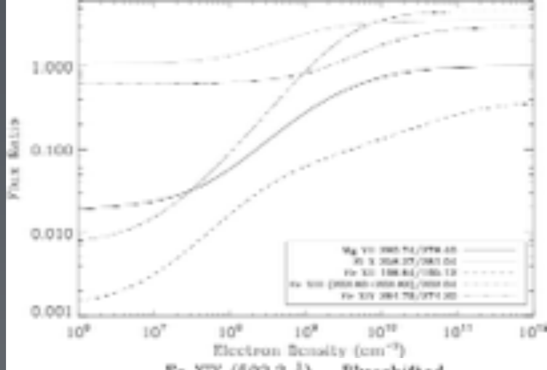


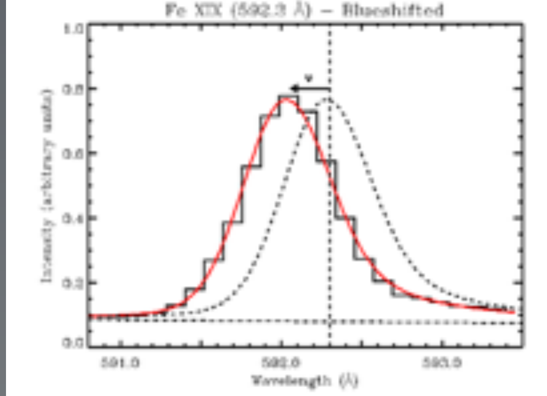
Outstanding Science Questions

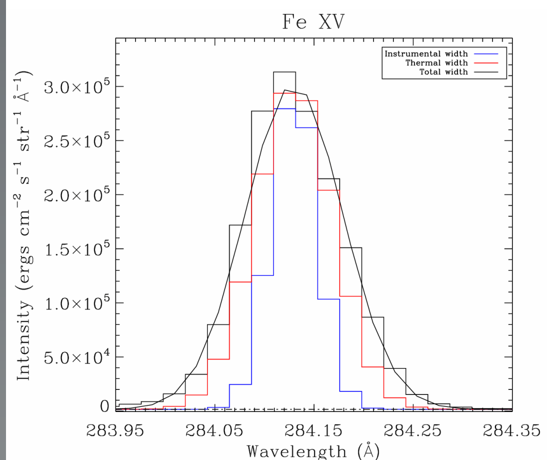
- How is energy stored in the corona transferred to the lower solar atmosphere during flares?
    - *Coulomb collisions? Backwarming? Conduction fronts? Proton beams? Alfvén waves?*
- At what depth (layer? height?) is this energy deposited?
    - *Upper/lower chromosphere? Photosphere?*
- What is the dominant emission mechanism during a flare?
    - *Recombination continua? Blackbody? Emission lines?*
- How is the anomalous 0.511 MeV line width produced?
    - *Doppler broadening at large column depths?*
- And how does chromospheric flare emission tie in with the broader field of space weather?
    - Chromospheric *Lyα affects the ionospheric D-layer. Impulsive vs. gradual? Disc centre vs. limb?*

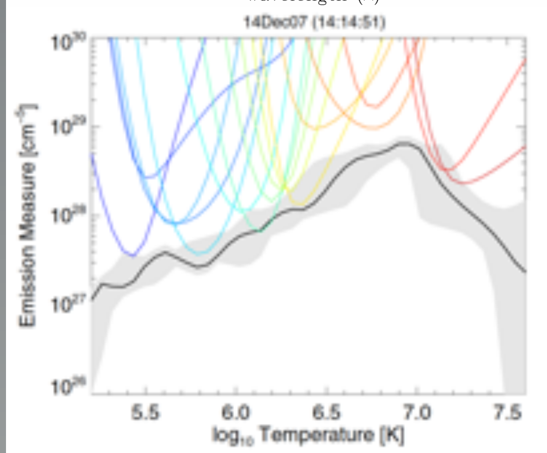
EUV Spectroscopy as a Diagnostic of Flare Plasma

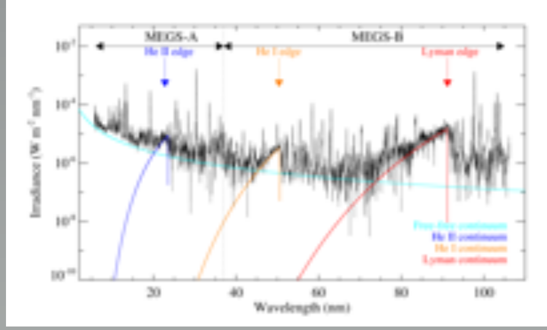
- Temperatures and densities (from line ratios)
- Flow velocities (from line shifts)
- Turbulence, opacity and pressure broadening (from line widths)
- Differential Emission Measures and Emission Measure Distributions (from line intensities)
- Energetics (from line and continuum fluxes)
- Effective and colour temperatures (from the slope and height of the continua)
- Elemental abundances (from equivalent widths, line/continuum ratios)



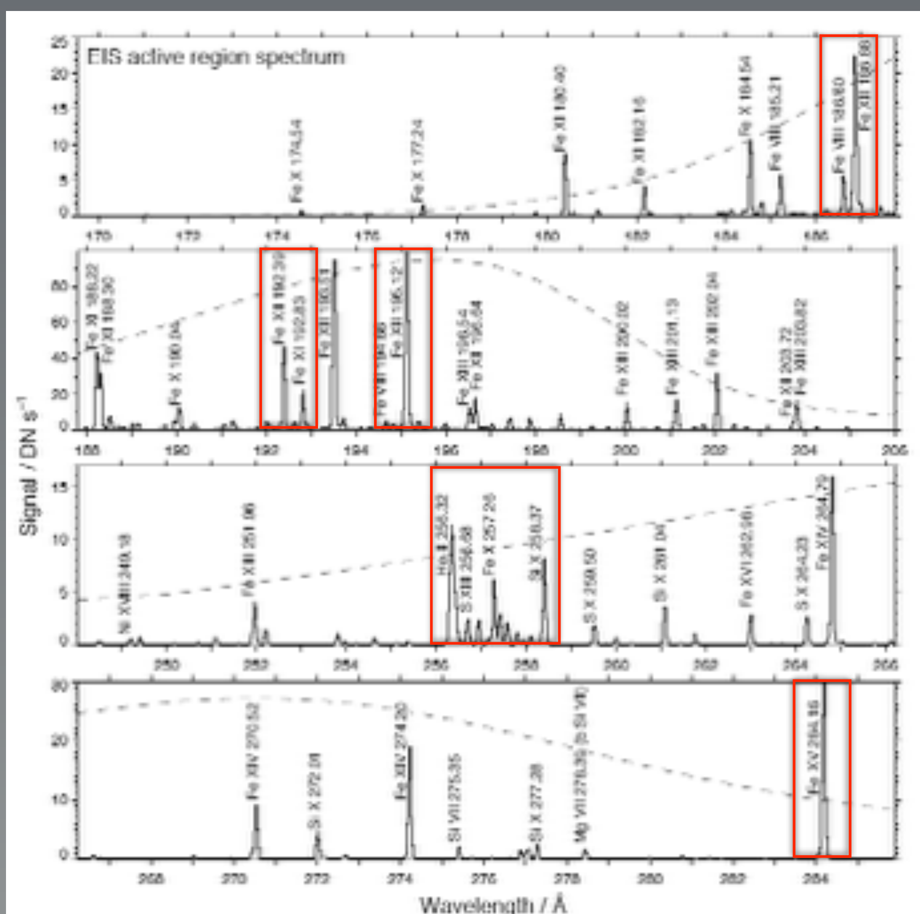


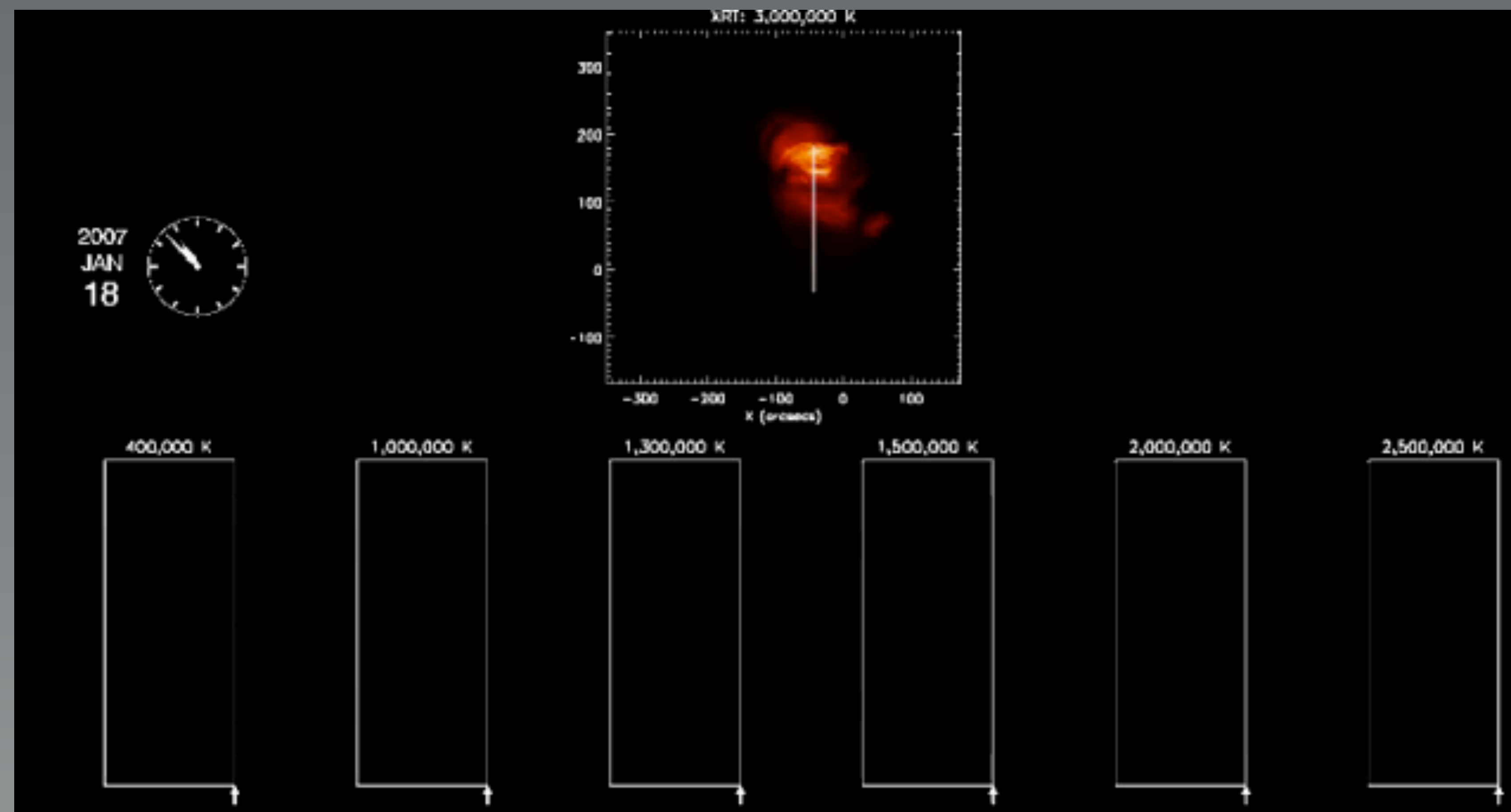




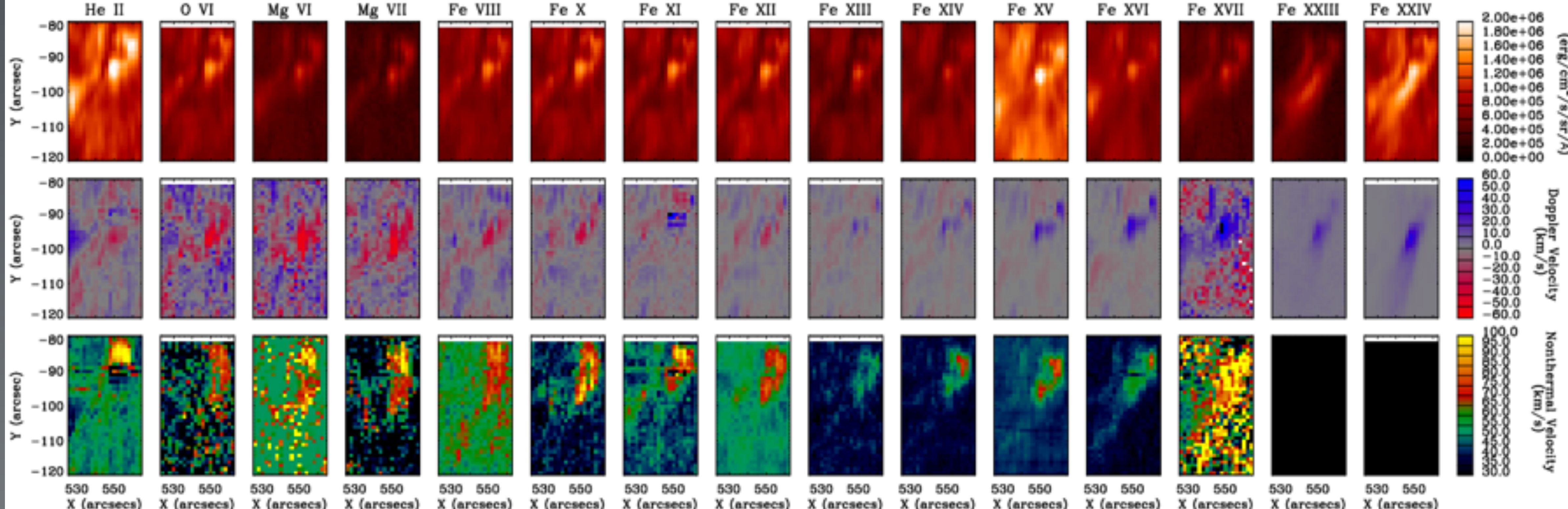


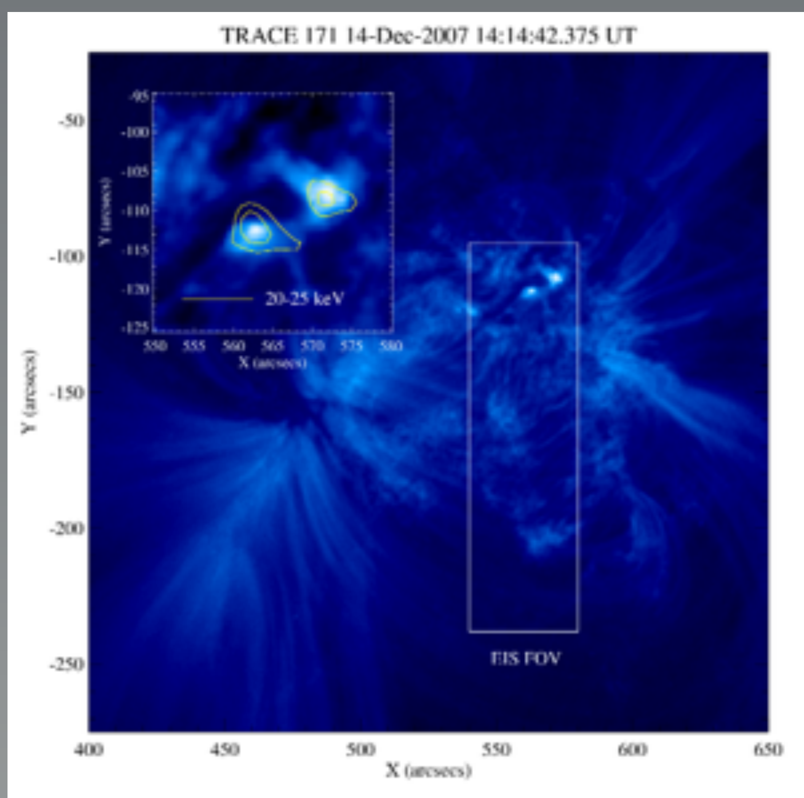
EUV Imaging Spectrometer (EIS)

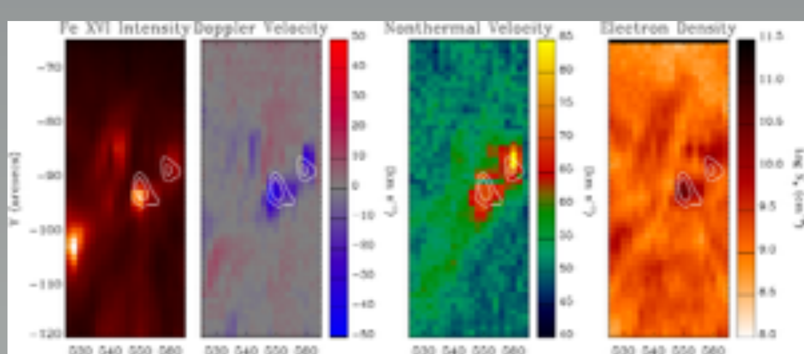




Hinode/EIS can provide spatially resolved (albeit, rastered) observations of multiple layers of the solar atmosphere simultaneously.



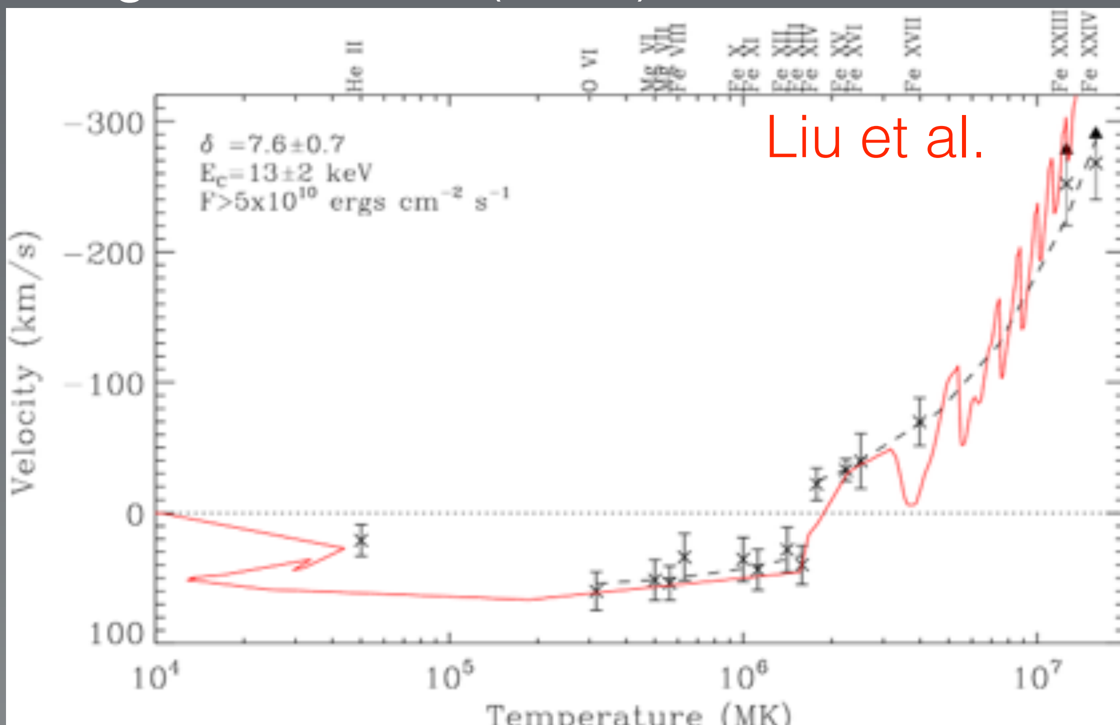


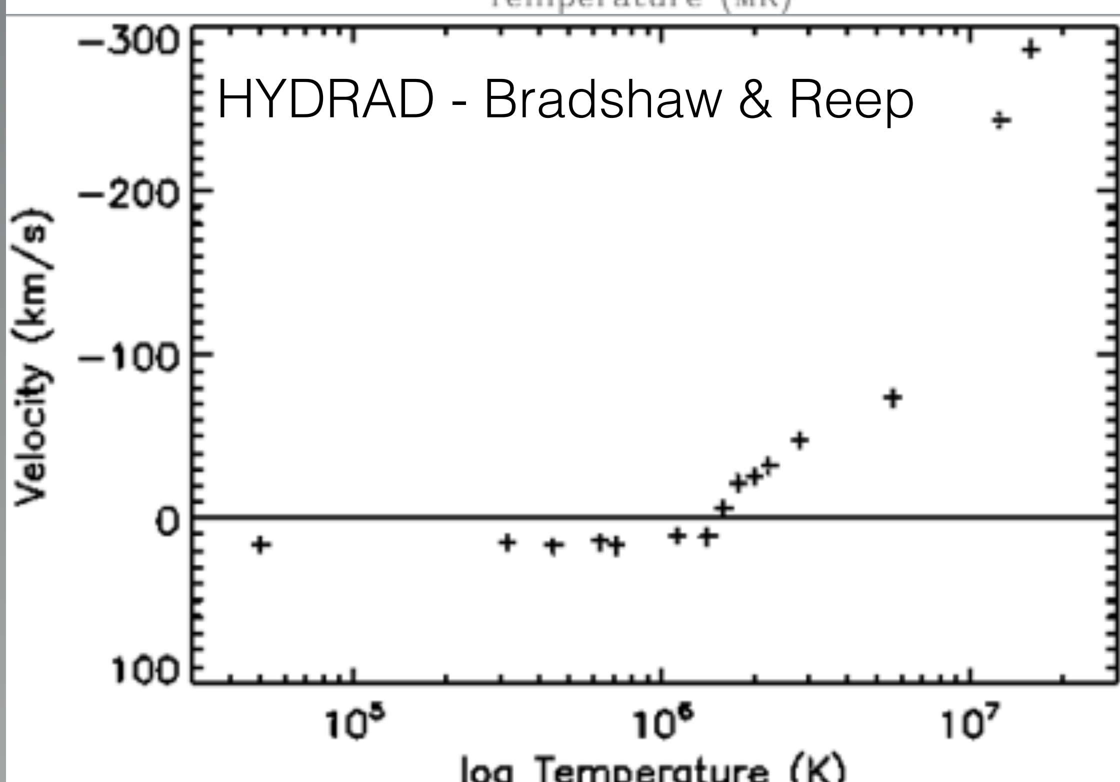


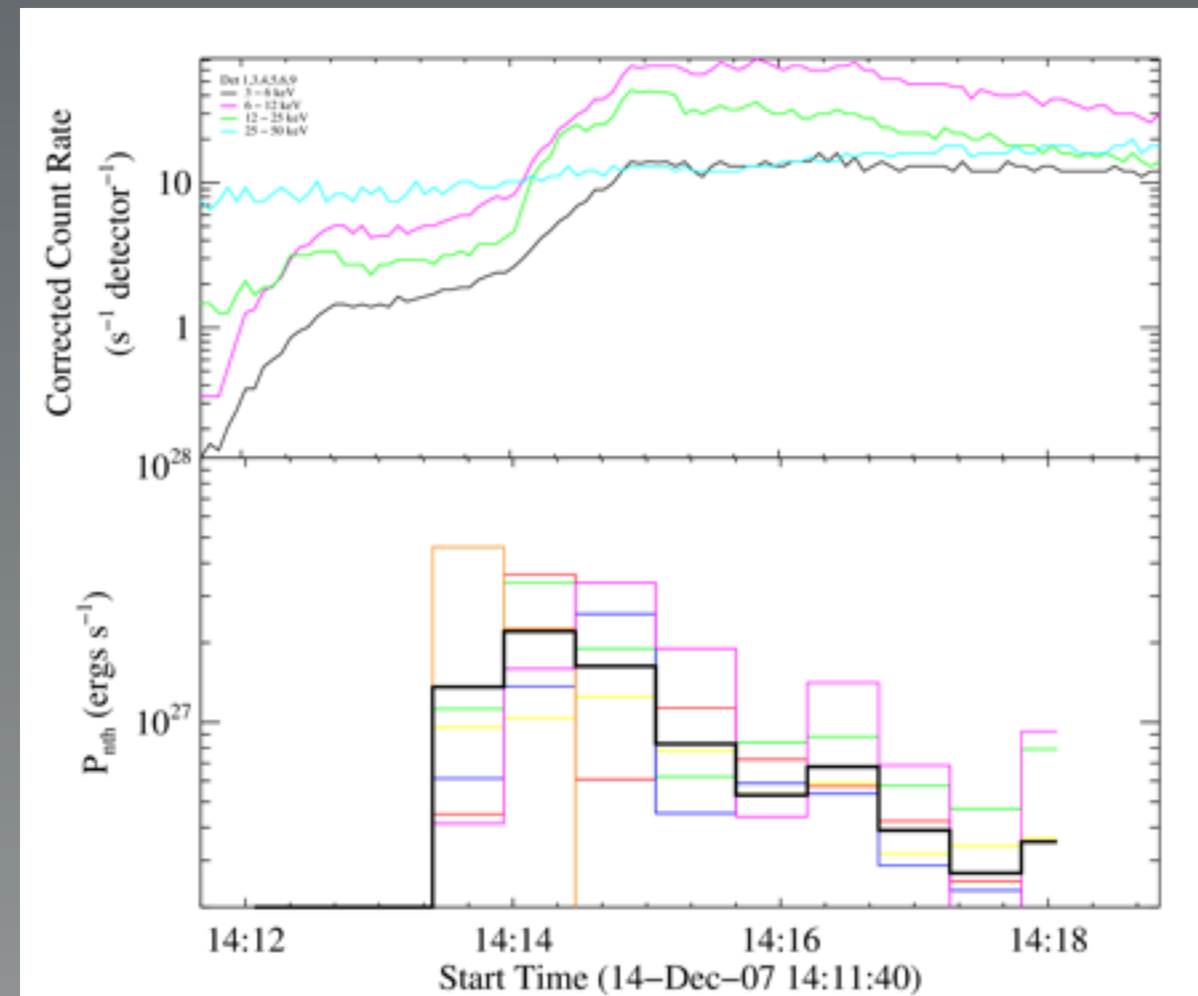
- 14 December 2007: C1.1 Flare
- Before X-band problem and after 1st RHESSI anneal
- 3.5 minute raster cadence (CAM_ARTB_RHESSI_b_2)
- He II, O IV/V/VI, Mg V/VI/VII, Si X, Ca XVII, Fe VIII-XXIV
- 5 (6?) density sensitive line pairs
- Milligan & Dennis (2009), Milligan (2011), Ning & Cao (2011), Graham et al. (2013), Graham et al. (2014; In Prep)

Chromospheric Evaporation

Milligan & Dennis (2009)



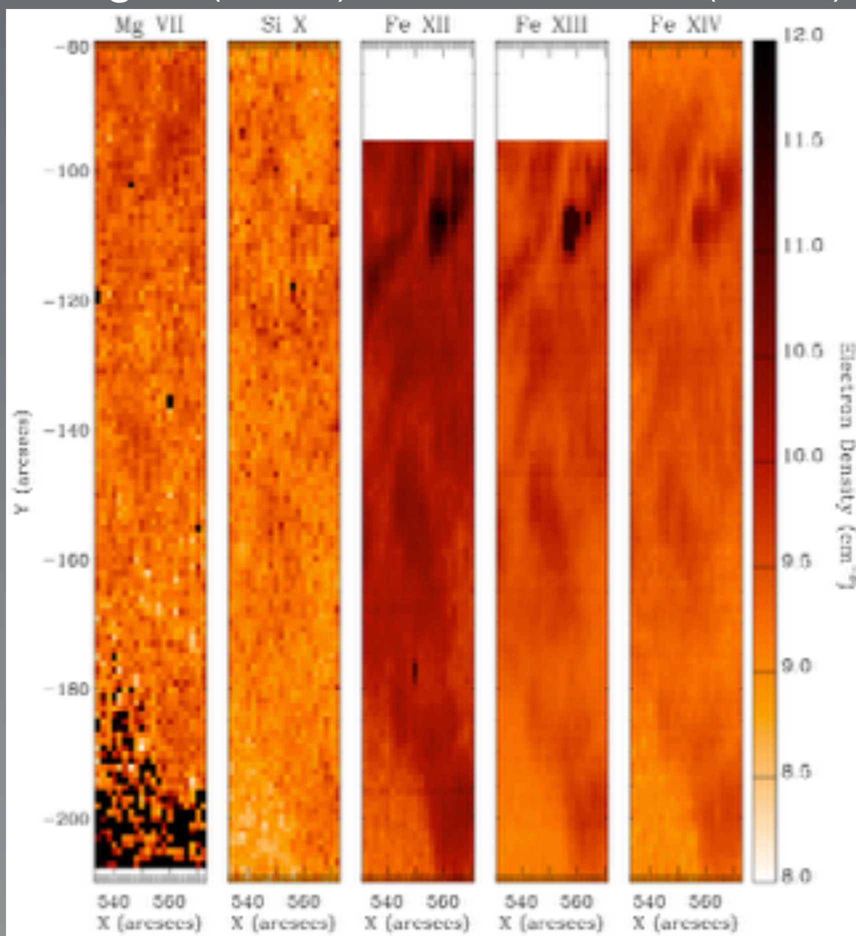




Modelled evaporation velocities in response to measured electron beam parameters from RHESSI give remarkably good agreement

Electron Density

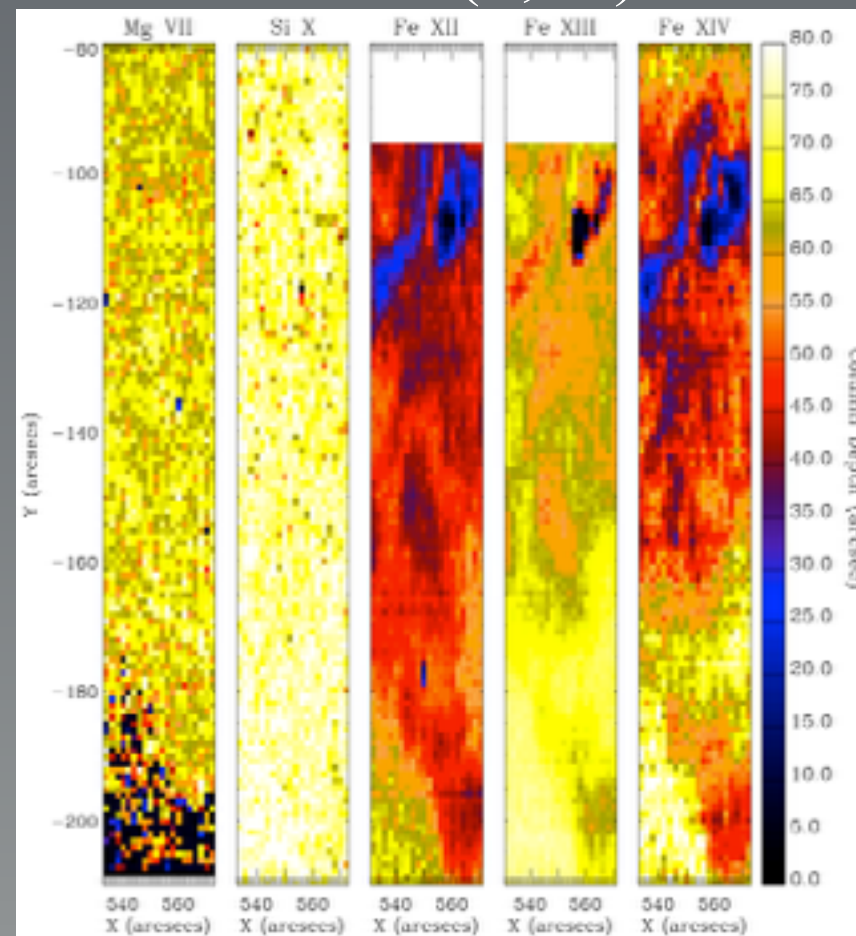
Milligan (2011), Graham et al. (2013)



FP densities > 10^{11} cm^{-3}

Column Depth

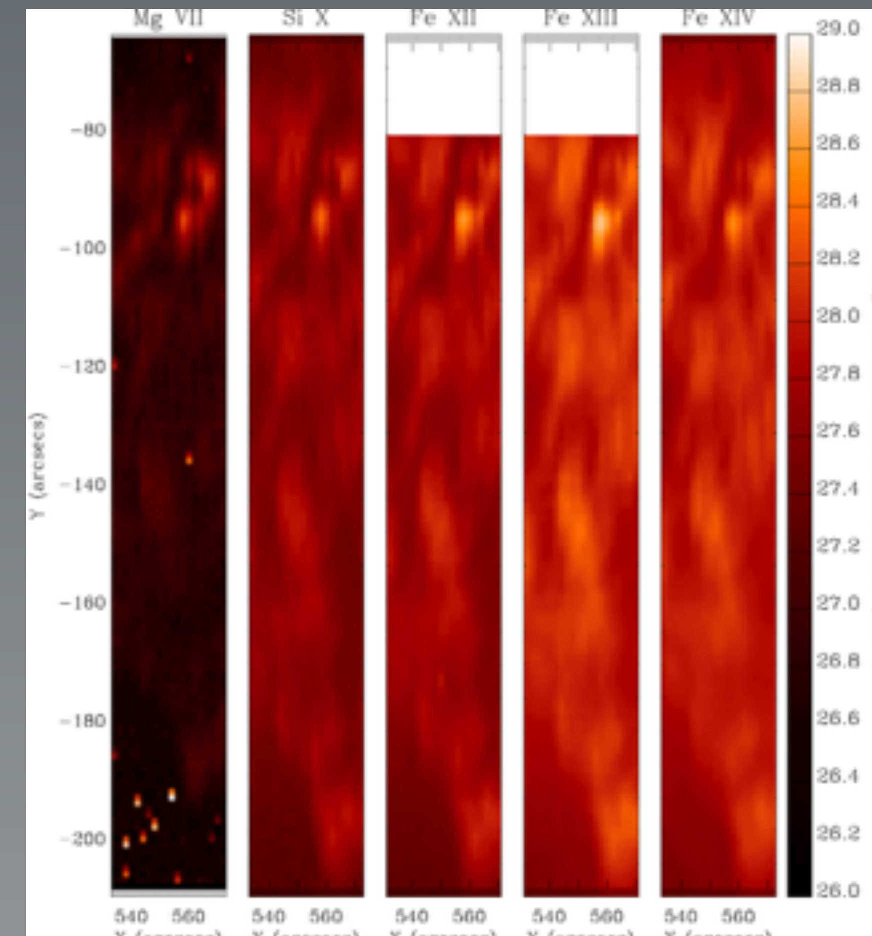
$4\pi I = 0.83\int G(T,N_e)N_e^2 dh$



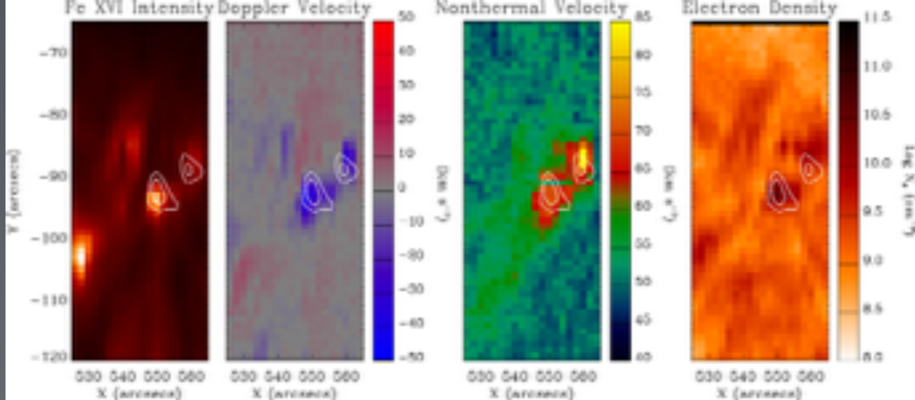
FP Column Depth <15″

Column Emission Measure

$EM_{col}=\int N_e^2 dh$

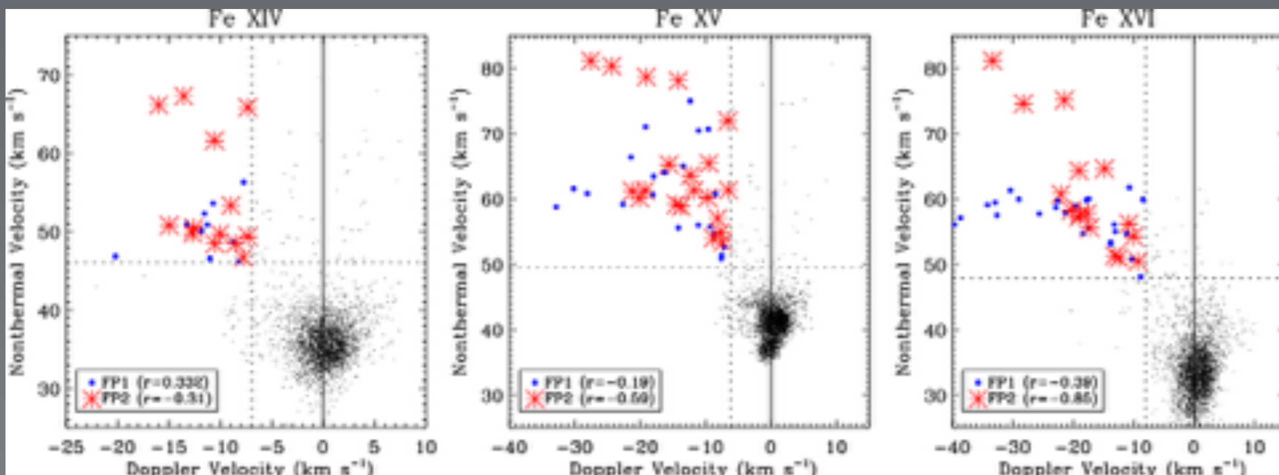


FP Column EM >10^{28} cm^{-5}

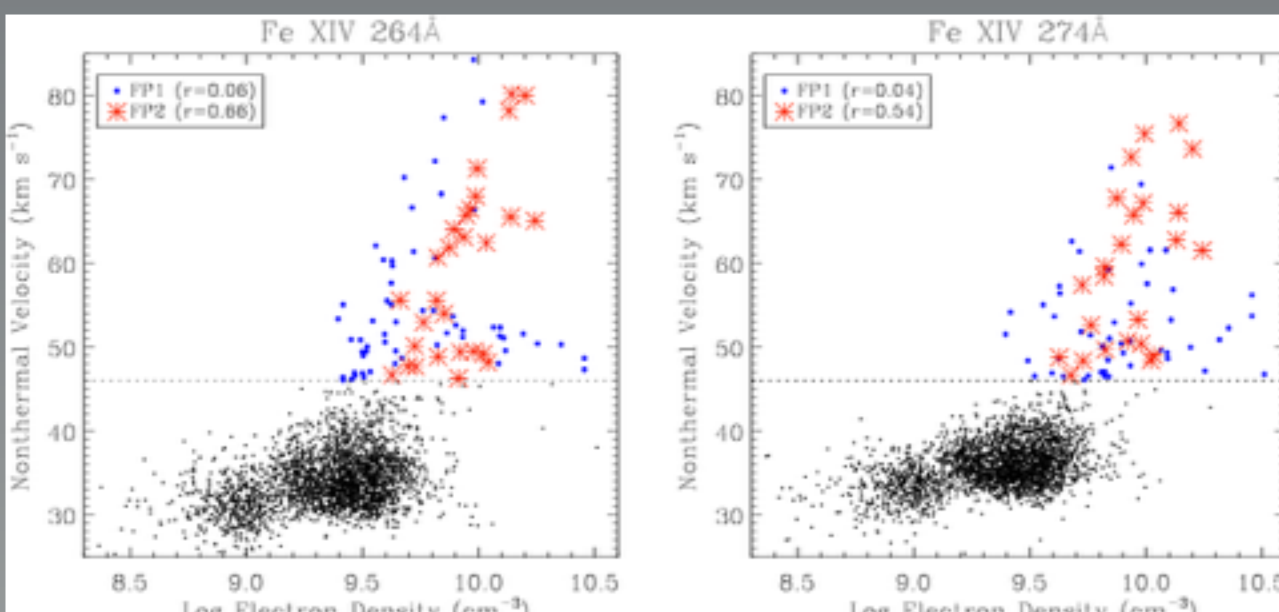


Nonthermal Line Broadening

$$W_{tot} = W_{inst} + W_{th} + W_{nth}$$



Correlation with Doppler velocity implies unresolved Doppler components (turbulence)



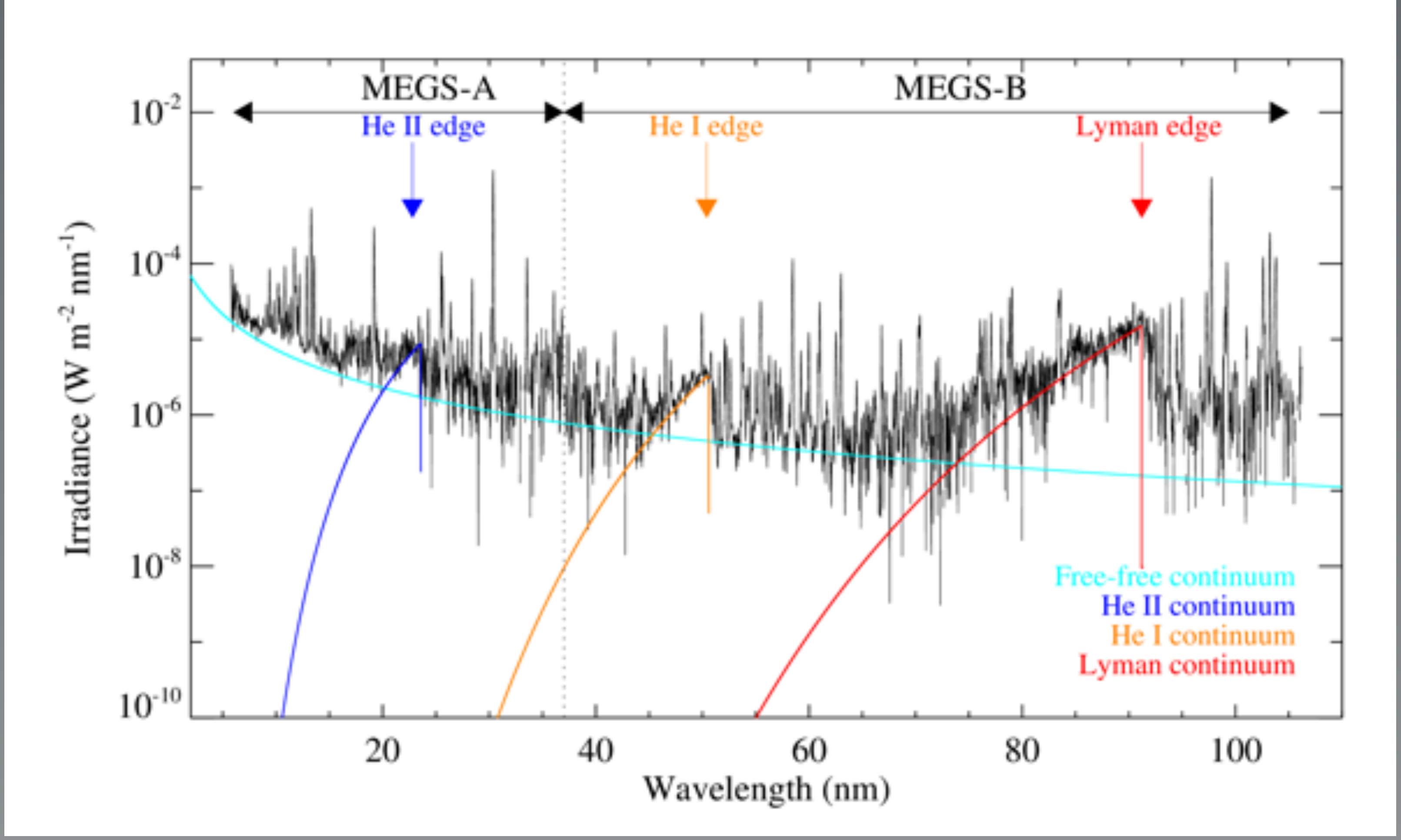
Milligan (2011)

Correlation with density suggests either opacity or pressure broadening (assuming ionization equilibrium)

See also Doschek et al. (2013) and Young et al. (2013)

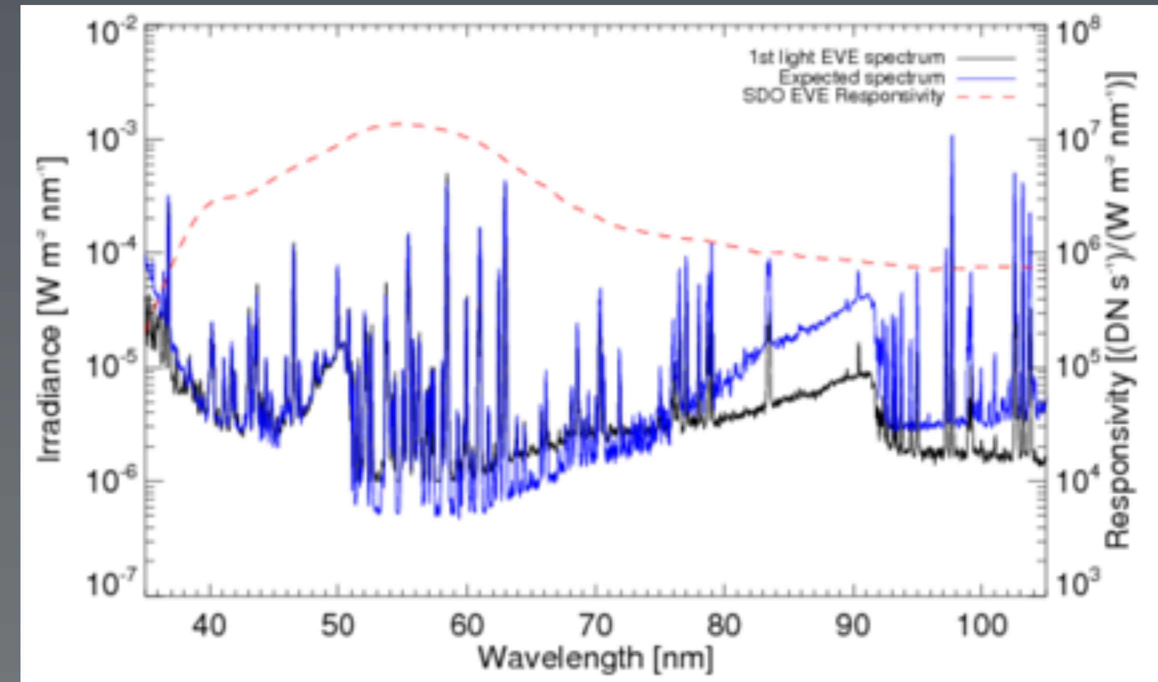
EUV Variability Experiment (EVE)

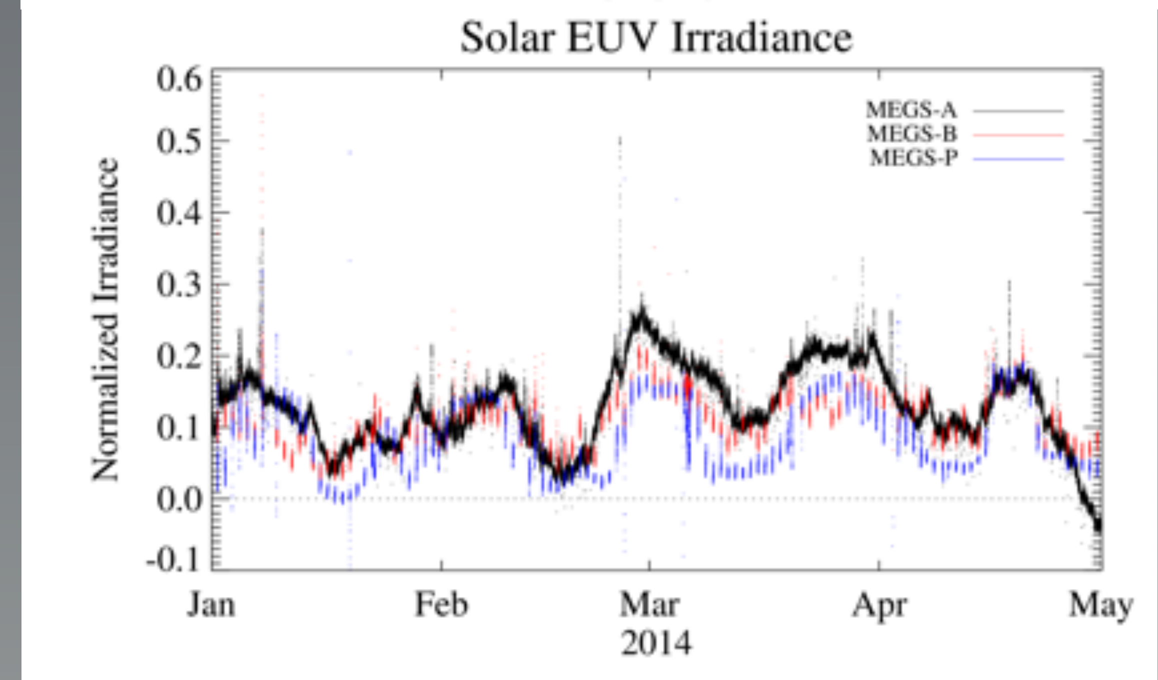
- “Sun-as-a-star” observations
- MEGS-A: 60-370Å
  - Emission lines formed 10^4-10^7K, including He II 304Å, free-free & He II continua
- MEGS-B: 370-1050Å
  - He I & Lyman continua
- MEGS-P: 1216Å
  - Lyman-alpha line (broad-band diode)
- All components have 10s cadence, but MEGS-B & -P have reduced duty cycles due to instrumental degradation



On May 26th, 2014 MEGS-A suffered a power anomaly and is no longer taking data

- MEGS-B has suffered significant degradation since launch
- This has been corrected using data from underflight rocket calibration
- Version 4 data was released on December 20, 2013
- Current MEGS-B observing restricted to 3 hours per day (0800-1100 UT)





Extreme ultraviolet Variability Experiment

EVE flare observations for the MEGS B instrument. MEGS B is nominally exposed for only a few hours per day, however during flare campaigns, MEGS B is exposed for a full 24 hour period.

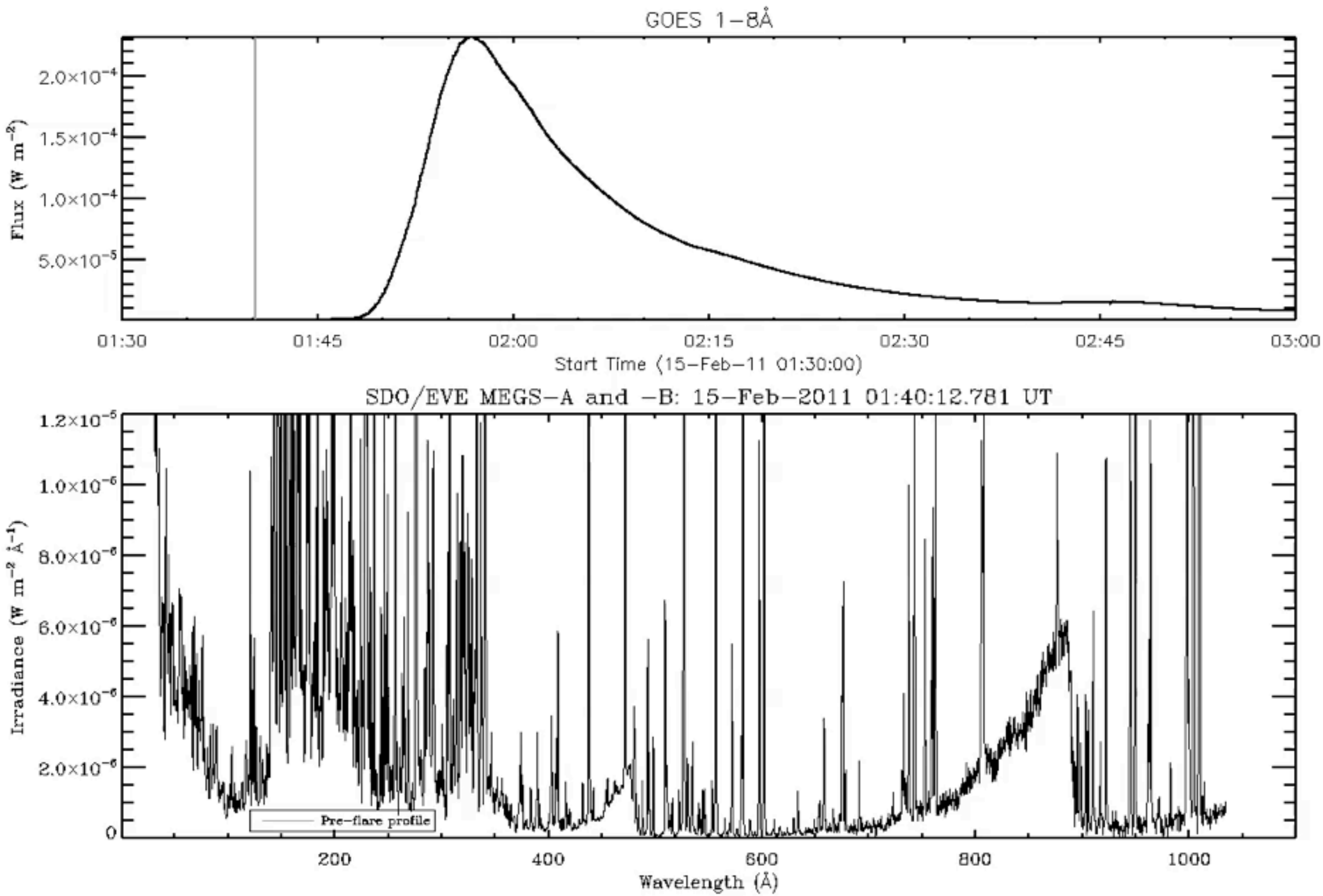
Download this table as a CSV file.

Read the instructions on how to use this page here.

The table below defines the magnitude of flares observed (C and above) during MEGS B exposure.

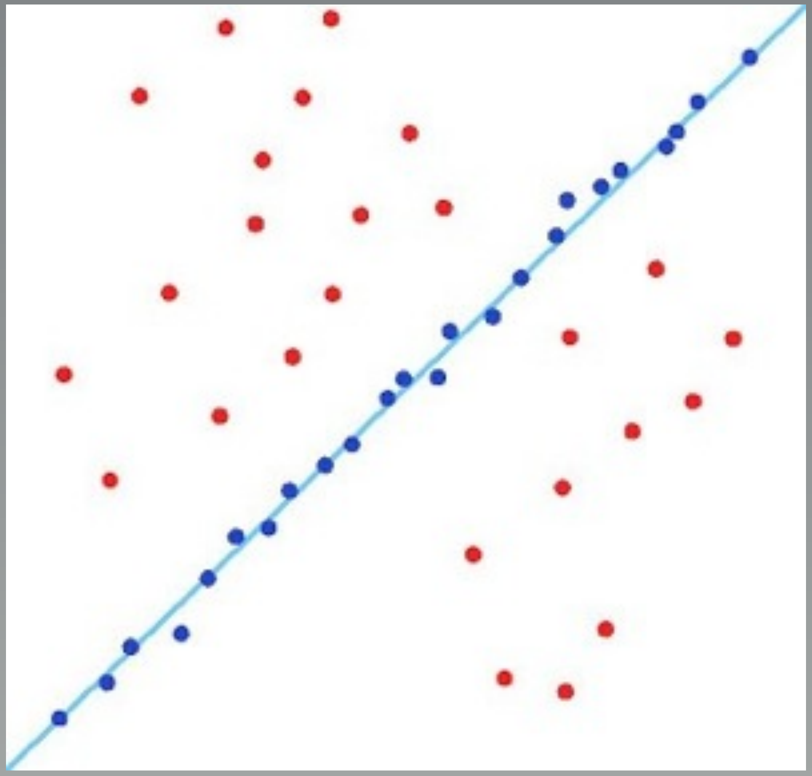
Date ▲▼	NOAA GOES X-ray Class C Flares ▲▼	NOAA GOES X-ray Class M Flares ▲▼	NOAA GOES X-ray Class X Flares ▲▼	Display Data ▲▼
2011/221 (Aug 09)	C2.2, C2.4, C2.0	M2.5	X6.9	png pdf plot
2012/067 (Mar 07)			X5.4, X1.30	png pdf plot
2013/309 (Nov 05)	C1.6, C8.0, C2.5, C2.3, C2.1	M2.5, M1.0	X3.3	png pdf plot
2013/302 (Oct 29)	C1.7, C2.1, C3.7, C2.3, C6.3, C2.0, C9.4		X2.3	png pdf plot
2011/046 (Feb 15)	C2.7, C4.8, C1.0, C4.8, C1.7, C6.6, C1.3		X2.2	png pdf plot
2011/249 (Sep 06)		M5.3	X2.1	png pdf plot
2011/307 (Nov 03)	C4.4, C3.4, C1.5, C2.2, C4.5, C5.4, C5.8, C9.2	M2.1	X1.9	png pdf plot
2011/250 (Sep 07)	C3.0, C1.6		X1.8	png pdf plot
2013/133 (May 13)	C9.3, C2.0, C4.5, C1.7, C8.3	M1.3	X1.7, X2.8	png pdf plot
2013/298 (Oct 25)	C3.4, C7.9, C3.2, C3.6	M1.0, M1.3, M2.3, M1.9	X1.7	png pdf plot
2014/007 (Jan 07)			X1.2	png pdf plot
2013/135 (May 15)	C1.1, C1.1		X1.2	png pdf plot
2013/312 (Nov 08)	C5.7, C1.4, C1.1		X1.1	png pdf plot
2012/065 (Mar 05)	C3.4, C2.4, C2.3, C5.9, C1.2, C5.5, C7.8, C9.8, C4.6, C6.8, C1.7	M1.3	X1.1	png pdf plot
2013/323 (Nov 19)	C2.1, C1.6		X1.0	png pdf plot
2013/301 (Oct 28)		M5.1, M1.4, M2.8	X1.0	png pdf plot
2014/115 (Apr 25)	C1.0			png pdf plot
2014/114 (Apr 24)	C2.9			png pdf plot

http://lasp.colorado.edu/eve/data_access/evewebdata/interactive/flare_campaign_observations.html



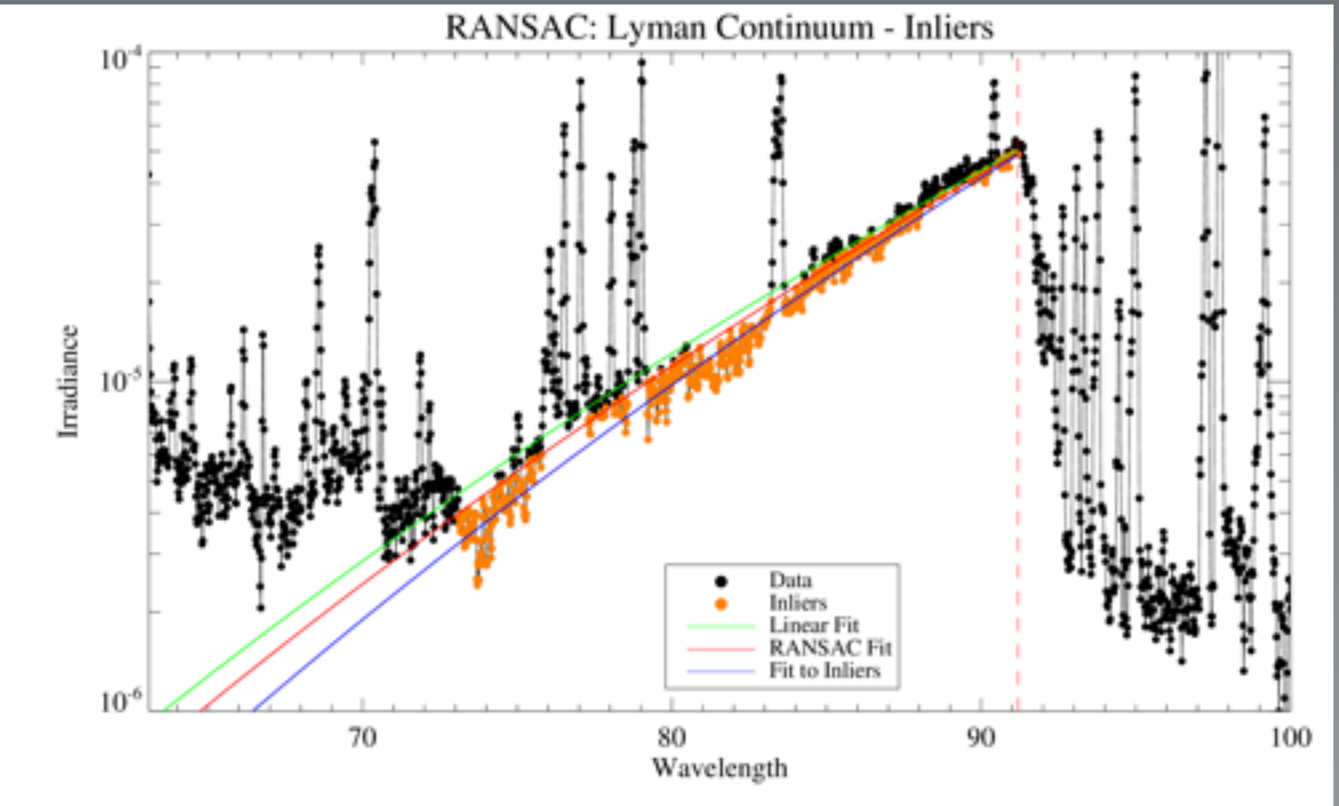
Complete EVE spectra during
15 Feb. 2011 X2.2 flare (10 s cadence)

RANSAC: RANdom Sample Consensus



- An iterative method to estimate the parameters of a mathematical model from a set of observed data that contains outliers (Fischler & Bolles 1981)
- In the case of EVE data we assume that emission lines are outliers

RANSAC: RANdom Sample Consensus

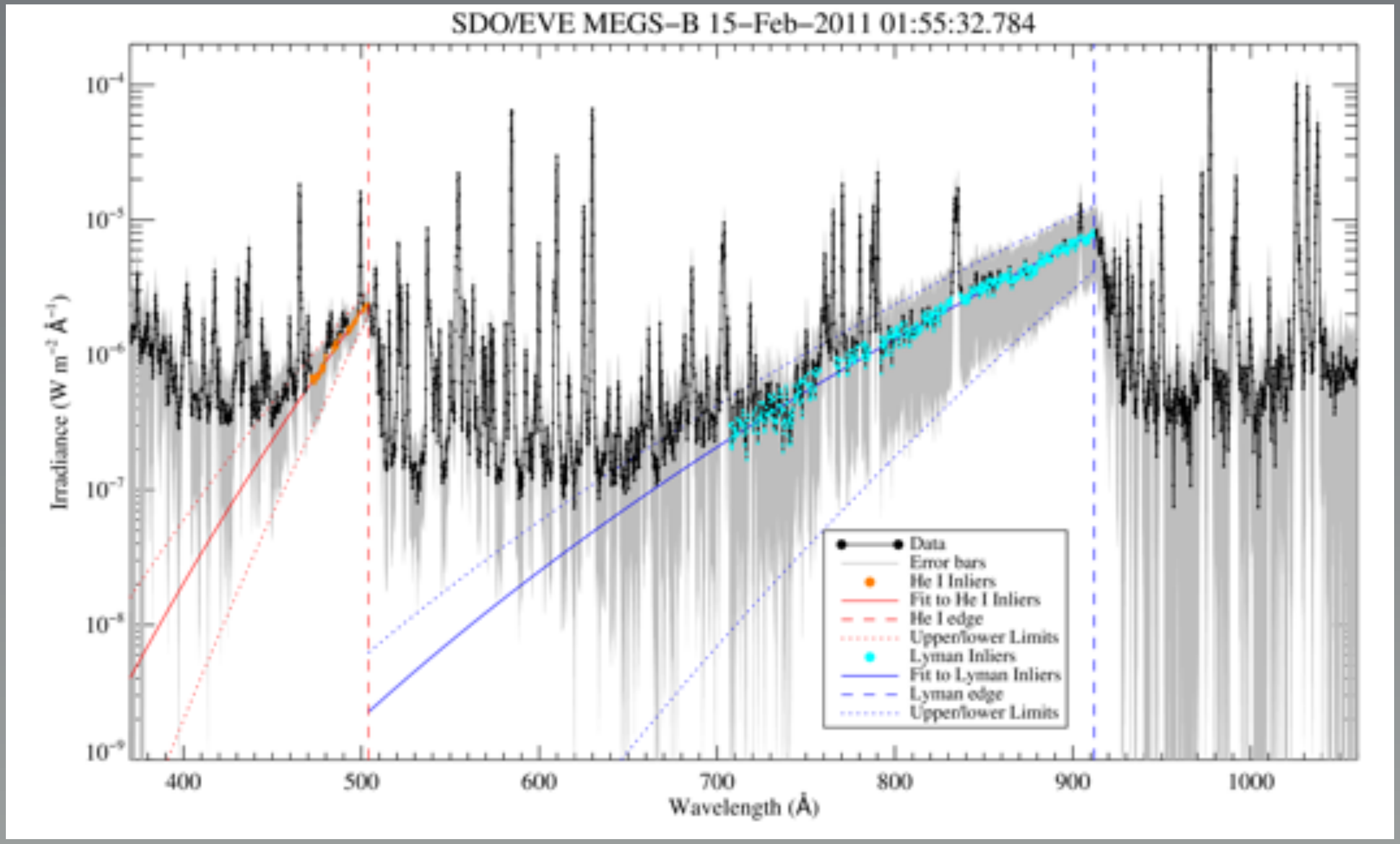


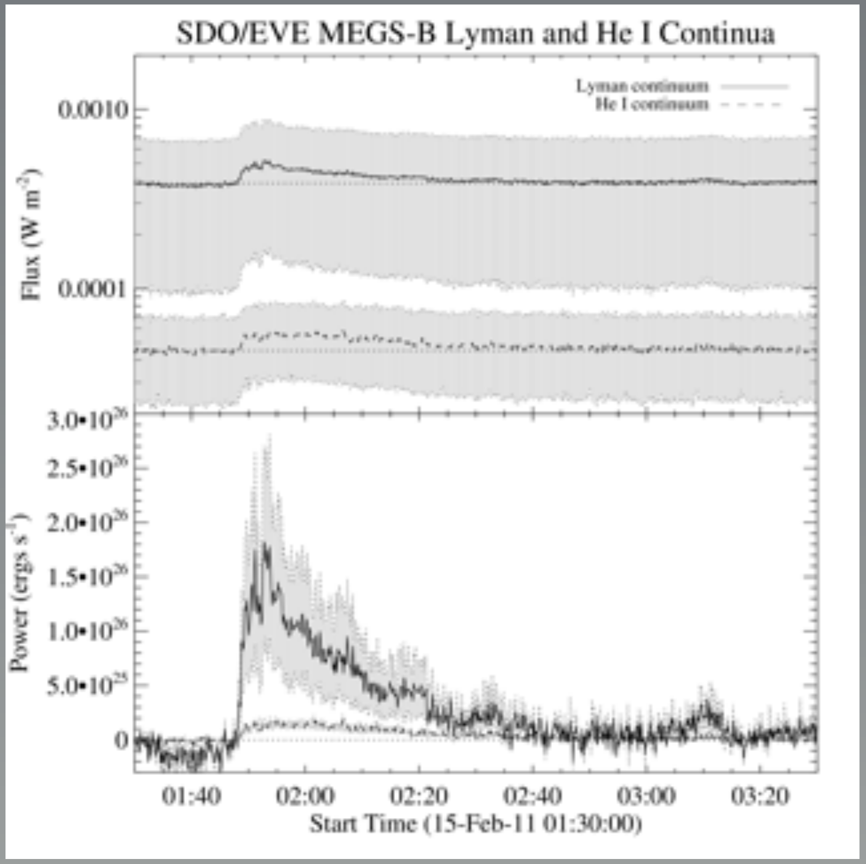
- Step 1: randomly select a subset of data points (5%) and fit with chosen function (power law). Stop when acceptable χ^2 is reached.
- Step 2: define "inliers" as all data points that lie within some threshold of the best fit.
- Step 3: fit inliers with chosen function and extrapolate to shorter wavelengths
- Repeat for upper and lower limits, and for each 10 second integration throughout a flare

EVE can now measure these continua at high cadence and with high precision

We have developed a fitting routine (RANSAC; RANdom SAmple Consensus) to model these emissions

This provides timing and energy information throughout a flare



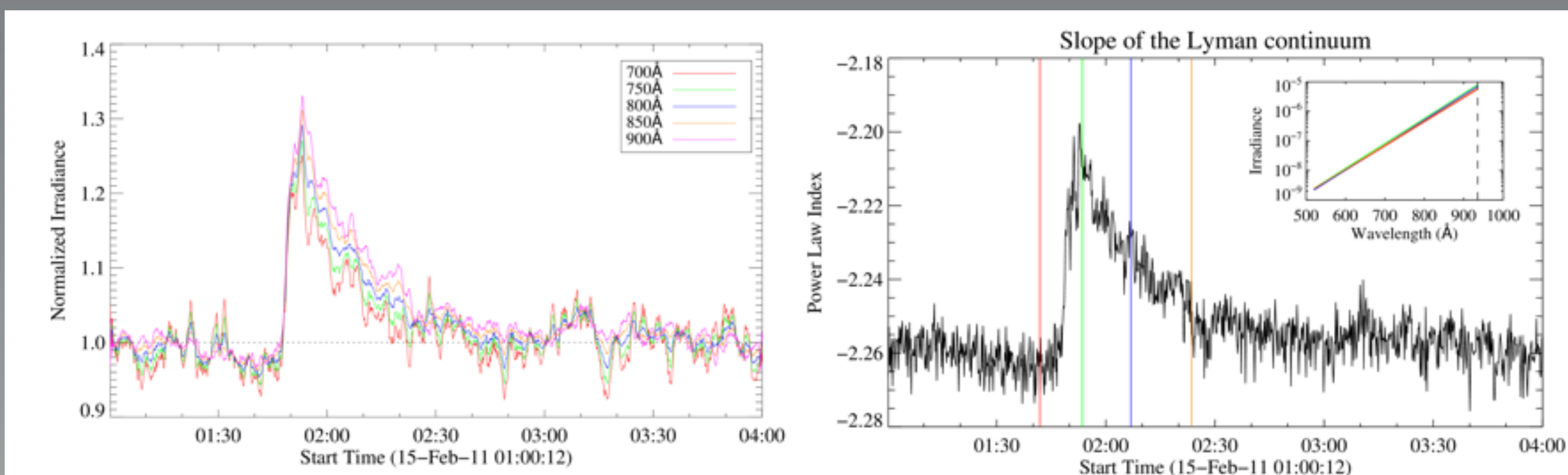


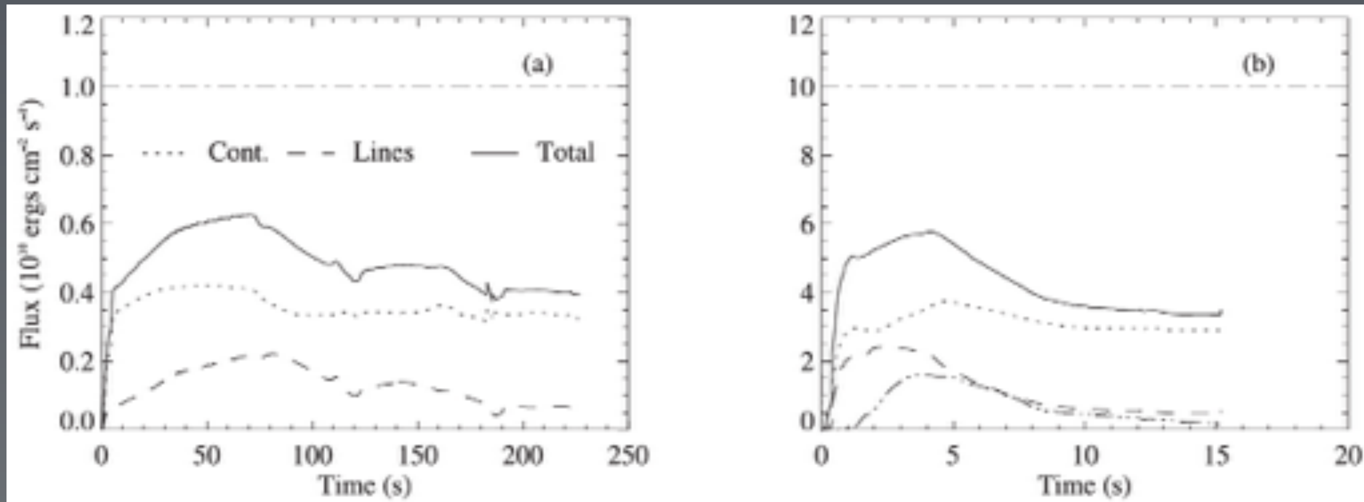
Milligan et al. (2012, 2014)

Fits can then be used to determine the relative increases as a function of λ

The slope (power law index) can be measured as a function of time

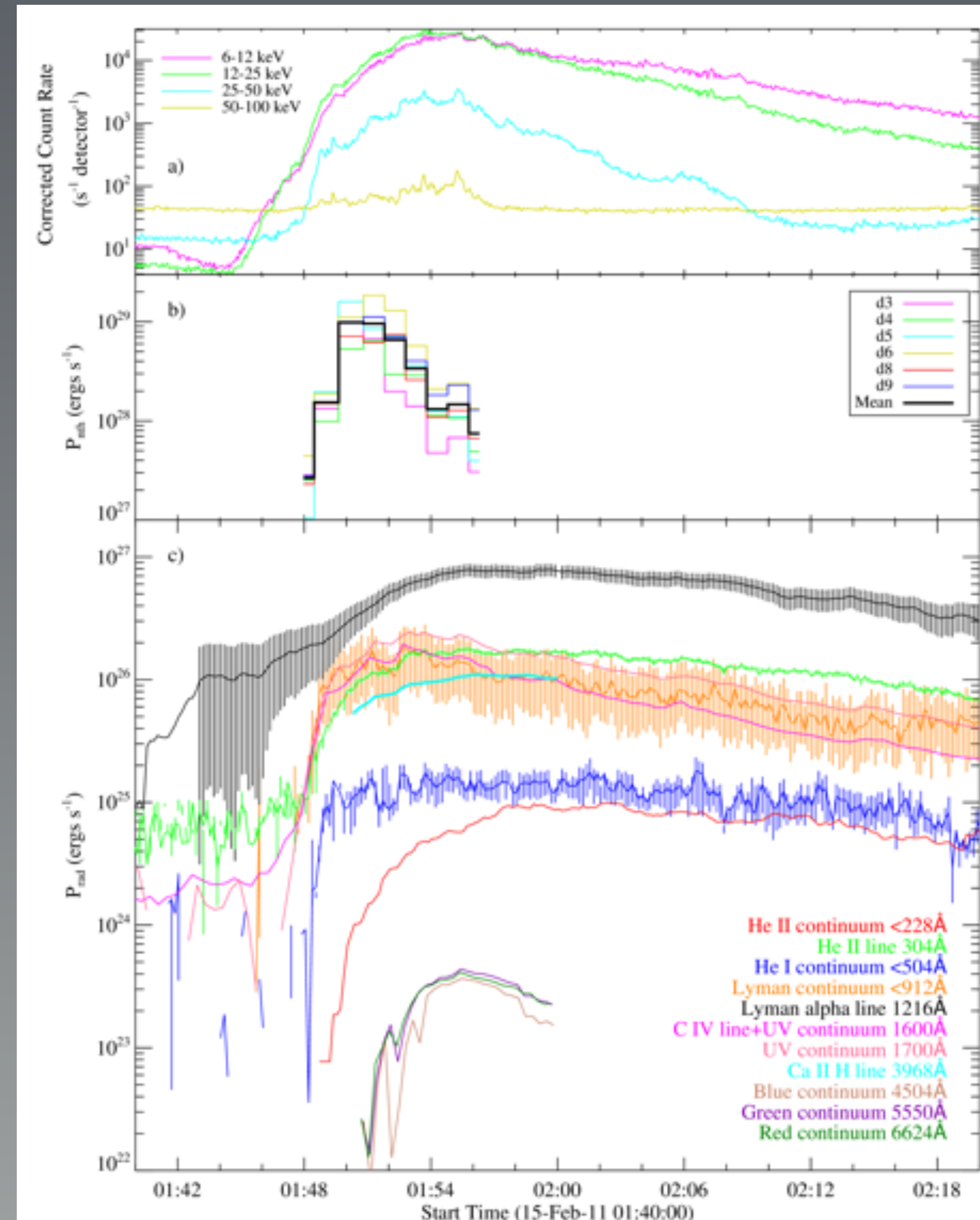
Reveals the temperature of the continuum $b_1(\tau=1)=B_\lambda(T_c)/I_\lambda(\sigma=1)$, and the depth of formation, ionisation state, etc.



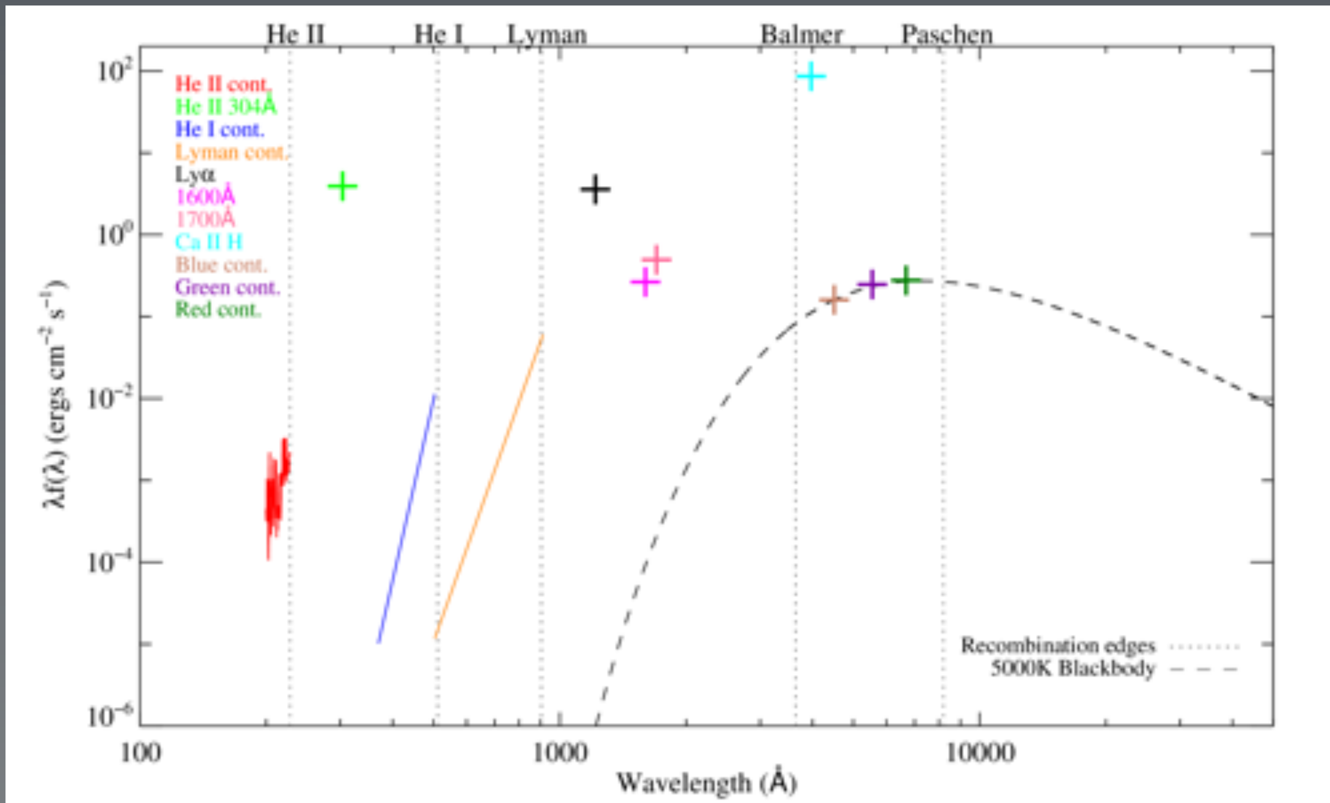


F10 and F11 models from Allred et al. (2005)

- Radiative hydrodynamic models predict that continuum emission dominate over emission line radiative losses
- EUV, UV, and WL continuum energetics can be compared with line emission (He II 304Å, Lyα, Ca II H) for 15 Feb. 2011 flare
- Timing showed most emission to be synchronous with power in nonthermal electrons



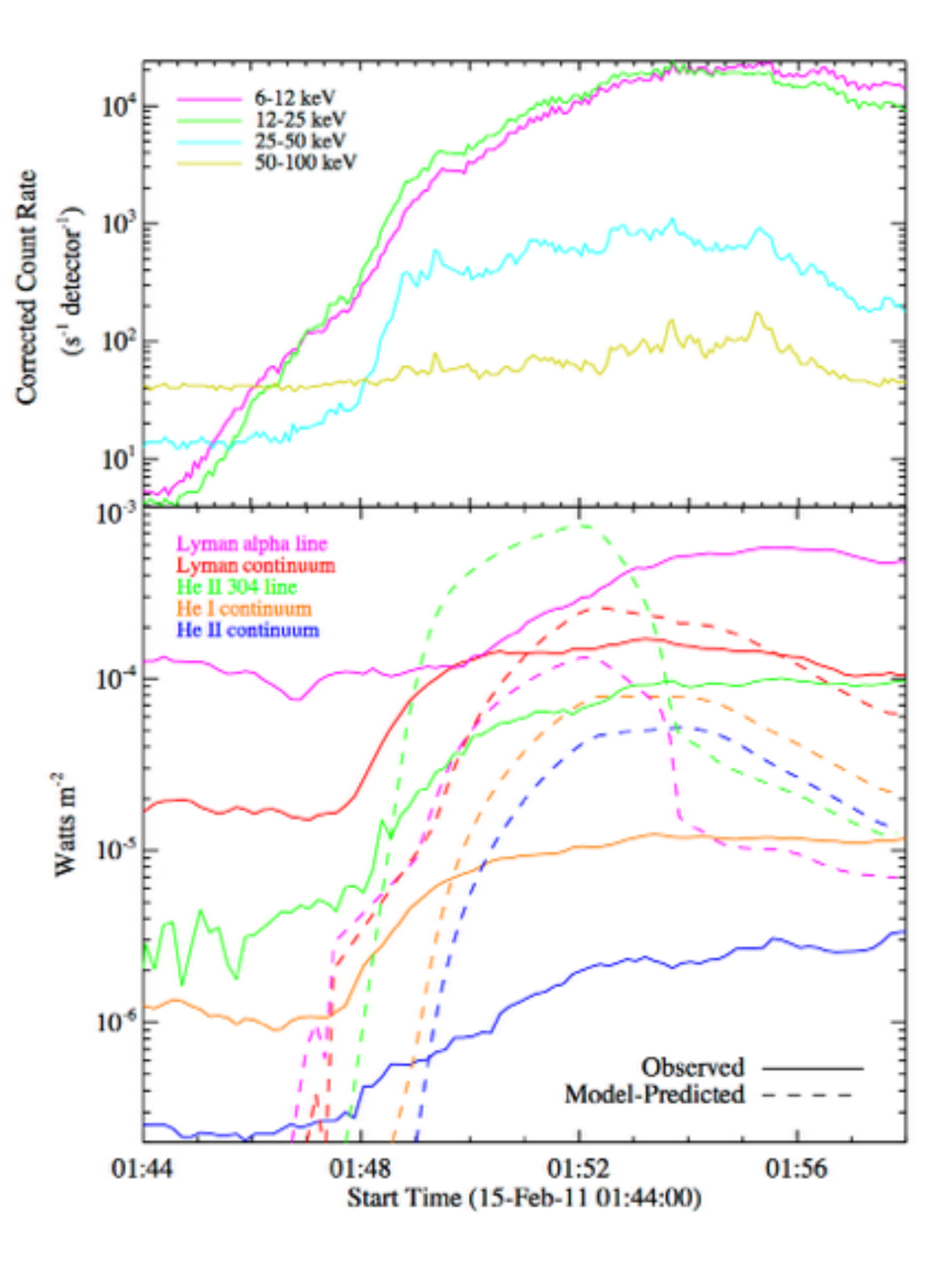
Milligan et al. (2014)



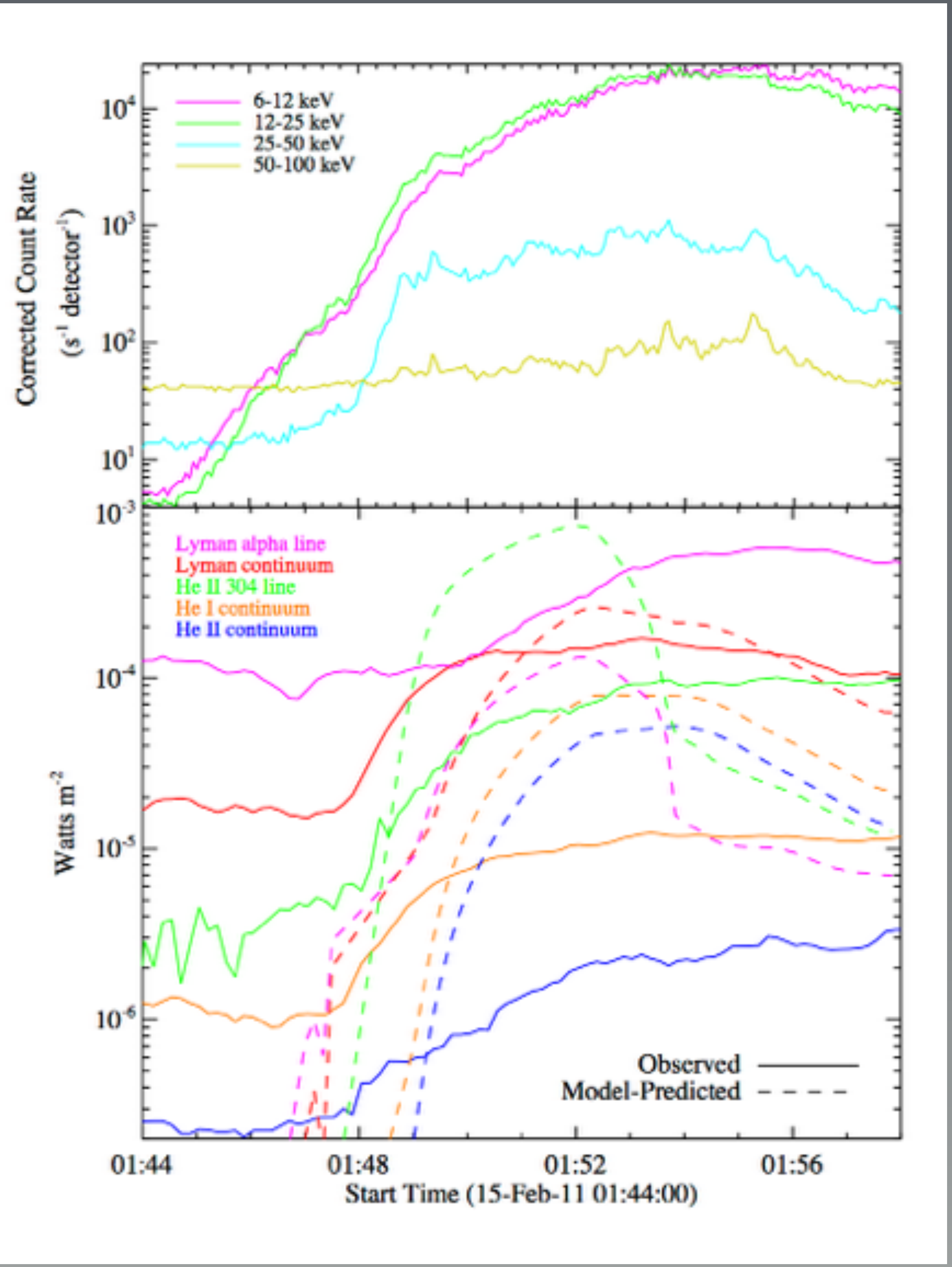
Spectral Energy Distribution (λf(λ)) plot for 15 February 2011 flare

Despite exceptional data coverage, only 15% of the energy deposited by nonthermal electrons was detected through chromospheric observations during this event (Milligan et al. 2014)

	λ (Å)	Energy (erg)
Lyα	1170-1270	1.2x10
He II line	303-305	3.4x10
UV cont.	1600-1740	2.6x10
C IV line + UV	1464-1609	1.7x10
Lyman cont.	504-912	1.8x10
Ca II H line	3967-3970	5.5x10
He I cont.	370-504	3.0x10
He II cont.	200-228	1.6x10
Green cont.	5548-5552	1.5x10
Red cont.	6682-6686	1.4x10
Blue cont.	4502-4506	1.2x10
E		3x10
E		>2x10



- Beam heating parameters were derived from HXR observations from RHESSI
- These were used to drive a numerical simulation (RADYN)
- Preliminary results showed that the relative continuum intensities were in good agreement
- However, the He II 304Å line was predicted to be stronger than Lyα, while the observations showed that the reverse was true



- Once an agreement is met between theory and observation, we can:
    - determine the depth at which electrons lose their energy
    - determine the height at which various continua are formed
    - predict what unobserved quantities would have been
    - establish whether low-energy cut-off in electron spectrum is accurate

What next..?

- More co-ordinated observing campaigns (Max Millennium program):
  - *SDO/EVE+AIA, Hinode/EIS+SOT, RHESSI, IRIS, ROSA, IBIS,…*
- Comparisons between observations and theory…
  - *RADYN, HYDRAD, HyLoop, NRL, etc.*
- … preferably using RHESSI (or Fermi) data as input
- Statistical analyses of flaring events (using EVE)
- Comparison with stellar flare observations (e.g. EUVE, Ultracam)