Non-thermal heating in M dwarf flares: new radiative hydrodynamic models and constraints from observations

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Cool Stars 17

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Eric Hilton, Sarah Schmidt (UW), James Davenport (UW), Mats Carlsson (UiO)

Objectives and Outline

- What are the continuum components in the white-light of stellar flares?

→ Observational constraints from the "Flare Atlas": spectra during 20 flares, 5 dMe stars

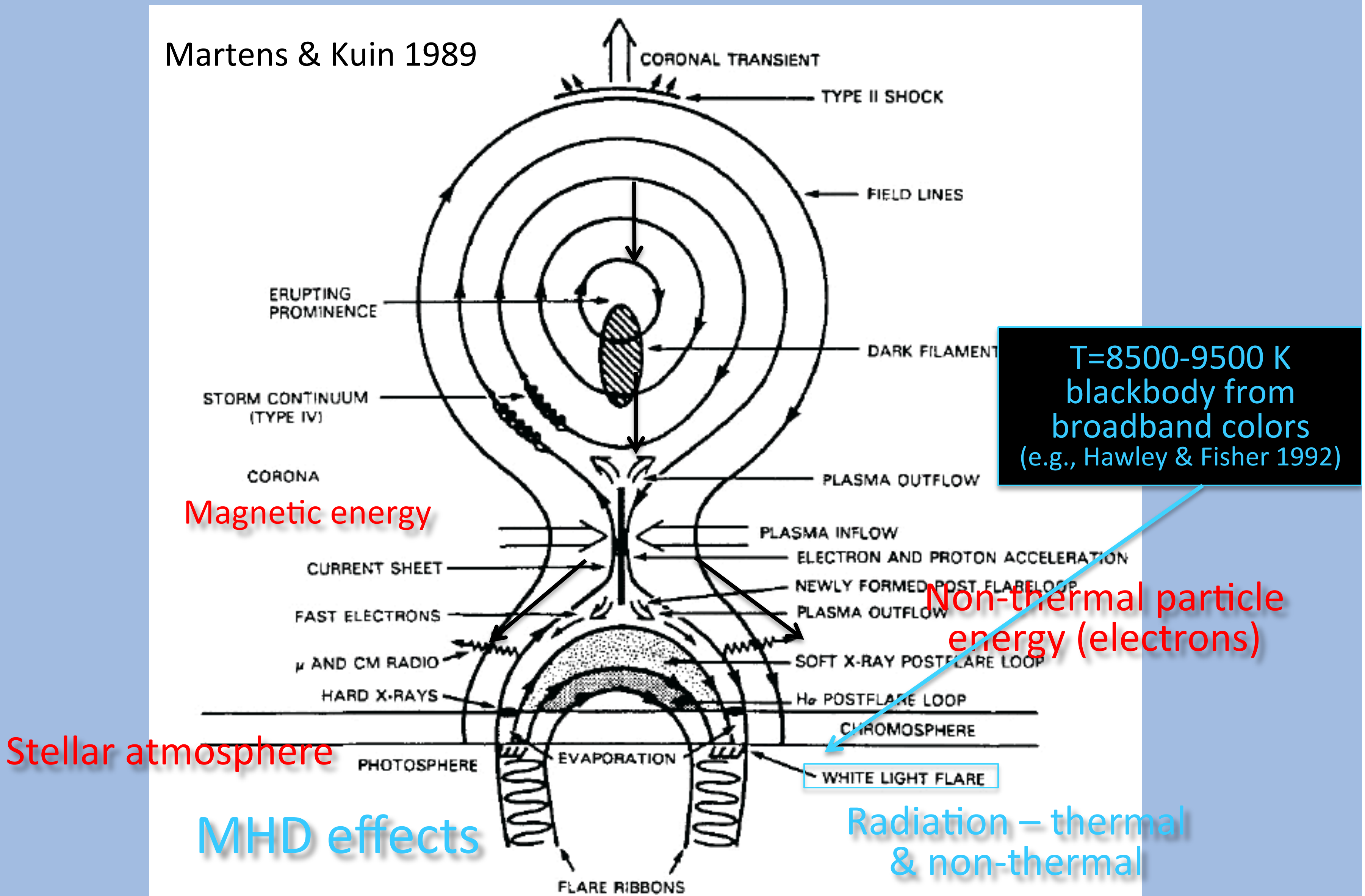
  - Results from Kowalski et al. (2010, 2011, 2012); main thesis paper in prep to ApJS

- What (non-thermal) heating mechanisms produce the continuum components? Where in the atmosphere?

→ New radiative-hydrodynamic (RHD) 1D modeling with RADYN code

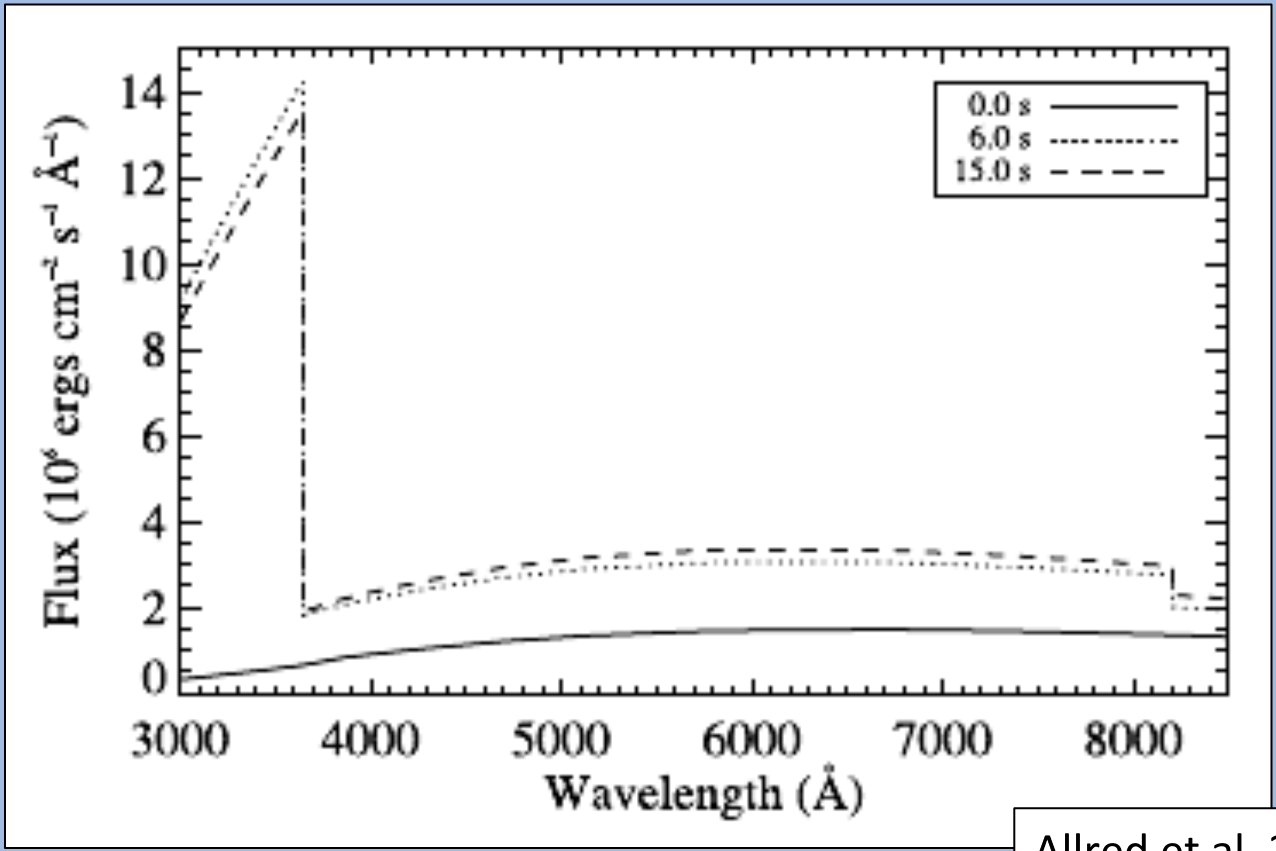
- How do the emission lines relate to the continuum?
- How do continuum components relate to broadband light curve evolution (fast rise, gradual decay)?

The Standard Model



The Allred et al. (2006) Stellar Flare Models using RADYN

Model continuum spectra show large Balmer discontinuity (not observed)



Allred et al. 2006

F11 e- beam (10^{11} ergs s^{-1} cm^{-2})
Double-power law energy distribution

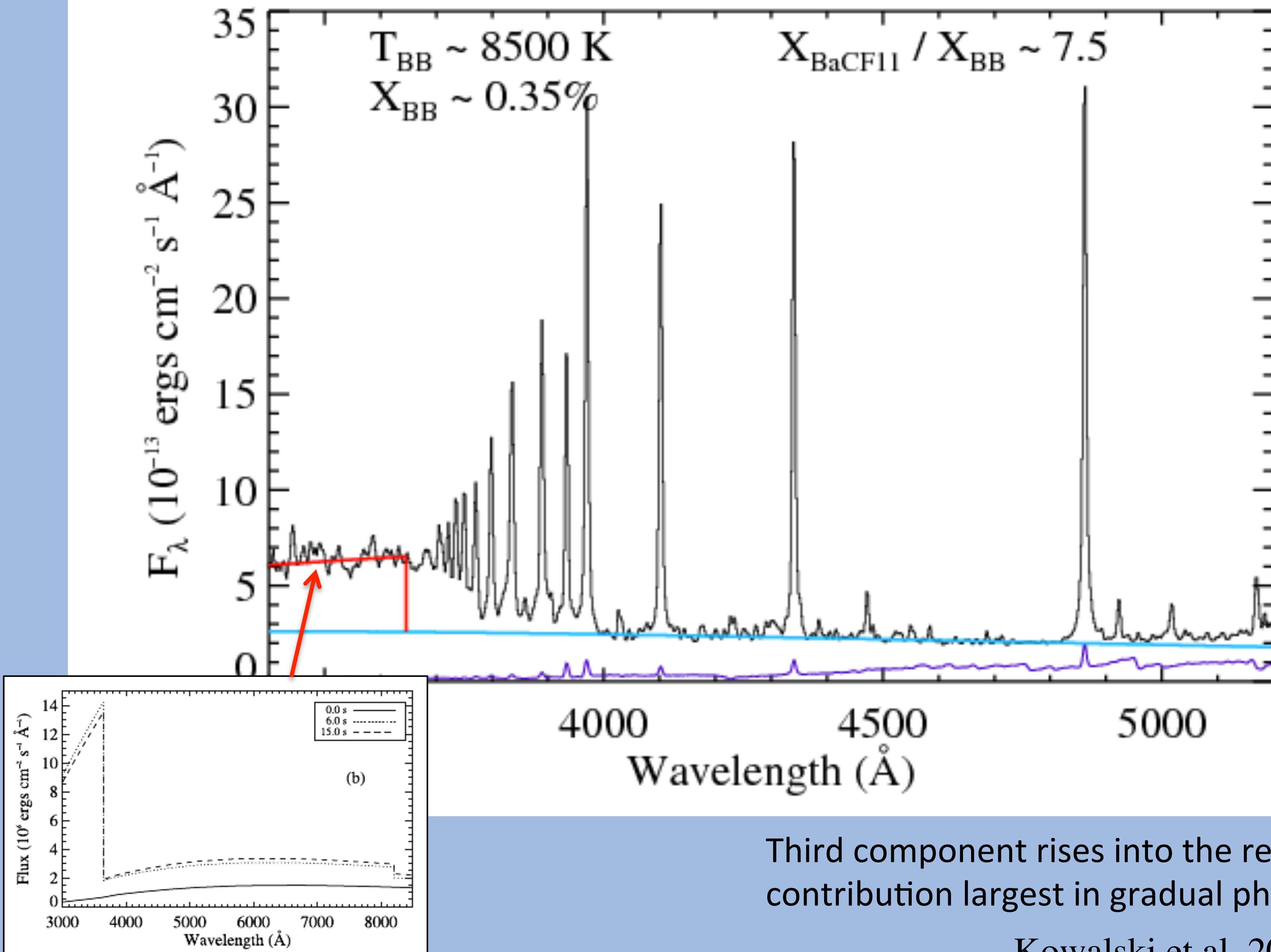
RADYN: Carlsson & Stein (1994, 1995, 1997)

Spectroscopic Flare-Monitoring

- APO 3.5-m Dual Imaging Spectrograph (DIS)
- 3420 – 9200 Å, R ≈ 650
- 1 sec – 45 sec integrations (+9 sec readout)
- 75 hours of monitoring (five stars); 15,000 spectra
- Additional calibration in blue; new method for obtaining absolute fluxes from spectra
- U band (≈3250-3950Å) photometry: NMSU 1-m, ARCSAT 0.5-m (w/ Flarecam) at APO
- Megaflare on YZ CMi from Kowalski et al. 2010
- Great Flare on AD Leo from Hawley & Pettersen 1991
- EV Lac flare from Schmidt et al. 2012

A sample of 20 flares for detailed line and continuum analysis

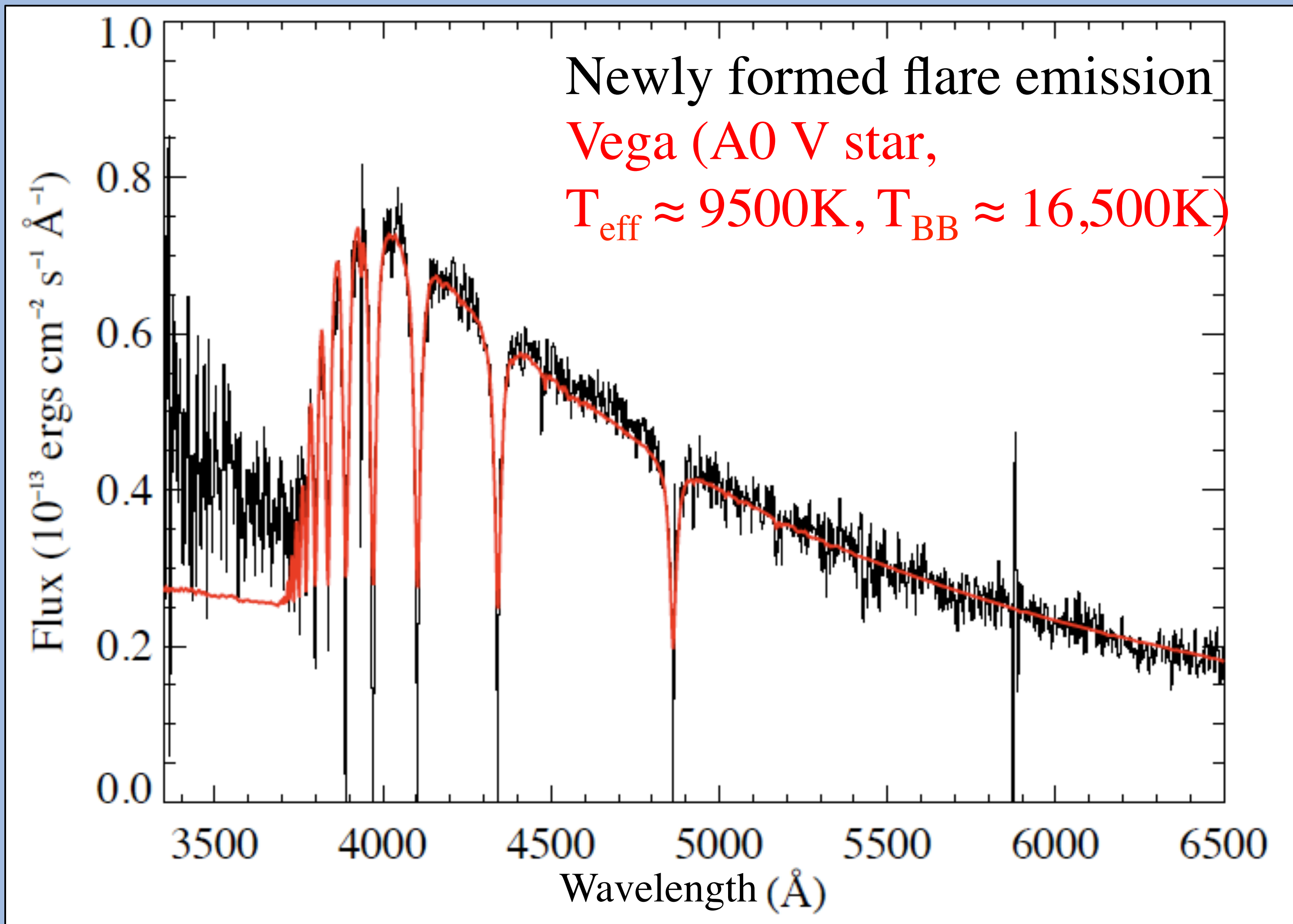
Three continuum components during decay phase spectra of the "Megaflare" on YZ CMi



Third component rises into the red, its relative contribution largest in gradual phase

Kowalski et al. 2010, ApJL

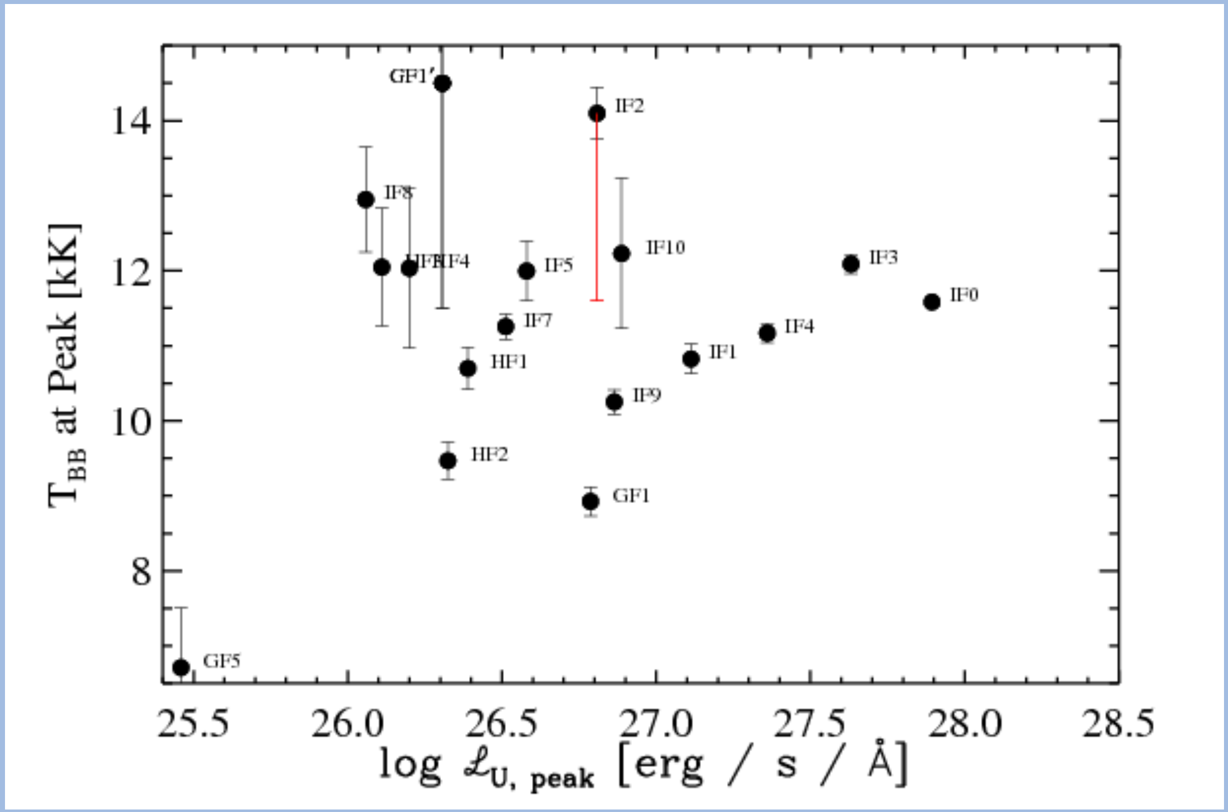
“Blackbody” has an A star spectrum!



Kowalski et al. 2011

1a) T ≈ 10,000 – 12,000 K "blackbody" at peak from λ=4000-4800Å

Blackbody function (color temperature, surface area coverage) used to parameterize shape

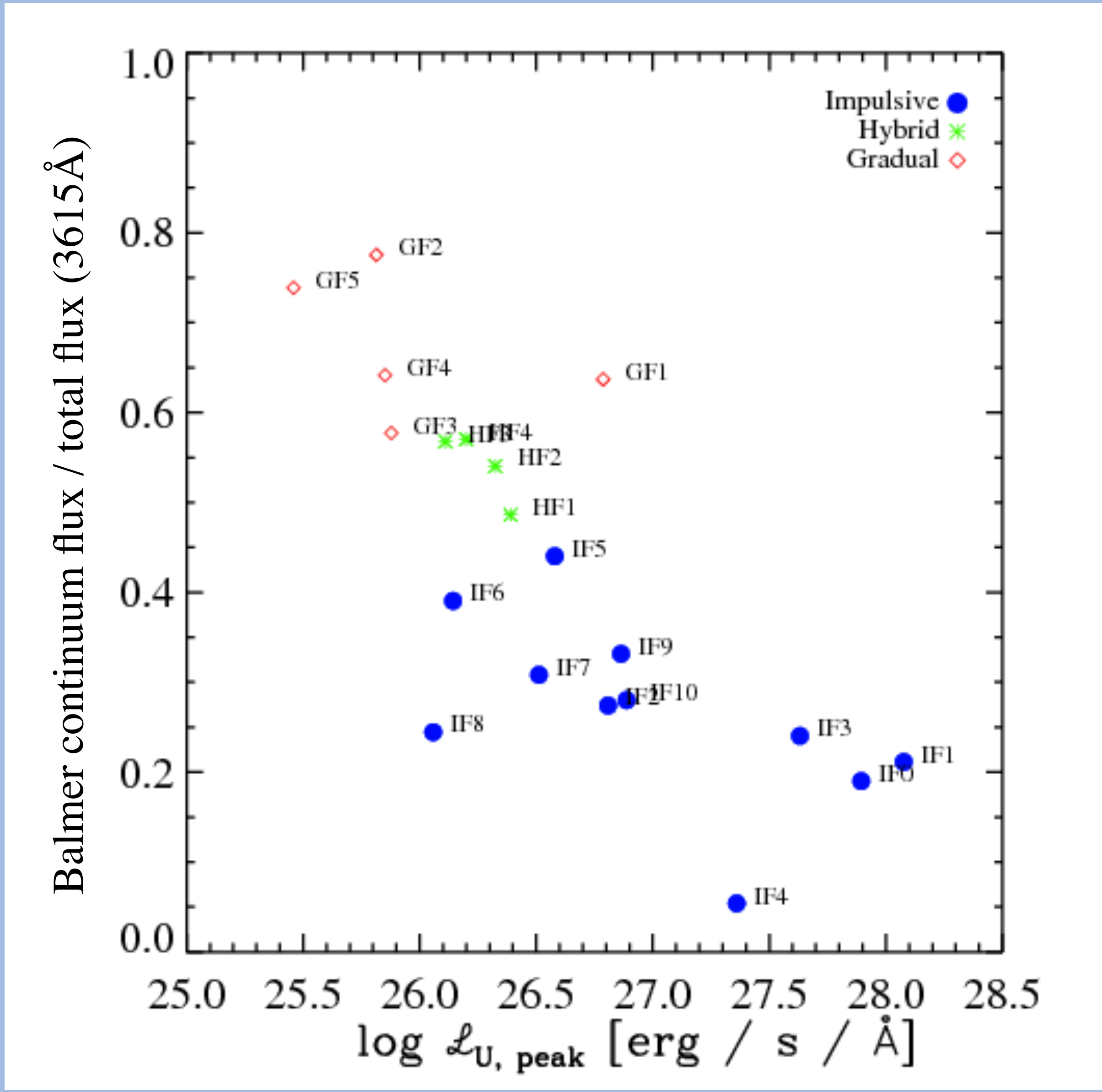


Systematic temperature uncertainty 500-1000 K

1b) T ≈ 8000 K "blackbody" in gradual phase from λ=4000-4800Å

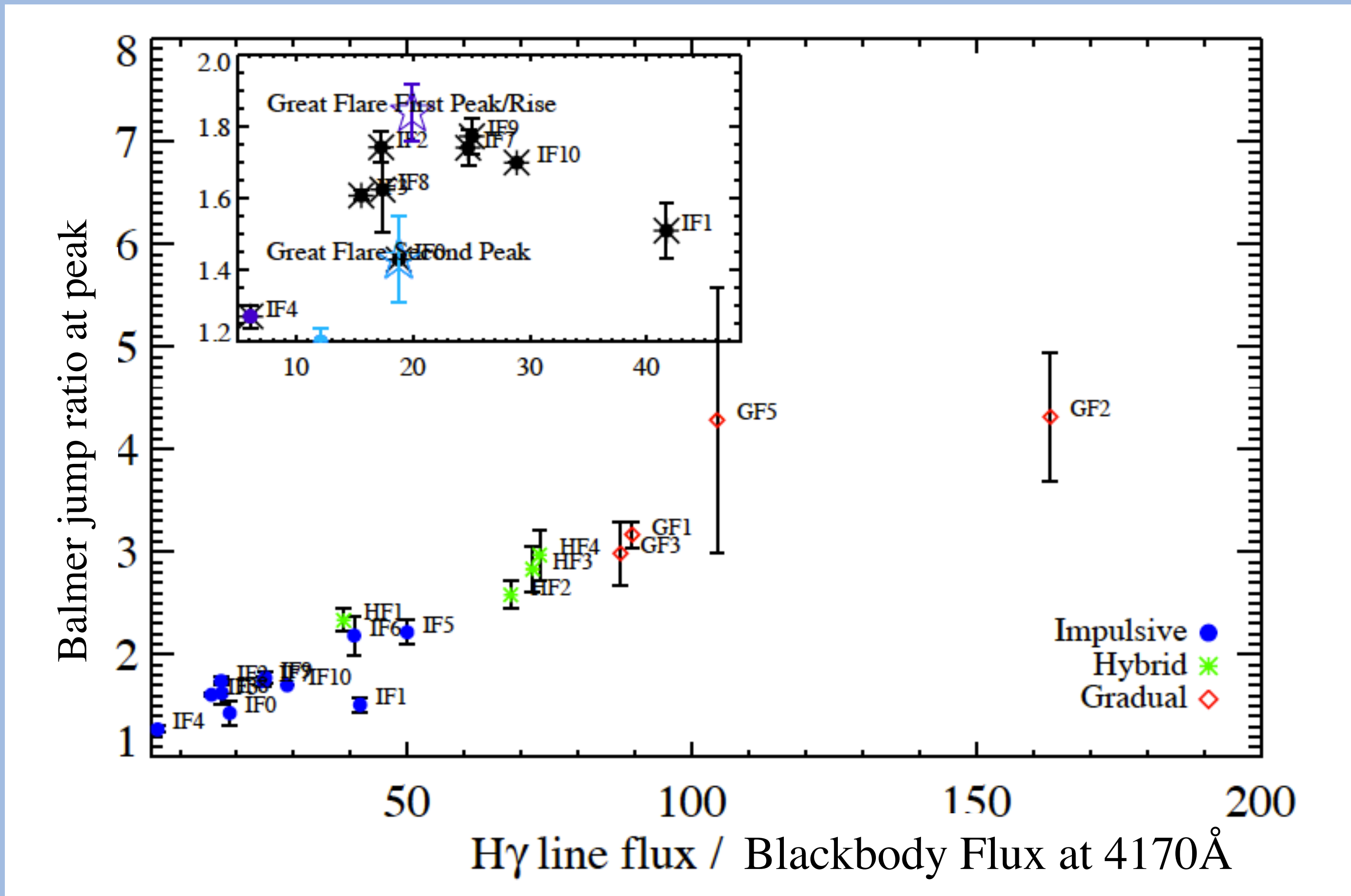
Kowalski et al. 2012, ApJS in prep

2a) Balmer continuum emission ubiquitous



Kowalski et al. 2012, ApJS in prep

2b) Balmer jump ratio 1.5-4.5



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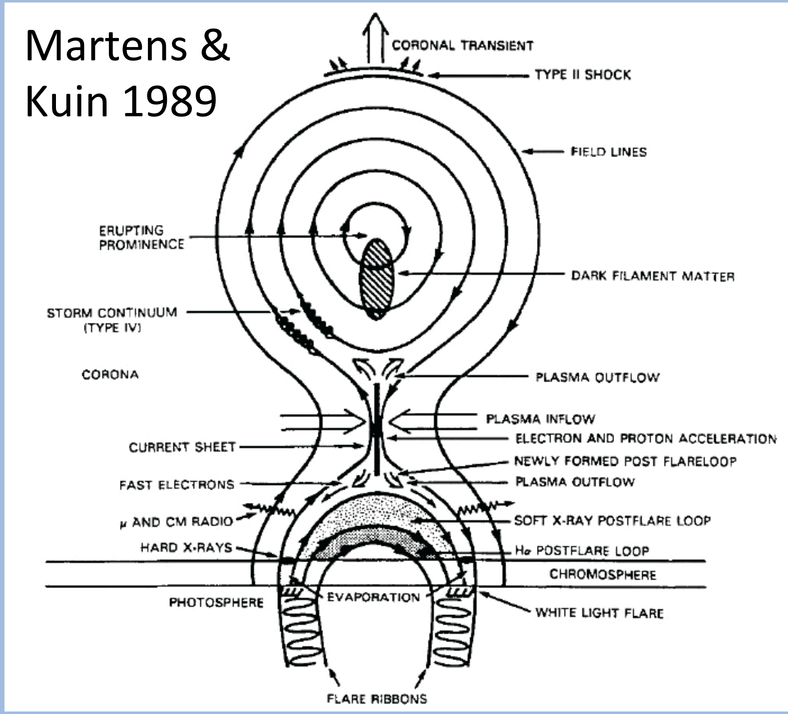
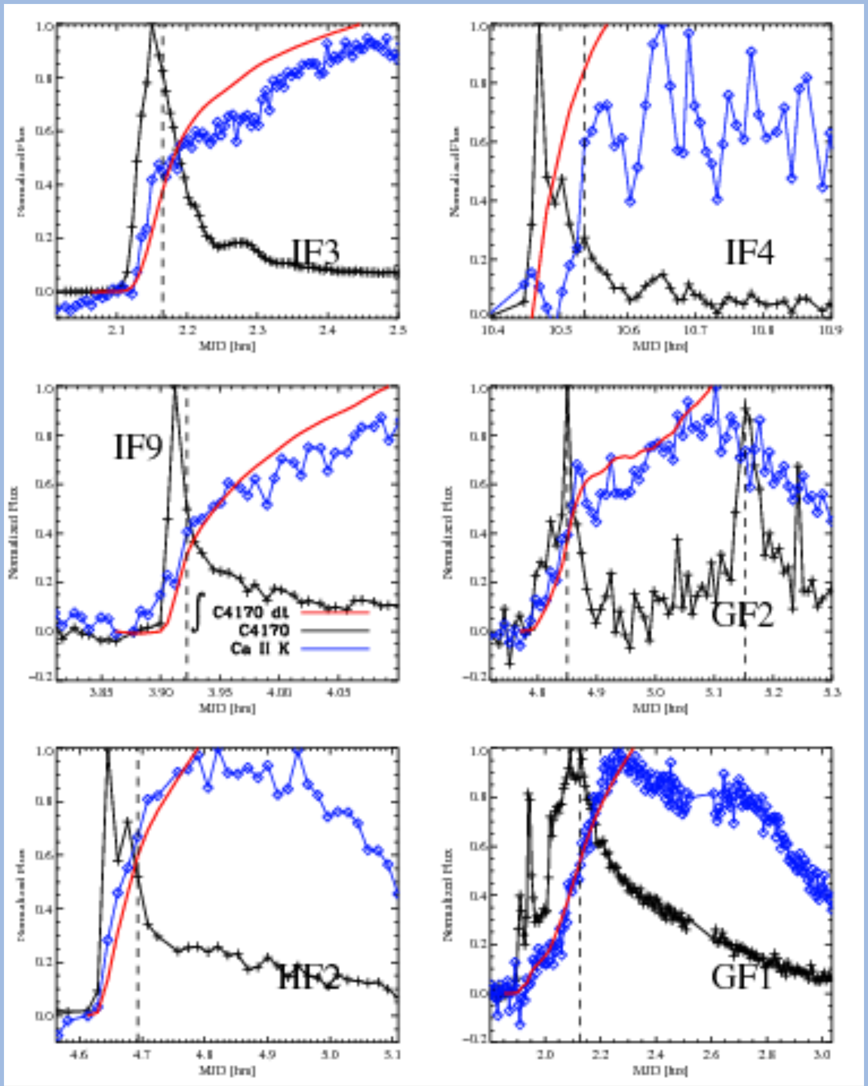
Ca II K "Neupert-like" relationship with blackbody

Martens & Kuin 1989





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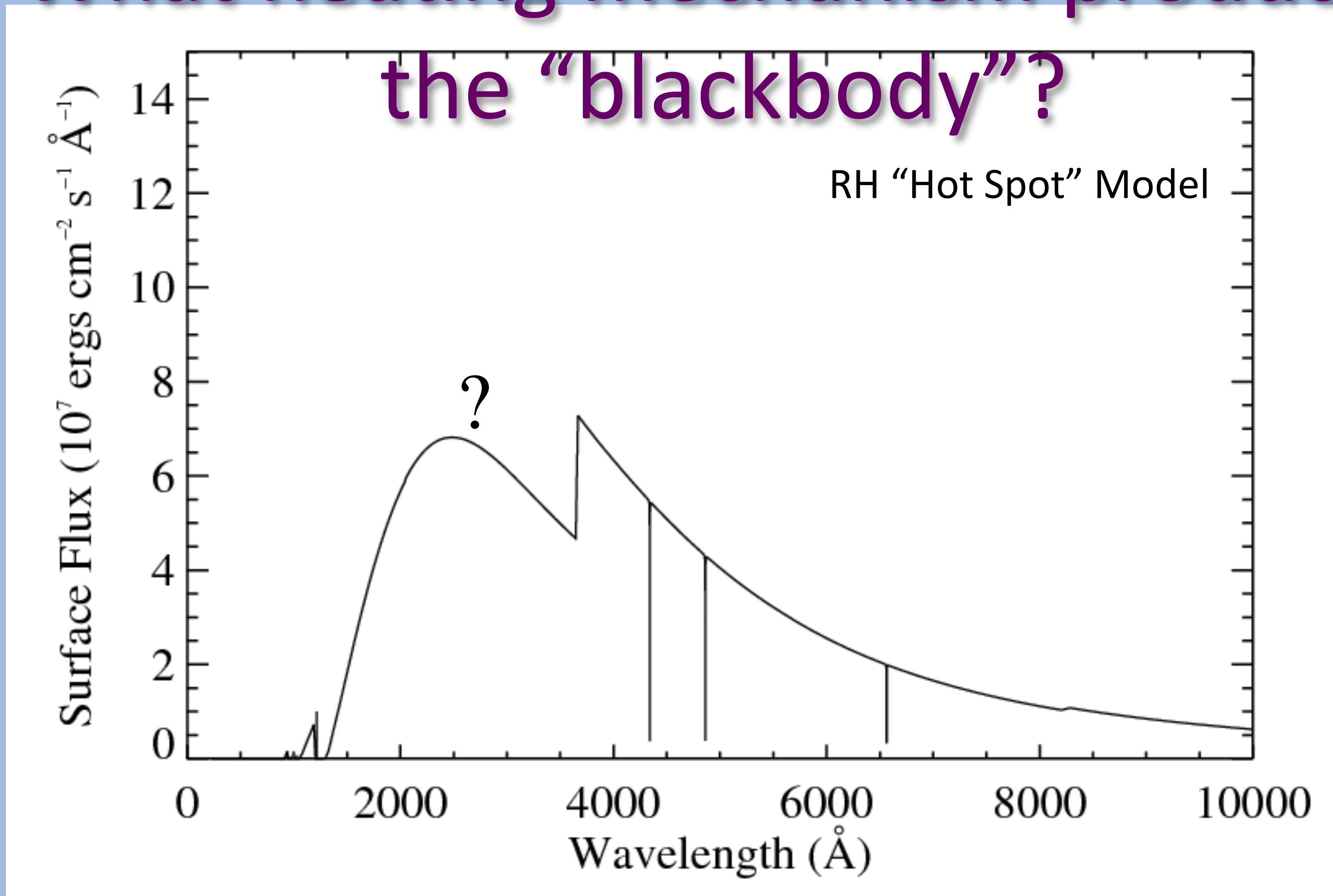
What heating mechanism produces the “blackbody”?



≈55-85% of 3420-5200Å peak flux in “blackbody” emission (95% when you look at FUV-optical broadband distribution; Hawley & Pettersen 1991)

RH: Uitenbroek 2001

1D RHD Modeling with RADYN

In collaboration with Mats Carlsson, University of Oslo

- 1D adaptive grid
- Detailed radiative losses; for H (n6), He (n9), Ca II (n6), with continua
- "Catch-all" thin radiative losses (~10^5 K); C/N/Ne/O/Fe, bremsstrahlung
  -- e.g., Rosner et al. 1978
- XEUV backwarming (CHIANTI, ATOMDB)
- Non-thermal electron beam heating given E_{cutoff}=37 keV, δ_{lower}=3, δ_{upper}=4, E_{break}=105 keV, F#
  -- beam parameters taken from peak time of a solar flare (Holman et al. 2003)
  -- Formulae from Emslie (1978), Hawley & Fisher (1994), Ricchiazzi & Canfield (1983)

- Same initial conditions as Allred et al. (2006)

But with two differences in the flare heating

A. Need an F12! (F12 = 10^{12} ergs / s / cm^2)

- Obs of blackbody indicate that you need > 2×10^{11} ergs / s / cm^2

B. Short-duration (5 sec) bursts with a gradual phase

- Increasing area & relatively constant spectral shape (e.g., Hawley et al. 2003, see my poster (P04.3.4) on "flare speeds")

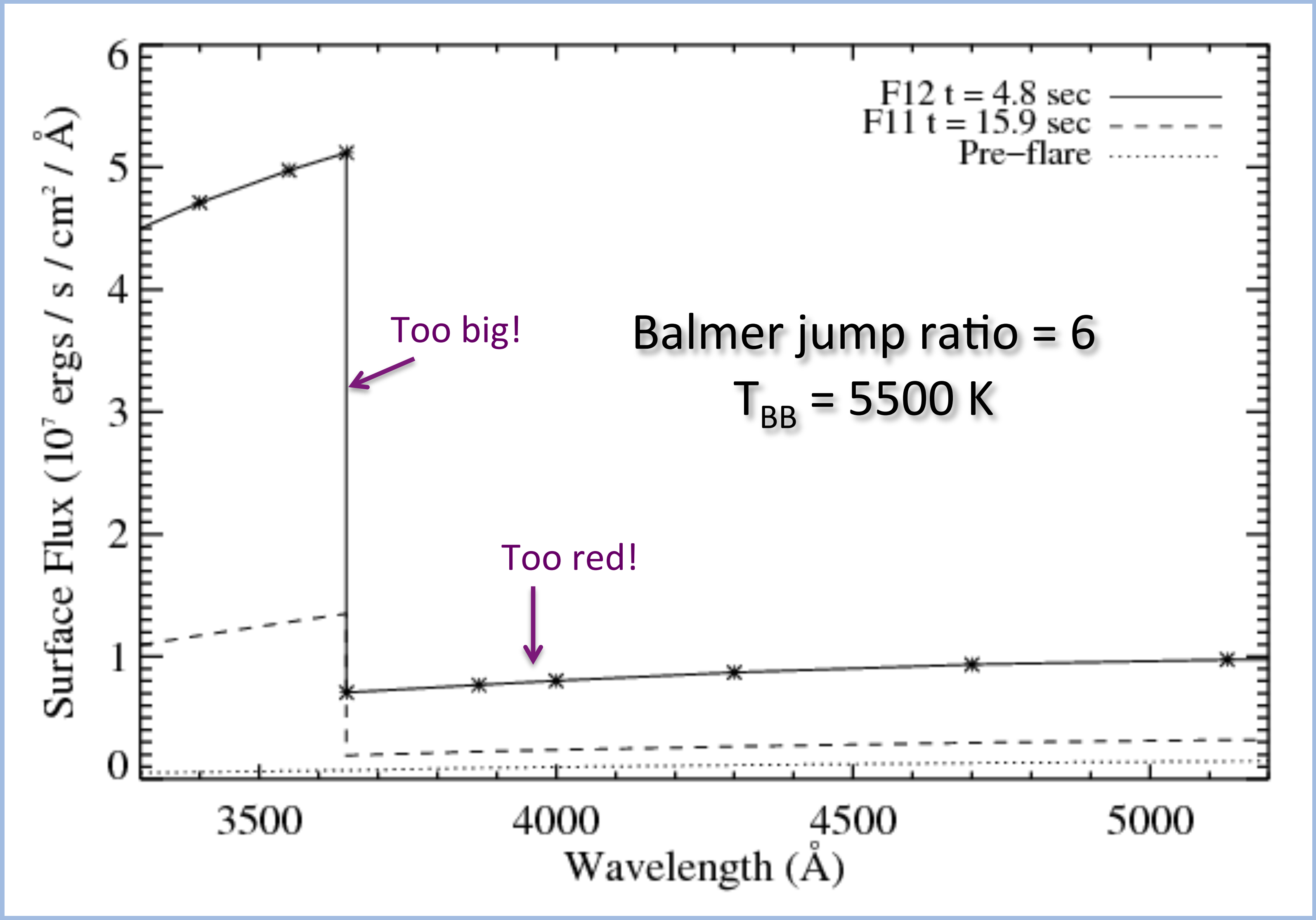
Motivation for each of these found in solar observations too!

Previous gas-dynamic F12 simulations

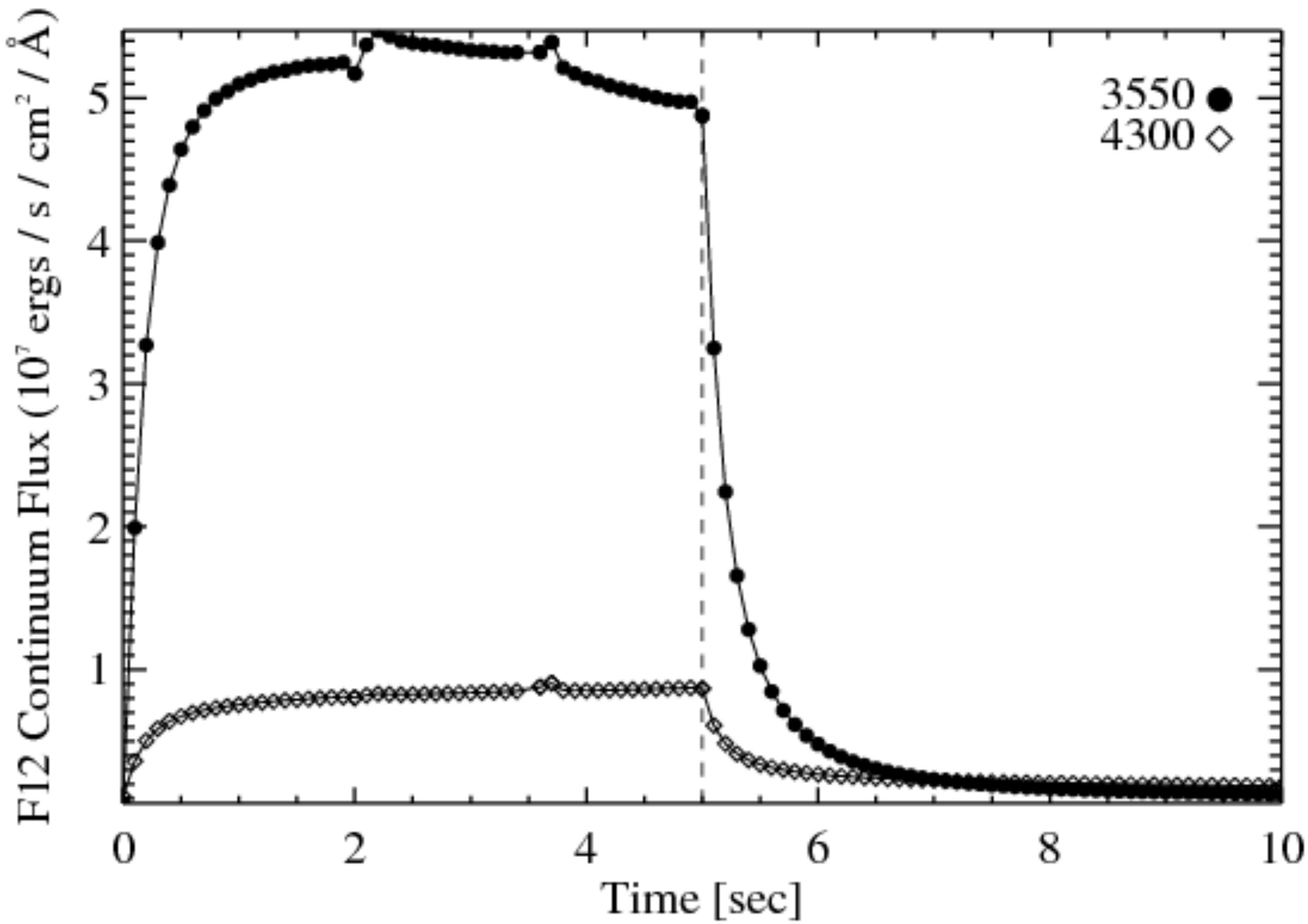
- Livshits et al. 1981: chromospheric condensations produce WL optically thick emission having T≈9000 K

- Schmitt et al. 2008: coronal response with gradual phase

Model F12 White-Light Spectrum

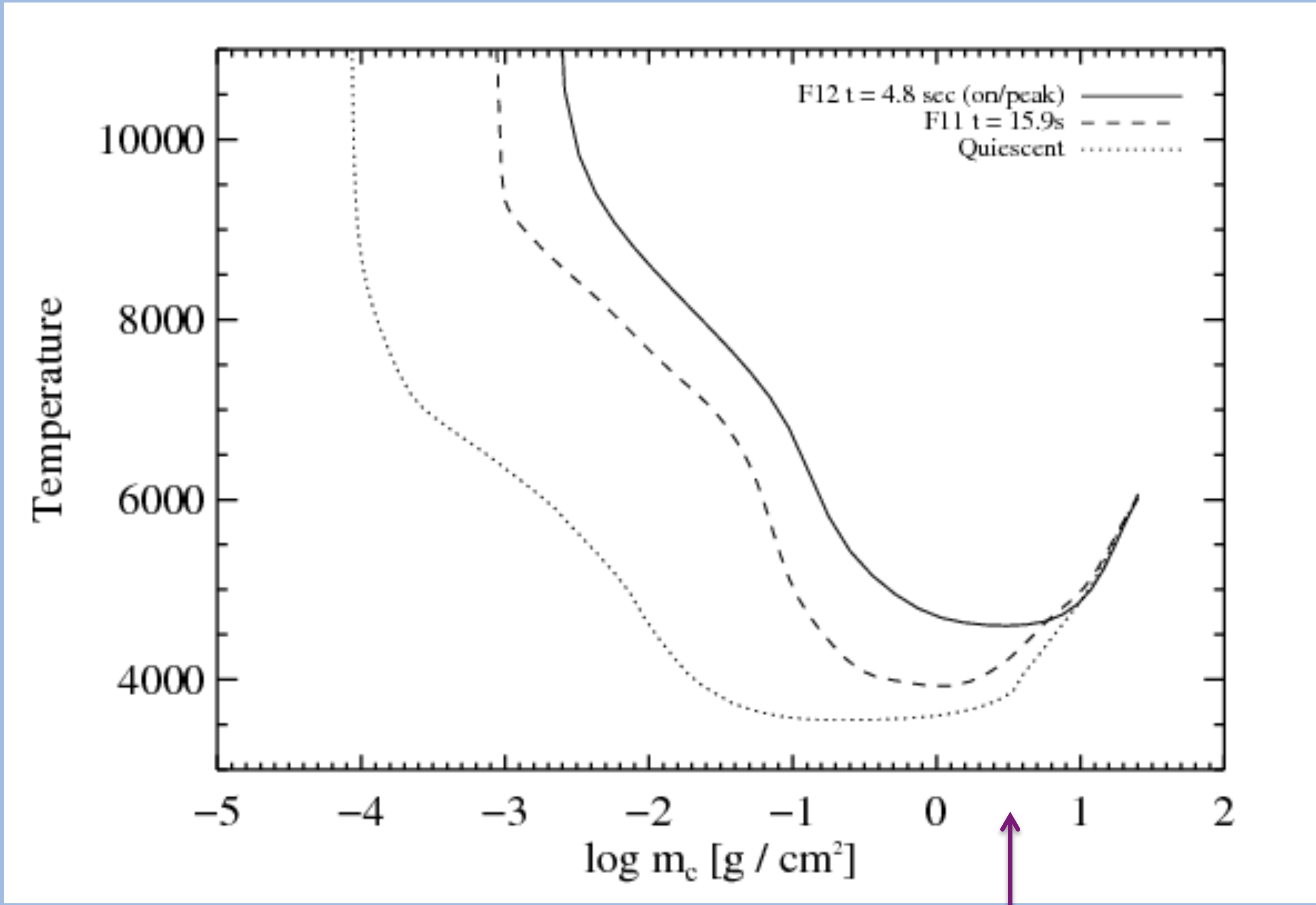


Model F12 NUV & Optical light curve



Need beam heating to sustain high levels of continuum

Heating in the Lower Atmosphere



Phenomenological modeling

F12 Energy Budget

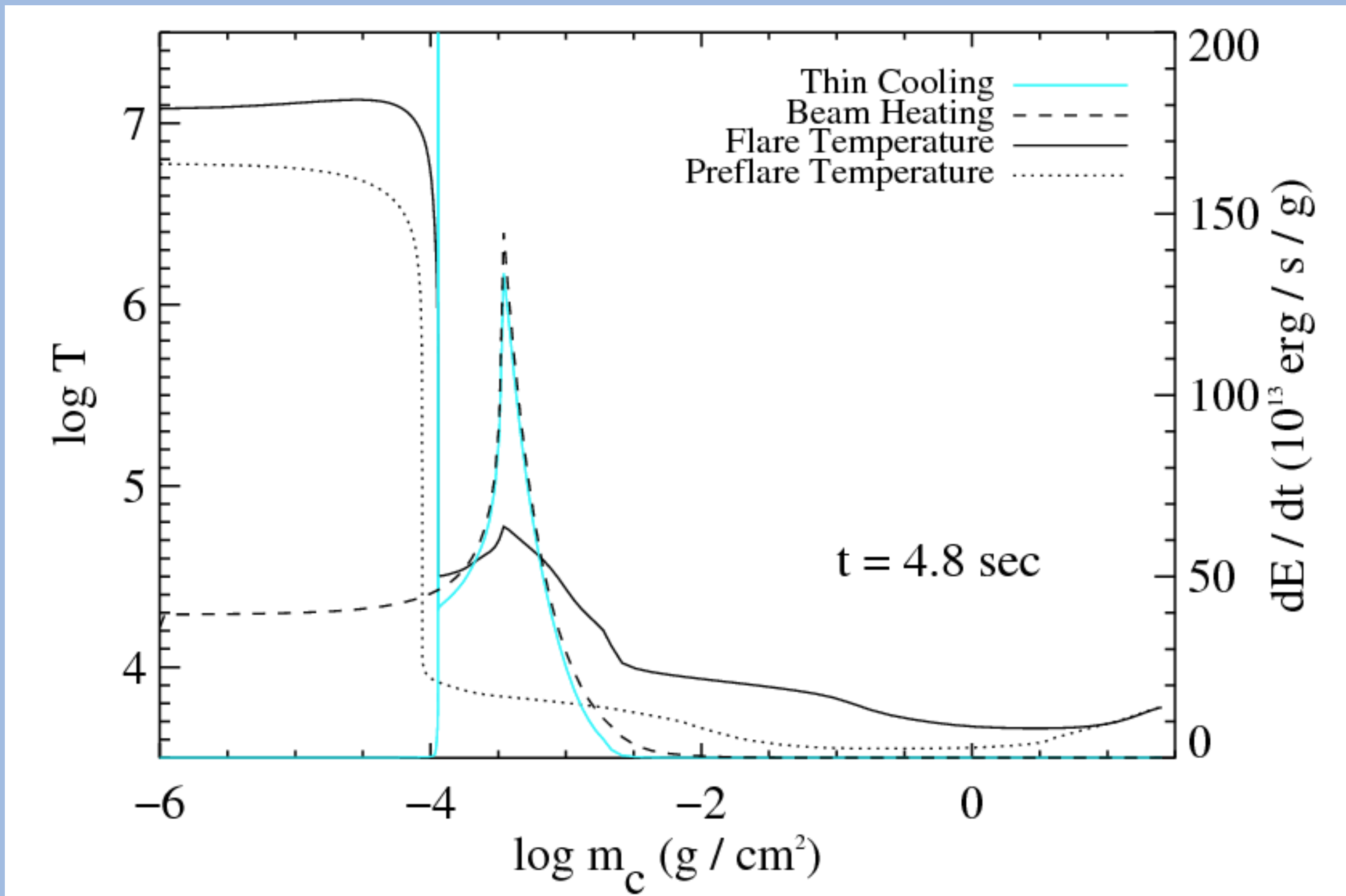
- Detailed radiative losses; H, He, Ca II
- "Catch-all" thin radiative losses (~10^5 K); C/N/Ne/O/Fe, bremsstrahlung

- ≈1 x 10^{11} ergs / cm^2 / s in detailed radiation losses in continuum at λ > 1000Å

  But this energy does not have the correct spectral shape!

- ≈6 x 10^{11} ergs / cm^2 / s in optically thin losses

Thin Losses Very Important in Dynamics & Energy Balance



Future Modeling

* More heating at higher column mass *

- F13 in progress: very different dynamics
- More accurate description of non-thermal electrons (e.g., Fokker-Planck)
- Details of optically thin loss function
- Alfvén wave energy (Fletcher & Hudson 2008)
- Non-thermal protons!
- Many other additions/modifications needed
- 3D Flare Modeling

Summary & Conclusions

Evidence for 3 continuum components in white-light: connected to light curve morphology

Many more results (line and continuum) in ApJS, in preparation – or ask me for my thesis

New 1D RADYN simulations up and running: Extended the Allred et al. (2006) M dwarf flare models to higher energy, short burst of heating with gradual phase

RHD models on the right track with
Balmer continuum in blue,
continuum in red

RHD models fail to produce absorption and/or hot blackbody: getting blackbody right will improve the predictions for the BaC

More heating at higher column mass

Observations in NUV important to understanding the peak of the “blackbody” spectrum

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