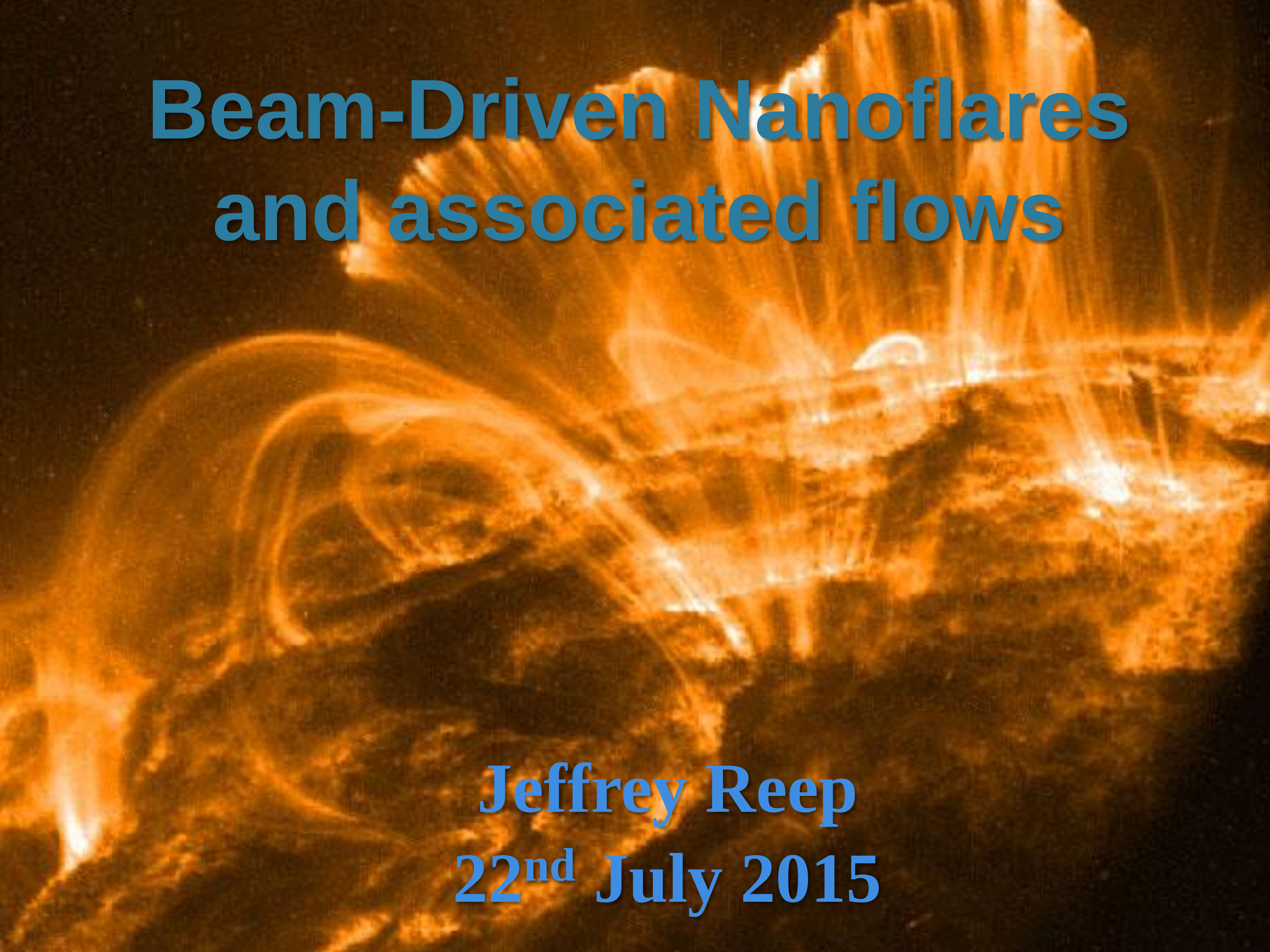
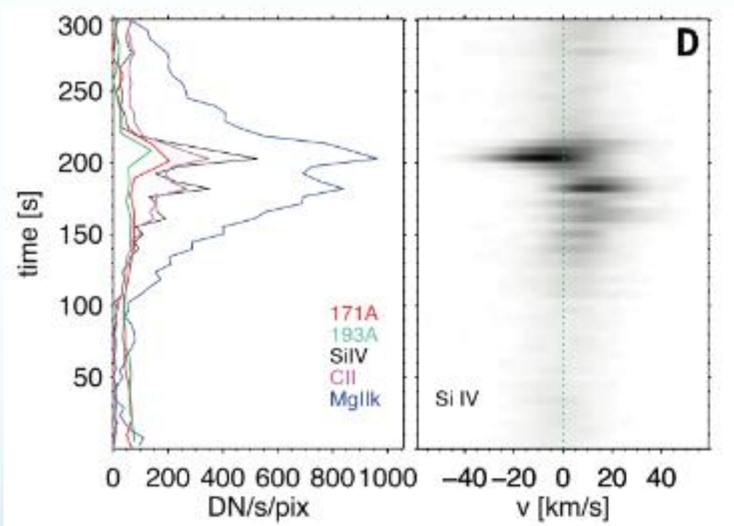


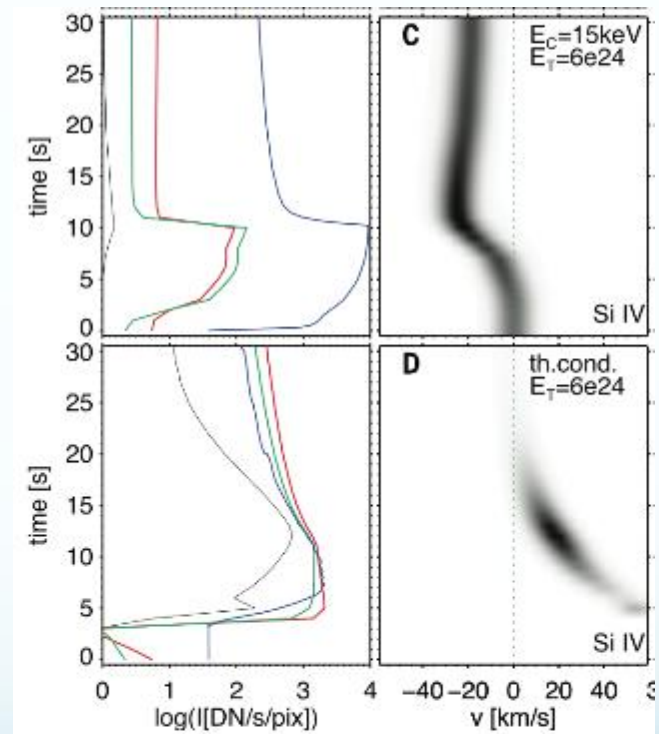
Beam-Driven Nanoflares and associated flows

Jeffrey Reep
22nd July 2015

Motivation from IRIS observations

Testa et al. 2014 found Si IV blue-shifts consistent with electron beam heating in nanoflares





Let’s examine the physics!

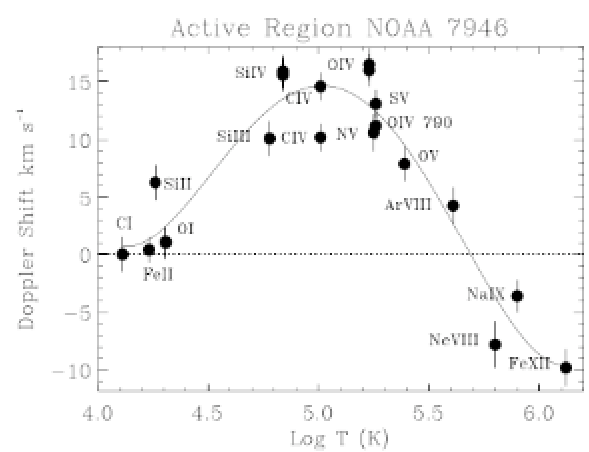
General flow properties in loops

In general, no obvious flows at 10^4 K

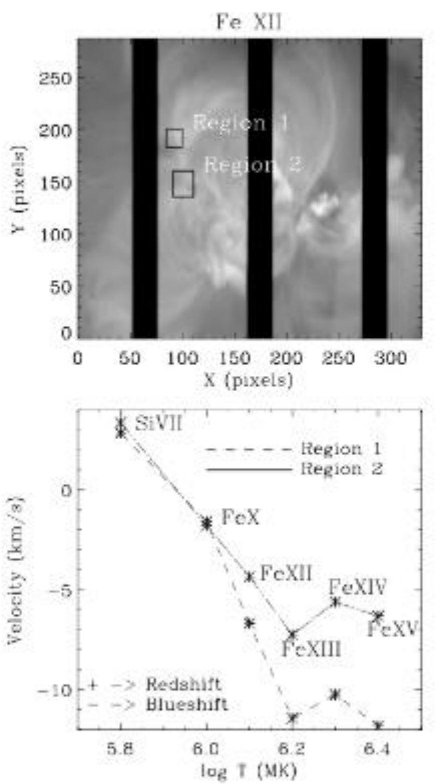
Redshifts of 10-15 km sec^{-1} at 10^5 K

Temperature at which flows switch from blue to red:
log T ~ 5.4-5.7 (0.3-0.5 MK)
As high as 1 MK in some ARs

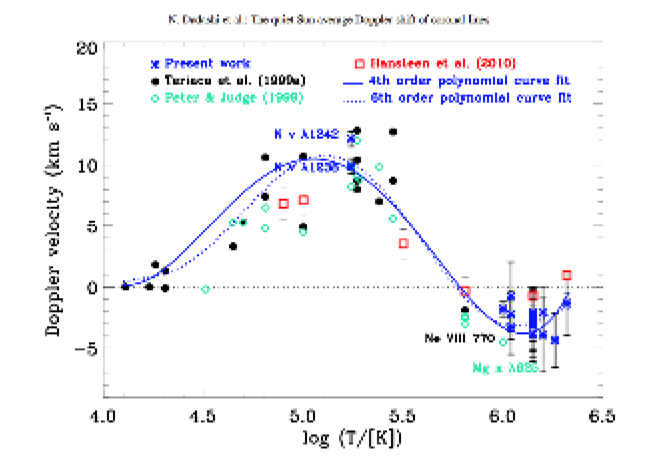
Note: redshifts on top in these plots



Teriaca et al. 1999

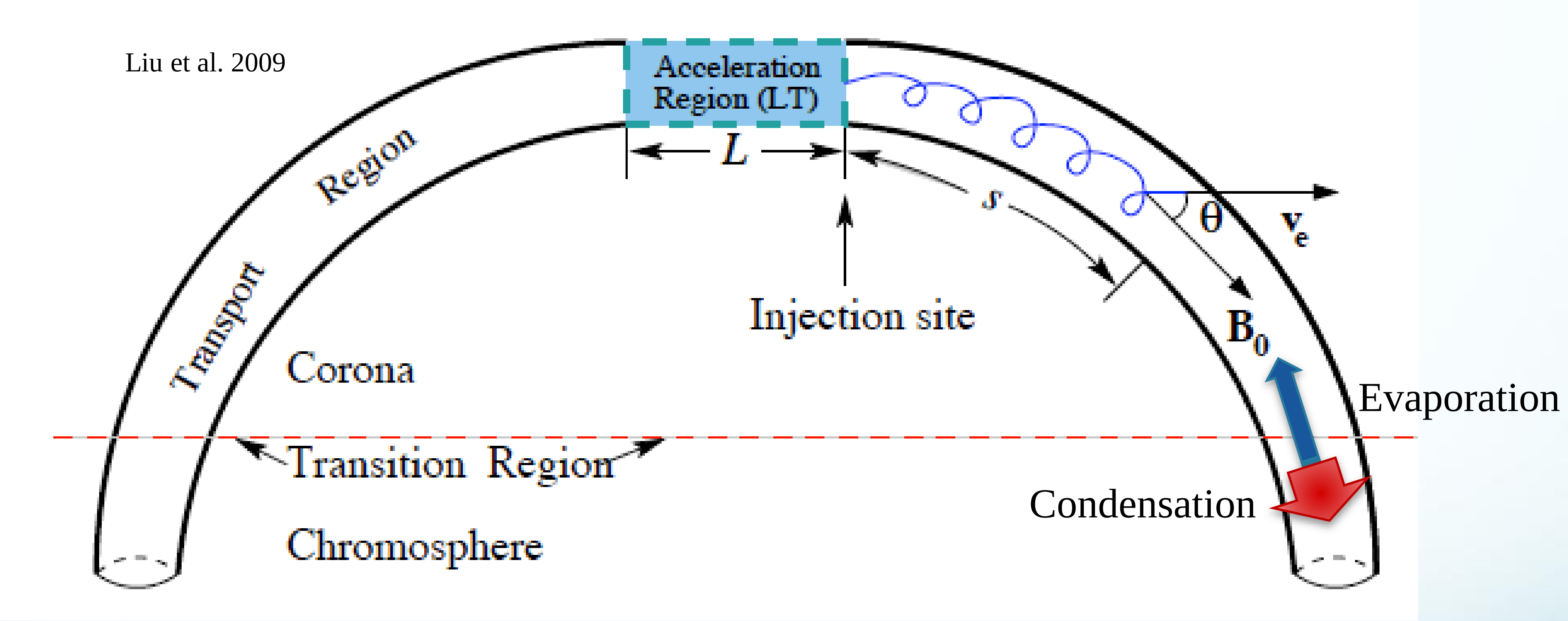


Tripathi et al. 2009



Dadashi et al. 2011

Beam-driven Nanoflare Model



Electrons precipitate, depositing energy in chromosphere
Drives fast-moving evaporation upwards,
slow-moving condensation downwards

HYDRAD beam heating

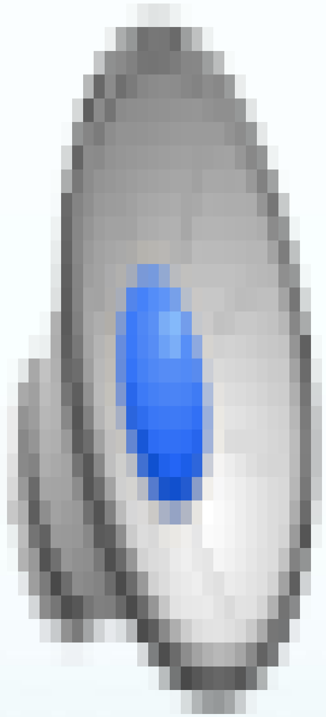
HYDRAD solves the hydrodynamic equations for an isolated magnetic flux tube (Bradshaw & Cargill 2013)

- Adaptive mesh refinement > properly resolved TR
- Full non-equilibrium ionization
- Radiation treated with CHIANTI, and soon KAPPA

Adapted for electron beam heating studies (Reep et al. 2013)

$$H_{sharp} = \frac{1}{2} K n_H \gamma (\delta - 2) \frac{F_0}{E_c^2} \left(\frac{N}{N_c}\right)^{-\delta/2} B\left(\frac{\delta}{2}, \frac{2}{4+\beta}\right)$$

(and soon Alfven wave heating…)



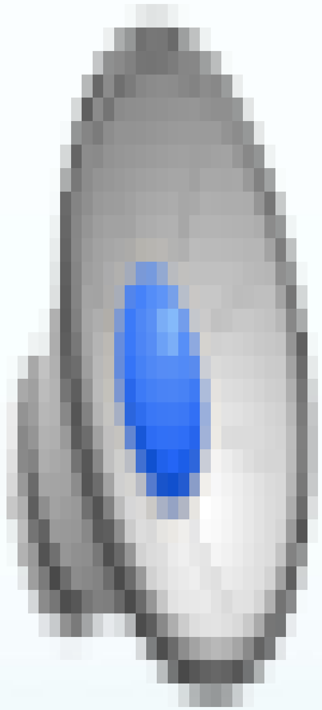
Nanoflare simulation

300 seconds of electron beam heating, with cut-off of 3 keV

~ 3 x 10^{24} erg total energy

Temperature vs position as a function of time

Color-coded by velocity at a given point (blue for up-flows, red for down)

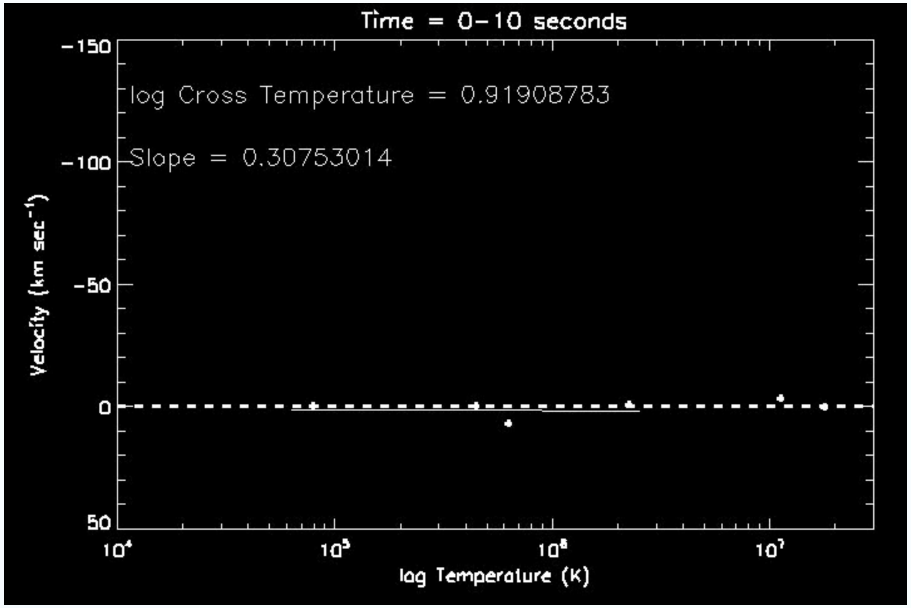


Pressure vs position as a function of time

Flows stem from point where pressure peaks due to heating (TR)

Temperature at which flows switch from blue- to red-shifts thus at TR ~ few x 10^5 K

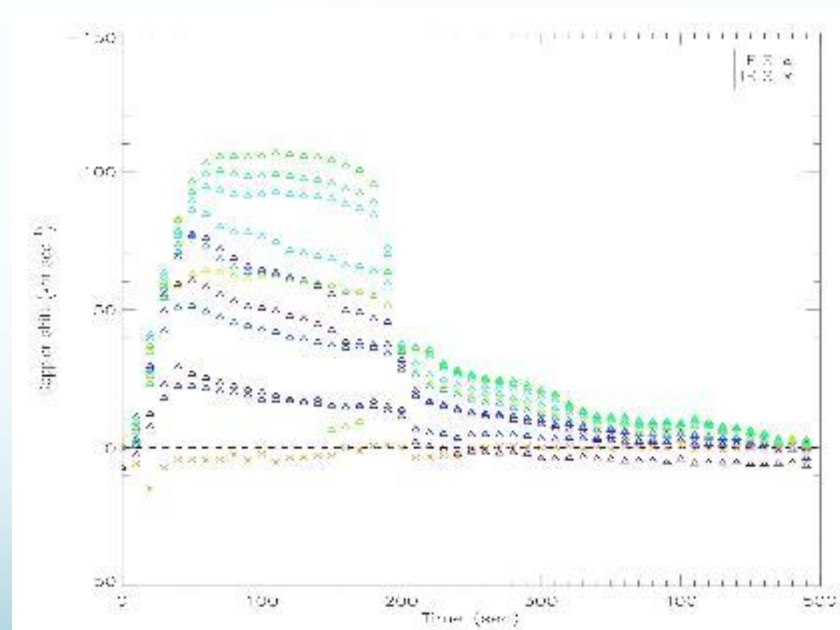
Forward Model EIS and IRIS lines



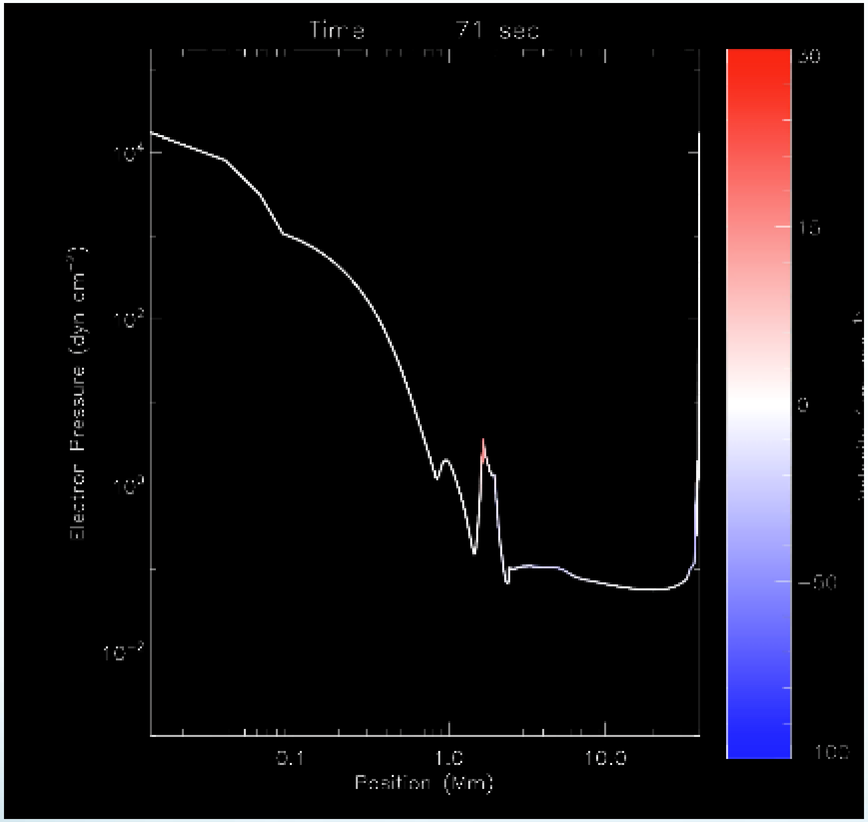
Fe and Si lines ranging from log T ~ 4.5 to 7.2

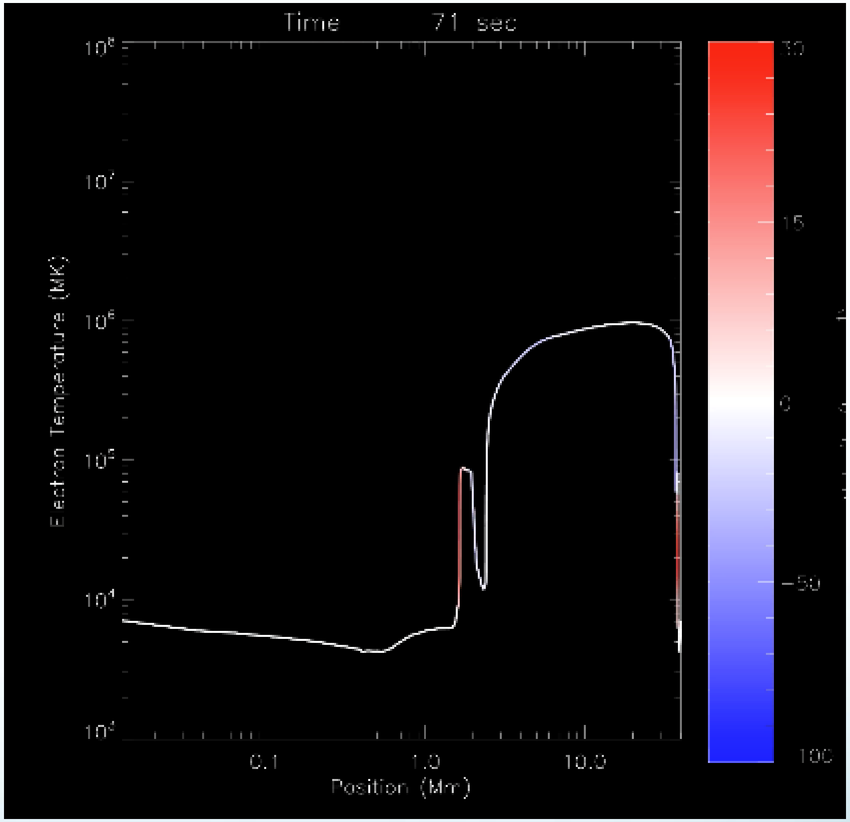
Full non-equilibrium ionization

Crossing temperature at a few x 10^5 K



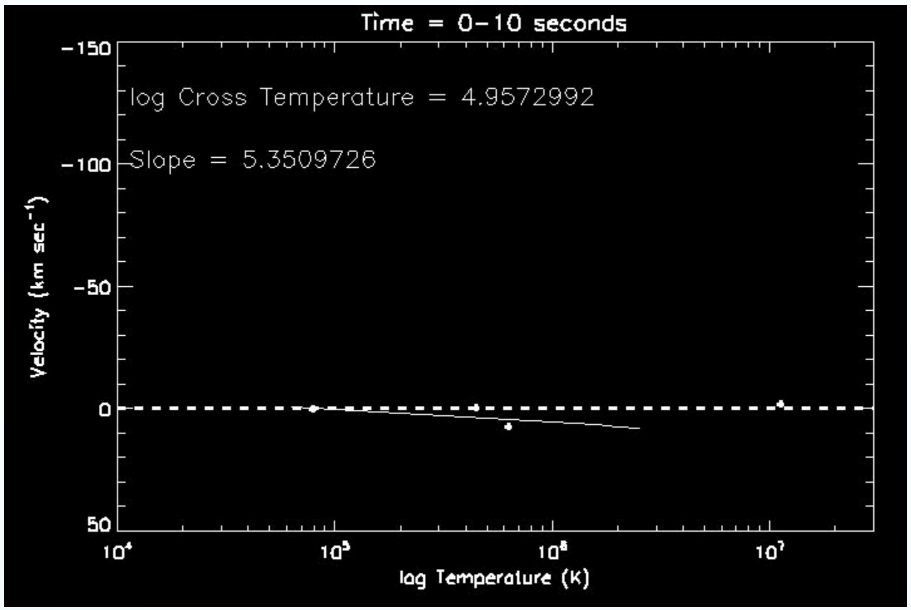
10 keV Cut-off



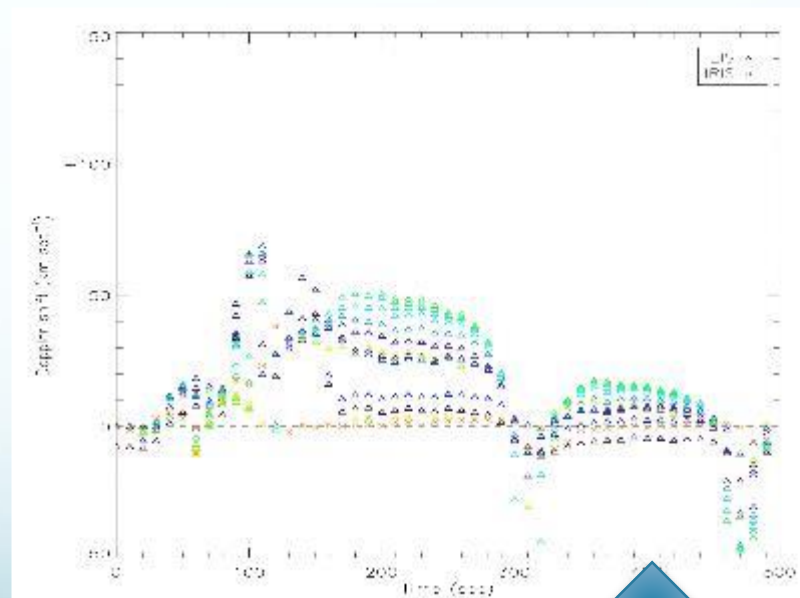


Pressure spike now in chromosphere,
flows emanate from region with T < 10^5 K

Forward Modeling 10 keV



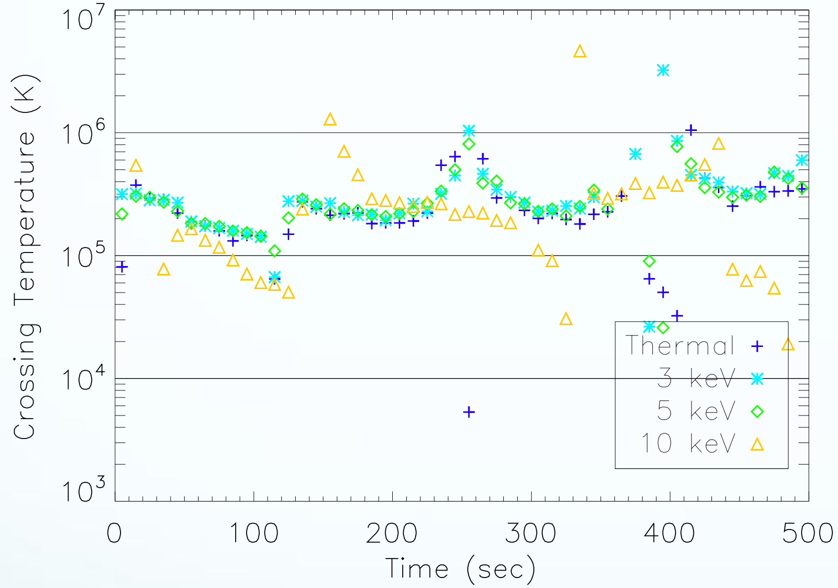
Change in the **depth of energy deposition** causes cooler lines to now be blue-shifted



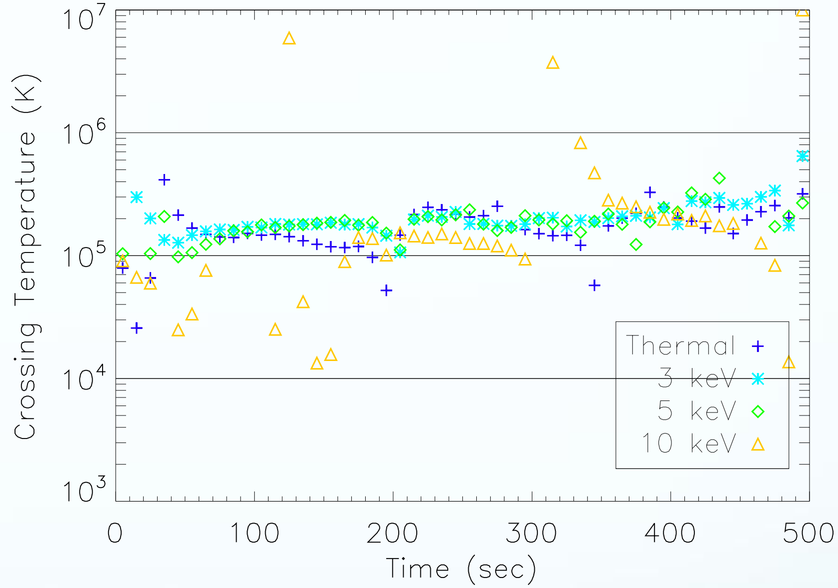
The crossing temperature is an observable which tells us the depth of energy deposition

(Sound waves at late times)

Model Crossing Temperature



60 seconds heating



300 seconds heating

Measure the x-intercept of linear fits to the simulated spectra
Ignore time periods where the fitted line has a slope ~ 0

Potential Beam Diagnostics

- Wish to determine the parameters of the electron beam
  - Blue-shifted Si IV and other TR lines establish low-energy cut-off ≥ 10 keV (Testa et al. 2014)
  - Depth of energy deposition proportional to electron energy squared, measurable by crossing temperature (if below TR)

- Hard X-ray photon spectra can be inverted to give electron spectra, but current instruments not sensitive enough to use with nanoflares

- In the absence of routine hard X-ray observations of nanoflares, can we determine other parameters?

Energy Flux Diagnostic

- Suggested by George Fisher, albeit regarding flares, in 1989:

As a final comment on Figure 7, we note that for thermal models of flare heating or thick-target heating below the explosive evaporation threshold, the peak downflow speed can be expressed as

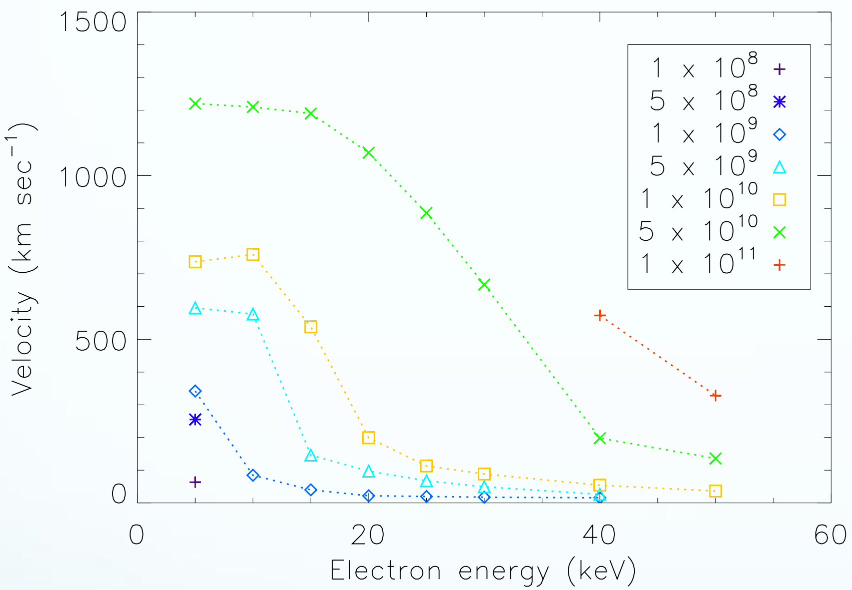
$$v_{\text{peak}} \simeq 0.4\left(\frac{F_{\text{evap}}}{mn_{\text{ch}}}\right)^{1/3}, \tag{34a}$$

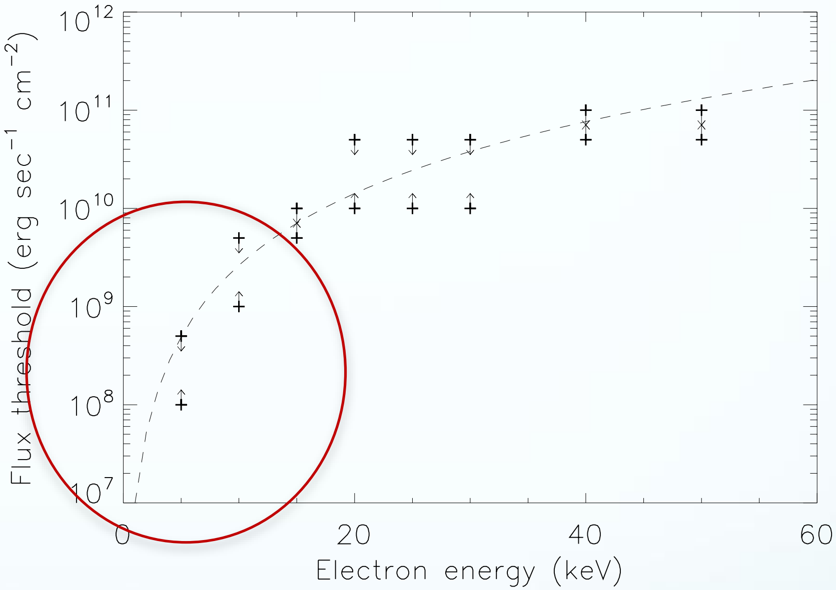
while for explosive evaporation the downflow speed is given by

$$v_{\text{peak}} \simeq 0.6\left(\frac{F_{\text{evap}}}{mn_{\text{ch}}}\right)^{1/3}. \tag{34b}$$

If both the condensation speed and TR density/pressure can be measured, then a lower limit on energy flux is determined.

Explosive Evaporation in Nanoflares?





$$\log F \propto \log E_*^2$$

Reep, Bradshaw, & Alexander 2015

Conclusions

- Flows emanate from region of over-pressure via standard chromospheric evaporation (Fisher et al. 1985)
  - Condensations always present, perhaps hard to detect
  - Depth of energy deposition is the key! (*e.g.* Reep et al. 2015)
- Crossing temperatures for energetic electrons often $< 10^5$ K
  - Diagnostic of depth of energy deposition
  - Inconsistent with observations, so such events not the norm
- Condensation speeds can perhaps give information about energy flux of beams