2019/11/7 17:30-18:00
in Session 4: Solar flares and coronal mass ejections

“Observations and Modeling of Chromospheric Lines during a Solar Flare”

Akiko TEI,[1, *]

J. KASPAROVA[2], P. HEINZEL[2], K. SHIBATA,[1] T. NAKAMURA,[(1)]
T. J. OKAMOTO[3], T. SAKAUE[1], T. KAWATE[4], A. ASAI[1], S. UENO[1], K. ICHIMOTO[1]

[1]Kyoto Univ., [2]Astronomical Institute, Czech Academy of Sciences, [3]NAOJ, [4]ISAS/JAXA

IRIS-10, 2019/11/4-8, in Bangalore, India

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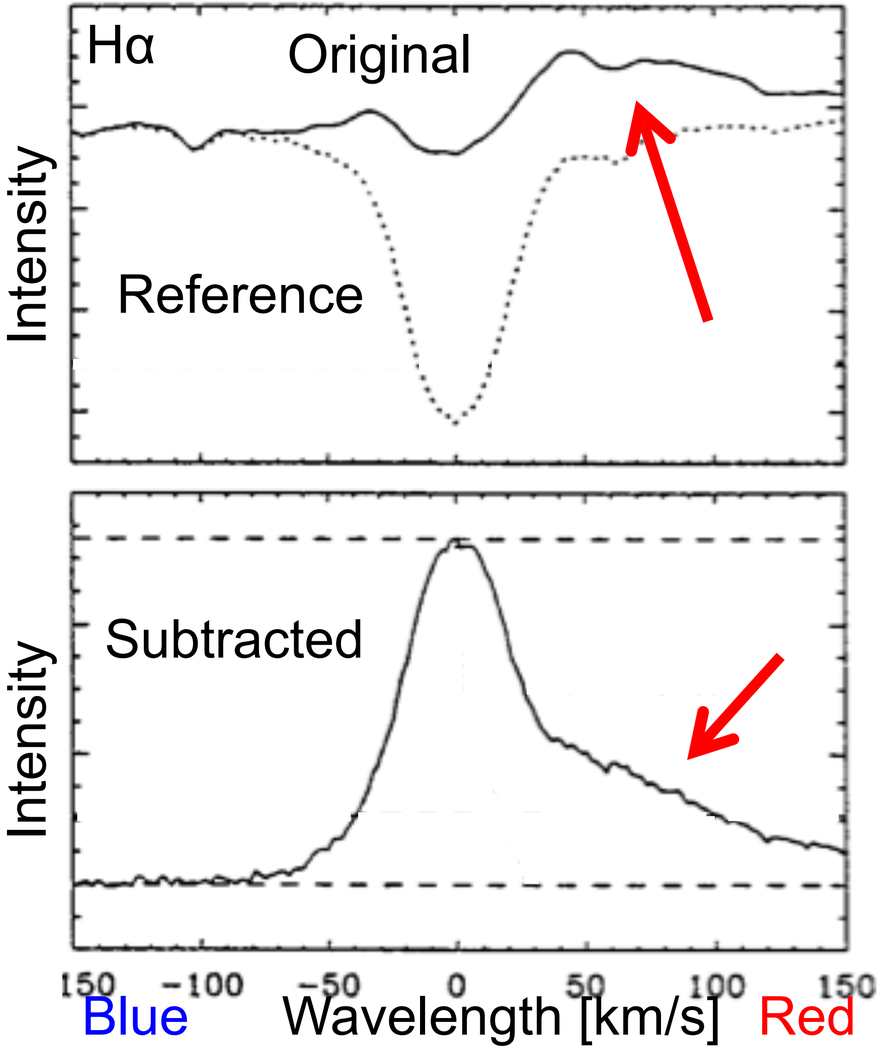
Outline

- **<u>Observation of a solar flare</u>** (Tei+ 18)
  - Chromospheric lines by IRIS and Hida/DST
  - Blue wing enhancement in Mg II hk lines
  - Cool upflow scenario

- **<u>RHD and RT modeling solar flare atmosphere</u>** (Ongoing work)
  - Flarix + MALI
  - Qualitatively cool upflow scenario is OK

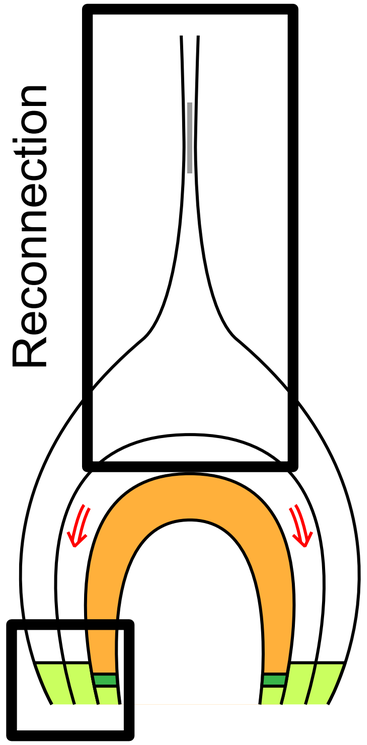
Chromospheric Line Profile in Flares
— Red Asymmetry

Example (Ding & Huang 95)



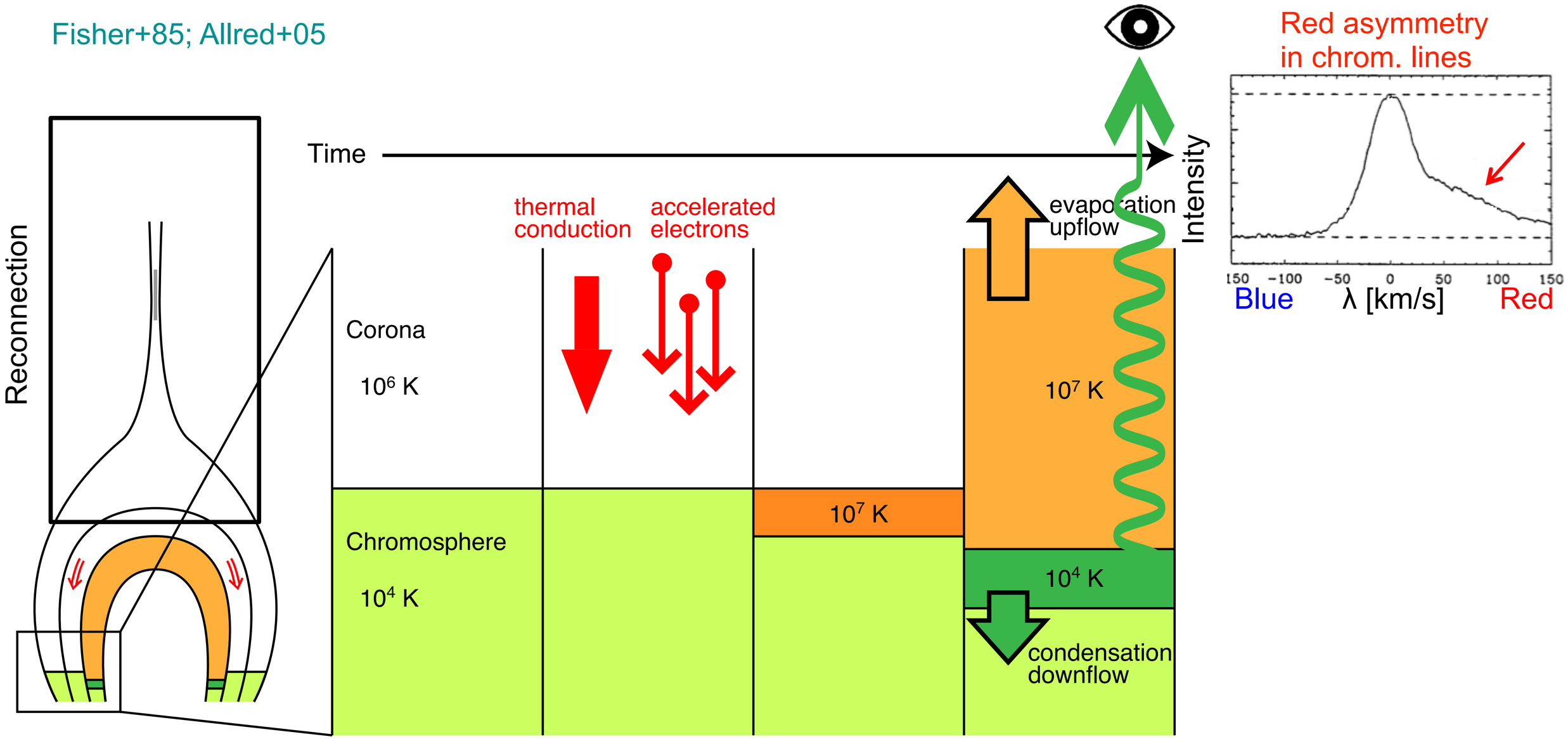
Many observations. Mostly in the impulsive phase.
In Hα/β/γ, He D3, Ca II H/K, Mg II h/k/triplet.
(Ichimoto & Kurokawa 84; Shoji+95; Wulser & Marti 89; Ding & Huang 95, Kerr+15; Graham & Cauzzi 15)

Interpreted to be caused by **condensation downflow** in the chromosphere.



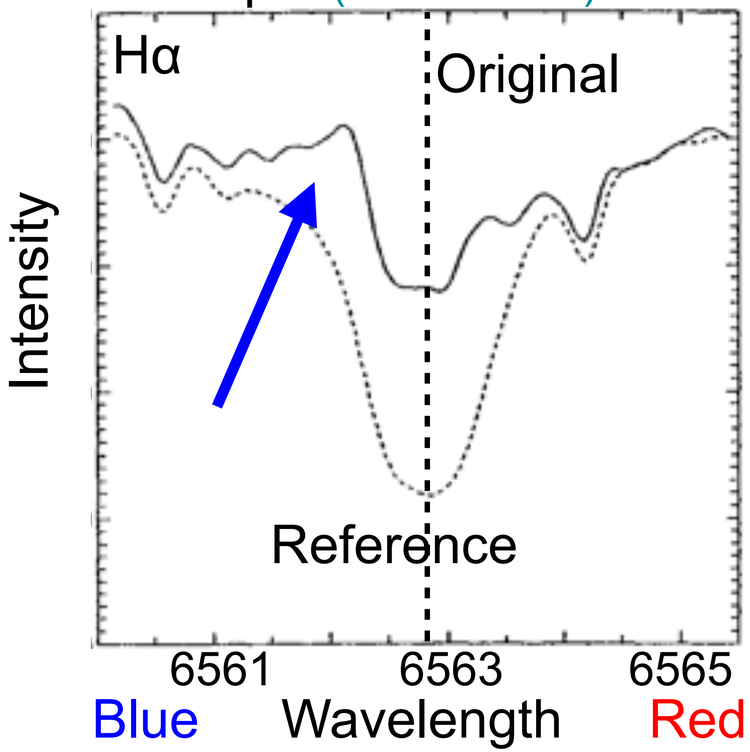
Chromospheric Evaporation & Condensation

Fisher+85; Allred+05



Chromospheric Line Profile in Flares
—Blue Asymmetry

Example (Heinzel+94)



Sometimes reported.

Mostly in **early phase** of a flare.

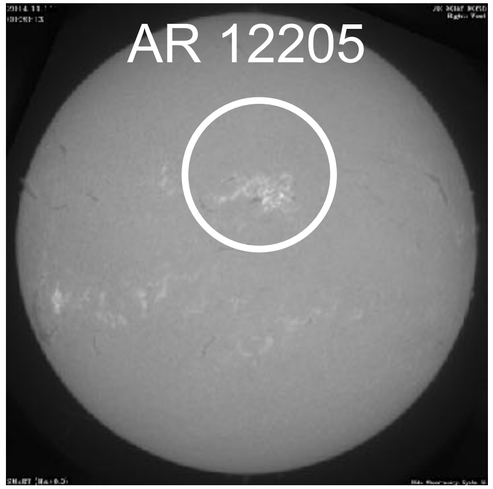
In Hα/β/γ, He D3, Ca II H, Mg II k.

(Svestka 62; Canfield+ 90; Heinzel+ 94; Gan+ 93; Ding & Fang 96/97; Kuridze+15/16; Kerr+15)

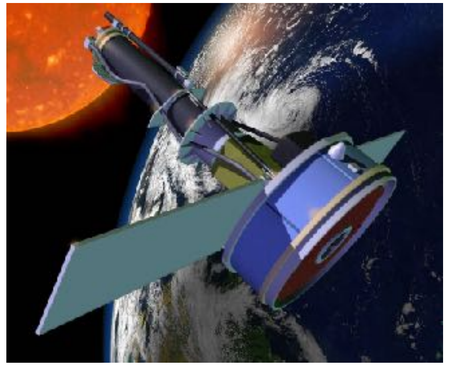
A few interpretations (Canfield+ 90; Heinzel+ 94) but poorly understood.

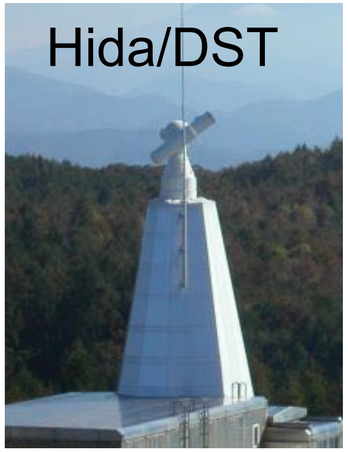
Aim of our study :
We clarify both spatial & temporal evolution of red/blue asymmetry at footpoints of a flare using chromospheric lines.

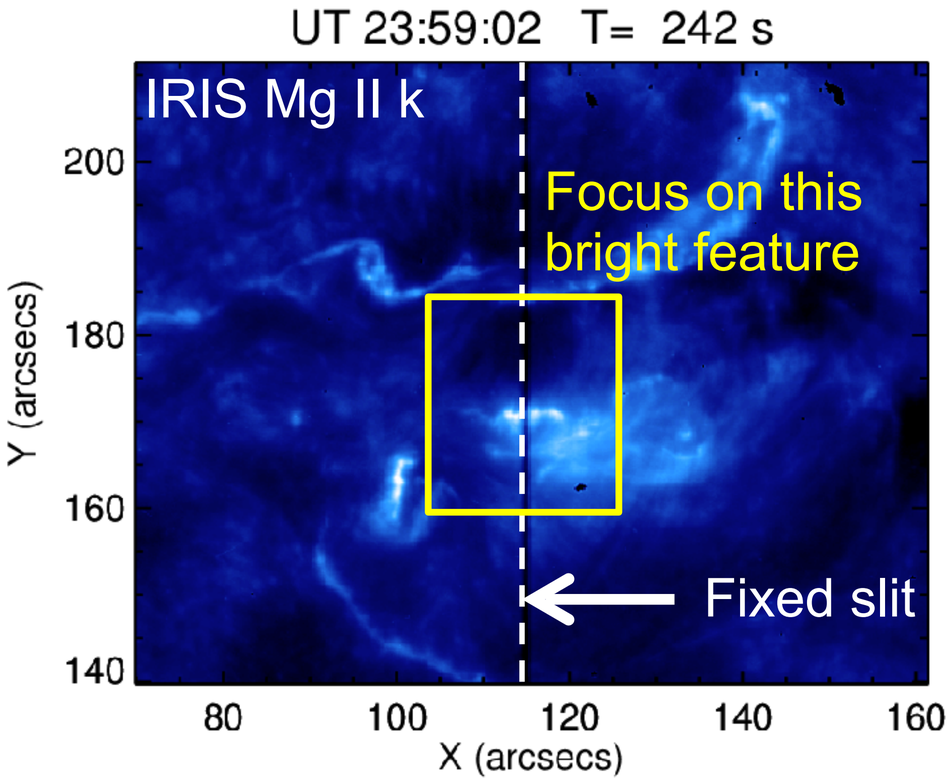
C5.4 Class Flare on 10 Nov, 2014



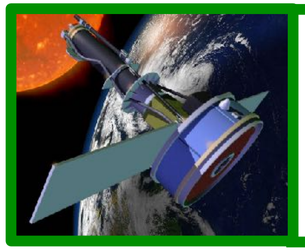
IRIS



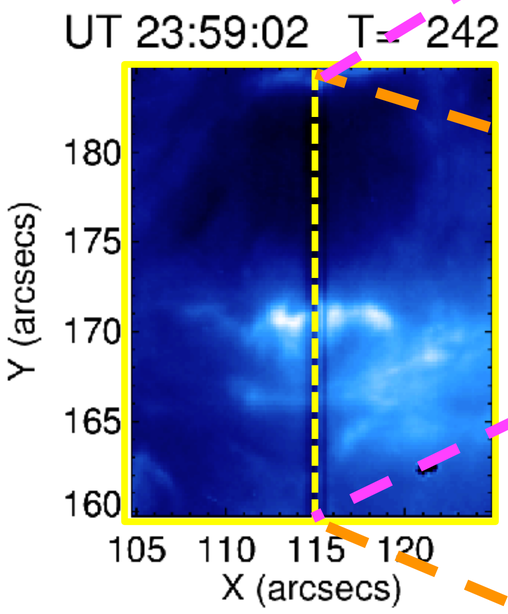




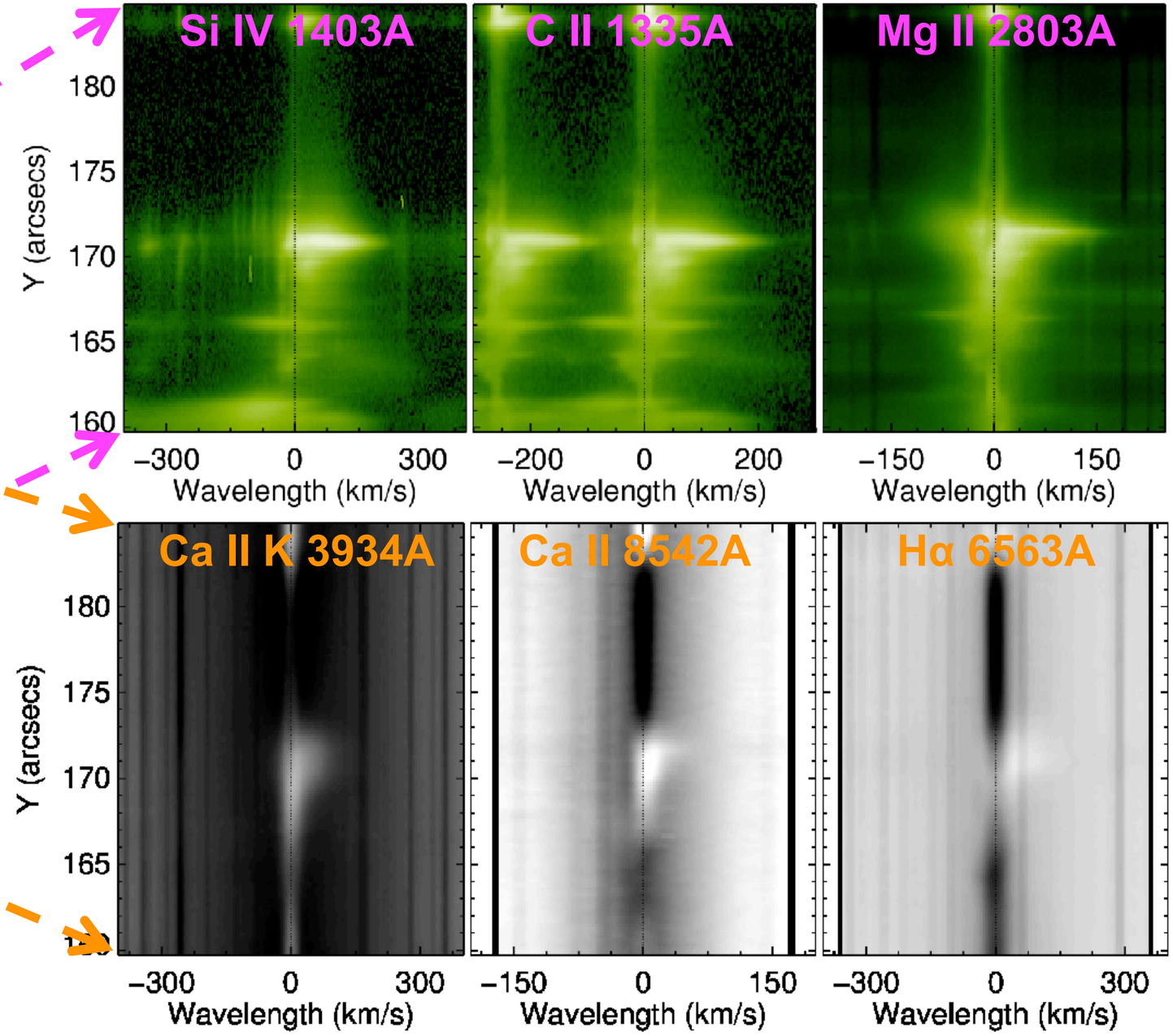
Spectra at Flare Footpoints



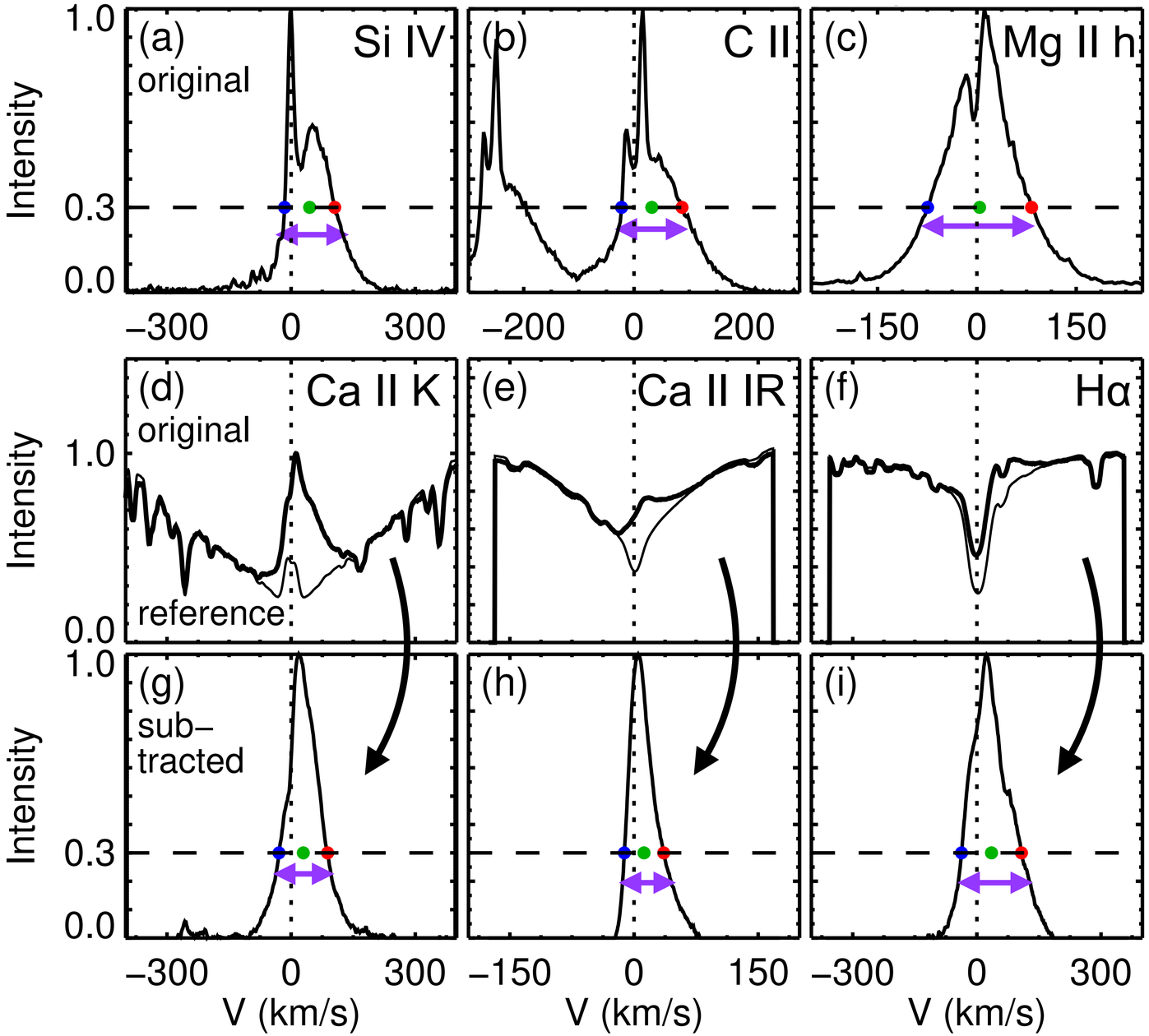
IRIS (fixed slit)
- 9.5 s cadence
- 0.17"/pix



Hida/DST (raster scan)
- every 10 s
- seeing ~2"



Measurements of Intensity, Velocity, & Widths



← Original profiles are used for IRIS lines.

✓ **Peak intensity**

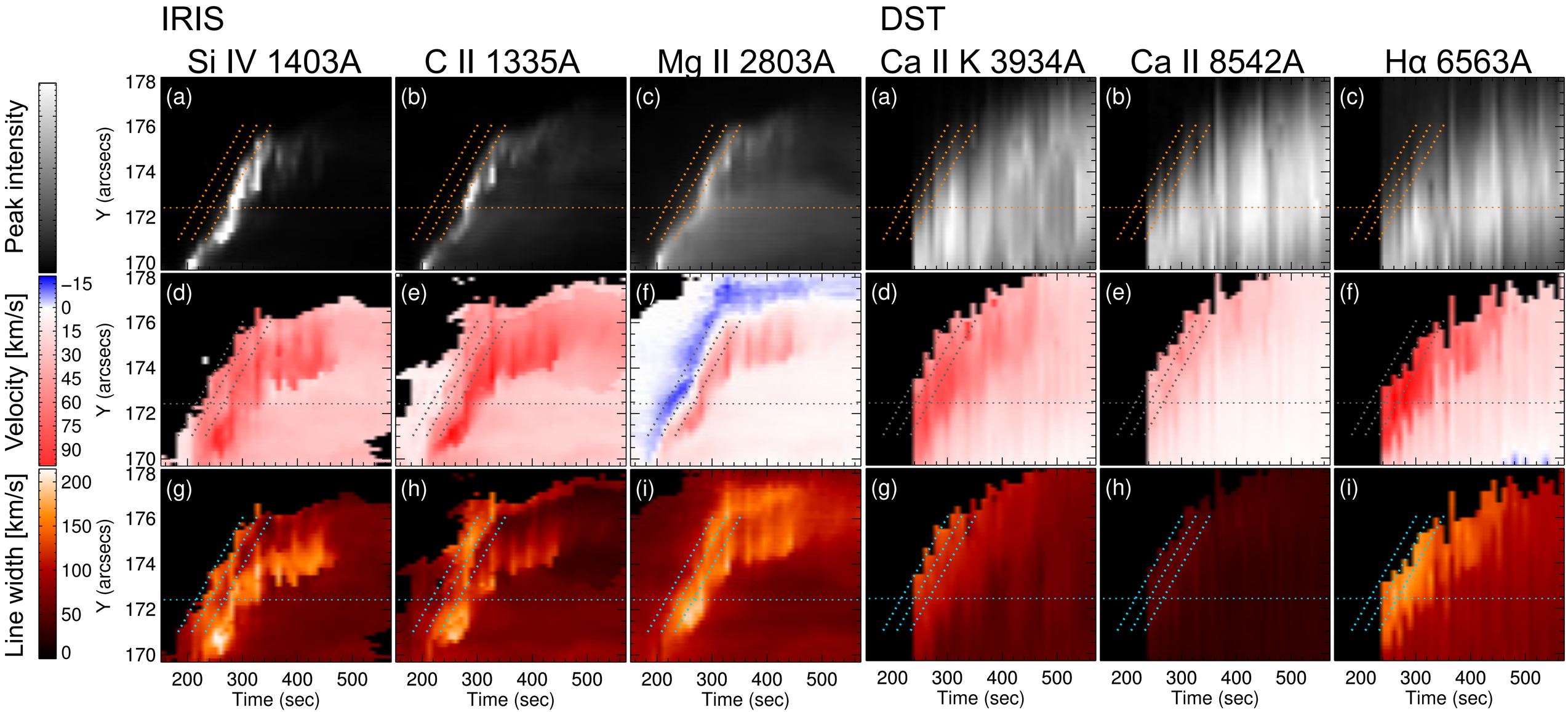
- Blue wing at 30% intensity ≡ V_B
- Red wing at 30% intensity ≡ V_R

→ **Doppler velocity ≡ $(V_R+V_B)/2$**

Line width ≡ $(V_R-V_B)/2$

← Subtracted profiles are used for DST lines.

Time-distance Maps of Intensity, Velocity, & Widths

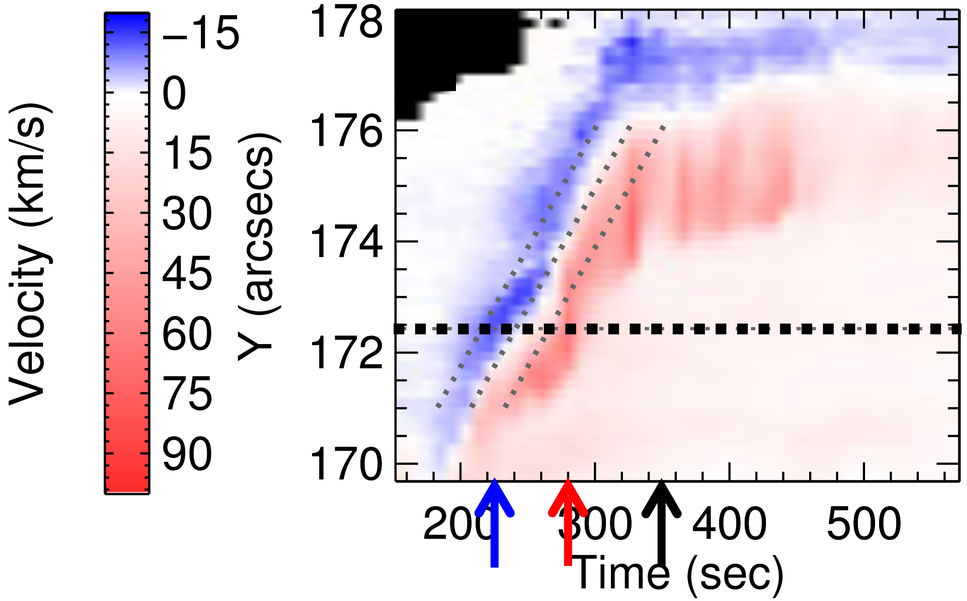


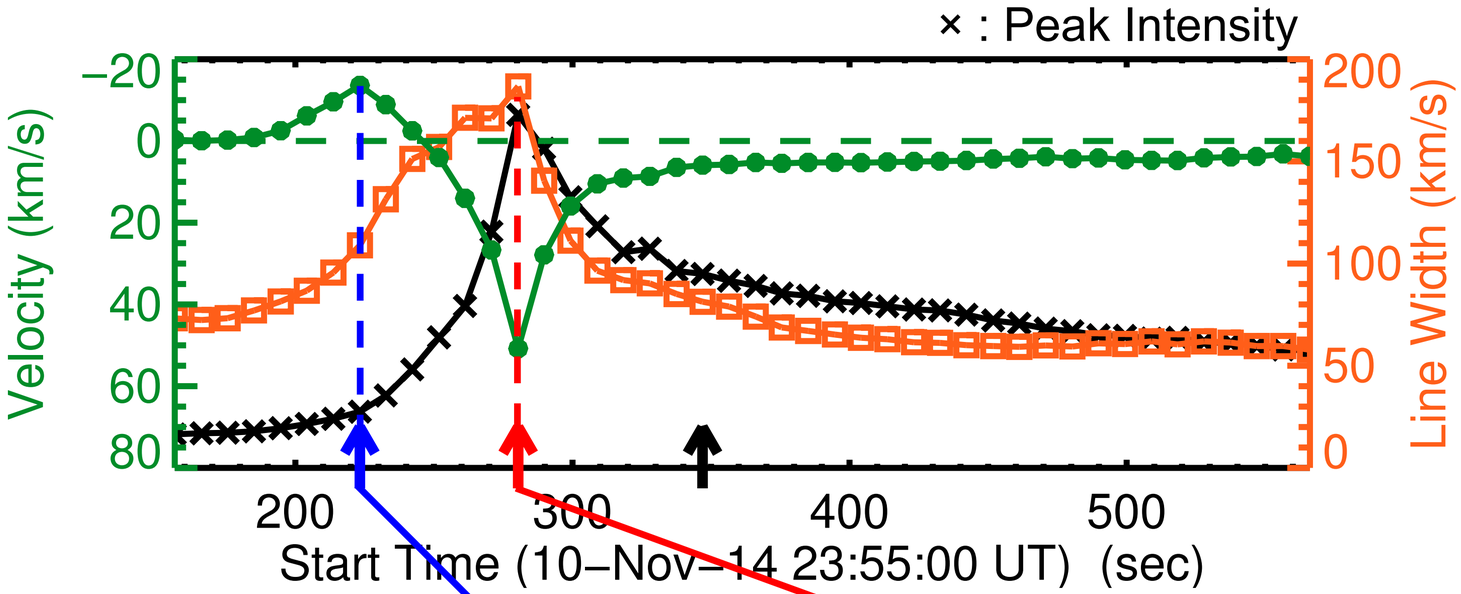
Flare footpoints moved northward.

Redshifts with broad widths.

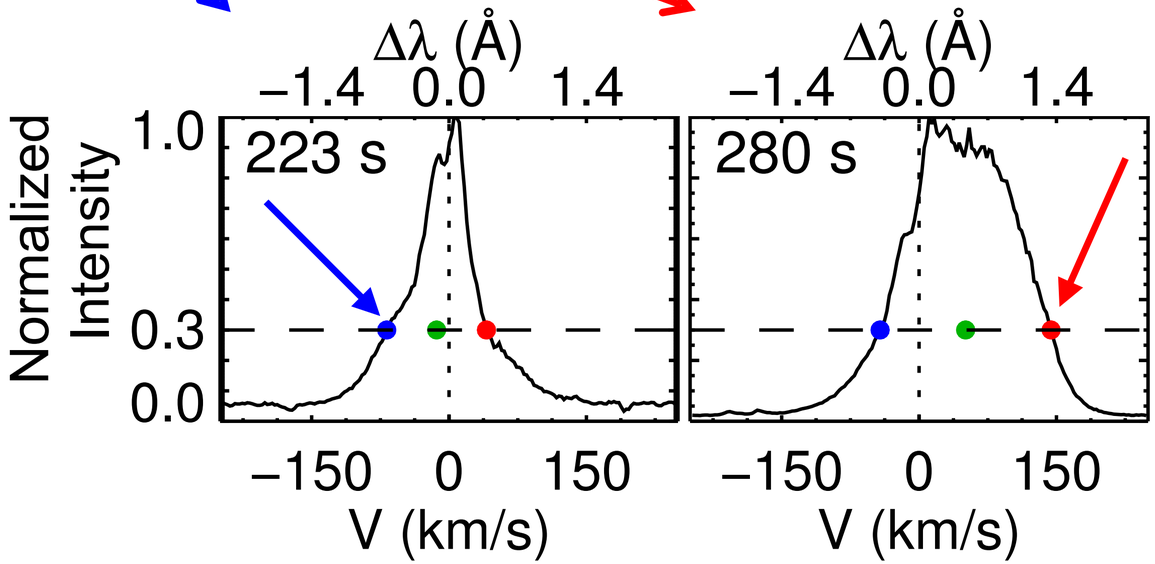
Blueshifts only in Mg II h.

Evolution of Mg II h at a Location

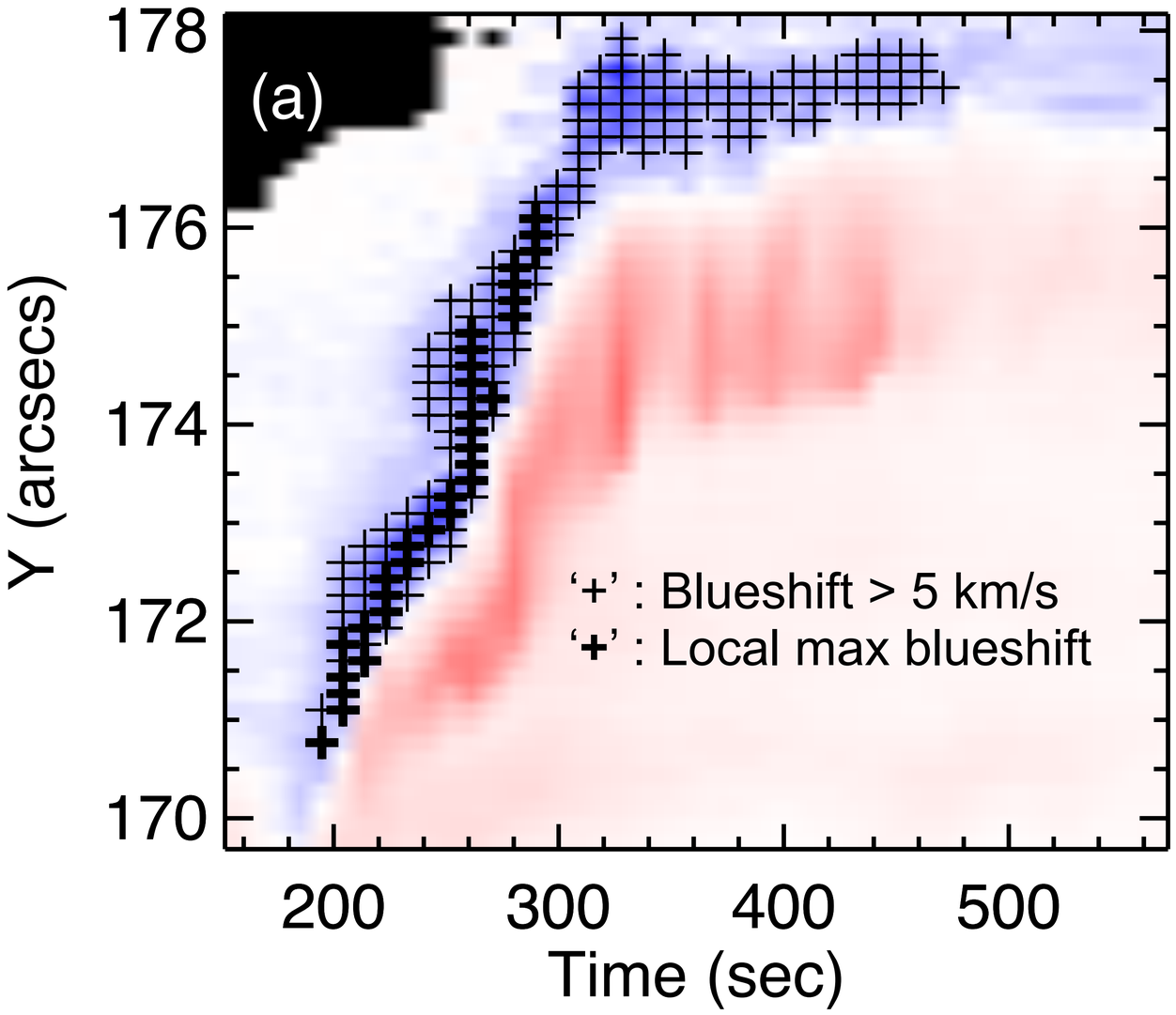


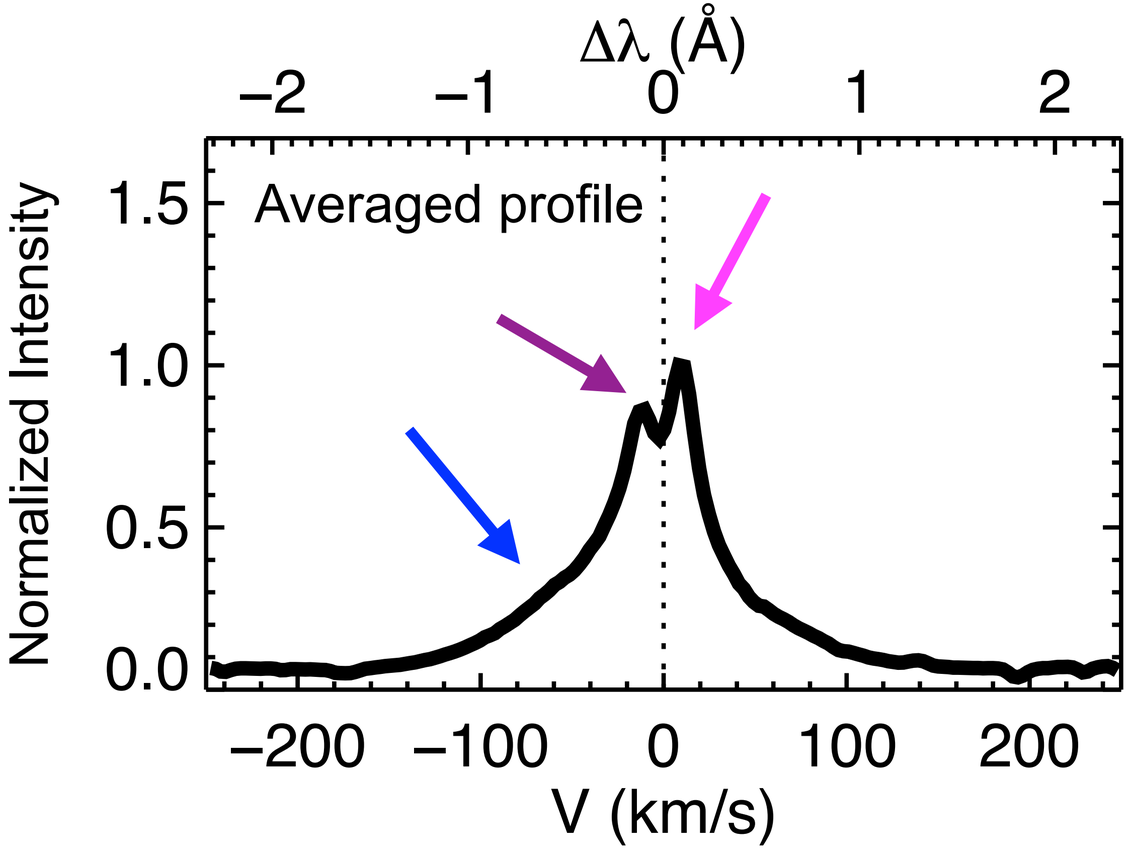


Small peak **intensity**
Weak **blue-wing enhancement** (Blueshift)
↓
Large peak **intensity**
Large **red-wing enhancement** (Redshift)



The Mg II h Line Profile with Blueshifts





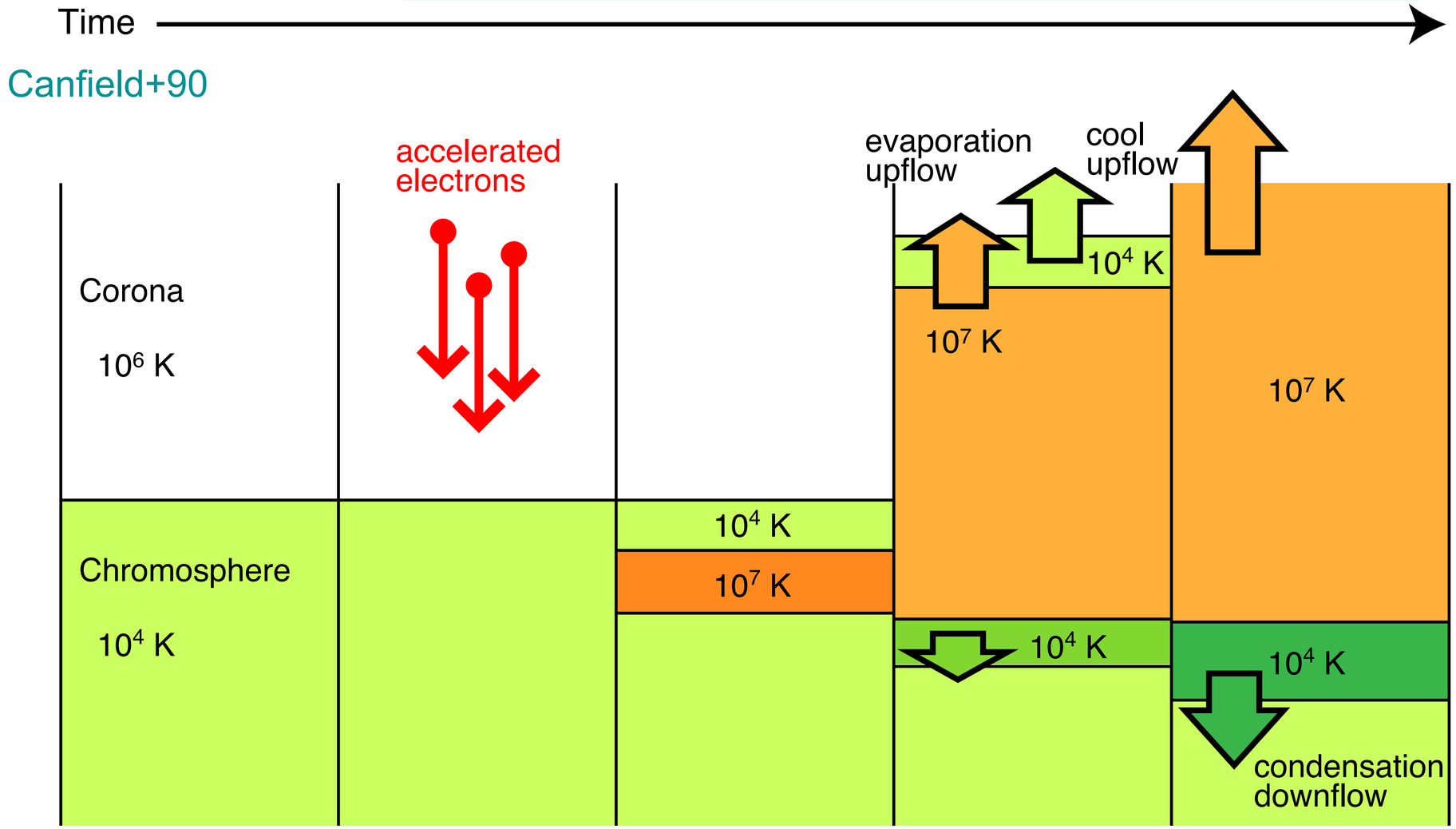
- **Blue wing enhancement**
- **Blue-side peak < Red-side peak**

Local max blueshift: -10 km/s Duration: 30 s

Scenario of Cool Upflow

An upflow of cool plasma is lifted up by expanding hot plasma owing to the deep penetration of high-energy electrons into the chromosphere.

Canfield+90



Implied in 1D HD simulation of flaring loops by thick-target heating
(Nagai & Emslie 84; Allred+05; Kennedy+15; Rubio da Costa+15b)

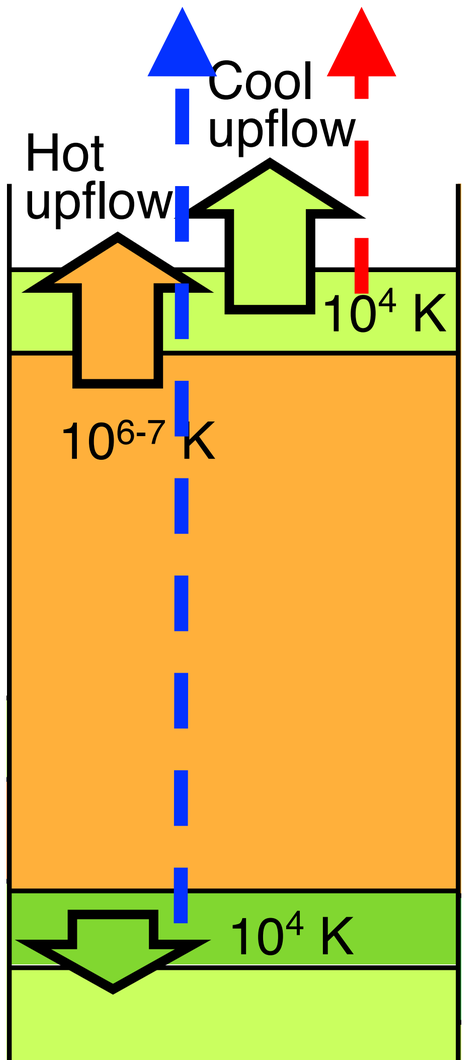
Cloud Modeling of the Cool Upflow Scenario

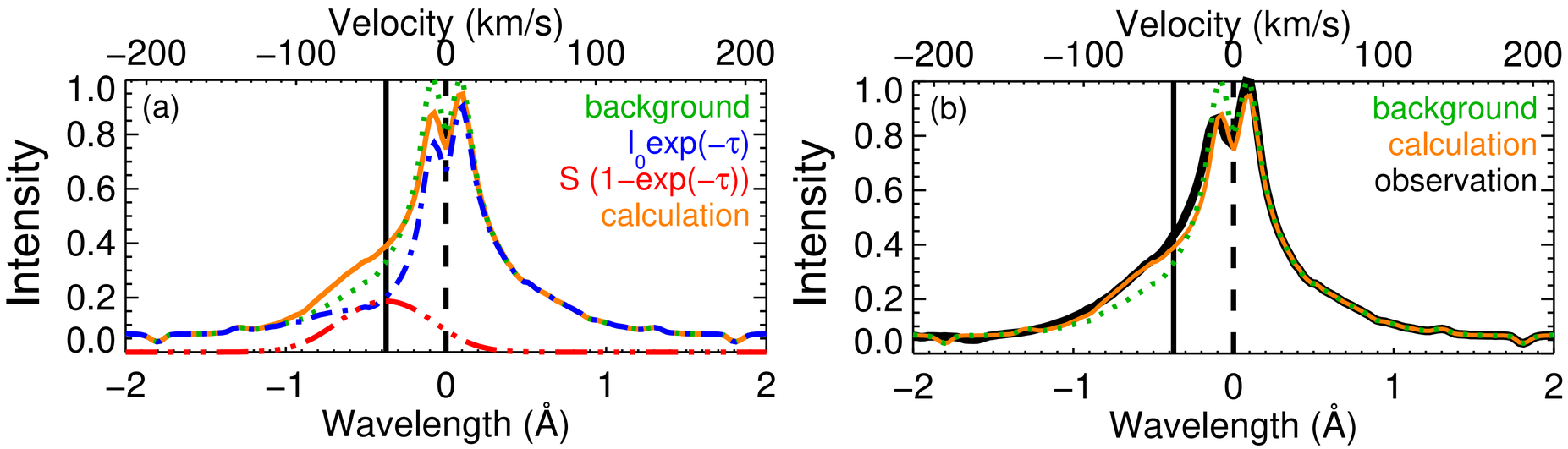
$$\Delta\lambda_{LOS} \equiv \frac{\lambda_0}{c} V_{LOS}$$

$$I(\Delta\lambda) = I_0(\Delta\lambda)\, e^{-\tau(\Delta\lambda)} + S\left[1 - e^{-\tau(\Delta\lambda)}\right]$$

$$\tau(\Delta\lambda) = \tau_0 \exp\left[-\left(\frac{\Delta\lambda - \Delta\lambda_{LOS}}{\Delta\lambda_D}\right)^2\right]$$

$$\Delta\lambda_D = \frac{\lambda_0}{c}\sqrt{\frac{2k_BT}{m_{Mg}} + V_{turb}^2}$$

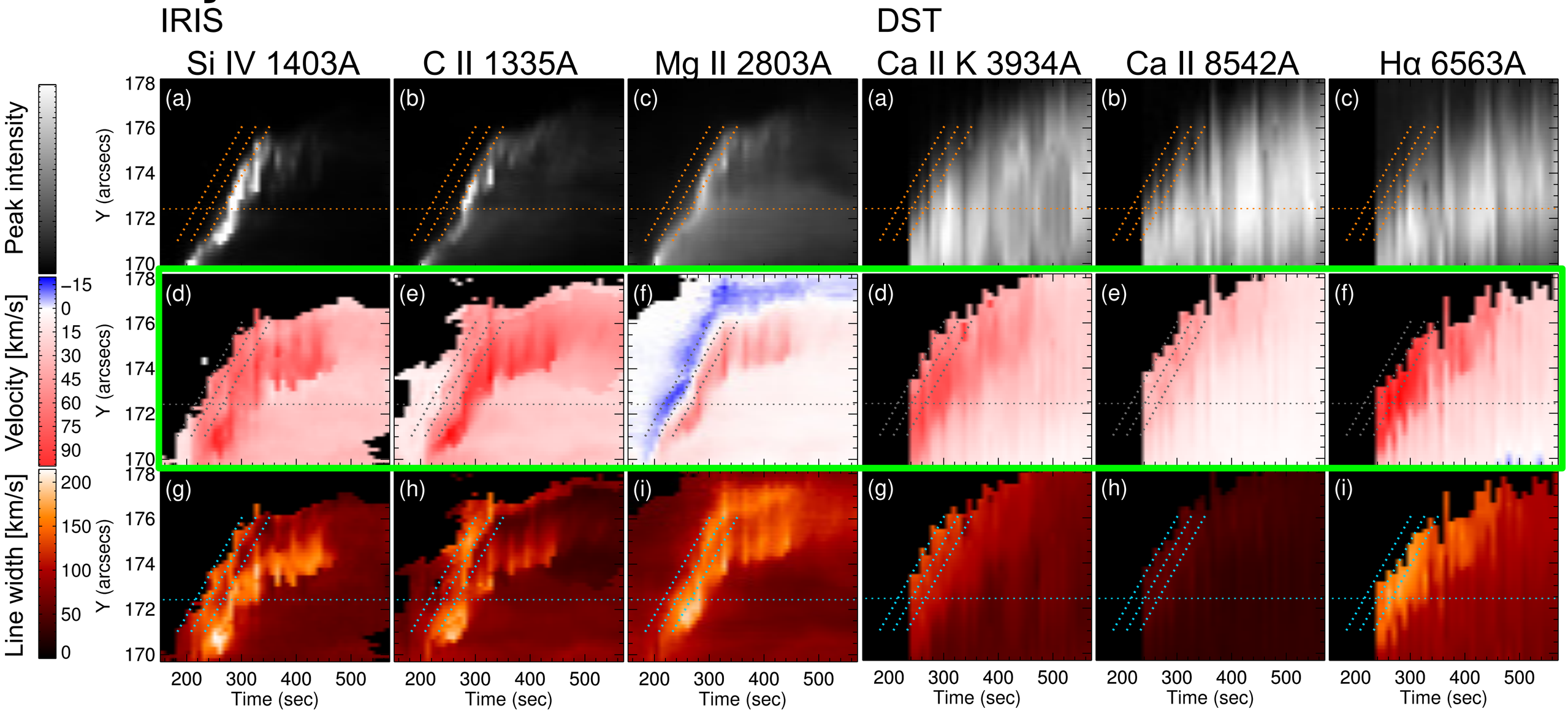




The observed line profile is successfully reproduced with :
V_{LOS} = -40km/s, V_{turb} = 40km/s, τ_0 = 0.5, and $S/I_0(0)$ = 0.6

Attenuation of the background intensity by cool upflow
→ **Blue-side peak < Red-side peak**
Emission of cool upflow → **Blue wing enhancement**

Why was No Blueshift Observed in Other Lines ?



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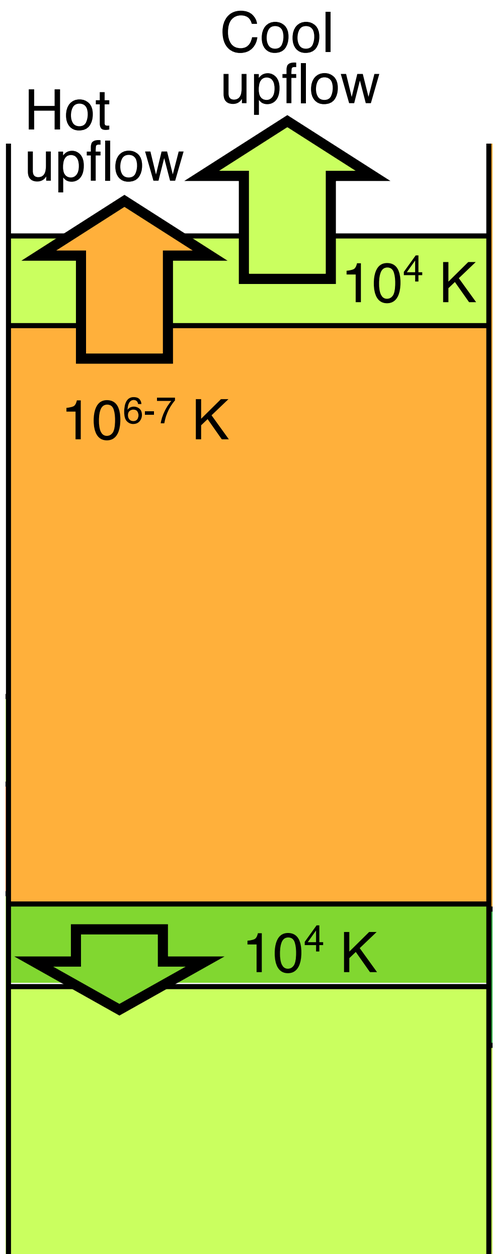
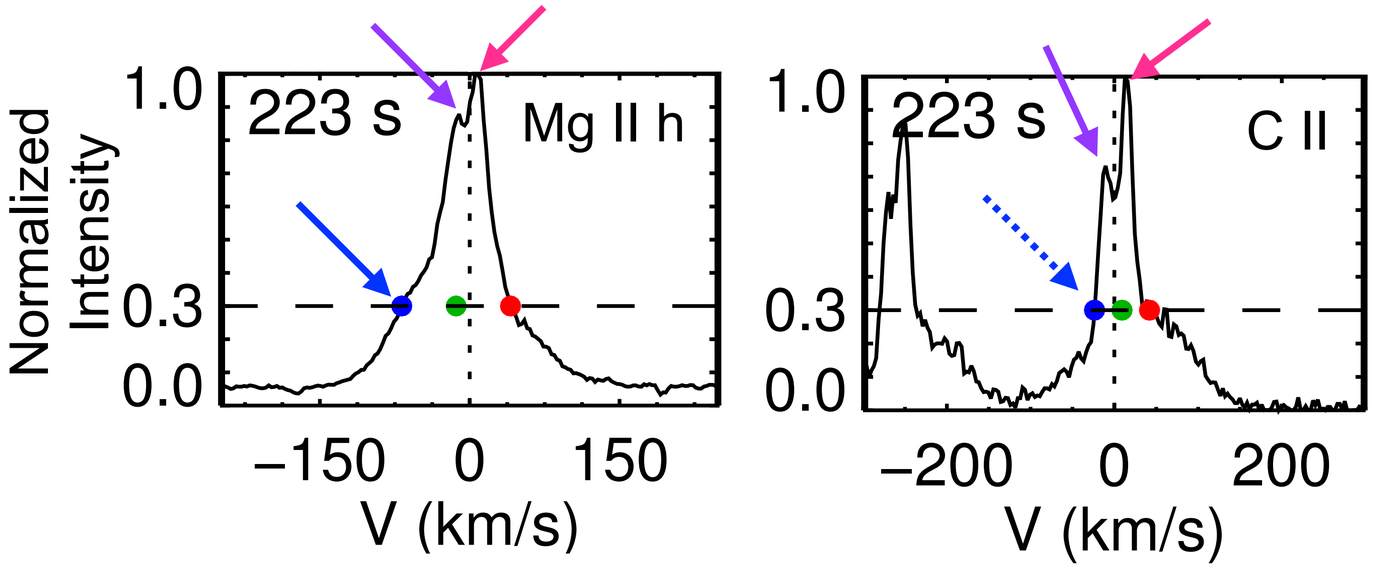


- Si IV → forms at higher (TR) temperature. (De Pontieu+14)
- Ca II K, Ca II IR, and Hα → have smaller opacities than Mg II h. (Leenaarts+13)
- C II 1335Å → has the similar opacity to Mg II h. (Rathore+15)
  - The blue peak is smaller than the red peak ← the same as the Mg II
  - But no blue wing enhancement ← possibly a small source function



Only Mg II h could catch the cool upflow.

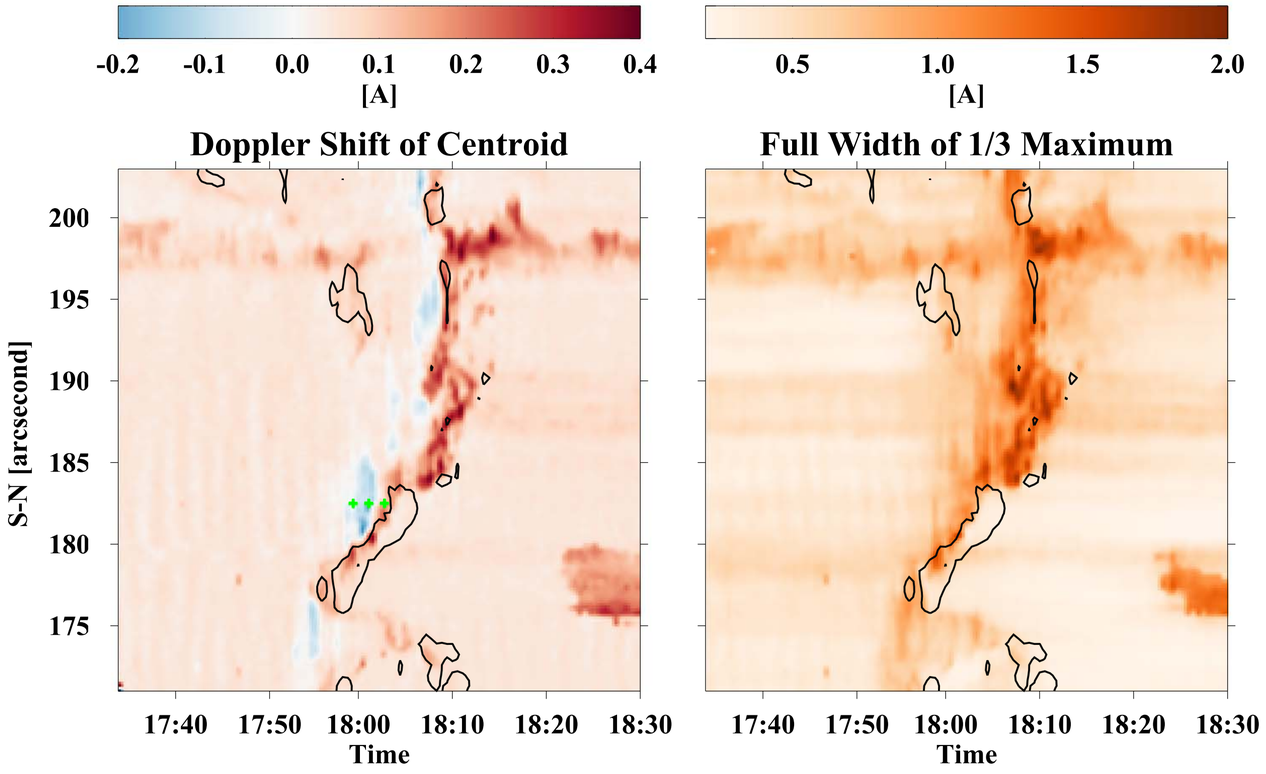
Summary of Observations

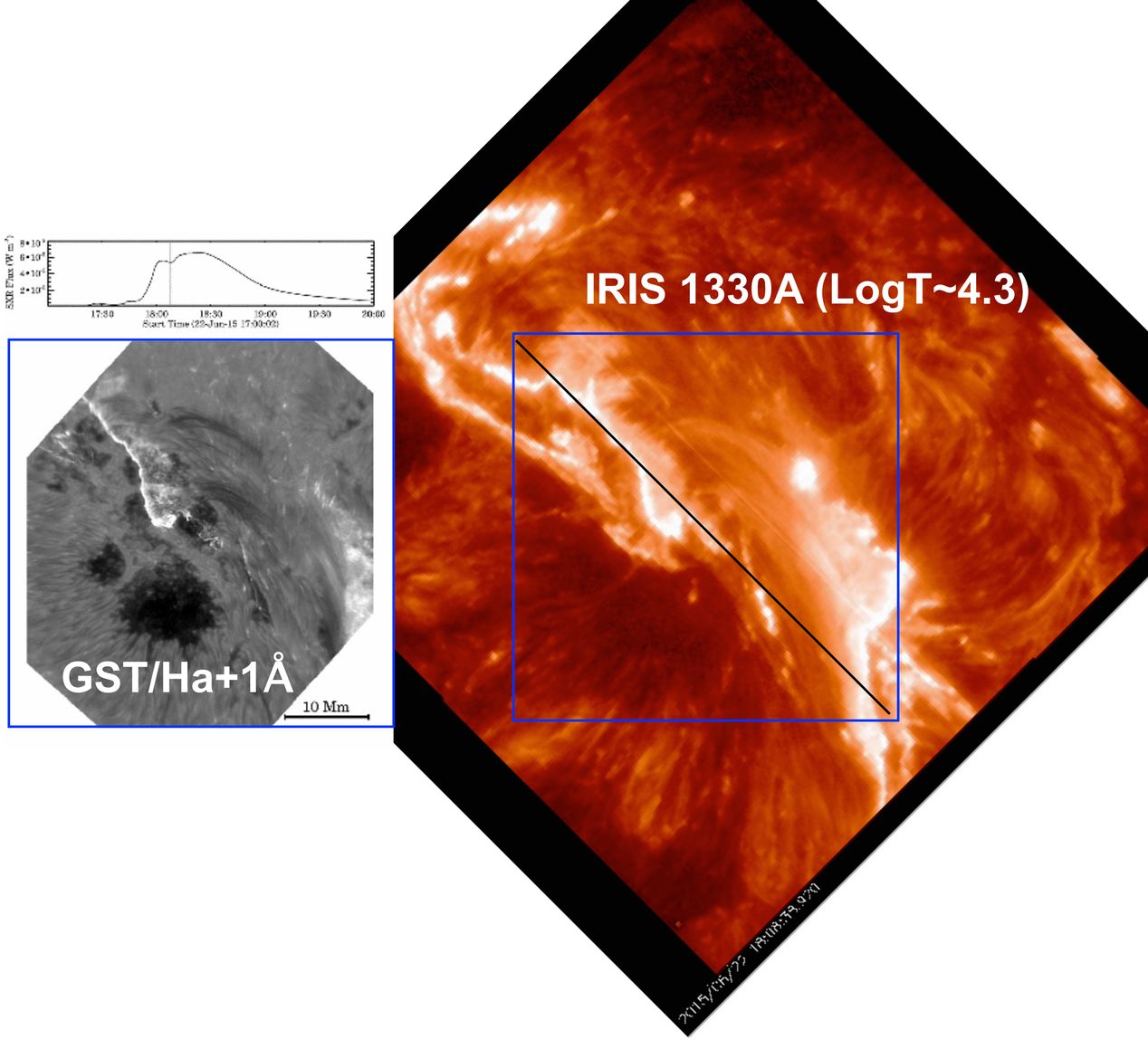
- We investigated flare footpoints apparently moving along the IRIS slit in the C5.4 flare on Nov 10, 2014.
- **Blue wing enhancements preceded the strong emission and strong red wing enhancements in the Mg II h line.**
- The Mg II h line profile with blueshifts had a good agreement with the cloud modeling of the cool upflow scenario.
- It's possible that only the Mg II h line catches the cool upflow among the investigated 6 lines (Si IV, C II, Mg II h, Ca II K, Ca II 8542A, Hα).
- **We propose that the chromospheric-temperature (cool) plasma was lifted up by the evaporated (hot) plasma owing to the penetration of non-thermal electrons into the deep chromosphere.**

Tei+ 18

Another Observation of Blue-wing Enhancement

Huang+ 19

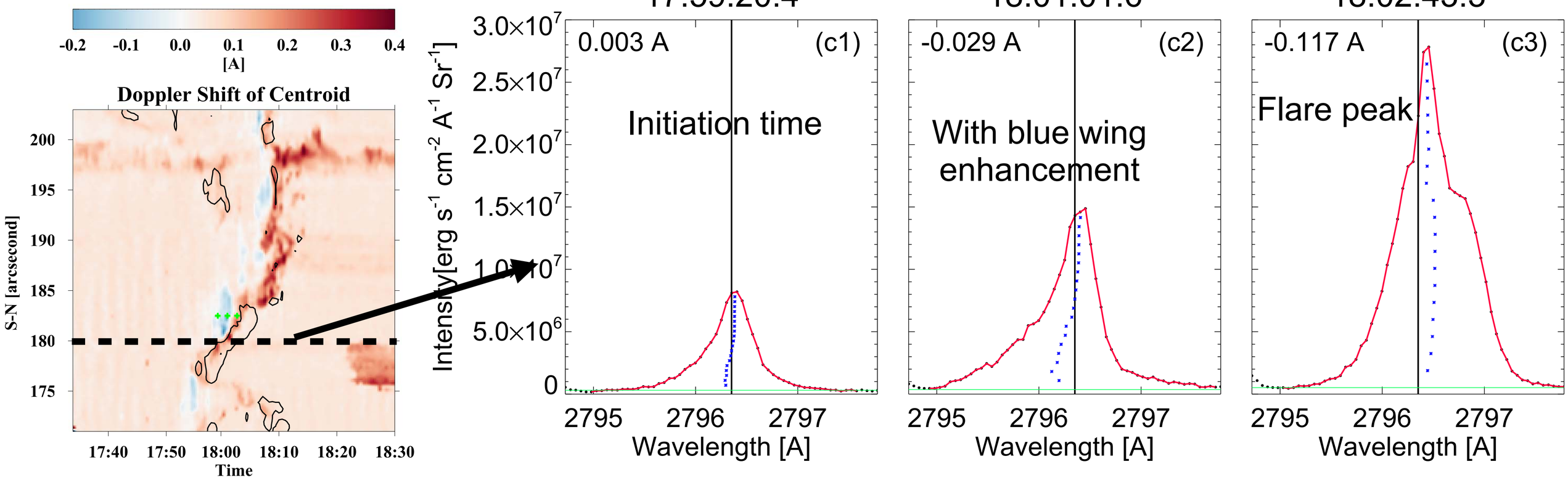




Contours: intensity maxima

Another Observation of Blue-wing Enhancement

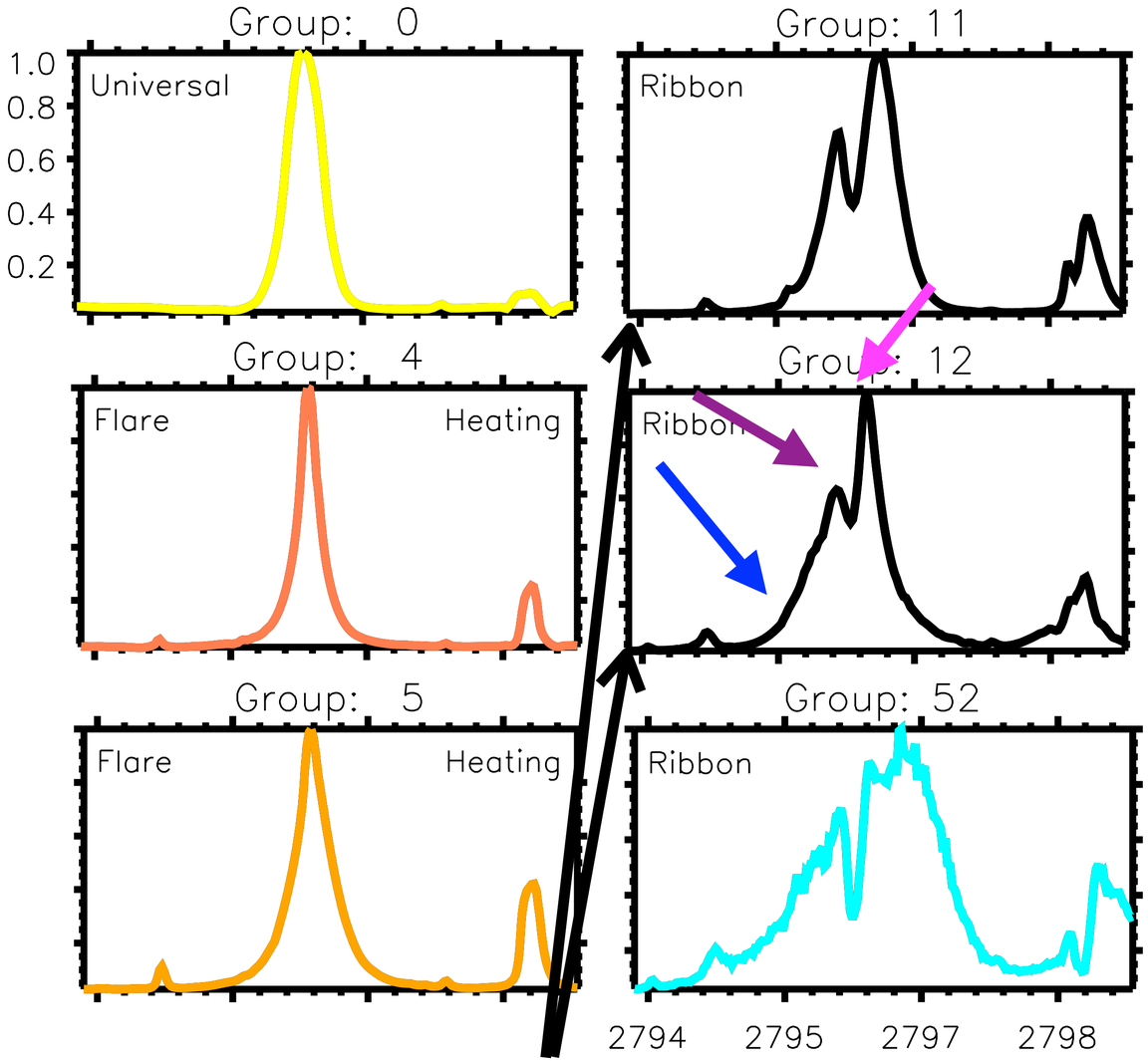
Huang+ 19

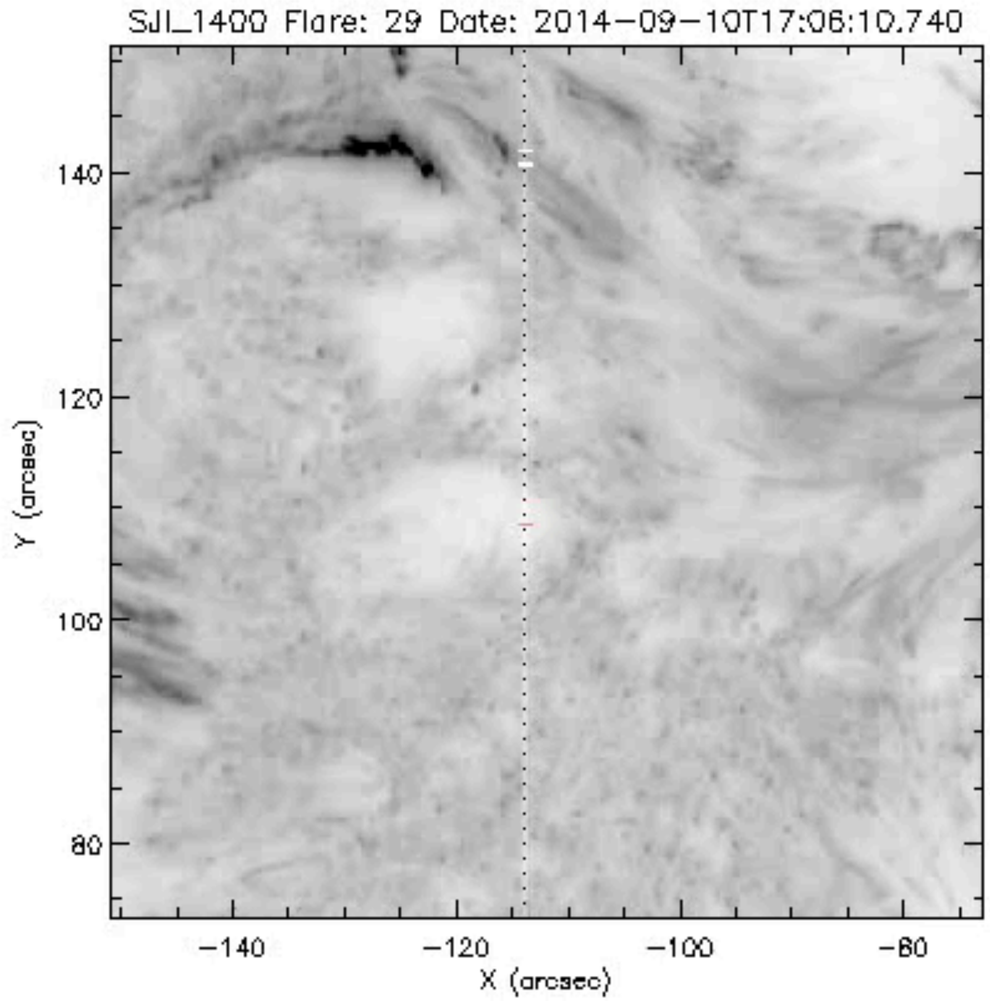


Contours: intensity maxima

Is Blue-wing Enhancement Rare?

Panos+ 18 “Identifying Typical Mg II Flare Spectra Using Machine Learning”





Profiles at the leading edge of fast-moving flare ribbons

Modeling of Flare Atmosphere using *Flarix*: Non-LTE Radiation Hydrodynamic (RHD) Code

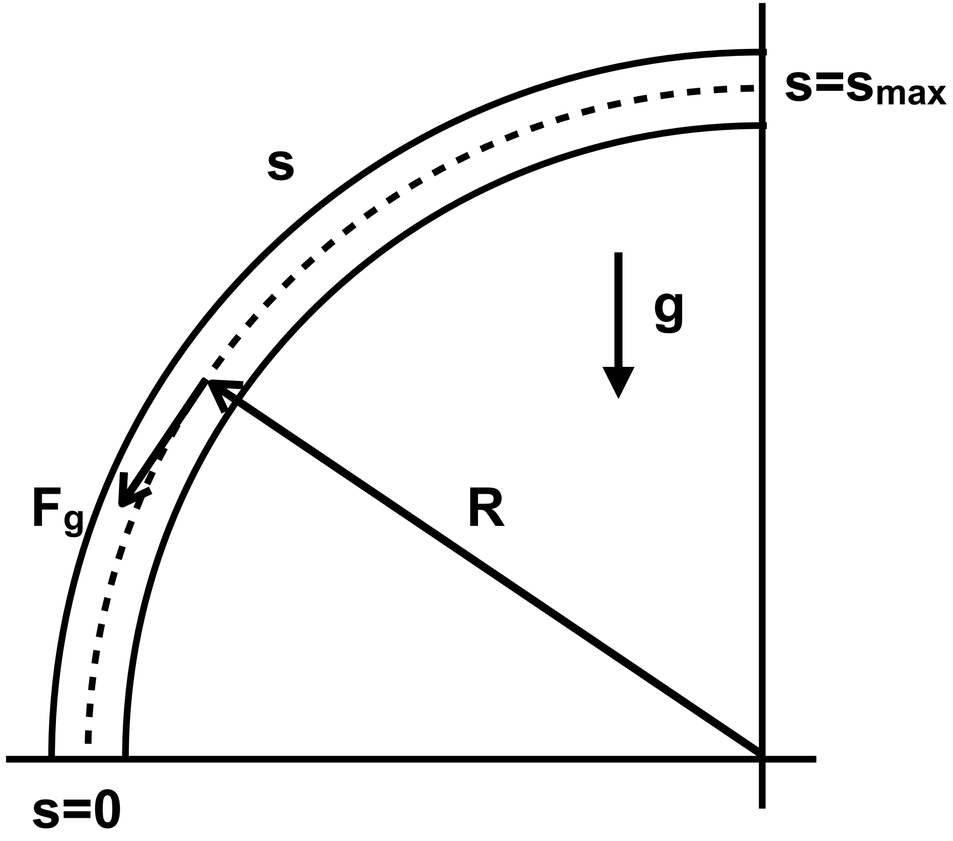
- Flarix (Varady+ 10; Heinzel+ 16; Kasparova+ 19)
- Agreement with RADYN (Kasparova+ 19)
- 1D atmosphere in a semi-circular loop
- heating by non-thermal electron beams propagating from the apex in the corona to the lower atmosphere.

1D RHD equations

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial s}(\rho v_s) = 0$$

$$\frac{\partial (\rho v_s)}{\partial t} + \frac{\partial}{\partial s}\left(\rho {v_s}^2\right) = -\frac{\partial P}{\partial s} + \underbrace{\rho g_s}_{\text{Gravity}}$$

$$\frac{\partial E}{\partial t} + \frac{\partial}{\partial s}((E+P)v_s) = \underbrace{\rho g_s v_s}_{\text{Gravity}} + H + Q - R - \underbrace{\frac{\partial}{\partial s} F_c}_{\text{Conduction}}$$



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$$\frac{\partial (\rho v_s)}{\partial t} + \frac{\partial}{\partial s}(\rho {v_s}^2) = -\frac{\partial P}{\partial s} + \rho g_s$$

Gravity

$$\frac{\partial E}{\partial t} + \frac{\partial}{\partial s}((E+P)v_s) = \rho g_s v_s + \boxed{H} + Q - \boxed{R} - \frac{\partial}{\partial s} F_c$$

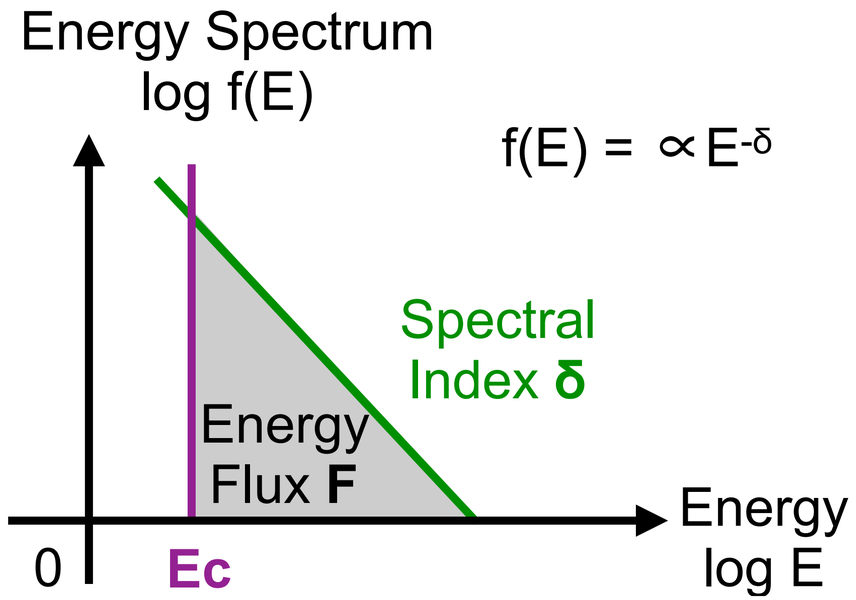
Gravity

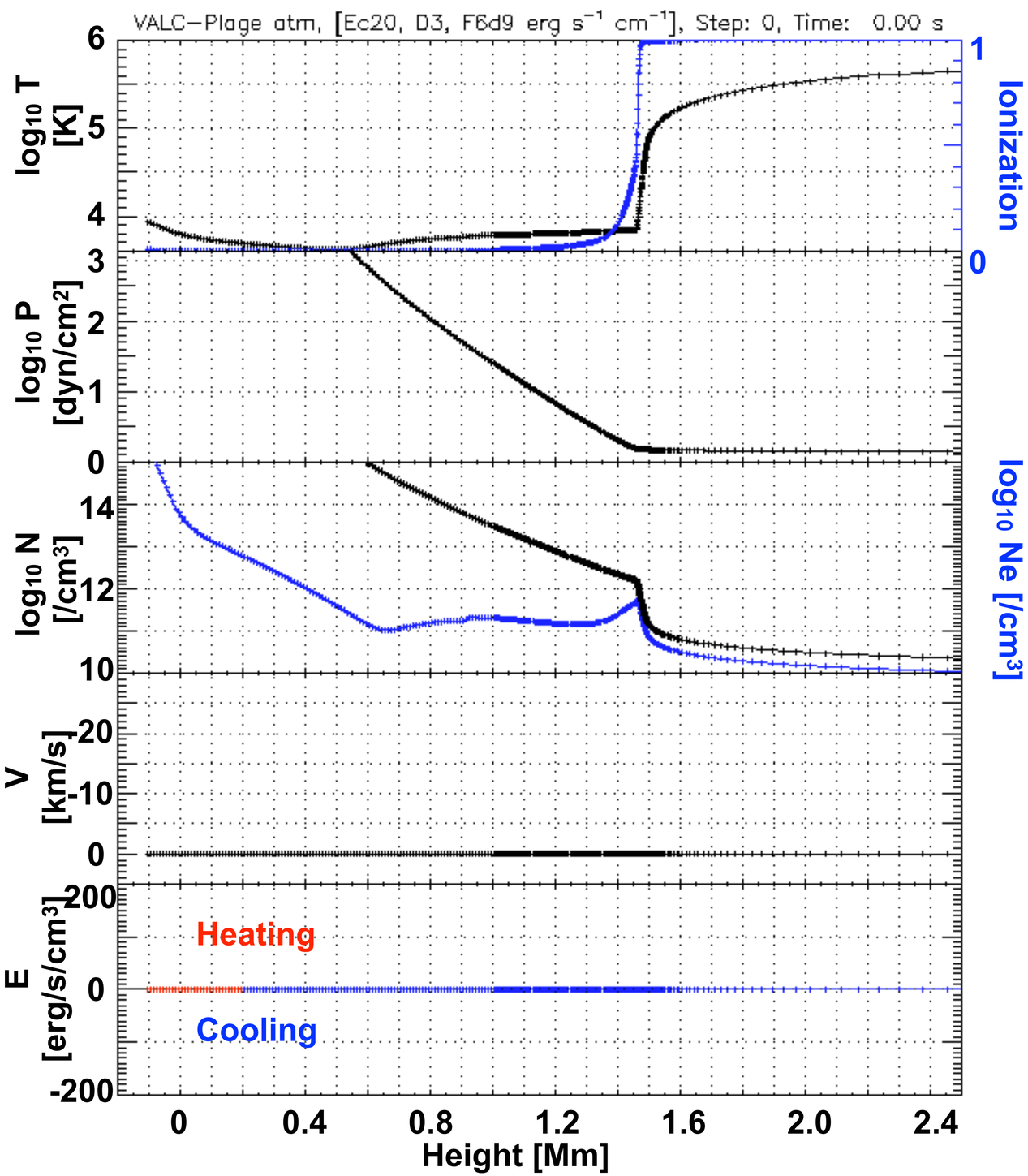
e beam heating

Radiative rosses

Conduction

Heating to assure stability of the initial atmosphere





Result of Modeling (*Flarix*)

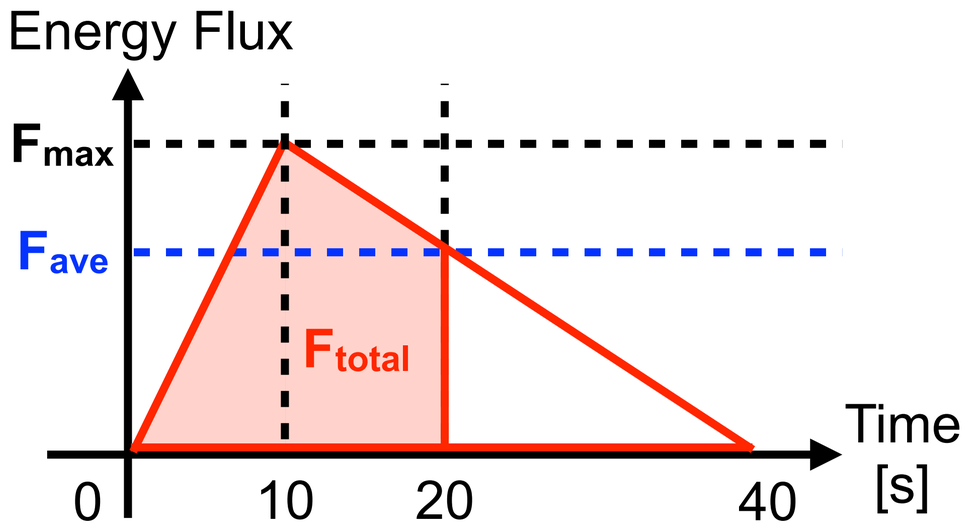
E_c = 20 keV, δ = 3,

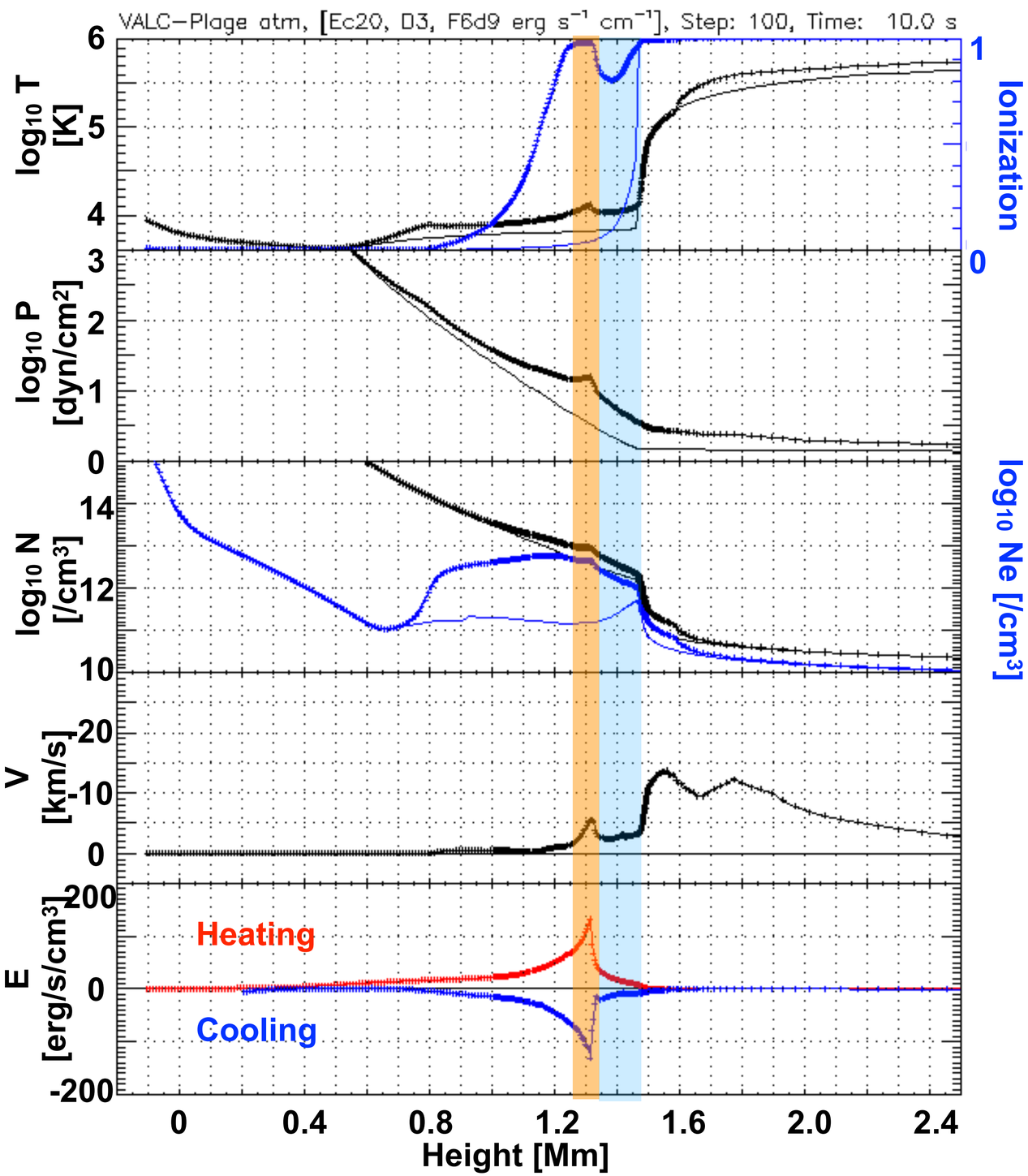
F_{max} = 6 × 10^9 erg/cm²/s

(increase till 10s then decrease towards 40s)

→ **F_{total} ~ 8 × 10^{10} erg/cm²** (in 20s)

→ **F_{ave} ~ 4 × 10^9 erg/cm²/s** (in 20s)





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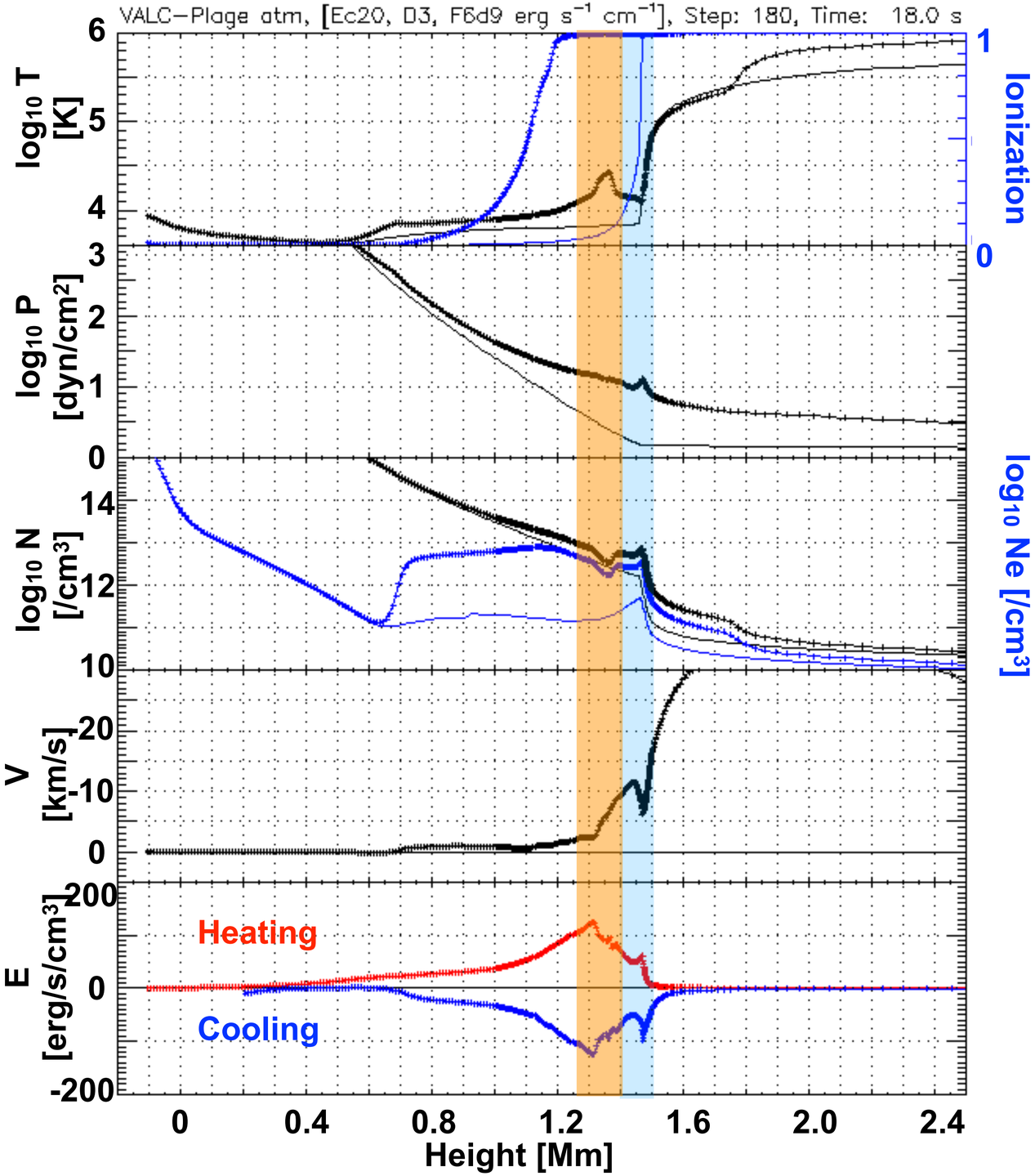
→ **F_{ave} ~ 4 × 10^9 erg/cm²/s** (in 20s)

Snapshot at Time = 10.0 sec

Increase of T and P by heating (at Z ~ 1.3 Mm)

Chromospheric plasma above the heated layer



Result of Modeling (*Flarix*)

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F_{max} = 6 × 10^9 erg/cm²/s
(increase till 10s then decrease towards 40s)
→ **F_{total} ~ 8 × 10^{10} erg/cm²** (in 20s)
→ **F_{ave} ~ 4 × 10^9 erg/cm²/s** (in 20s)

Snapshot at Time = 18.0 sec

Cool ($\log_{10}$ T ~ 4.2 [K]),
dense ($\log_{10}$ N ~ 13 [/cm³]), and
upward moving (V ~ 10 [km/s]) plasma

Modeling of the Mg II h Line using *MALI*: Radiative Transfer Code (1D)

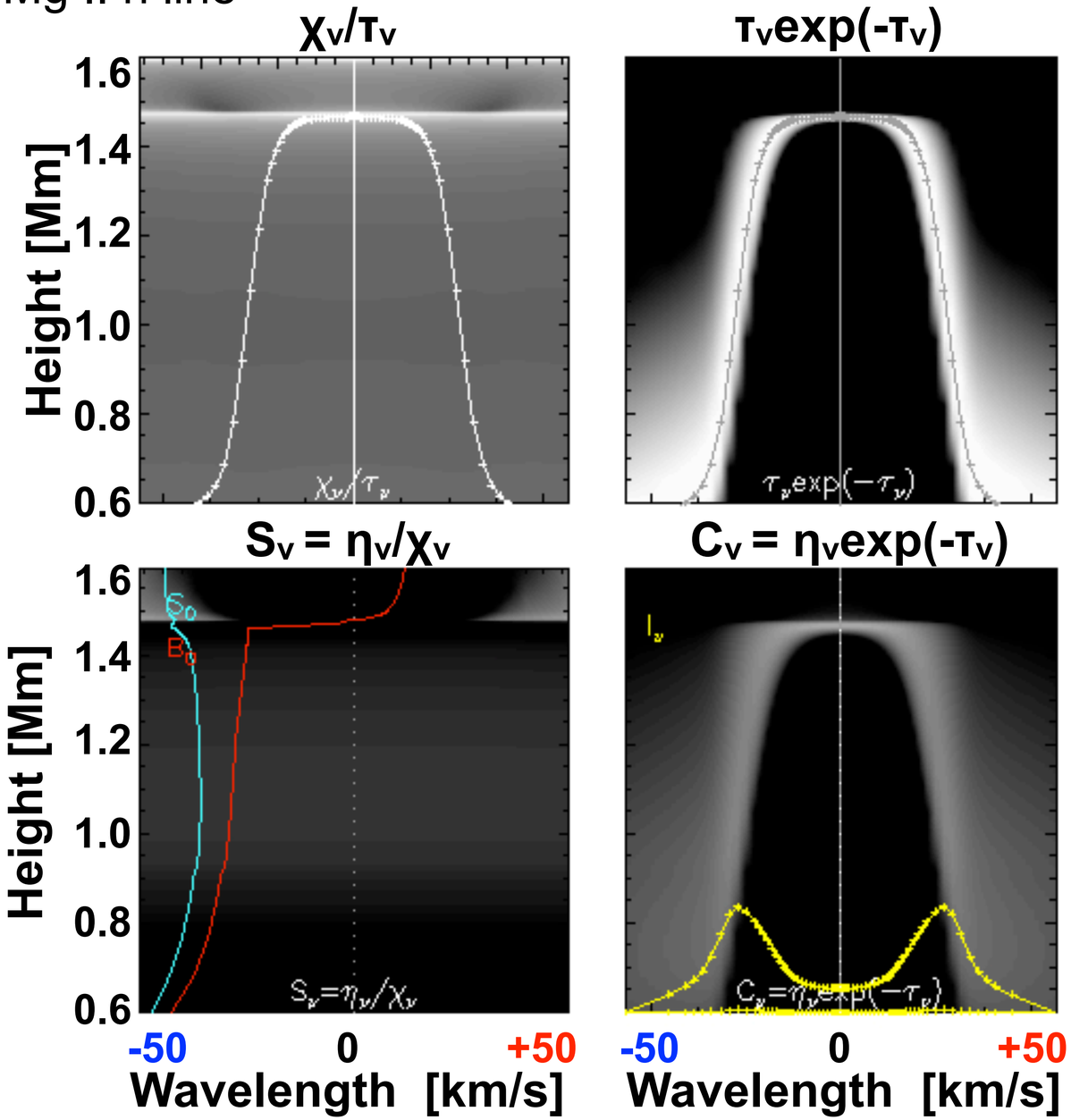
- 1D MALI: plane-parallel radiative transfer (Heinzel+ 14)
- Mg II lines are synthesized for each snapshot of the Flarix atmosphere.

- Mg II model: 5 levels + cont., 6 transitions
- Complete frequency re-distribution (CRD)
- Assume turbulent velocity

Result of Modeling (*Flarix+MALI*)

Step: 0, Time: 0.00 s

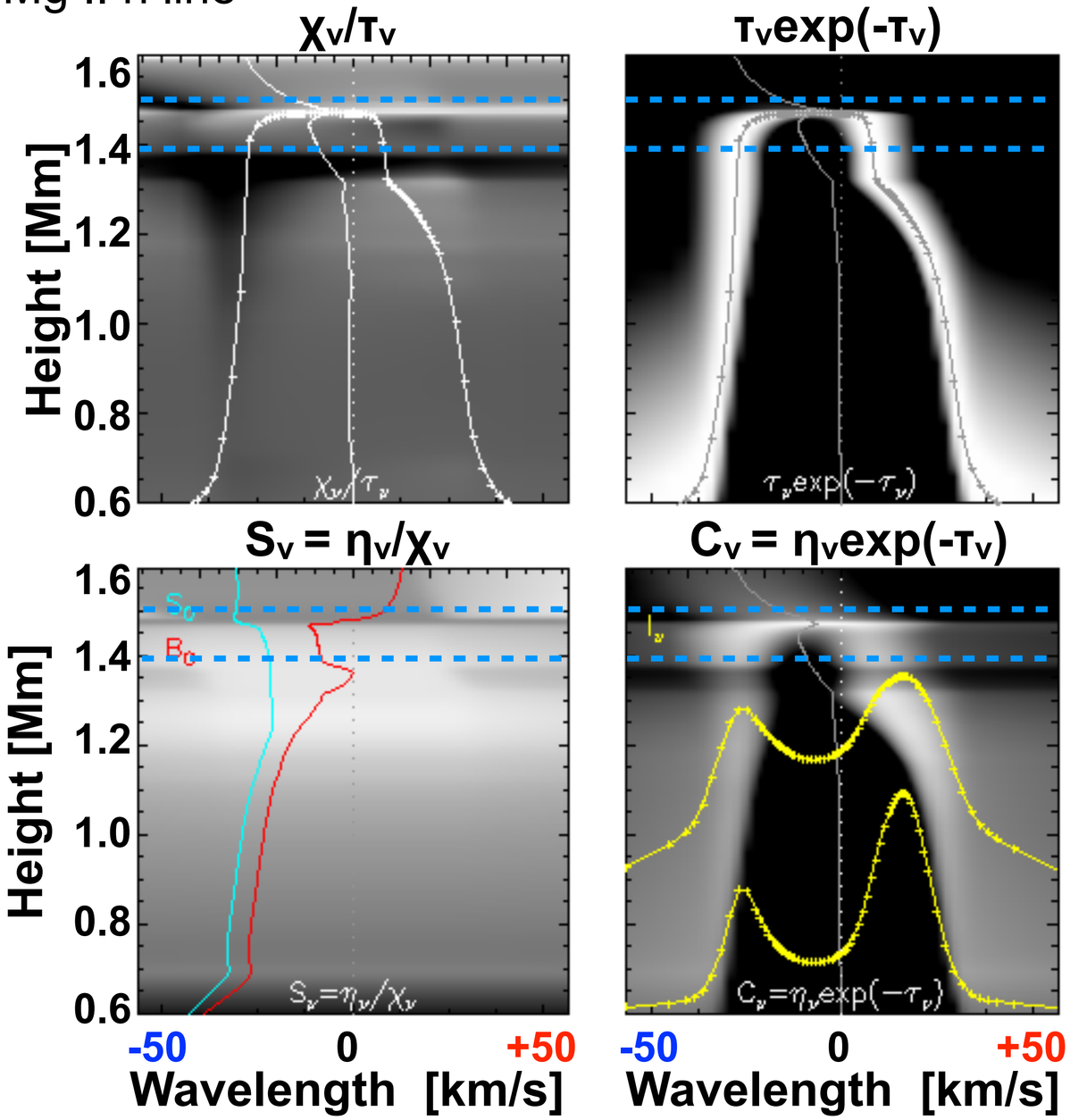
Mg II h line



$$I_\nu = \int_{z_0}^{z_1} S_\nu \, \tau_\nu \, e^{-\tau_\nu} \, \frac{\chi_\nu}{\tau_\nu} \, dz$$

Result of Modeling (*Flarix*+*MALI*)

Mg II h line



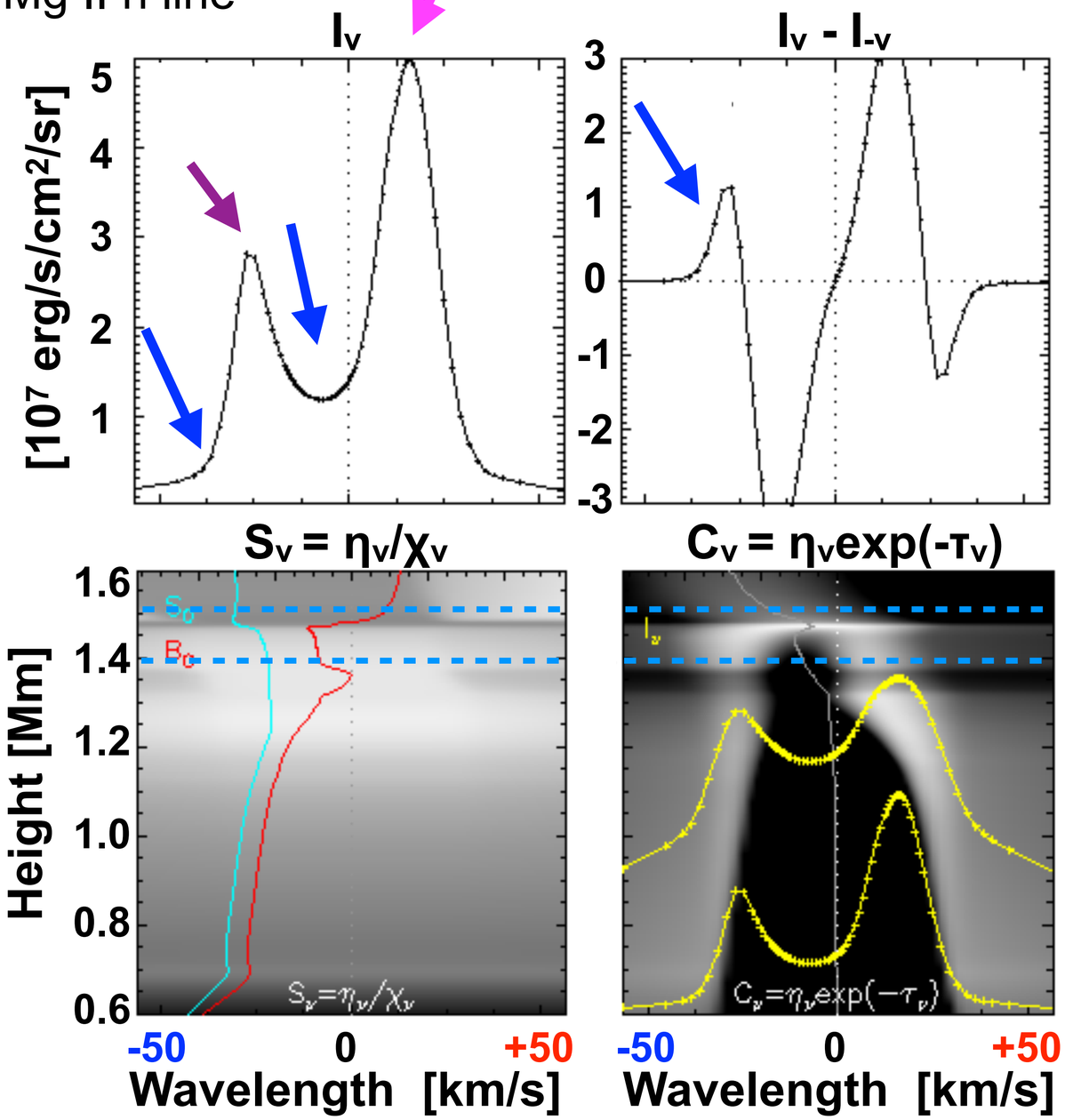
← Snapshot at Time = 18.0 sec

Cool ($\log_{10}T$ ~ 4.2 [K]), dense ($\log_{10}N$ ~ 13 [/cm^3]), and upward moving (V ~ 10 [km/s]) plasma

The surface of the cool upflow contributes to the intensity around the line center and its blue-side.

Result of Modeling (*Flarix+MALI*)

Mg II h line



← Snapshot at Time = 18.0 sec

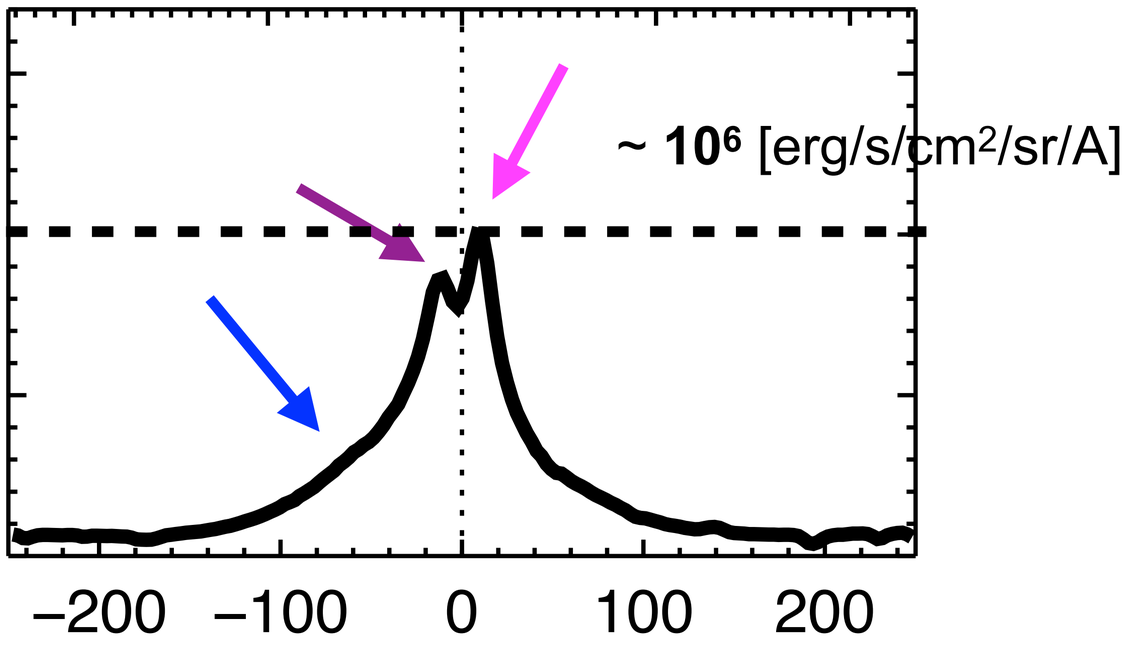
Cool ($\log_{10}T$ ~ 4.2 [K]), dense ($\log_{10}N$ ~ 13 [/cm^3]), and upward moving (V ~ 10 [km/s]) plasma

The surface of the cool upflow contributes to the intensity around the line center and its blue-side.

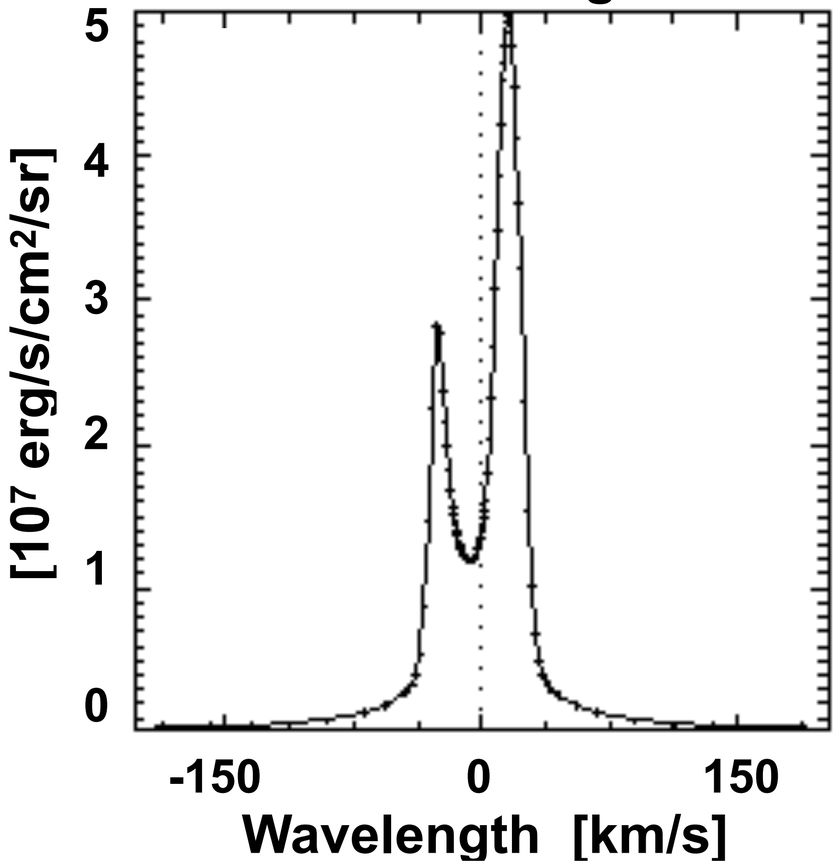
Blue wing enhancement, Blueshift of h3 dip
Blue peak < Red-peak
→ qualitatively similar to the observations

Quantitative comparison

Observation



Modeling

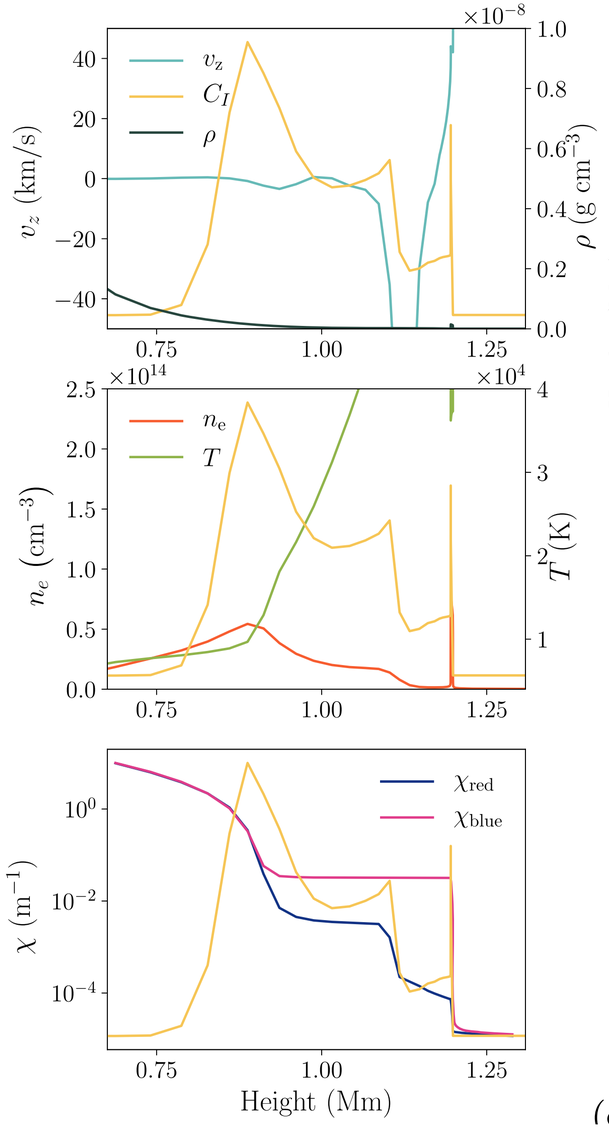


~ a few x 10^7 [erg/s/cm^2/sr/A]

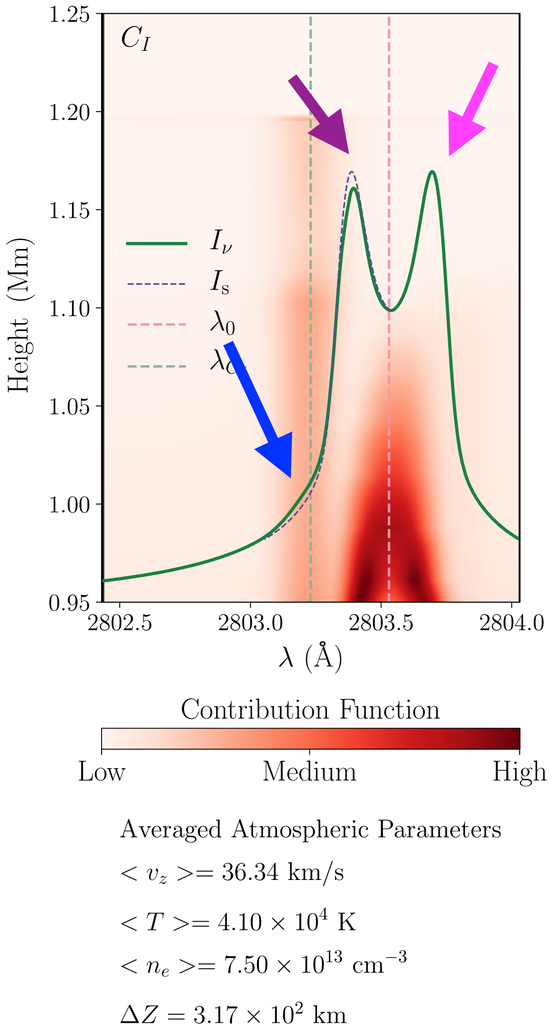
One order difference in the peak intensities.
Less enhanced wing in the modeling.

Flare Modeling by RADYN + RH

Zhu+ 19 (RADYN + RH)



RH+SB×30 model



(d)

$F_{max} = 5 \times 10^{11}$ erg/cm^2/s
(increase in 20s and decrease in 20s)

A tiny blue wing enhancement (t ~ 5.3-6.4 s)

- contributed by additional emission due to the opacity increase related to an upward propagating cool upflow (~ 4×10^4 K) with a speed of ~ 36 km/s.
- Wing is less extended unless assuming large broadening.

also see Huang+ 19

Summary & Prospectives

- **Blue asymmetry in the Mg II lines was observed at the foot points of a flare.**
  - **Cool dense upflow scenario?**

- **Modeling of the flare atmosphere and the Mg II h line (Flarix + MALI)**
  - **→ The scenario is qualitatively ok!**

- <u>What are needed to do:</u>
  - Investigate **more flare observations** in the Mg II lines.
  - Get more **quantitative** agreement.
  - Synthesize the **other lines.**

Tei+ 18; Tei+ in preparation