Solar flares and their connections to the lower solar atmosphere

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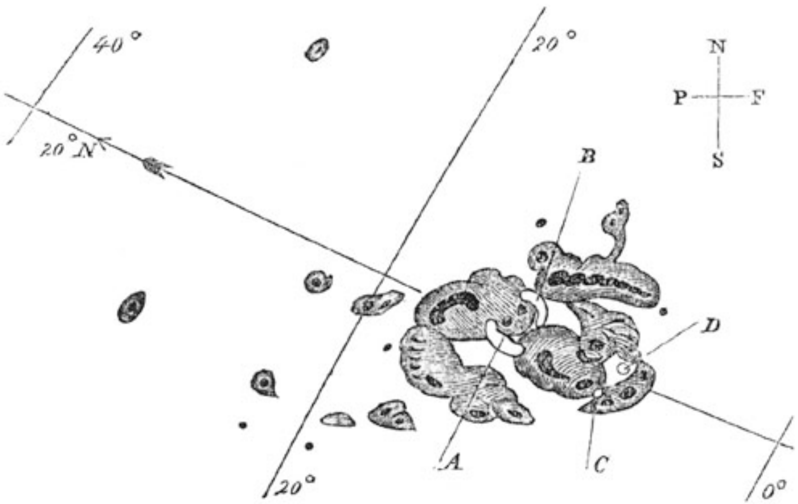
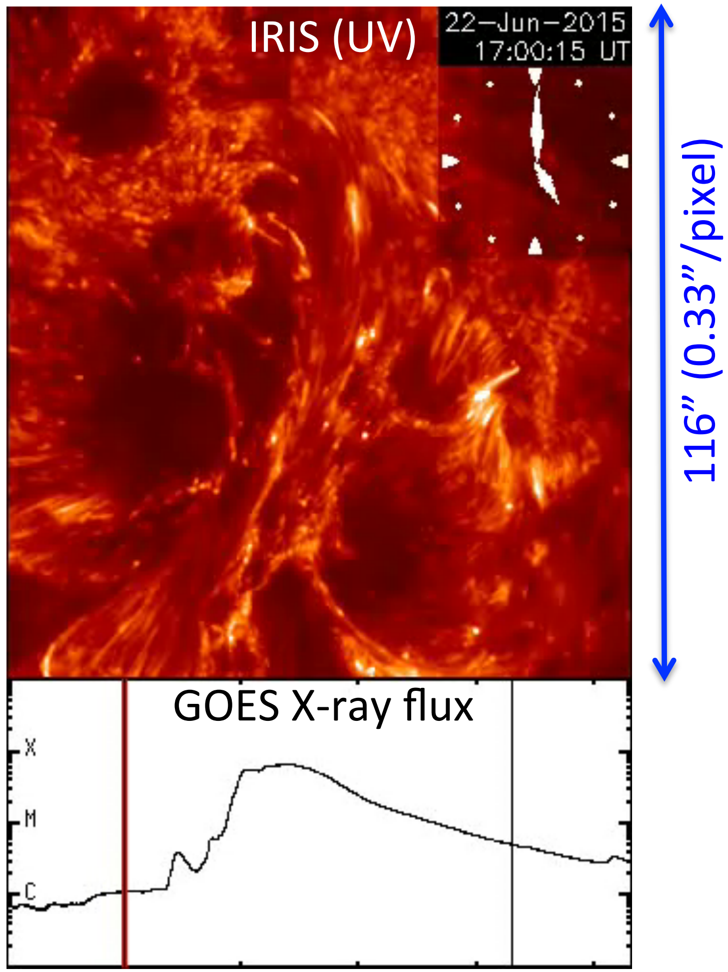
Flares in High Resolution



Carrington 1859
MNRAS 20, 13

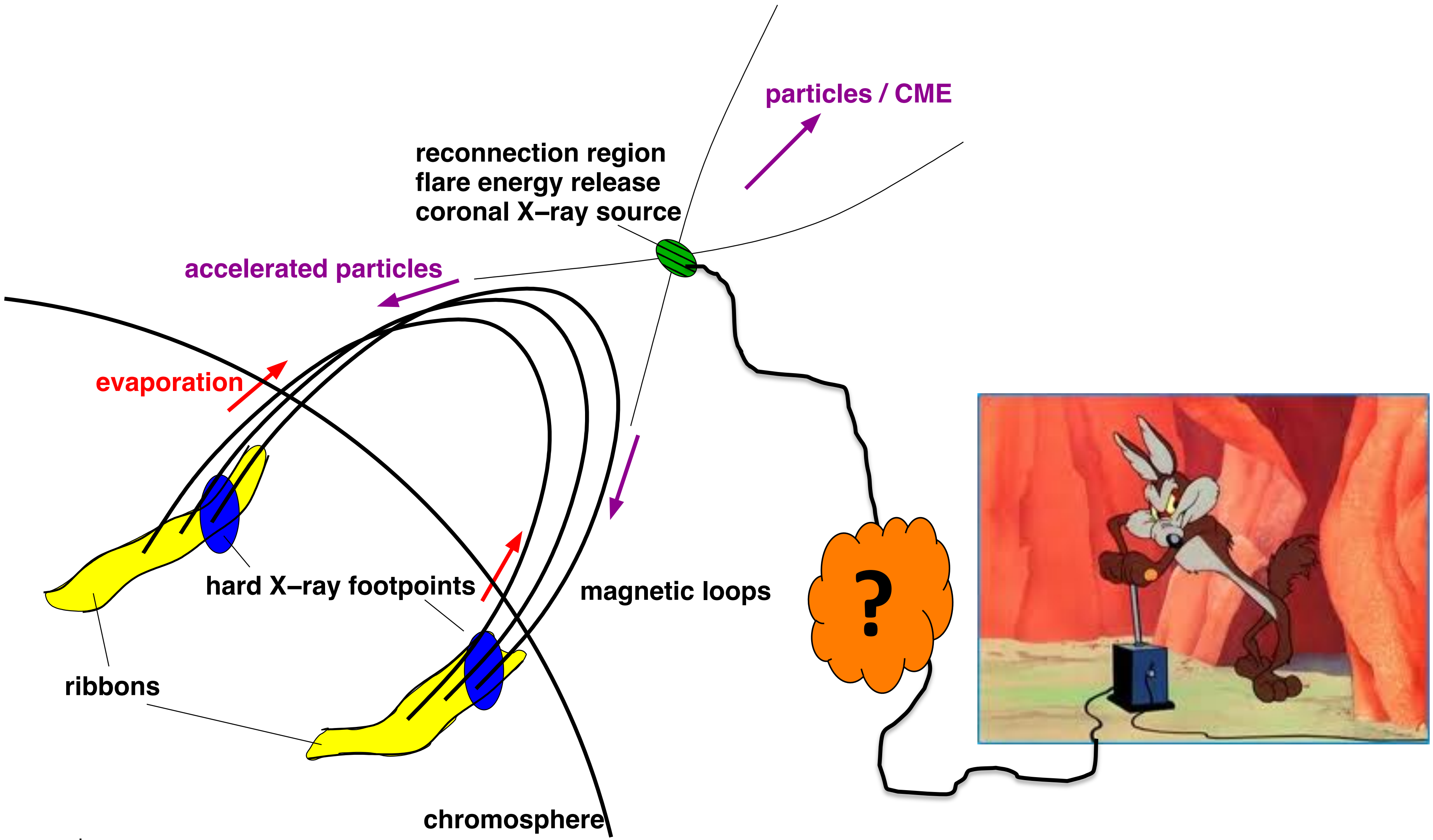
157 years later



sub-arcsecond observations
M6.5 flare observed by IRIS

Lucia Kleint, June 2016

Testing the Standard Flare Model with IRIS



Open Questions

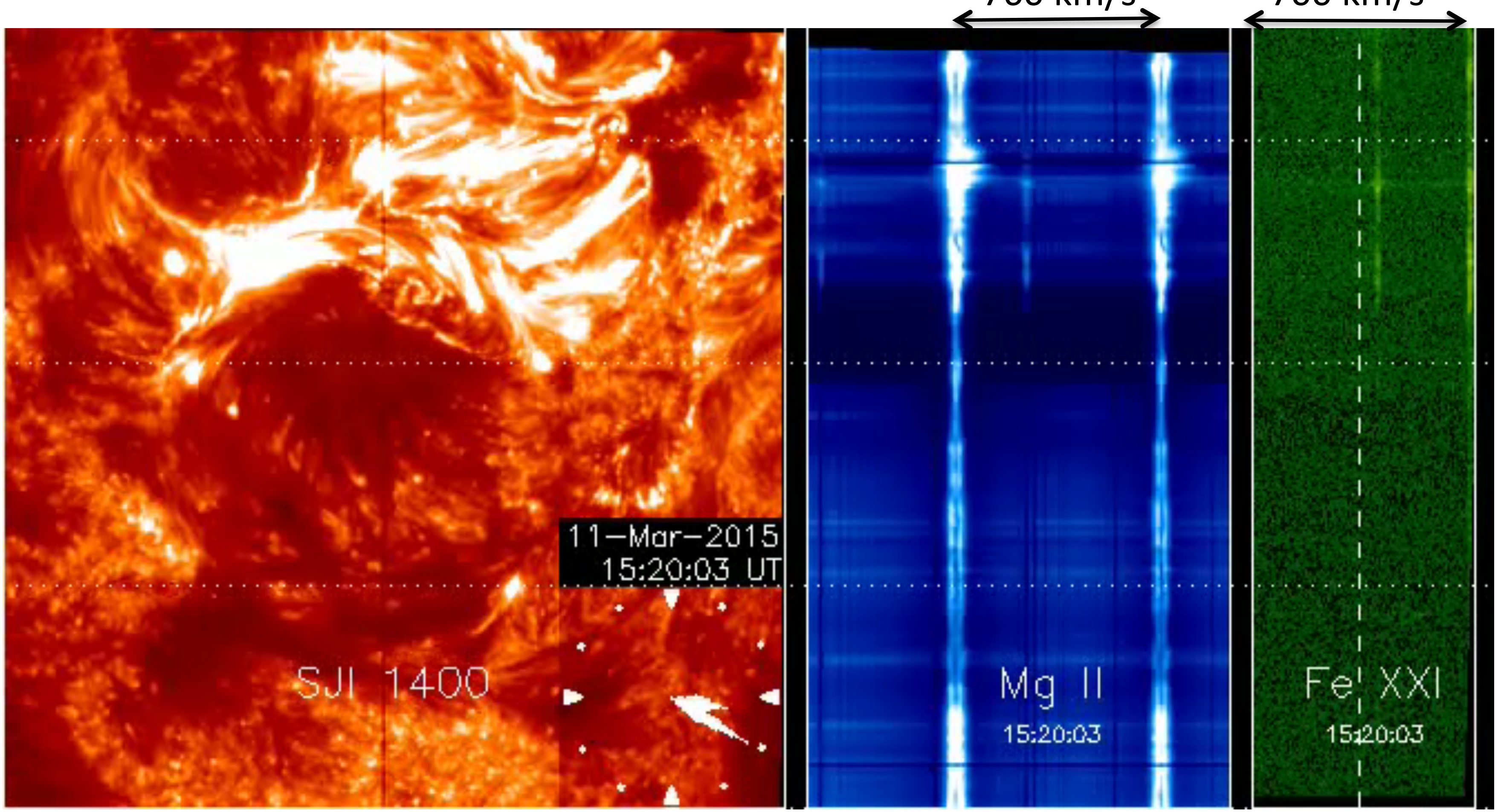
- **How is the chromospheric evaporation related to accelerated electrons?**
- **Which processes cause continuum emission and at which height is it formed?**
- **Are filament eruptions flare triggers?**
- **What is the response of the lower solar atmosphere? Which physics can we get from spectra?**

IRIS and Flares

- so far, ~41 papers about flares with IRIS
- 9 X-flares observed

Mg II: 0.01 MK

Fe XXI: 10 MK
(highest T for IRIS)



X2.1, 20150311

Chromospheric Evaporation

What can we learn about chromospheric evaporation?
Relation to accelerated electrons?

Are we resolving flare kernels?

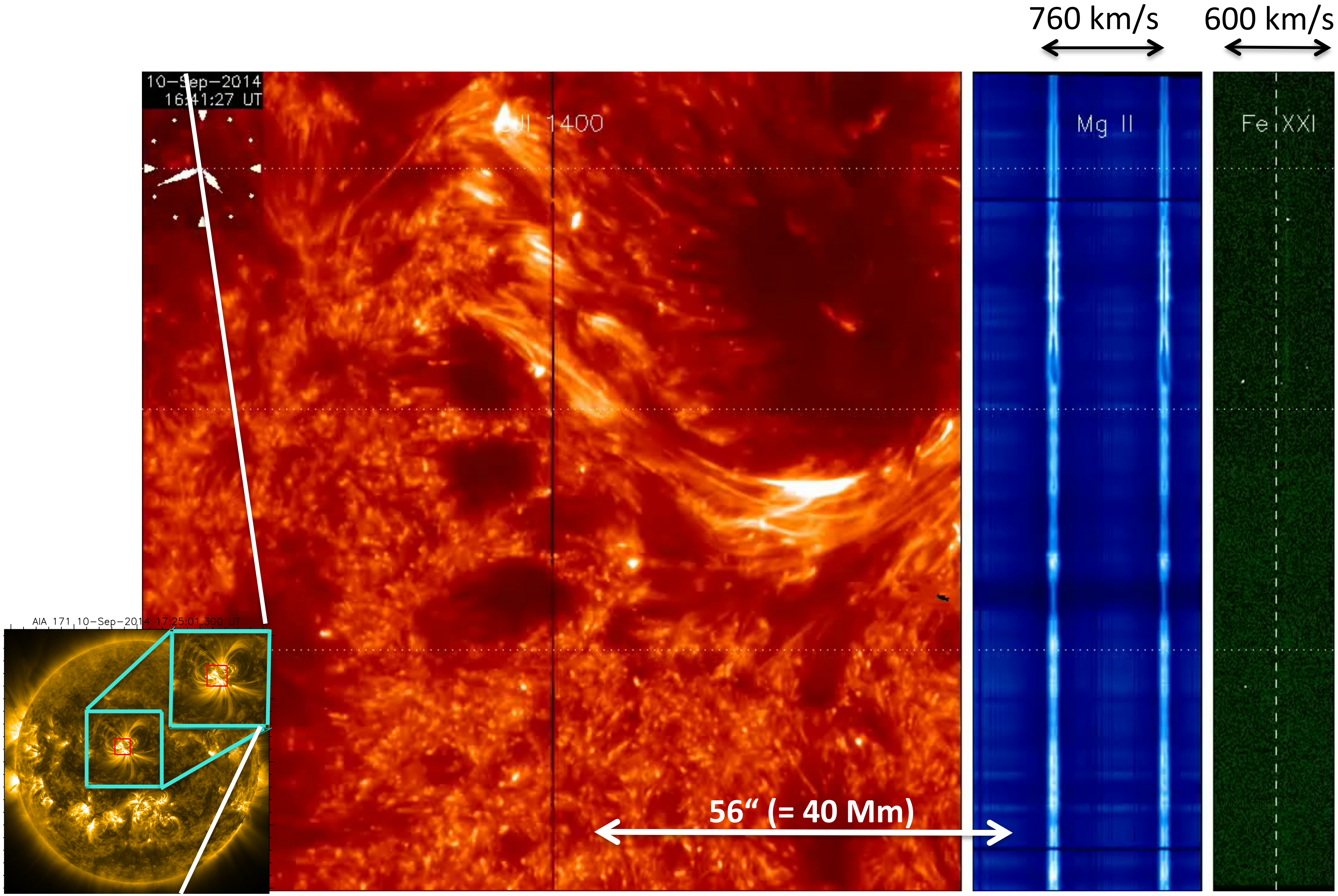
Chromospheric Evaporation

Recent studies of chromospheric evaporation

Are we resolving the evaporation spatially?

Authors	Flare class	V_{max} of Fe XXI	Δt for evap	multiple components?	broadening
Tian et al. 2014	C1.6, 20140419	125 km/s down, ~260 up	(64-step raster)	no	44 km/s (single point)
Polito et al. 2015	C6.5, 20140203	82 +- 7 km/s	6 min to rest	partially, interpreted as loops being filled	130-30 km/s., decreasing
Young et al. 2015	X1.0, 20140329	100-200 km/s	>6 min blueshifts (obs ended)	no	43-26 km/s
Tian et al. 2015	M1.1, 20140906, X1.6, 20140910	240 km/s to 0 km/s	~9 min	no	const. nonth width
Graham&Cauzzi, 2015	X1.6, 20140910	up to 300 km/s	8-10 min	no	up to 99 km/s
Battaglia et al. 2015	X1.0, 20140329	<200 km/s	>6 min	no	-

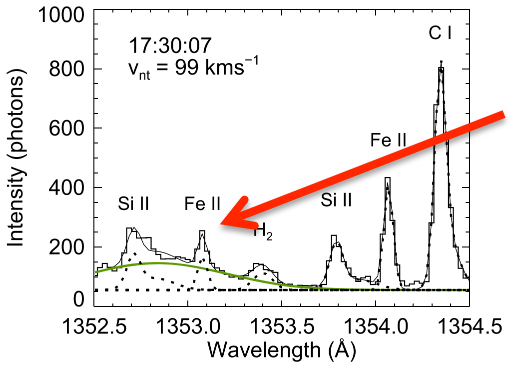
X1.6, 2014-09-10: chromospheric evaporation



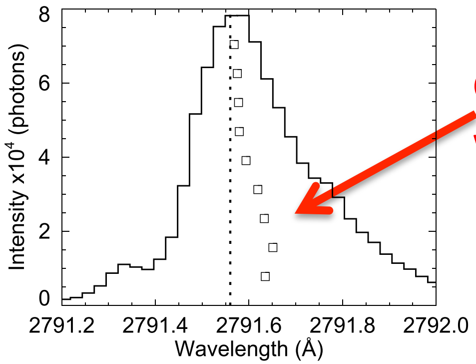
Chromospheric Evaporation (X1.6, 2014-09-10)

Graham & Cauzzi, ApJ 807, L22, 2015

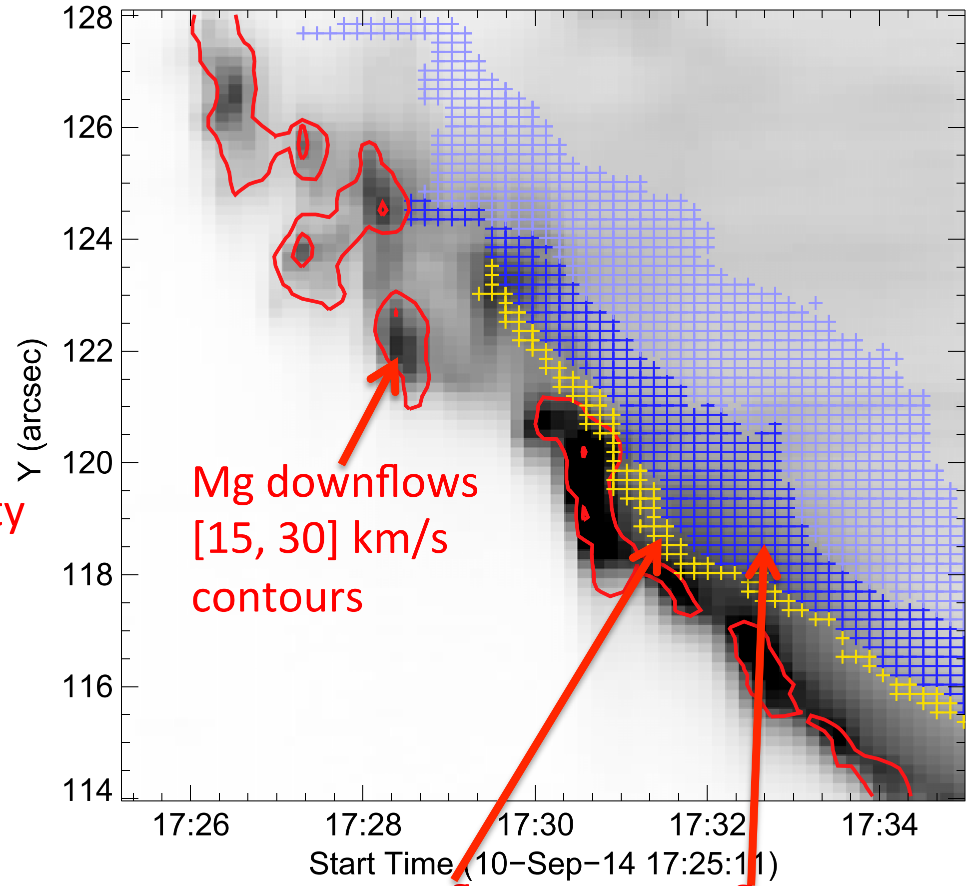
Compare velocities of Mg and Fe XXI



Fitting the Fe XXI line

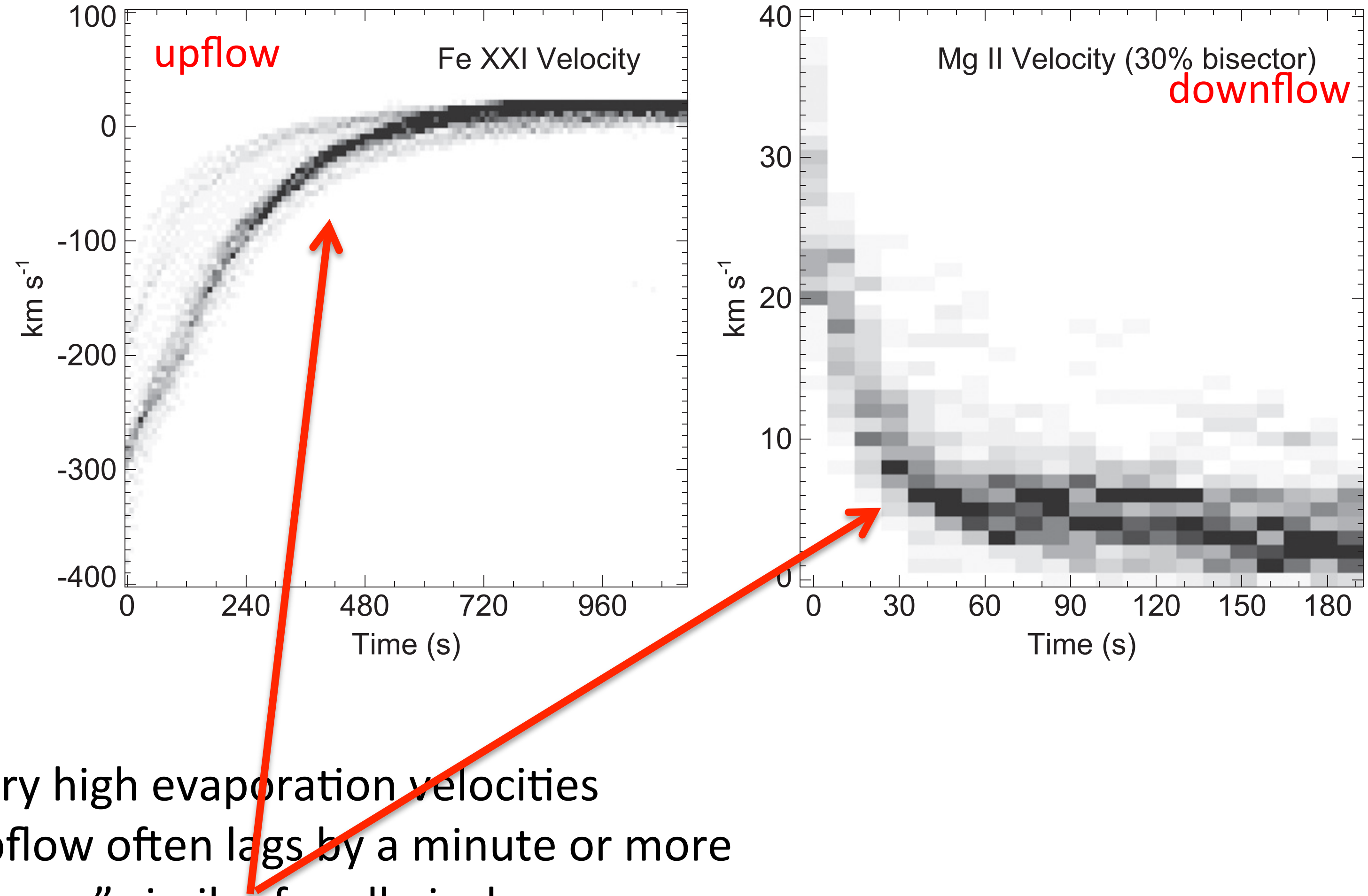


Getting Mg velocity with bisectors



- very high evaporation velocities
- upflow often lags by a minute or more

Chromospheric Evaporation (X1.6, 2014-09-10)



- very high evaporation velocities
- upflow often lags by a minute or more
- "decay" similar for all pixels

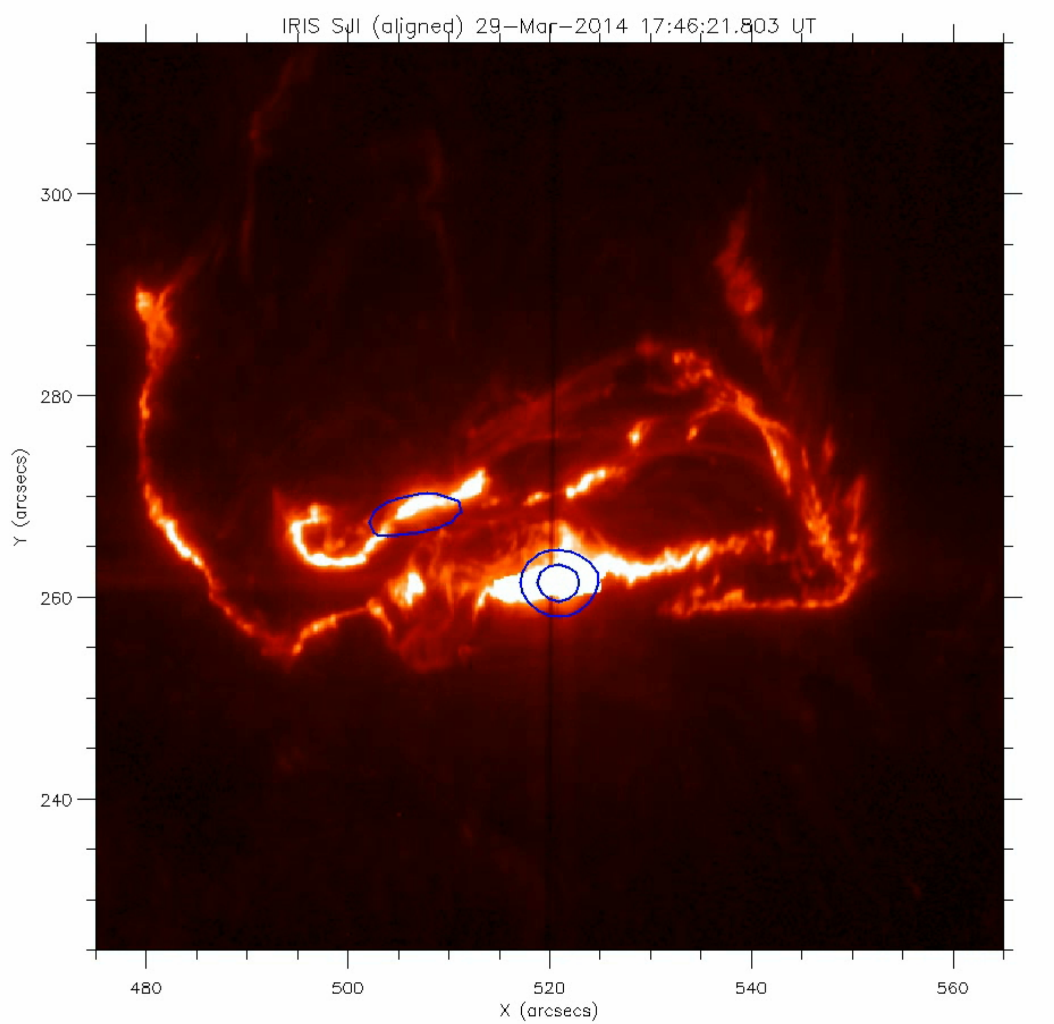
=> "elementary" flare kernels?

Graham & Cauzzi, ApJ 807, L22, 2015

Evaporation and electron beams?

Let's look at details… IRIS slit crossed HXR footpoint during X1 2014-03-29.

HXR 30-70 keV: blue
IRIS 1400 SJI: background image



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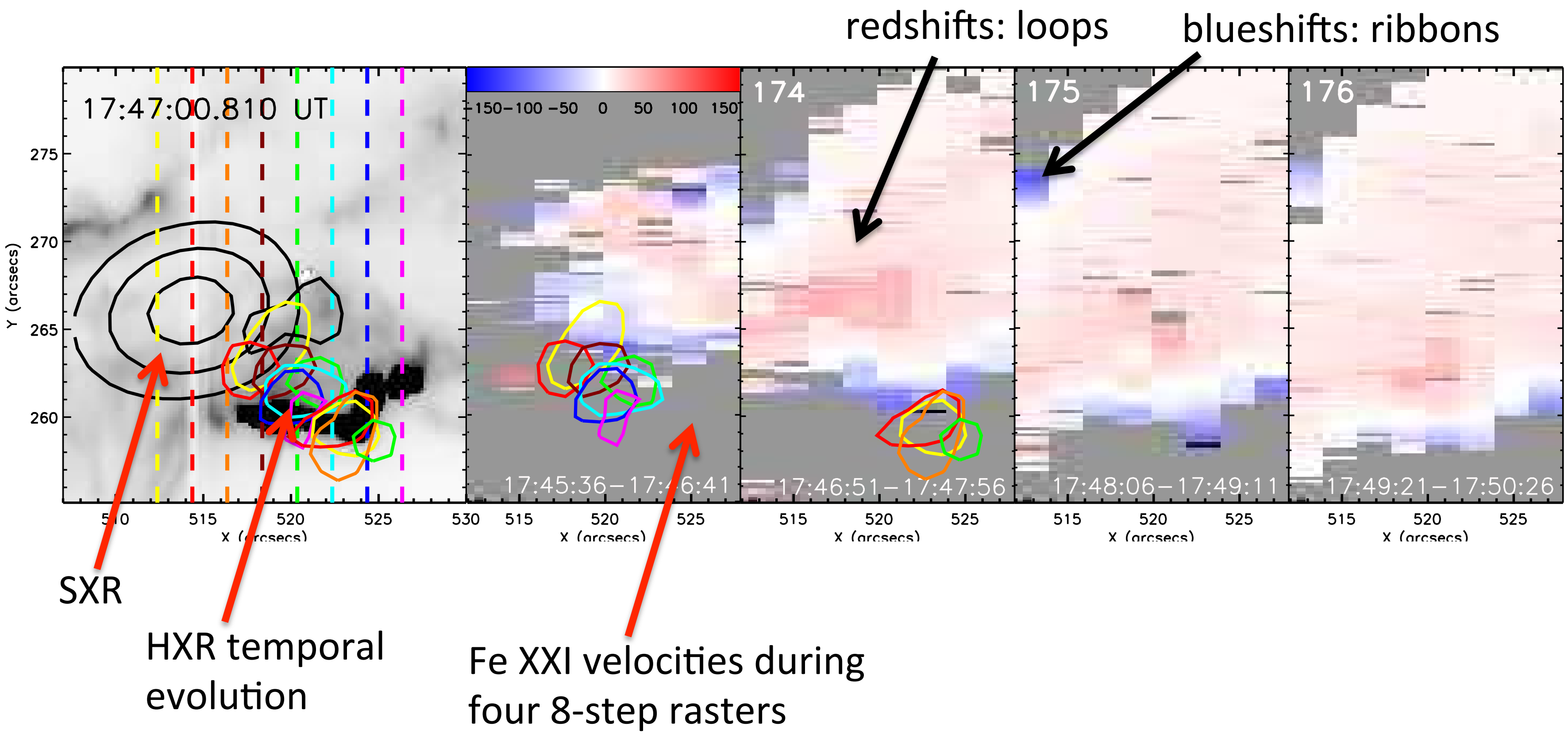
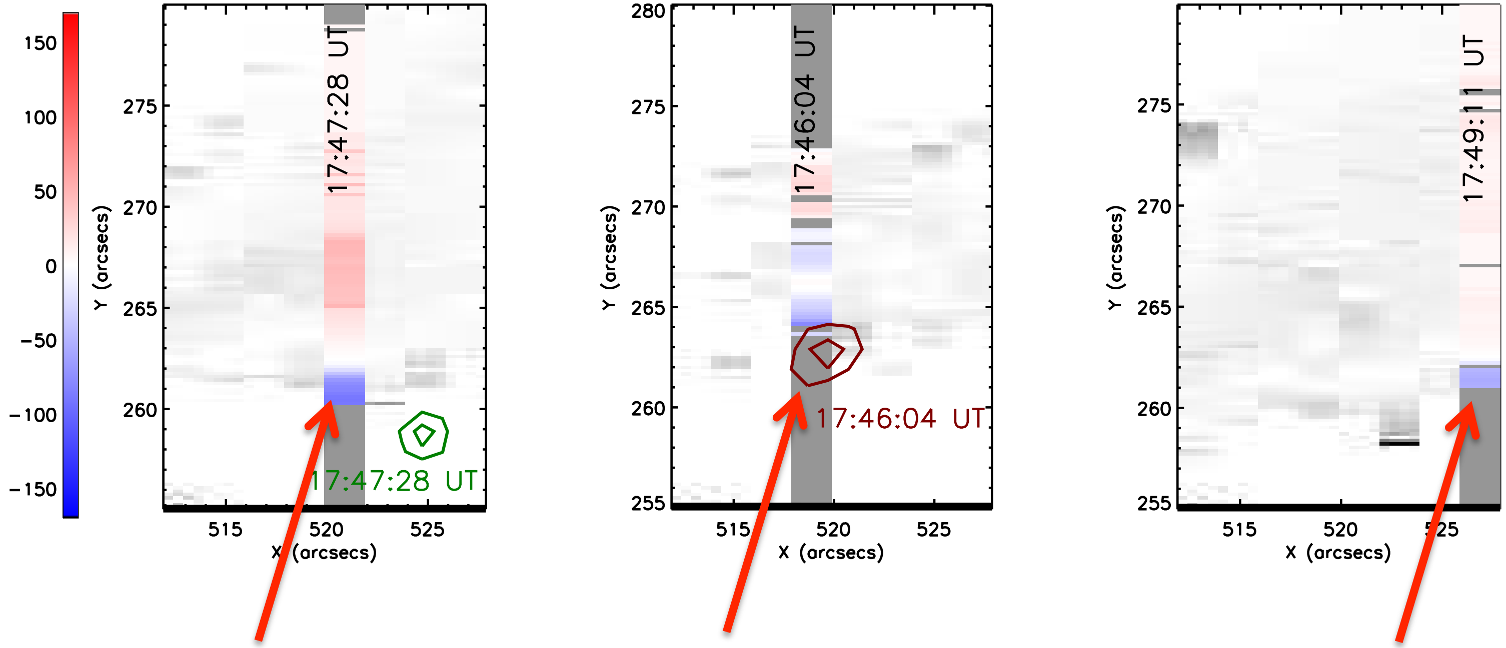


Battaglia et al, ApJ 813, 113, 2015

Evaporation and electron beams?

Differentiate 3 cases:



blueshift ~56 s after HXR was there	Slit and HXR co-spatial, but blueshift occurs further North. HXR was there ~28 s earlier	No HXR detected there, neither in space or time
Explosive -> gentle evaporation possible	**Fe XXI emission could be too weak in the beginning.**	**Hot coronal source -> thermal conduction? gentle evaporation**

Battaglia et al, ApJ 813, 113, 2015

Chromospheric Evaporation

What can we learn about chromospheric evaporation?
Relation to accelerated electrons?

Can be driven by conduction. Explosive and gentle. (Tian et al., 2015, Battaglia et al. 2015)

Are we resolving flare kernels?

Possibly. Pixels behave similarly (Graham & Cauzzi, 2015) and no stationary Fe XXI component seen (Polito et al. 2016 and others).

see today's talk by M. Battaglia

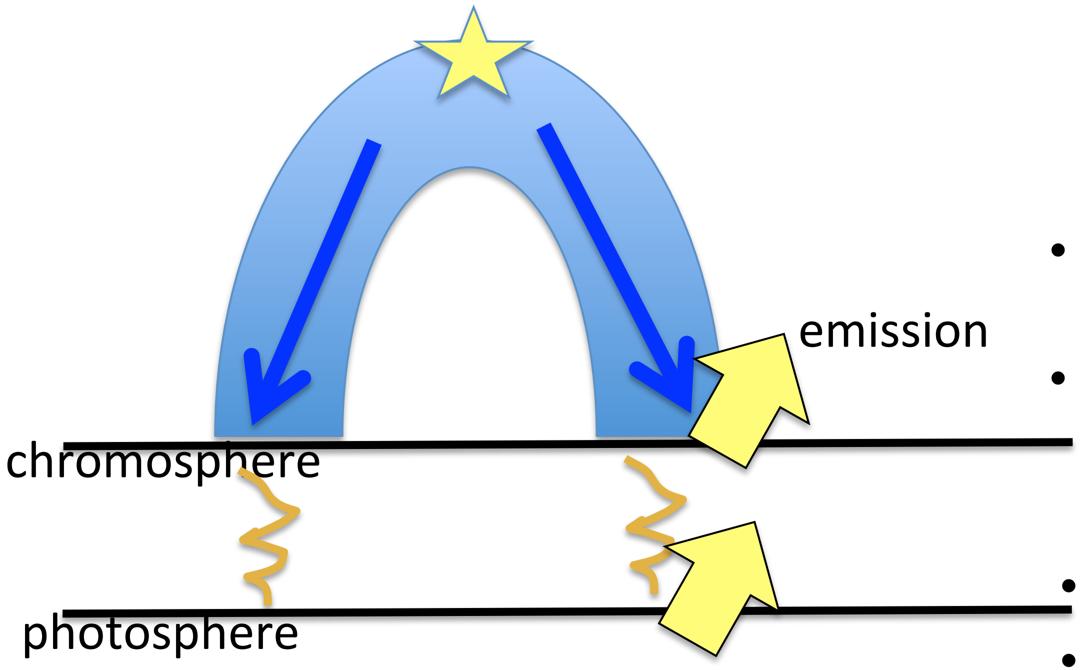
Continuum Emission

Where does the WL emission come from? Photosphere or Chromosphere?

What fraction of flare energy is radiated away by the continuum?

Continuum Emission

Problem: Where is the (whitelight) emission coming from?
Particles probably cannot reach low enough in the chromosphere.



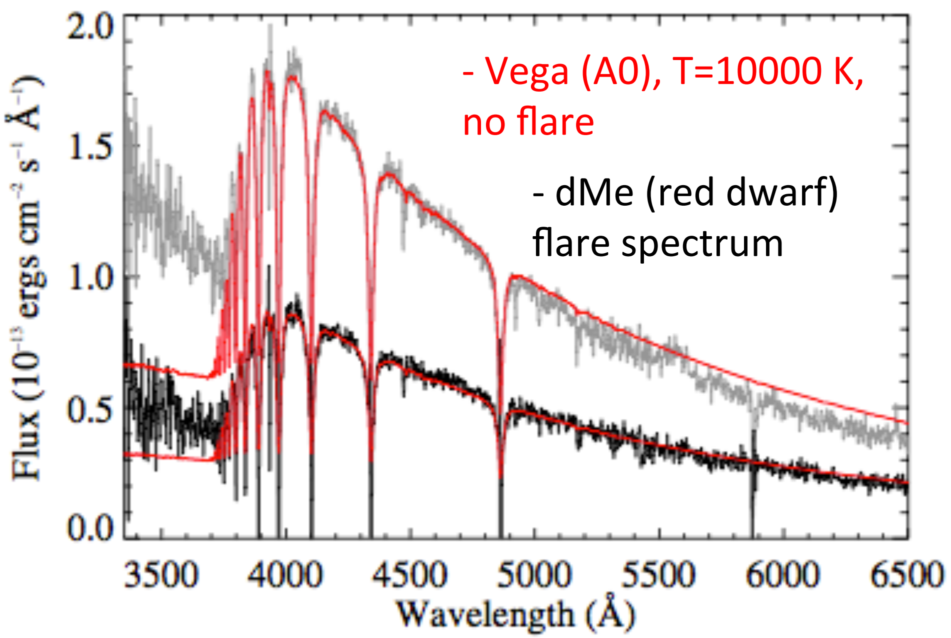
- electrons probably stopped in chromosphere
- hydrogen recombination (=jumps in spectra)

- backwarming may heat photosph.
- H^- and hydrogen continua

Multi-Wavelength Flare Observations

Stellar spectra have advantages:
1) wider spectral coverage, 2) larger field of view (whole star)

Red dwarf flare spectrum (Kowalski et al. 2011)



Solar flare spectra (Hudson et al. 2010)

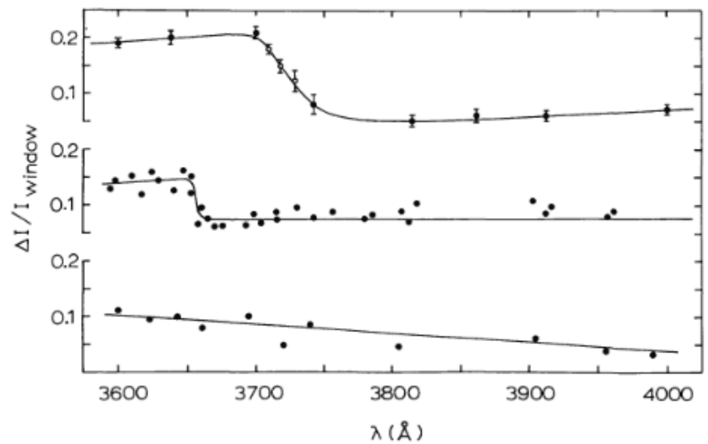


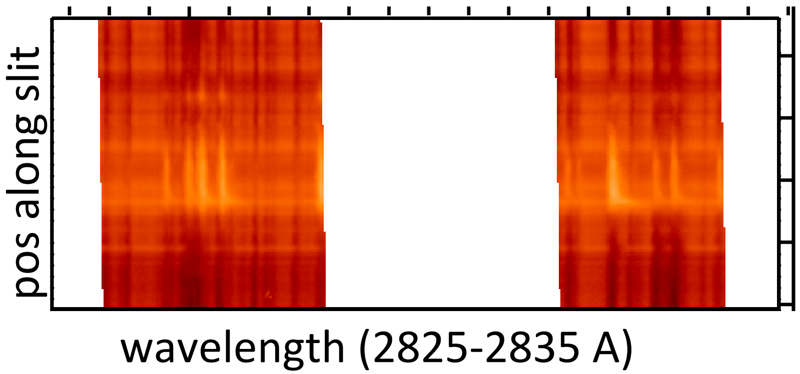
Fig. 1. Comparison of UV spectra of three white-light flares, from Neidig (1983): (*upper*), Hiei (1982, *middle*), and Machado & Rust (1974, *lower*).

=> Combine multiple instruments for solar flare spectra

IRIS: 2014-03-29 (X1.0), WL emission

Detection of the Balmer continuum.

The whole spectrum is enhanced at some locations.



Heinzel & Kleint, ApJL 794, 23, 2015

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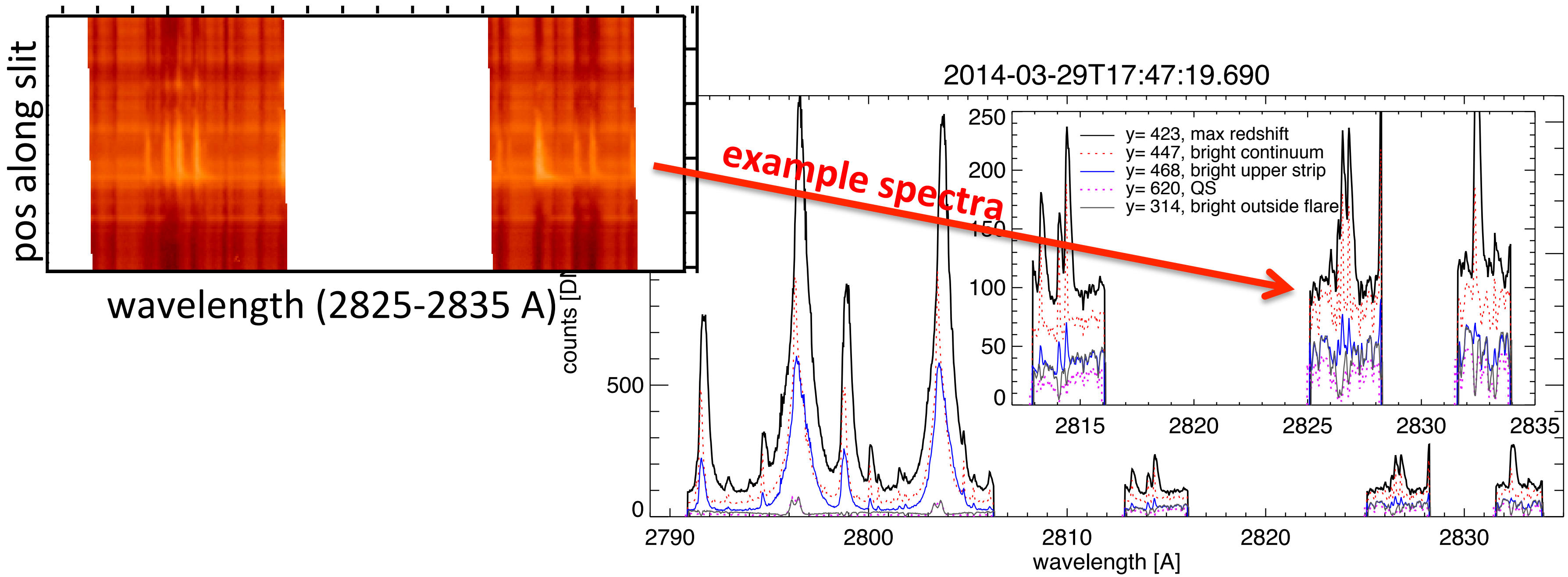

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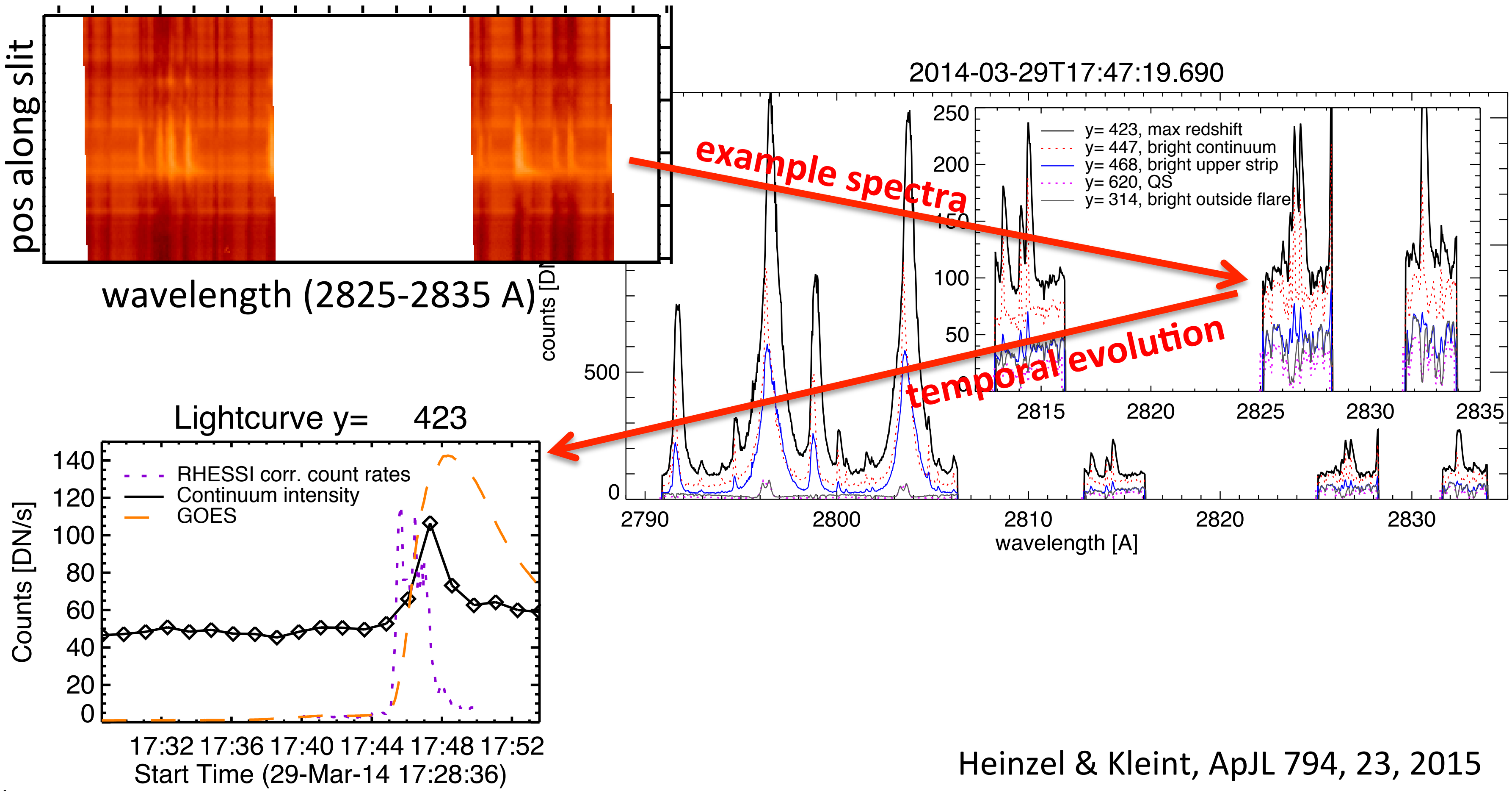

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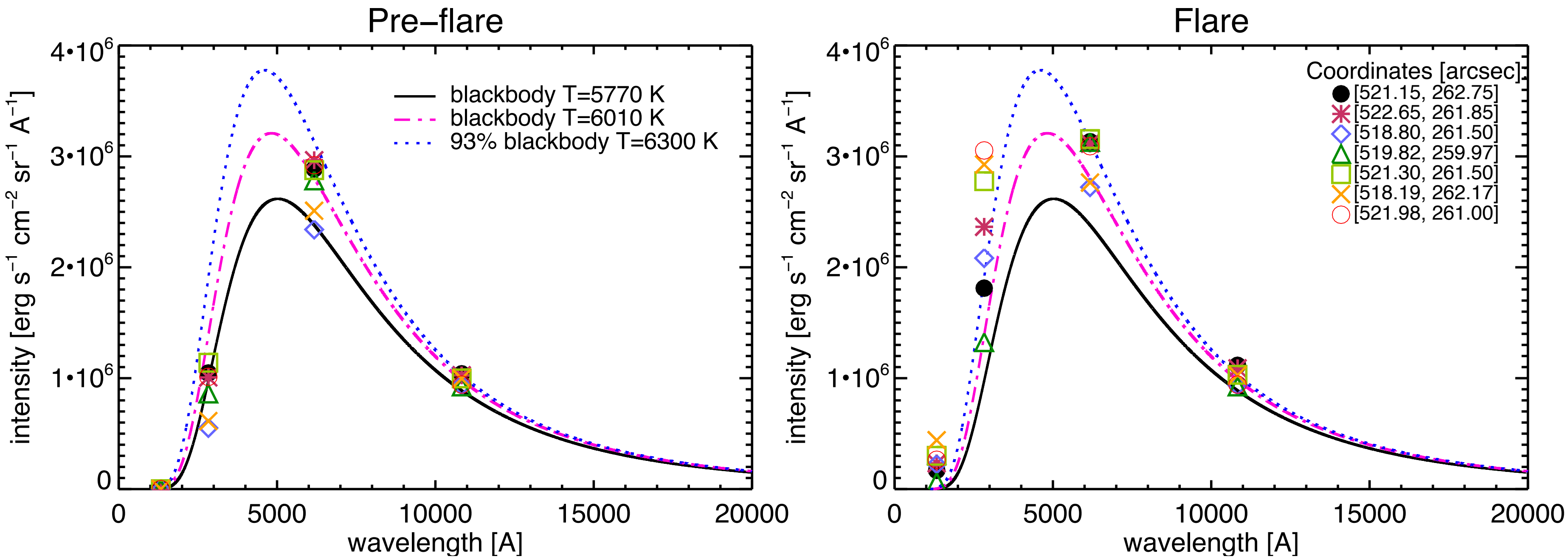
Multi-Wavelength Flare Observations



Widest spectral coverage for a solar flare: IRIS + HMI + DST/FIRS

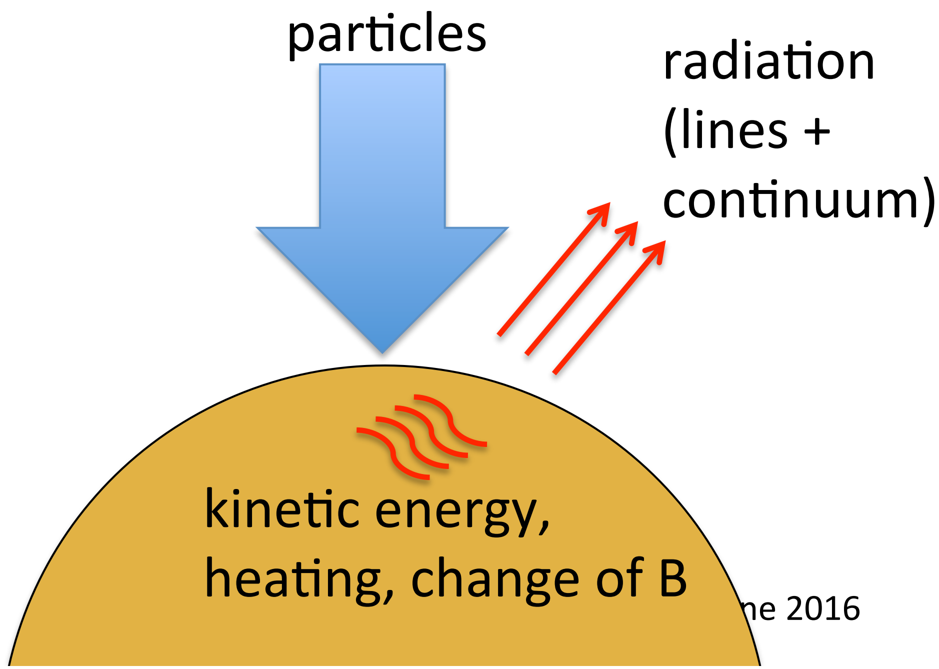
NUV increases more than VIS+IR. Therefore Balmer continuum, not H^- in UV.
=> Continuum has contribution from H^- (VIS+IR)=photosphere and hydrogen recombination (UV)=chromosphere.

Kleint, Heinzel, Judge & Krucker, ApJ, 816, 88, 2016

Flare Energetics

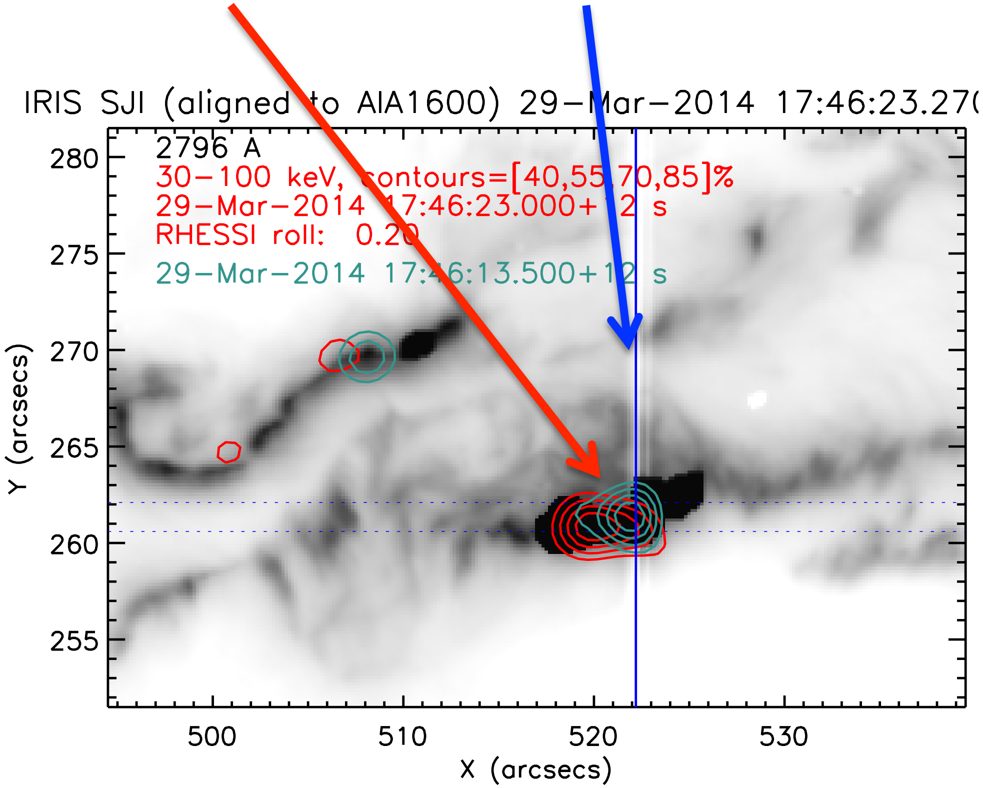
How is flare energy dissipated?

Compare energy input derived from RHESSI (accelerated electrons) to energy output in continuum and line radiation.



Continuum Emission: X1 Flare

RHESSI (red) and IRIS slit coincided => input vs. output energies



Input energy calculated from RHESSI (cutoff 20 keV):
3.5×10^{11} erg s^{-1} cm^{-2}

Energy losses in the continuum (from spectra):
8×10^{10} erg s^{-1} cm^{-2}

=> ~20% of input energy emitted by continuum (method not exact!)

Future step: estimate radiation by spectral lines, heating

Kleint, Heinzel, Judge & Krucker, ApJ, 816, 88, 2016

Continuum Emission

Where does the WL emission come from?
Photosphere or Chromosphere?

Both. NUV from chromosphere (Balmer continuum), indication of backwarming. (Heinzel & Kleint, 2014, Kleint et. al 2016)

What fraction of flare energy is radiated away by the continuum?

~20% (Kleint et al. 2016). Non-IRIS measurements found 15% for EVE/AIA/SOT continua + lines (Milligan et al. 2014)

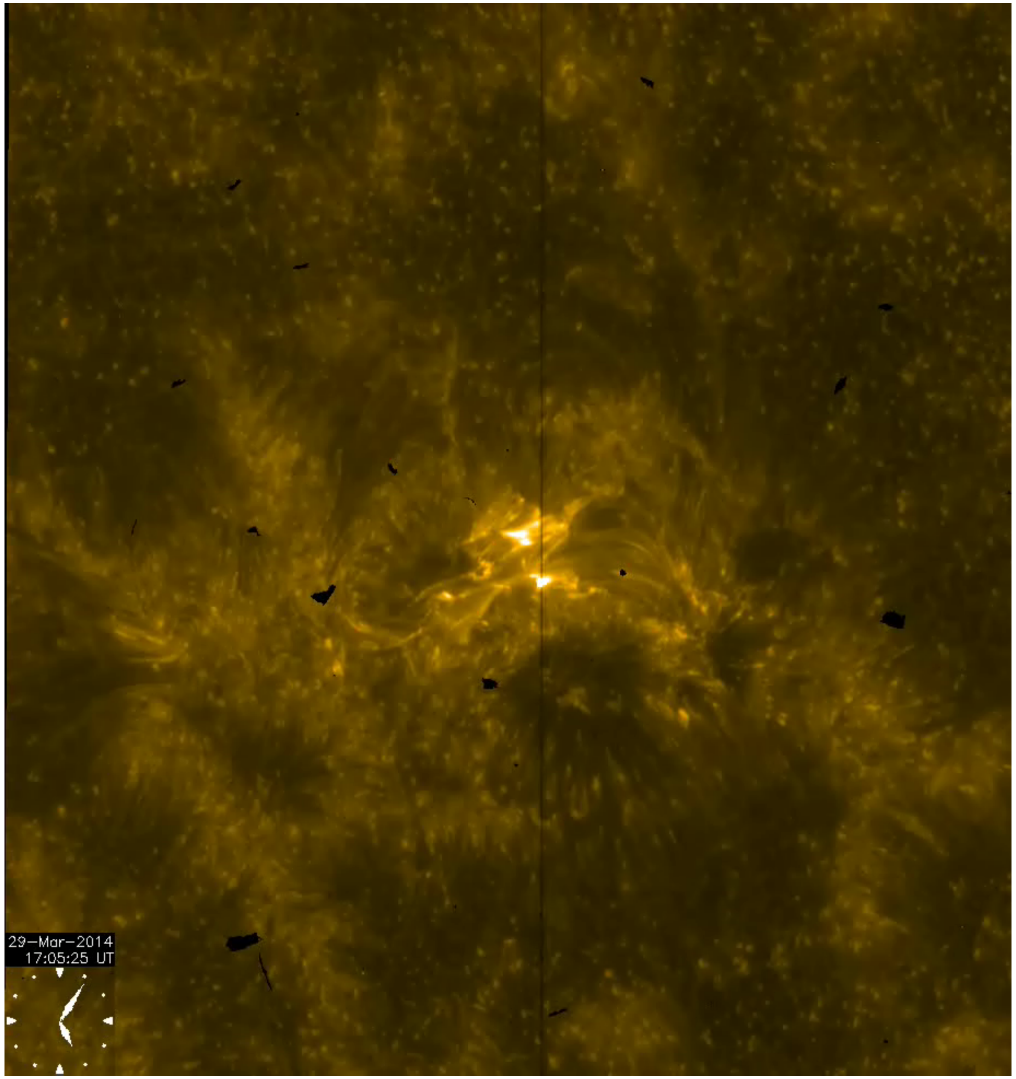
see also today's talk by A. Awasthi

Filament Eruptions

How fast do filaments erupt?

Are they causes or triggers of flares?

IRIS: 2014-03-29 (X1.0)



Kleint et al., ApJ 806, 9 (2015)

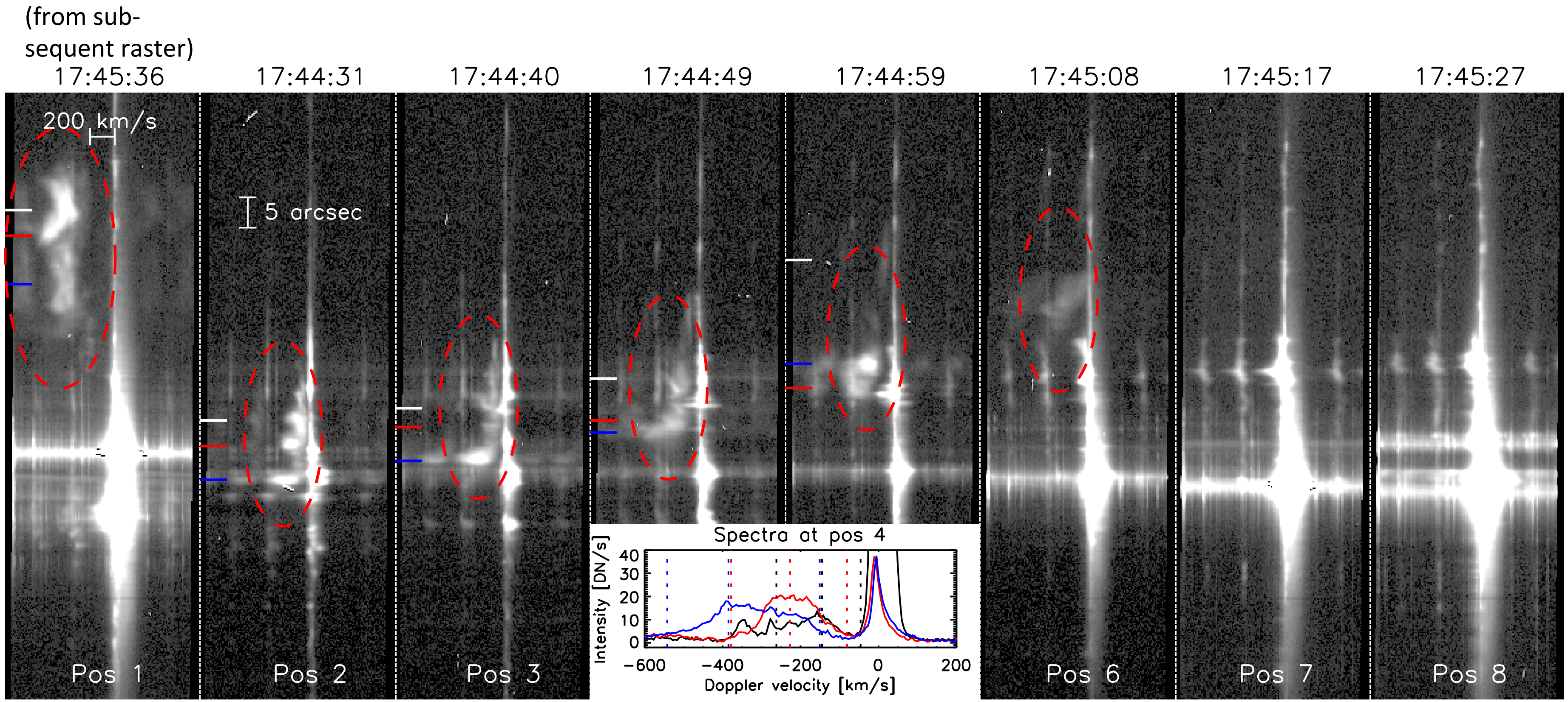
8 raster positions (every ~other shown in movie)

Filament eruption visible

FUV and NUV spectra recorded at each raster position.

First IRIS X-flare observation

IRIS: 2014-03-29 (X1.0), Flare trigger: filament eruption

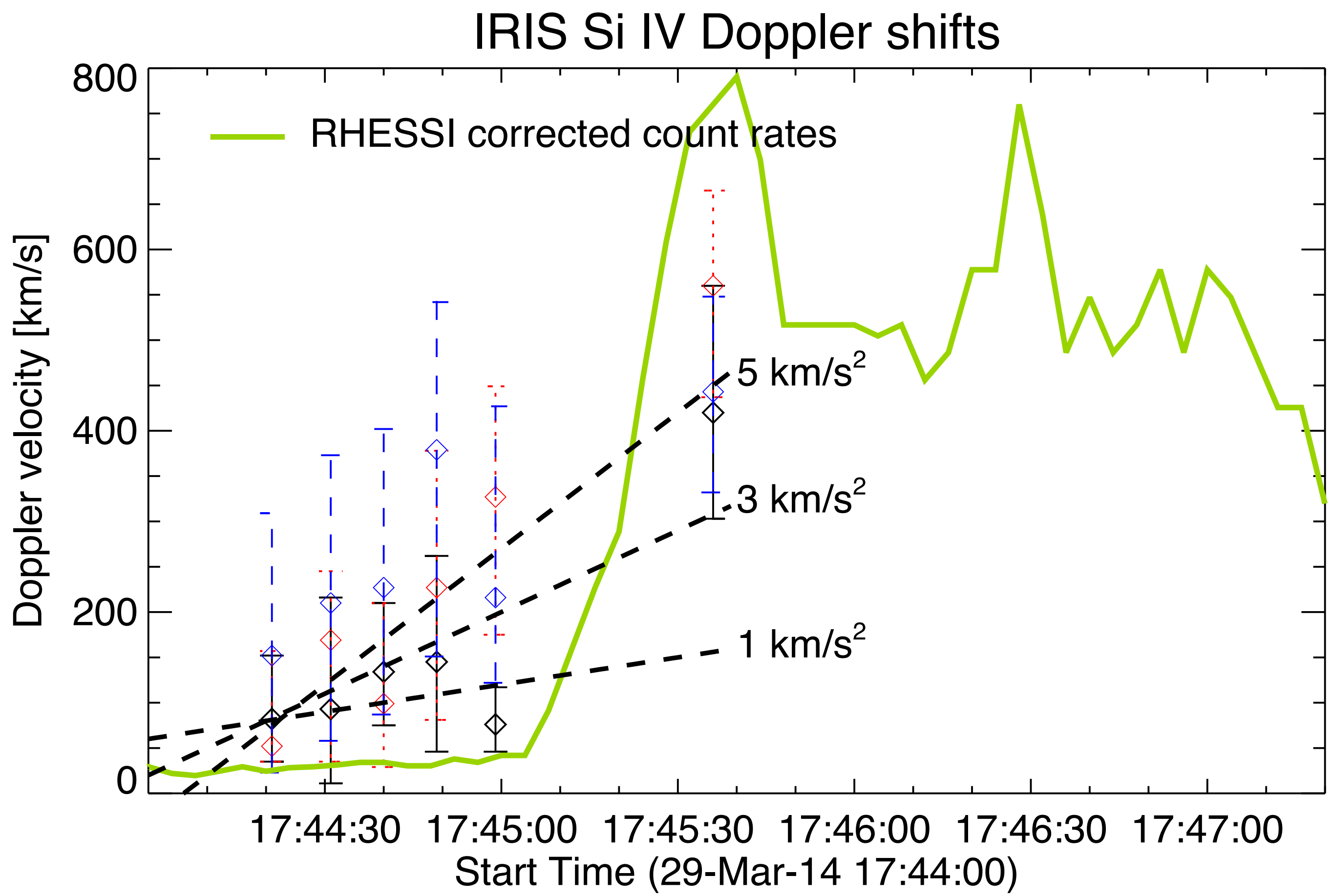


Si IV line at each raster position.
=> Filament is accelerating

Kleint et al., ApJ 806, 9 (2015)

IRIS: 2014-03-29 (X1.0), Flare trigger: filament eruption

Acceleration starts before HXR are visible. Eruption triggering the flare?
Acceleration high compared to previous observations (<1.5 km/s^2)



Kleint et al., ApJ 806, 9 (2015)

Filament Eruptions

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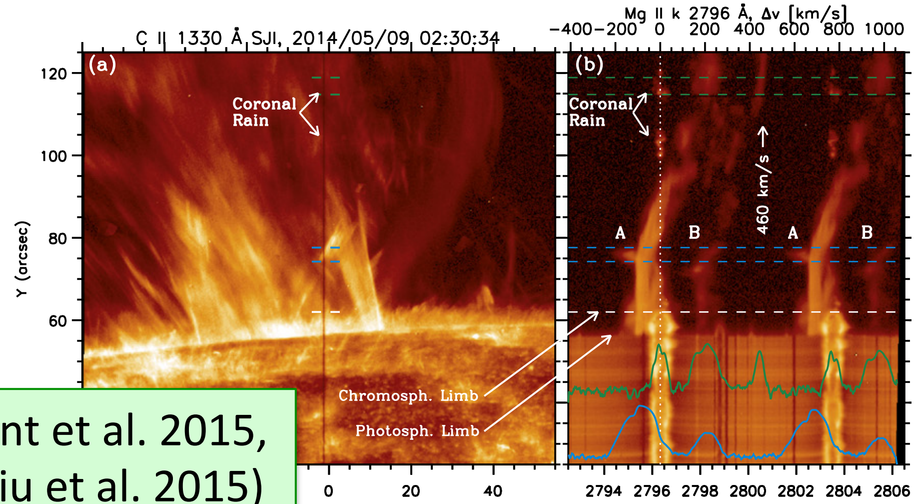


Prominence eruption from Liu et al. 2015

several hundred km/s. (>600 km/s: Kleint et al. 2015, >460 km/s Doppler + 1200 km/s POS: Liu et al. 2015)

Are they causes or triggers of flares?

HXR emission started after filament eruption.
Filament = Trigger (for X1 on 2014-03-29)

see also today's talk by M. Woods

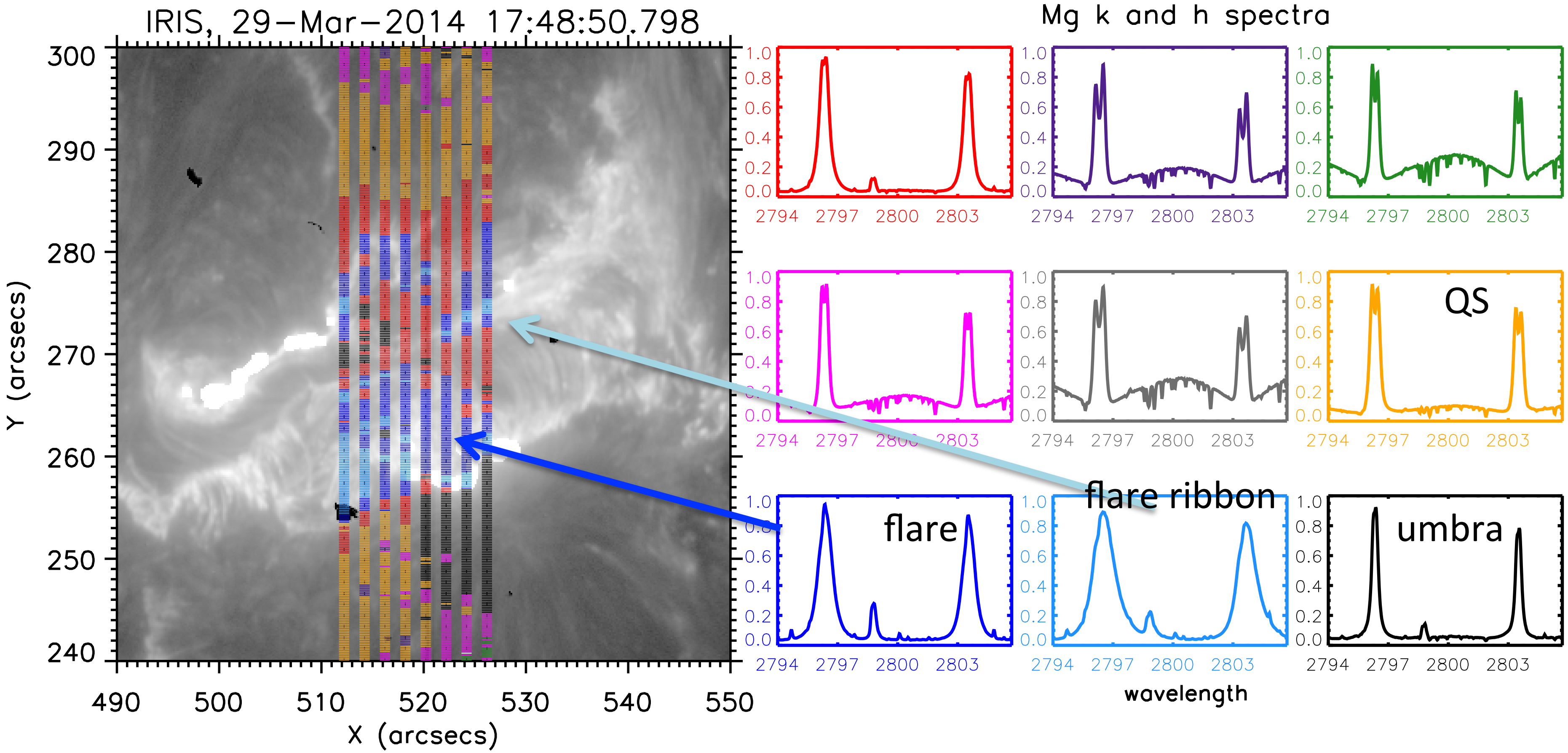
Modeling Solar Flares

How can we explain the unusual flare spectra?

What do we learn about the lower solar atmosphere?

Modeling Solar Flares

Types of spectra during a flare, found with machine learning (k-means).



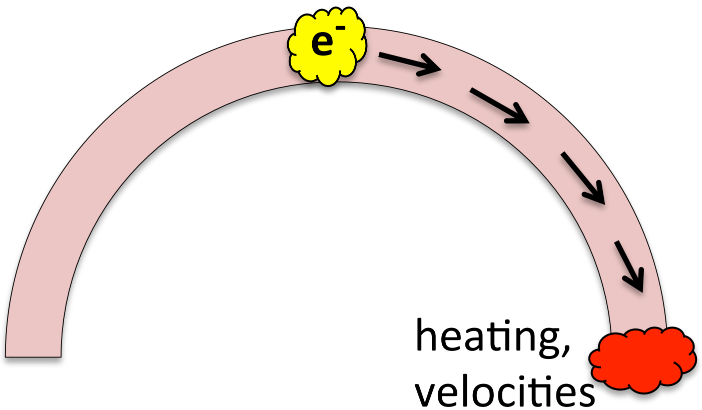
Mg flare spectra have a single peak and broad wings. Physics?

Modeling with RADYN

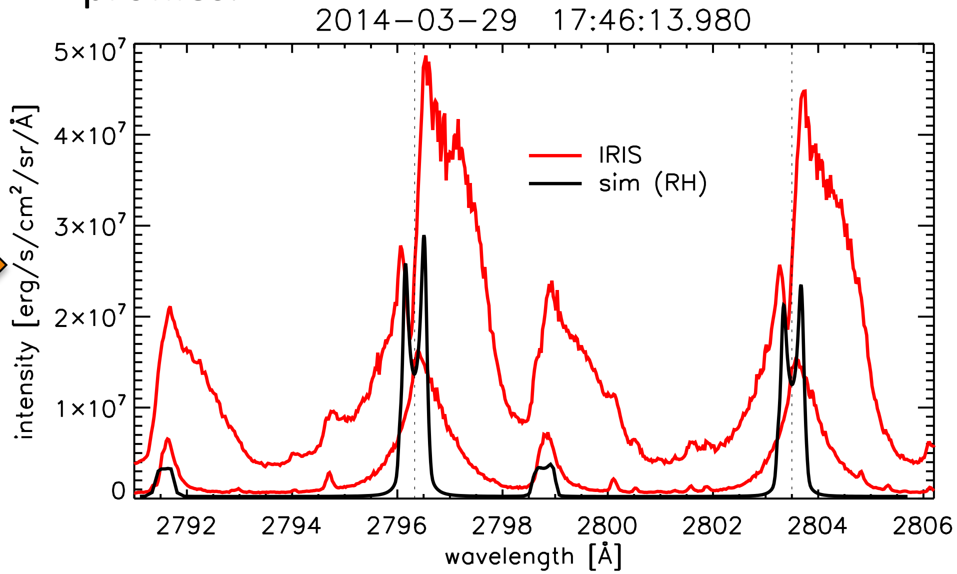
Simulations with RADYN: energy input constrained by RHESSI, simulate spectral lines and continuum

Assume:

- flare loop, 10 Mm
- inject electrons at top
- solve 1D nLTE radiative transfer



=> Comparison of observed and simulated profiles.

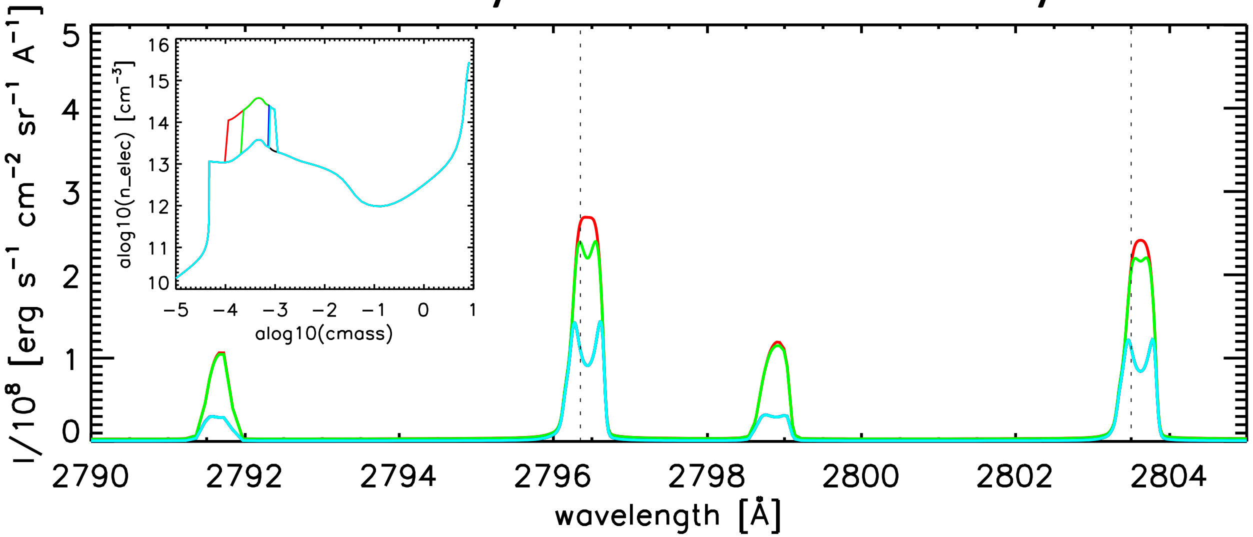


Rubio da Costa et al., ApJ in press (2016)

see Fatima's poster and today's talks by J. Kasparova and J. Allred

Modeling with RH

Models do not fit yet. => Parameter study

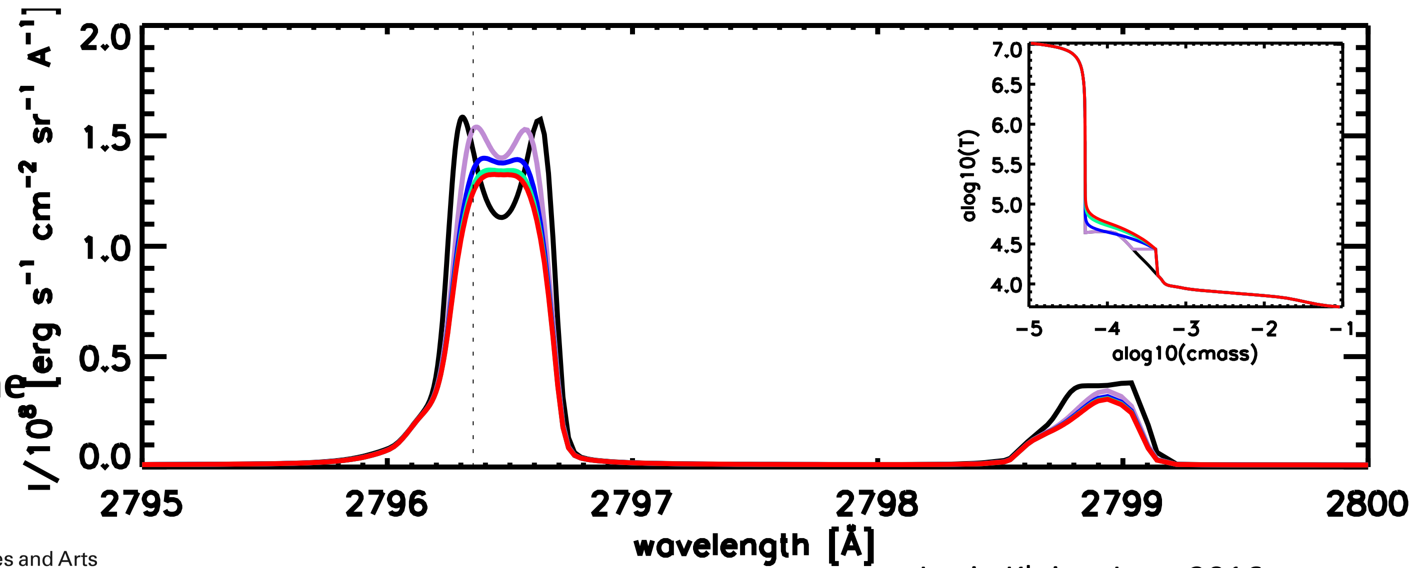


increasing density just below TR => single peak

broad wings not reproduced yet.

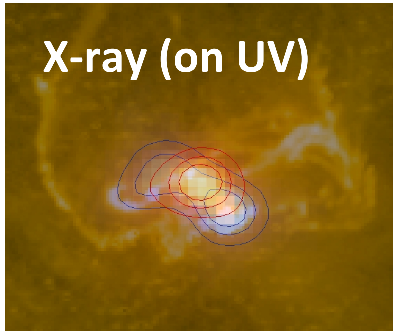
increasing temperature just below TR => single peak

=> Need to couple source function to the Planck function.

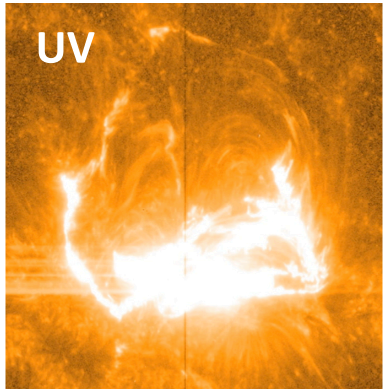


Conclusions

IRIS: ideal to study atmospheric response from 0.01 to 10 MK

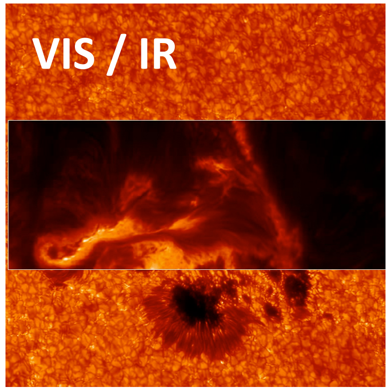


Chromospheric evaporation
- possibly resolving flare kernels
- observed upflow lags downflow
- gentle evaporation/conduction may be important



Can use **IRIS continuum** for data points in the UV
- chromospheric Balmer continuum
- during X1.0 2014-03-29: energy output = 20% of input

Filament eruptions seem to trigger flares. Doppler velocities measurable.



Modeling
- Mg flare spectra have single peak and broad wings
- use RADYN, but cannot get single peak
- parameter study indicates that we need higher T or e^- density