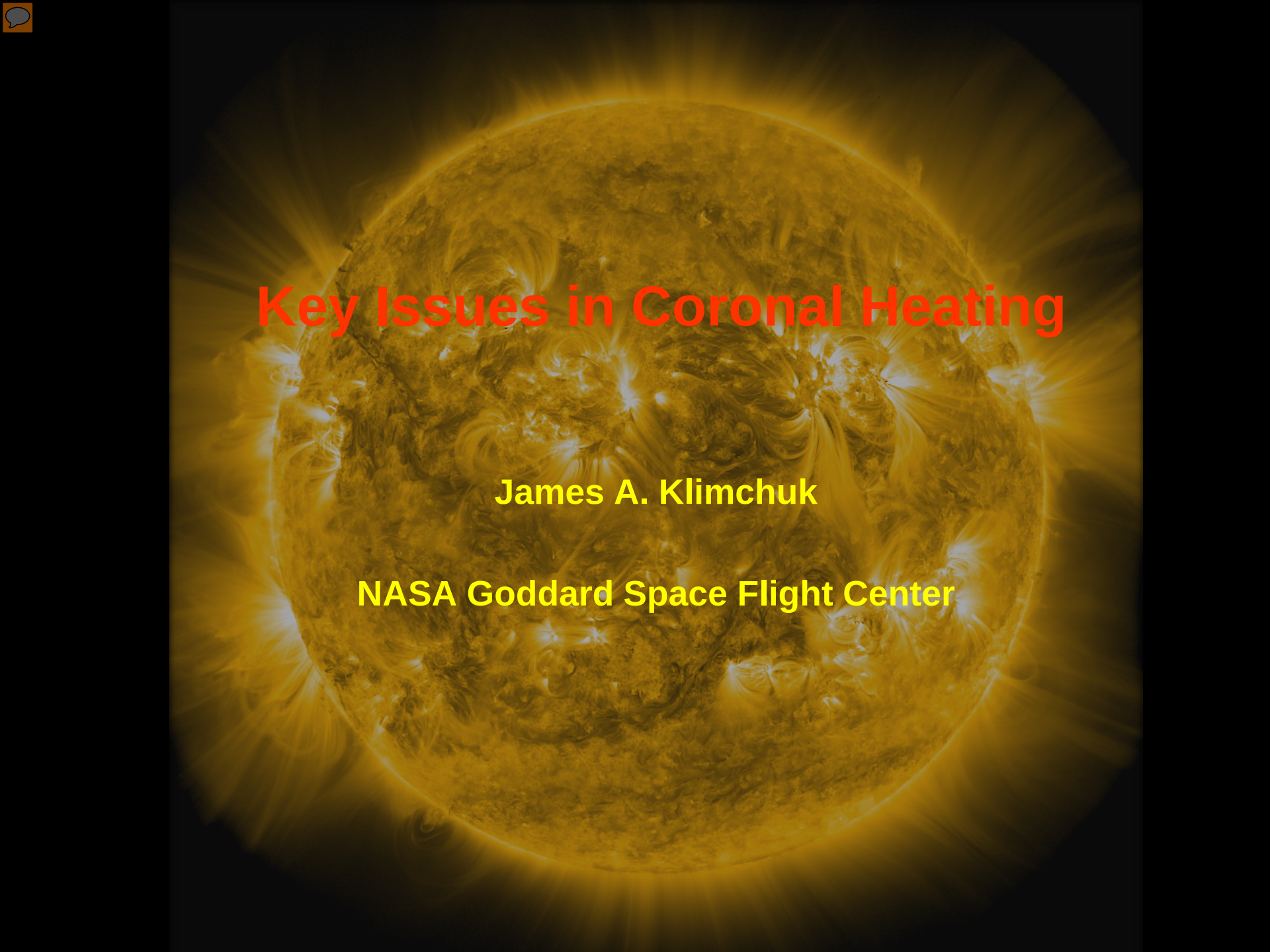


Key Issues in Coronal Heating

James A. Klimchuk

NASA Goddard Space Flight Center

1. All coronal heating is impulsive

All known mechanisms, when applied to a realistic nonuniform corona, predict that the heating of individual magnetic field lines (flux strands) is highly time dependent.

Includes wave heating.

The time delay between successive events may be short, in which case the heating is effectively steady.

NANOFLARE: An impulsive energy release on a small cross-field spatial scale with**out** regard to mechanism. (generic definition)

2. The details of coronal heating matter

Common misconception:

Photospheric flows stress the coronal magnetic field and inject a Poynting flux of energy that is determined by the driver velocity.

The corona adjusts so that the magnetic energy is converted into heat in a statistical steady state (energy out = energy in).

The Poynting flux and therefore the average heating rate do *not* depend on the details of this adjustment.

2. The details of coronal heating matter

Common misconception:

Photospheric flows stress the coronal magnetic field and inject a Poynting flux of energy that is determined by the driver velocity. **PARTIALLY TRUE**

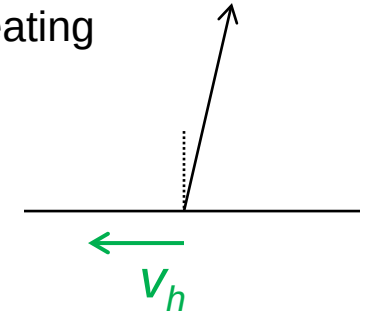
The corona adjusts so that the magnetic energy is converted into heat in a statistical steady state. **TRUE**

The Poynting flux and therefore the average heating rate do *not* depend on the details of this adjustment. **FALSE**

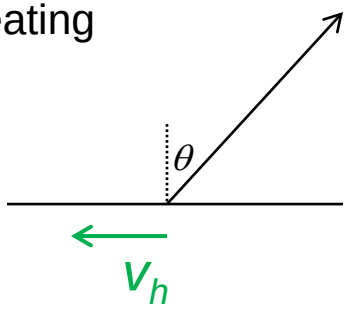
Poynting flux and heating rate

Poynting flux: $$F = \frac{1}{4\pi} B_v^2 \, V_h \tan(\theta)$$

Small *F*
Weak heating



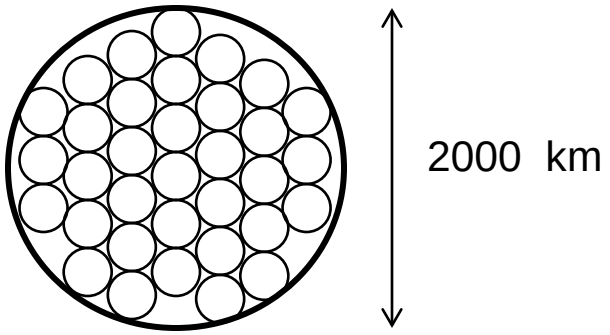
Large *F*
Strong heating



The heating rate depends on the tilt of the field (level of stress), which is determined by the heating mechanism.

Observed values of B_v and V_h imply $\theta \approx 10^{\circ}$ ("Parker angle")

3. The corona is filled with elemental strands

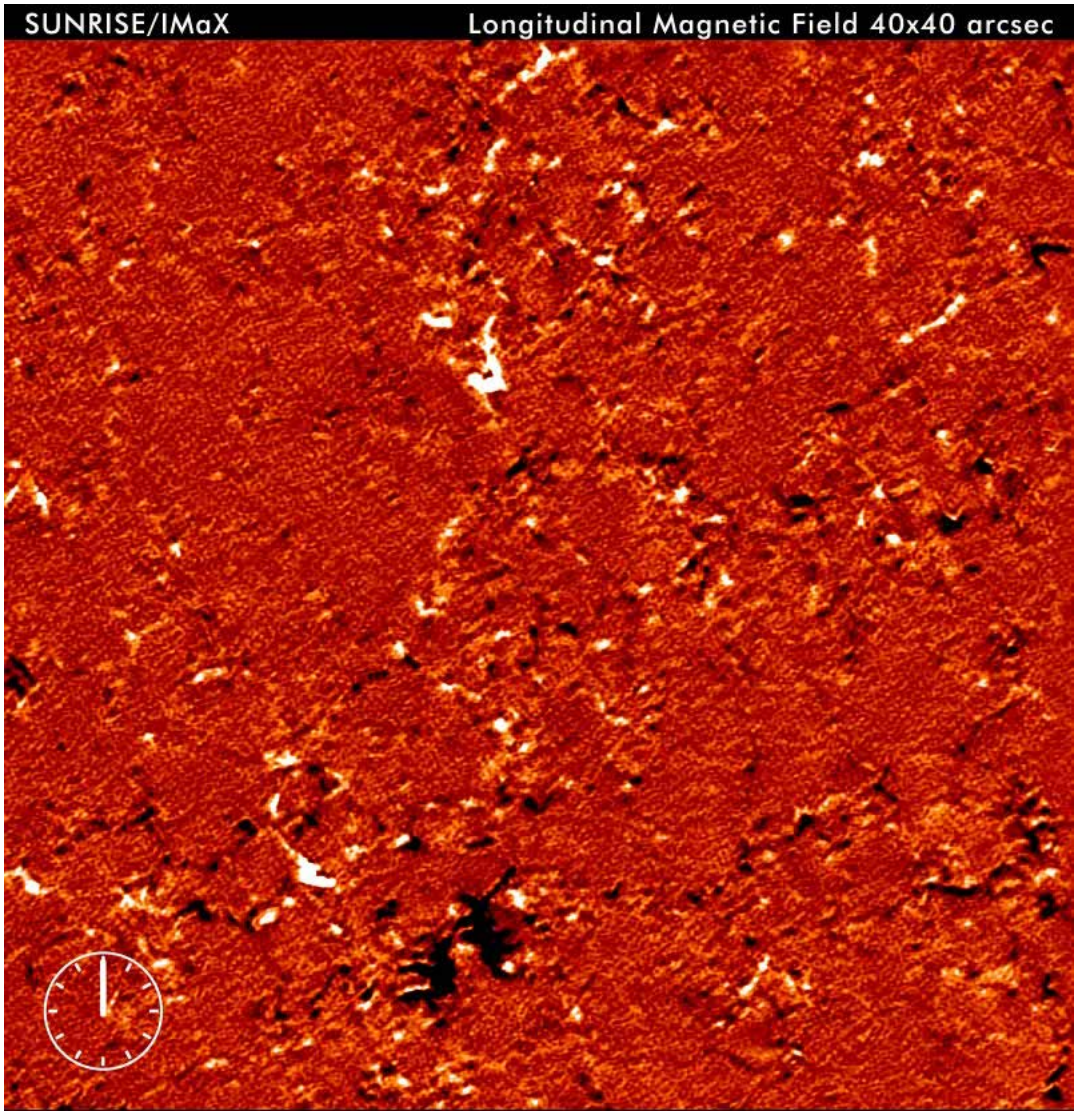


Number of strands in a coronal loop:

$$N = \frac{\Phi_l}{\Phi_s} = \left(\frac{d_l}{d_s}\right)^2 \frac{B_l}{B_s} \approx \left(\frac{2000}{150}\right)^2 \frac{100}{1000} \approx 20$$

~ 100,000 strands in an active region !!!

Photospheric Driving



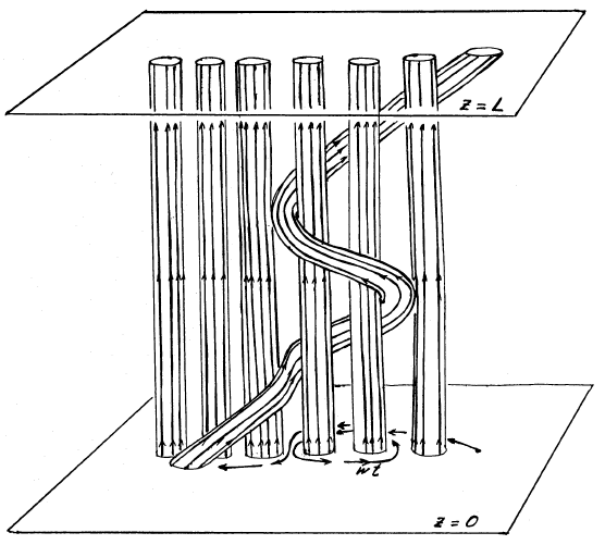
Loop cross-section

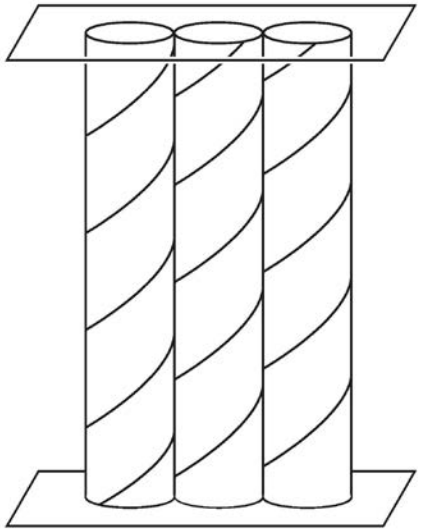
Exceptionally Quiet Sun

SUNRISE / IMaX

4. The corona is densely populated with current sheets

Current sheets are formed at the interfaces between tangled and twisted strands.





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

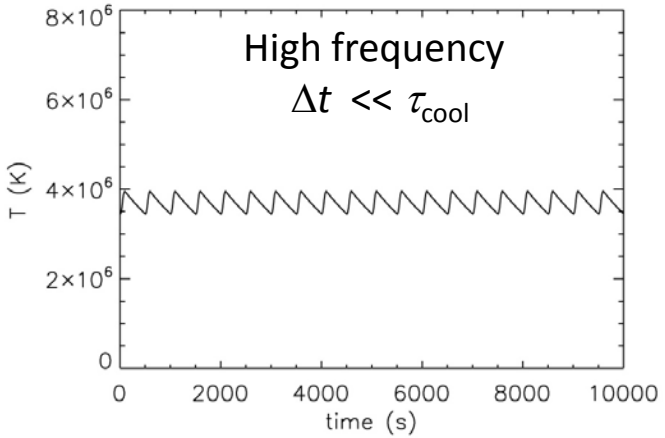
5. The strands MUST reconnect to avoid an infinite build up of stress

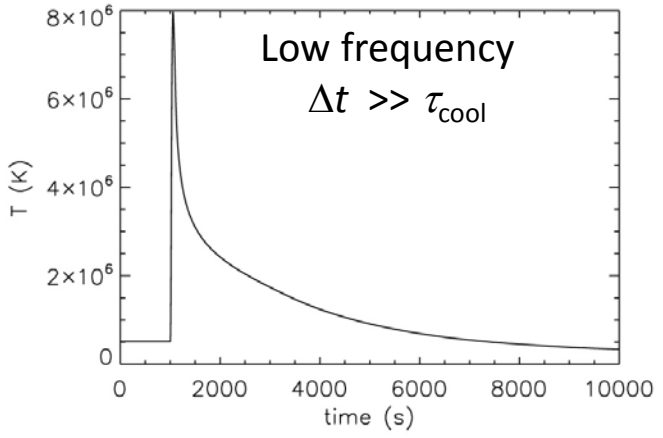
Energy is released in the form of nanoflares.

True whether or not there are other forms of heating, e.g., waves.

6. What determines the nanoflare frequency?

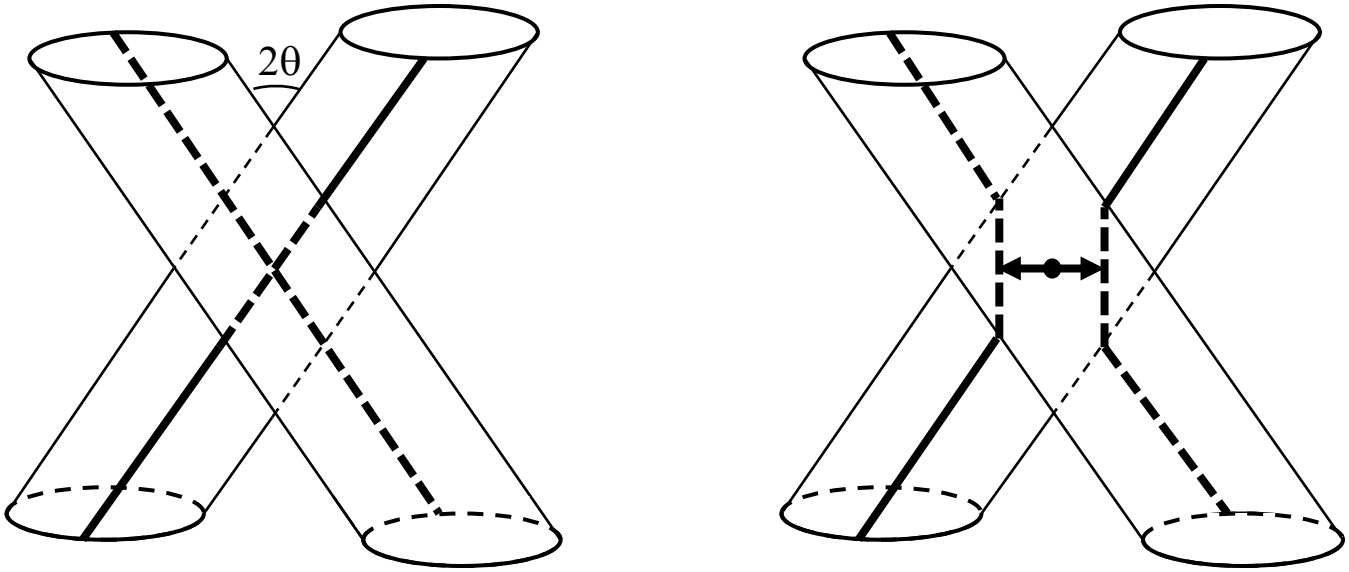
Frequency with which nanoflares repeat on a given strand in relation to the plasma cooling time?





- Distinguishable loops (observed features) heated by low freq. nano.
- Diffuse cores of active regions can be heated by high or low freq. nano.
- Some low freq. heating is present along “every” line-of-sight. (major or minor contribution?)

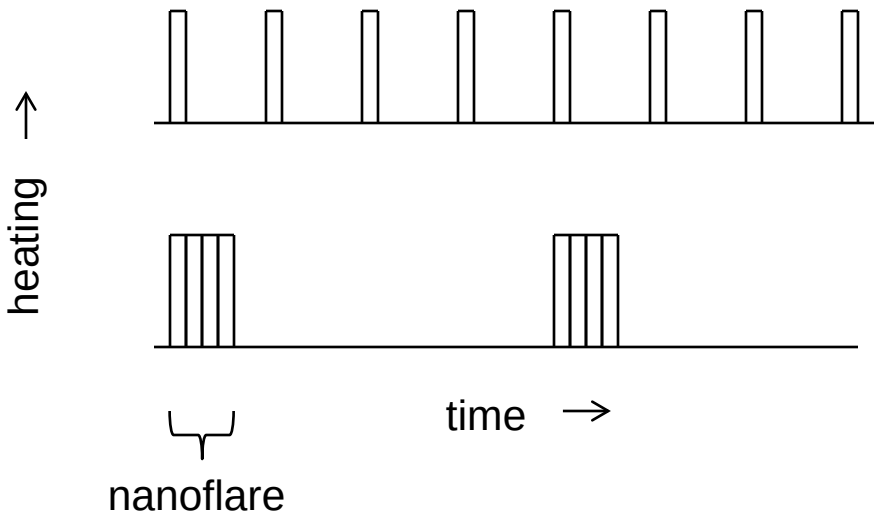
7. What is the quantum of energy release?



Energy release per unit area: $\frac{\Delta E}{A} = \frac{1}{8\pi} r B^2 \left(\frac{\sec\theta - 1}{\sin\theta} \right) \approx$ 2x10^9 erg cm^{-2}

→ average repetition time of **~ 200 s** in active regions (and QS)

Reconnection events can cluster

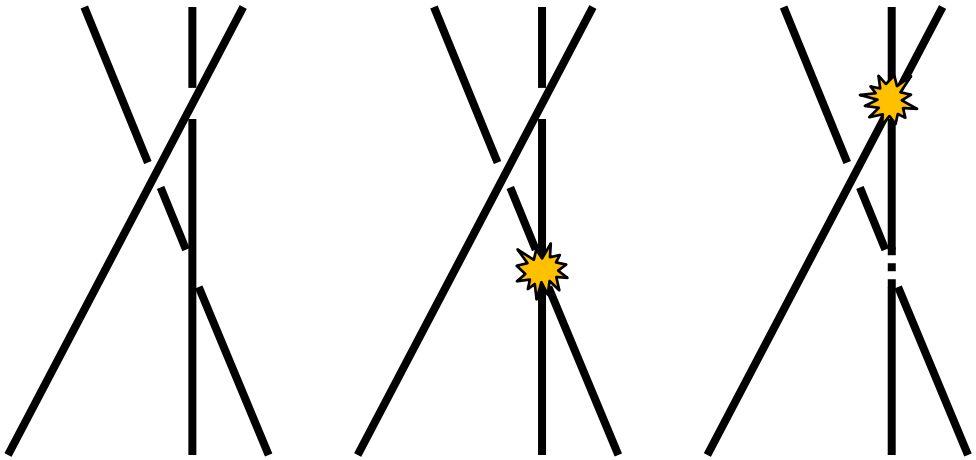


Frequent
weak nanoflares

Infrequent
strong nanoflares

…. so the nanoflare frequency can be slower than the average reconnection event frequency.

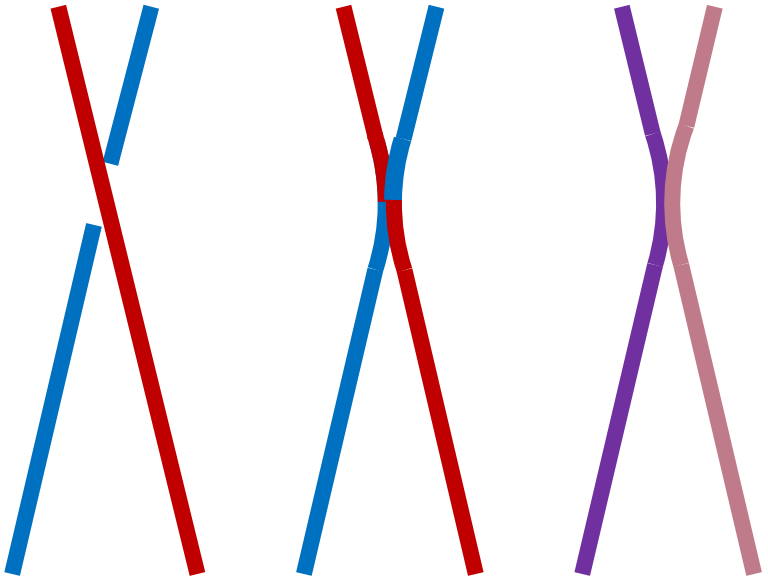
Successive events need not occur at the same place or even involve the same two strands.



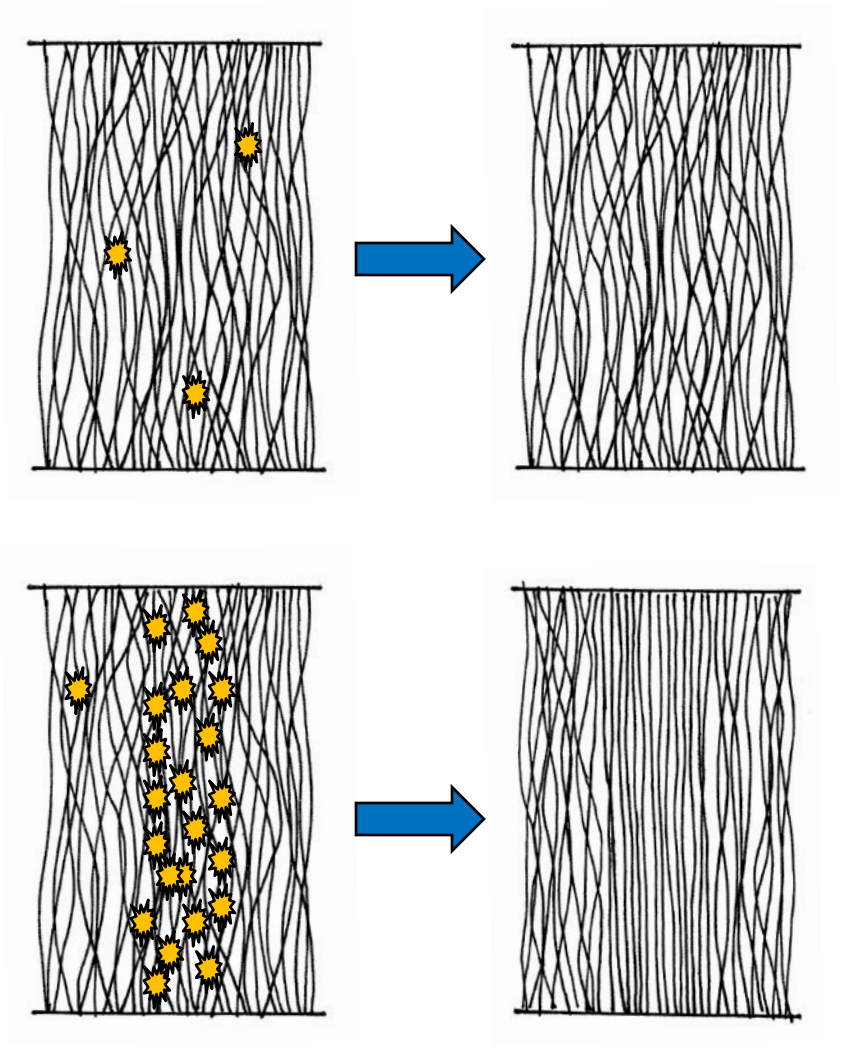
From the standpoint of the plasma evolution, the location of the heating is not very important (in general).

However….

Strands exchange parts during reconnection, something 1D hydro models have not taken into account (but could).



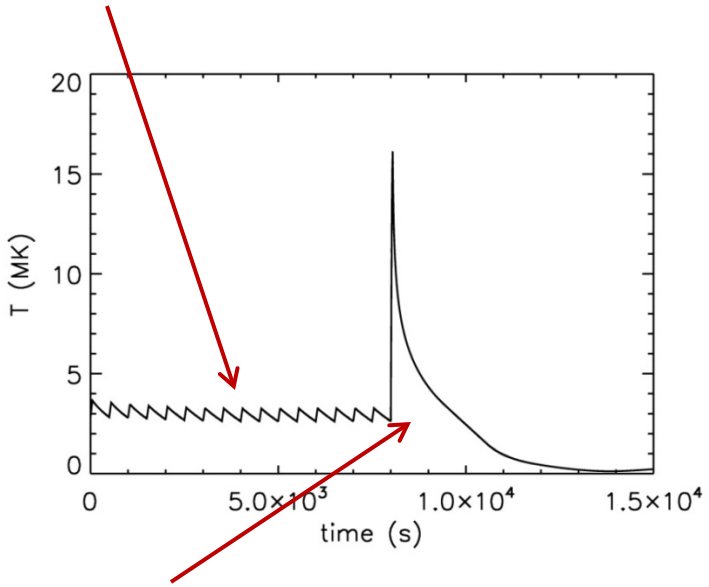
Possible Unifying Picture



Nanoflare Storm

Needs time to "recharge"

Diffuse component
(weak, high freq. nanoflares)



Loop
(strong, low freq. nanoflares)

8. What causes the collective behavior responsible for loops?

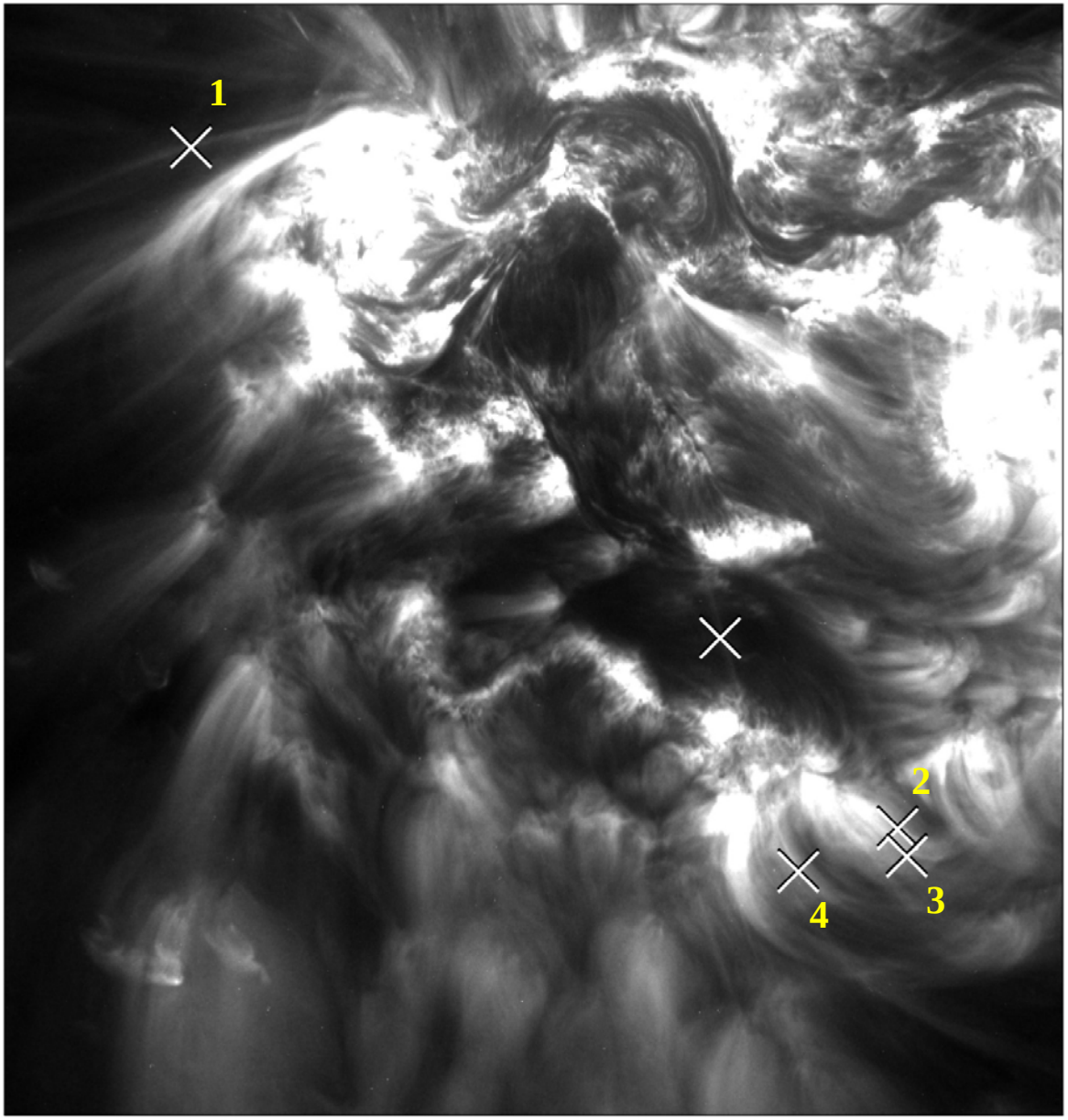
What is a nanoflare “storm”?

Is it an “avalanche” where one event triggers another, etc.?

Or are all events activated by a single source?

What determines the spatial scale of the storm (the characteristic diameter of loops)?

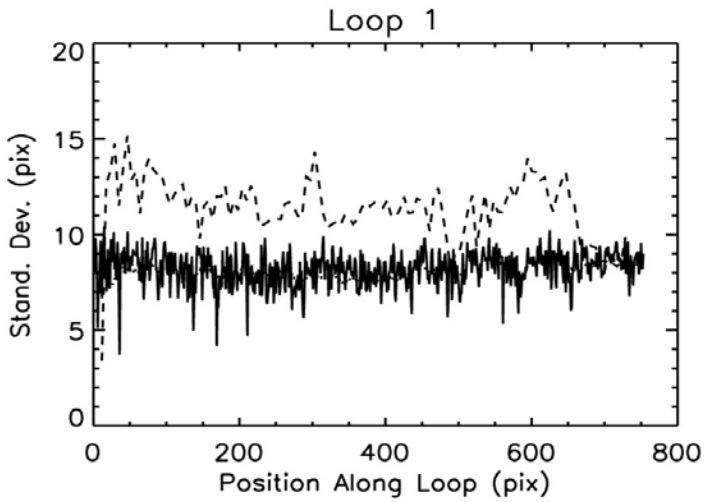
Hi-C Rocket

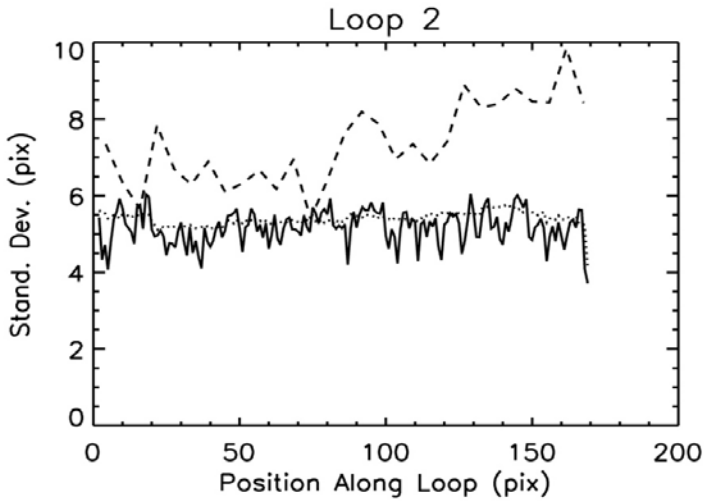


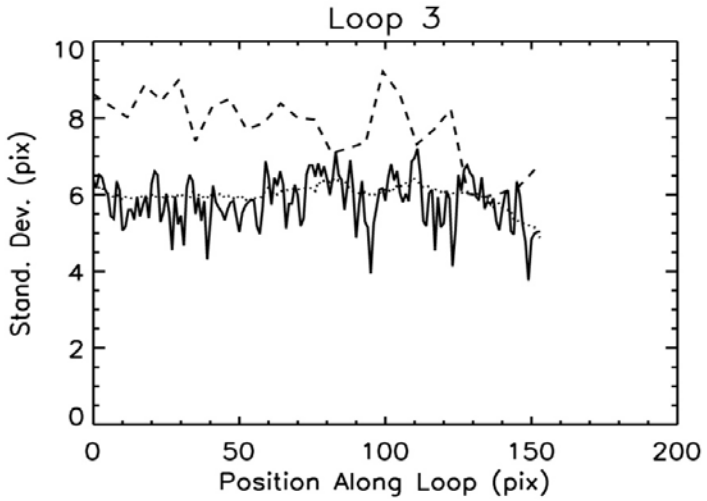
Hi-C has 3-6 times better spatial resolution than AIA

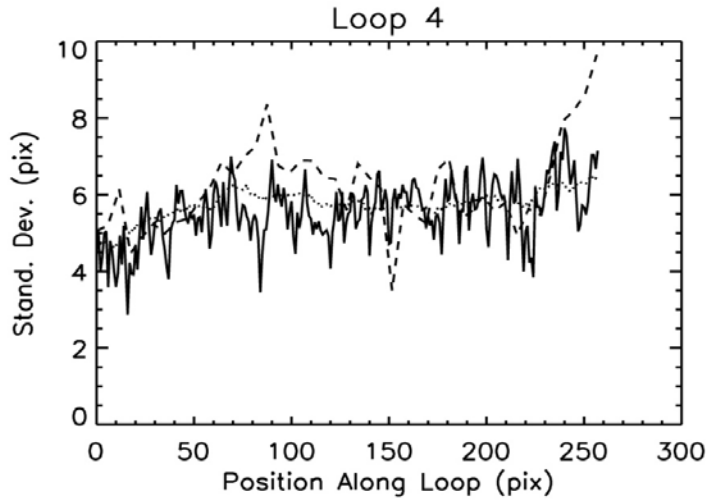
Measured Loop Width

Hi-C (solid), AIA (dashed), “degraded” Hi-C (dotted)









9. What are the onset conditions for energy release?

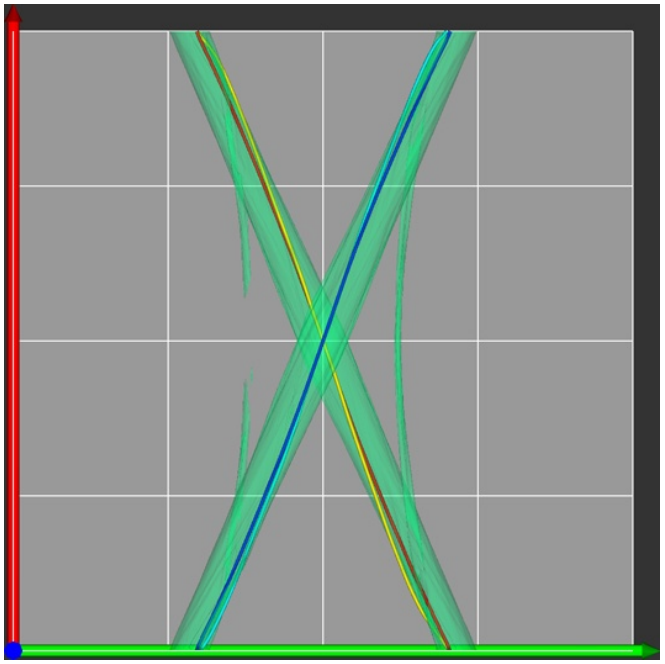
The magnetic energy release process must remain dormant to allow stresses to build, then “switch on.”

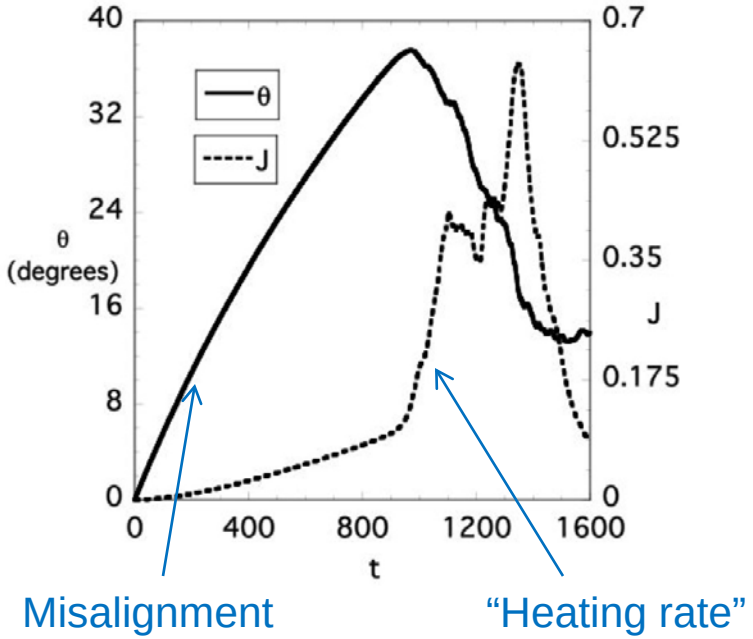
Applies to everything from coronal heating, to jets, to CMEs.

What are the onset conditions?

- Critical misalignment angle (secondary instability)
- Critical current sheet thickness or aspect ratio
- Critical twist (kink instability)

Secondary Instability





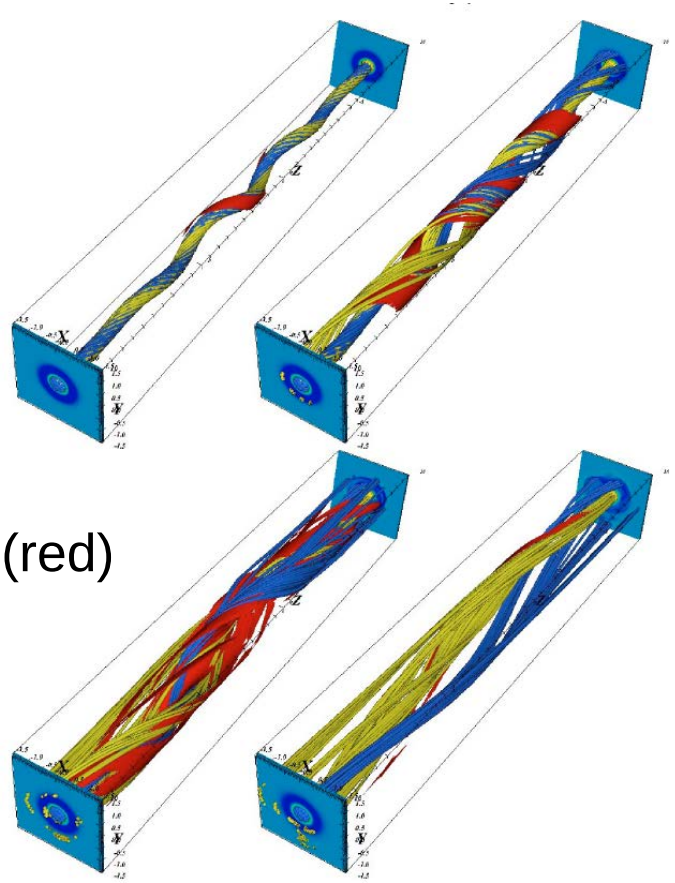
Nanoflare occurs when magnetic misalignment reaches ~35^{o}

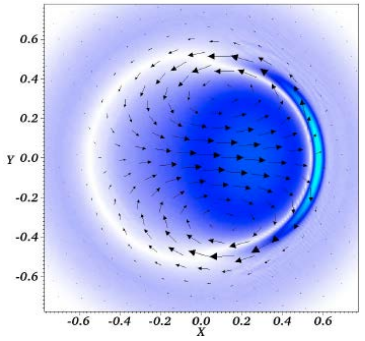
Consistent with “Parker angle” (in QS)

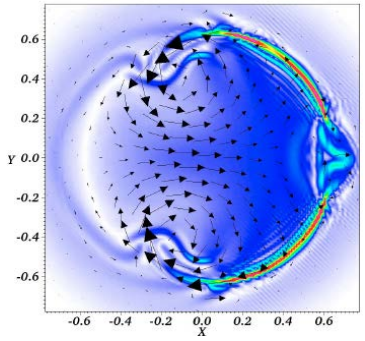
Dahlburg, Klimchuk, … (2005, 09)
Klimchuk, Lopez Fuentes, DeVore (2006)

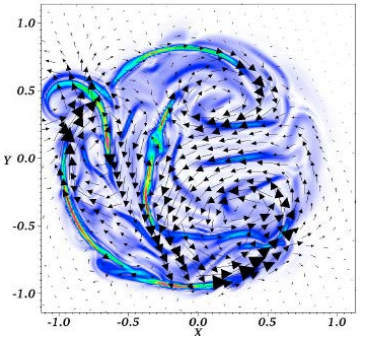
Kink Instability of Twisted Flux Tubes

field lines,
current sheet (red)









current
density

Hood, Browning, & Van der Linden (2009)

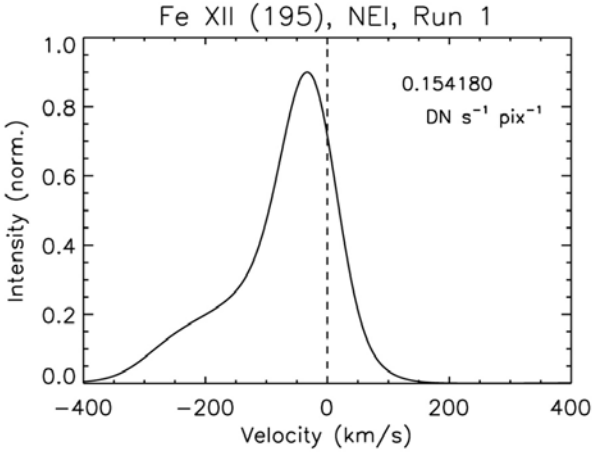
Chromospheric Nanoflares

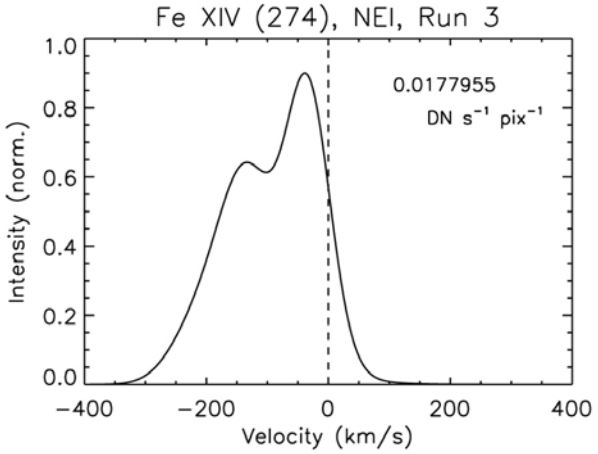
Are chromospheric nanoflares a major source of coronal plasma?

If the chromosphere is heated impulsively to coronal temperatures:

1. Pressure increases locally by factor 100
2. Expands explosively upward (several 100 km s^{-1})
3. Cools dramatically from the expansion ($T \propto n^{2/3}$)

Predicted Fe XII (195) and Fe XIV (274) line profiles





Klimchuk & Bradshaw (2014)

10. Chromospheric nanoflares are NOT a primary source of coronal plasma

Predicted line profiles disagree dramatically with observations:

1. Intensities much too faint
2. Blue shifts much too fast
3. BR asymmetries much too large
4. Emission confined to low altitudes (< 10 Mm)

Nanoflares may heat the chromosphere, but they do not, in general, raise the temperature to coronal values.

To explain the corona, need heating that occurs in the corona.

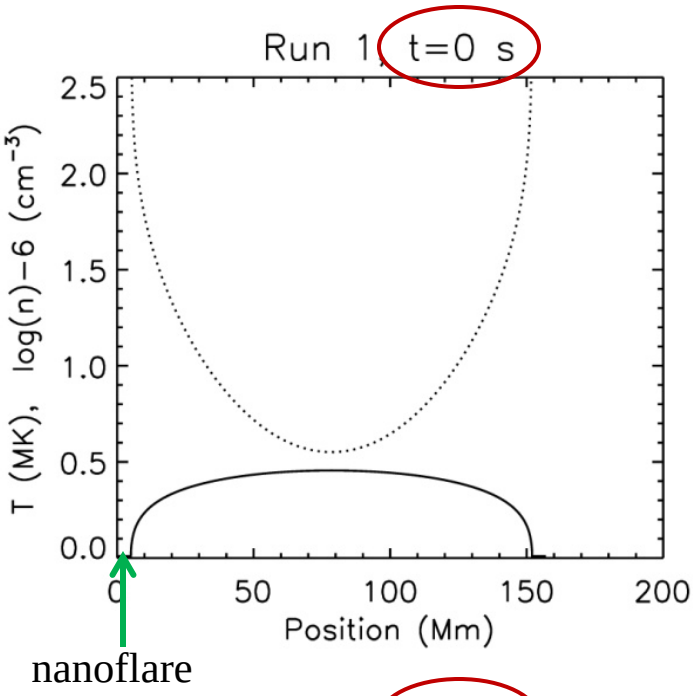
Chromospheric nanoflares may generate waves that contribute to this coronal heating.

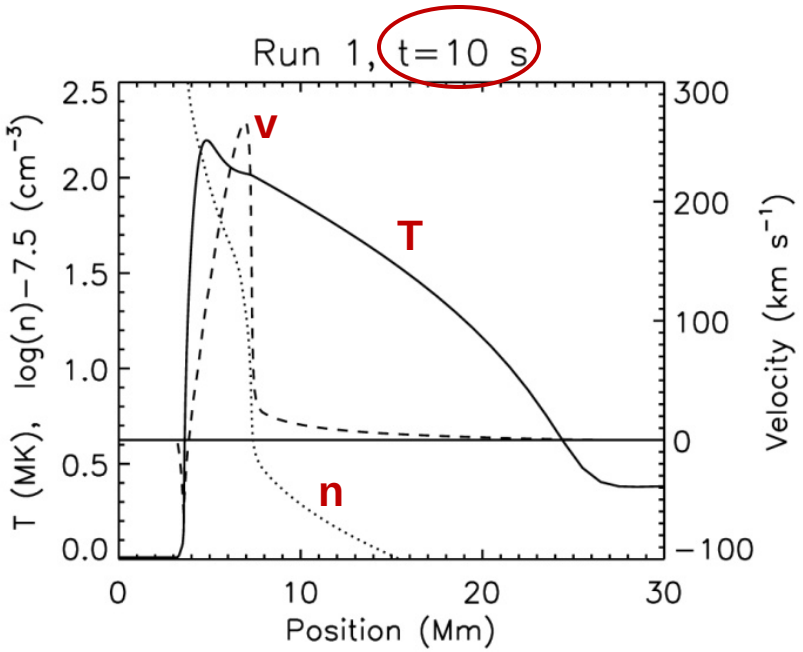
MHD effects do not alter these conclusions(?).

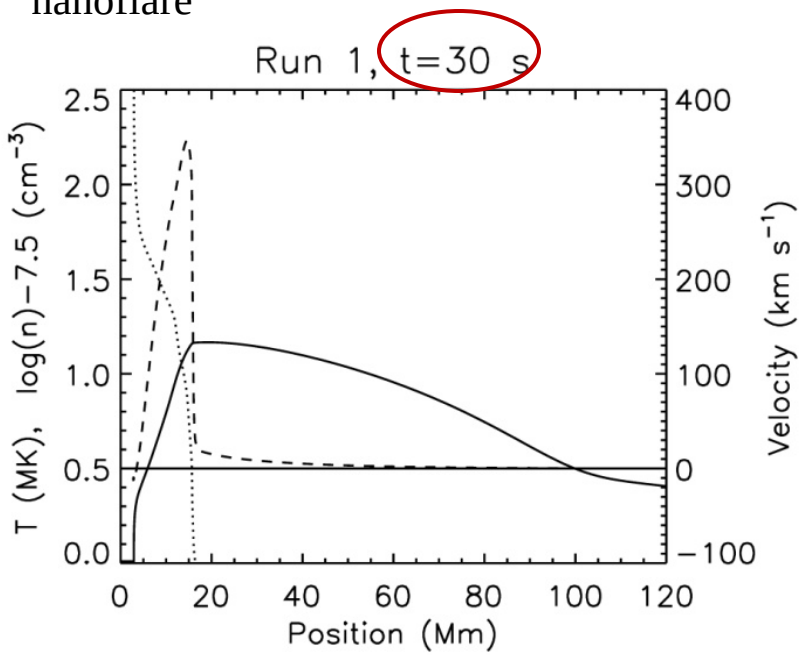
Summary

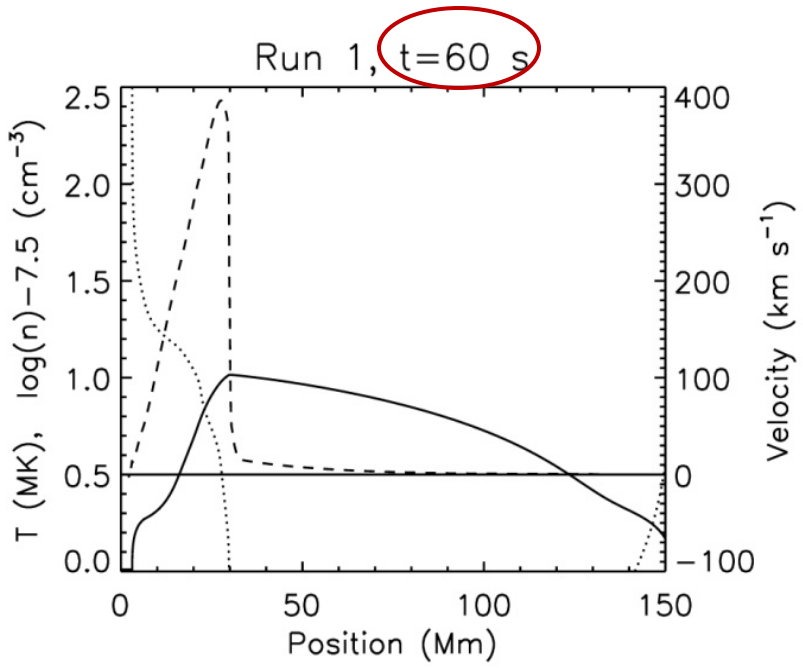
1. All coronal heating is impulsive.
2. The details of coronal heating matter.
3. The corona is filled with elemental strands.
4. The corona is densely populated with current sheets.
5. The strands must reconnect to avoid an infinite buildup of stress.
6. What determines the nanoflare frequency?
7. What is the quantum of energy release?
8. What causes the collective behavior responsible for loops?
9. What are the onset conditions for energy release?
10. Chromospheric nanoflares are not a primary source of coronal plasma

Backup Slides


Run 1, t=0 s
T (MK), log(n)−6 (cm^{-3})
Position (Mm)
nanoflare


Run 1, t=10 s
T (MK), log(n)−7.5 (cm^{-3})
Velocity (km s^{-1})
Position (Mm)
v
T
n


Run 1, t=30 s
T (MK), log(n)−7.5 (cm^{-3})
Velocity (km s^{-1})
Position (Mm)


Run 1, t=60 s
T (MK), log(n)−7.5 (cm^{-3})
Velocity (km s^{-1})
Position (Mm)

Other reasons the details are important

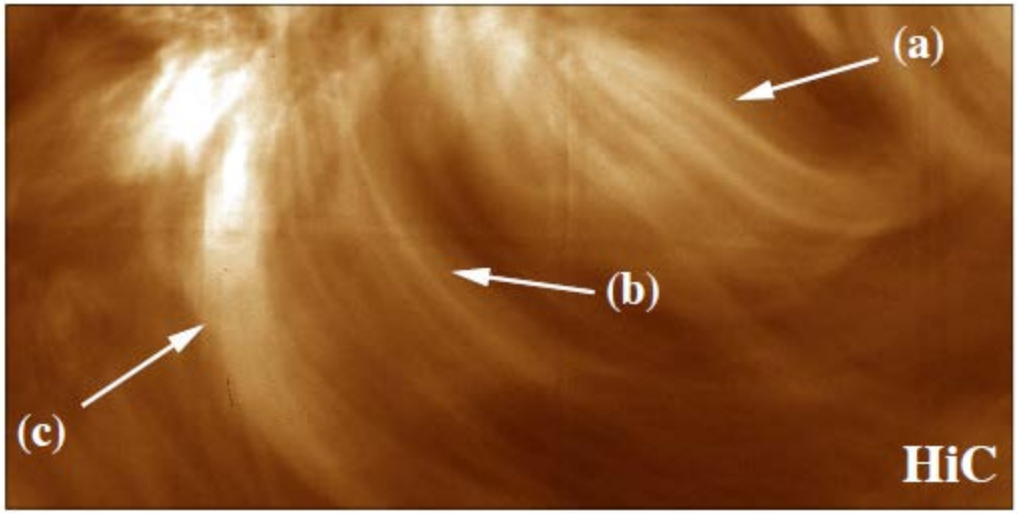
The properties of the plasma and emergent spectrum depend critically on the properties of the heating.

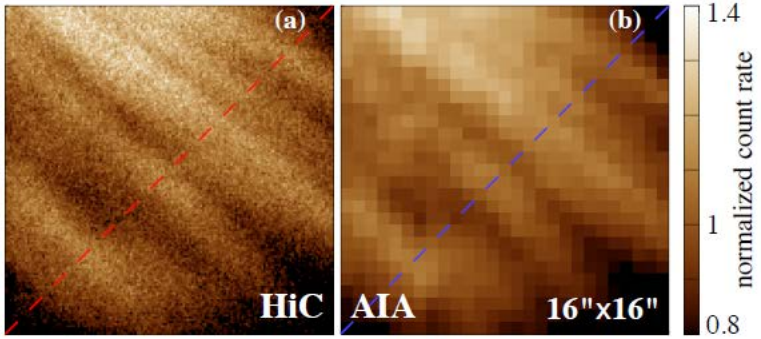
Time Variability
Emission measure distribution
Density-temperature relationship (“over dense” loops)

The evolution of helicity is depends on the heating mechanism.

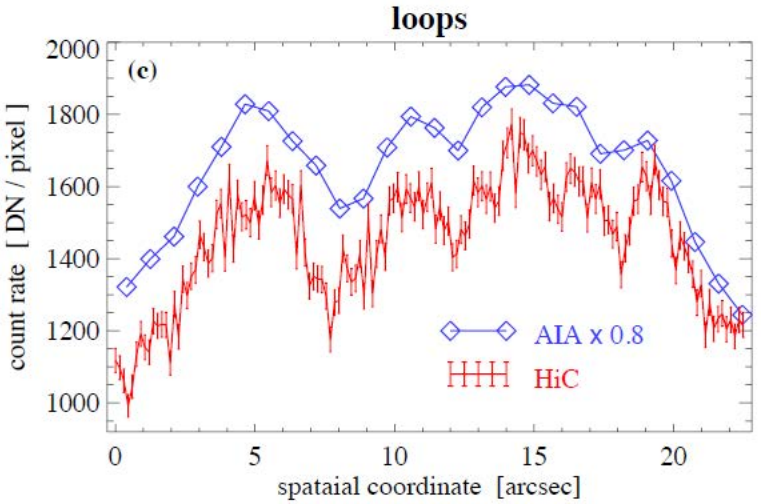
Helicity conservation is (or is not) an important constraint. Affects things such as shear build-up at neutral lines and CME eruption (Antiochos 2013).

Ohmic heating does not conserve helicity.

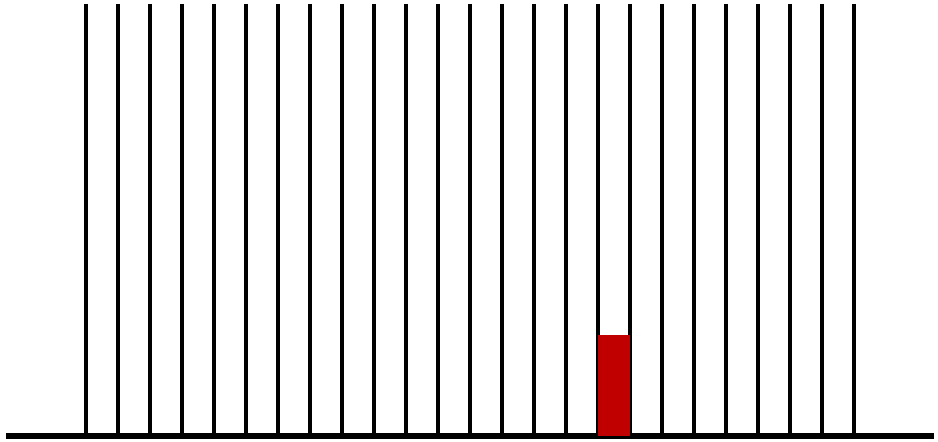


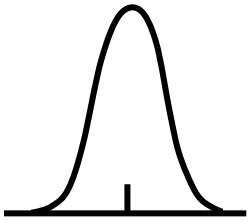
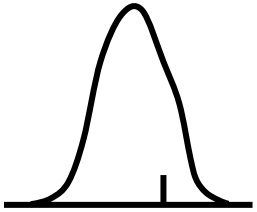
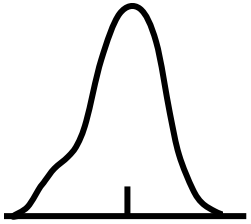
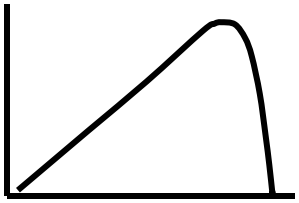
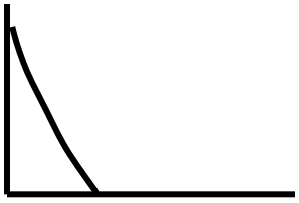


Hi-C has 4-6 times better spatial resolution than AIA



Peter et al. (2013)



	Coronal Heating Strands		Type-II Spicule Strand		Composite (Observed)
Line Profile	100 x		+		=	
Emission Measure Distribution	100 x		+		=