

# **Radiative Hydrodynamic Modeling of the Lyman-alpha Line in Solar Flares**

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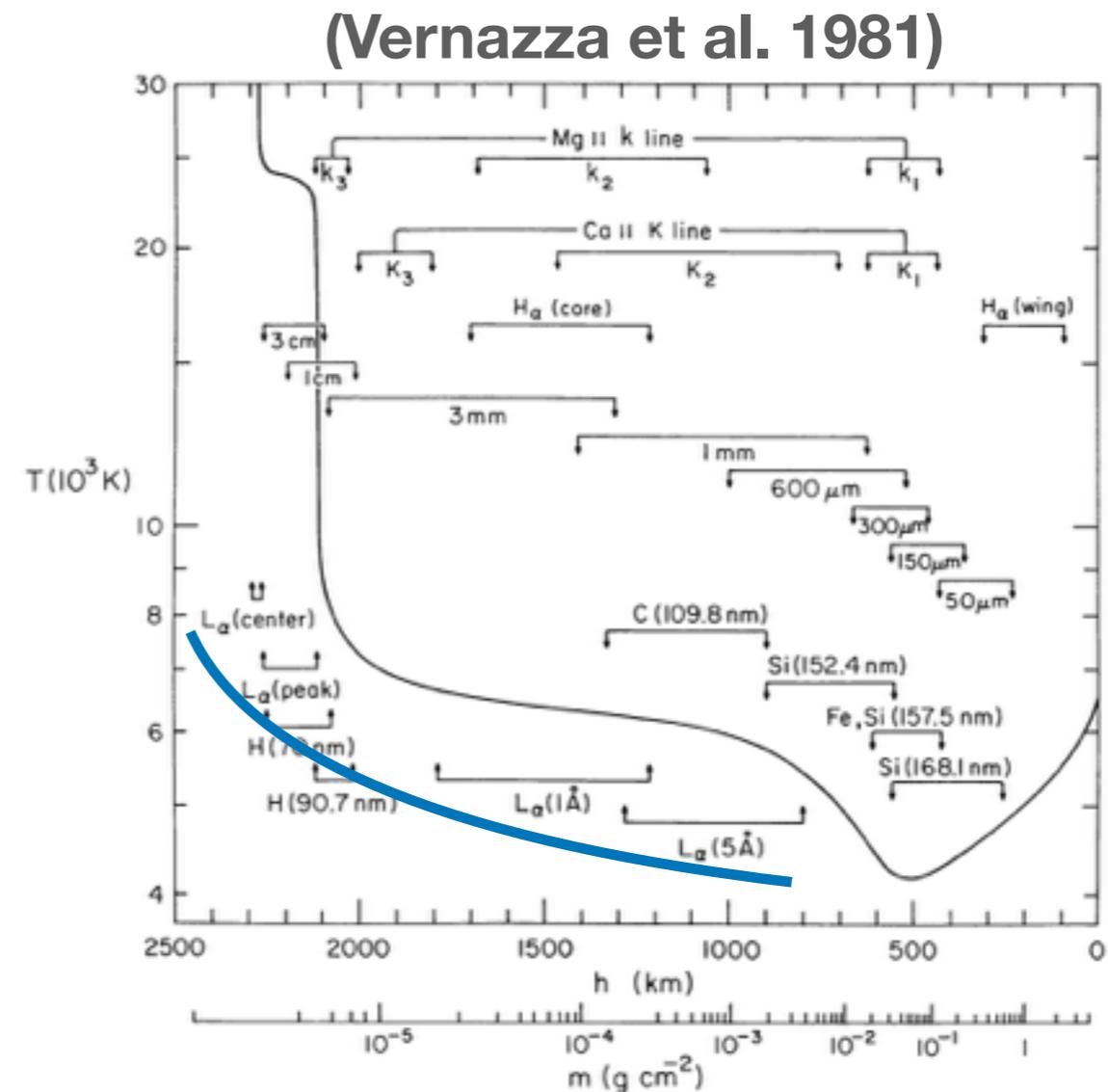
**2019.1.18**

# OUTLINE

- **Introduction**
- **Modeling**
- **Results**
- **Summary**

# Introduction

The Lyman-alpha ( $\text{Ly}\alpha$ ) line at 121.6 nm is formed in the Sun's chromosphere and transition region in quite-Sun region.



## \*flare\* observations in Ly $\alpha$

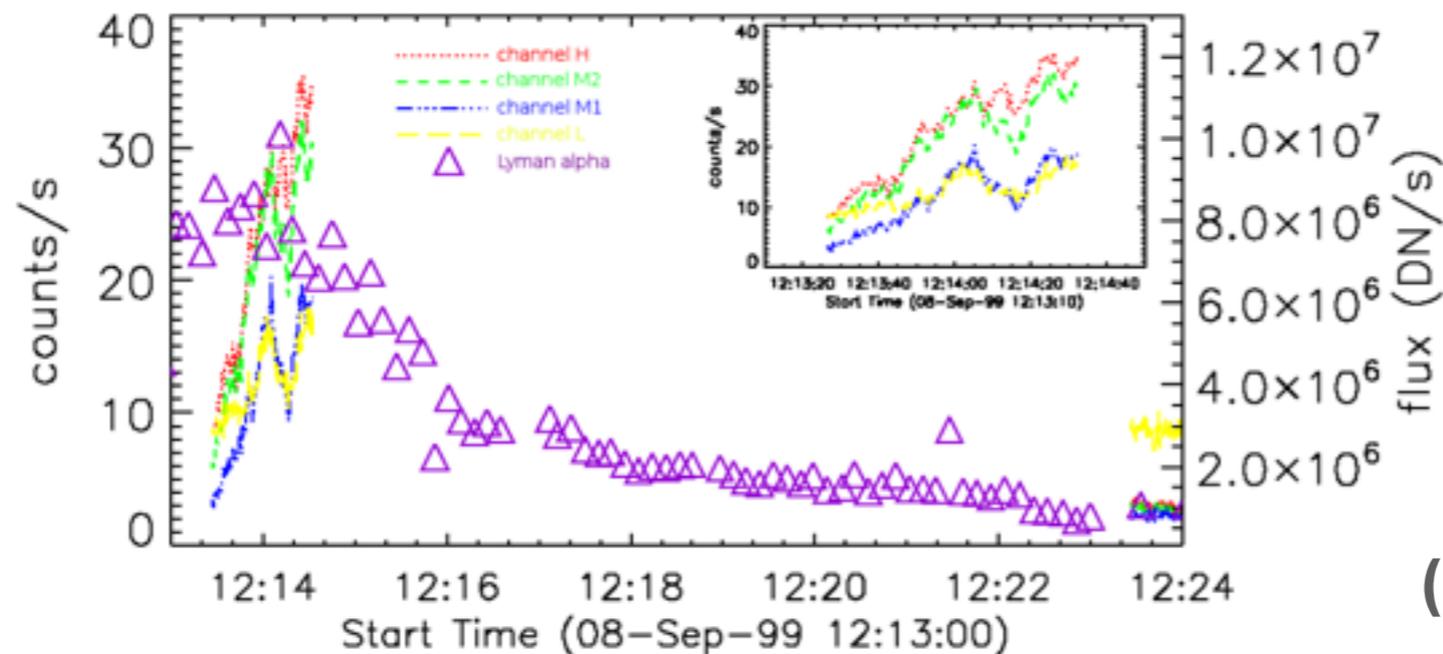
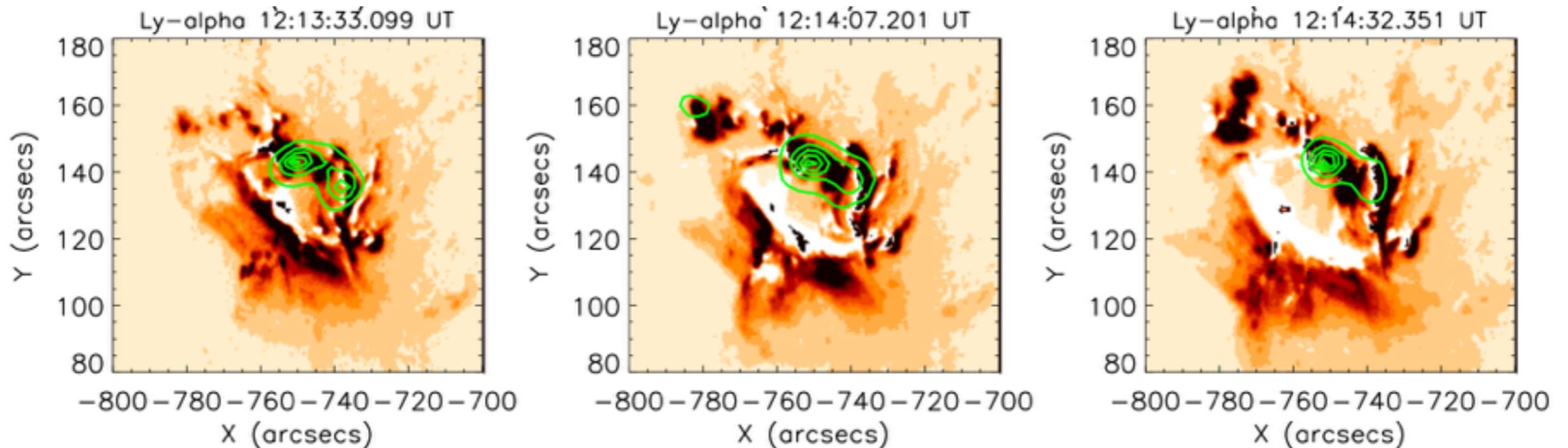
- imaging: TRACE, VAULT, ...
- spectral: SDO/EVE, SORCE/SOLSTICE, OSO/LPSP, ...
- irradiance: GOES/EUVS, PROBA2/LYRA, ...

relatively rare!!

# Introduction

## TRACE observations: images & light curves

The majority of the  $\text{Ly}\alpha$  emission originates from the flare footpoints, which are co-spatial with the HXR sources in general.

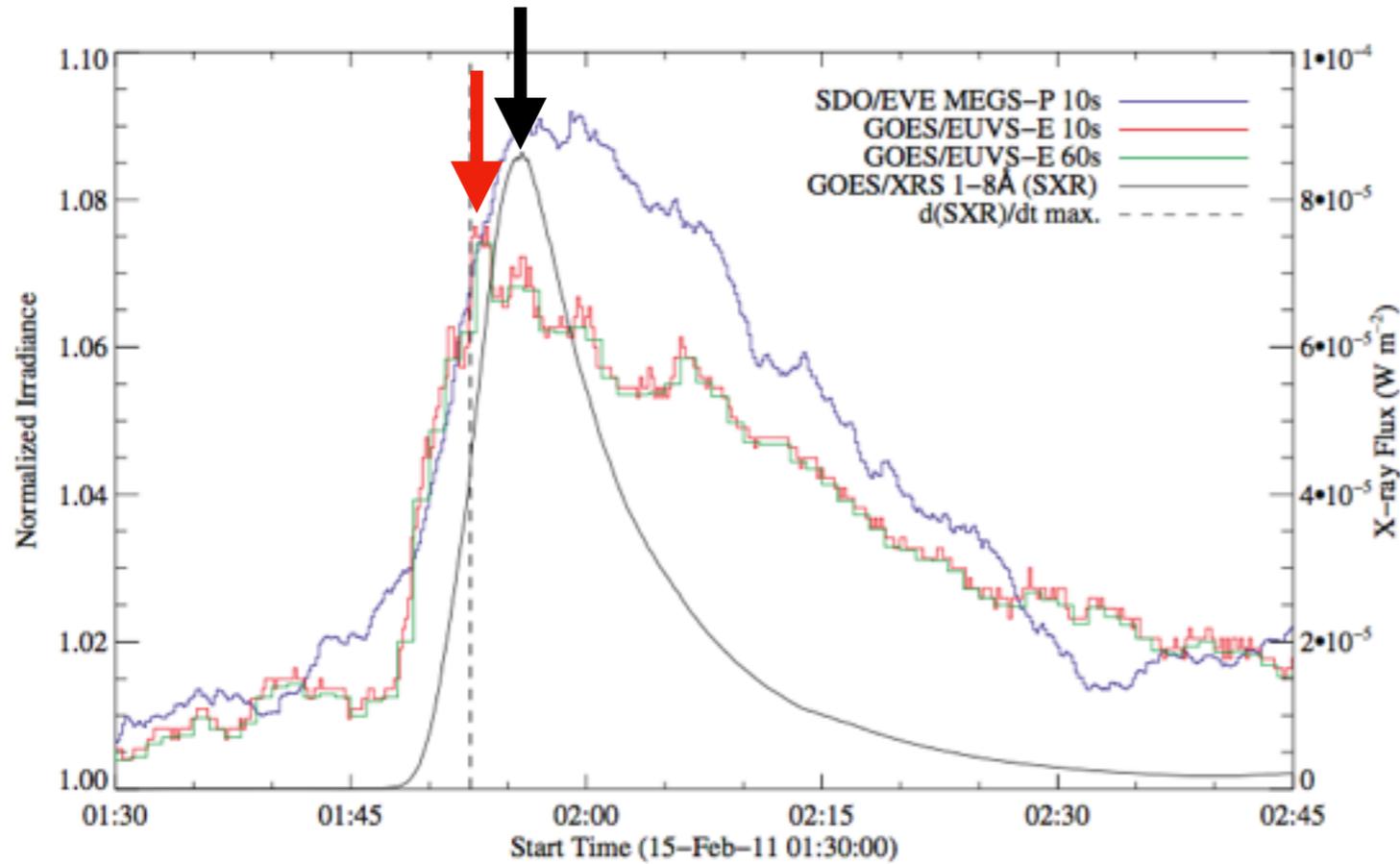


The  $\text{Ly}\alpha$  peak is at approximately the same time as the HXR peak.

(Rubio da Costa et al. 2009,2010)

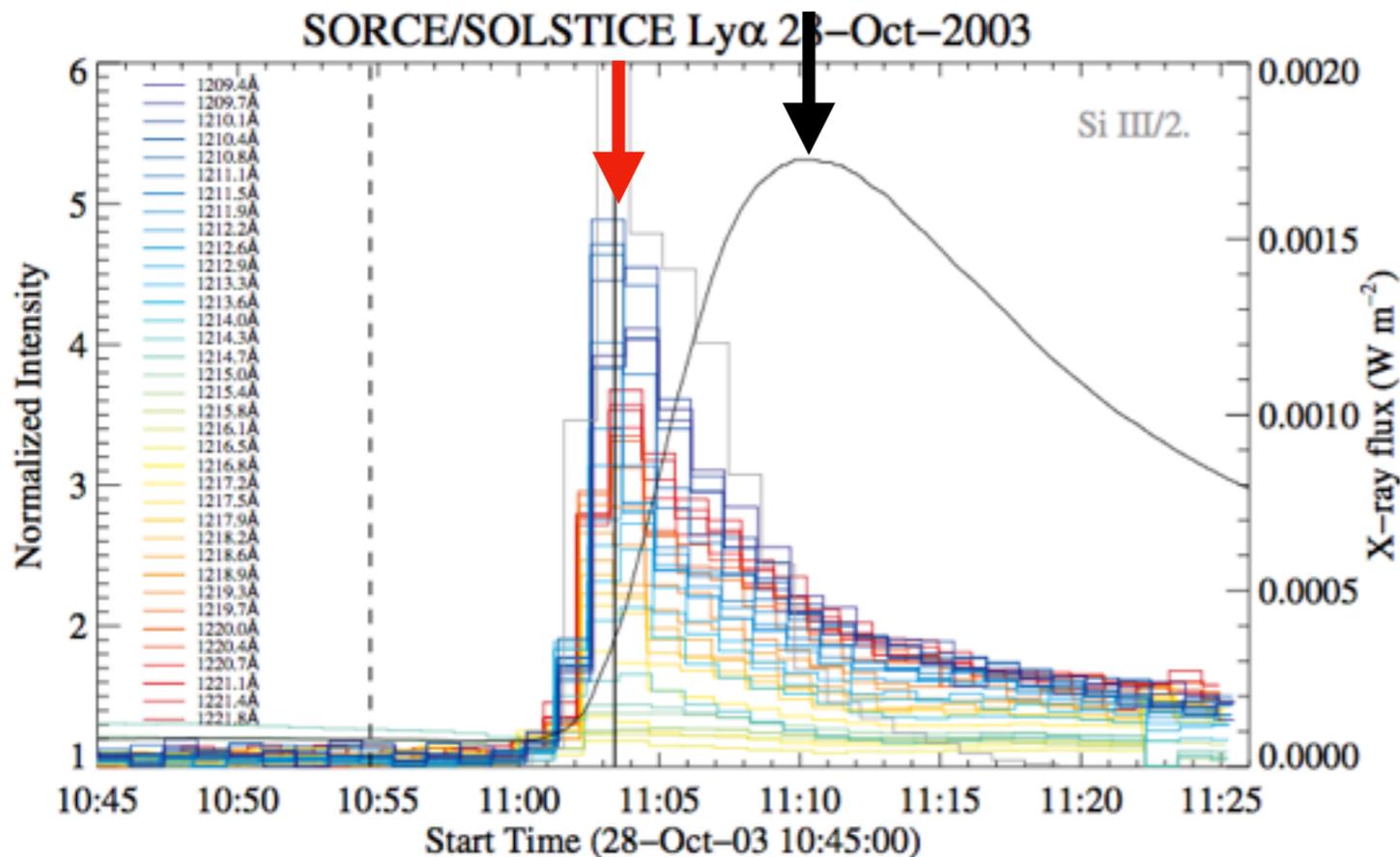
# Introduction

(Milligan et al. 2016)

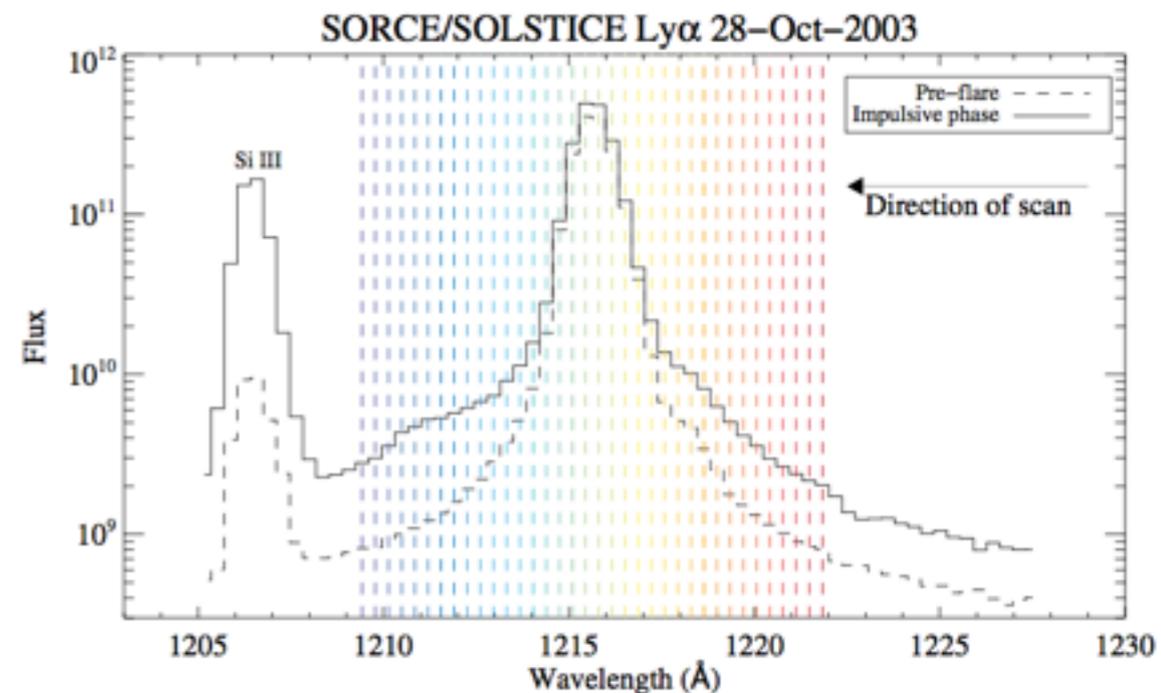


**SDO/EVE & GOES/EUVS:**  
 light curves (full-disk)

The Ly $\alpha$  emission peaks earlier than the GOES soft X-ray flux.  
 ("Neupert" effect)



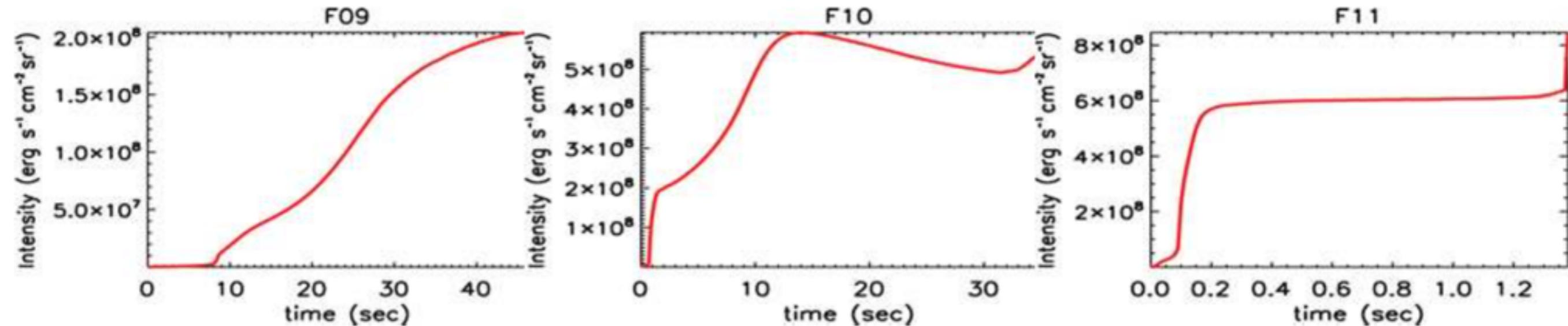
**SORCE/SOLSTICE:**  
 spectral observation



# Introduction

(Rubio da Costa et al. 2010, 2012)

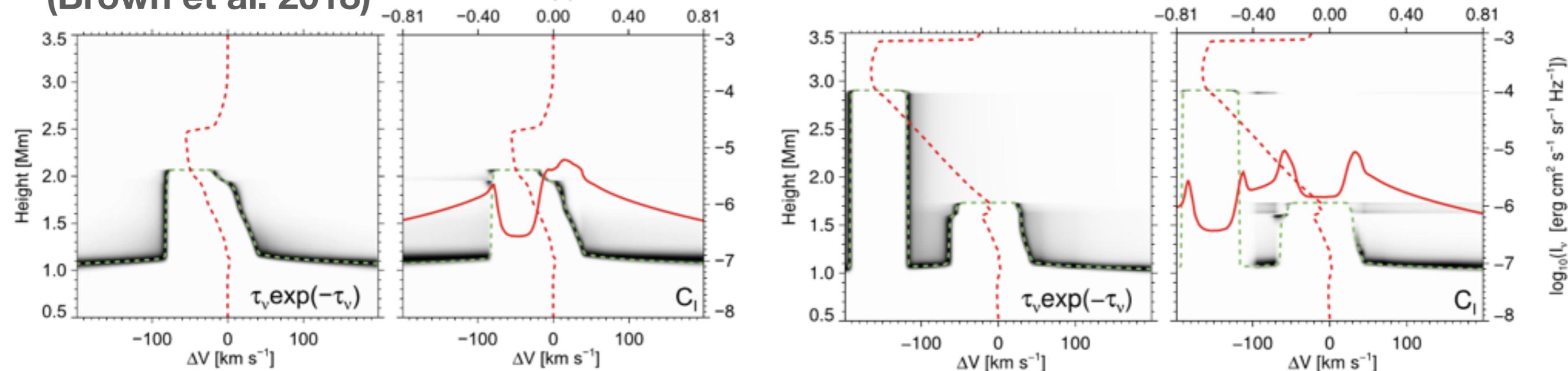
**RADYN simulation:  
integrated Ly $\alpha$  intensity**



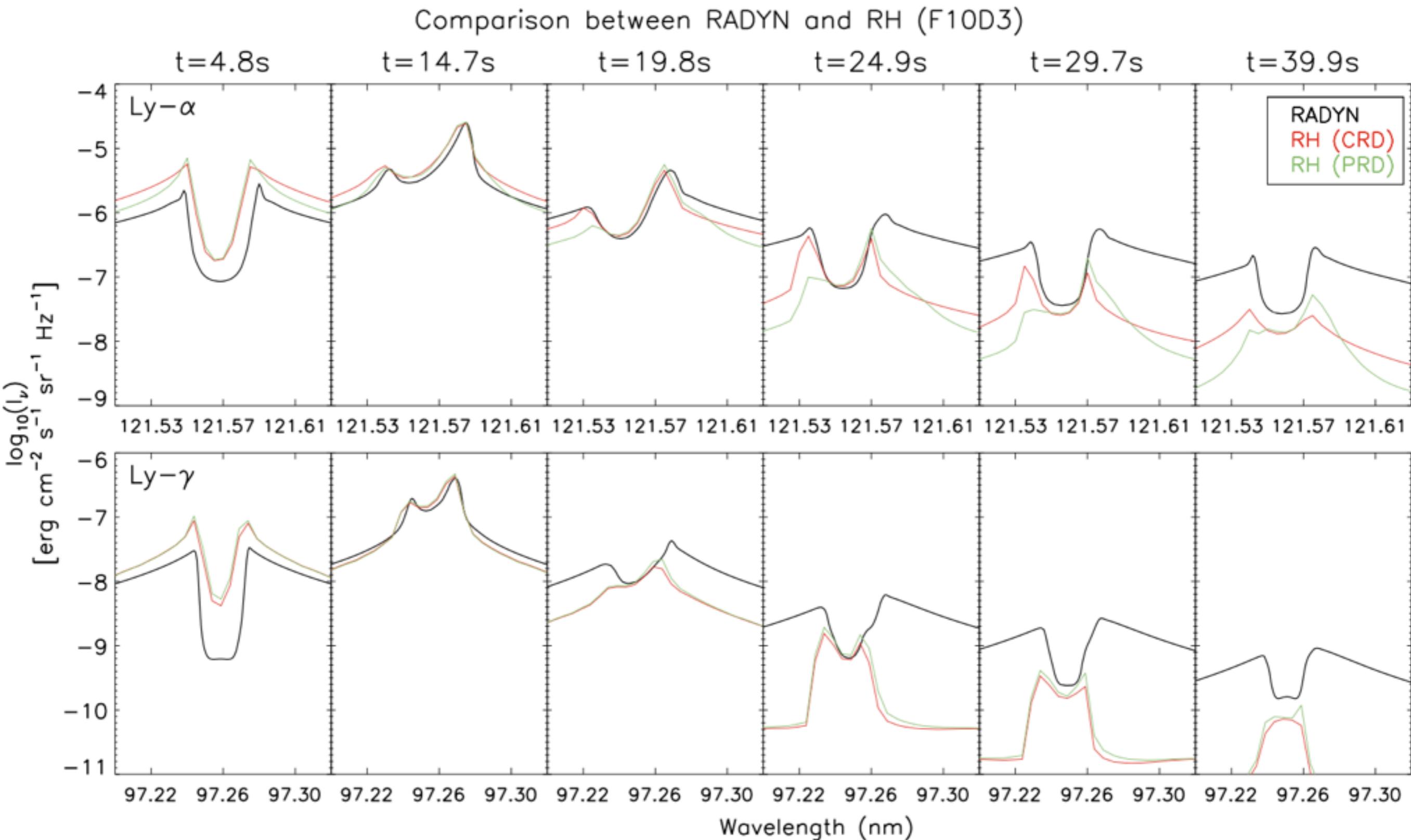
These might be used to compare with the future high-resolution observations.

**RADYN simulation:  
Ly $\alpha$  profiles**

(Brown et al. 2018)



# Non-equilibrium effects and PRD effects are important, especially the former.



(Brown et al. 2018)

**Our radiative hydrodynamical modeling from RADYN:  
non-equilibrium + PRD effects**

**try to understand Ly $\alpha$  characteristics in flaring conditions,  
such as formation height, line profile evolution, etc.**

***help interpret the future observations of ASO-S/LST/SDI***

# RADYN

- non-LTE radiative hydrodynamics code
- 1D plane-parallel atmosphere
- with an adaptive grid

## code papers:

Carlsson, M., & Stein, R. F. 1992, *ApJL*, 397, L59

Carlsson, M., & Stein, R. F. 1995, *ApJL*, 440, L29

Carlsson, M., & Stein, R. F. 1997, *ApJ*, 481, 500

Carlsson, M., & Stein, R. F. 2002, *ApJ*, 572, 626

Abbett, W. P., & Hawley, S. L. 1999, *ApJ*, 521, 906

Allred, J. C., Hawley, S. L., Abbett, W. P., & Carlsson, M. 2005, *ApJ*, 630, 573

Allred, J. C., Hawley, S. L., Abbett, W. P., & Carlsson, M. 2006, *ApJ*, 644, 484

Allred, J. C., Kowalski, A. F., & Carlsson, M. 2015, *ApJ*, 809, 104

.....

# RADYN simulations

Flares	$F_{\text{peak}}$ (erg cm <sup>-2</sup> s <sup>-1</sup> )	$E_c$ (keV)	$\delta$	Label
weak	$10^{10}$	25	3	F10_25_3
moderate	$10^{11}$	25	3	F11_25_3
strong	$3 \times 10^{11}$	25	3	3F11_25_3
thermal (weak)	$10^{10}$	-	-	F10_thermal

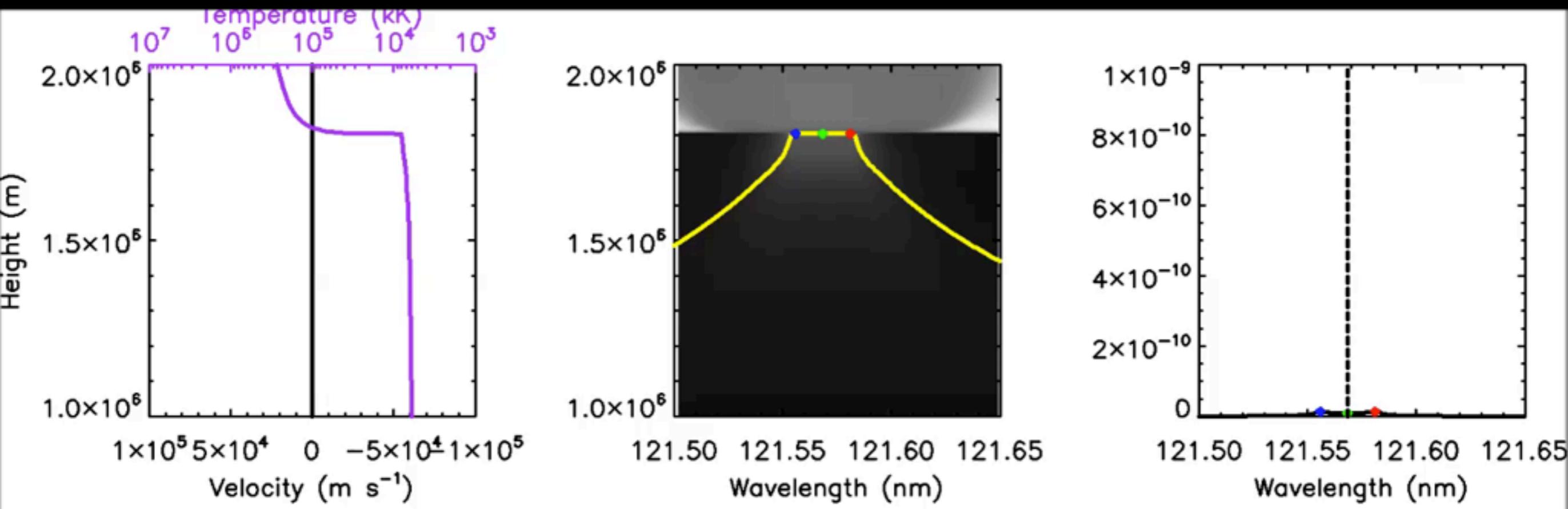
- Quiet-Sun atmosphere (VAL3C), 10 Mm loop
- 20 s heating, triangular shape

- Beam heating: injected at the loop top, F-P treatment

- Thermal heating: uniformly distributed over the uppermost 8 Mm of the loop

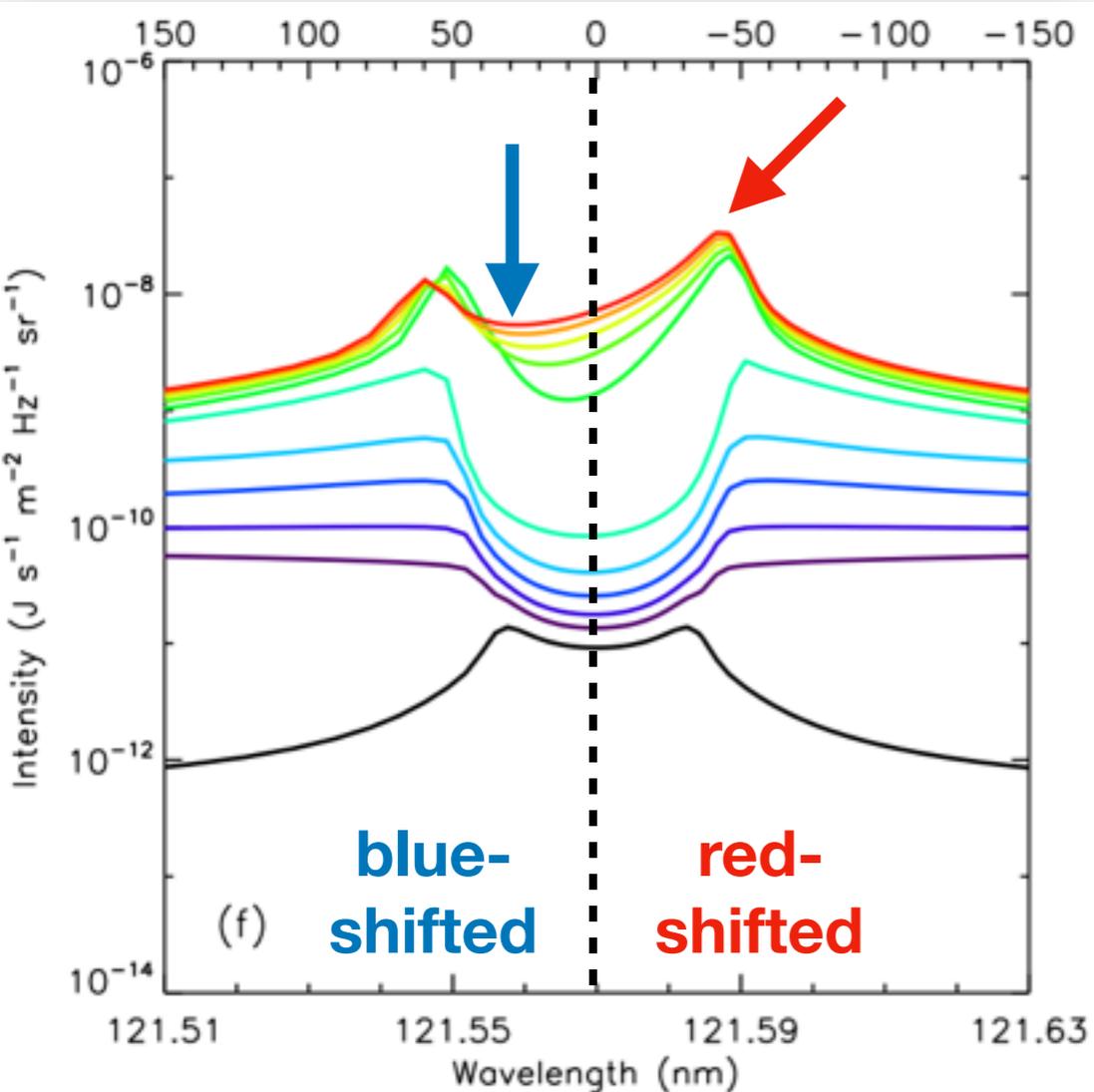
# F10\_25\_3

(non-thermal, weak flare)



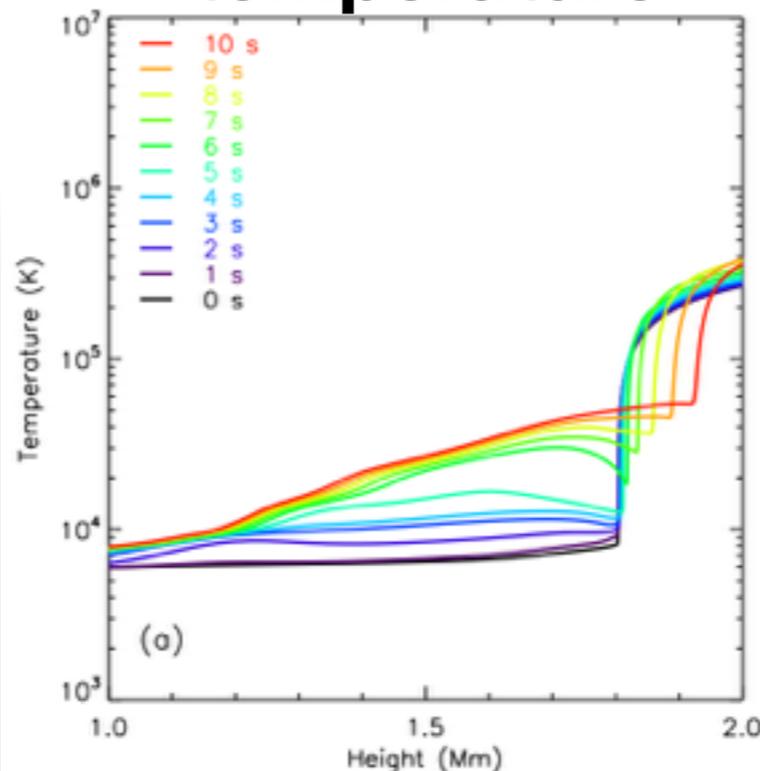
**F10\_25\_3: time evolution**  
(from black to red)

**Ly $\alpha$  line profiles**

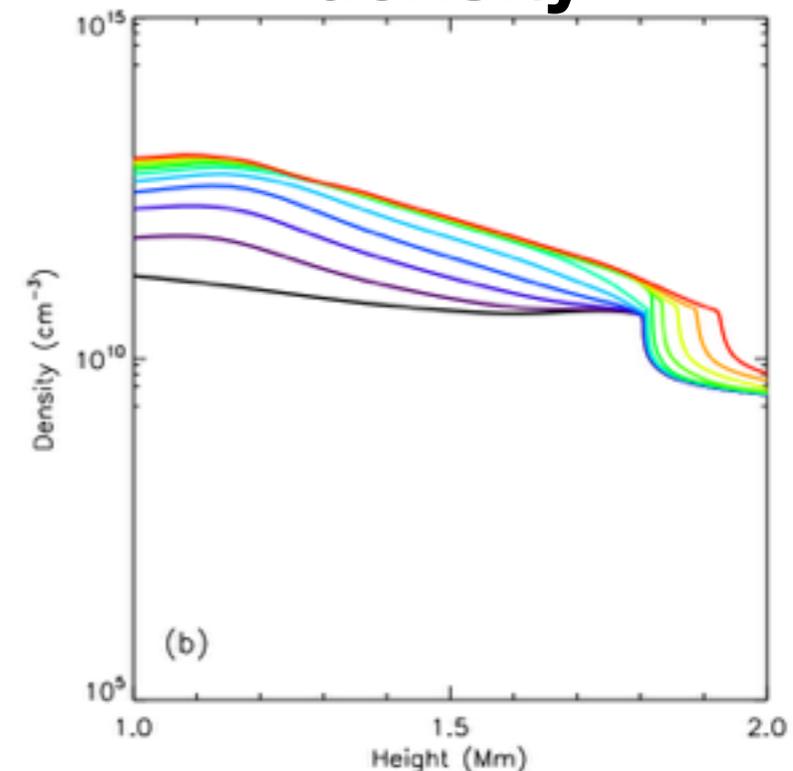


**red asymmetry**  
**blueshifted line center**  
(gentle evaporation)

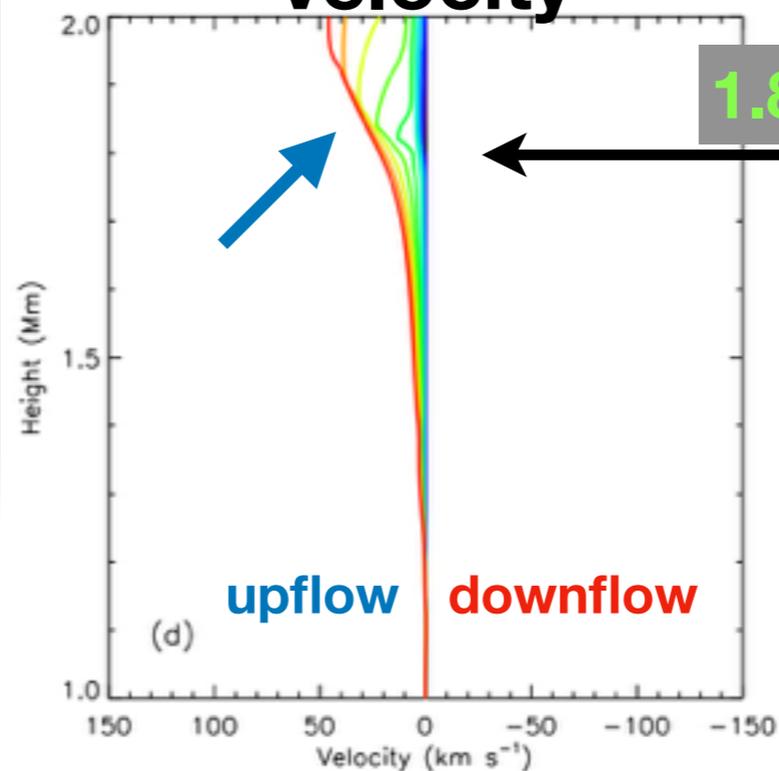
**temperature**



**density**

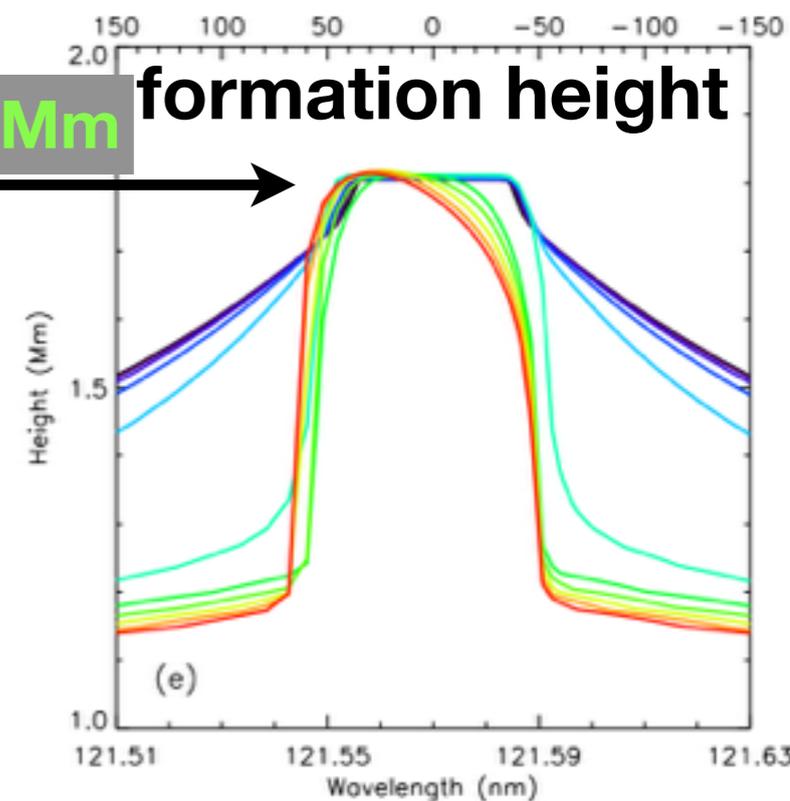


**velocity**



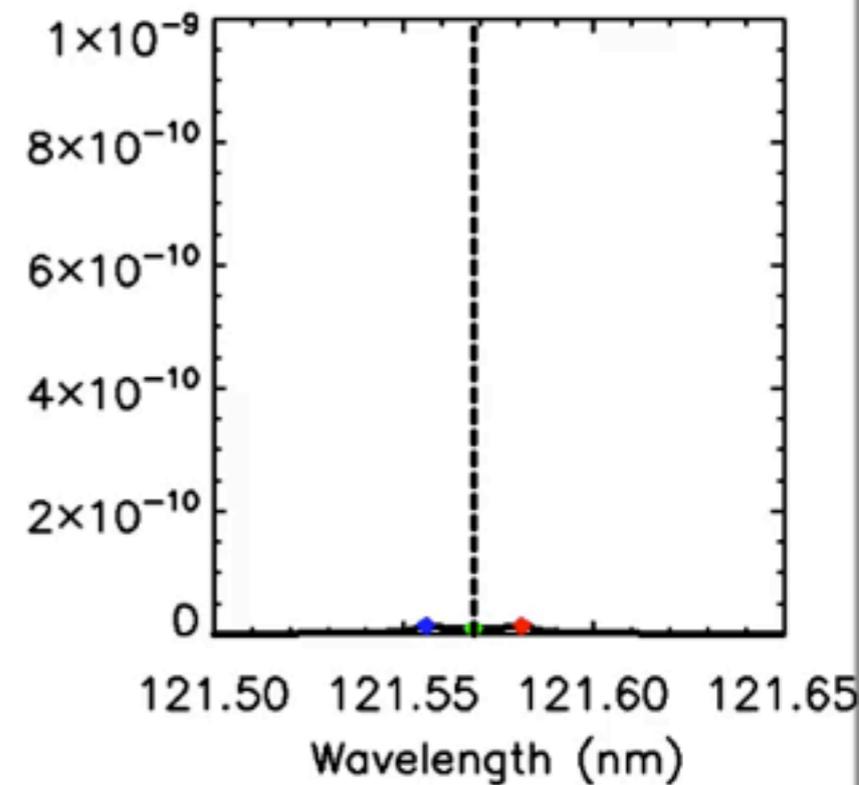
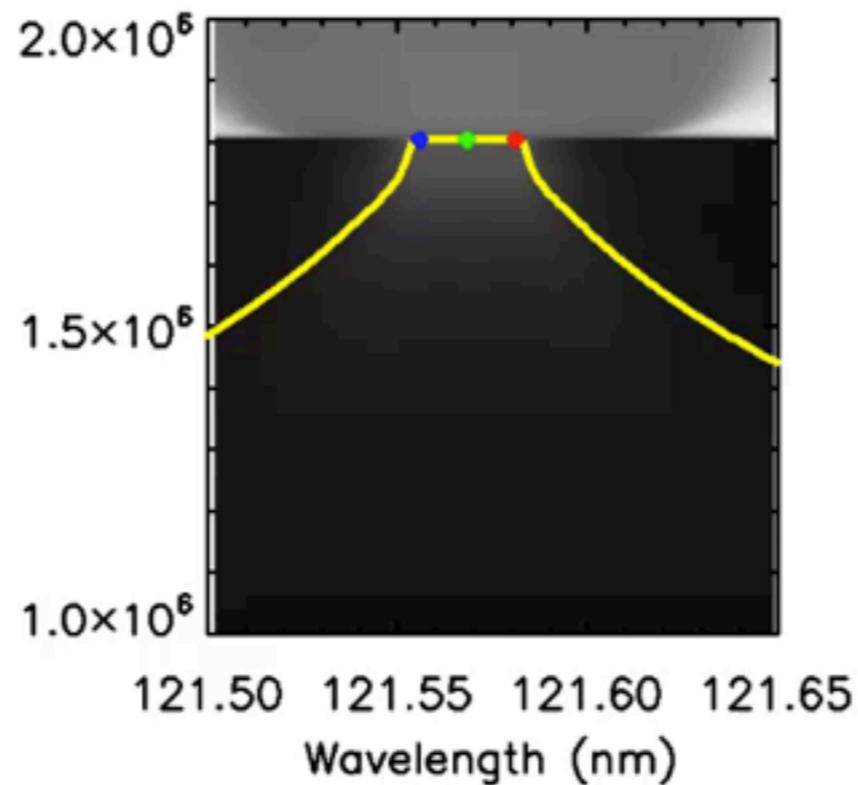
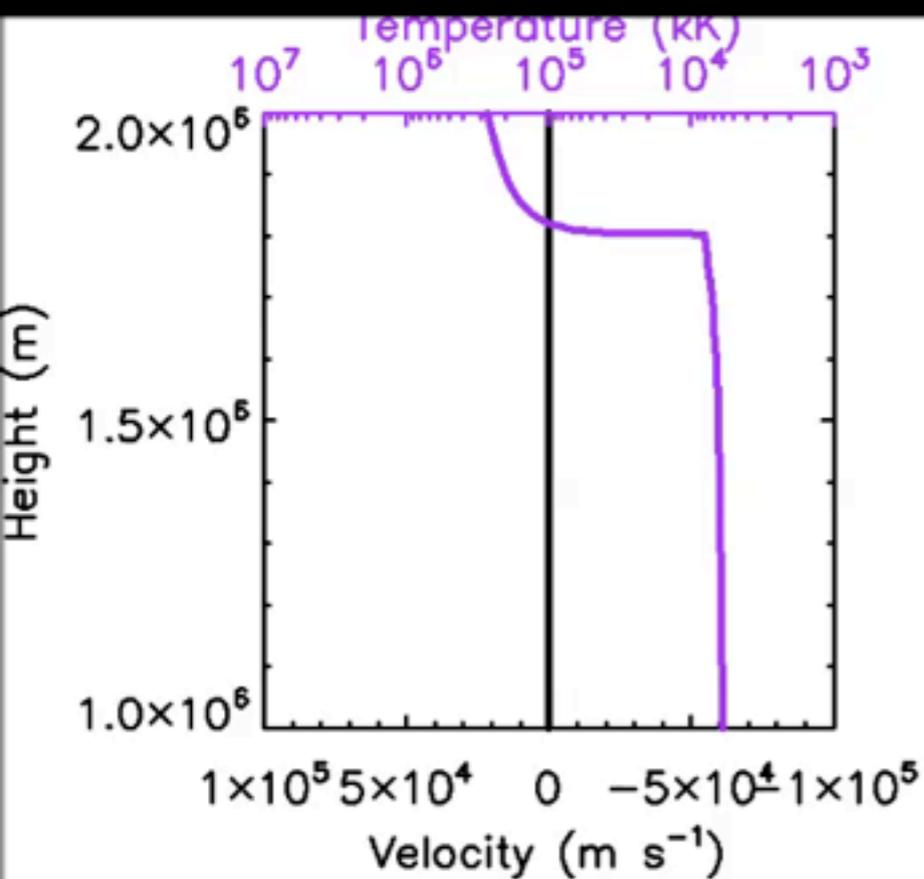
**formation height**

1.8 Mm



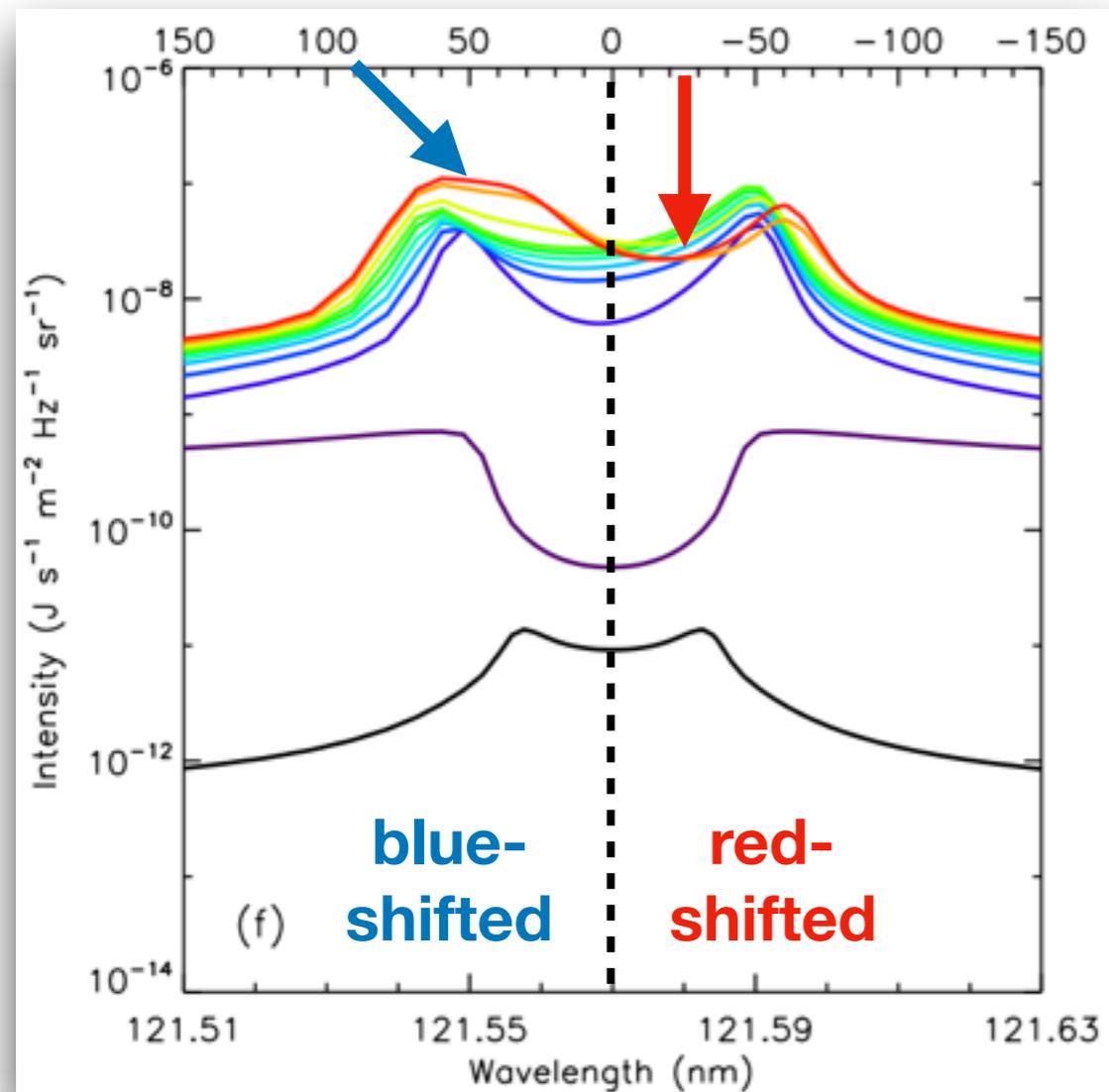
# F11\_25\_3

(non-thermal, moderate flare)



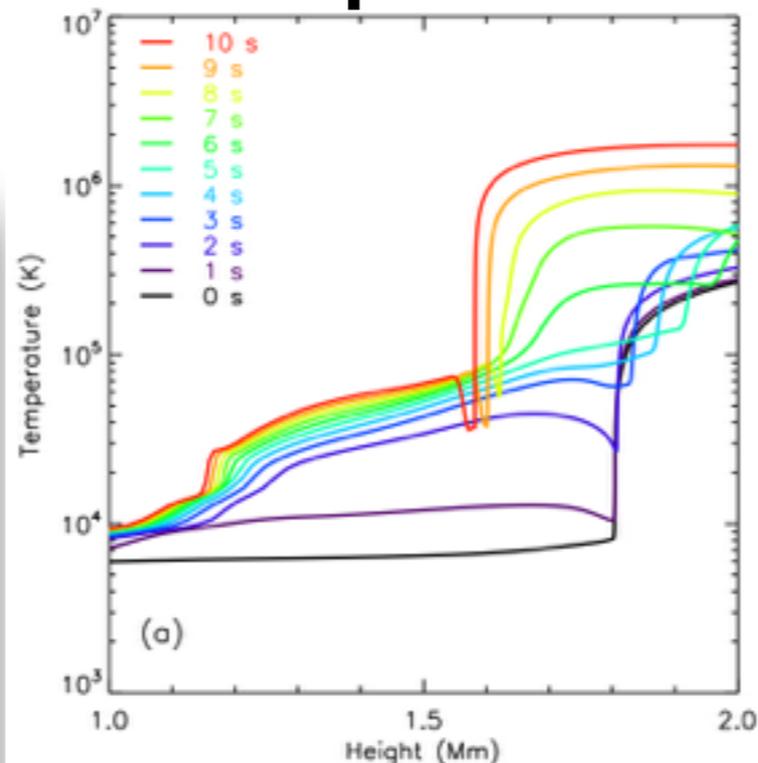
# F11\_25\_3: time evolution (from black to red)

## Ly $\alpha$ line profiles

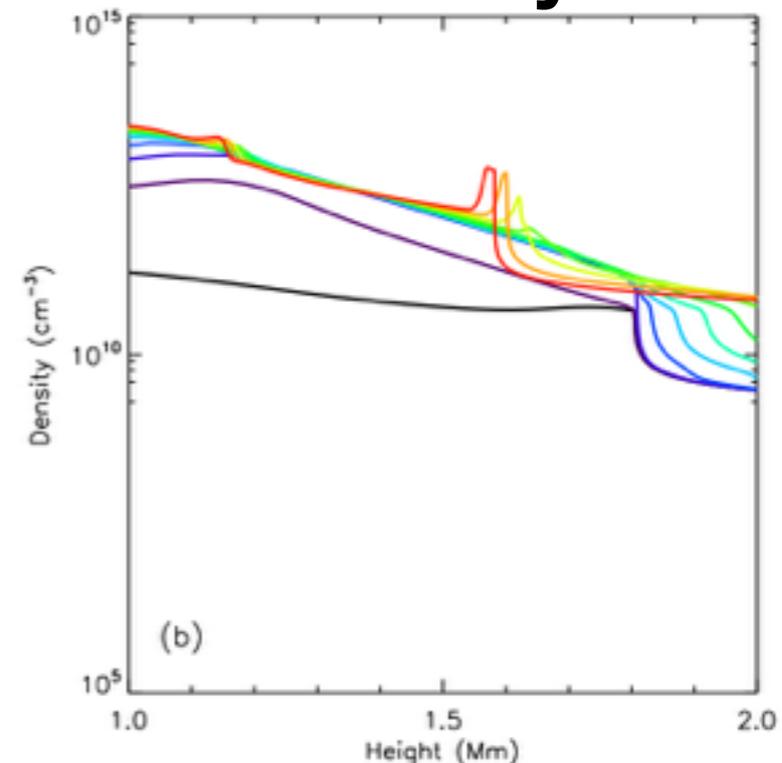


—> blue asymmetry  
 —> redshifted line center  
 (explosive evaporation)

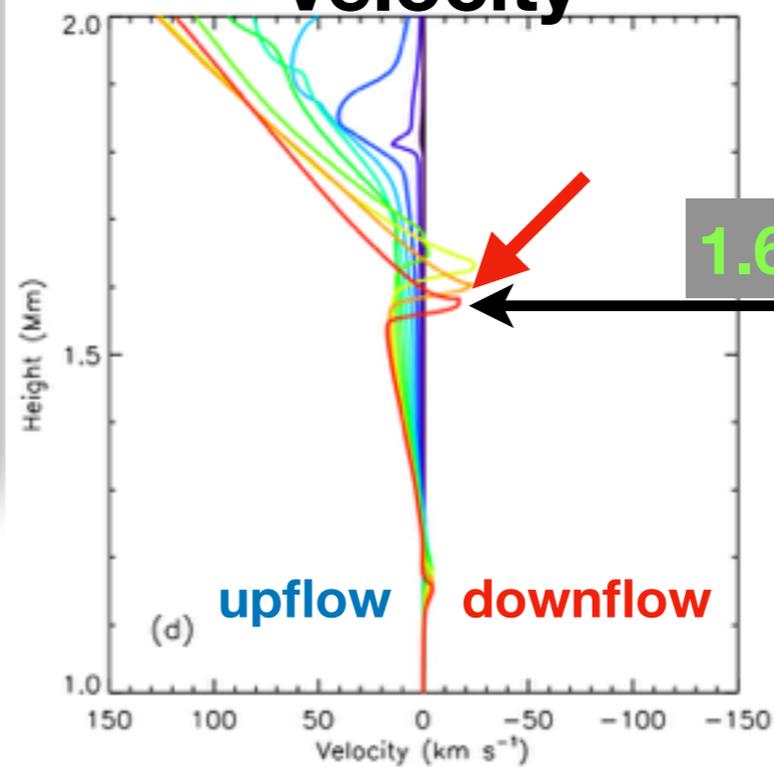
## temperature



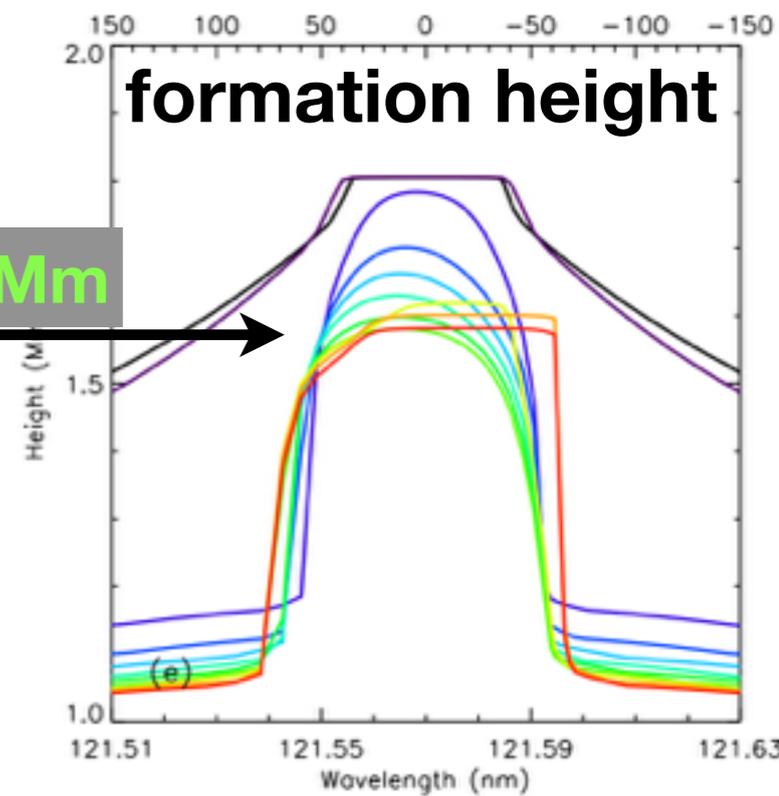
## density



## velocity

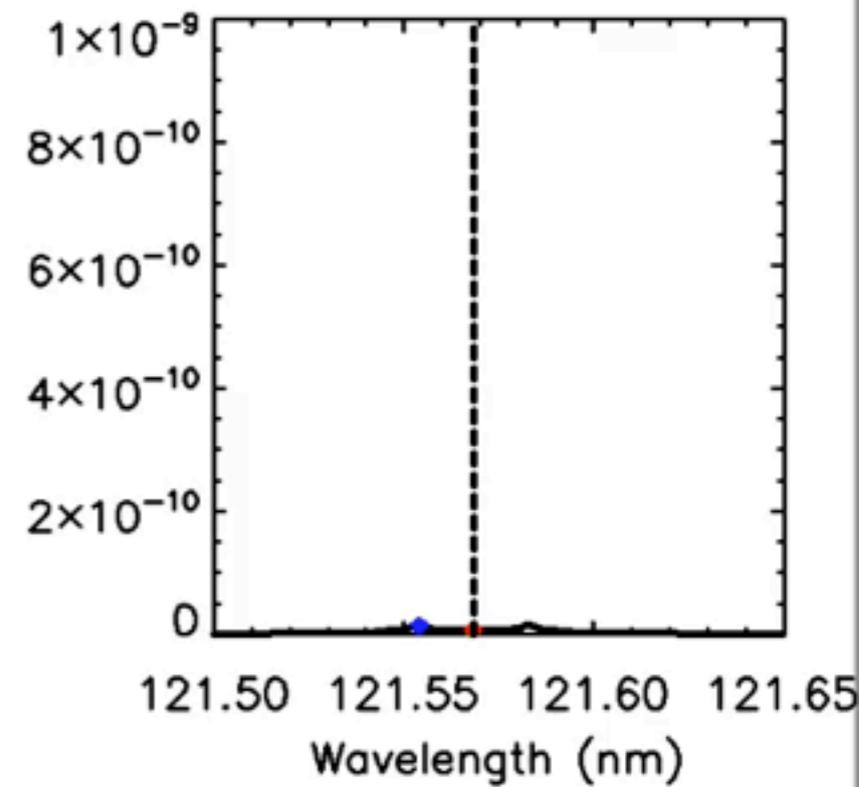
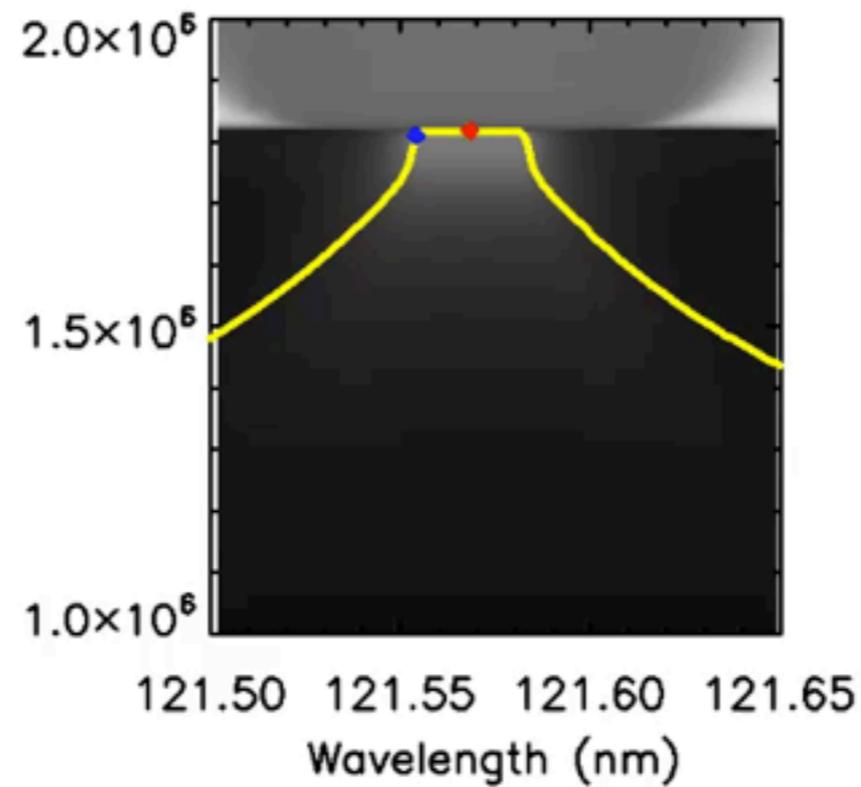
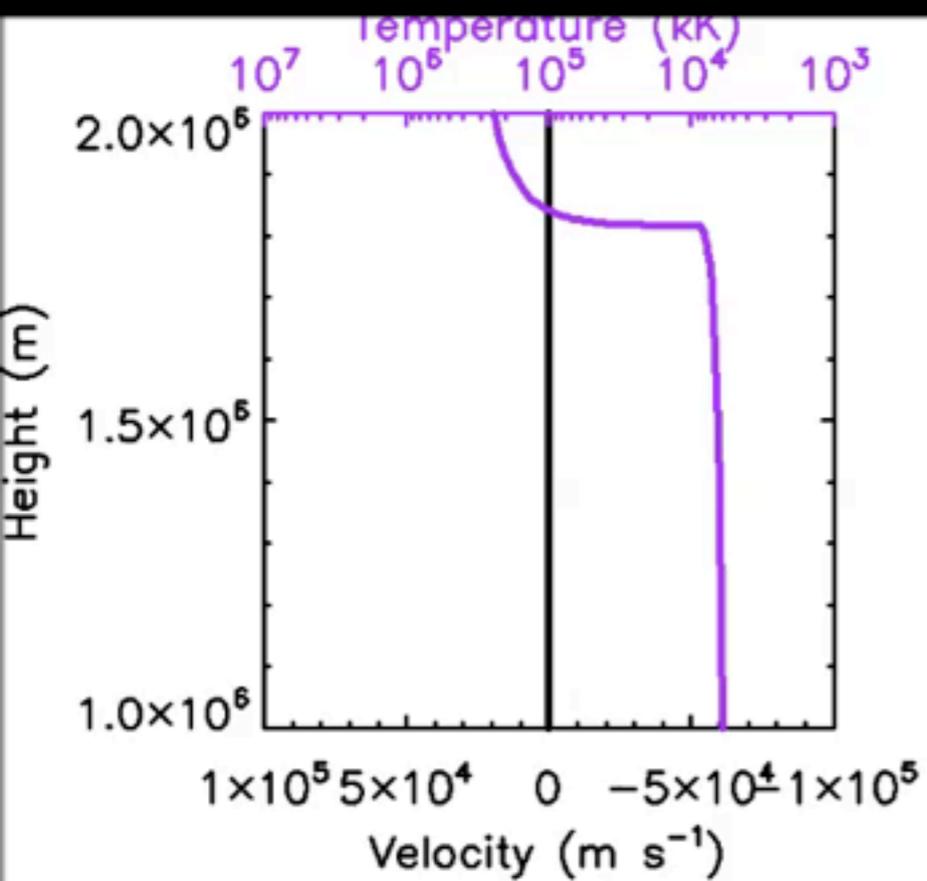


## formation height



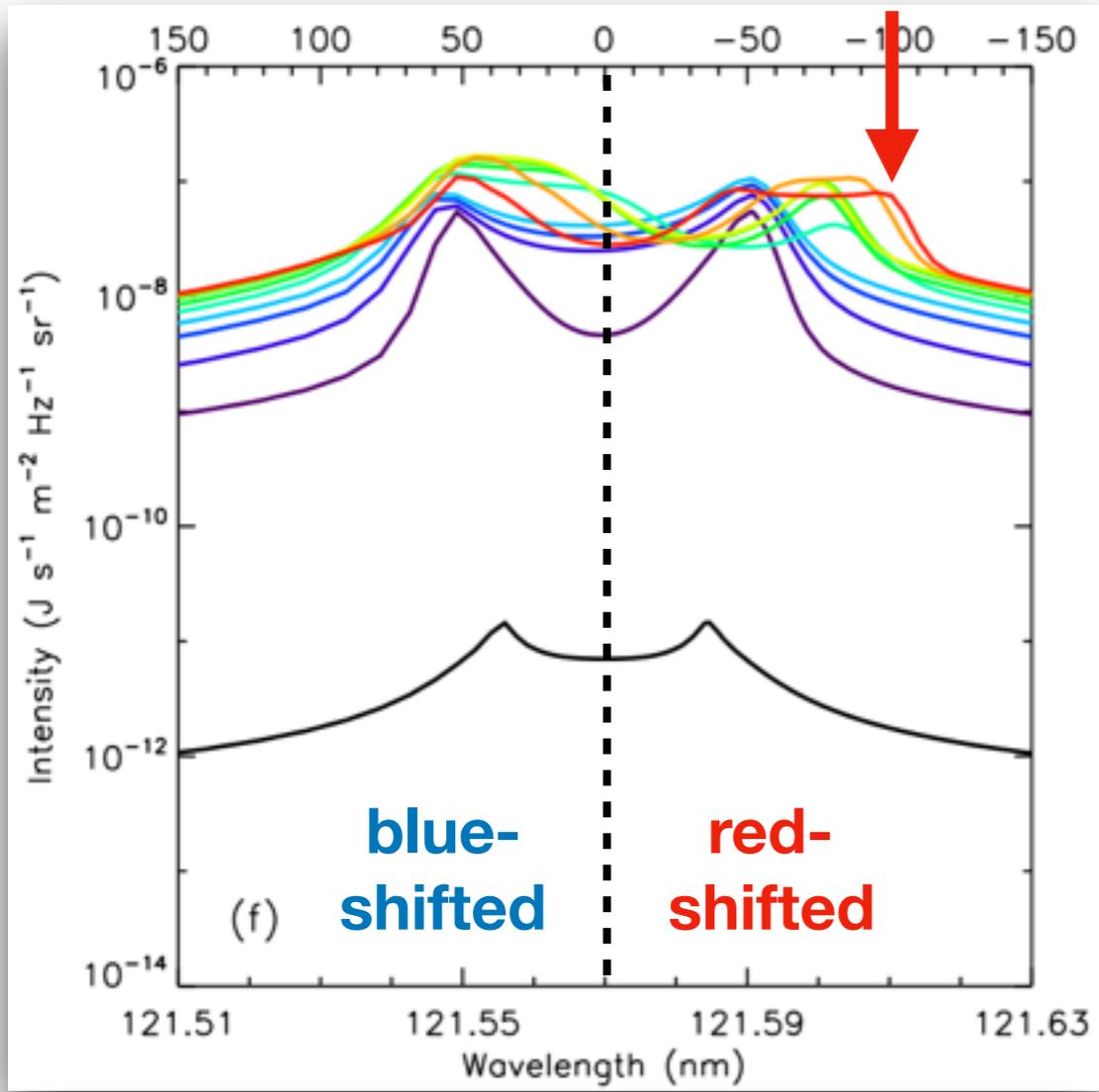
# 3F11\_25\_3

(non-thermal, strong flare)



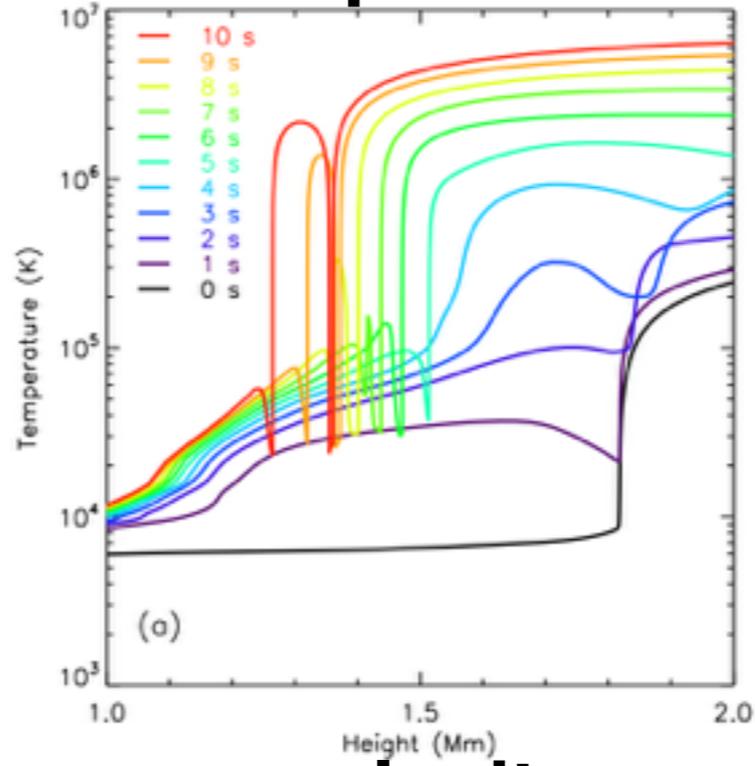
**3F11\_25\_3: time evolution**  
(from black to red)

**Ly $\alpha$  line profiles**

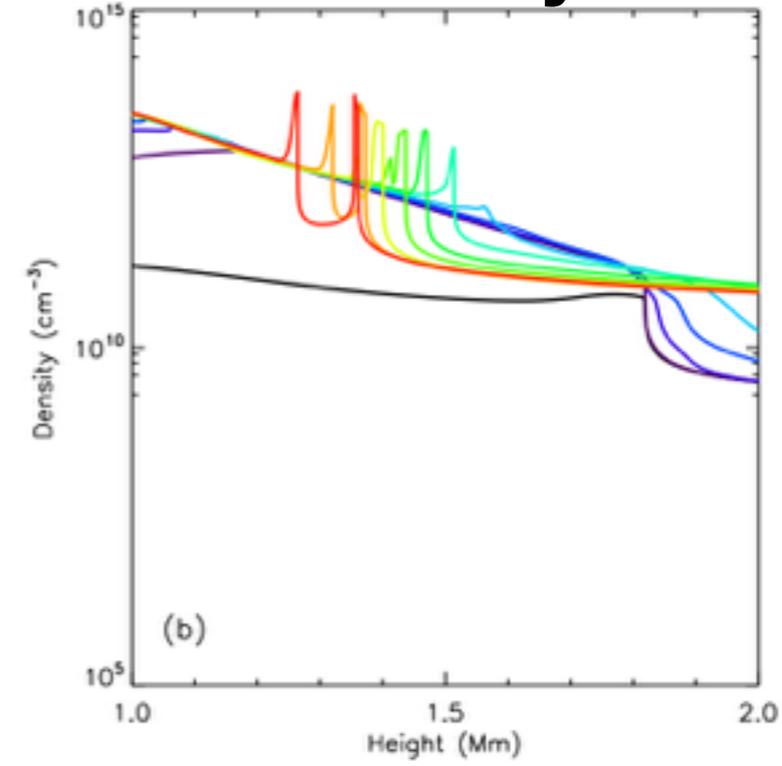


→ additional red component at a later time

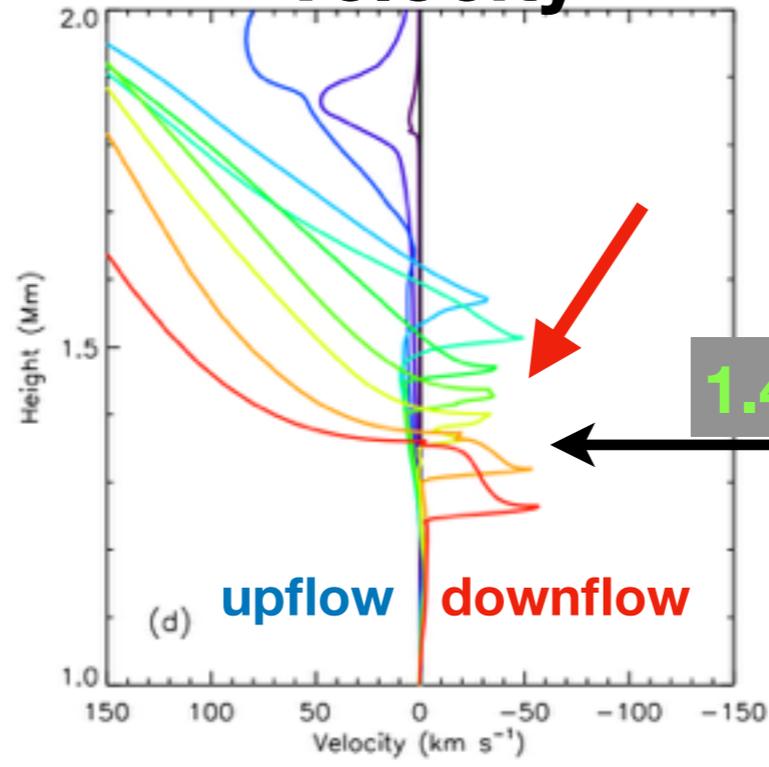
**temperature**



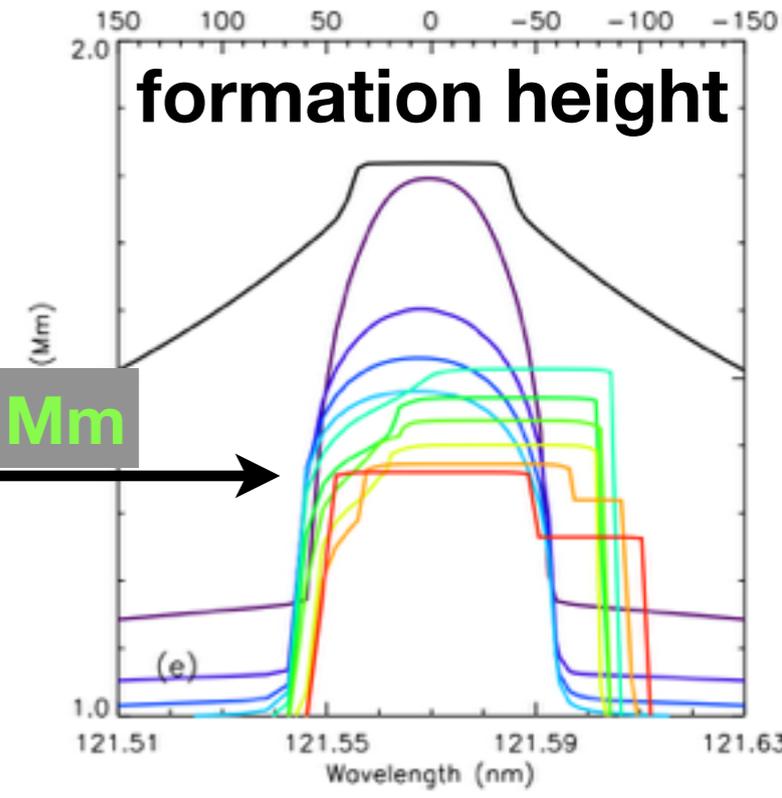
**density**



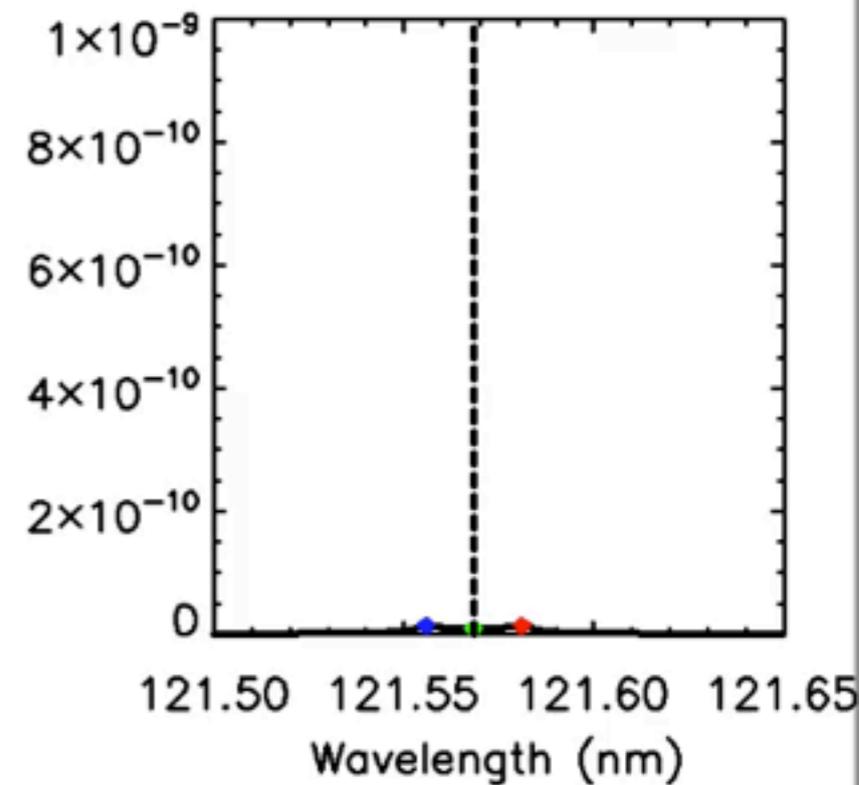
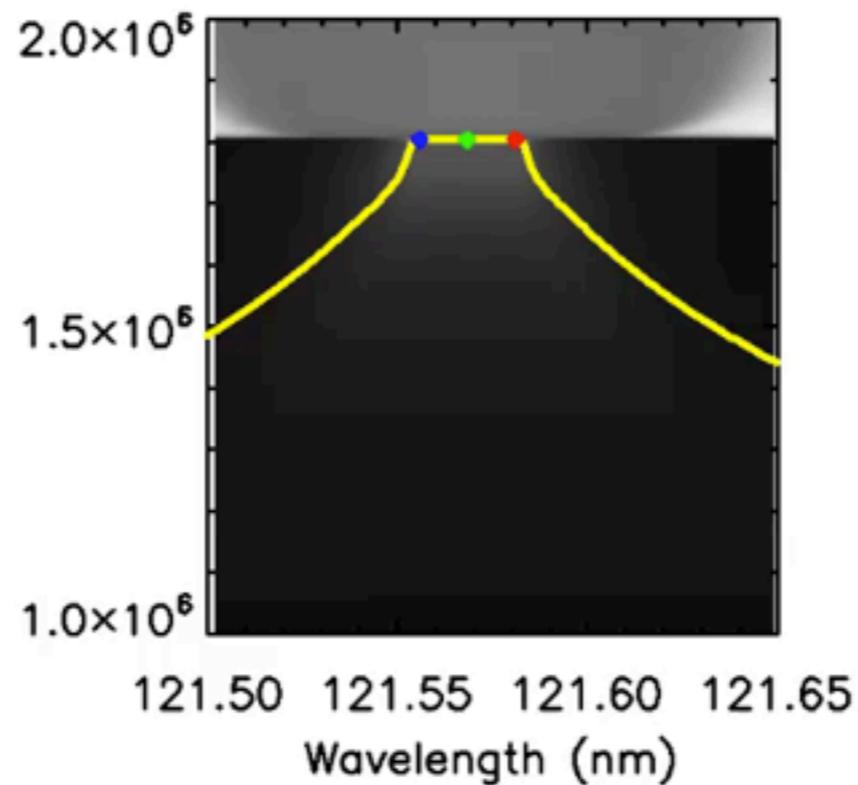
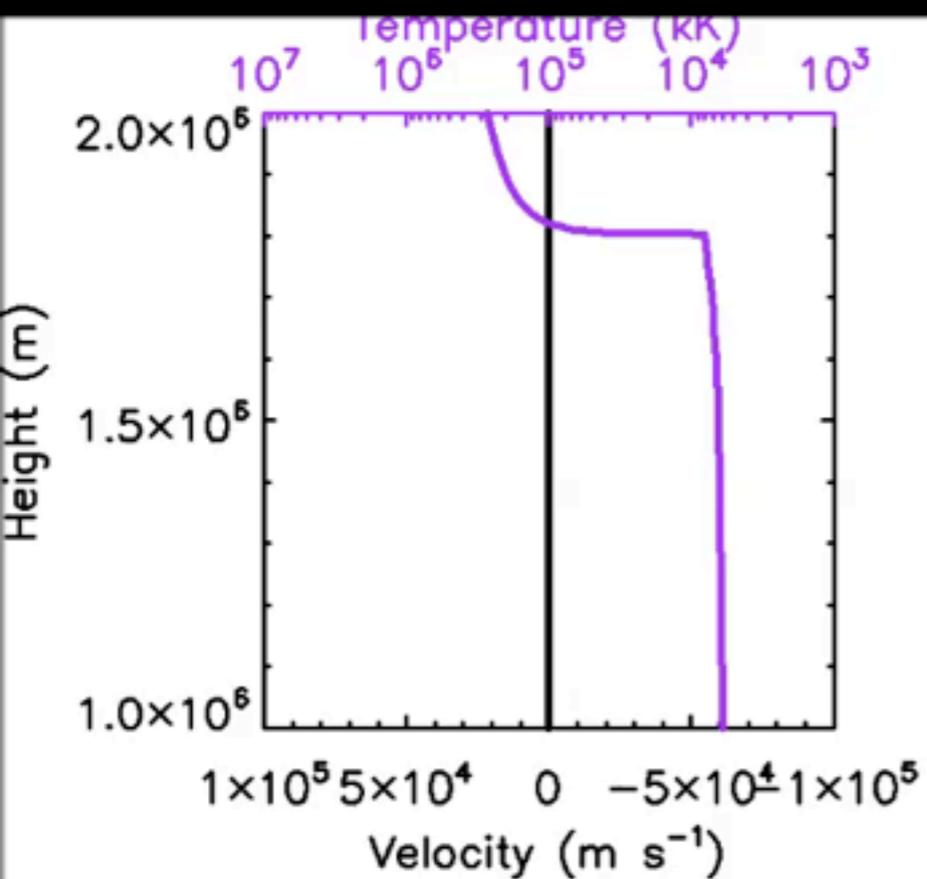
**velocity**



**formation height**

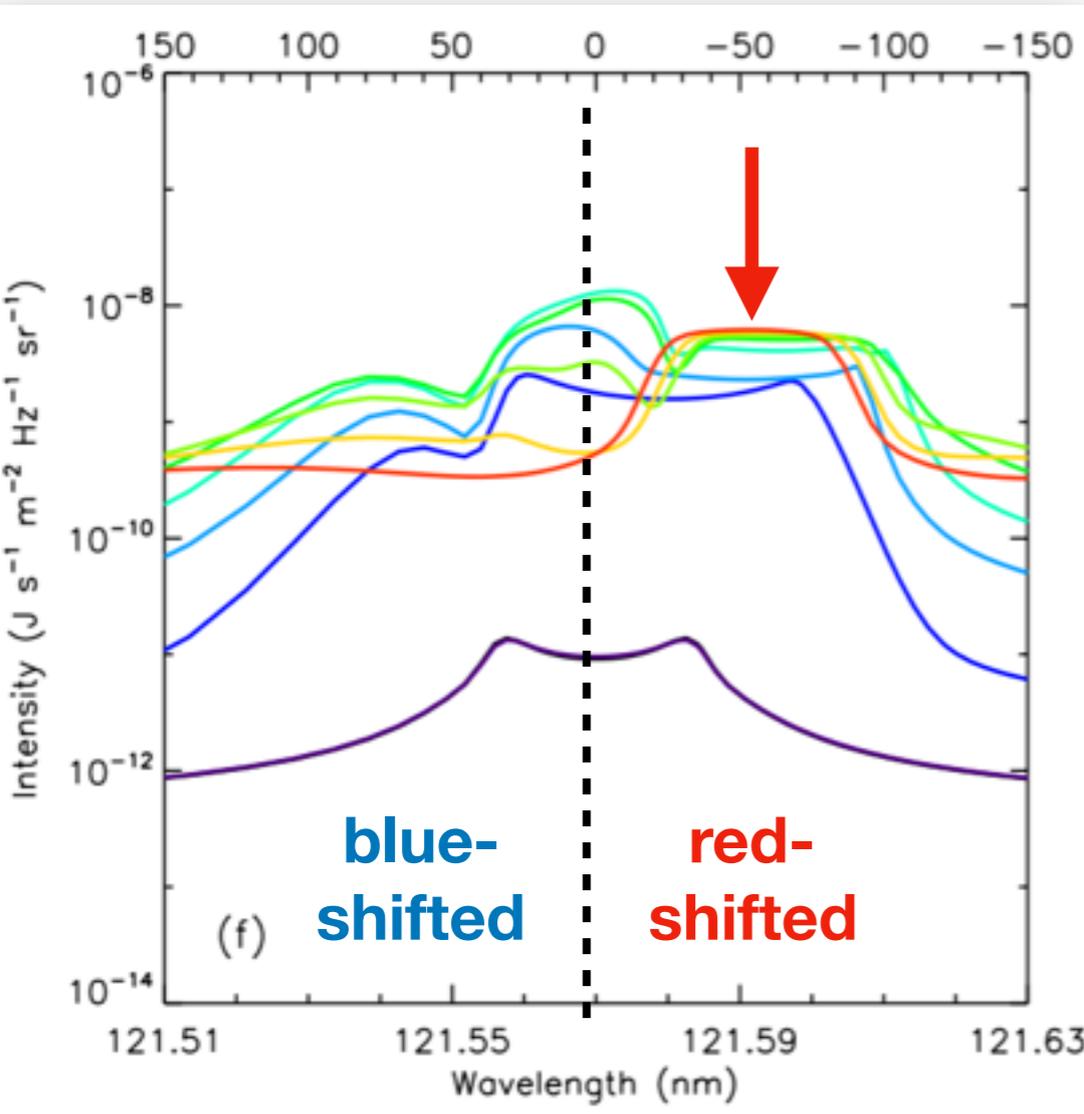


# F10\_thermal (thermal, weak flare)



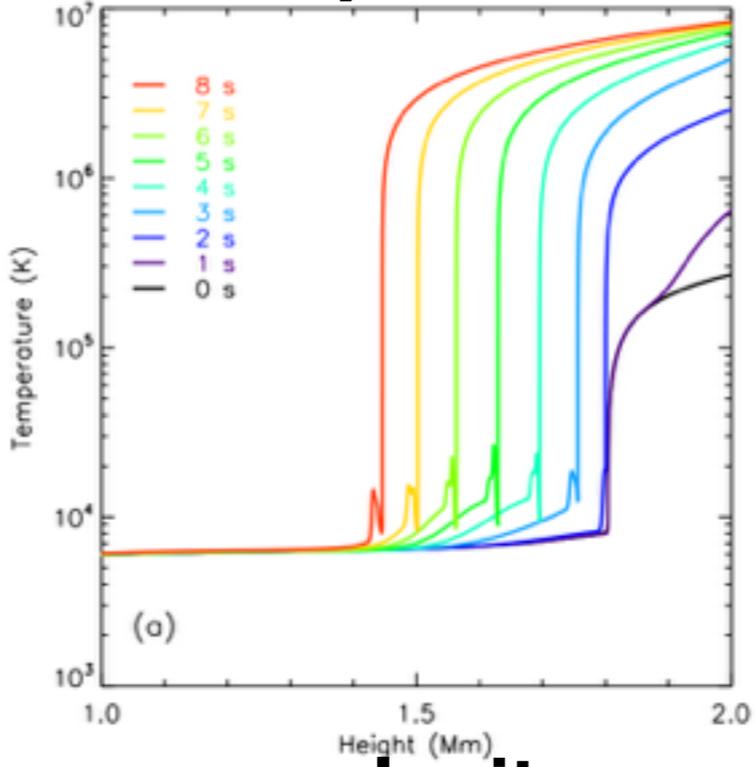
**F10\_thermal: time evolution**  
(from black to red)

**Ly $\alpha$  line profiles**

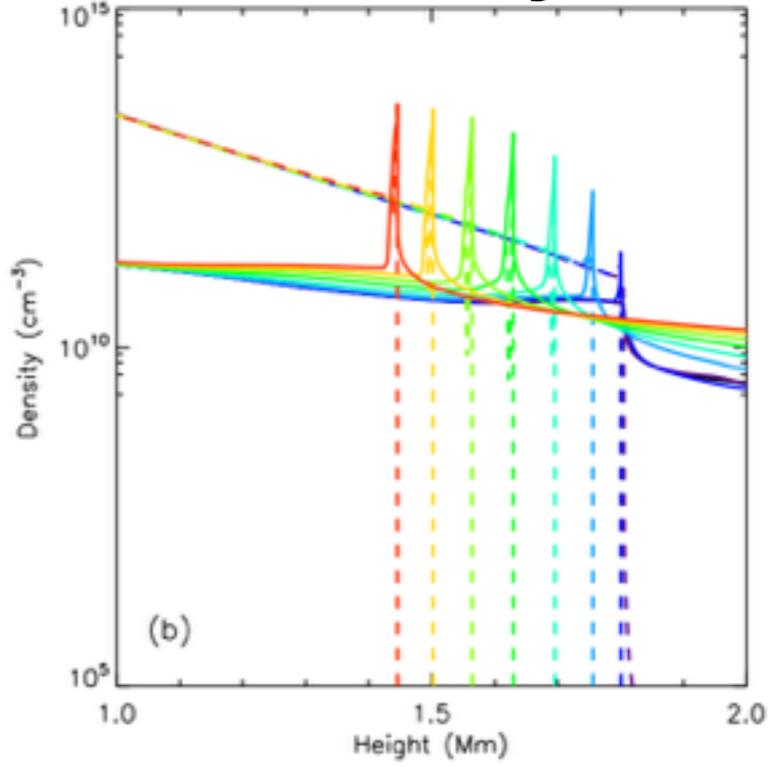


dominant redshifts  
 → a single red peak ( $\sim 50 \text{ km/s}$ )

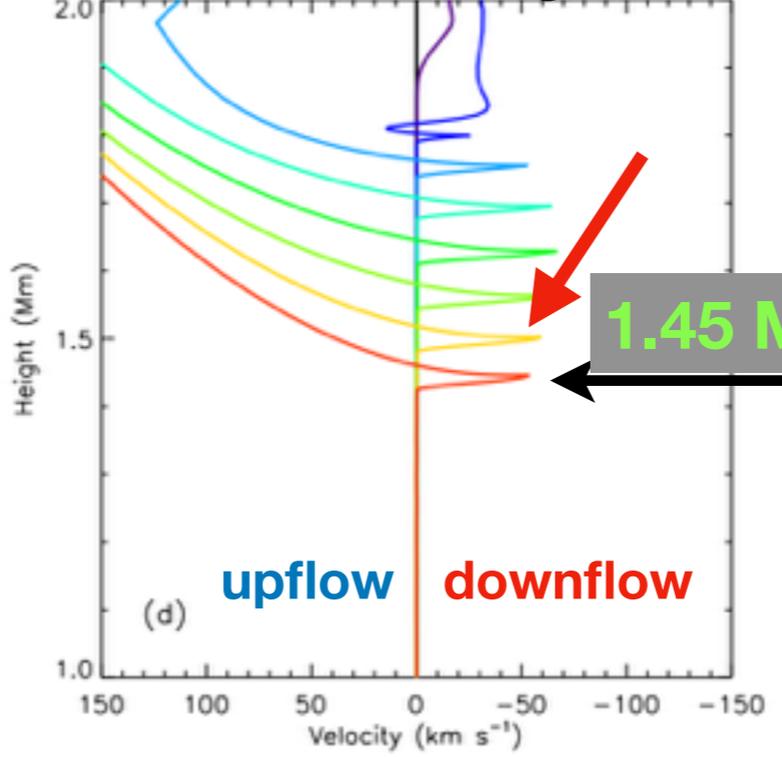
**temperature**



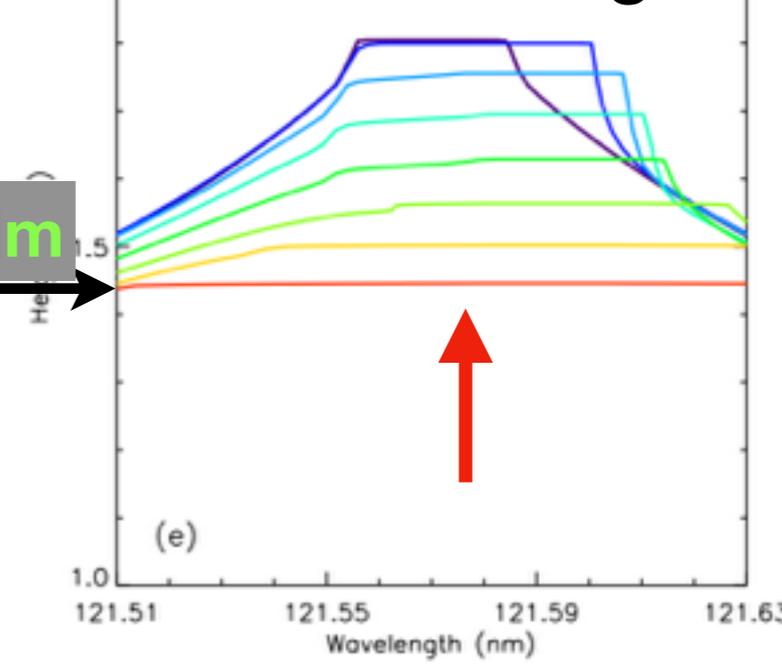
**density**



**velocity**

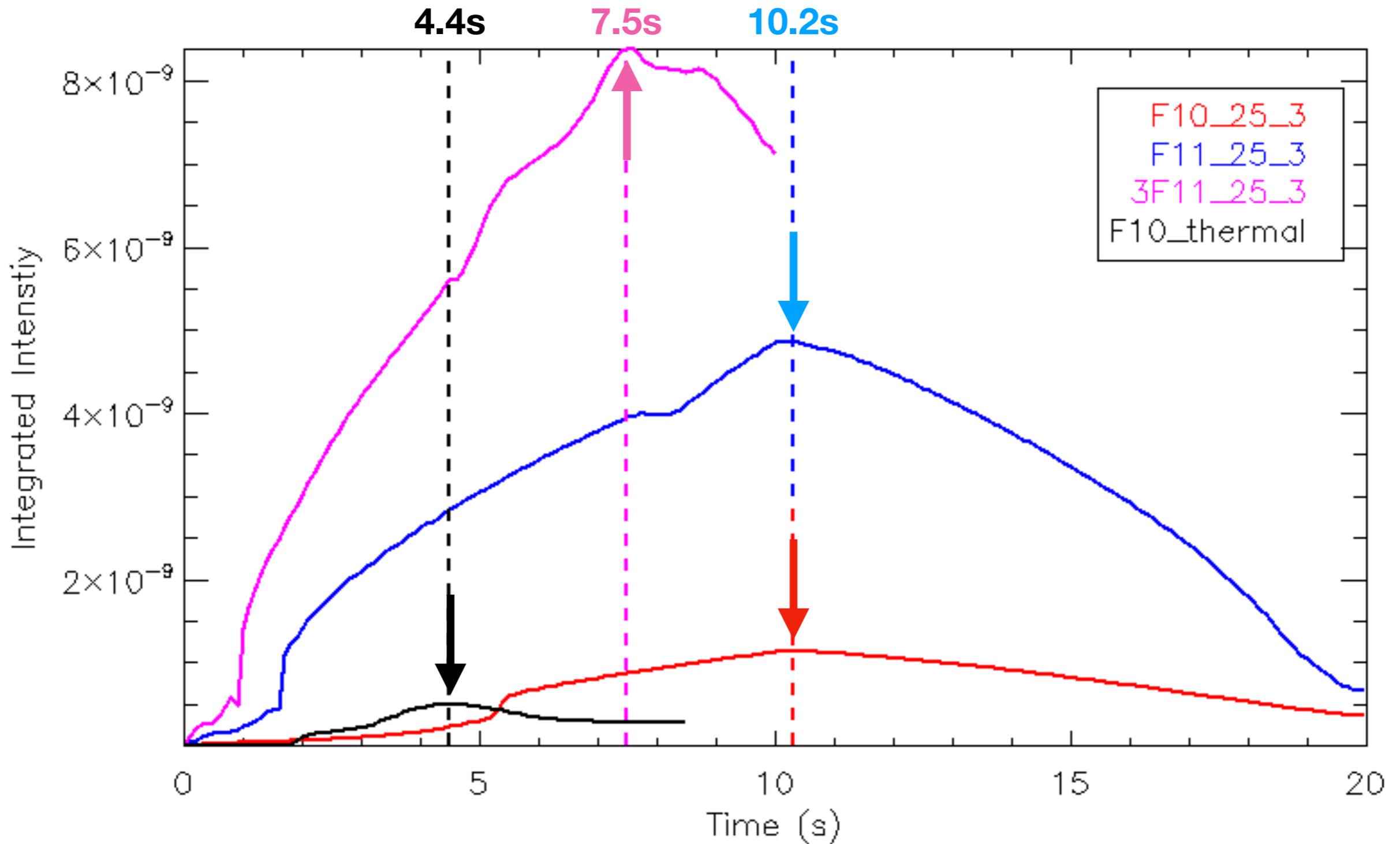


**formation height**



# Integrated Ly $\alpha$ light curves in RADYN simulations

*(could compare with the future ASO-S/LST/SDI observations)*



# Summary

	Tau = 1 height of the line center	Asymmetry of the line profiles	Dynamics (line center)
<b>F10_25_3</b> (weak flare)	1.8 Mm	red	<b>blueshifted</b> <i>(gentle evaporation)</i>
<b>F11_25_3</b> (moderate flare)	1.8 Mm → 1.6 Mm	red → blue	<b>blueshifted</b> → <b>redshifted</b> <i>(explosive evaporation)</i>
<b>3F11_25_3</b> (strong flare)	1.8 Mm → 1.4 Mm	red → blue → 2nd red component	<b>blueshifted</b> → <b>redshifted</b> <i>(explosive evaporation)</i>
<b>F10_thermal</b> (weak flare)	1.8 Mm → 1.45 Mm (along the wavelength)	a single red peak (entirely redshifted)	<b>dominant redshifts</b> <i>(explosive evaporation)</i>

↑ peak time

## More ...

- **The Ly $\alpha$  line is capable of indicating **dynamics** as well as **heating mechanisms** in flaring loops.**
- **Further steps:** 1) constrain heating function from real flare observations; 2) run multi-loop simulations; 3) compute soft X-ray & EUV emissions and compare with GOES & SDO/AIA observations, 4) study the relation between Ly $\alpha$  intensity and plasma temperature/density; ...
- **Perspectives:** *Our Ly $\alpha$  simulations could help interpret the future observations of ASO-S/LST/SDI (with a highest cadence of 3-4 s), particularly combining with ASO-S/HXI (for non-thermal electron beam observations).*

Thanks for your attention!