Coronal Heating:

The Loops Guidepost

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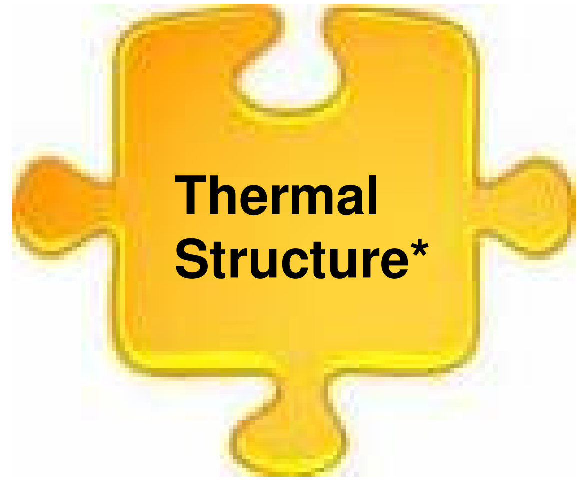
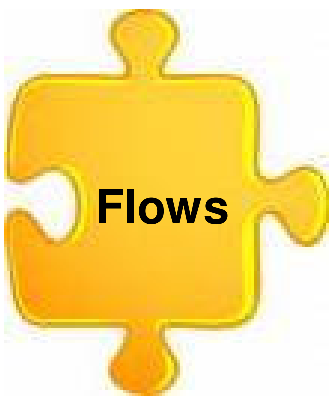
Pieces of the Coronal Loops Puzzle





* Over cross section
** Along axis

The Good Ol' Days
(pre SOHO)

Soft X-Ray Loops:

- Hot (T > 2 MK)
- Long-lived ($\tau_{life} >> \tau_{cool}$)
- Obey static equilibrium scaling laws
- Consistent with steady heating

Rosner, Peres, Tsuneta, Antiochos, Priest, ….

Then came SOHO and TRACE, and the trouble started….

EUV Loops:

- Warm (T ~ 1 MK)
- Over dense relative to static equilibrium
- Super hydrostatic scale heights
- Flat temperature profiles

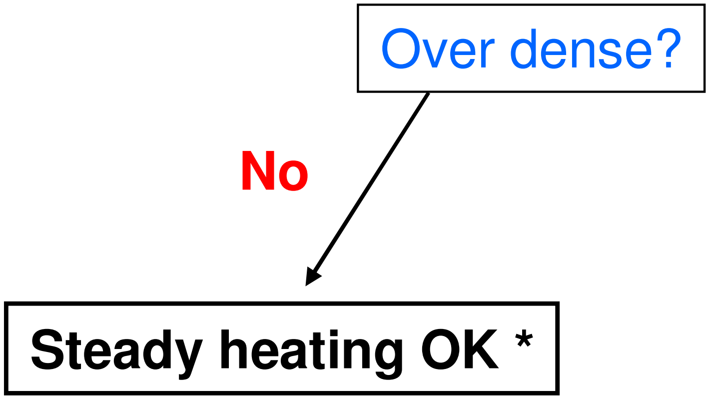
Aschwanden, Warren, Winebarger, Reale, Testa, ….

Solutions to the Loops Puzzle

Consider a loop.

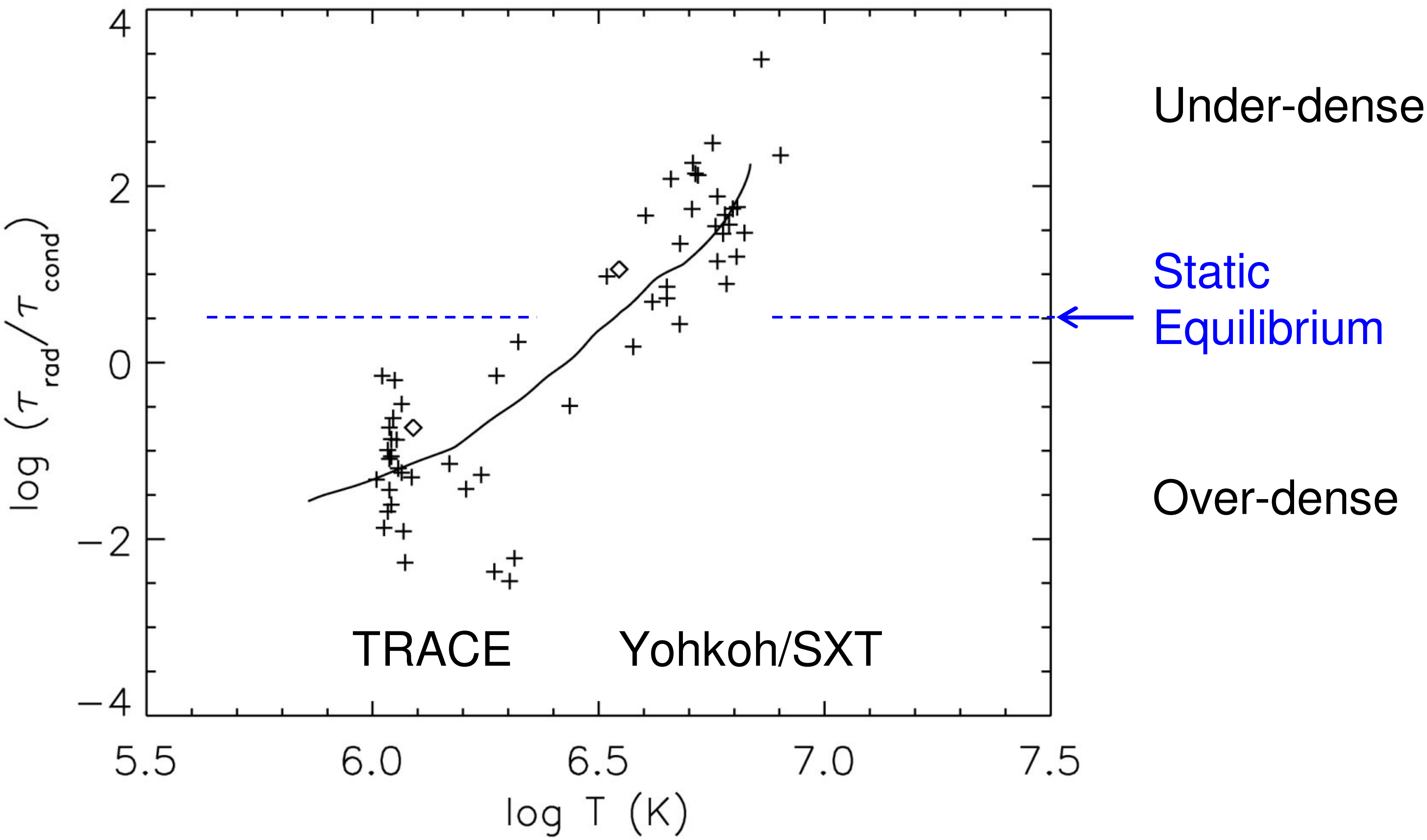
Over dense?

Solutions to the Loops Puzzle



* Steady heating not required (not unique solution)

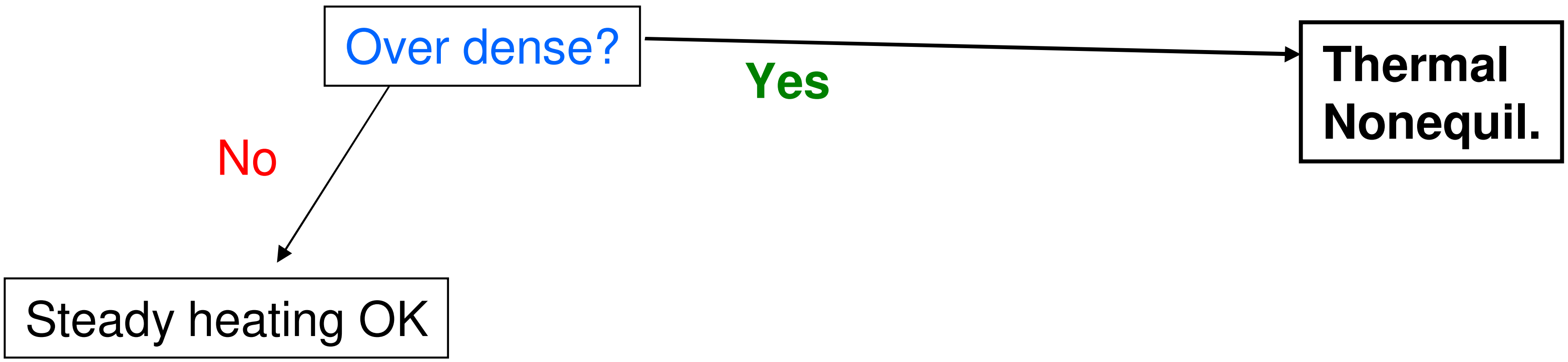
Cooling Time Ratio vs. Temperature



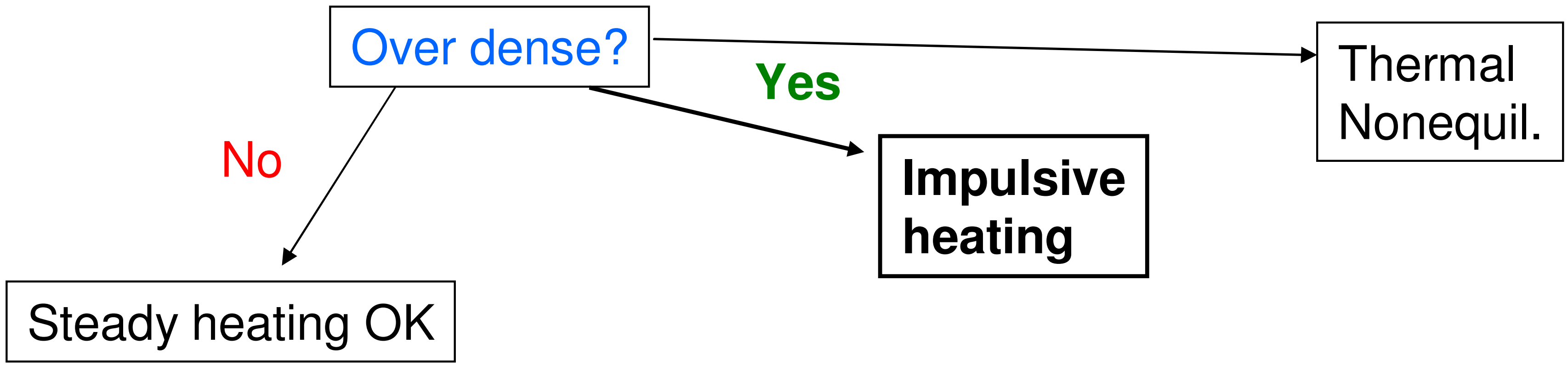
$$\tau_{rad}/\tau_{cond} = T^4 / (nL)^2$$

Klimchuk (2003, 06)

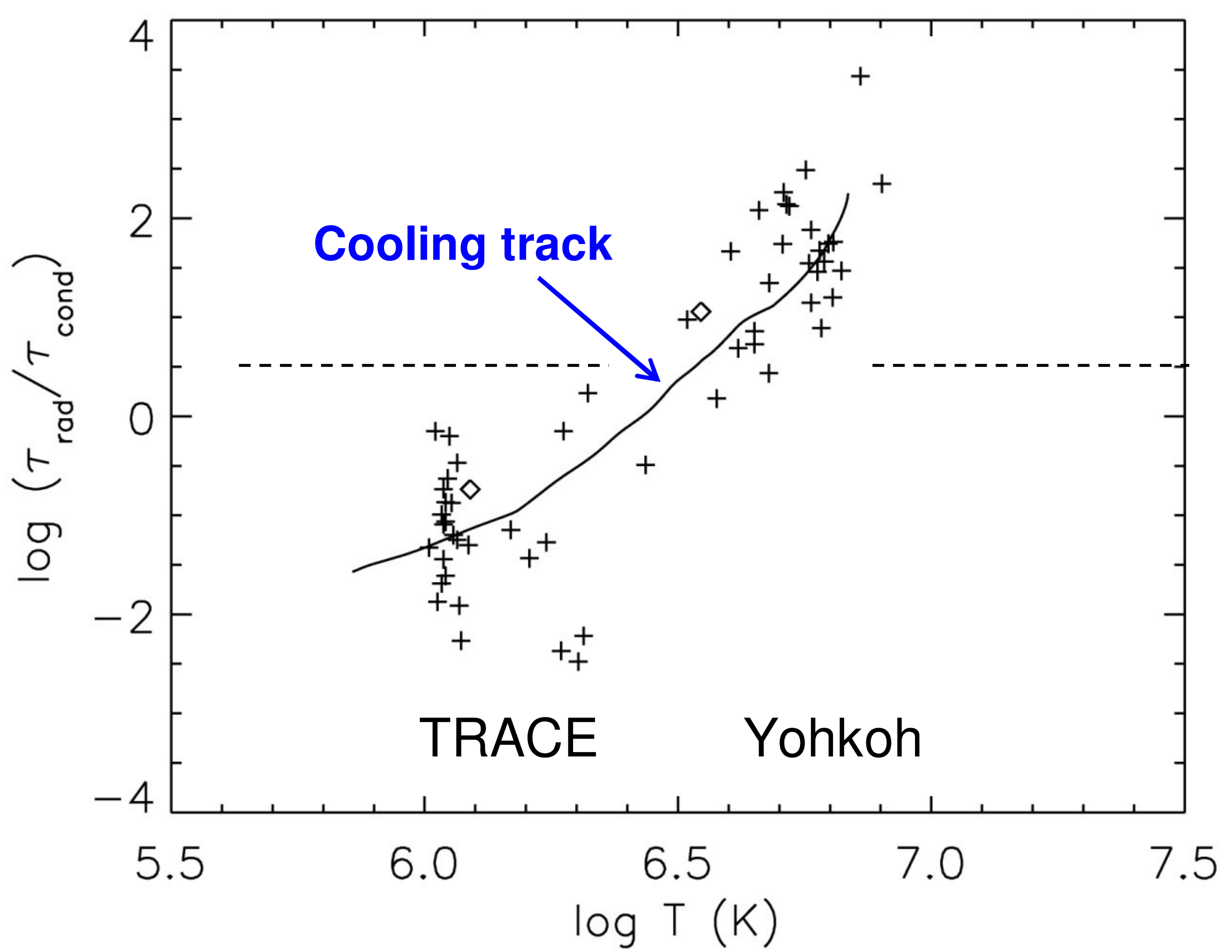
Solutions to the Loops Puzzle



Solutions to the Loops Puzzle



Cooling Time Ratio vs. Temperature



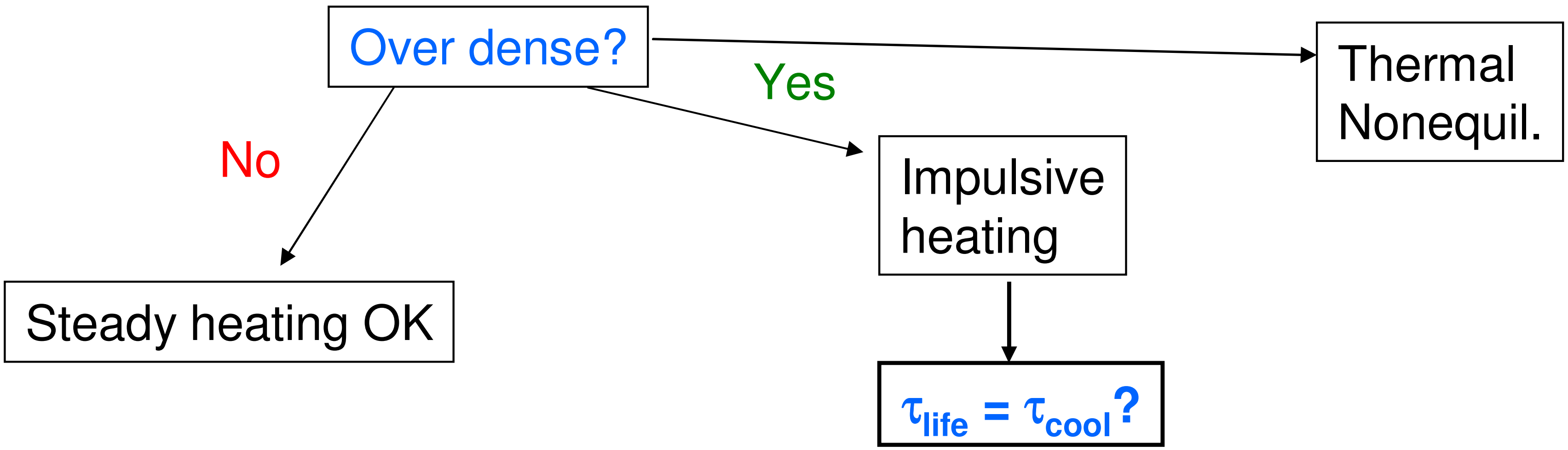
Thermal cond. dominates

Radiation dominates

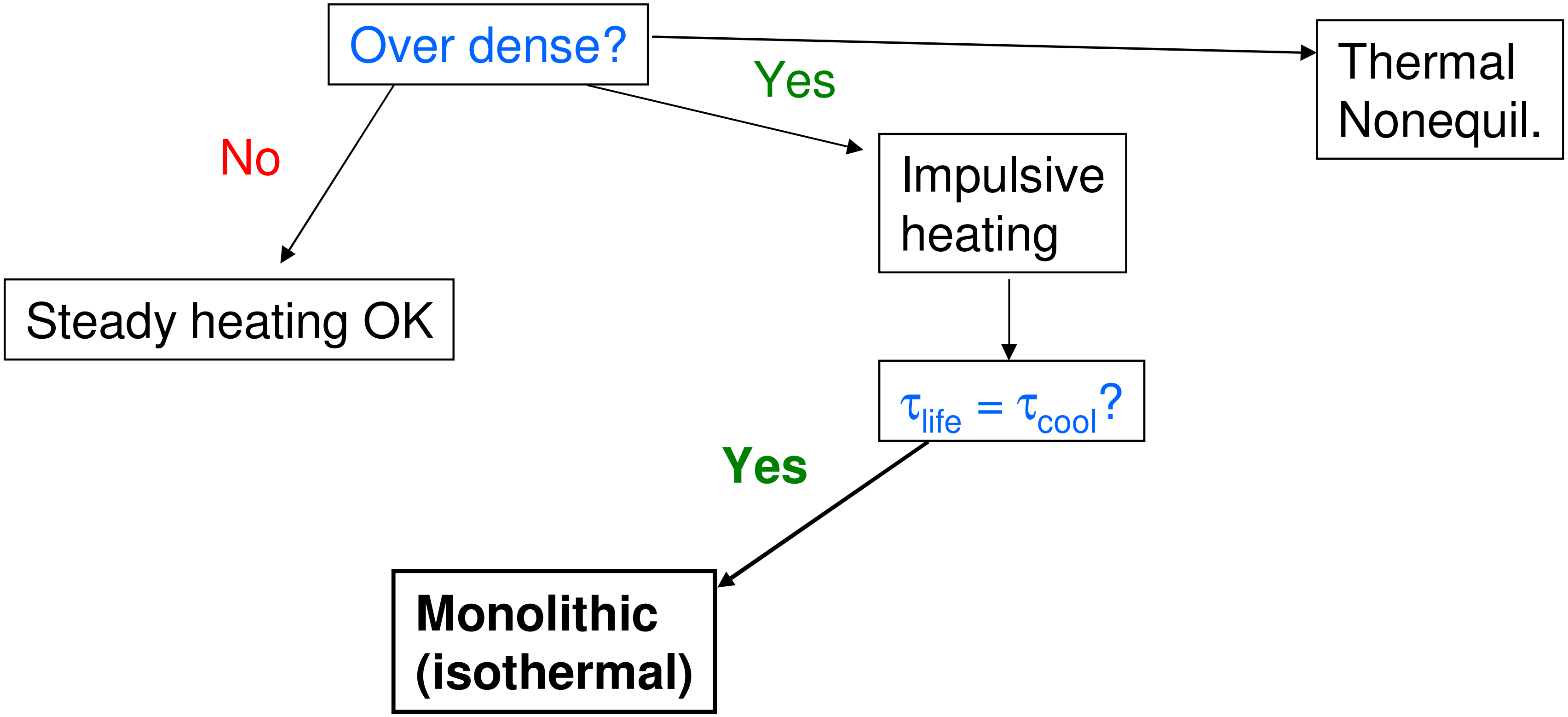
$\tau_{rad}/\tau_{cond} = T^4 / (nL)^2$

Klimchuk (2006)

Solutions to the Loops Puzzle

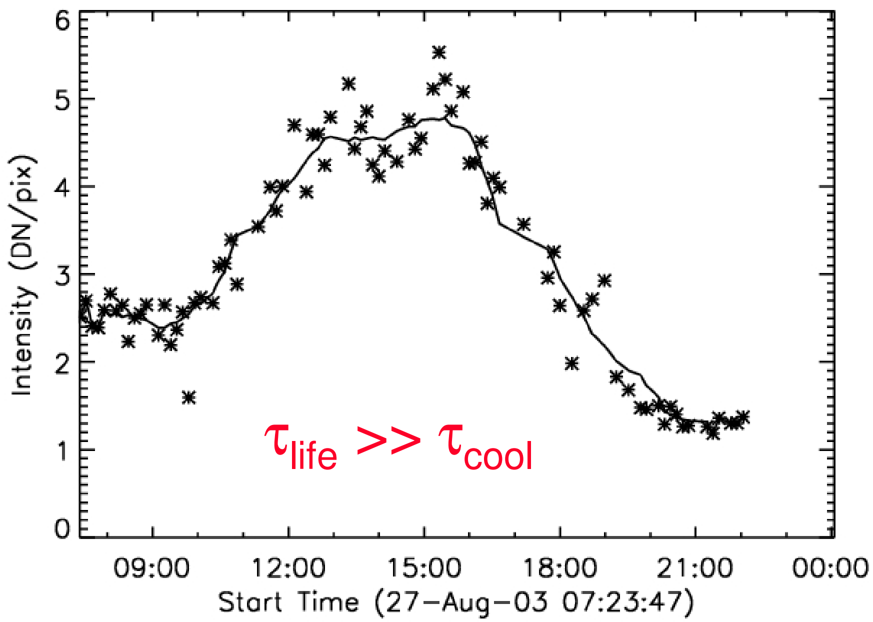


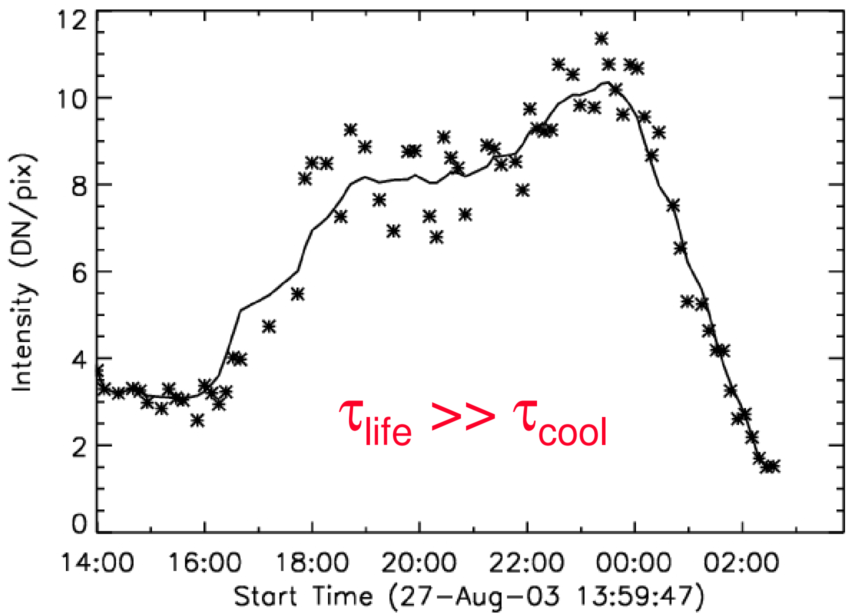
Solutions to the Loops Puzzle



Loop Light Curves

GOES / SXI

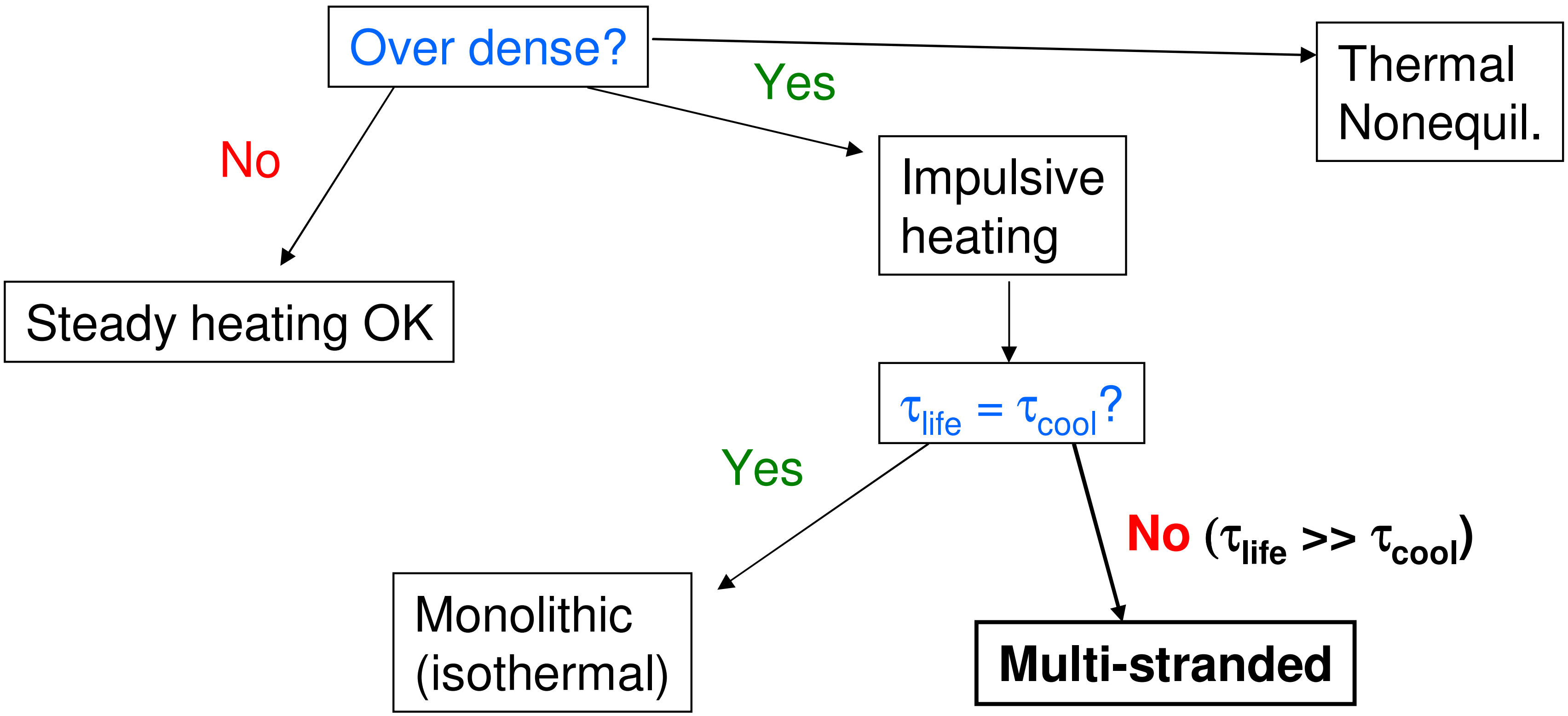




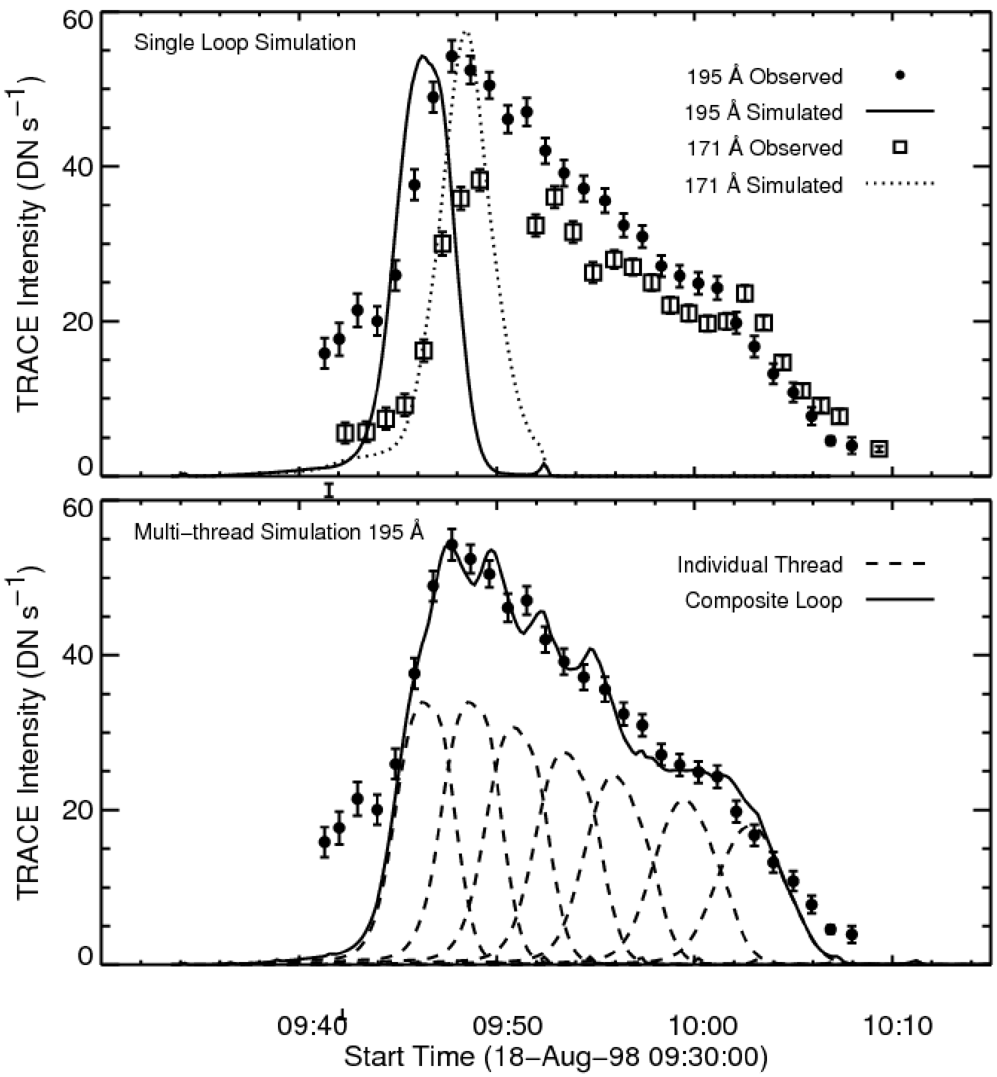
Can be modeled as a self organized critical (SOC) system driven by footpoint shuffling and magnetic field tangling.

Lopez Fuentes, Klimchuk, & Mandrini (2006)

Solutions to the Loops Puzzle



Multi-Stranded Loop

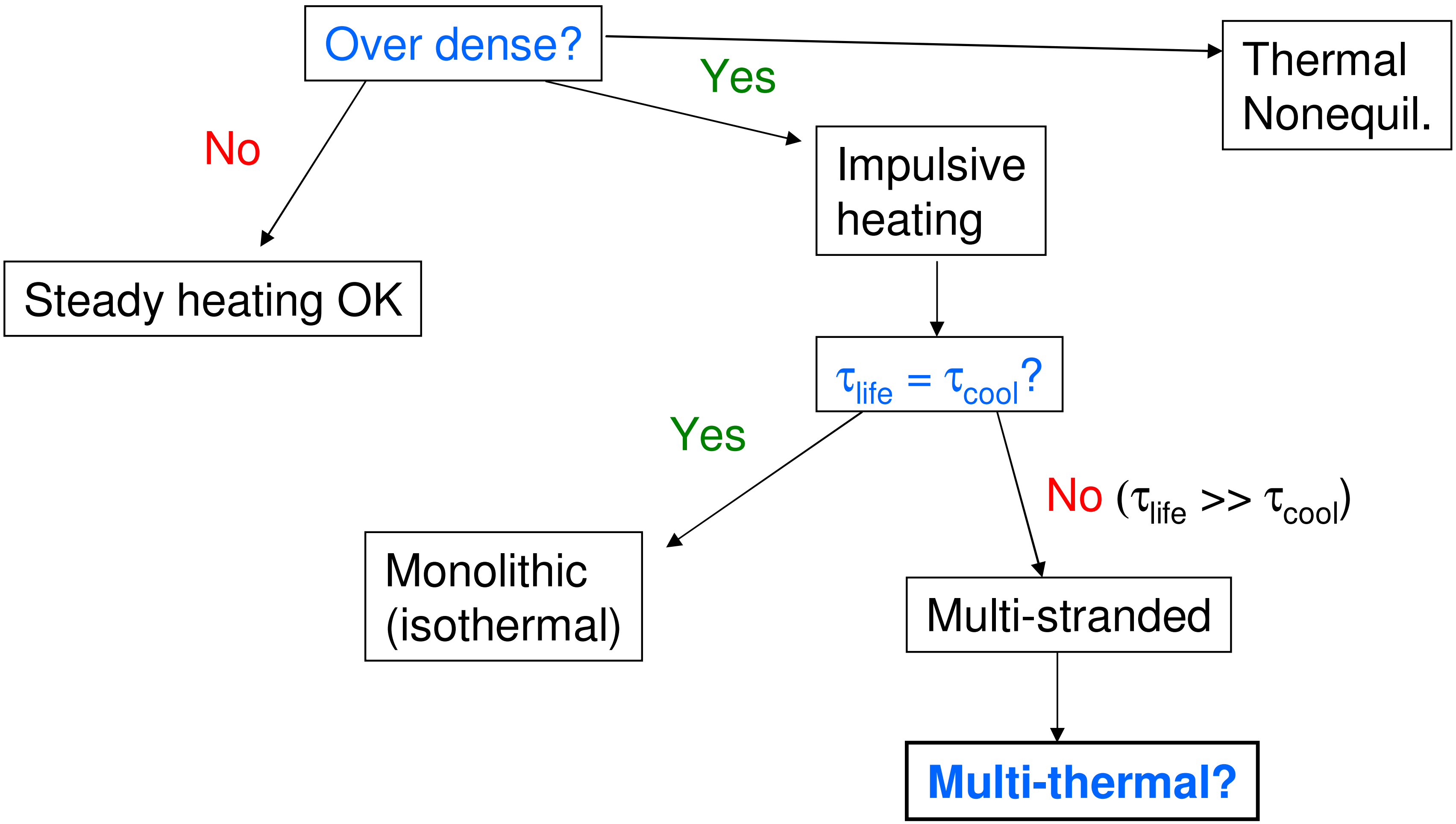


Single nanoflare

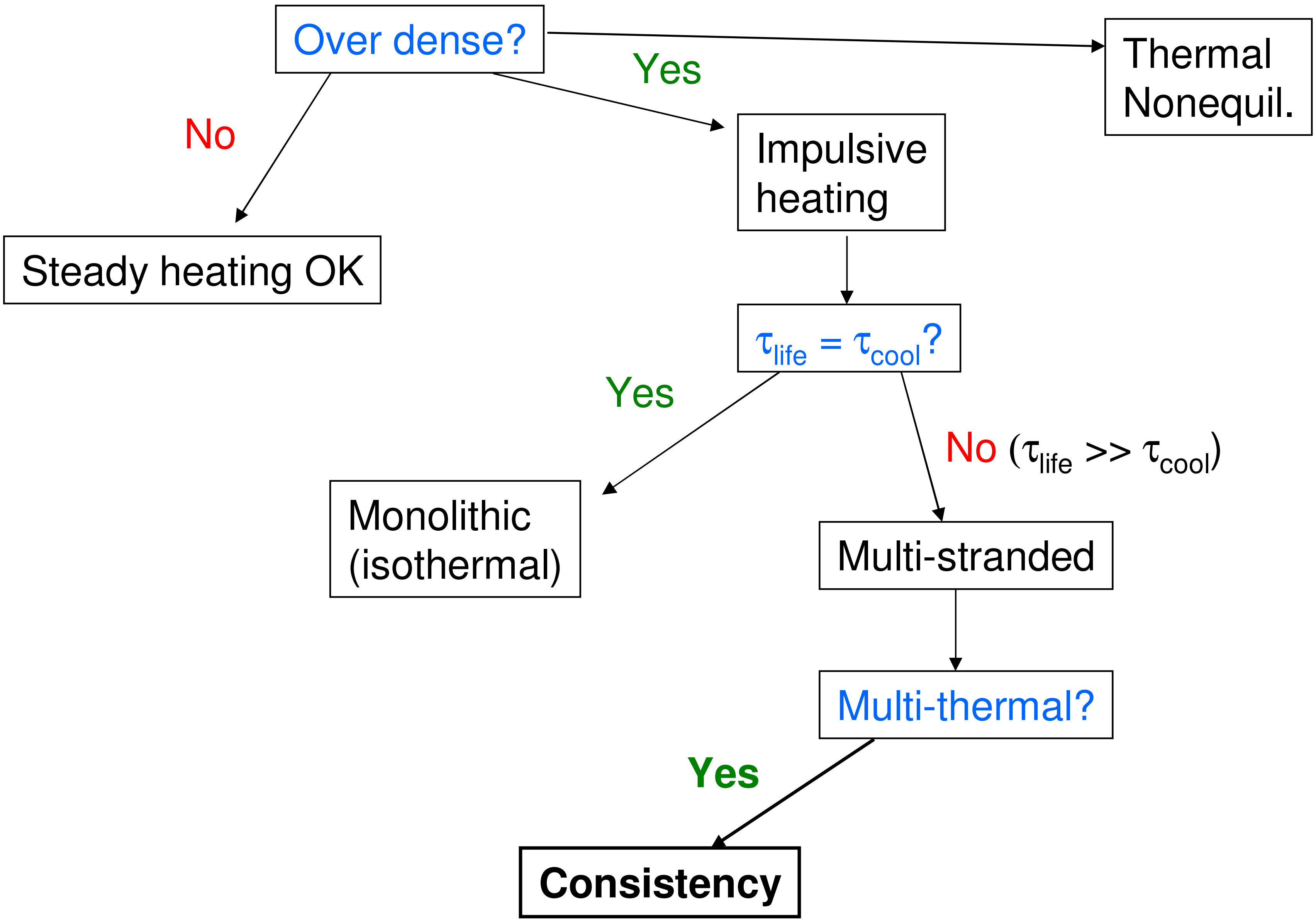
Nanoflare “storm”

Warren, Winebarger, & Mariska (2003)

Solutions to the Loops Puzzle



Solutions to the Loops Puzzle



The Isothermal / Multi-thermal “Debate”

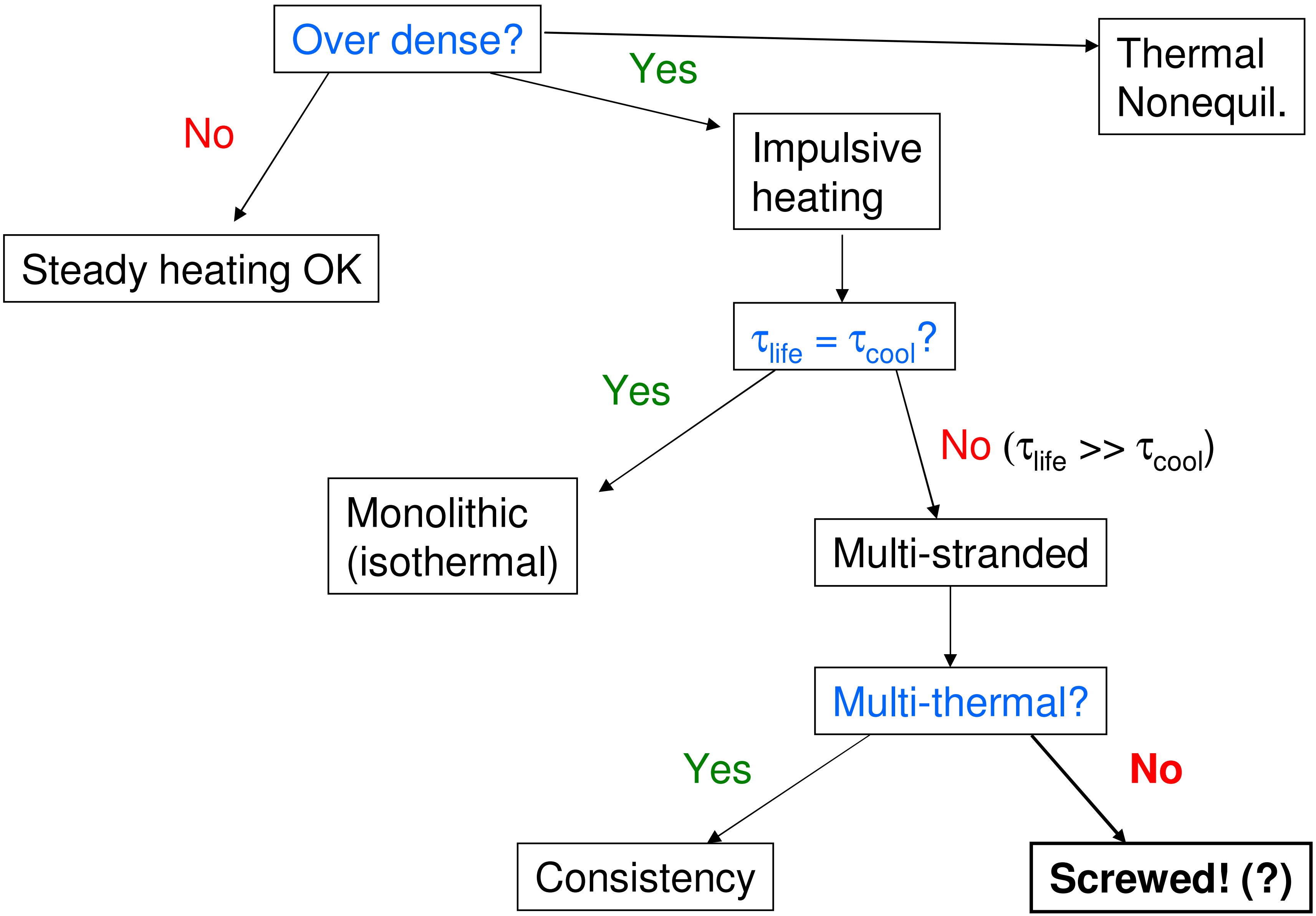
MULTI-THERMAL

Schmelz
Martens
Cirtain
Noglik
Walsh
Patsourakos
etc.

ISOTHERMAL

Aschwanden
Nightingale
Landi
Nagata
Del Zanna
Mason
Schmeider
etc.

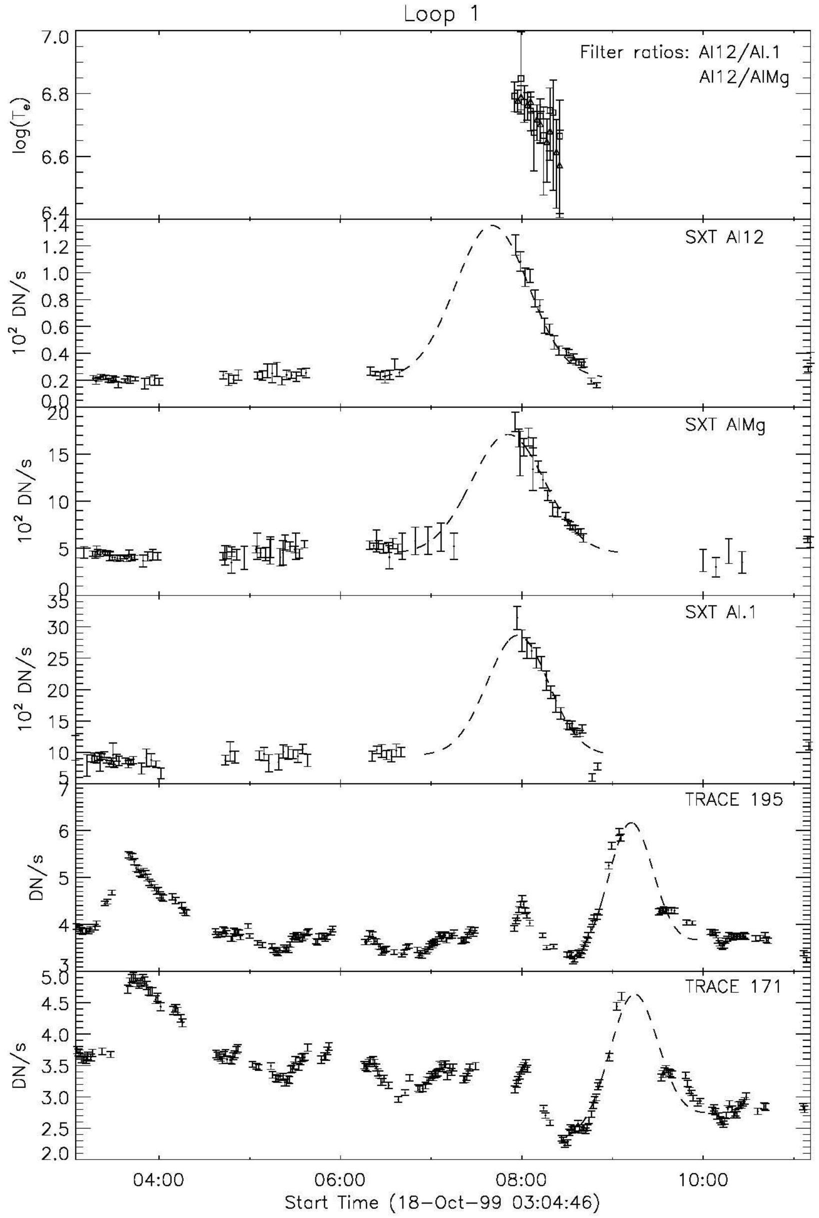
Solutions to the Loops Puzzle



Nanoflare Storm Duration

Yohkoh / SXT

TRACE

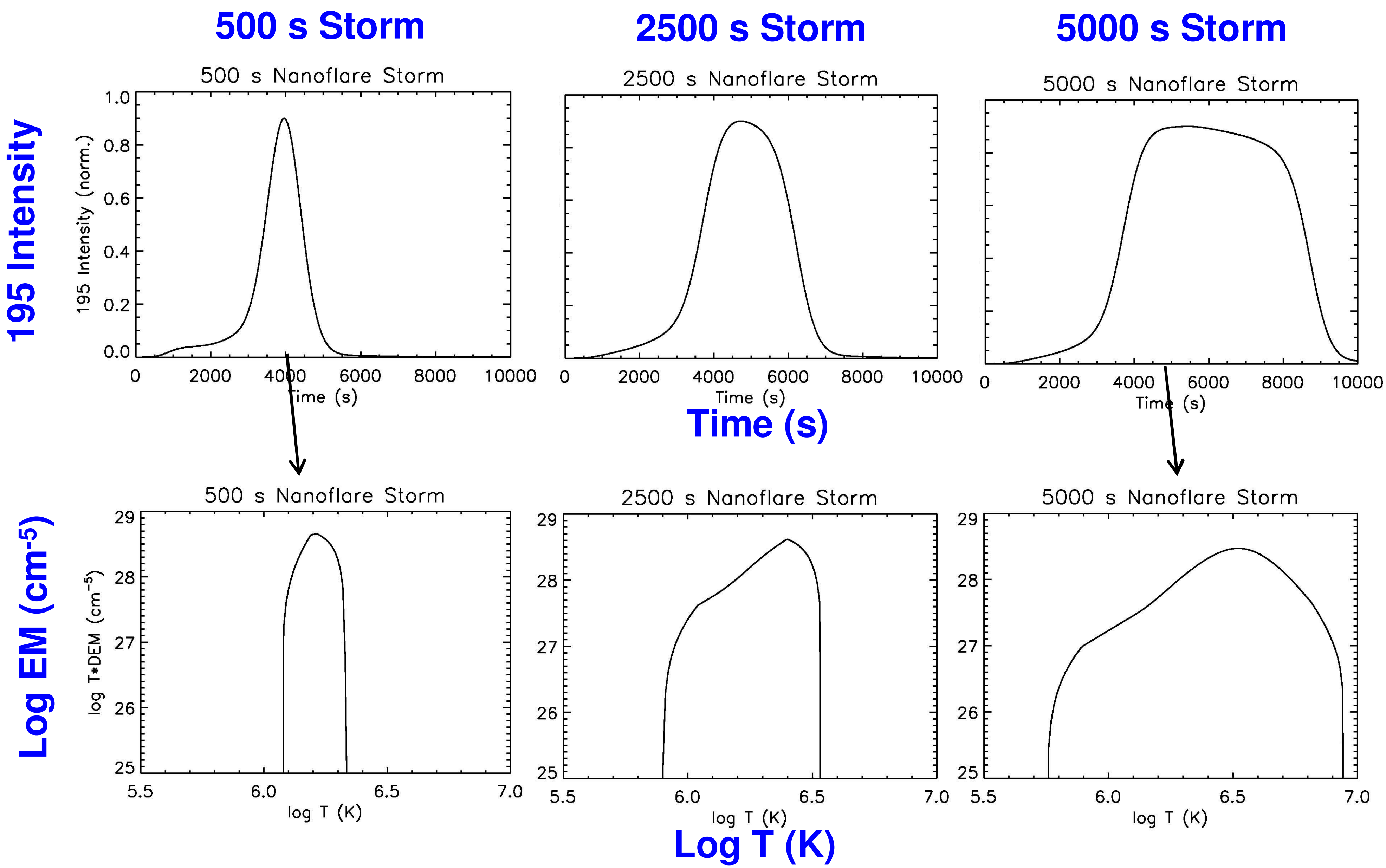


Nanoflare storms do not last forever.

Light curve overlap depends on storm duration.

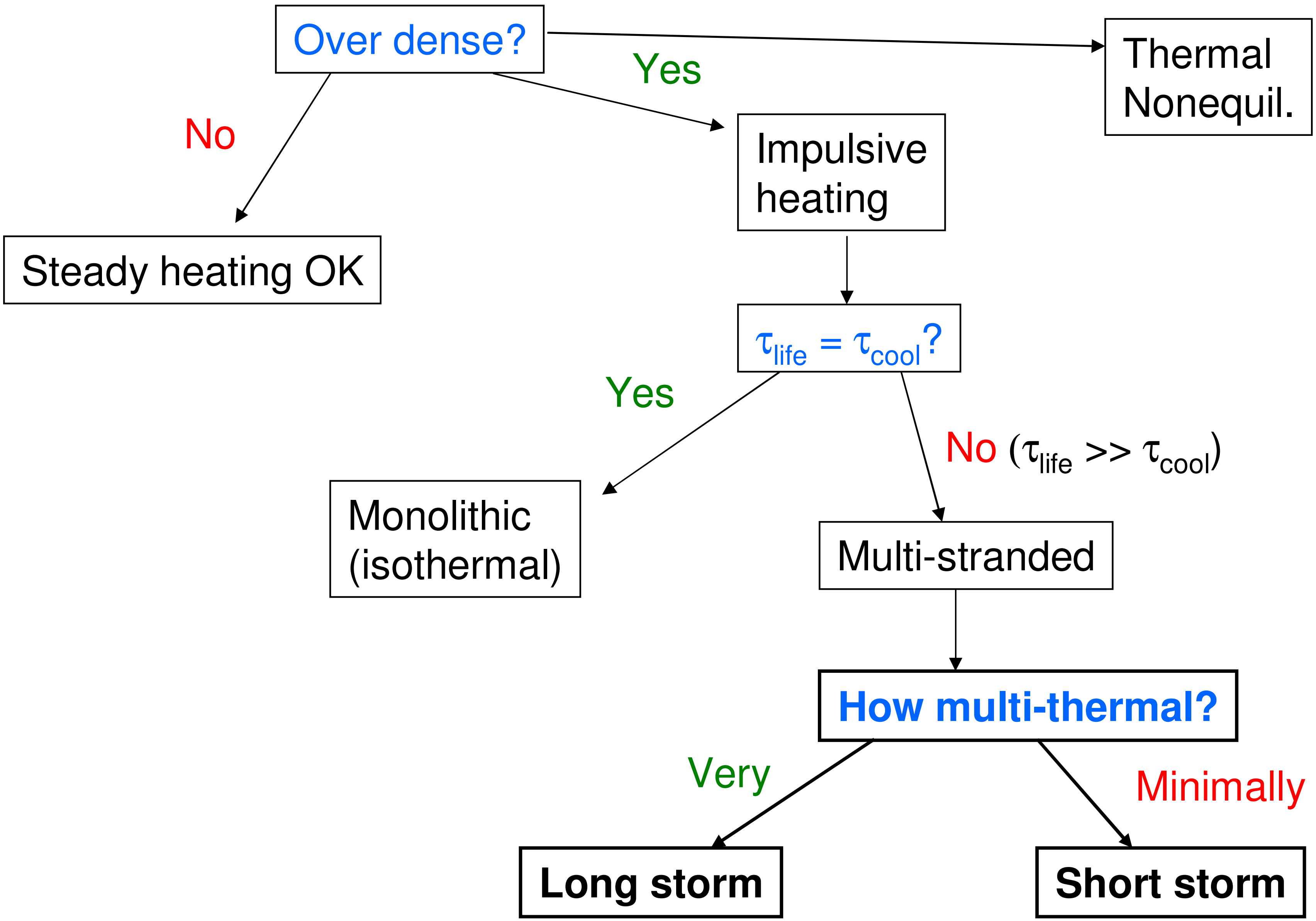
Ugarte-Urra, Winebarger, & Warren (2006)

Lifetime and Thermal Width



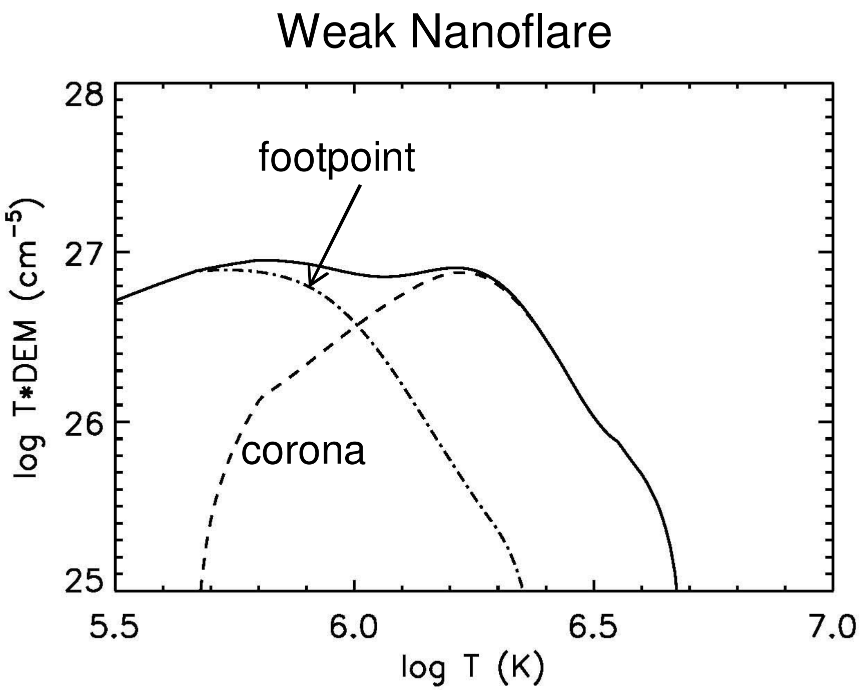
EM(T) at time of max. 195 intensity

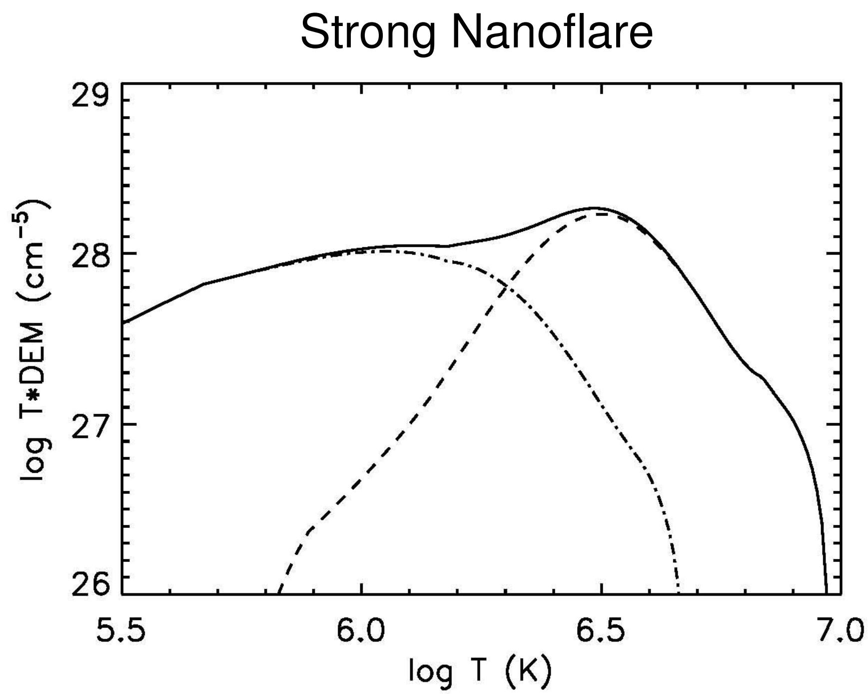
Solutions to the Loops Puzzle



Need lifetime / thermal width consistency check

(Super) Hot Plasma

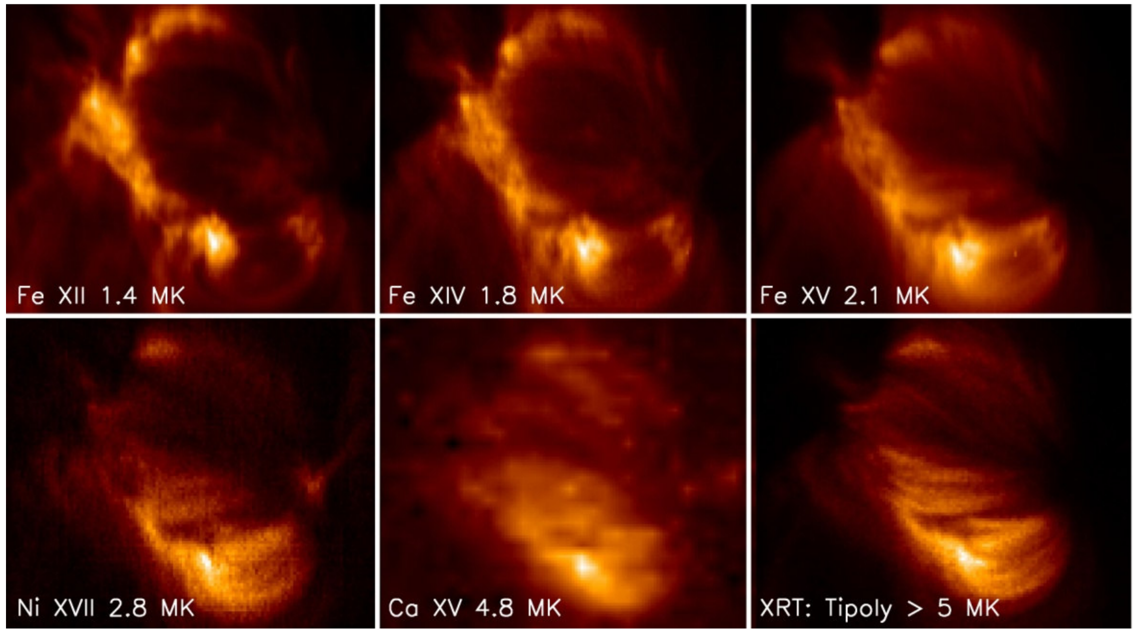


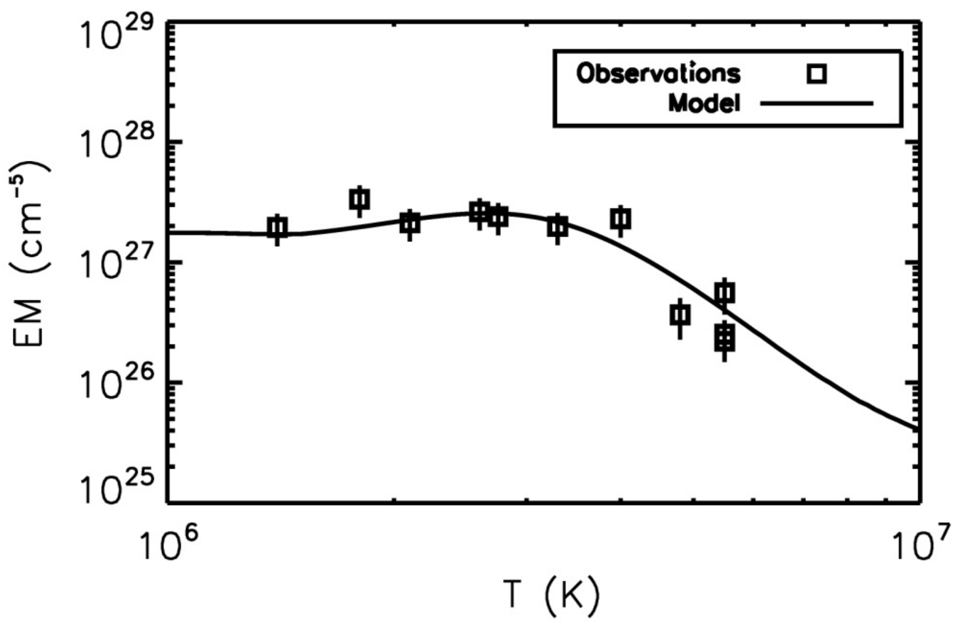


Hot plasma predicted to be **very faint**:

- Super hot plasma cools very quickly (short-lived)
- Takes time for evaporation to fill the loop (small density & EM)

Seen by CORONAS-F (Zhitnik et al. 2006), RHESSI (McTiernan 2008), XRT (Siarkowski et al. 2008; Schmelz et al. 2008; Reale et al. 2008); EIS (Patsourakos & K 2008; Ko et al. 2008)

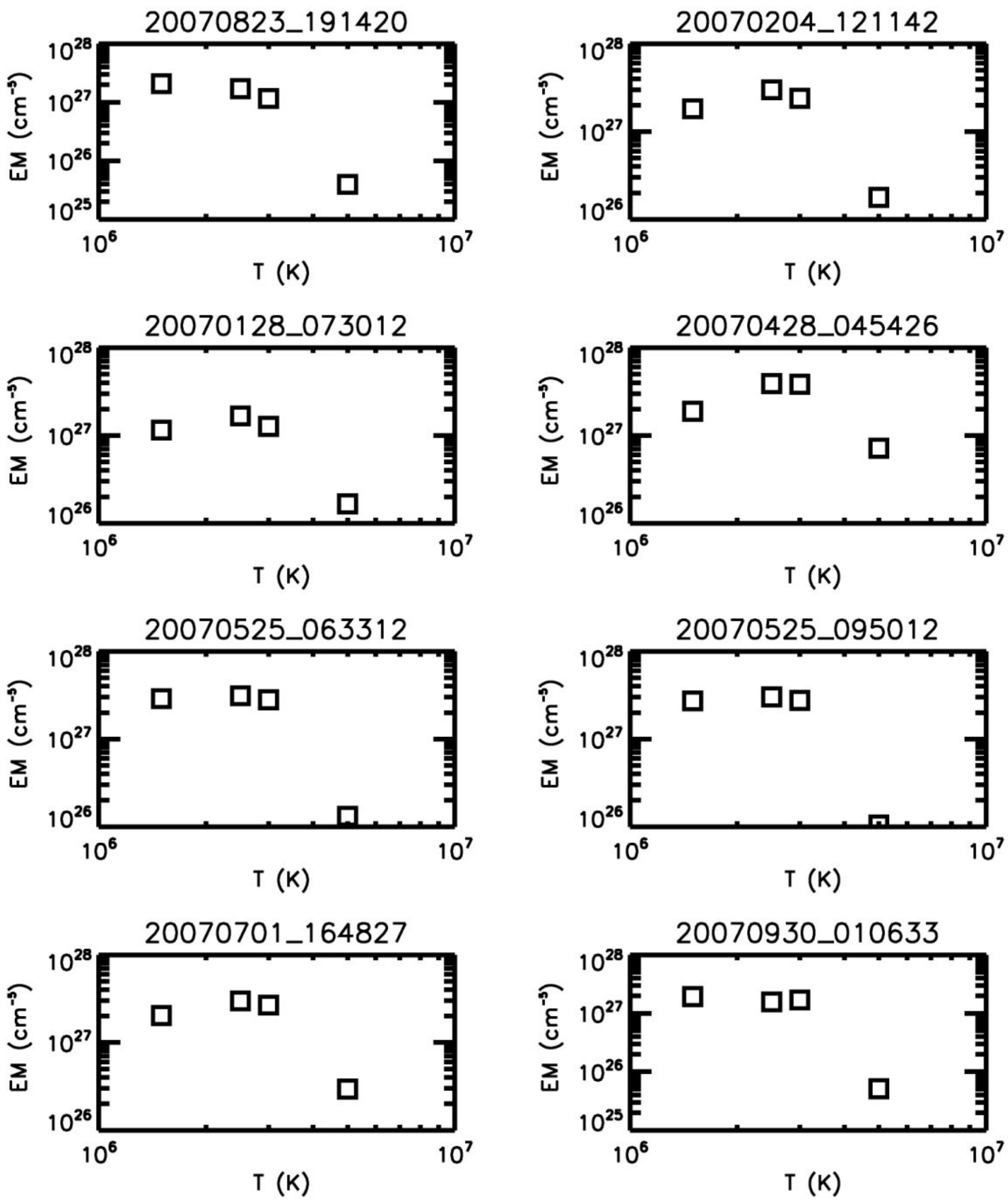




Hinode/EIS:

Fe XII – XVII
Ca IV – VI
Ni XVII

Patsourakos & Klimchuk (2008)

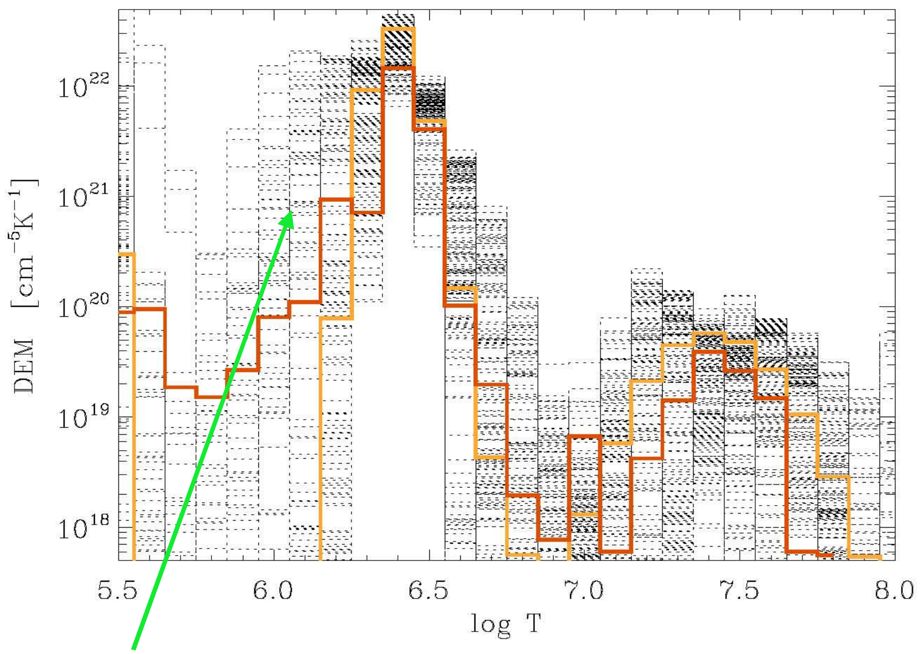


Different Active Regions

Fe XII, Fe XV, Ni XVII, Fe XVII

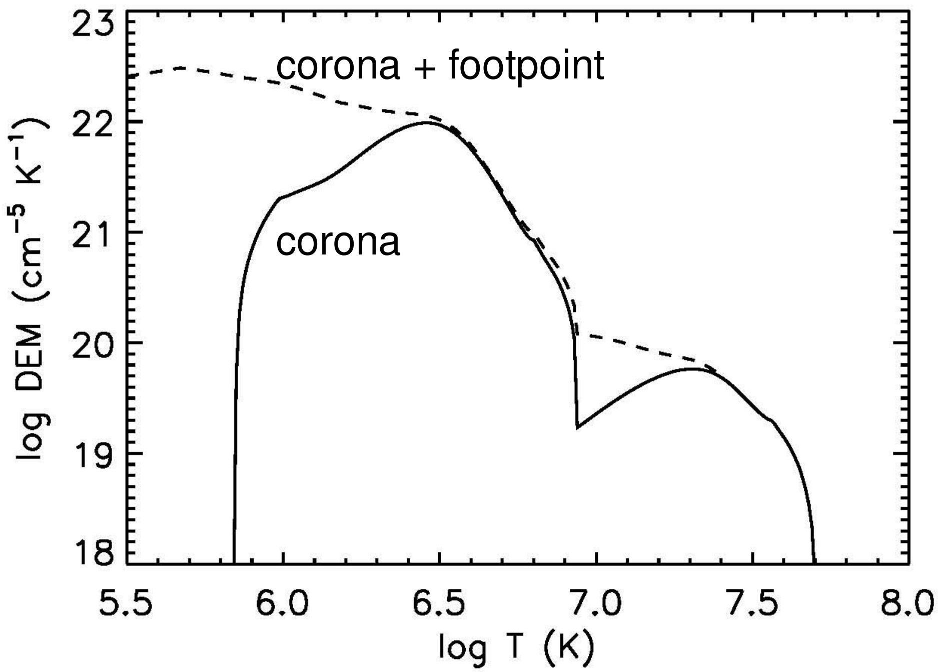
Hinode / XRT (Schmelz et al. 2008)

Observation



Cool part not constrained by observations

Simulation



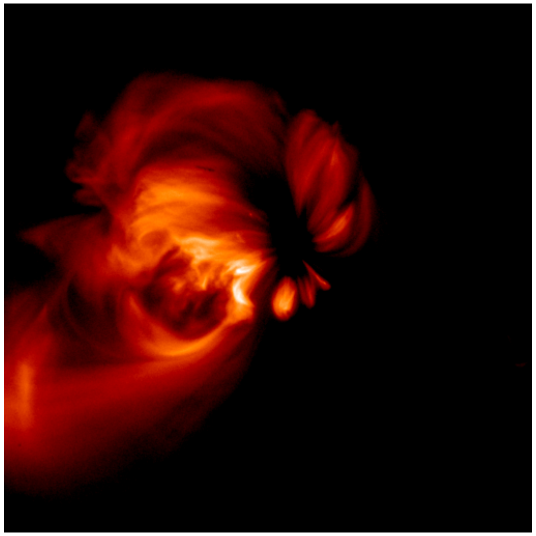
Two component model:
- weak & strong nanoflares
- recur every 1 & 100 hrs
- energy flux ~ 10^7 erg cm^{-2} s^{-1}

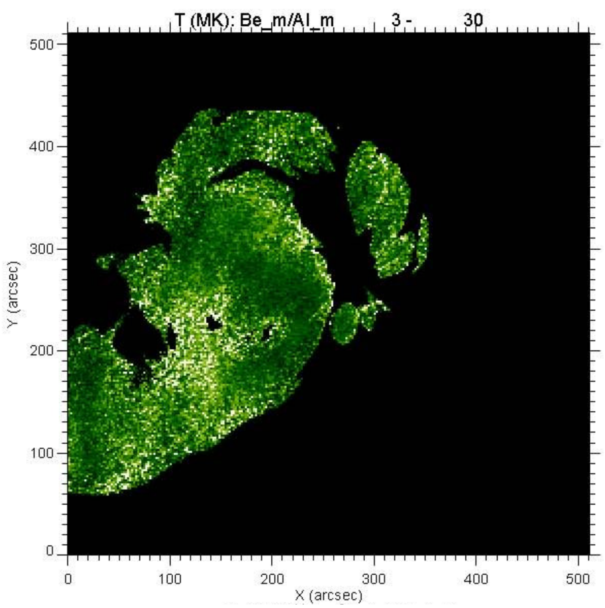
Steady heating ***not*** plausible

20 MK equilibrium loop requires:
- energy flux ~ 10^9 erg cm^{-2} s^{-1}
- DC: footpoint velocity ~ 100 km s^{-1}
- AC: fluctuation velocity ~ 1000 km s^{-1}

Hinode / XRT

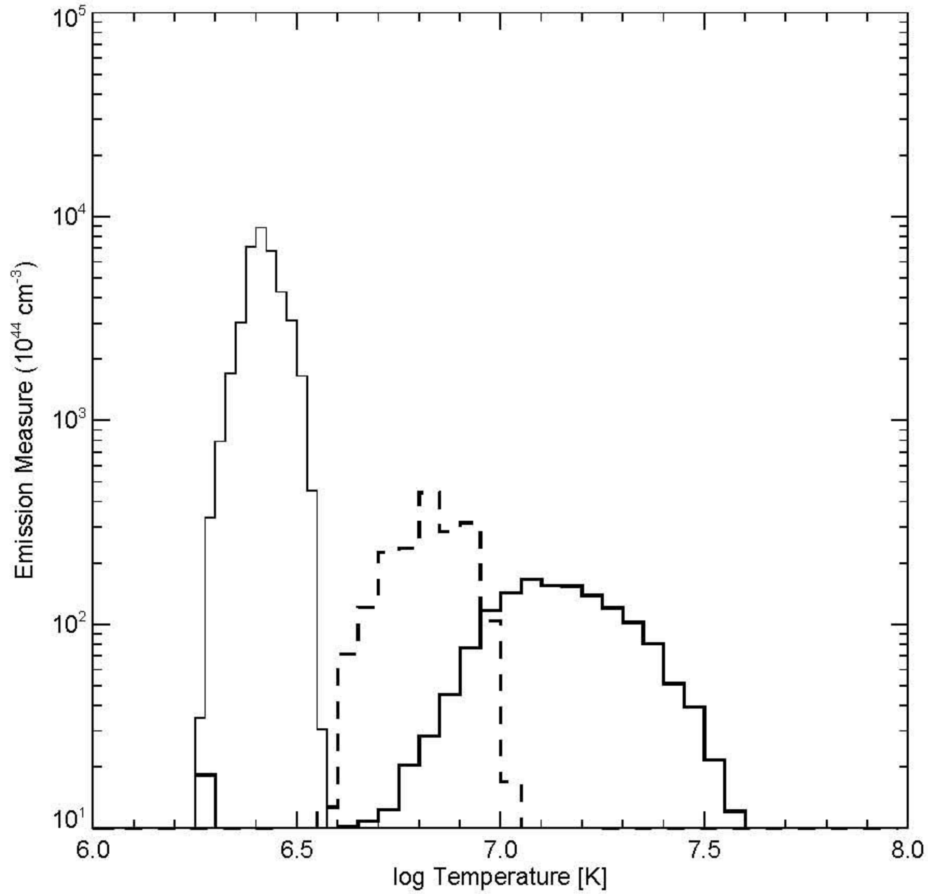
Be_m Image





Be_m/Al_m T map

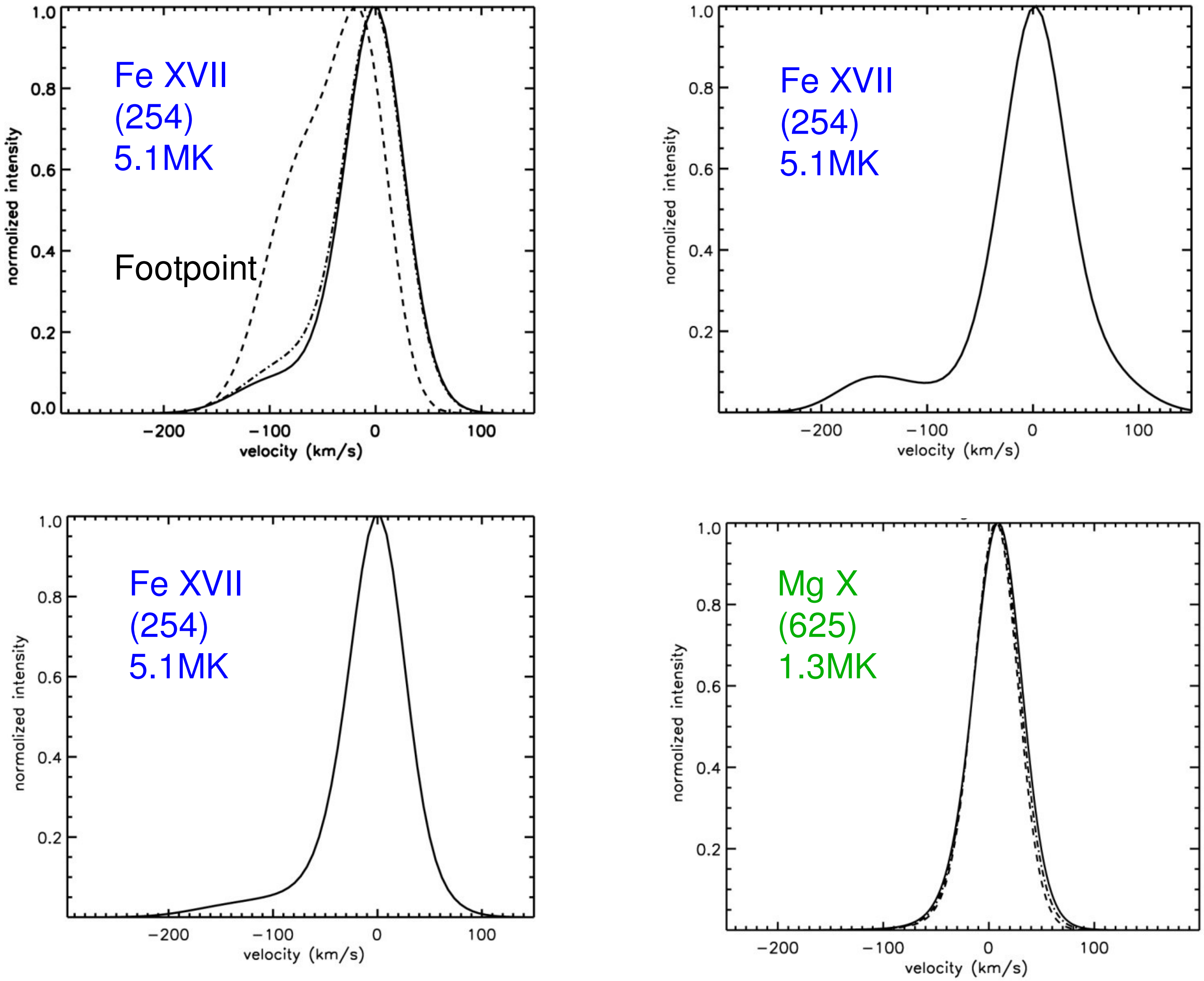
EM (cm^{-3})



Log T

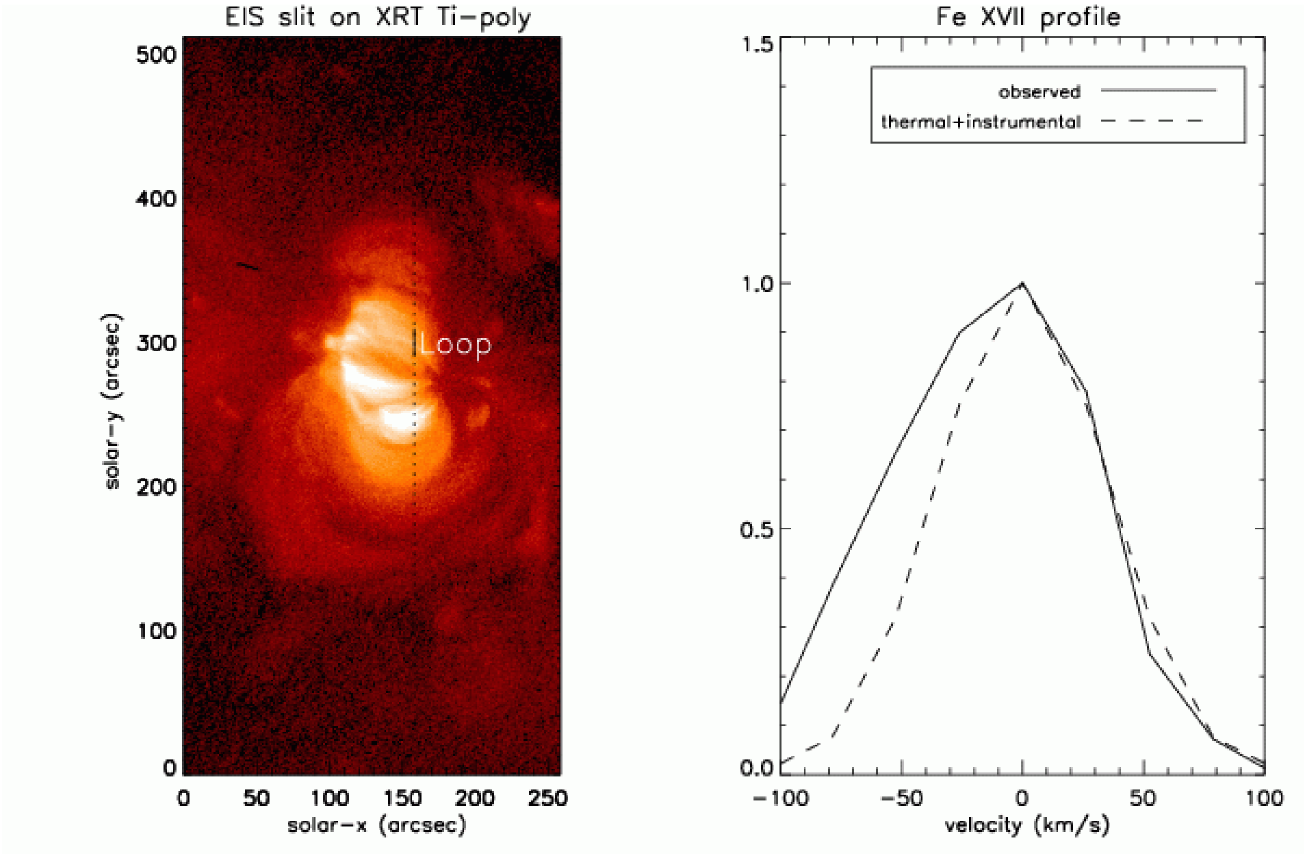
Reale et al. (2008)

Simulated Line Profiles



Patsourakos & Klimchuk (2006)

Observed Fe XVII Profile

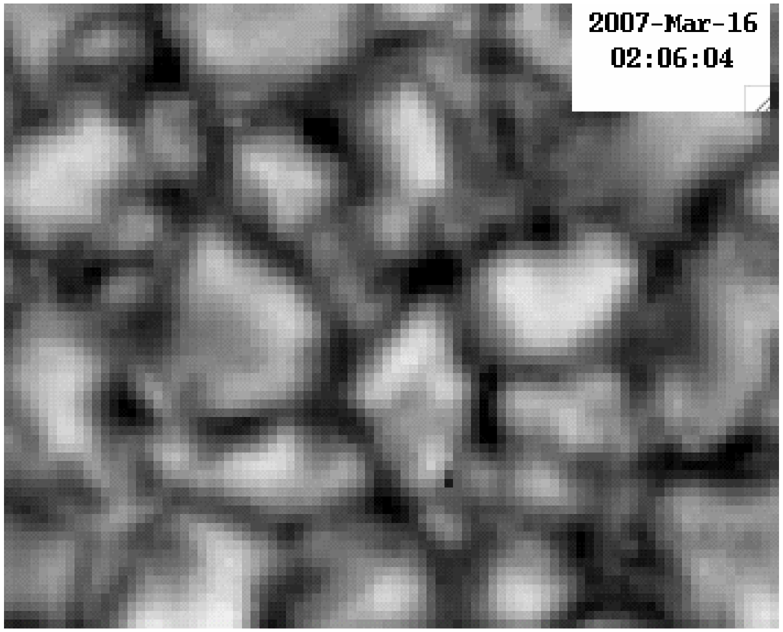


EIS sit and stare observations

See also Hara et al. (2008)

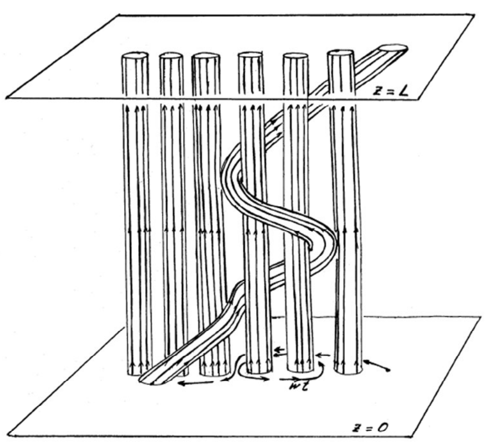
“Reconnection” of Tangled Coronal Fields

Hinode / SOT G-band

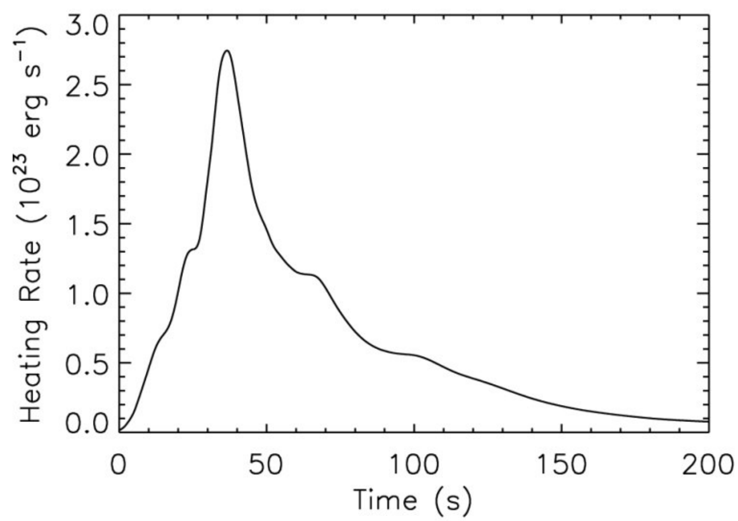


- Coronal magnetic field becomes tangled and twisted by random footpoint motions associated with photospheric convection.

- Impulsive heating occurs via the secondary instability when the misalignment angle between adjacent strands reaches a critical value.



Parker (1983), Priest et al. (2002)

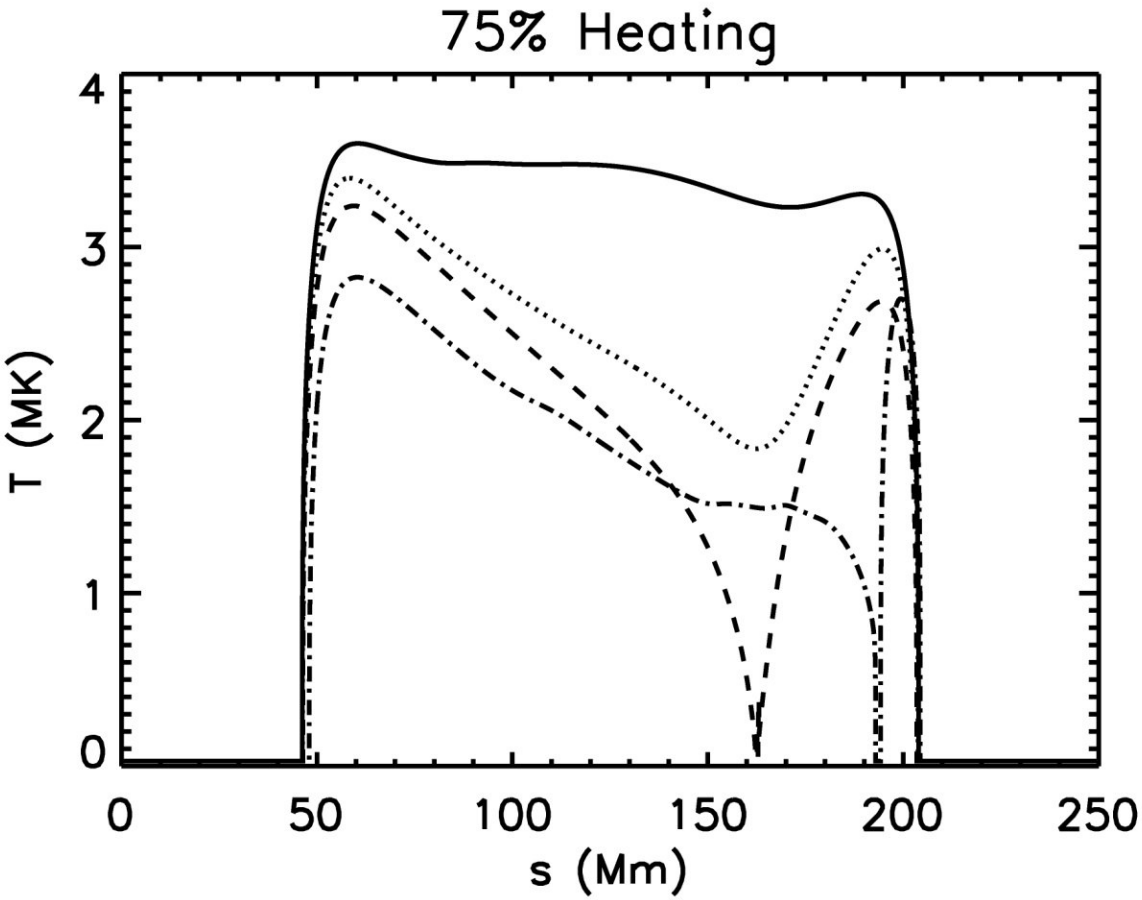


Dahlburg, Klimchuk, & Antiochos (2003, 05, 08)

THERMAL NONEQUILIBRIUM

- Dynamic behavior with steady heating!
- No equilibrium exists if the heating is concentrated close to the loop footpoints
- Cool condensations form and fall in cyclical pattern

Serio et al. (1981), Antiochos & Klimchuk (1991), Karpen et al. (2001-2008), Mueller et al. (2003-2005), Mok et al. (2008)



t = 2950, 4500, 4850, 5750 s

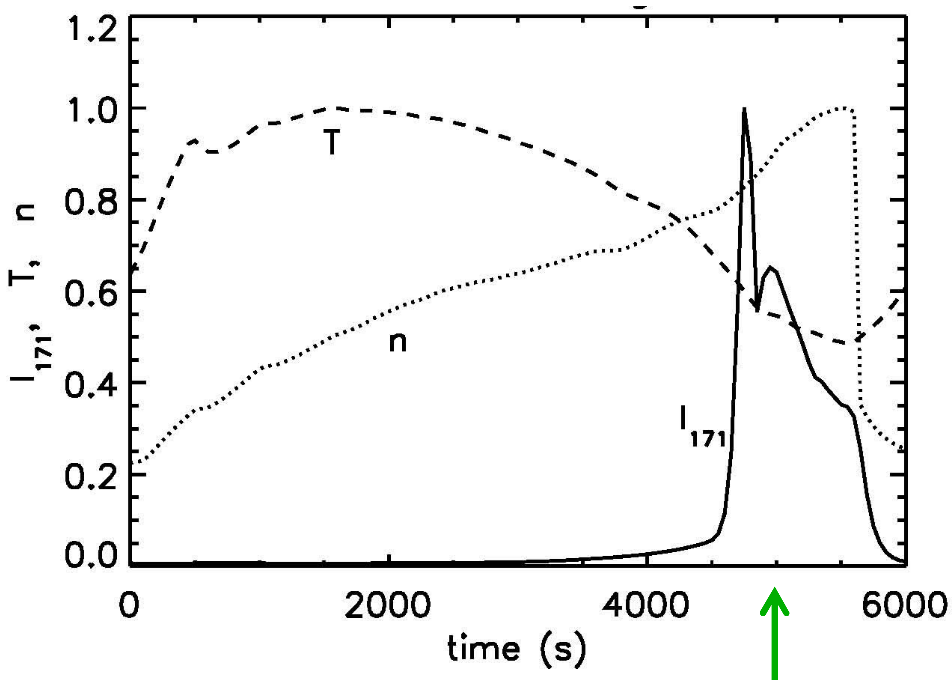
Heating scale height = 5 Mm = L/15
Imbalanced heating (right leg = 75% left leg)

With Judy Karpen

Monolithic Loop

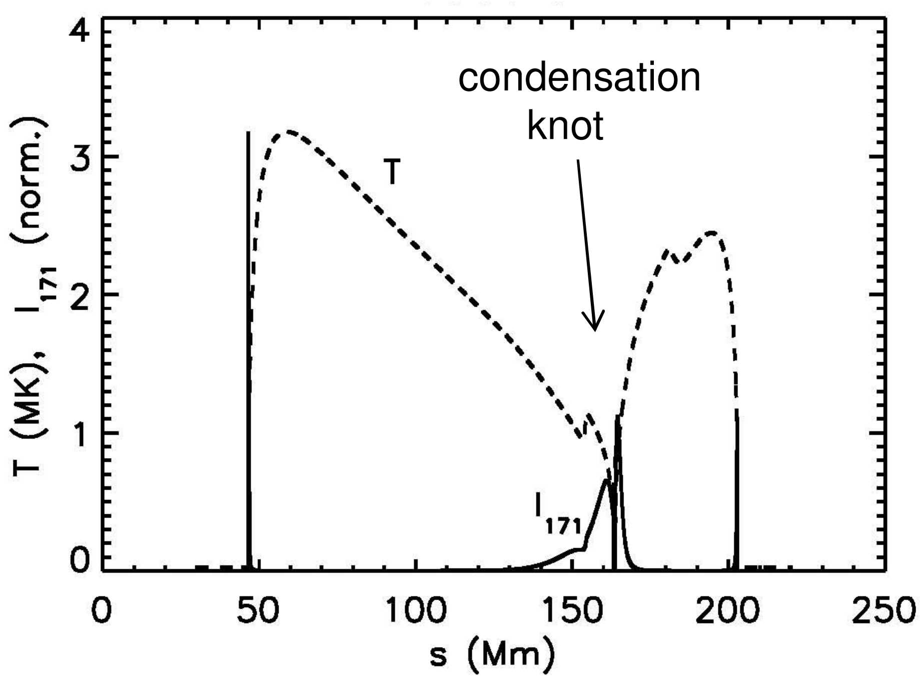
171 Light Curve

(averaged over corona)



171 Intensity Profile

(5000 s)

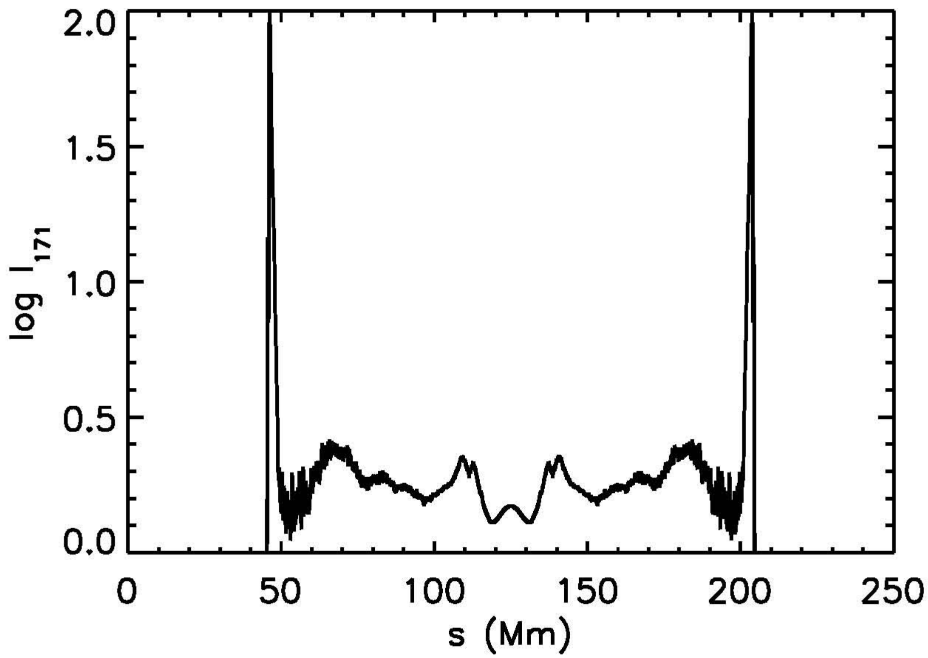


Intensity profile **not** like observed (uniform)

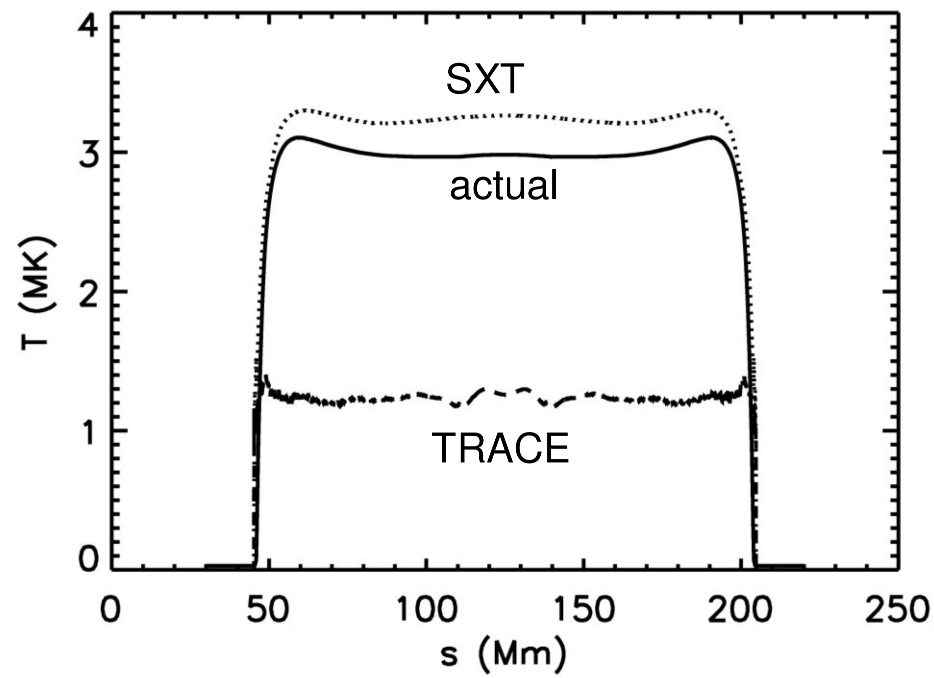
With Judy Karpen

Multi-Strand Bundle

171 Intensity Profile
(time average)



Temperature Profile
(time average)



"Uniform" intensity profile
Flat temperature profile
Over dense in TRACE: $n/n_{eq} = 23$

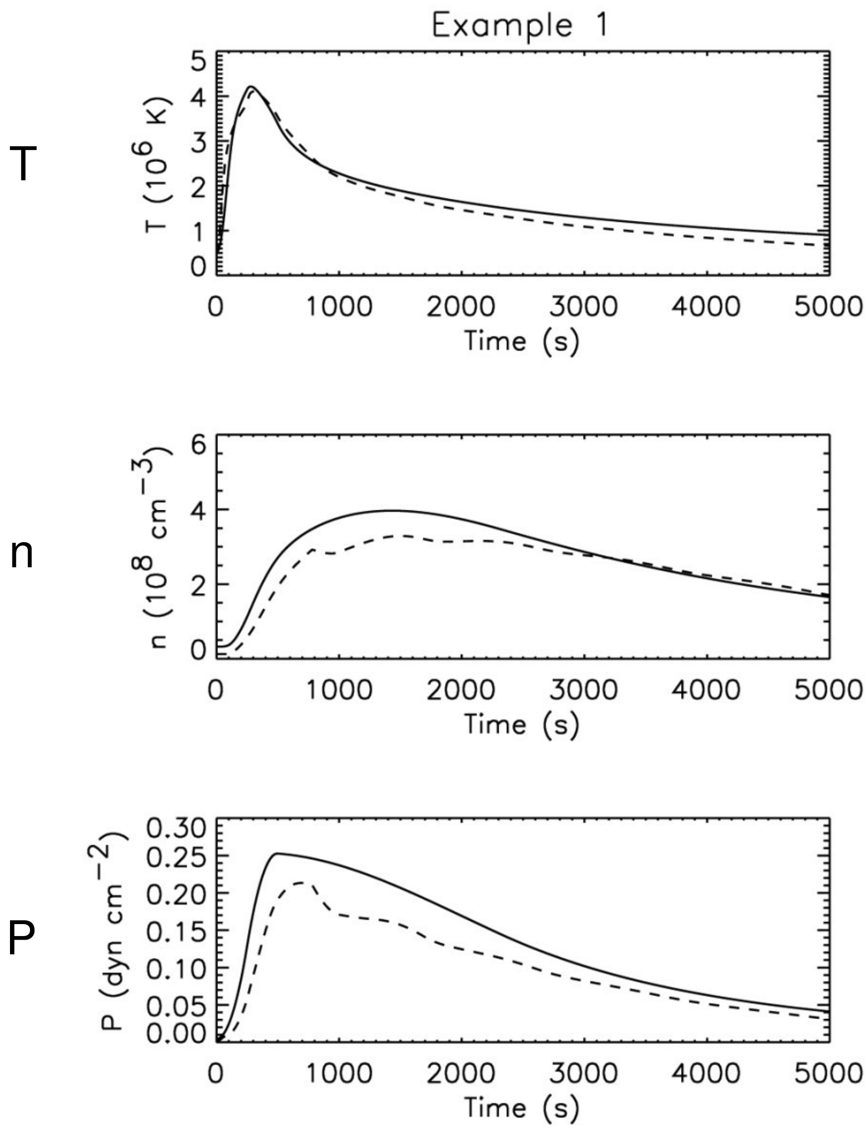
Issues with Thermal Nonequilibrium

- Condensations repeat on timescale > 2 hr
- Observed 171 loop lifetimes ~ 1 hr
- Strands must be sufficiently out of phase to produce “uniform” intensity profiles, but not so much as to produce long-lived loops
- Plausible? Even if phasing correct for one cycle, not likely to be maintained for subsequent cycles.

Key Points

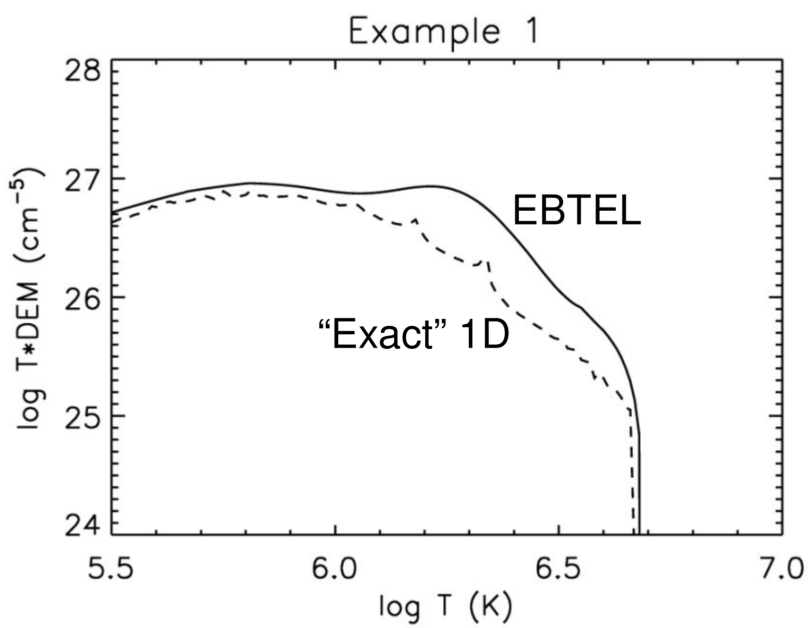
- Strong evidence that many loops are bundles of unresolved strands heated by storms of nanoflares
  - True of all loops?
  - True of diffuse corona?
- Strong evidence of super-hot (~10 MK) plasma in active regions
  - Can only be produced by nanoflares
- Nanoflares are likely due to the secondary instability occurring in tangled coronal magnetic fields
- All coronal heating mechanisms produce impulsive energy release on individual magnetic flux surfaces (field lines)
  - but rapid repetition gives quasi-equilibrium conditions
- Some EUV loops may be produced by thermal nonequilibrium in multi-strand bundles

Enthalpy Based Thermal Evolution of Loops (EBTEL)



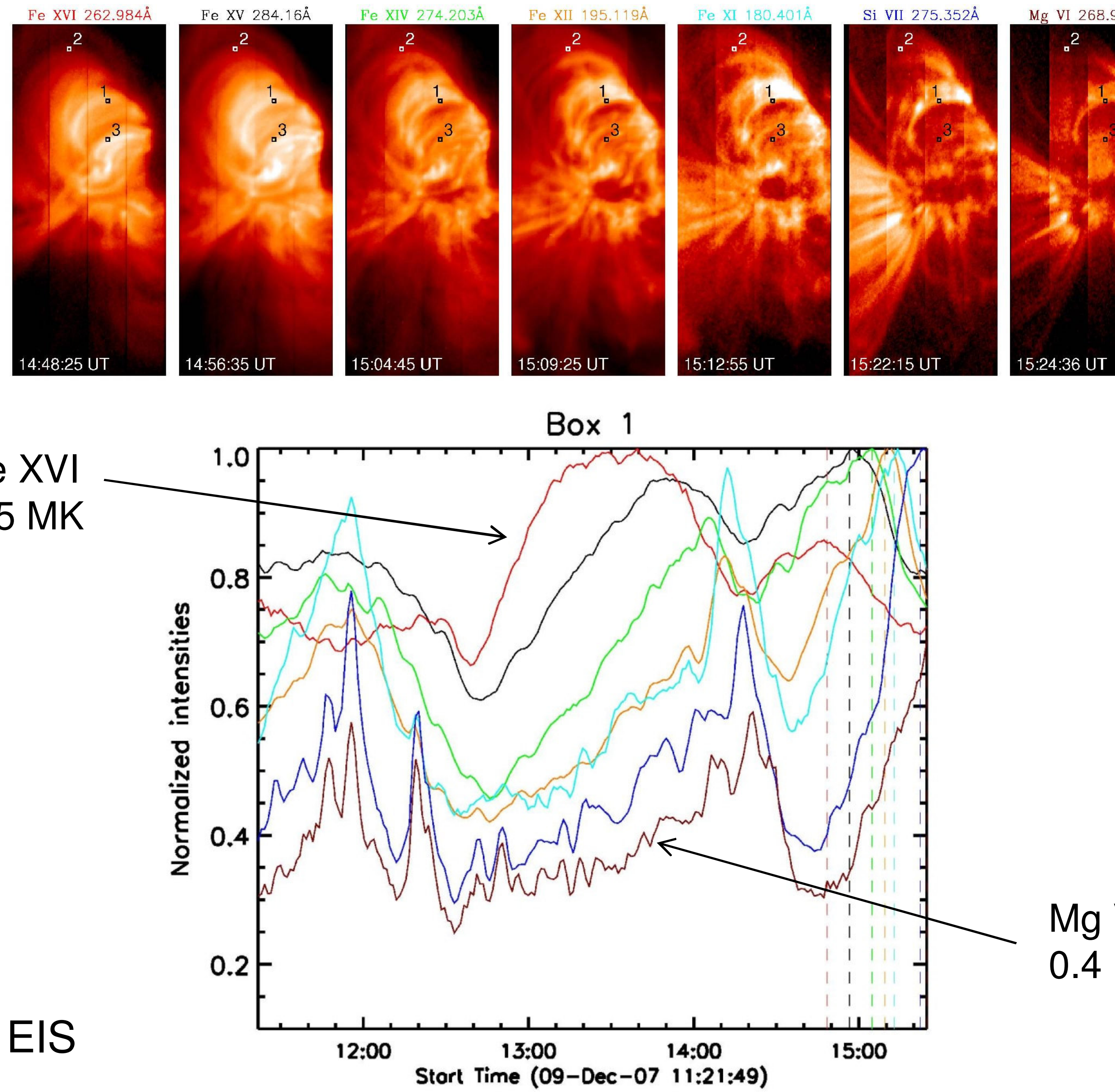
500 s nanoflare

“0D” hydro code
Easy to use, runs in IDL
Any heating function, H(t)
DEM(T,t) in transition region
Heat flux saturation
Non-thermal electron beam
10^4 time faster than 1D codes



Klimchuk, Patsourakos, & Cargill (2008)

Backup Slides



Fe XVI
2.5 MK

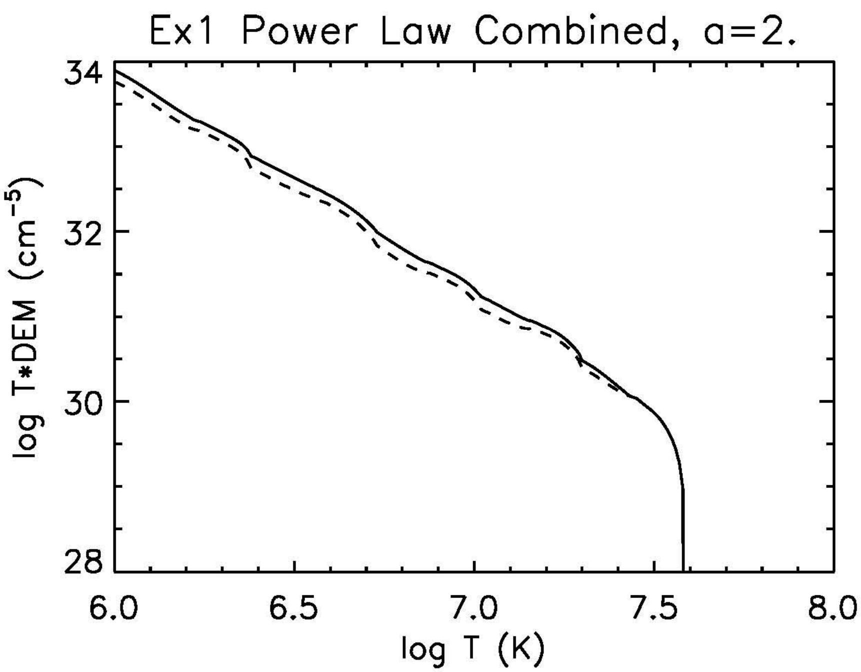
Mg VI
0.4 MK

Hinode / EIS

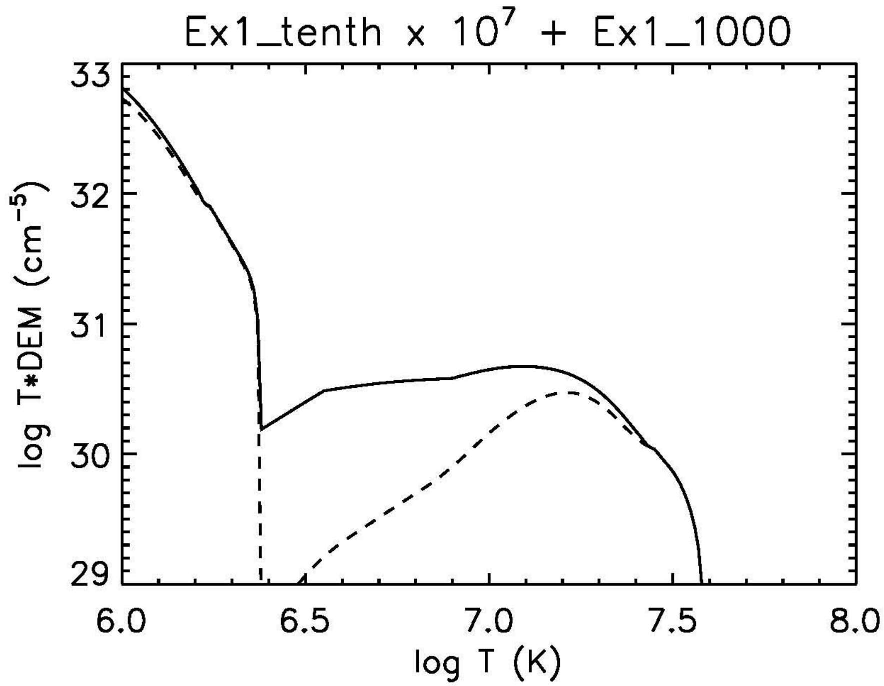
Ugarte-Urra, Warren, Brooks (2008)

DEM(T) depends on nanoflare energy distribution

Nanoflare Power Law



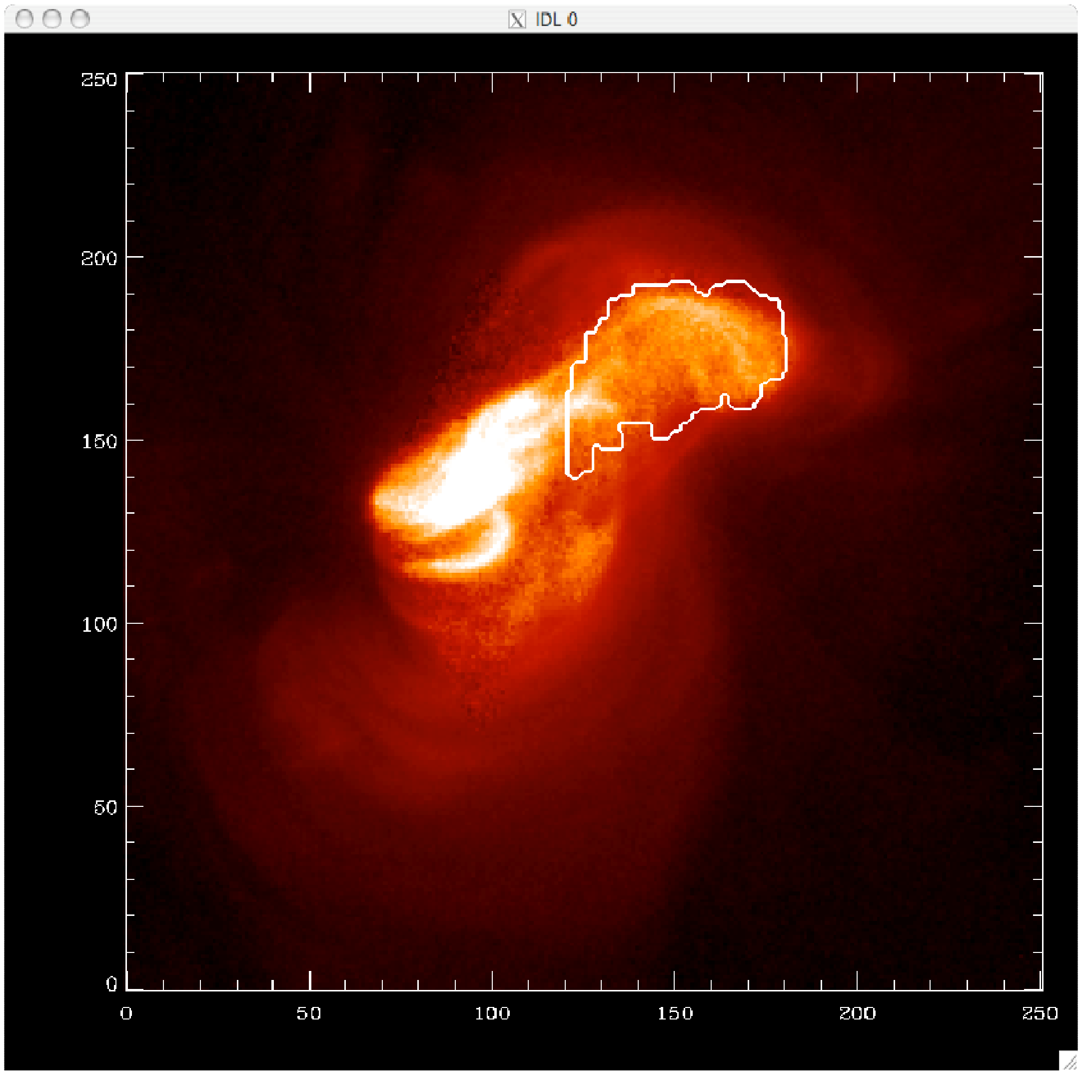
Two Nanoflare Components



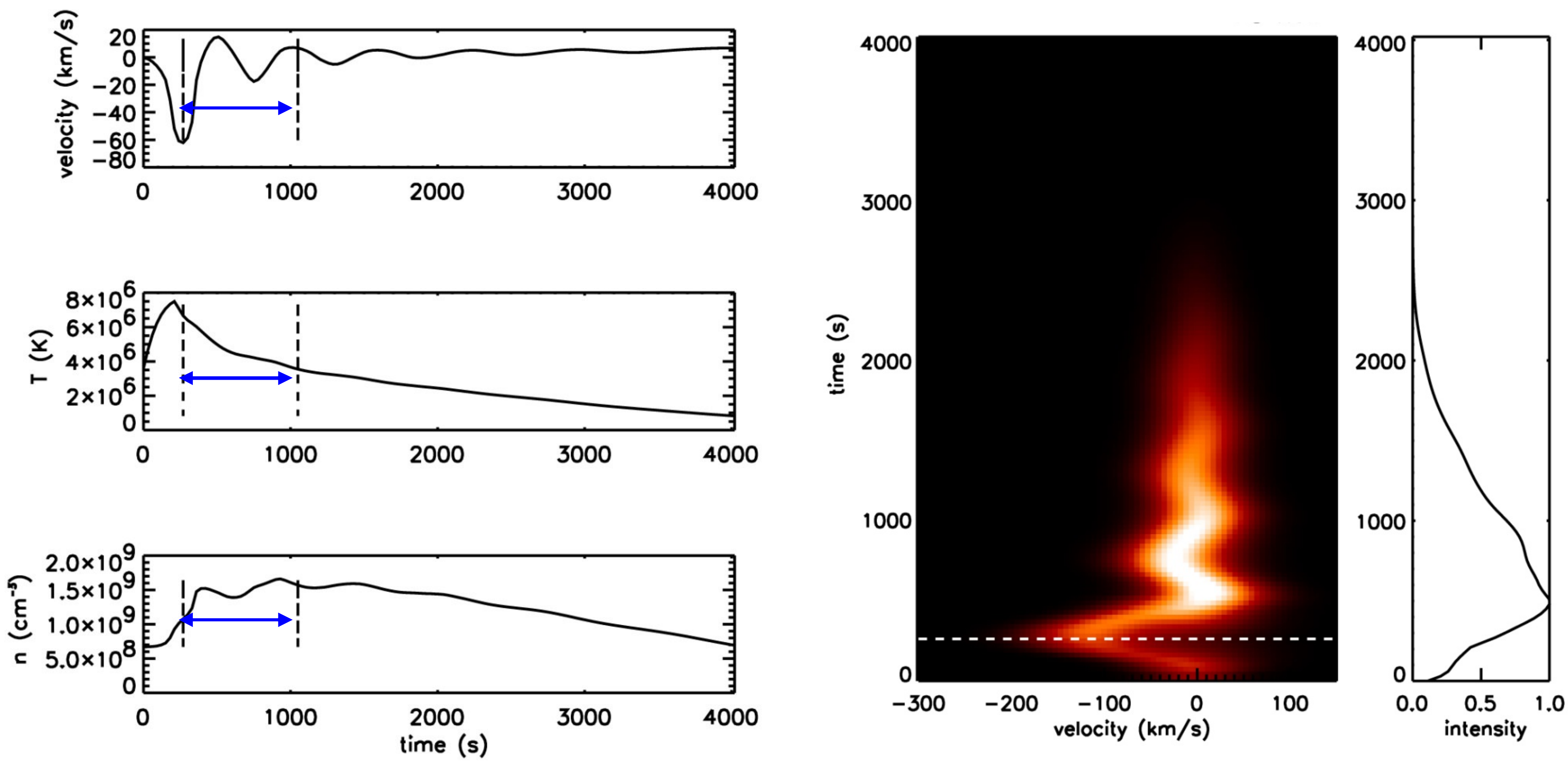
Seems to best fit the observations.

Surprising! Important! Uncertain.

Schmelz et al. (2008)



Fe XVII (254)



Patsourakos & Klimchuk (2006)