Coronal Loop Models and Those Annoying Observations (!)

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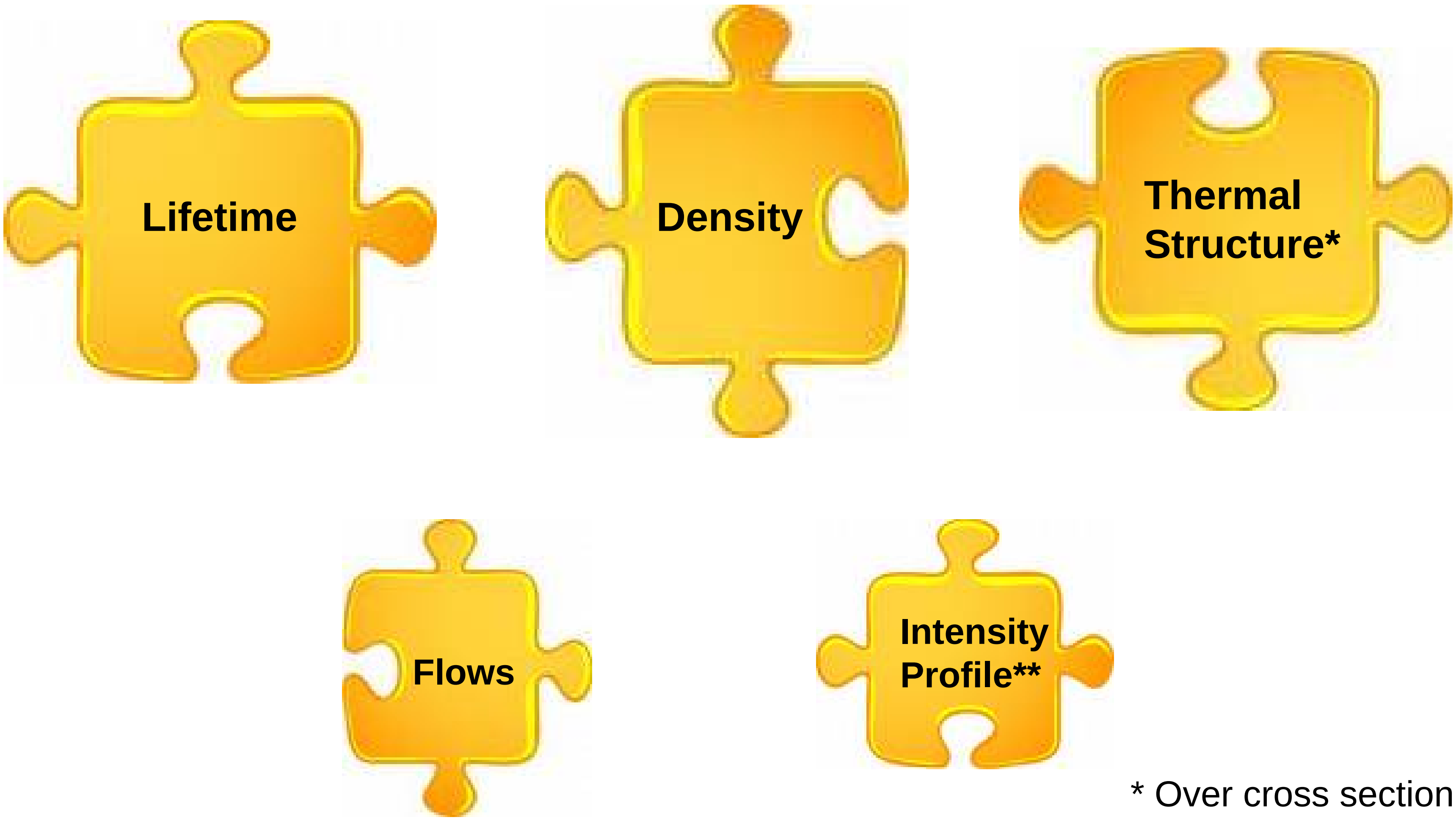
Pieces of the Coronal Loops Puzzle



* 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, Golub, ….

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, ….

Solutions to the Loops Puzzle

Consider a loop.

Over dense?

Solutions to the Loops Puzzle

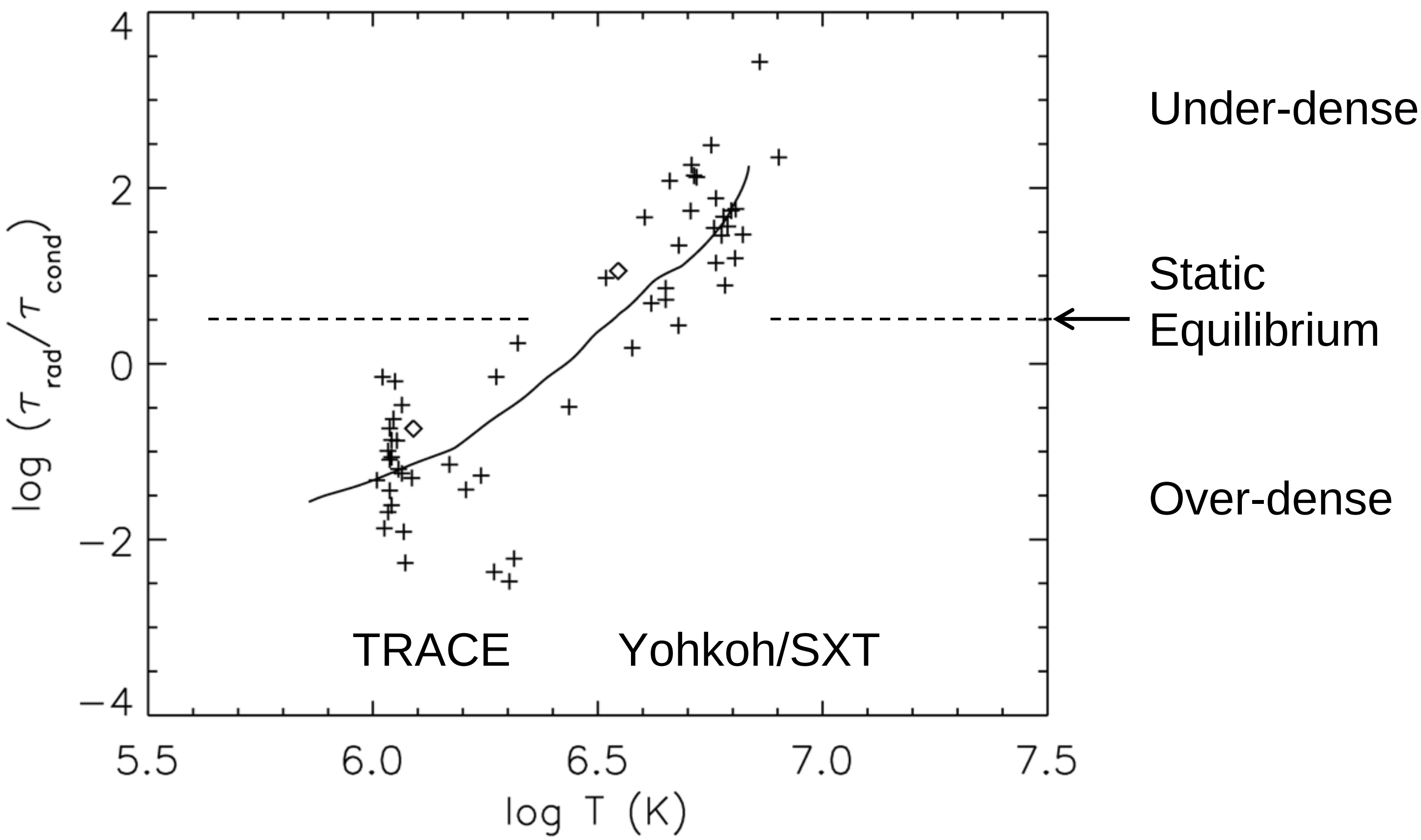
Over dense?

No

Steady heating OK *

* Steady heating not required (not unique solution)

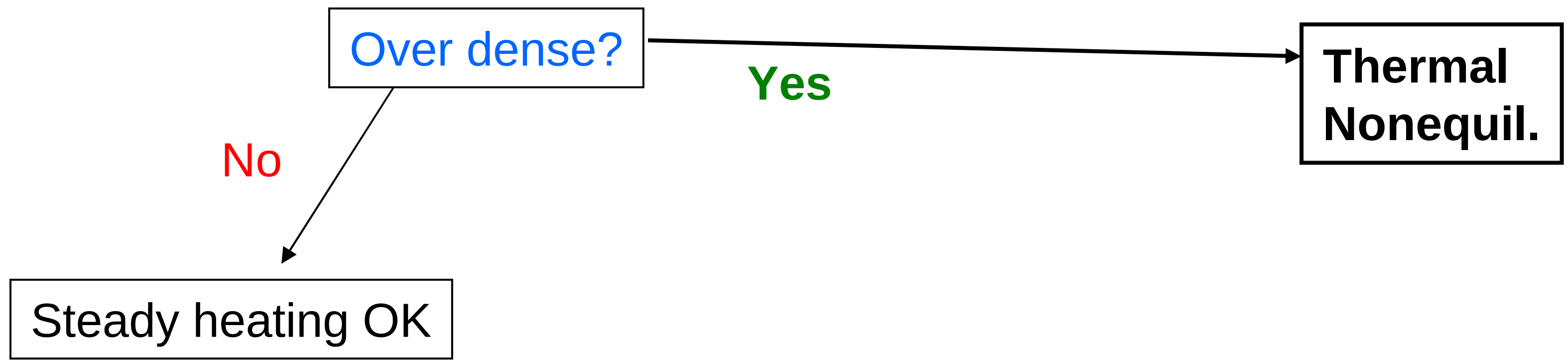
Cooling Time Ratio vs. Temperature



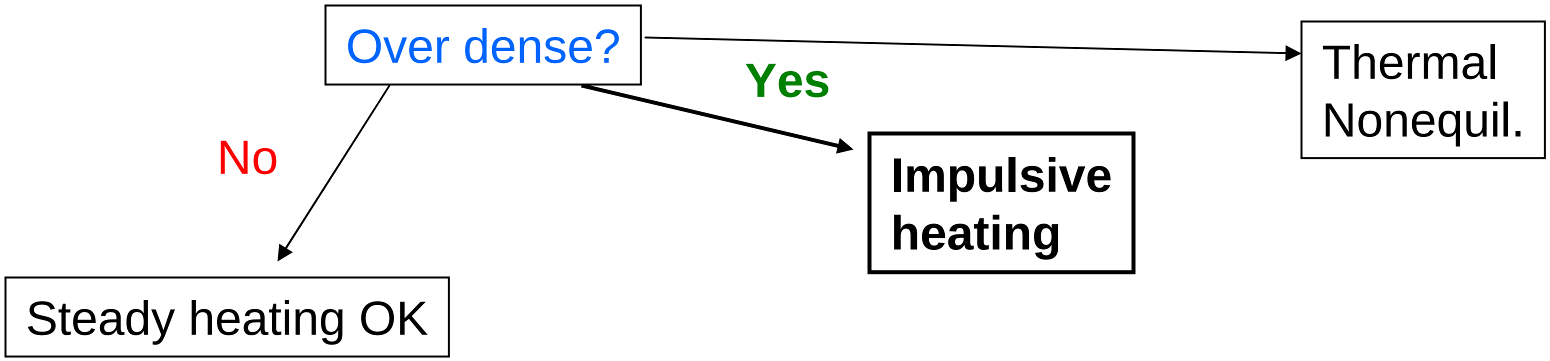
$\tau_{rad}/\tau_{cond} = T^4 / (nL)^2$

Klimchuk (2003, 06)

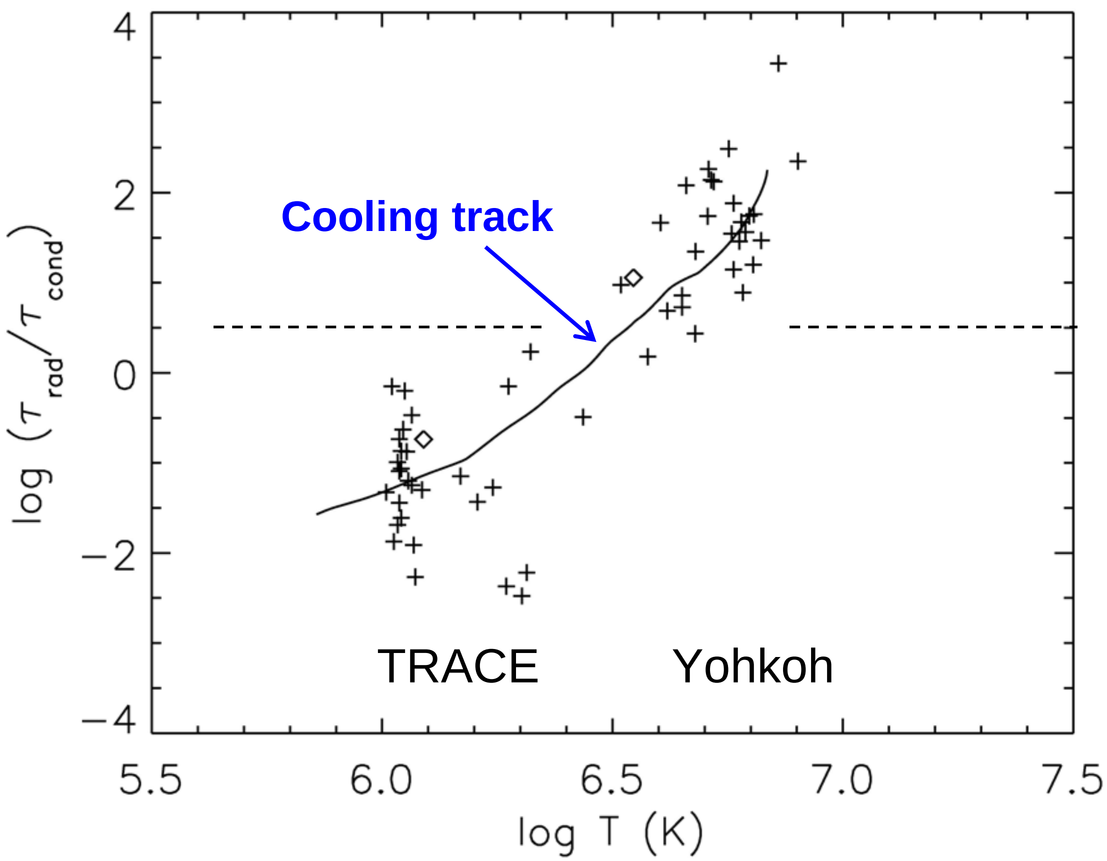
Solutions to the Loops Puzzle



Solutions to the Loops Puzzle



Cooling Time Ratio vs. Temperature



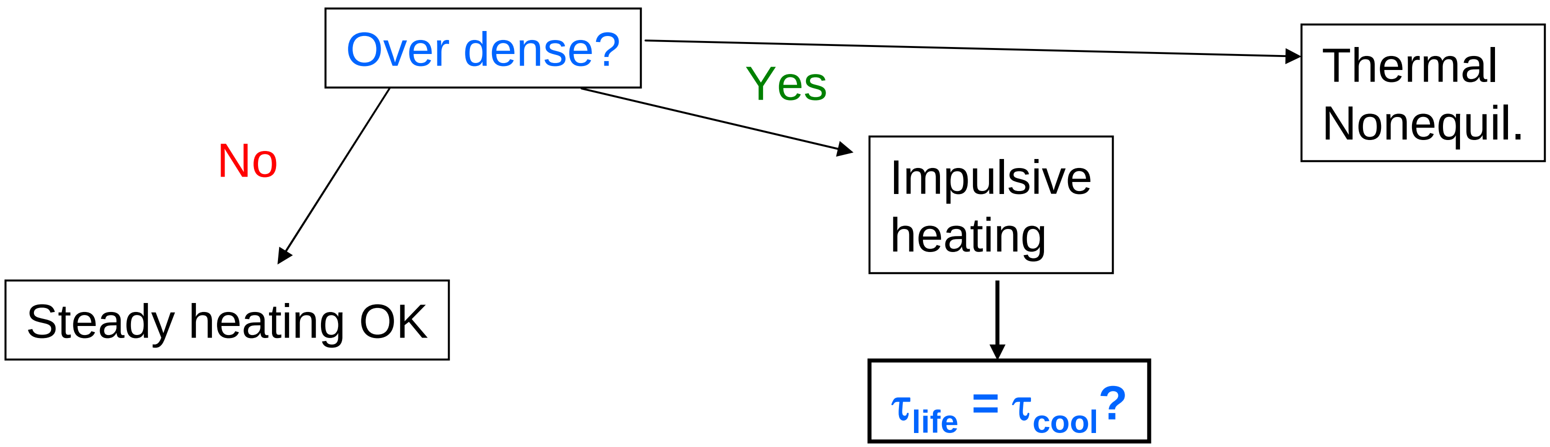
Thermal cond. dominates

Radiation dominates

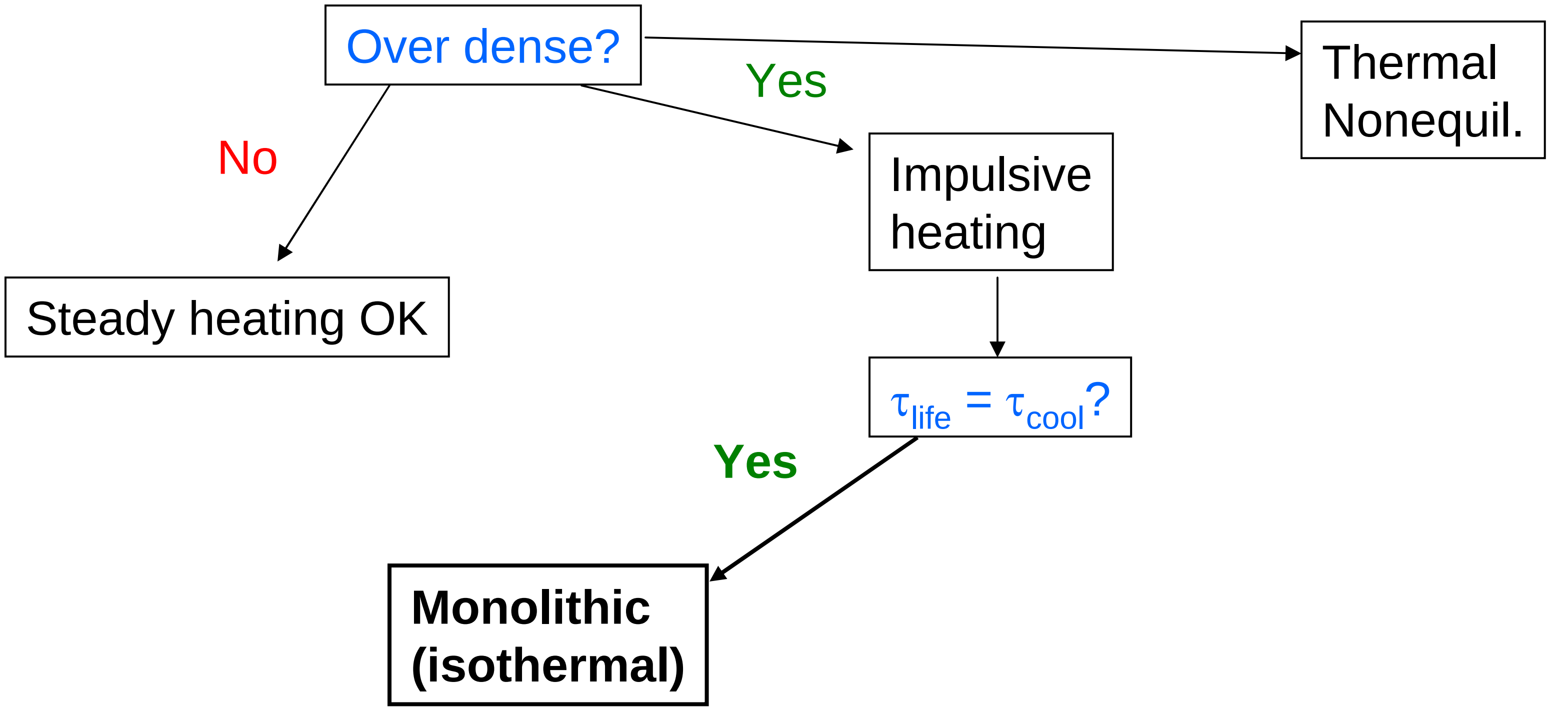
$$\tau_{rad}/\tau_{cond} = T^4 / (nL)^2$$

Klimchuk (2006)

Solutions to the Loops Puzzle

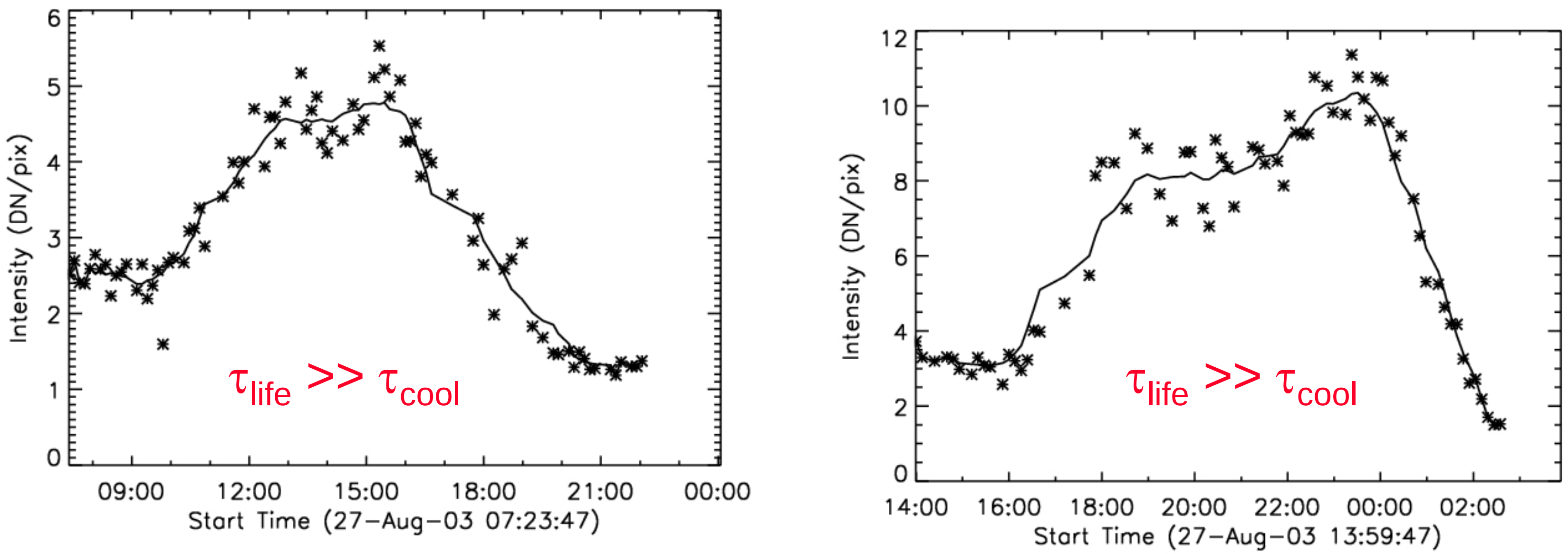


Solutions to the Loops Puzzle



Loop Light Curves

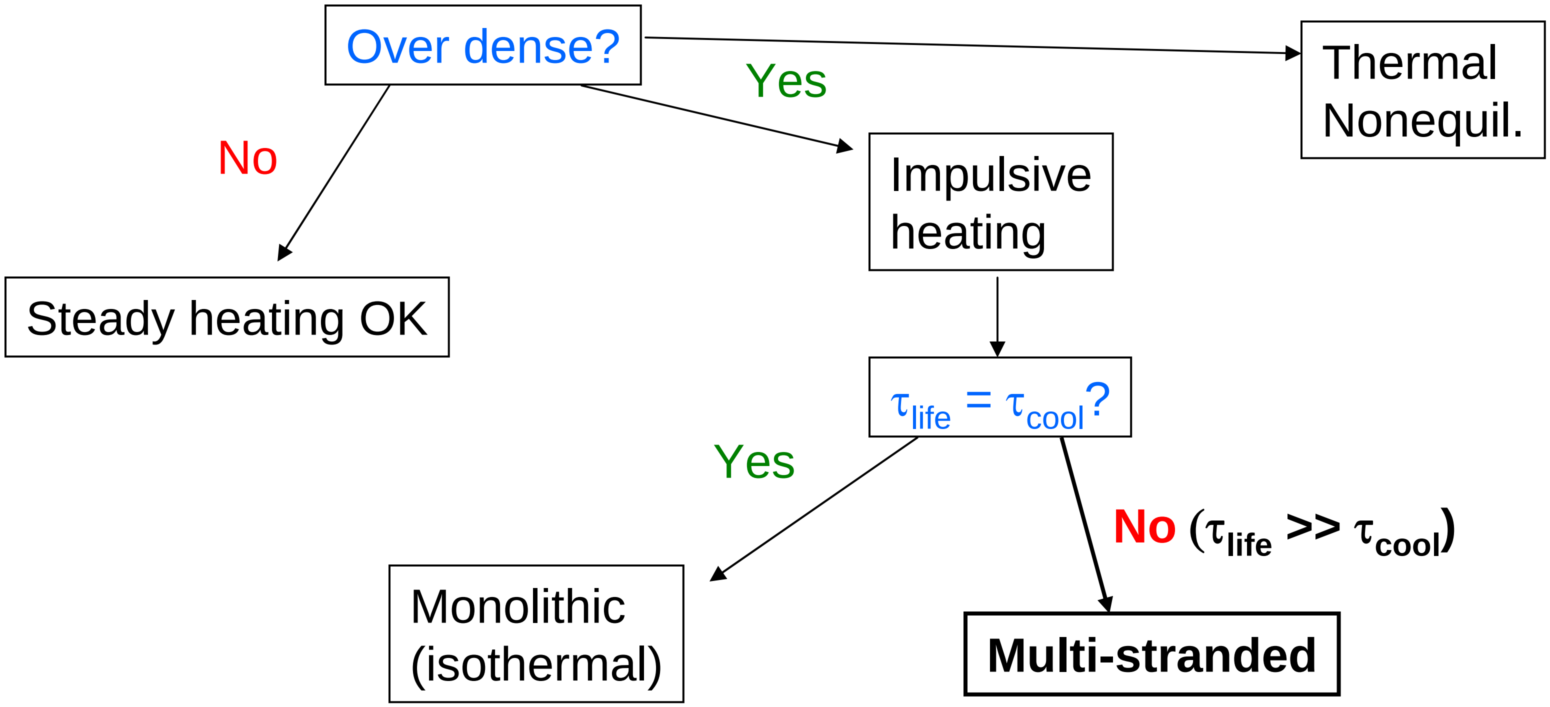
GOES / SXI



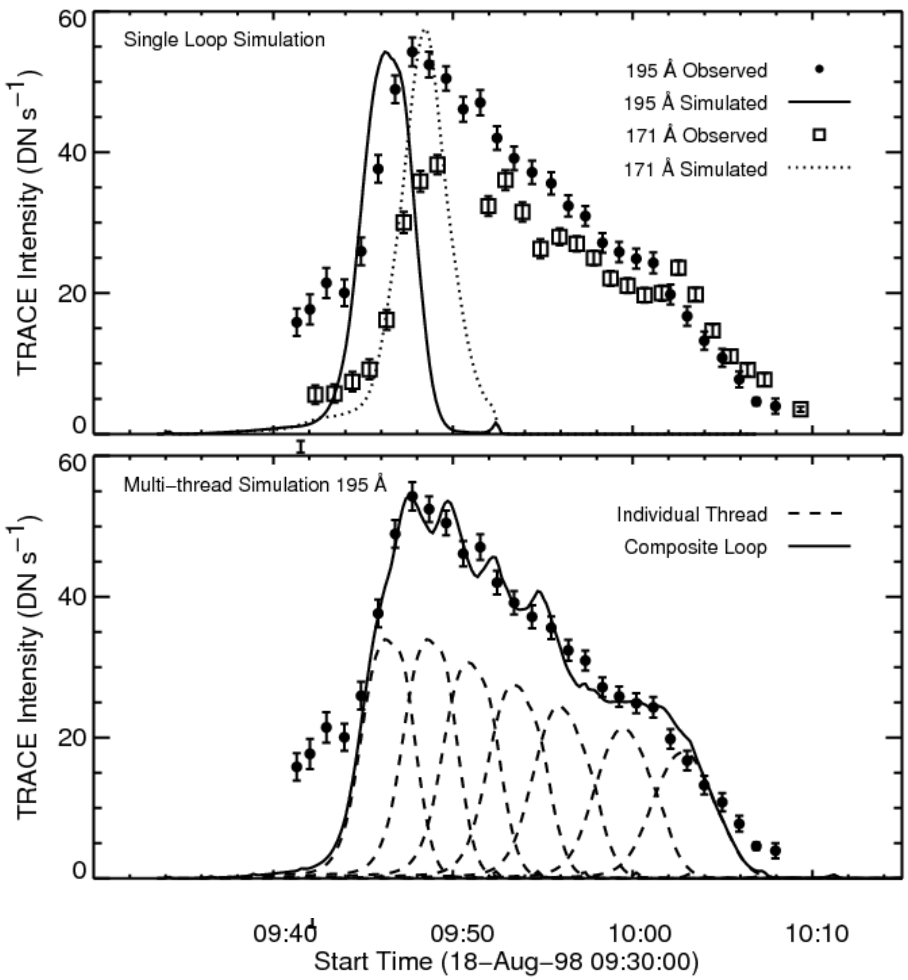
Can be modeled as a self organized critical (SOC) system driven by footpoint shuffling and magnetic field tangling.

Lopez Fuentes, Klimchuk, & Mandrini (2006)

Solutions to the Loops Puzzle



Multi-Stranded Loop

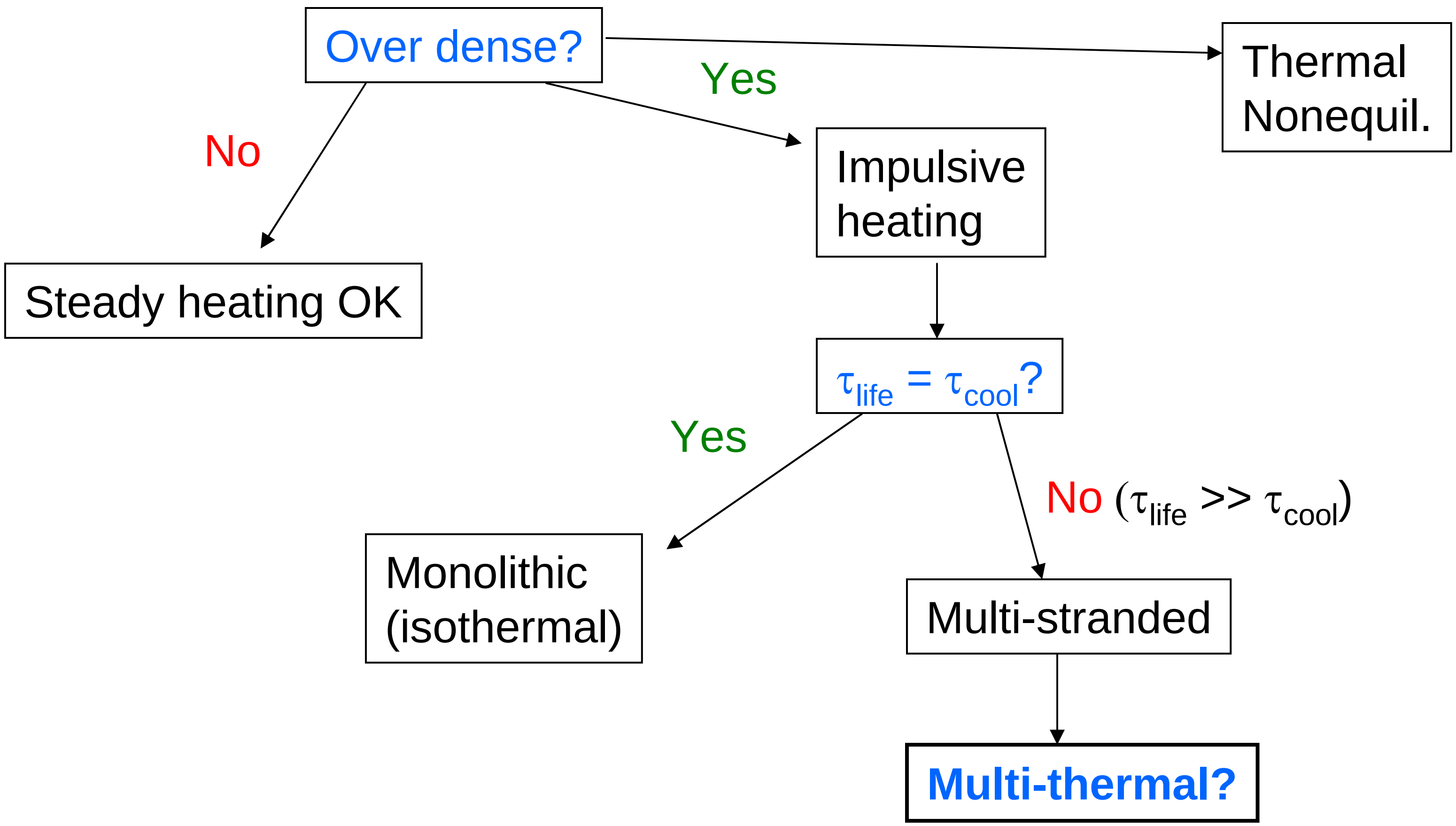


Single nanoflare

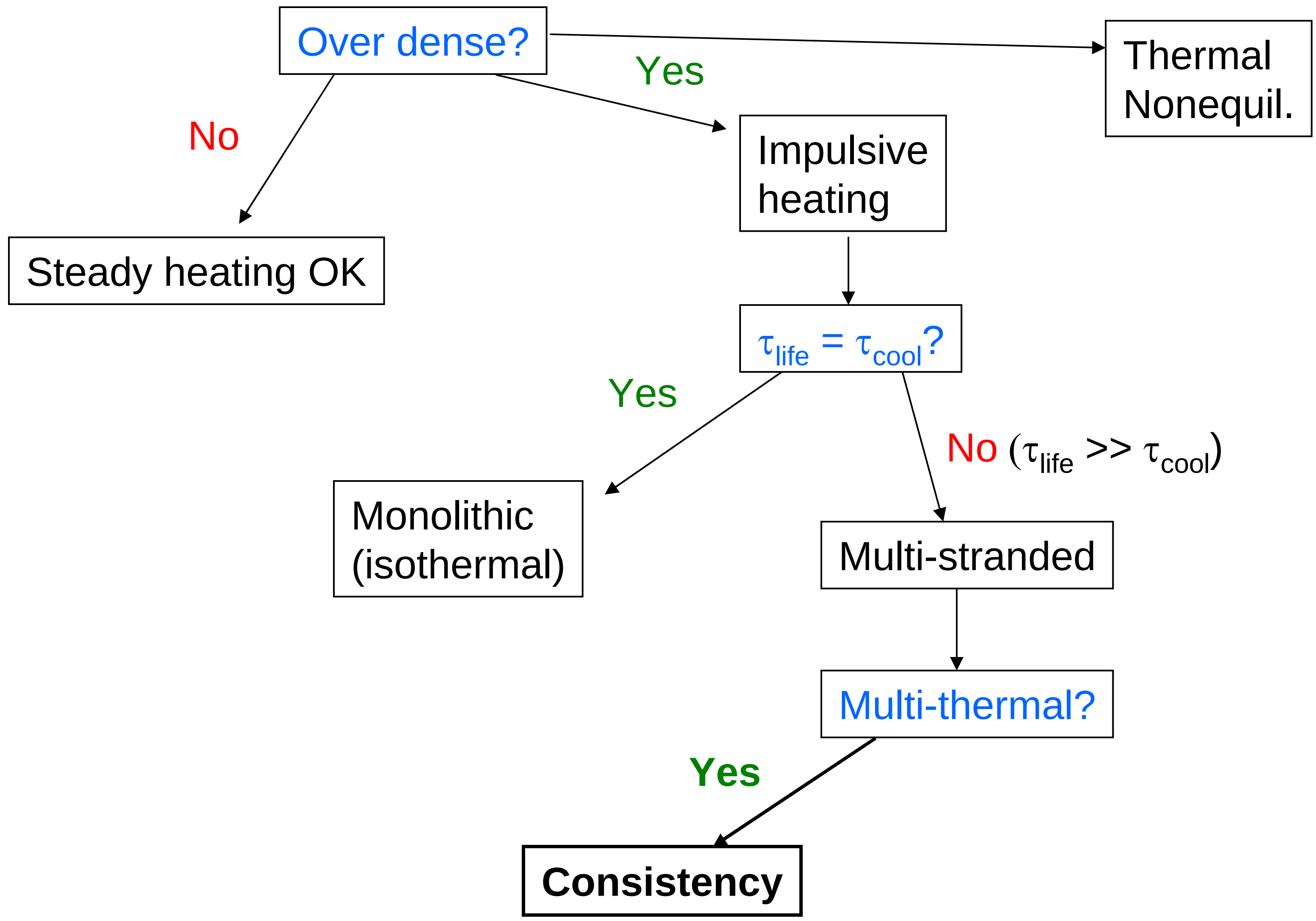
Nanoflare “storm”

Warren, Winebarger, & Mariska (2003)

Solutions to the Loops Puzzle



Solutions to the Loops Puzzle



The Isothermal / Multi-thermal “Debate”

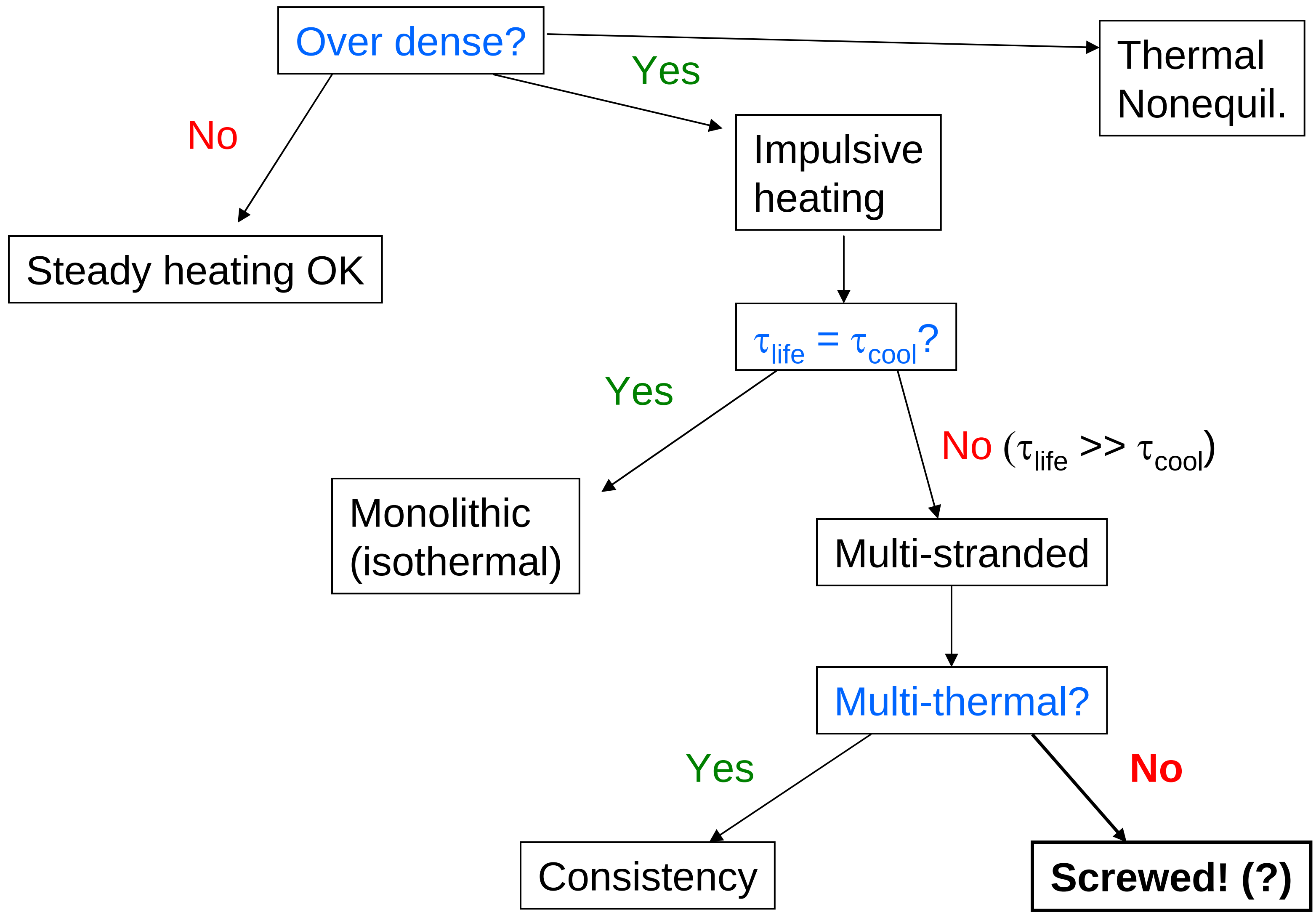
MULTI-THERMAL

Schmelz
Martens
Cirtain
Noglik
Walsh
Patsourakos
etc.

ISOTHERMAL

Aschwanden
Nightingale
Landi
Nagata
Del Zanna
Mason
Schmeider
etc.

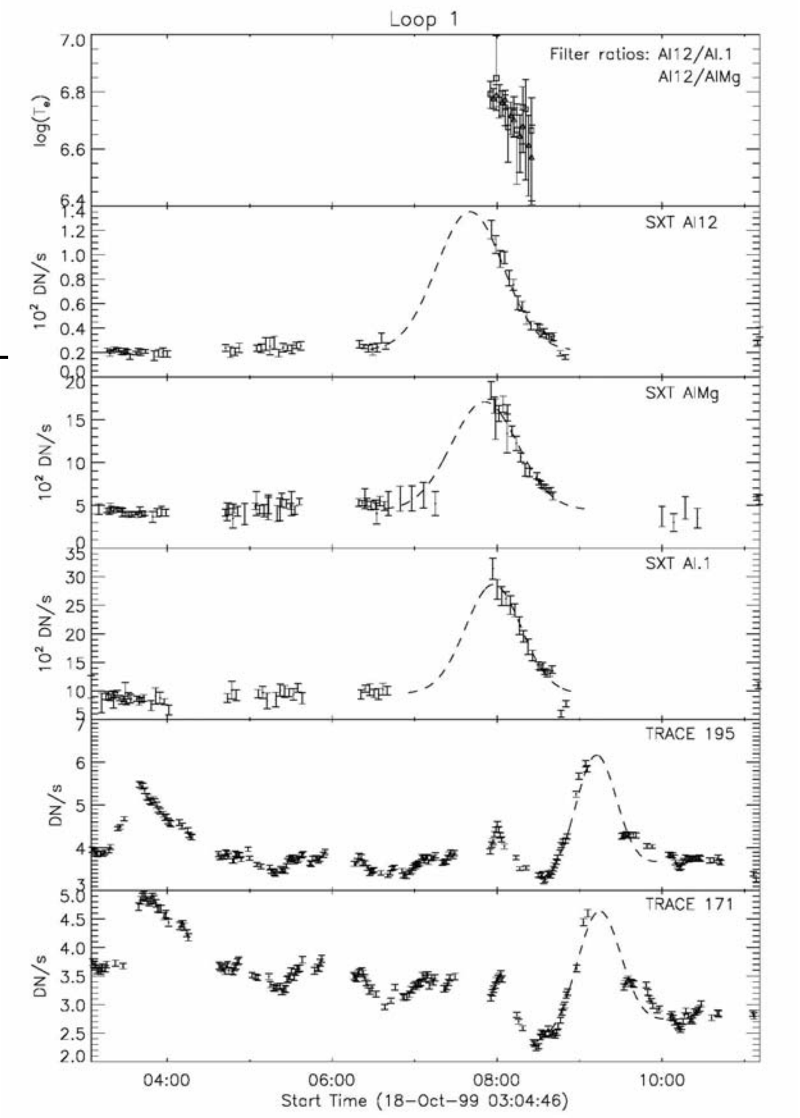
Solutions to the Loops Puzzle



Nanoflare Storm Duration

Yohkoh / SXT

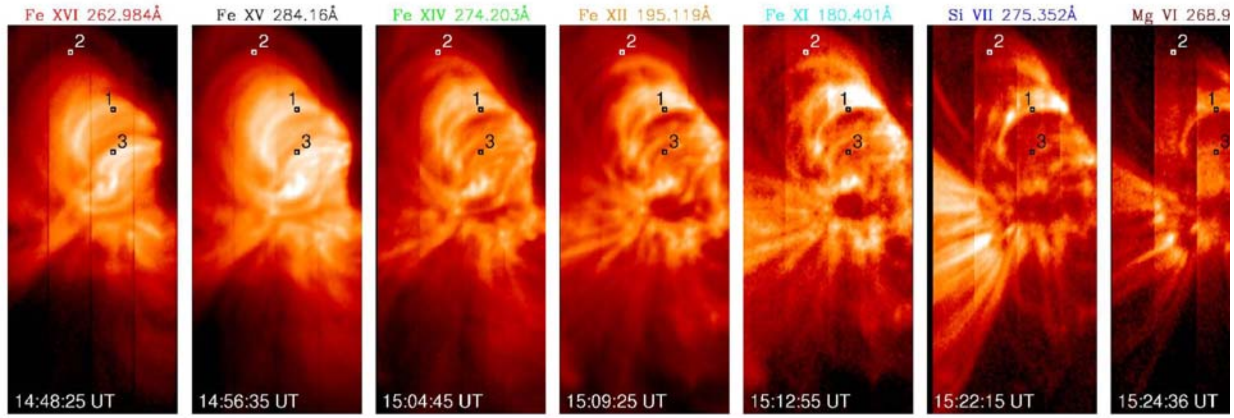
TRACE



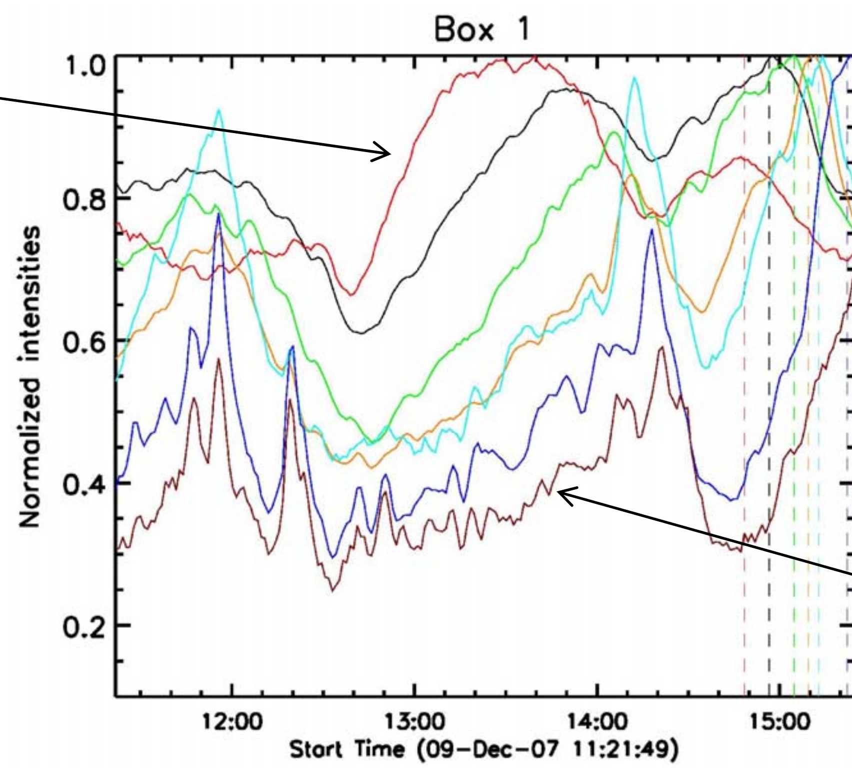
Nanoflare storms do not last forever.

Light curve overlap depends on storm duration.

Ugarte-Urra, Winebarger, & Warren (2006)



Fe XVI
2.5 MK

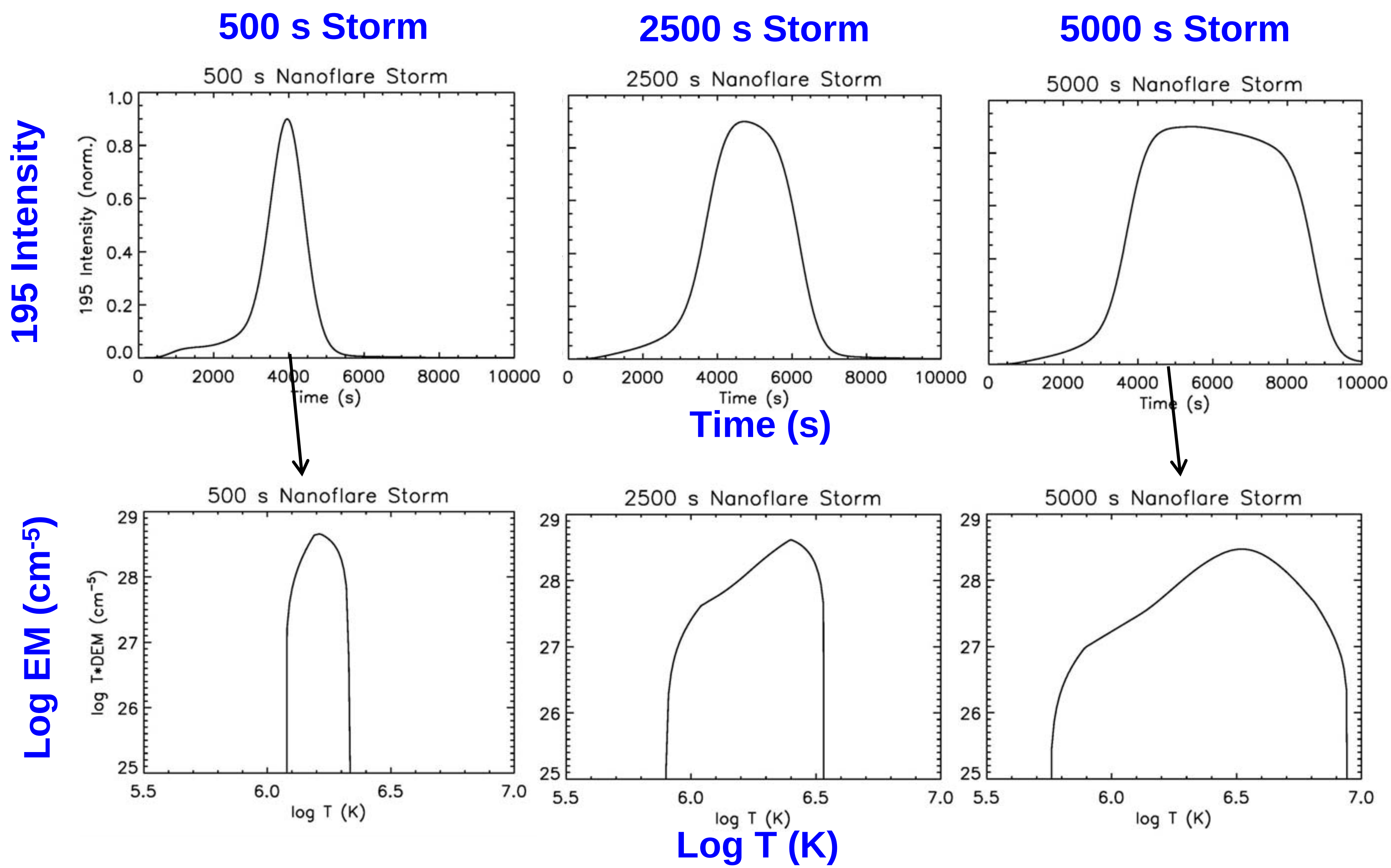


Mg VI
0.4 MK

Hinode / EIS

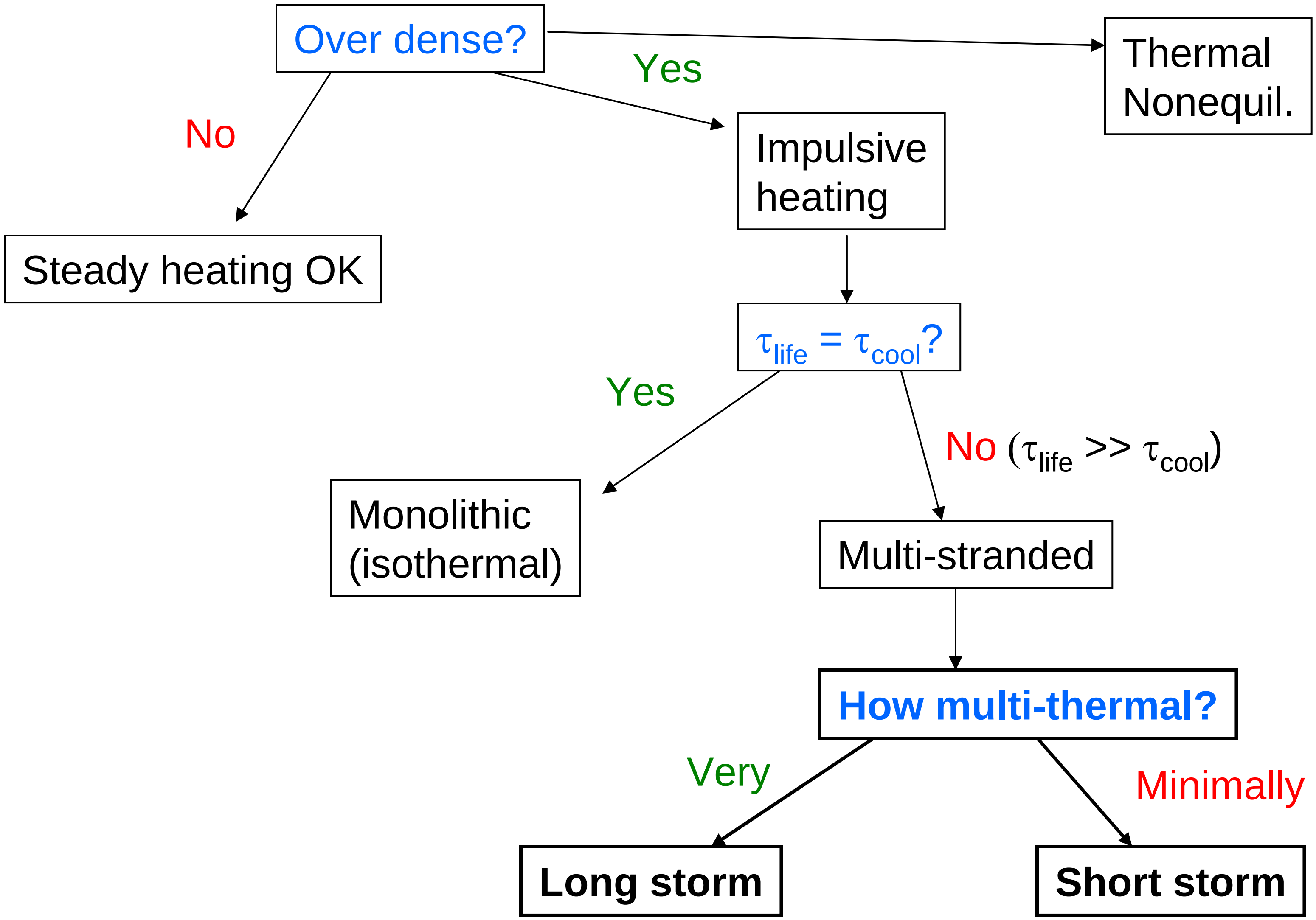
Ugarte-Urra, Warren, Brooks (2008)

Lifetime and Thermal Width



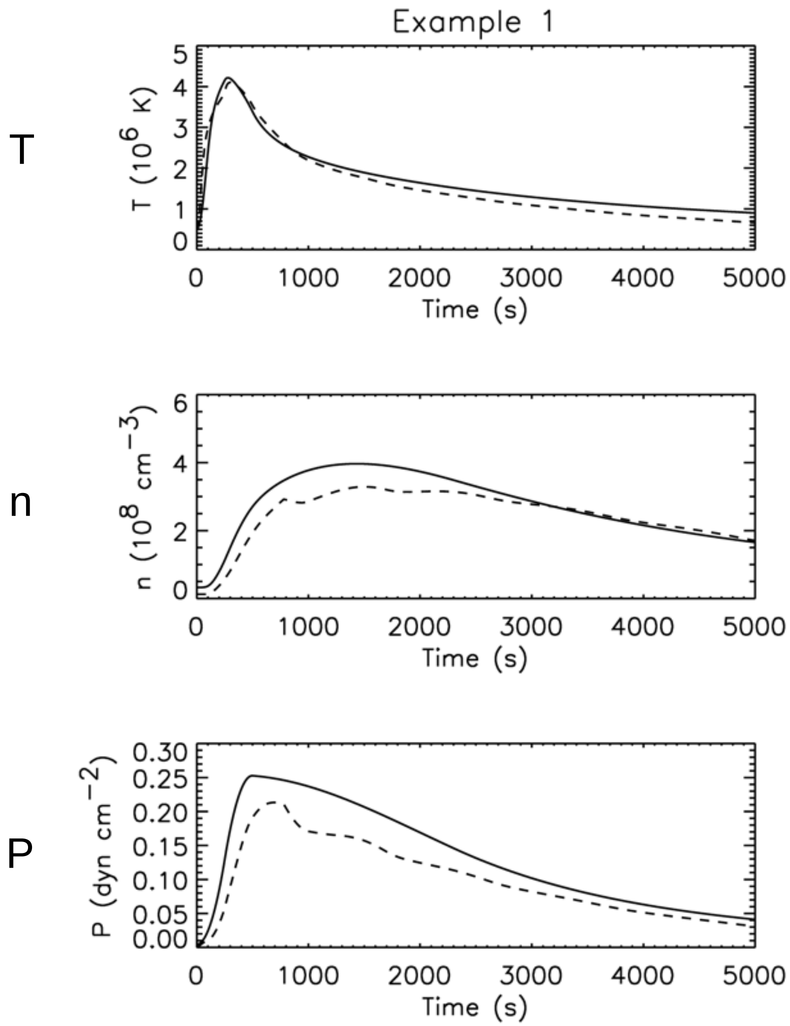
EM(T) at time of max. 195 intensity

Solutions to the Loops Puzzle



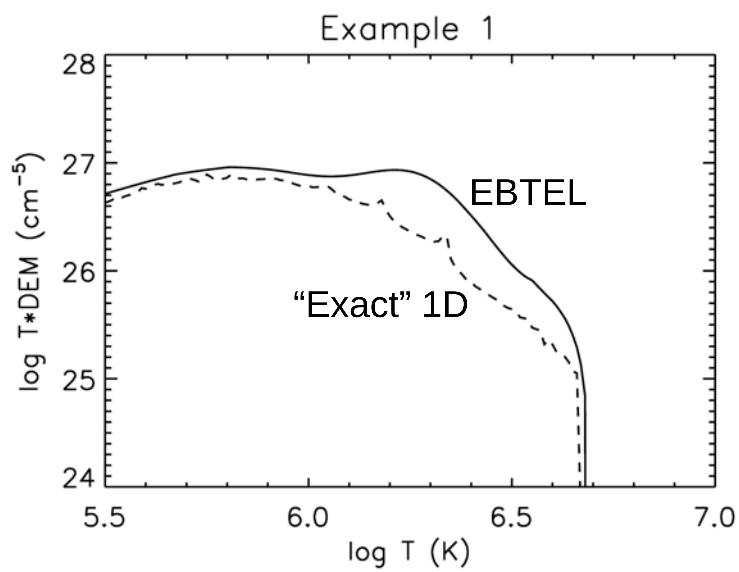
Need lifetime / thermal width consistency check

Enthalpy Based Thermal Evolution of Loops (EBTEL)



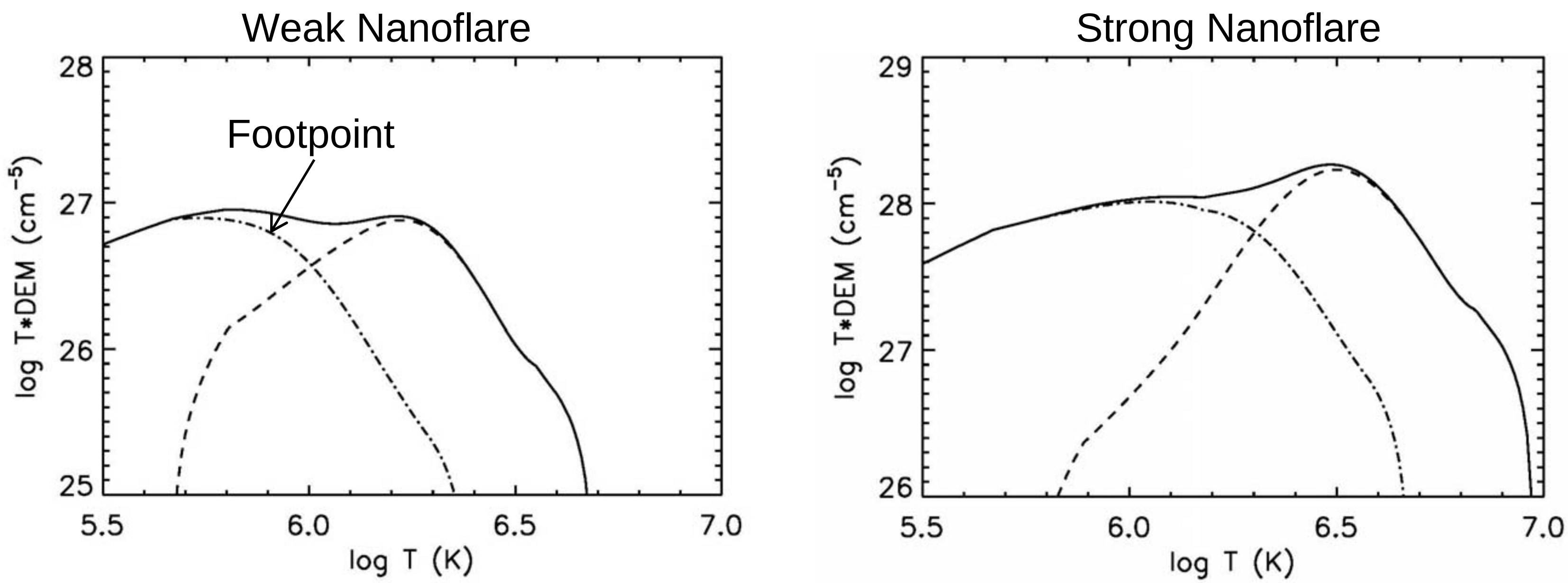
500 s nanoflare

"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)

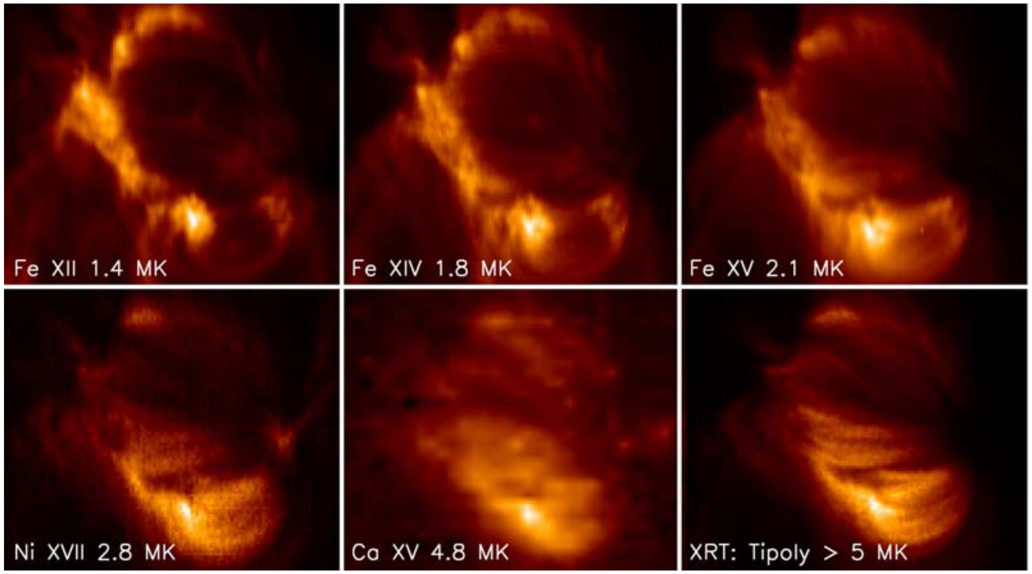
(Super) Hot Plasma

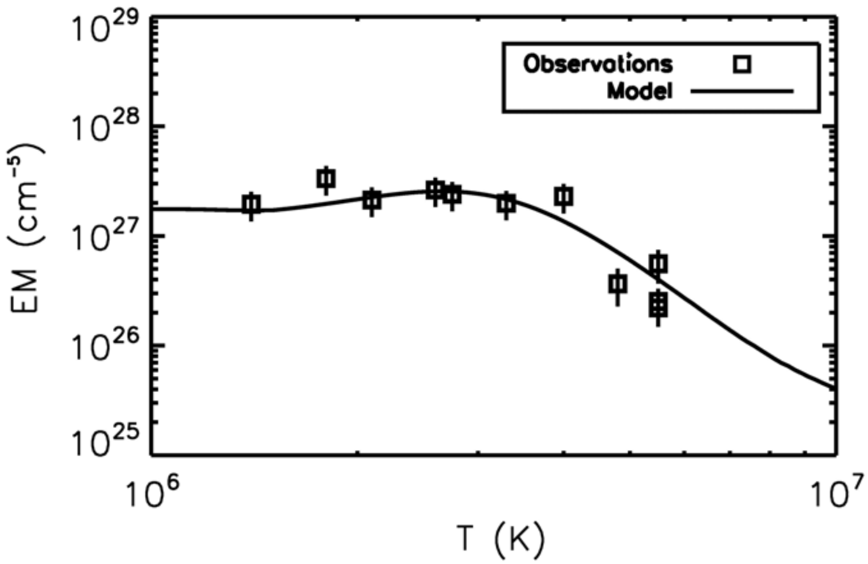


Hot plasma predicted to be **very faint**:

EM (cm^{-5}) = T x DEM reduced by **1-1.5 orders** magnitude
DEM (cm^{-5} K^{-1}) reduced by **1.5-2 orders** magnitude

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

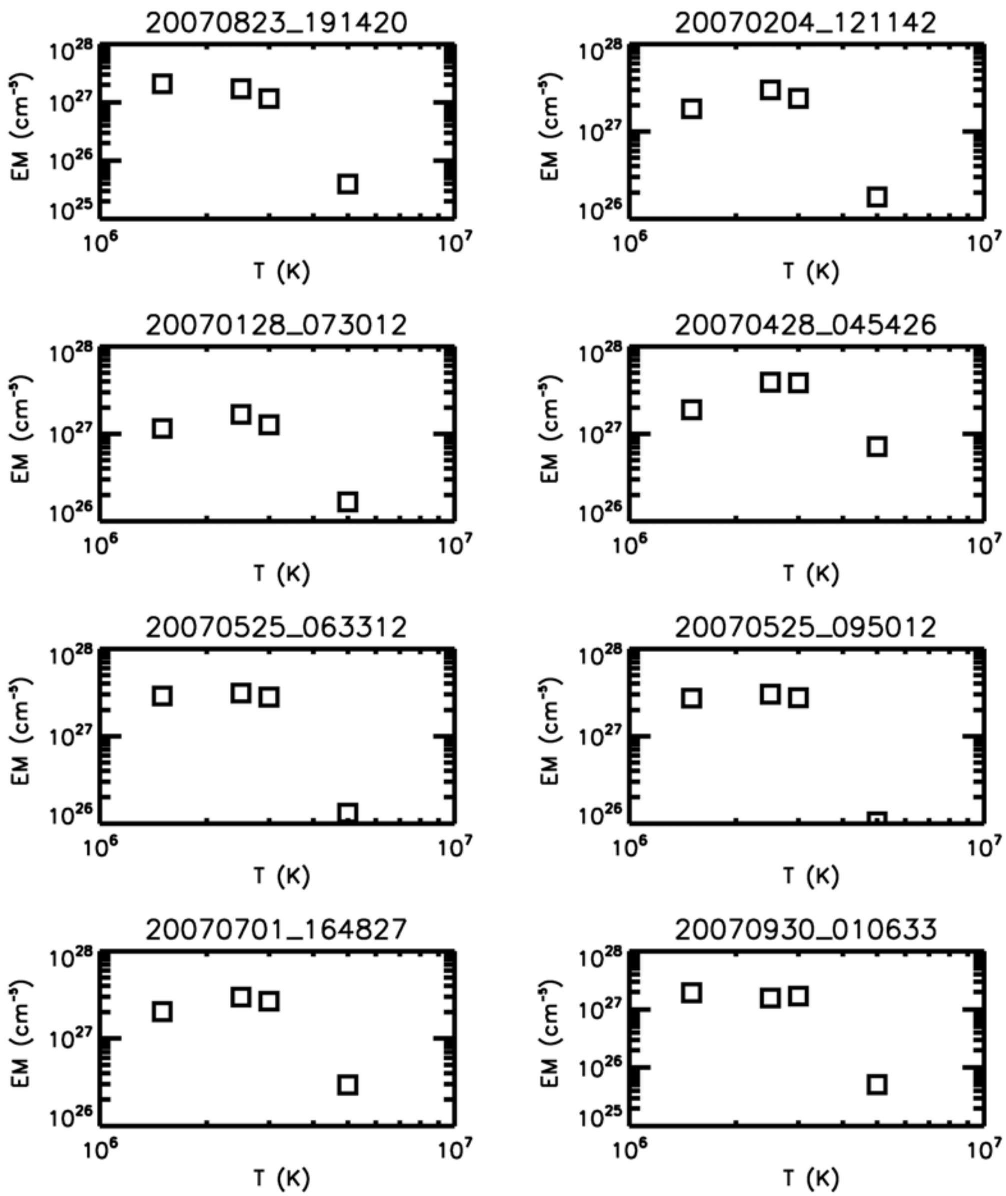




Hinode/EIS:

Fe XII – XVII
Ca IV – VI
Ni XVII

Patsourakos & Klimchuk (2008)

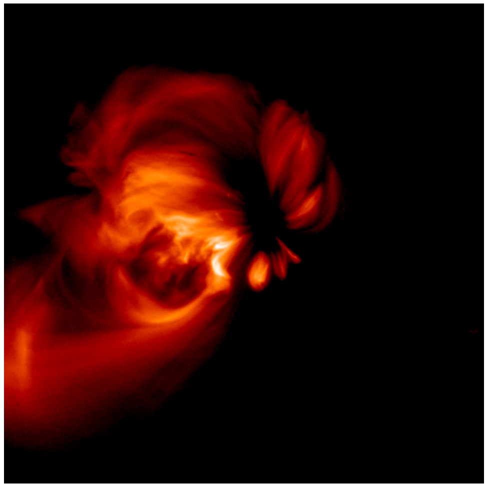


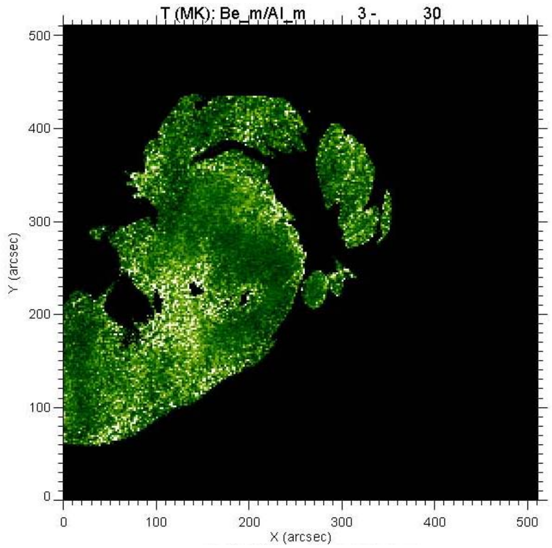
Fe XII, Fe XV,
Ni XVII, Fe XVII

See also
Ko et al. (2008),
Ca XVII

Hinode / XRT

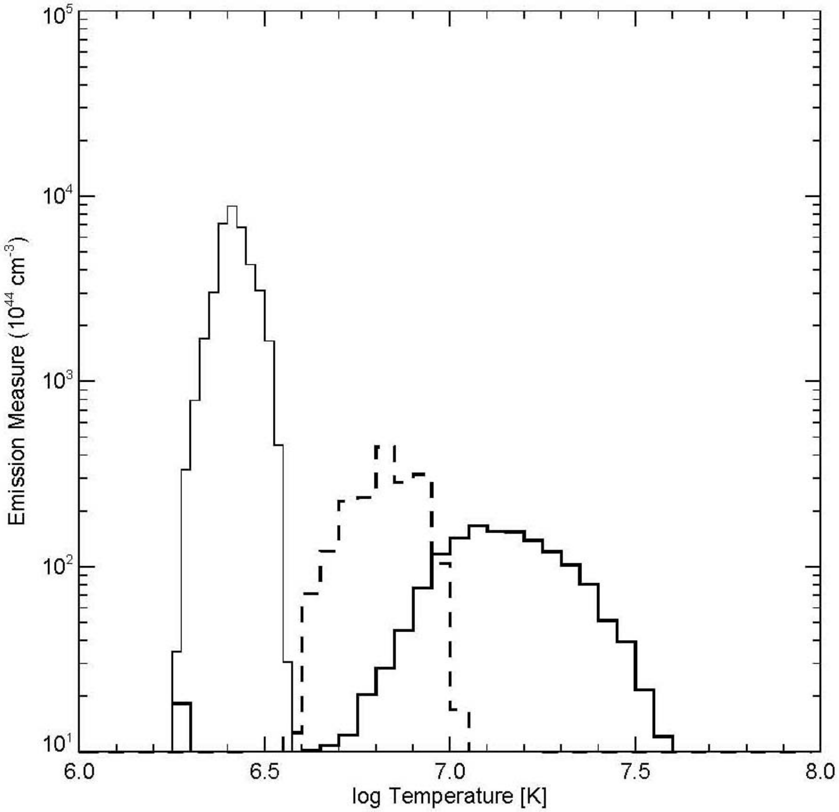
Be_m Image





Be_m/Al_m T map

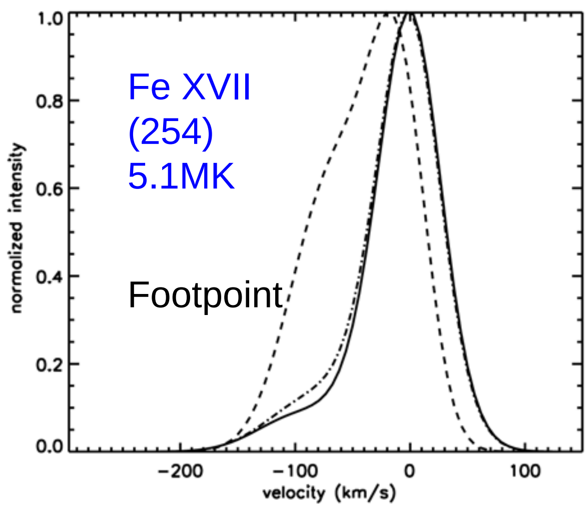
EM (cm^{-3})

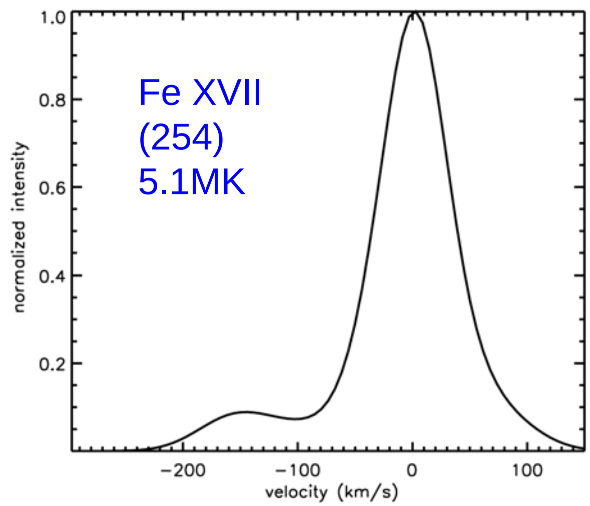


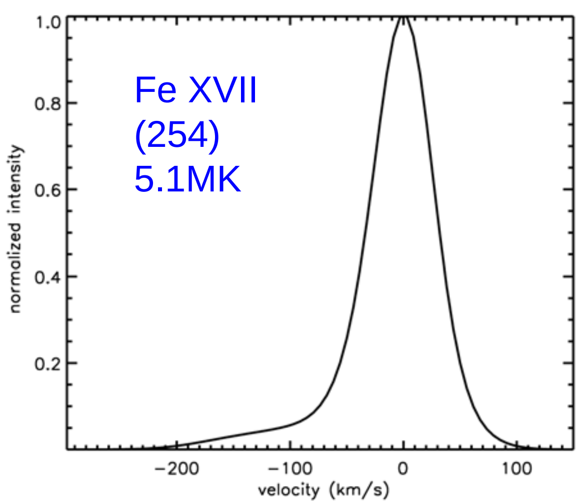
Log T

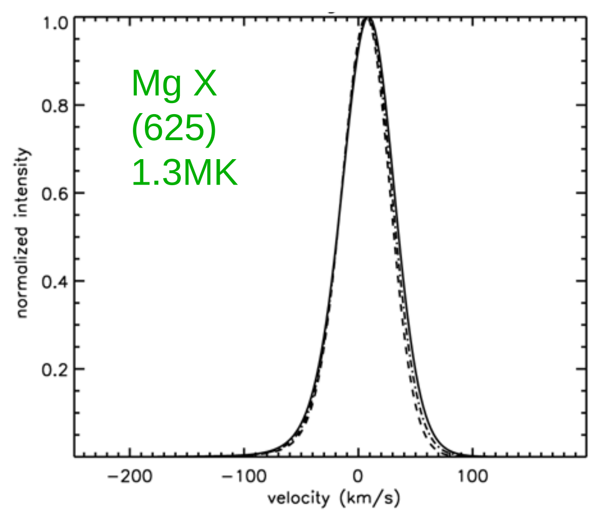
Reale et al. (2008)

Simulated Line Profiles



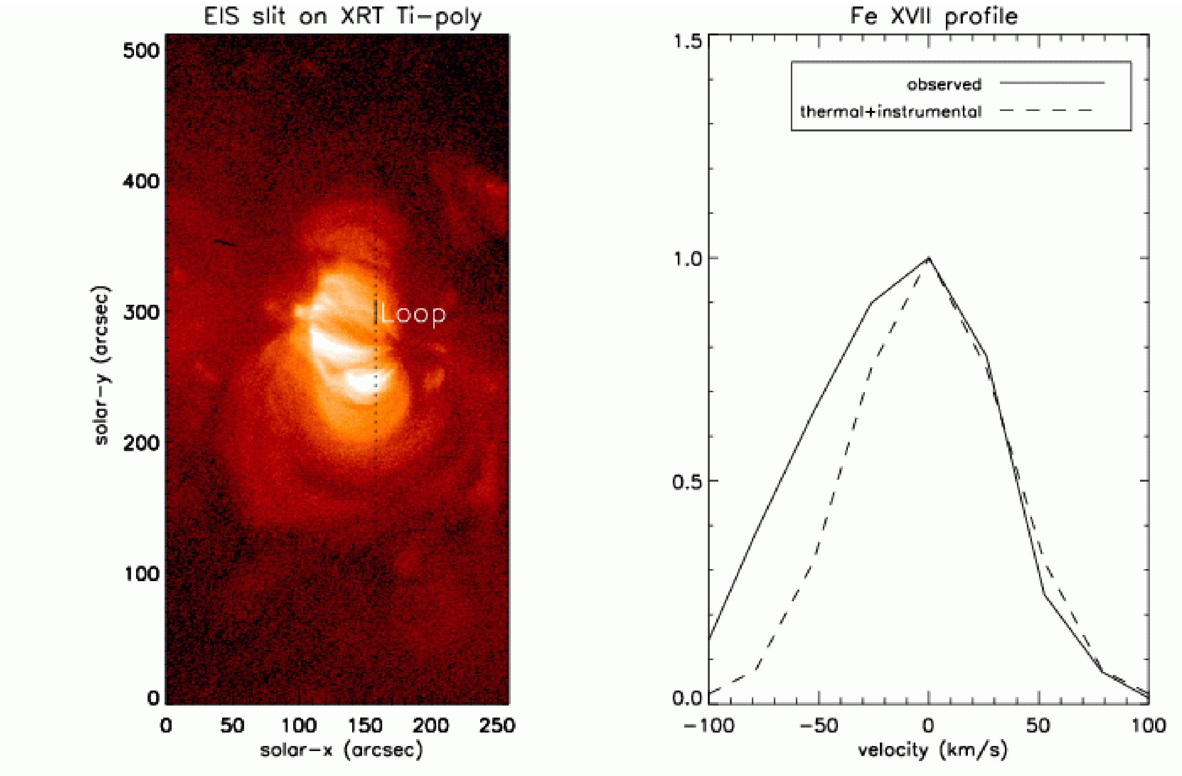






Patsourakos & Klimchuk (2006)

Observed Fe XVII Profile



EIS sit and stare observations

See also Hara et al. (2008)

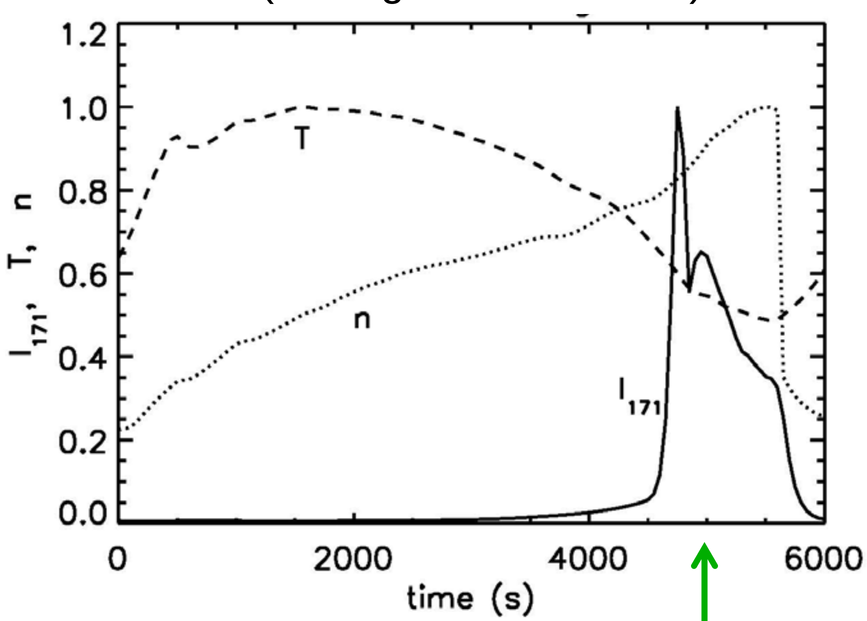
THERMAL NONEQUILIBRIUM

- 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

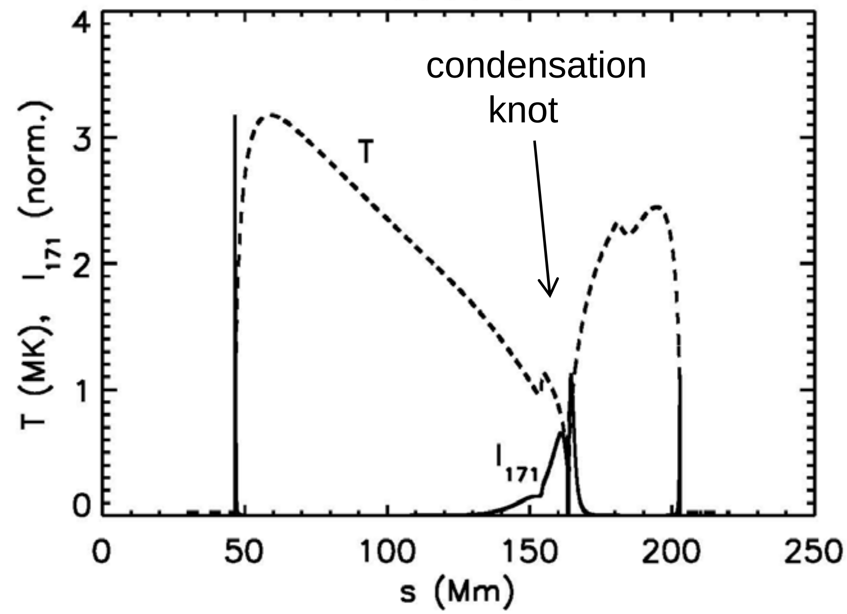
Serio et al. (1981), Antiochos & Klimchuk (1991), Karpen et al. (2001-2008), Mueller et al. (2003-2005), Mok et al. (2008)

Monolithic Loop

171 Light Curve
(averaged over corona)



171 Intensity Profile
(5000 s)

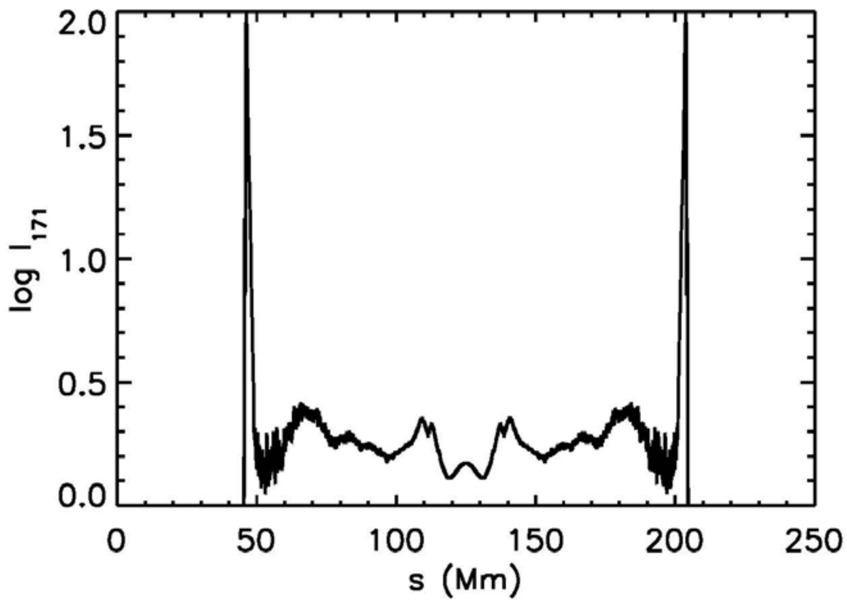


Intensity profile **not** like observed (uniform)

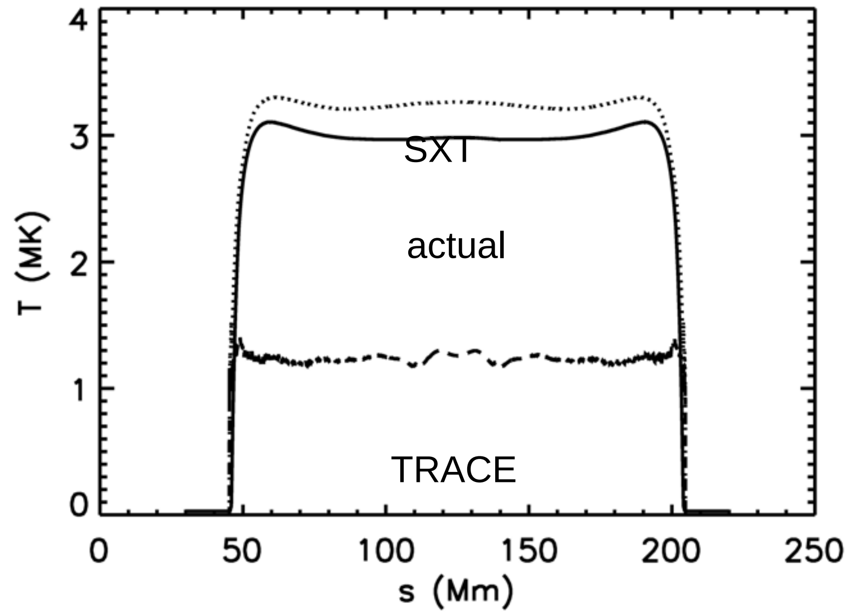
With Judy Karpen

Multi-Strand Bundle

171 Intensity Profile
(time average)



Temperature Profile
(time average)



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

Conclusions

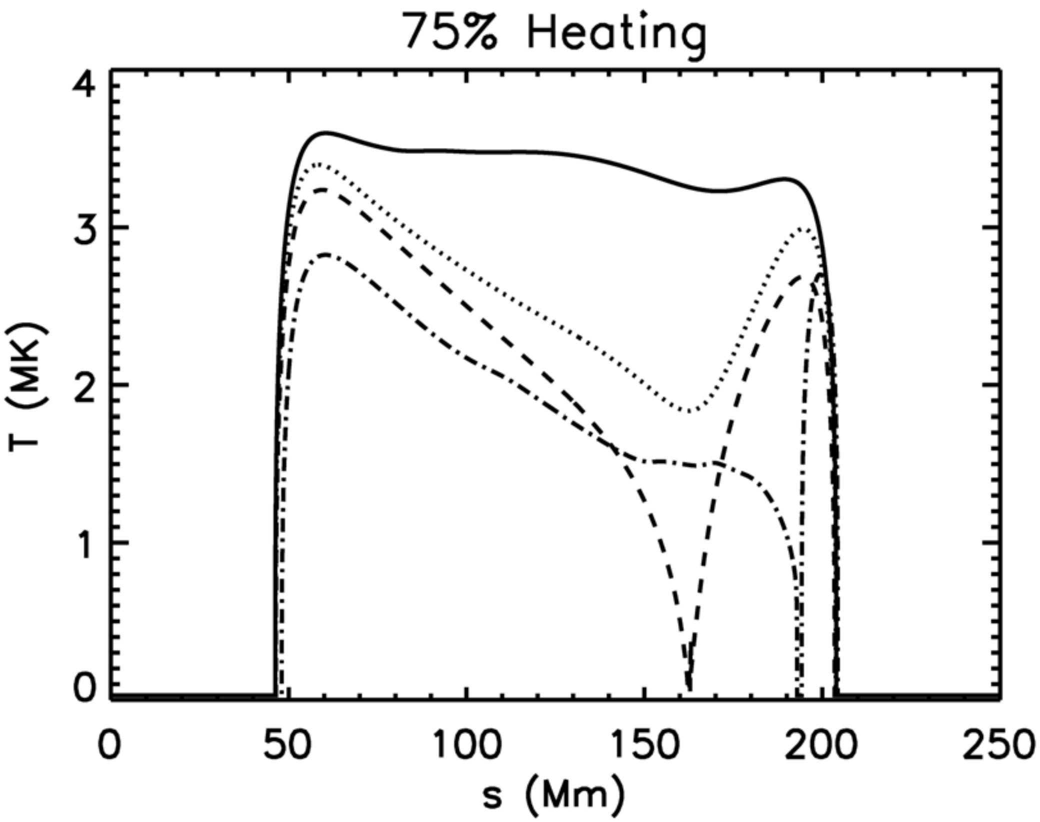
- Need to examine all pieces of the puzzle for individual loops
  - Lifetime, thermal distribution, density (flows, intensity profile)

- Strong evidence that many EUV loops result from nanoflare storms

- Are there different classes of loops?
  - EUV loops without SXR counterparts (e.g., fan loops)?
  - SXR loops without EUV counterparts?

- Diffuse component of active regions is important
  - Background brighter than most loops
  - Preliminary indications of impulsive heating

- All coronal heating mechanisms produce impulsive energy release on individual magnetic flux surfaces (field lines)
  - but rapid repetition gives quasi-equilibrium conditions



t = 2950, 4500, 4850, 5750 s

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

With Judy Karpen

Consistency

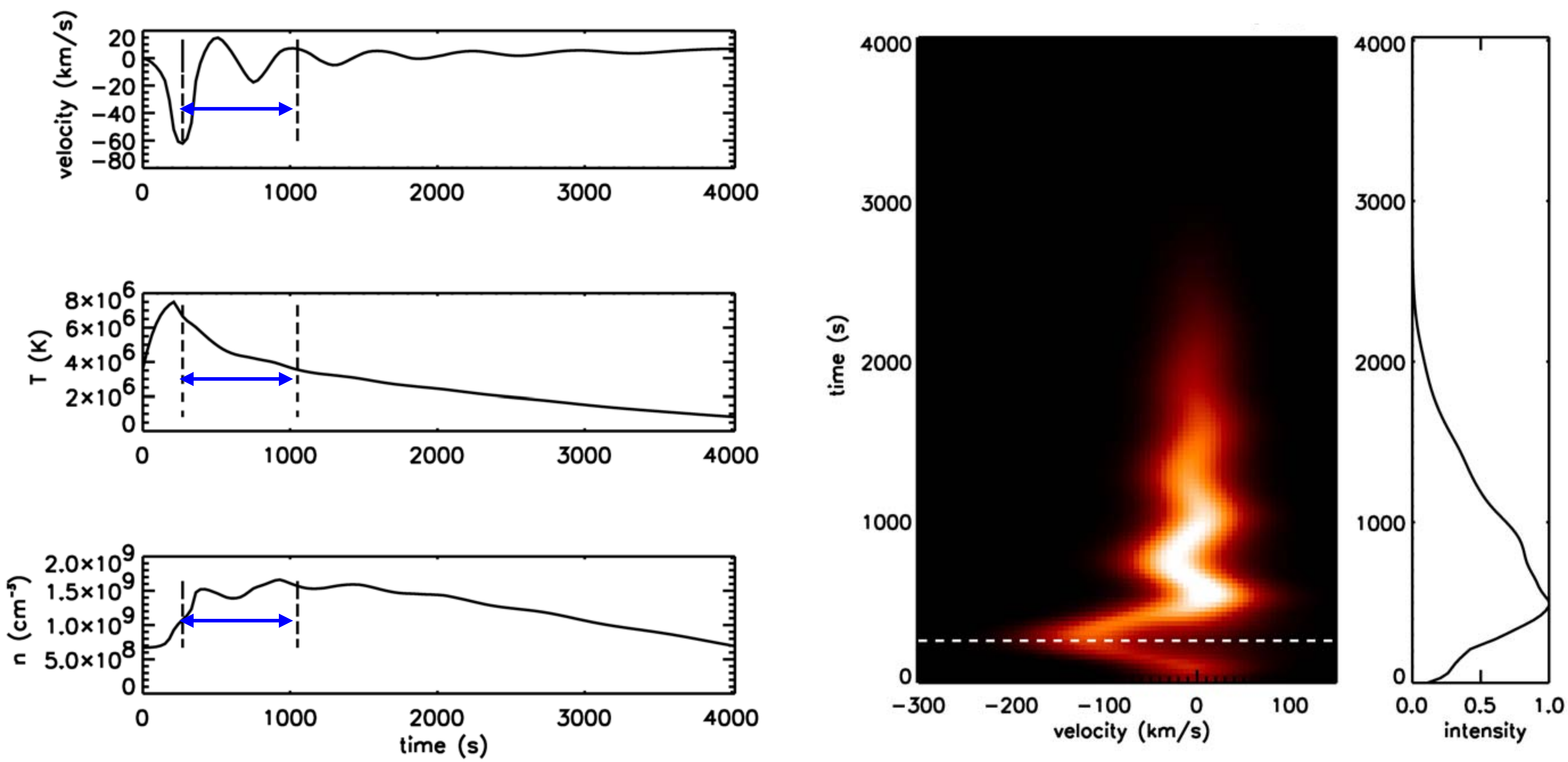
$\Delta T_{FWHM} \sim 0.8$ MK (EIS; Warren et al. 2008)

Implies $\tau_{195} \sim 1$ hour, as observed
(TRACE; Ugarte-Urra et al. 2006)

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.

Fe XVII (254)



Patsourakos & Klimchuk (2006)