Advances in Understanding Solar and Stellar Flares

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Cool Stars 19

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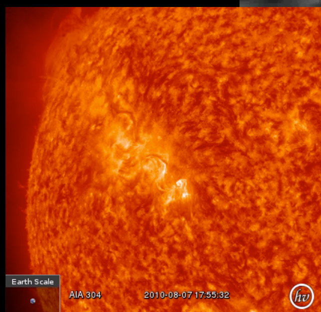
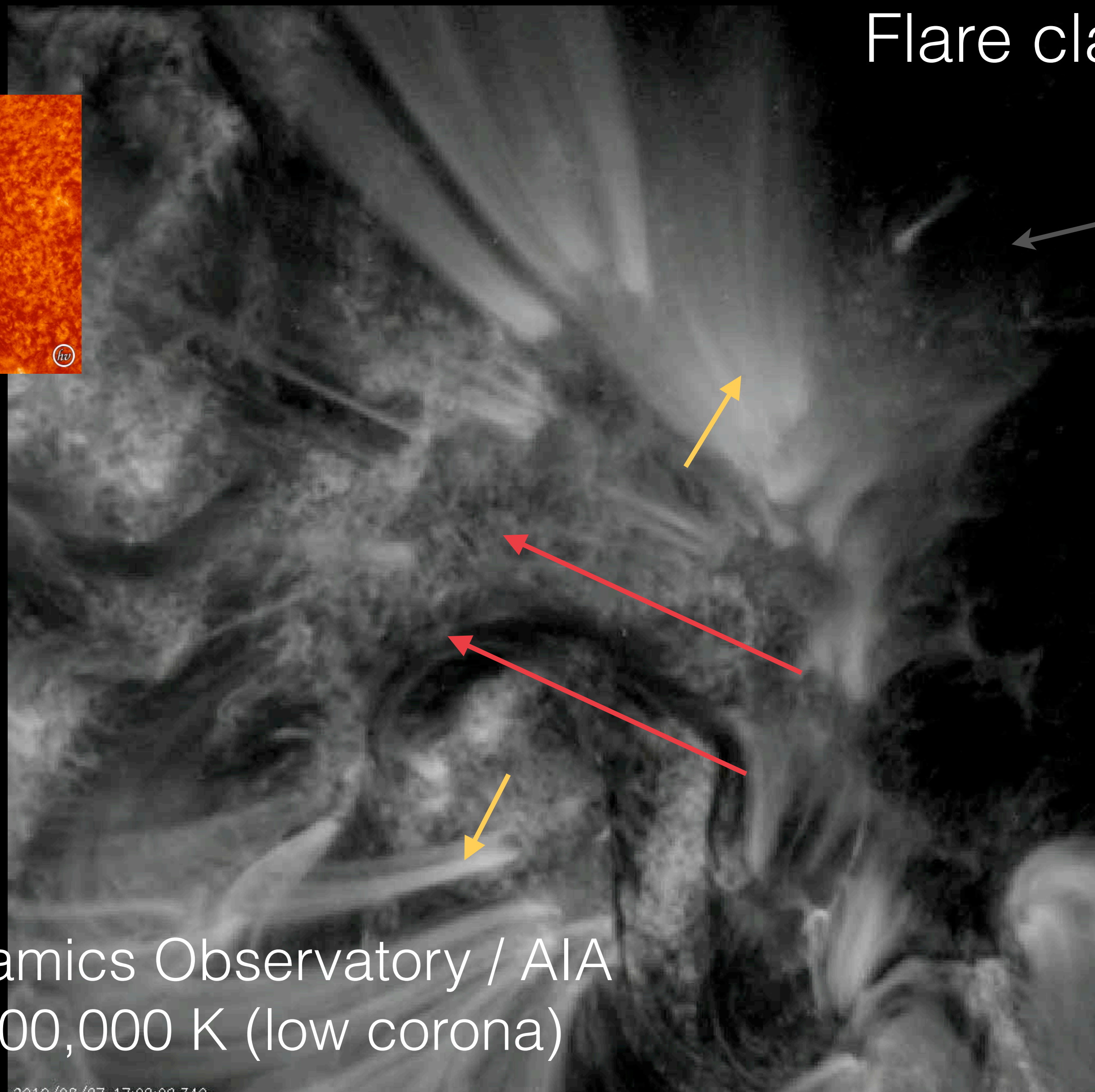
Outline

Standard flare mechanism: magnetic energy —> particle acceleration —> atmospheric heating (flare)

- ✦ Overview of solar & dMe flares: solar imagery and stellar Balmer jump spectra
- ✦ New solar data from the Interface Region Imaging Spectrograph (IRIS)
- ✦ 1D radiative-hydrodynamic modeling of > 2500Å spectrum
- ✦ Theoretical challenges of high beam energy fluxes
- ✦ Stellar coronal mass ejections

Two Ribbon Solar Flares



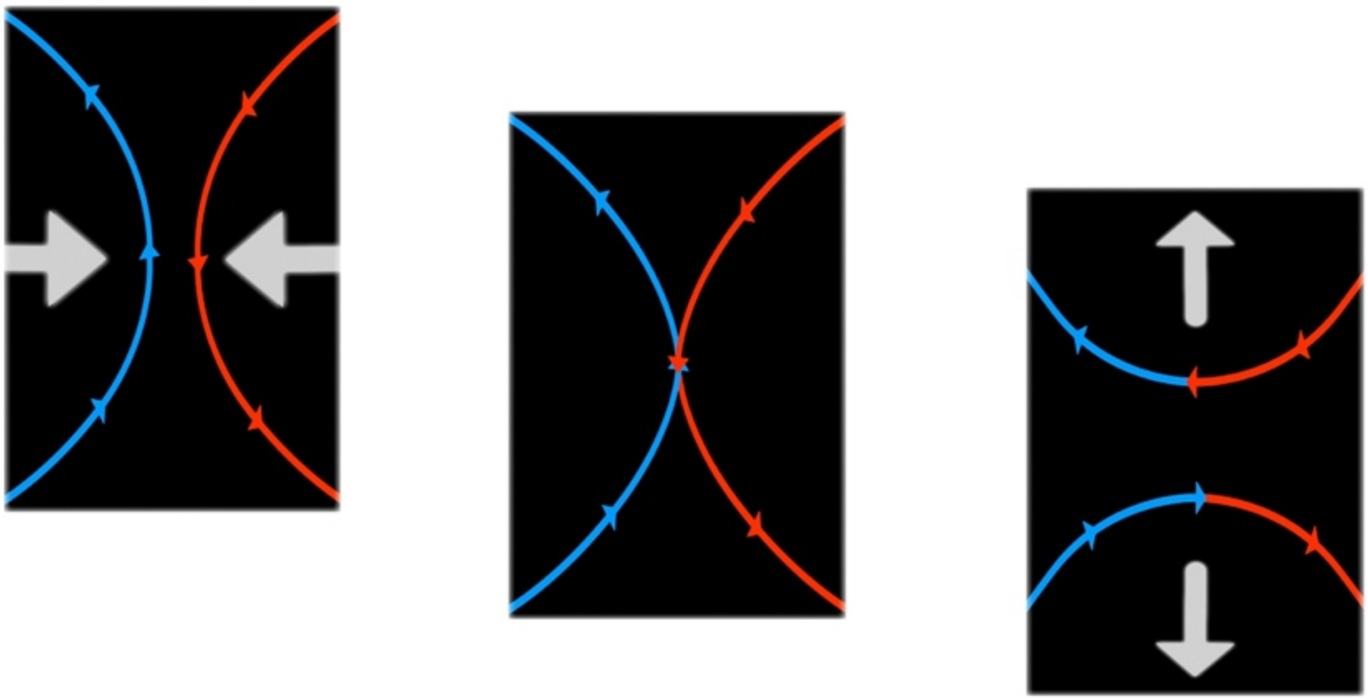


Flare classification

X
M
C
B

Solar Dynamics Observatory / AIA
171A: 800,000 K (low corona)

Magnetic Reconnection

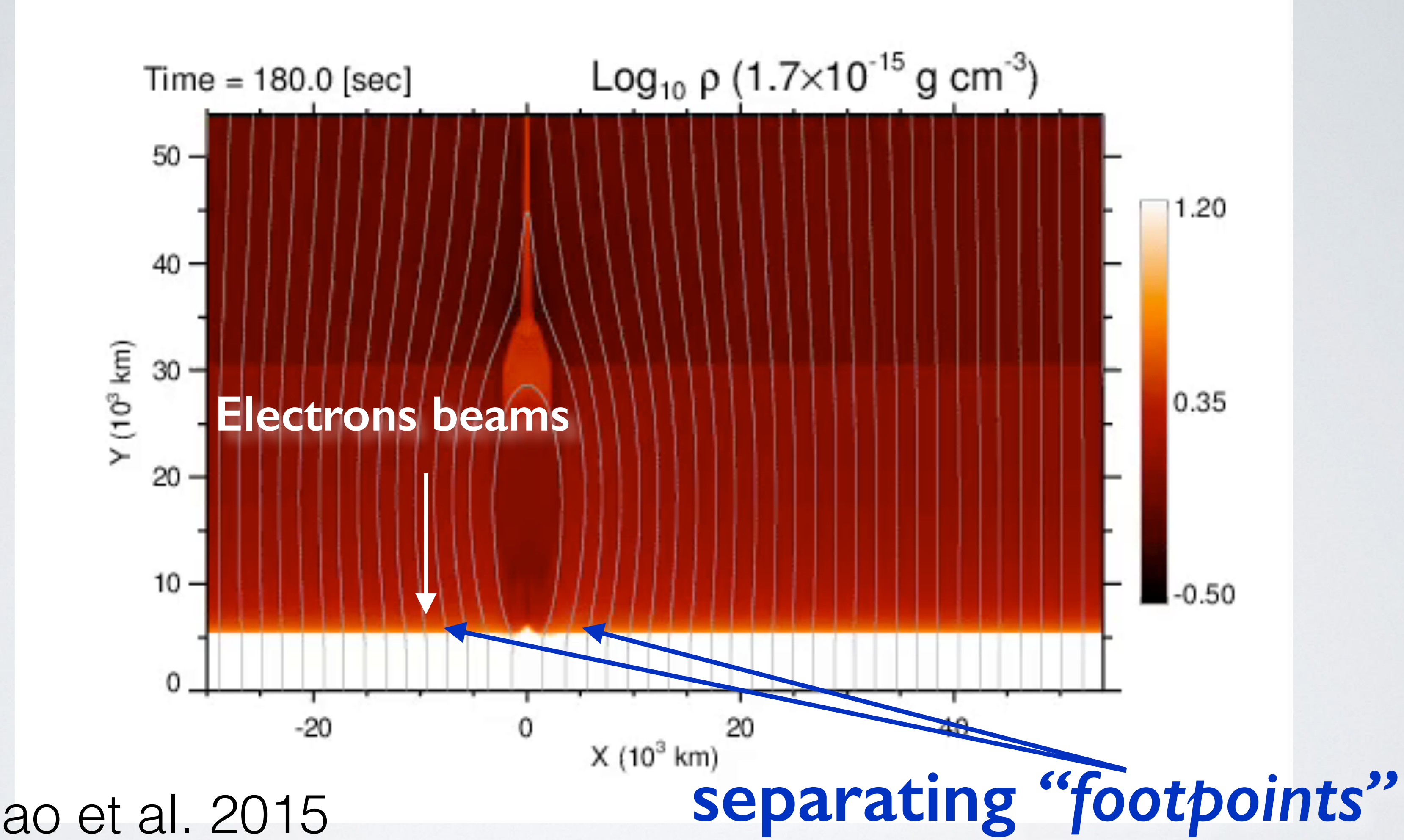


NASA Goddard

Magnetic energy ➠ Kinetic energy of particles

(via merging magnetic islands; e.g., Drake et al. 2013, stochastic/turbulent, betatron, Alfven wave, shock acceleration)

2DMHD Flare Models



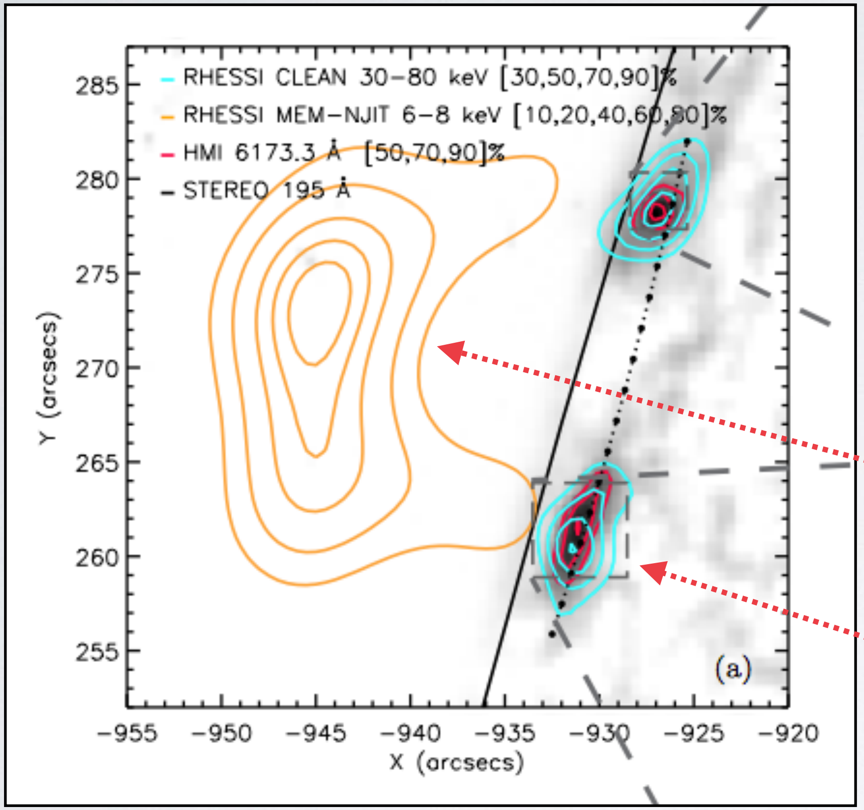
Takasao et al. 2015

(see also Longcope 2014)

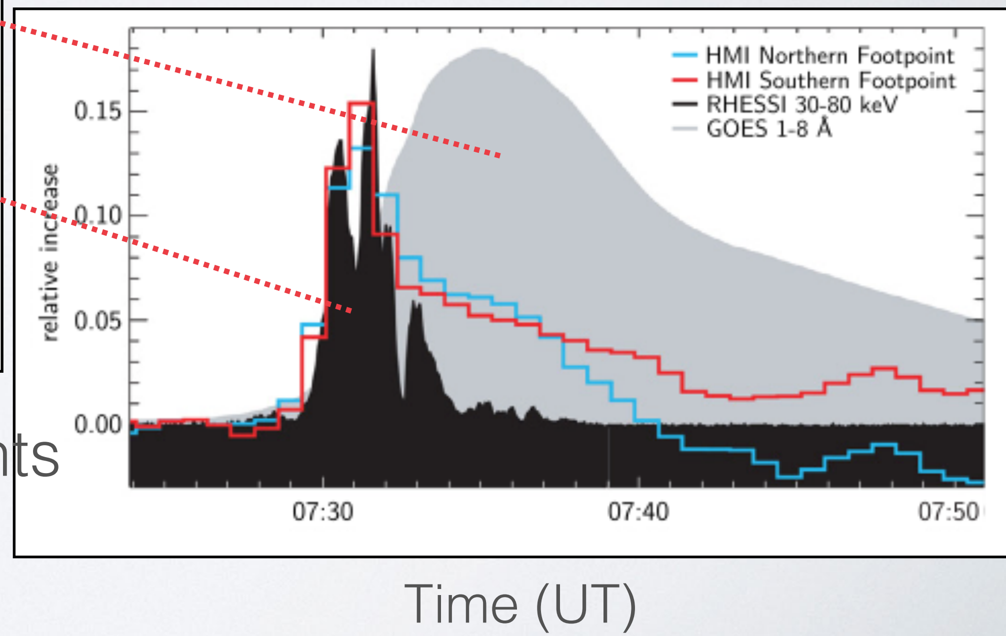
3DMHD models: "slipping reconnection"
(e.g., Janvier et al. 2014, Dudik et al. 2014)

Solar flare optical / white-light footpoints

- Coincident in time and space with hard X-rays (E> 20 keV)



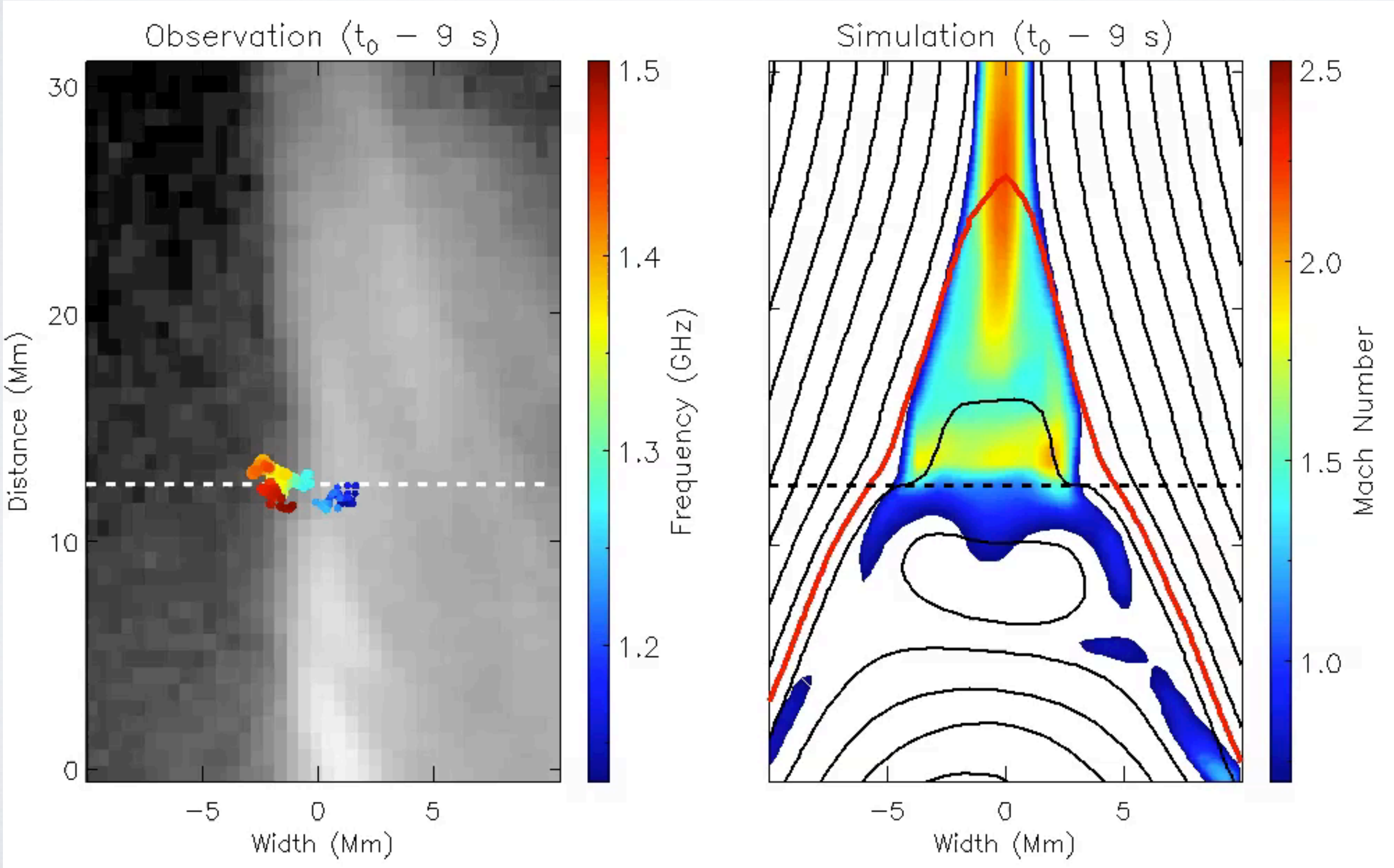
Observations of limb flares:
Martinez-Oliveros et al. 2012,
Krucker et al. 2015



- Spatially confined to footpoints

Radio Imaging Spectroscopy with VLA

- Type III radio bursts indicate beams of electrons (0.1c) propagating upward and downward (Chen et al. 2013)
- Radio emission found at termination shock in corona, disrupted by reconnection plasmoids (Chen et al. 2015)

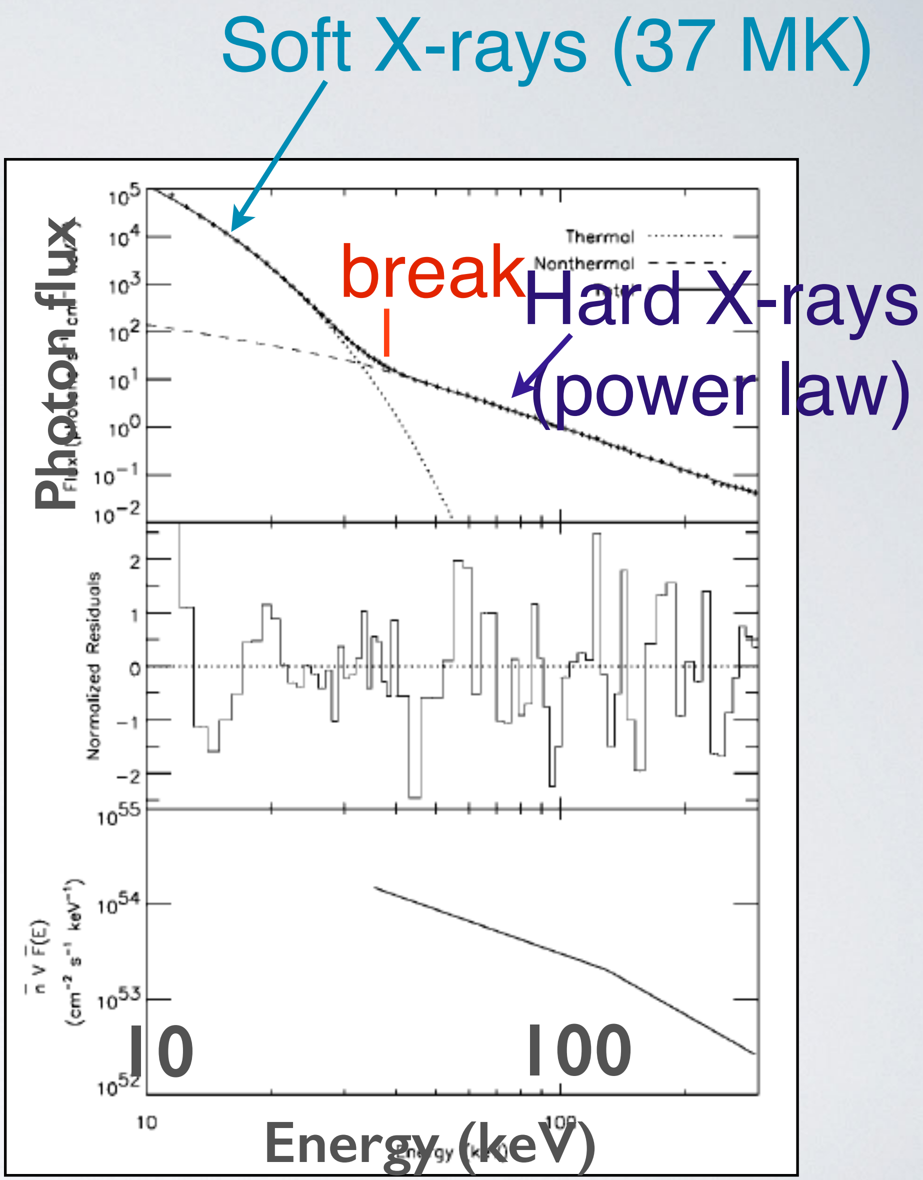


Chen et al. 2015

Solar Hard X-ray Footpoints

Hard X-rays (20-100s keV) from RHESSI

- Beam electrons lose energy in chromosphere and emit nonthermal, hard X-ray bremsstrahlung radiation
- Can infer the spectrum of nonthermal electrons (power-law), most have E~20 keV or less

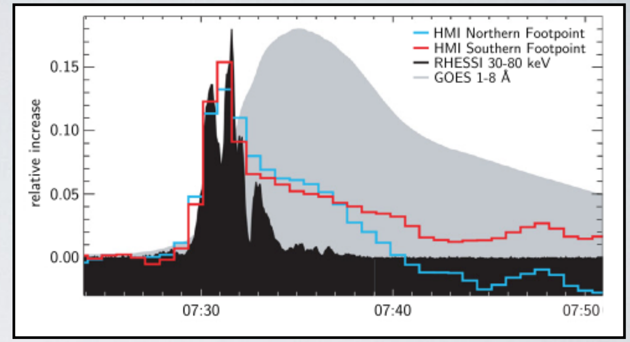


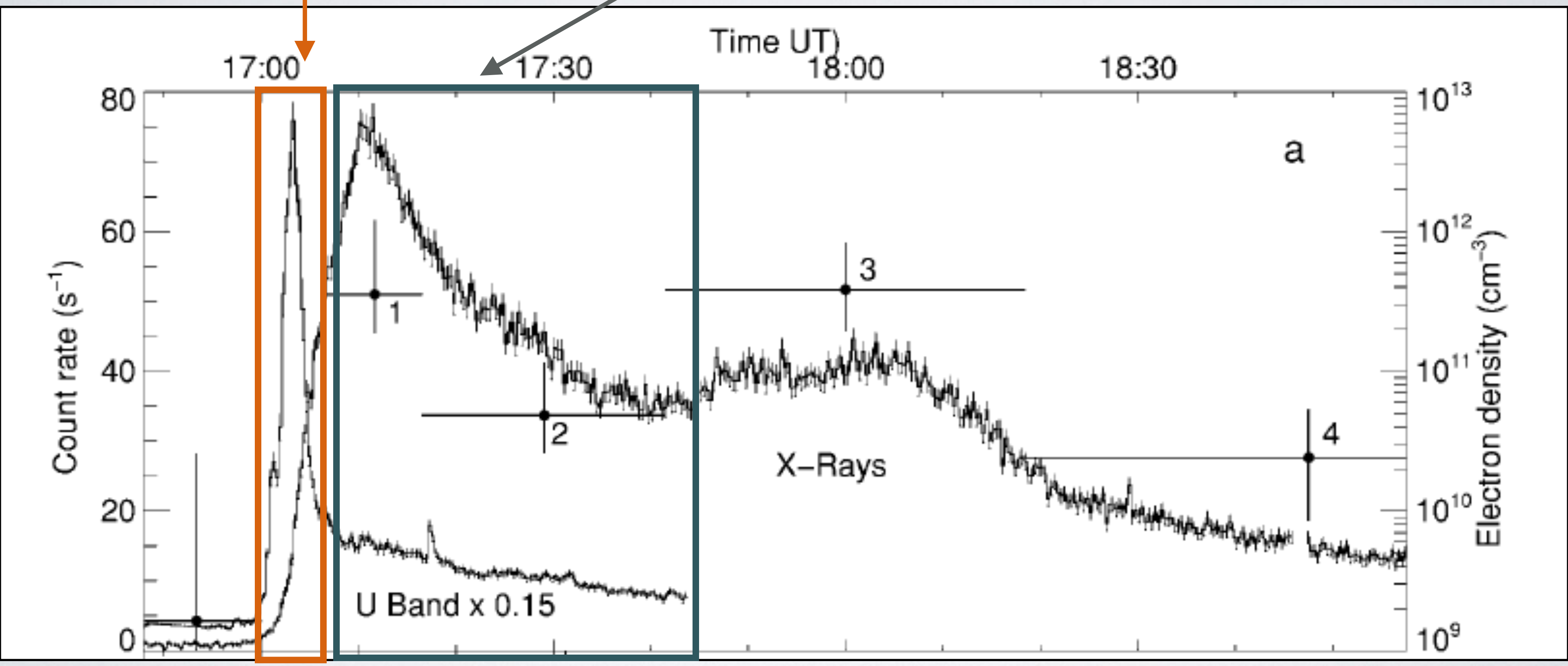
Holman et al. 2003

The solar-stellar connection

Impulsive phase (U-band is white-light, proxy for hard X-rays), 10,000 K “footpoints”

Gradual phase (bright soft X-rays), 10 MK “loops”





Gudel et al. 2002 (flare on dM5.5e Proxima Centauri)

White-light emission in stellar flares:

A powerful diagnostic of flare heating at the highest densities

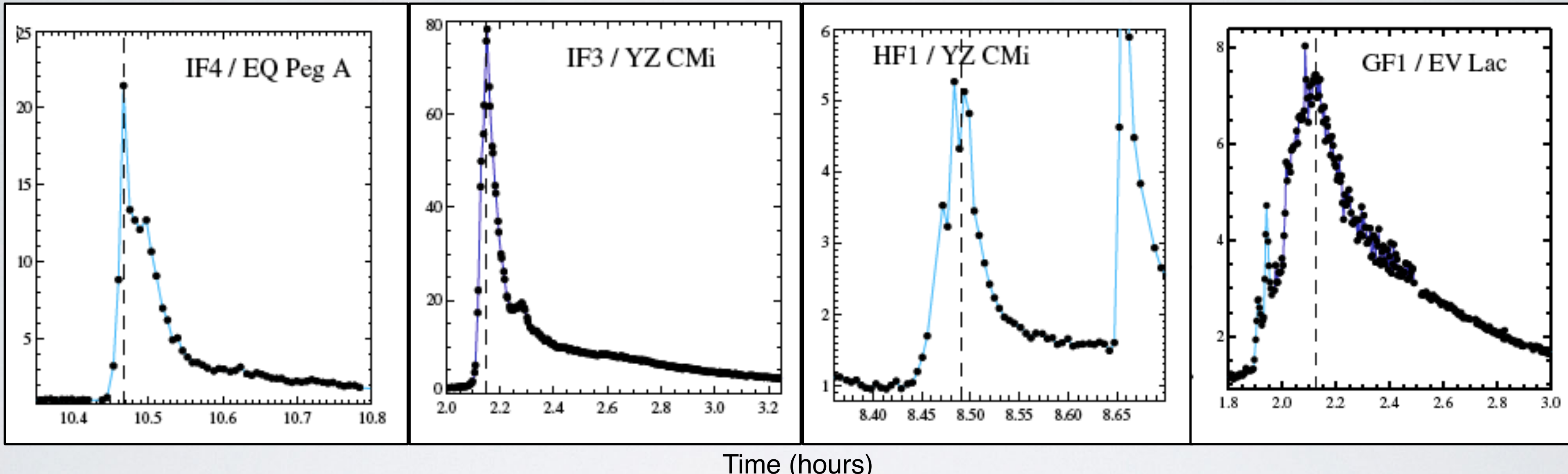
Is the white-light emission blackbody-like (photospheric) or optically thin hydrogen recombination radiation (chromospheric)?

- ➠broad wavelength coverage spectra around Balmer jump

- ➠do electron beams accelerated in the corona produce the observed spectral properties?

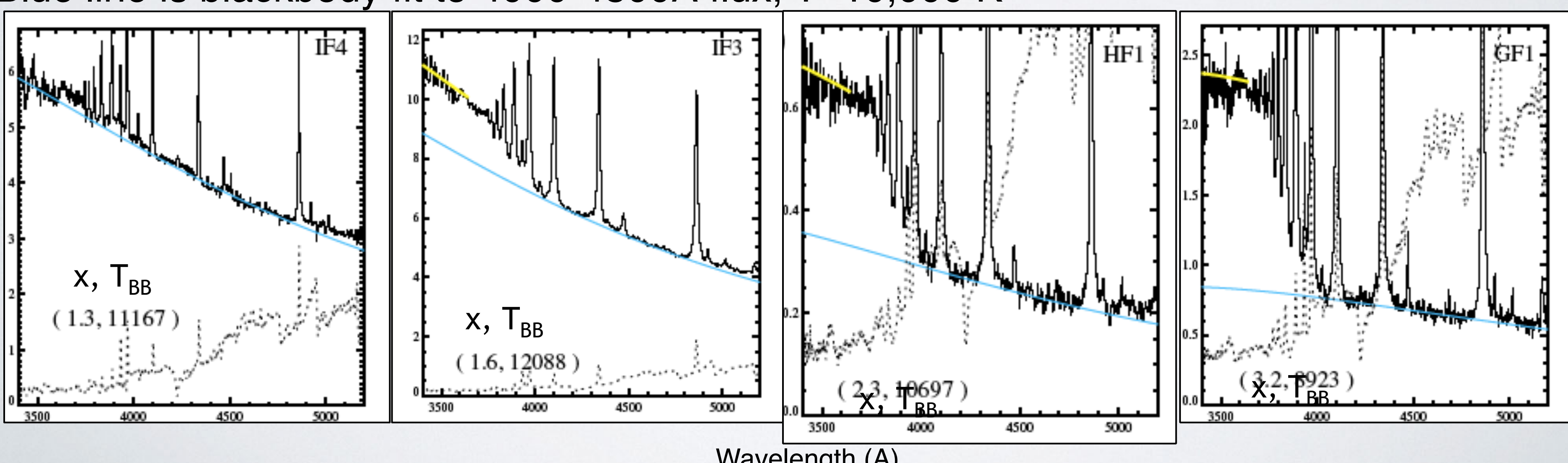
Balmer jump (3646Å) spectra: Kowalski, Hawley et al. 2013 (K13) flare atlas – 20 flares with U band photometry and simultaneous spectra from APO.

Flare light curves – impulsive (IF), hybrid (HF), gradual (GF) flares



Flare spectra show small Balmer continuum component (BaC) in IF, larger in HF, most in GF.

Blue line is blackbody fit to 4000-4800Å flux, T~10,000 K



White-light emission in stellar flares:

A powerful diagnostic of flare heating at the highest densities

Is the white-light emission blackbody-like (photospheric) or optically thin hydrogen recombination radiation (chromospheric)?

1: heating of upper photosphere & TMR (see Metcalf et al. 1990 for a review): not possible for typical energies of electron beams accelerated in corona

2: heating and compression of upper chromosphere (Fisher et al. 1985, Kowalski et al. 2015: *do electron beams compress and heat enough?*

Impulsive Phase Modeling with the RADYN code

with Joel Allred (GSFC), Mats Carlsson (UiO)

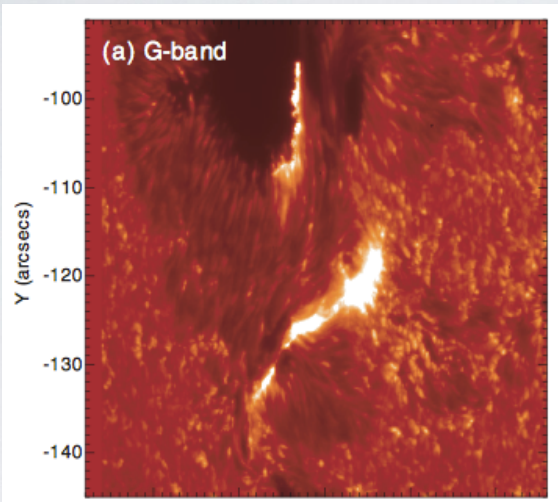
- *RADYN (Carlsson & Stein 1995, 1997), flare version: & Fisher 1994, Abbett & Hawley 1999, Allred et al. 2005, **Allred, Kowalski, & Carlsson 2015 ApJ*
- *Other state-of-the-art flare modeling codes: Flarix (Heinzel et al. 2016), HYDRAD (Reep et al. 2016, Polito et al. 2016)*

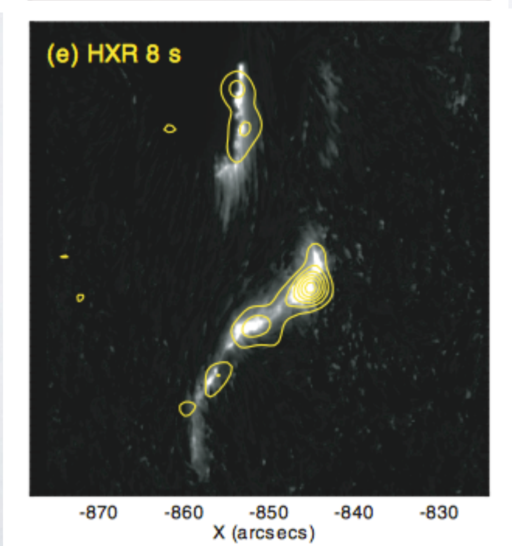
- 1D adaptive grid to resolve shocks
- nLTE radiative transfer for H, He, and Ca
  - use RH code (Uitenbroek 2001) for other transitions
- Optically thin radiative loss function from CHIANTI
- X-ray backwarming from corona
- Photosphere, chromosphere, transition region, corona
- Nonthermal electron (or proton) beam energy deposition Fokker-Planck solution (McTiernan & Petrosian 1990)

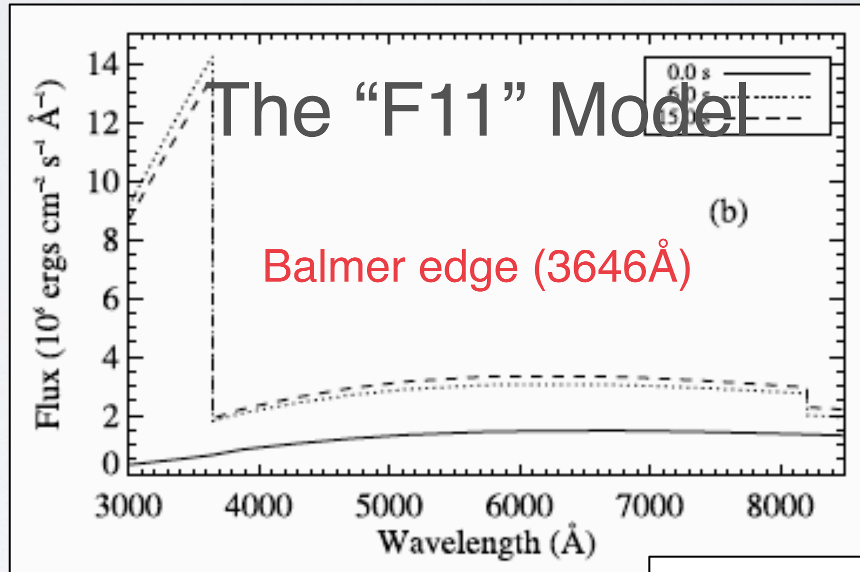
- *New high spatial resolution data of solar flares imply very high energy fluxes of electron beams!*

High spatial resolution footpoint “kernels” have inferred beam energy fluxes of $3x10^{11}$ - $5x10^{12}$ erg s^{-1} cm^{-2} (3F11-5F12)

Krucker et al. 2011, Kleint et al. 2016, Fletcher et al.







The “F11” Model

Balmer edge (3646Å)

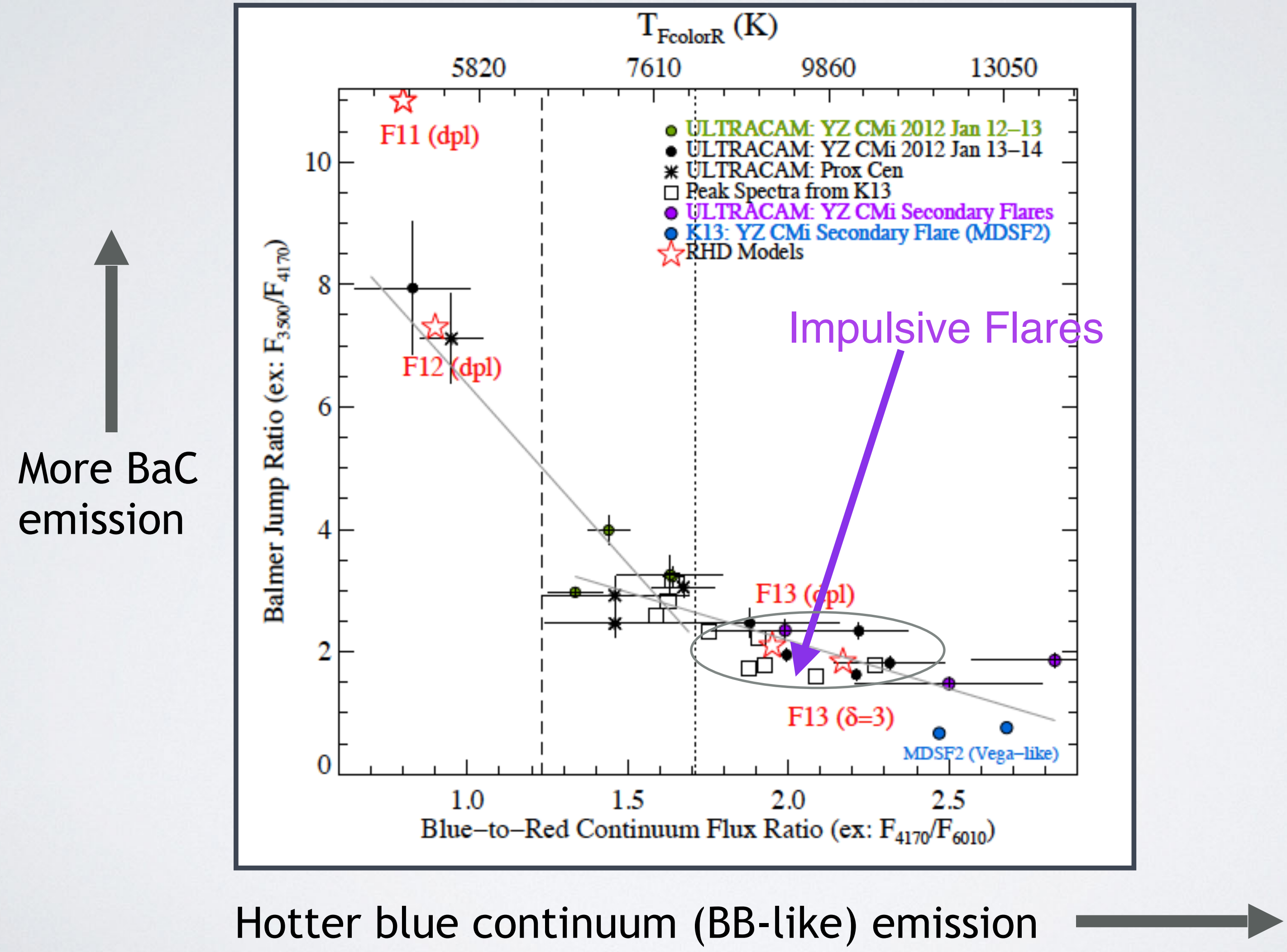
F11 e- beam (10^{11} erg s^{-1} cm^{-2})

Allred et al. 2005, 2006

Should consider higher beam fluxes for M dwarf flares

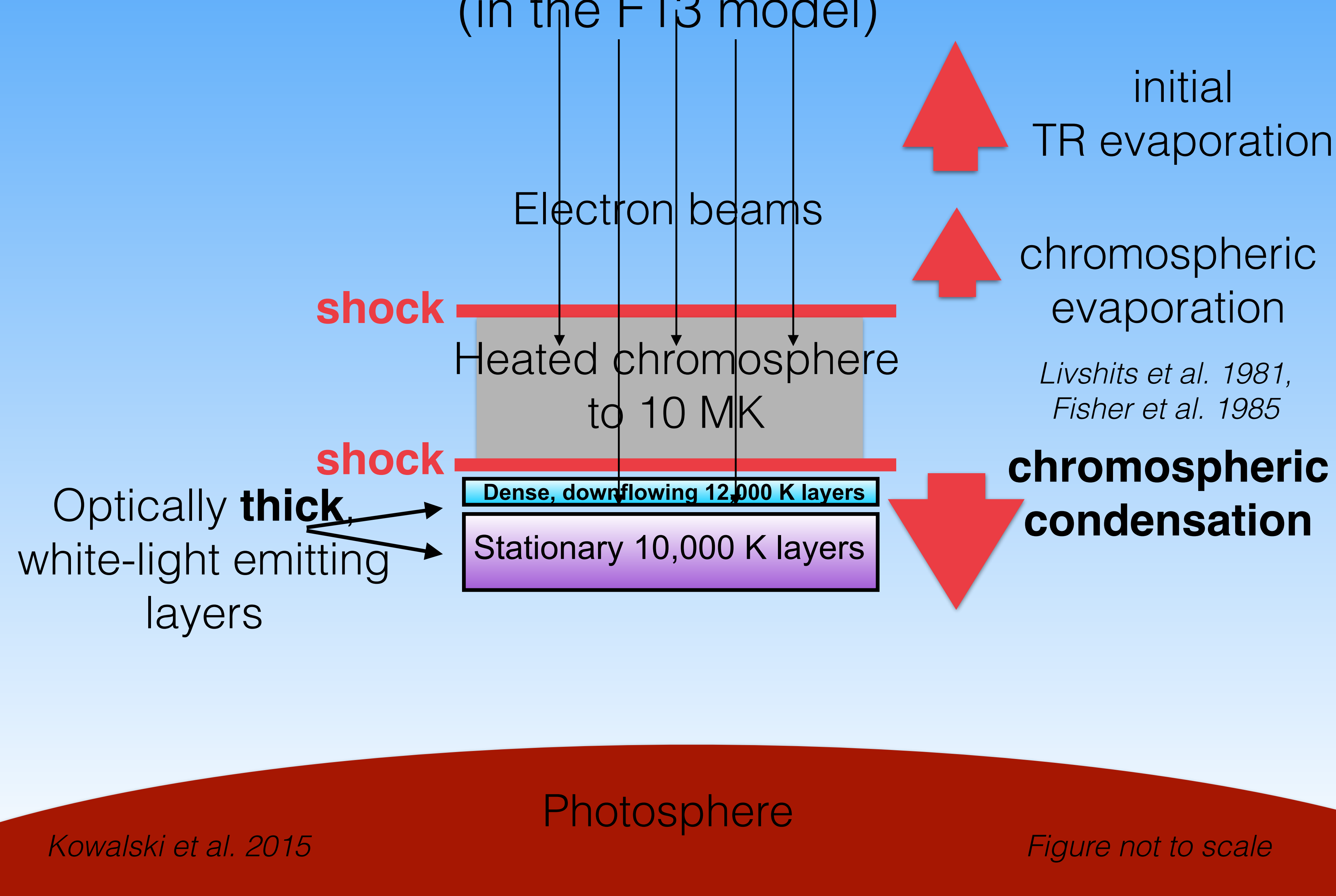
Flare (at peak) Color-Color Diagram

- F13 model reproduces observed continuum flux ratios of impulsive phases of “impulsive flare events”

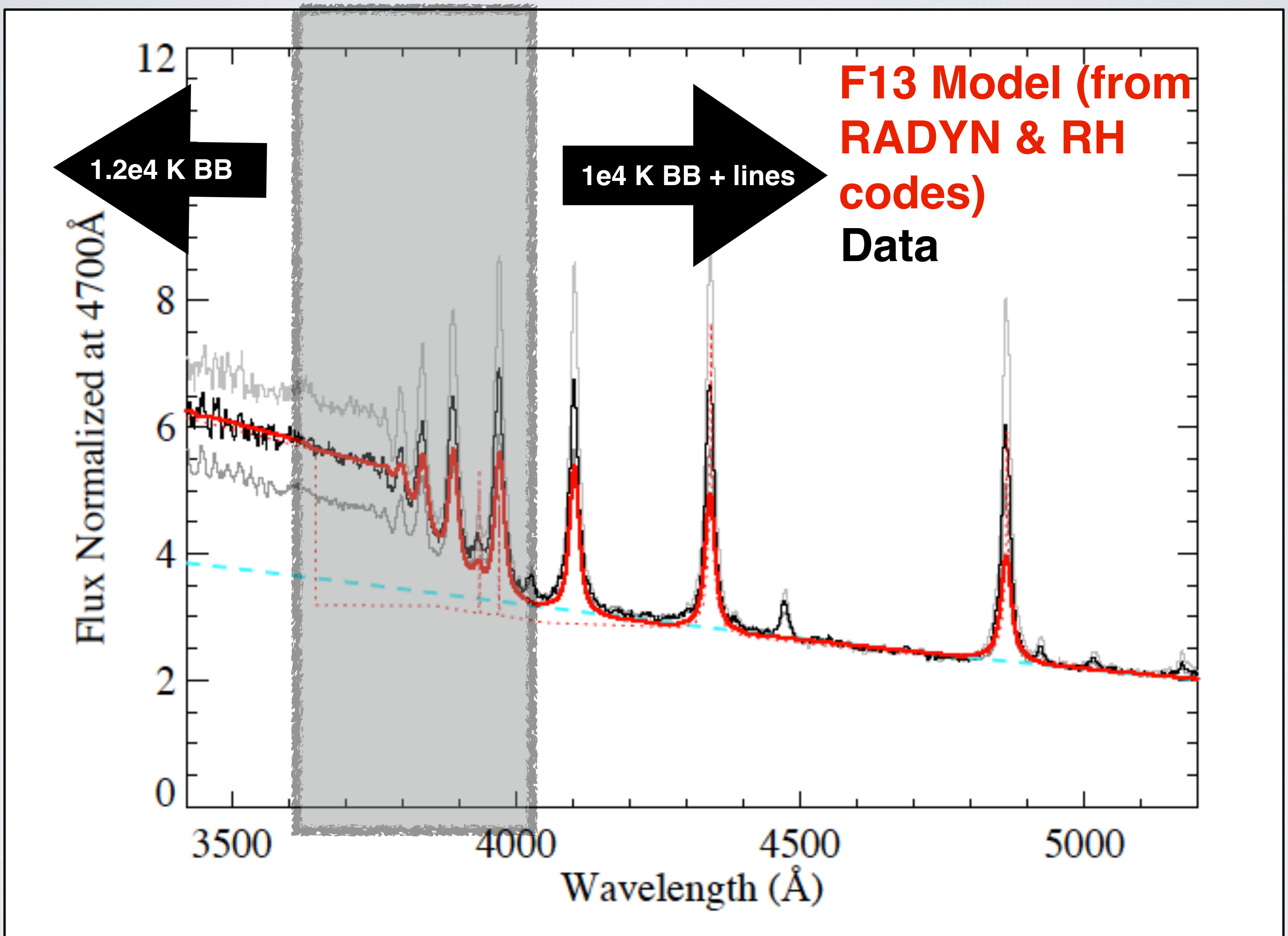


Kowalski, Mathioudakis, Hawley et al. 2016 ApJ

The Origin of the White-Light Emission
(in the F13 model)



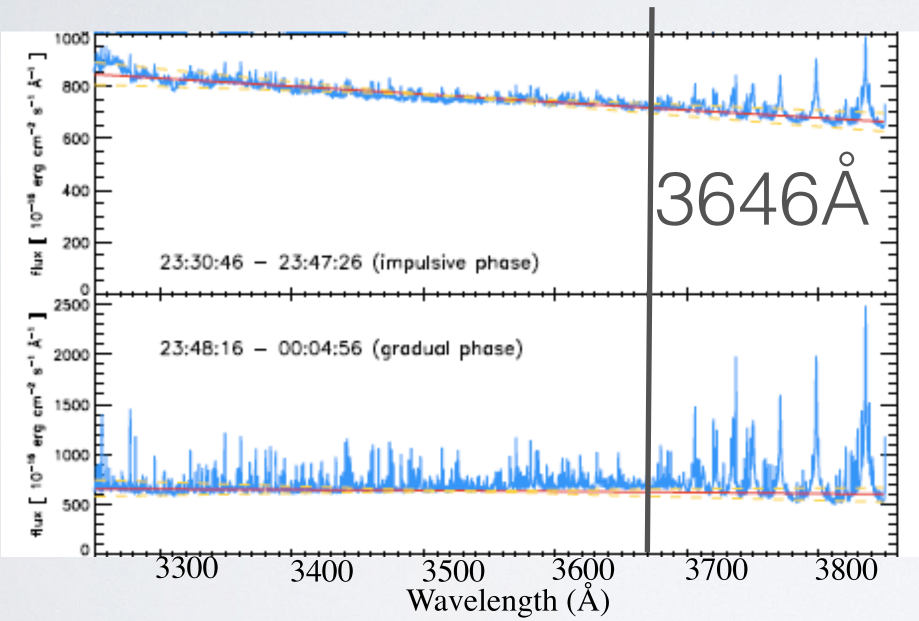
Our first flare model to produce T~10,000 K blackbody-like continuum self-consistently (with no Balmer discontinuity)



Kowalski et al. 2015 SoPh

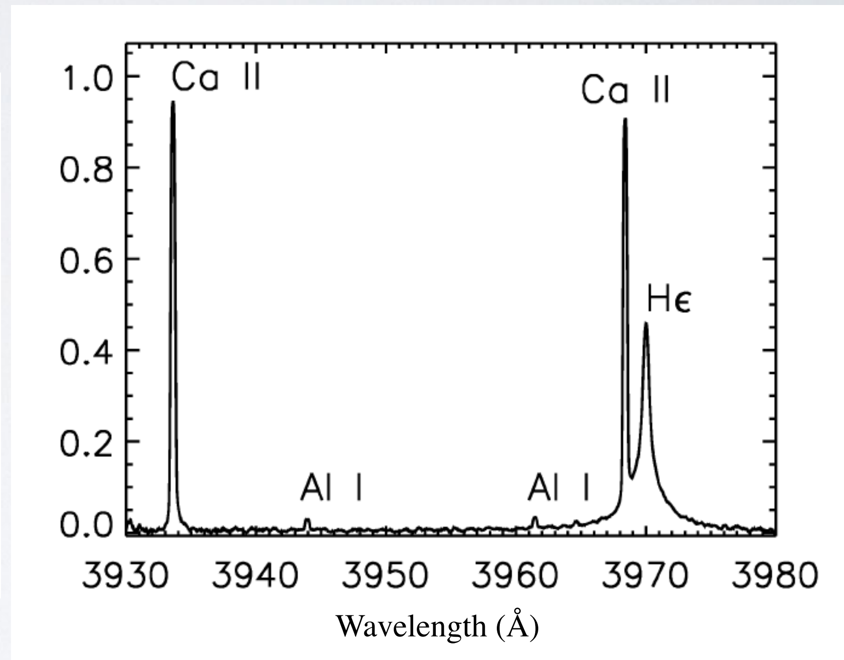
Balmer discontinuity (3646 Å) not observed

Last observed Balmer line is typically ~H15/16



Fuhrmeister et al. 2008

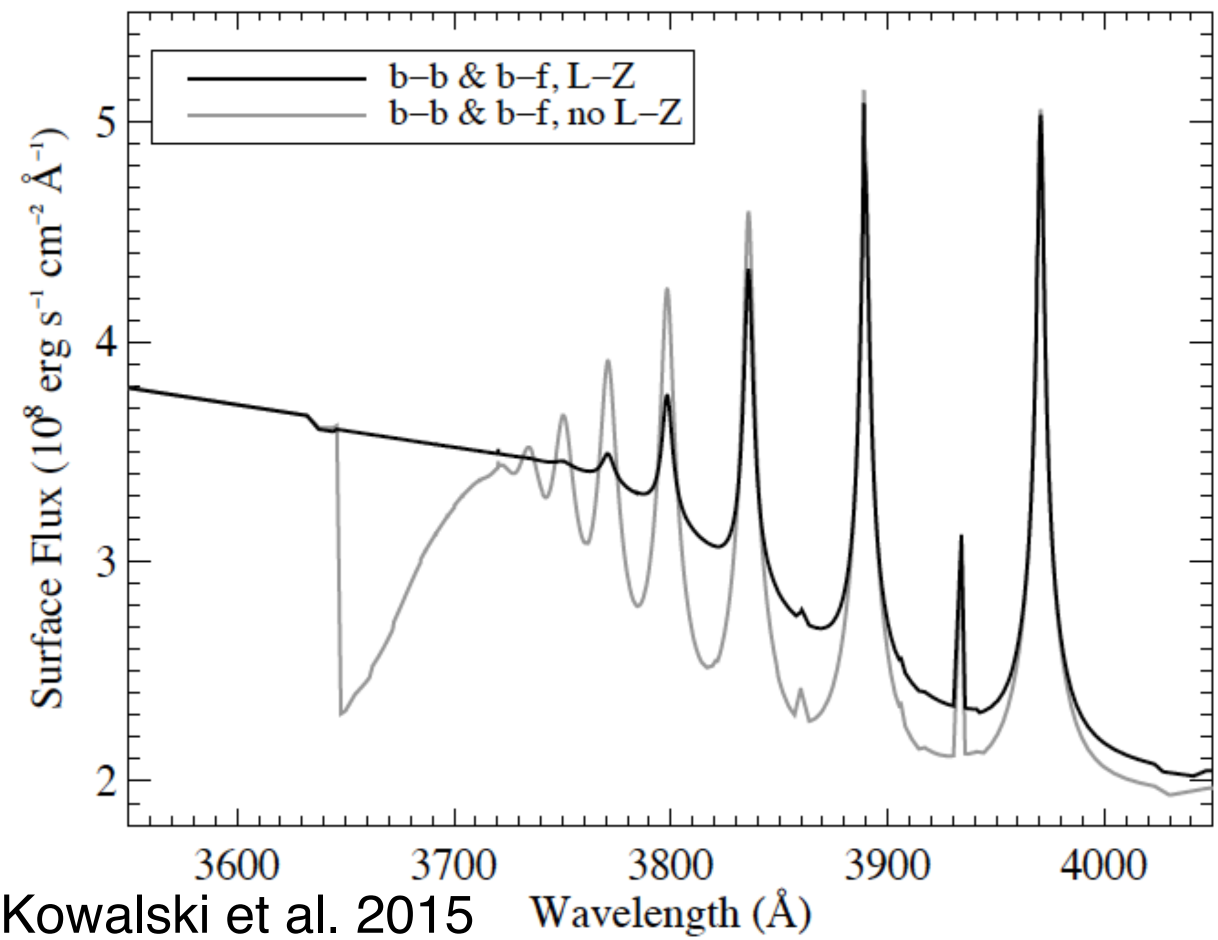
Balmer lines broaden due to Stark effect



Paulson et al. 2006

No Balmer discontinuity with opacities due to Landau-Zener transitions (from Stark Effect)

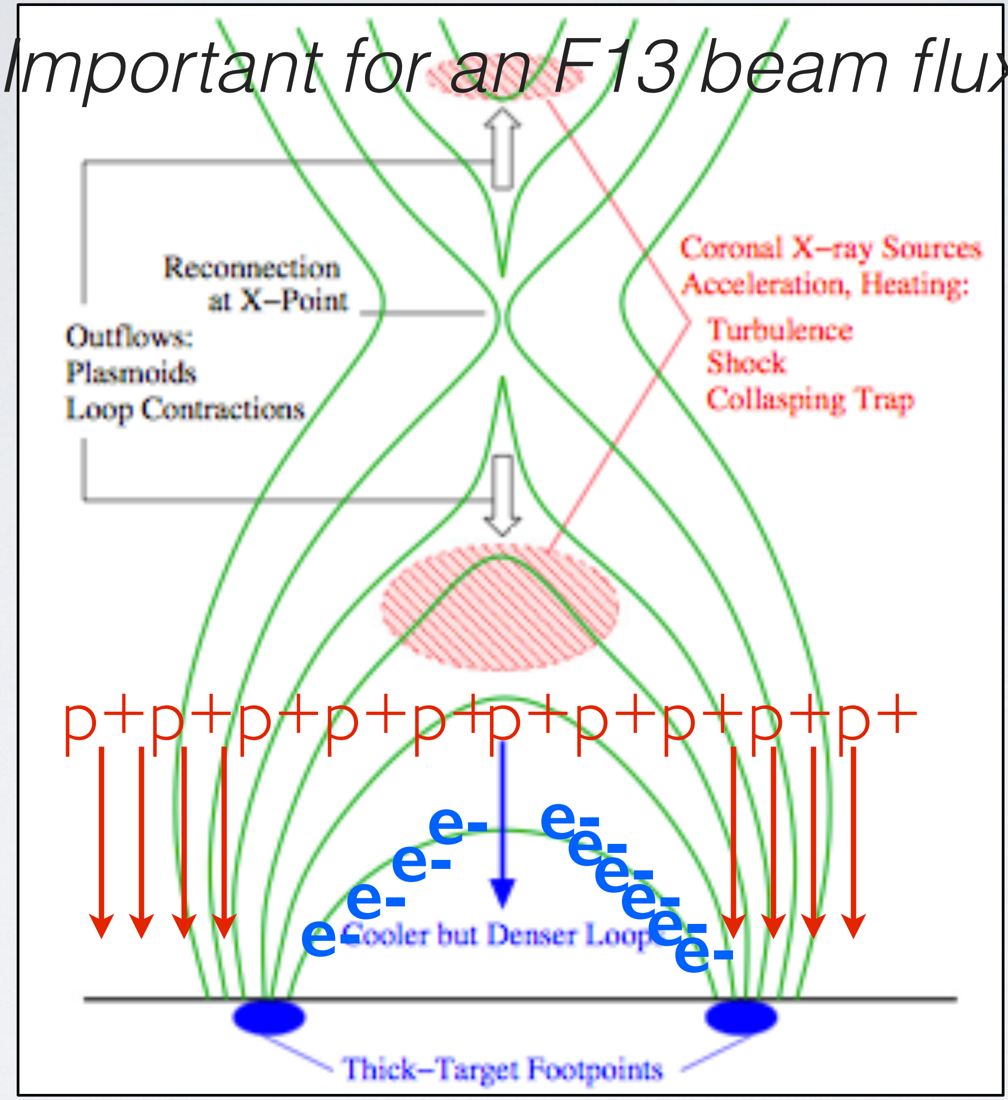
- Use the RH code (Uitenbroek 2001) to model L-Z transitions using hot star (e.g., white dwarf) modeling techniques (Tremblay et al. 2009)



Kowalski et al. 2015

The return current electric field stops the beam

Important for an F13 beam flux

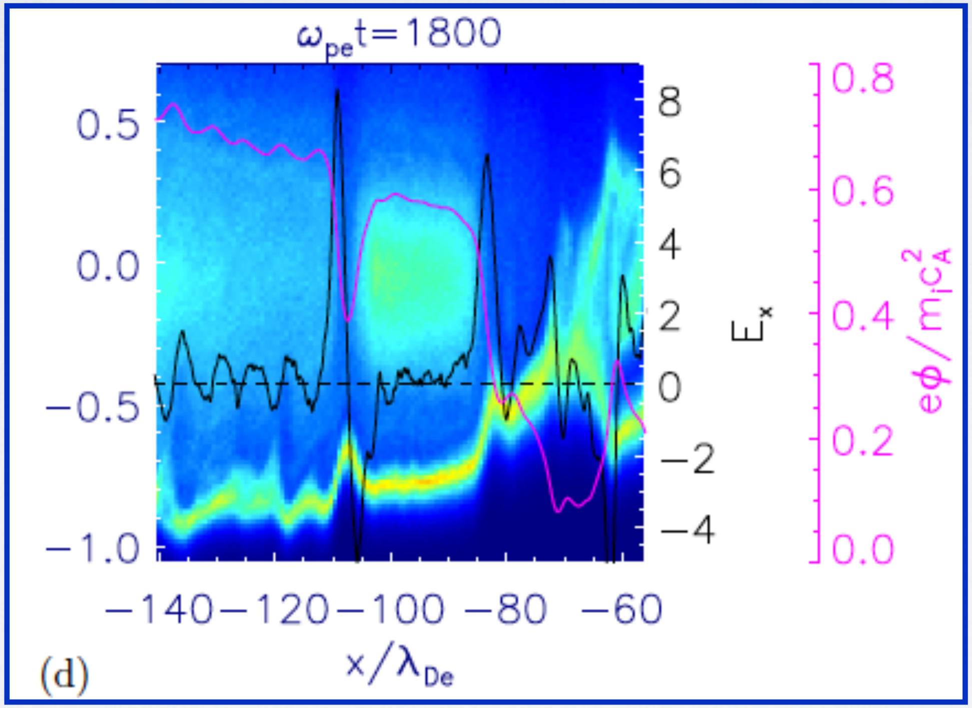


$E_{RC} = \eta J_{Beam}$

Allred et al. 2016 in prep

Instabilities & double-layers for high beam fluxes

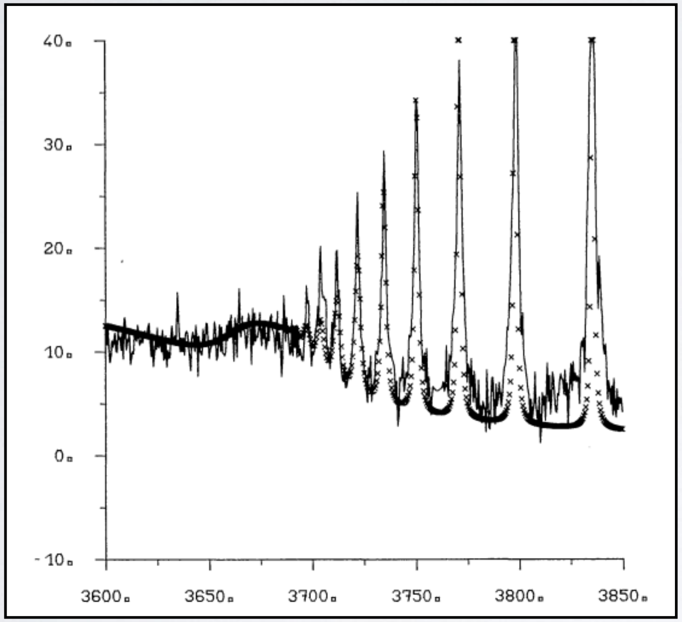
Particle-in-cell simulations: double-layers form (Lee & Buchner 2008, Li et al. 2014) for beam densities that are comparable to ambient coronal density



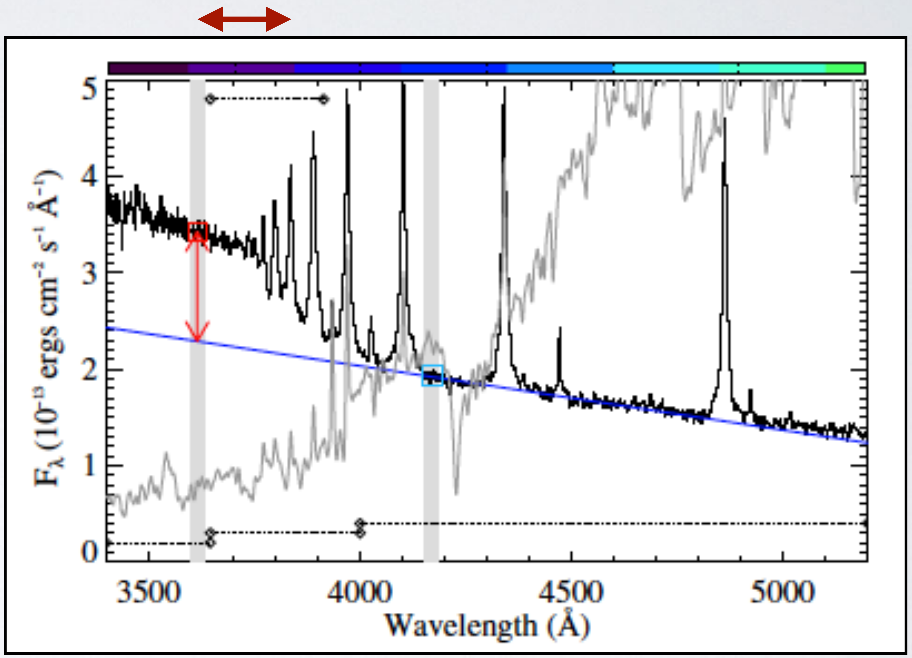
Net potential drop across double-layers:10s of keV

Solar Flare Spectra at Balmer jump

- Never systematically sampled brightest parts of solar flare with NUV/ optical spectra



Solar flare spectra; Donati-Falchi et al.1985

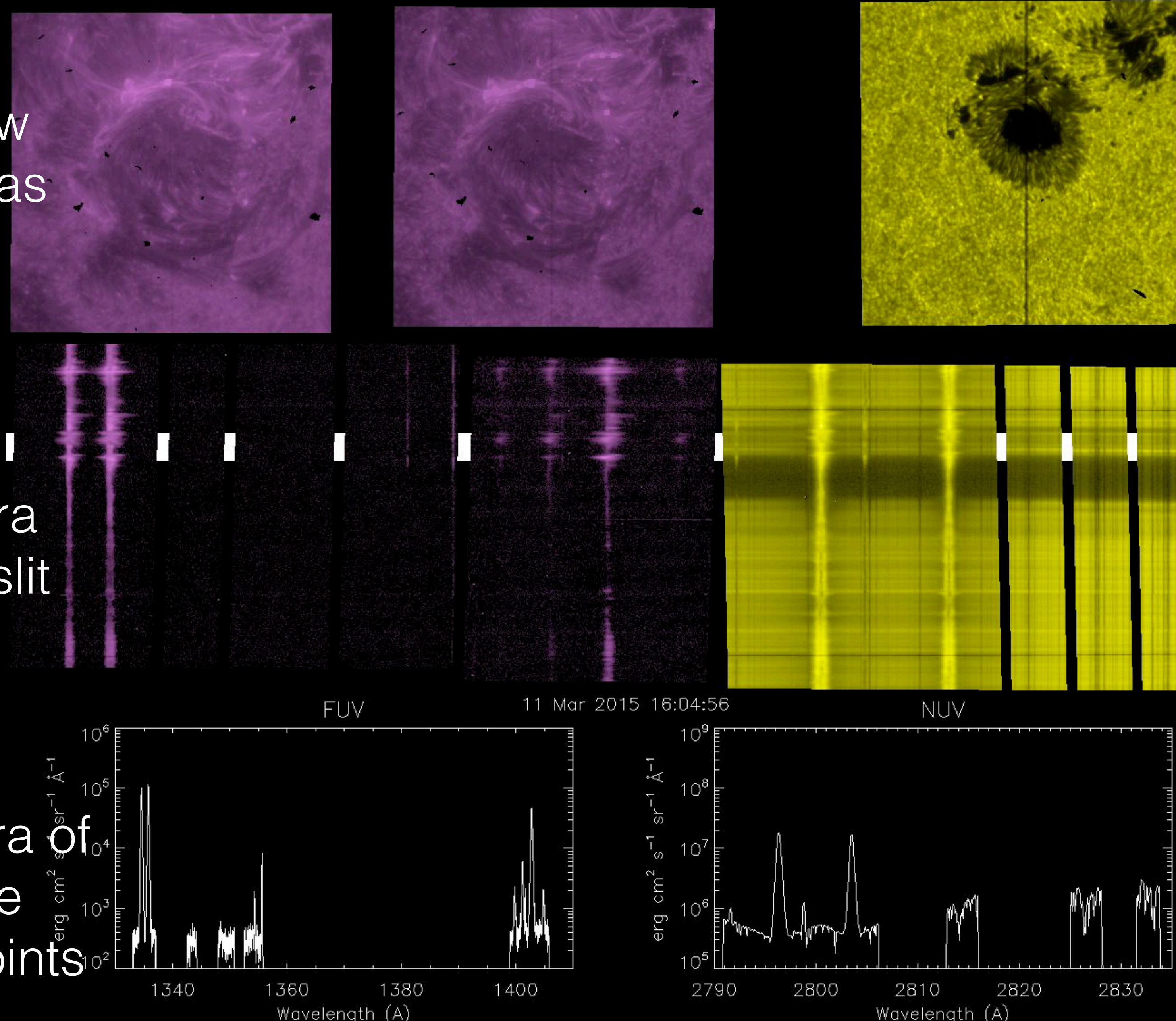


M dwarf flare spectra; Kowalski et al. 2013

Slit-jaw cameras

Spectra along slit

Spectra of flare footpoints

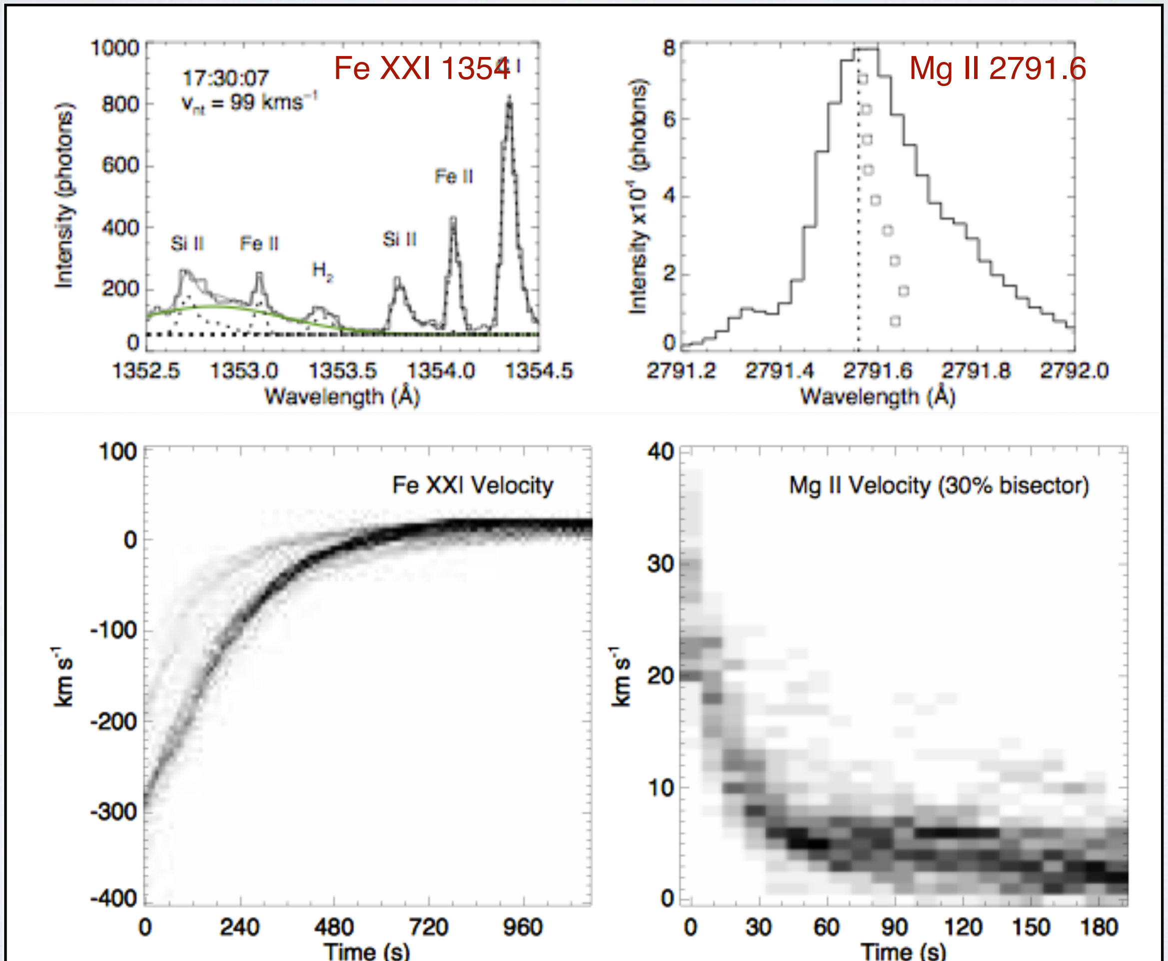


Kowalski, Allred, Daw, & Cauzzi 2016 in prep

IRIS: De Pontieu et al. 2014

New views of chromospheric evaporation and condensation from IRIS

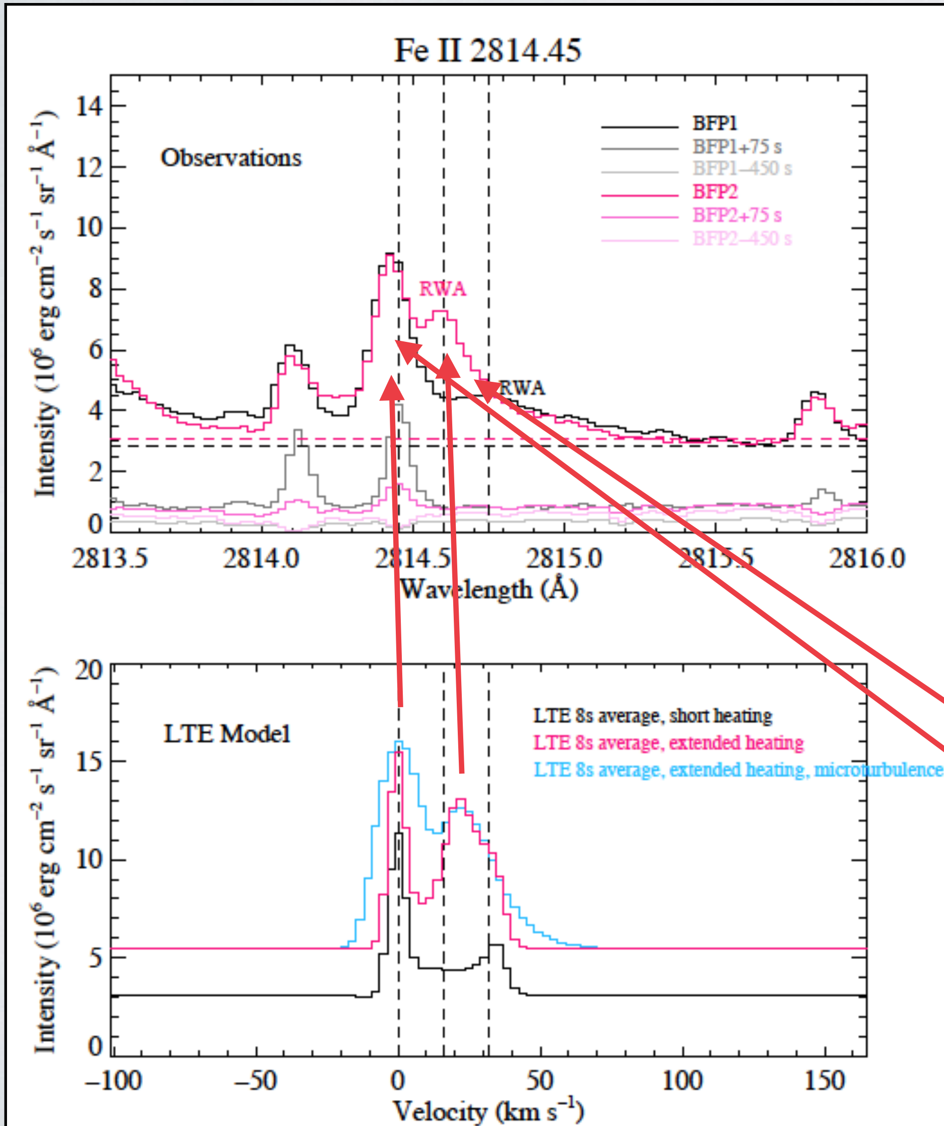
Redshifted emission in singly ionized chromospheric lines (Fe II, Mg II), blueshift of Fe XXI



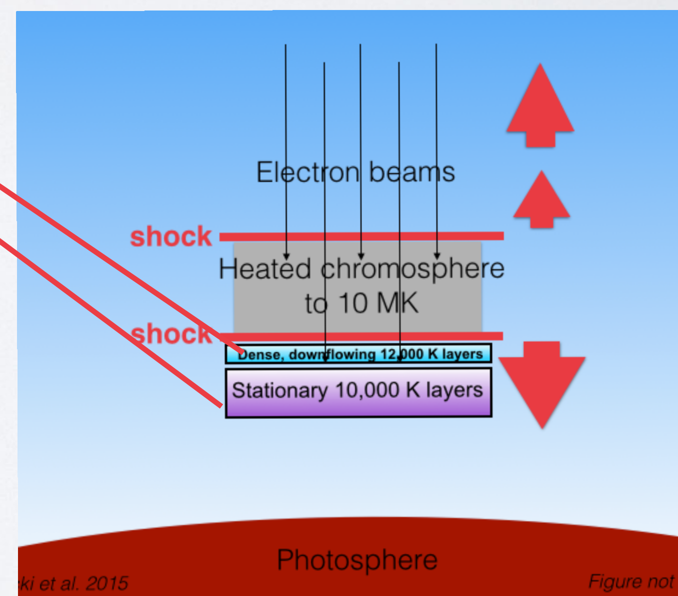
Graham & Cauzzi 2015

see also Polito et al. 2016, Battaglia et al. 2015

Modeling Redshifted Components with High Beam Fluxes (3-5F11, from RHESSI)



- Brightest spectra (pink and black) from X1 flare of 2014-Mar-29
- Two emission line components reproduced by 5 x F11 nonthermal electron beam model



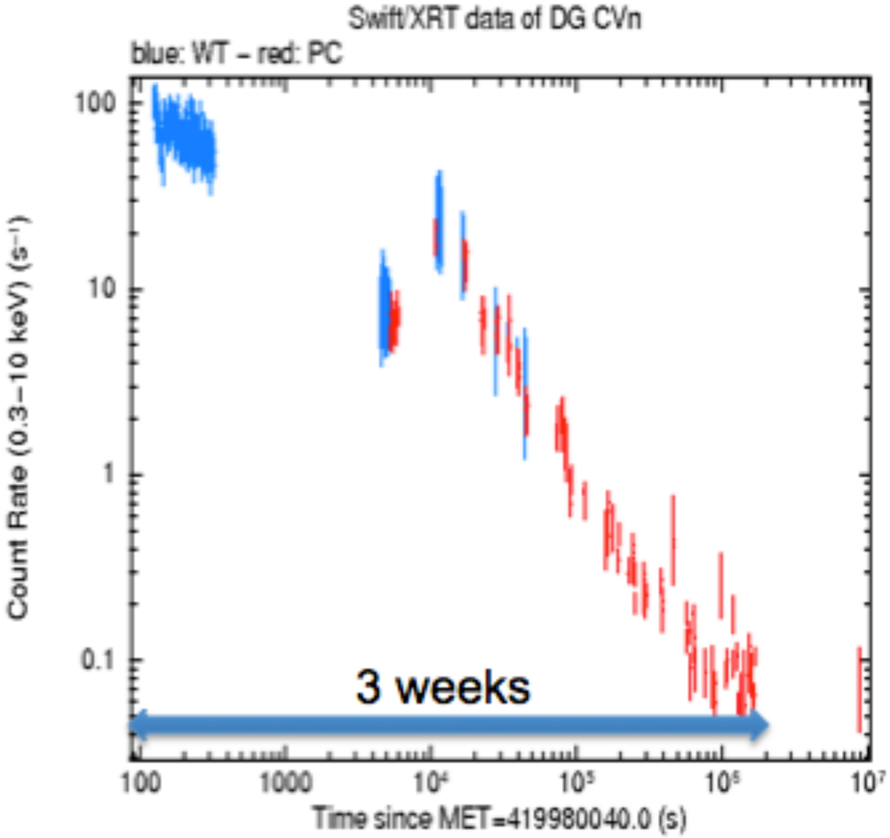
Kowalski, Allred, Daw, & Cauzzi 2016 in prep

Swift BAT Triggered on Large Stellar X-Ray Flare

- Record "super-flare" for solar neighborhood M dwarf star
- **Peak V-band increase 200x; X-ray super bolometric luminosity**
- Peak X-ray temperature of **300** MK is ~ 10 x solar flare T_{Peak}
- Total flare energy 10^{36} erg is 10^3 x largest solar flare energy
- Flare decay time is 2-3 weeks

DG CVn is pair of M4 V stars at ~18 pc believed to be very young ~ 30 Myr

DG CVn flared on April 23, 2014

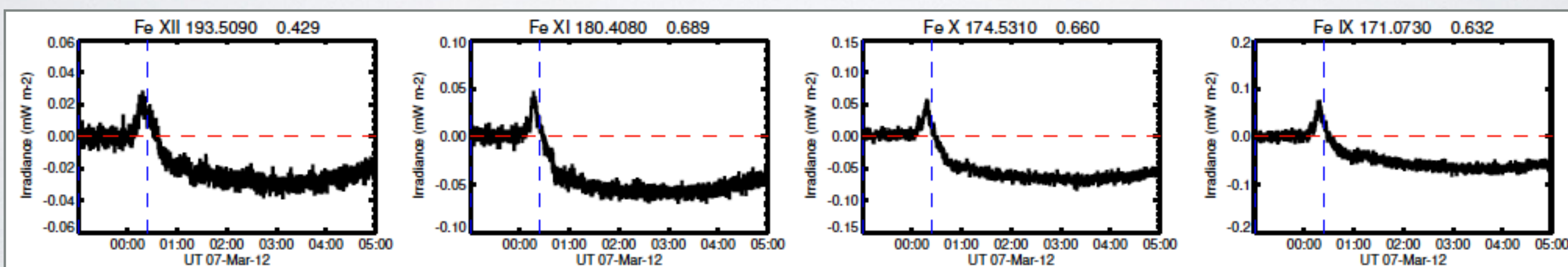


Swift XRT soft X-ray light curve of DG CVn flare (note that both axes are logarithmic!)

Osten et al. 2016 in prep

Stellar(?) Coronal Mass Ejections

- 25% of non potential magnetic energy released as coronal mass ejection (80% of total event energy); Emslie+2012
- Not all X-class solar flares produce coronal mass ejections (October 2014 X-class flares NOAA 12192; Thalmann +2015)
- How to detect CME's from other stars: Ambient coronal (1-2 MK) emission line dimming (Harra+2016), type II radio bursts (Villadsen #47)



Harra et al. 2016

Summary

- Spatial resolution, spectral resolution, HXRs for solar flares (beam fluxes, atmospheric dynamics), broad spectral range for dMe flares (for continuum, Balmer edge modeling)

- Impulsive phase modeling: 10,000 K blackbody-like spectrum in dMe flares and red wing emission component in solar flares can be produced by dense “chromospheric condensations”, heated by high flux electron beams (5F11-F13)

- Theoretical challenges (return current) to high flux electron beams in impulsive phase

- IRIS has revealed the details (timing, temperature) of evaporation and condensation; two flaring layers at ~10,000 K

- Balmer jump modeling (Stark effect, Landau-Zener transitions) gives constraint on charge density

Open questions

- What is the effect of microphysics (double layers, return currents) of high flux electron beams on chromospheric emission? Where are the electrons accelerated (Fletcher & Hudson 2008)?
- Are there other ways besides v. high beam fluxes to produce large optical depth at 10,000 K in dMe flares?
- Need more Balmer jump / optical spectra of solar flares
- Role of proton/ion beams, Alfven wave heating (Reep & Russell 2016)? How to combine these in one flare loop?
- Impulsive heating timescales ~sec: how to produce the gradual phase continuum (at least tens of minutes)?
- How/when do we jump to 3D RHD flare modeling?
- Do active stars with strong coronal magnetic fields produce CMEs?