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Predicting observational signatures of coronal heating by Alfvén waves and nanoflares

P. Antolin[1,2], K. Shibata[1], T. Kudoh[3], D. Shiota[4], D. Brooks[5]

[1] Kwasan Observatory - Kyoto University
[2] Institute of Theoretical Astrophysics - University of Oslo
[3] National Astronomical Observatory of Japan
[4] Earth Simulator Center - JAMSTEC
[5] Space Science Division - Naval Research Laboratory

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The solar corona

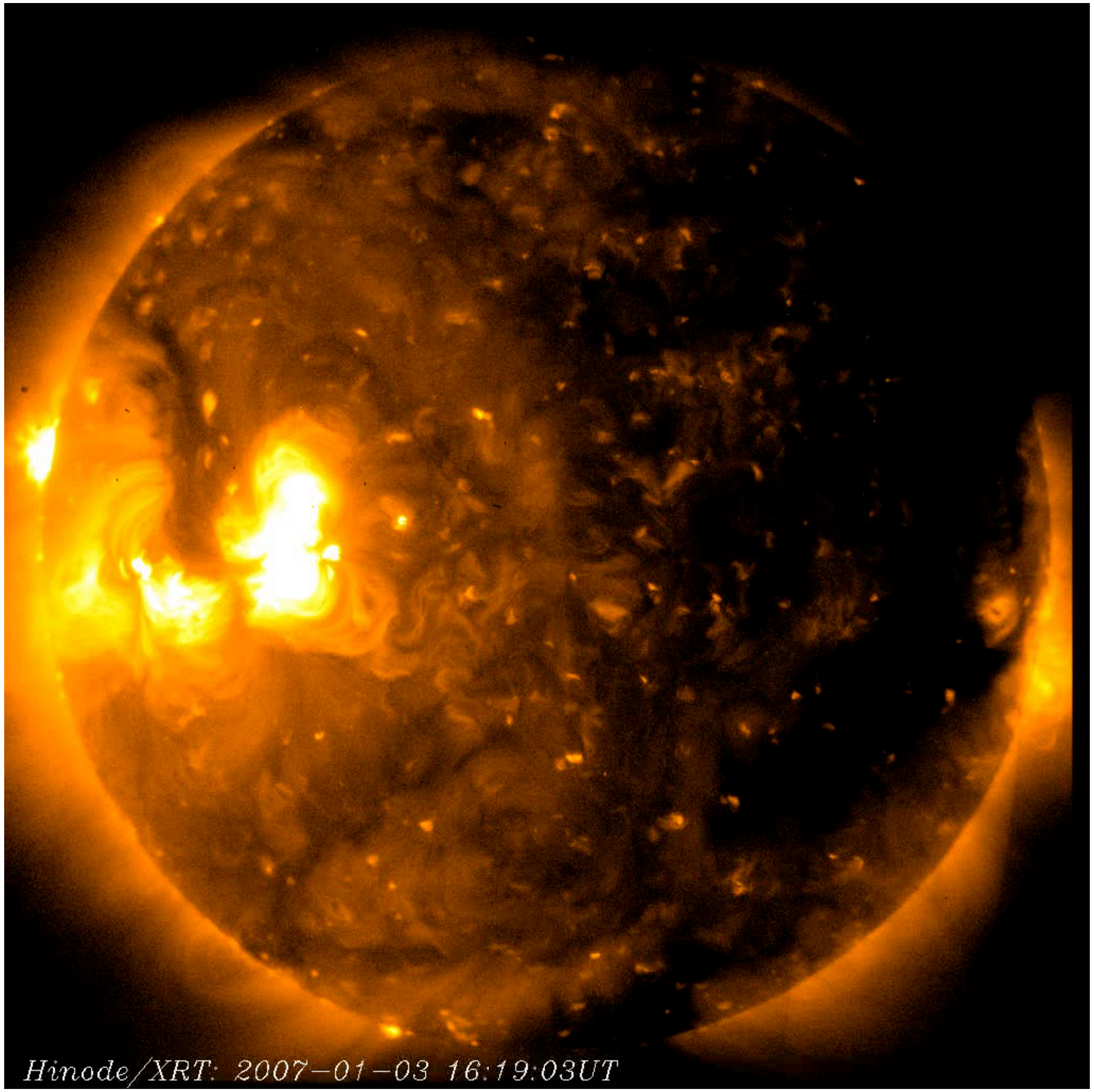
Grotrian, Edlén (1943): correct interpretation of coronal lines

↓

T > 1 MK

>200 times hotter than photosphere

Coronal heating problem



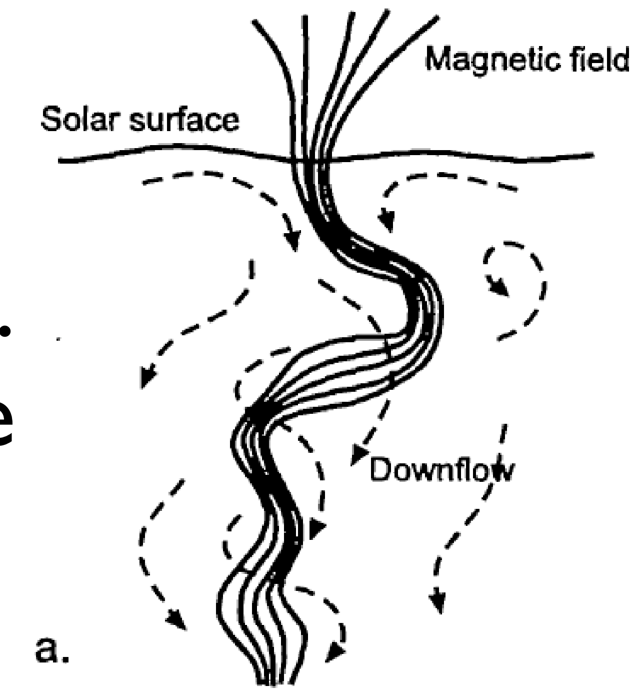
Hinode/XRT

Heating mechanisms

- Alfvén wave model (Alfvén 1947, Uchida & Kaburaki 1974, Wenzel 1974).

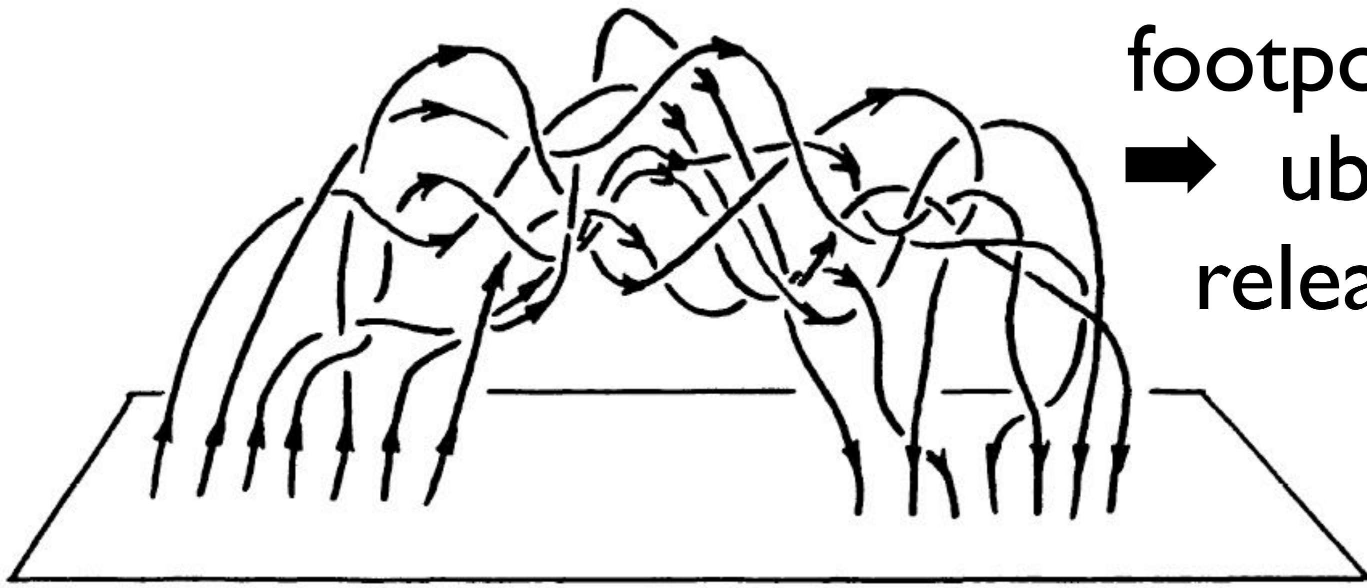
- Alfvén waves can carry enough energy to heat and maintain a corona (Hollweg et al. 1982, Kudoh & Shibata 1999)

- Waves may be created by sub-photospheric motions or by magnetic reconnection events. They propagate into the corona and dissipate their energy (linear & nonlinear mechanisms)

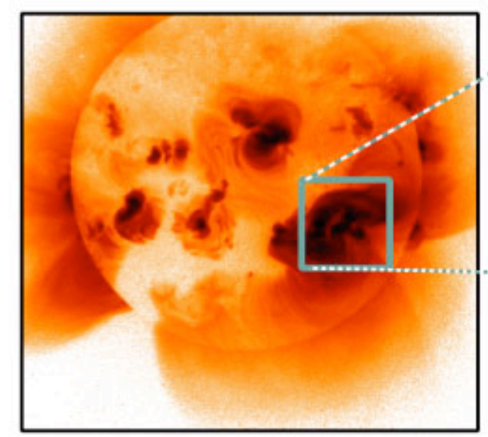


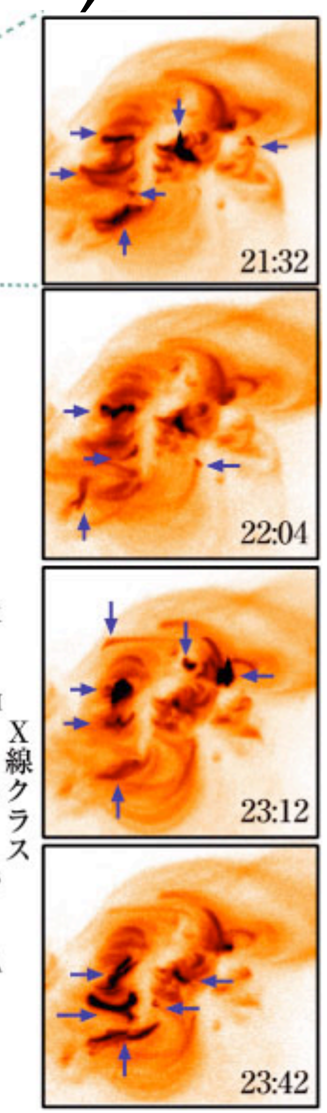
- Mode conversion: Alfvén waves convert into longitudinal modes during propagation, which can steepen into shocks and heat the plasma (Moriyasu et al. 2004)

Heating mechanisms

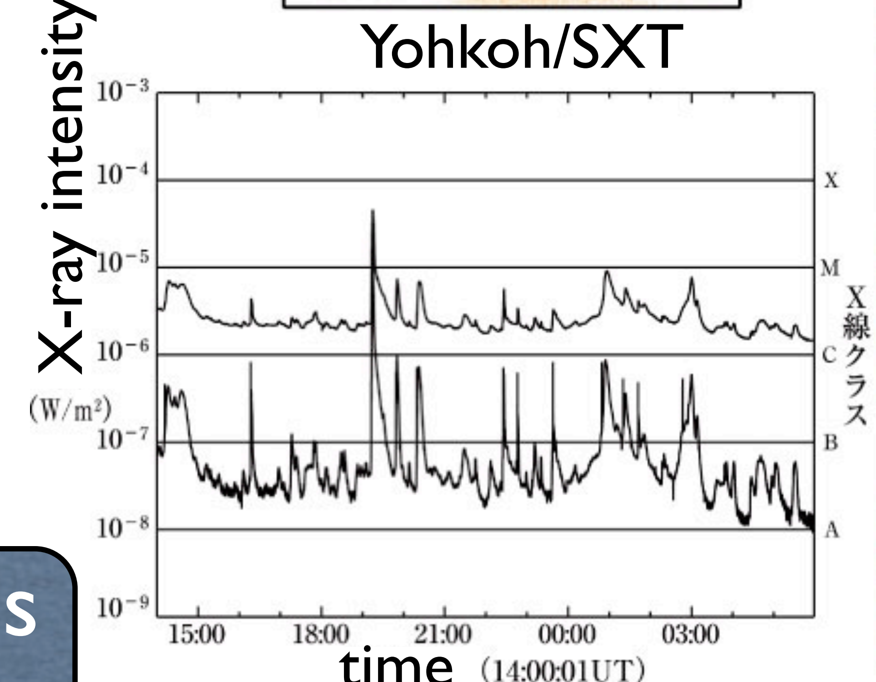


footpoint shuffling - braiding, twisting,...
➡ ubiquitous, sporadic and impulsive releases of energy in current sheets (nanoflares, Parker 1988)





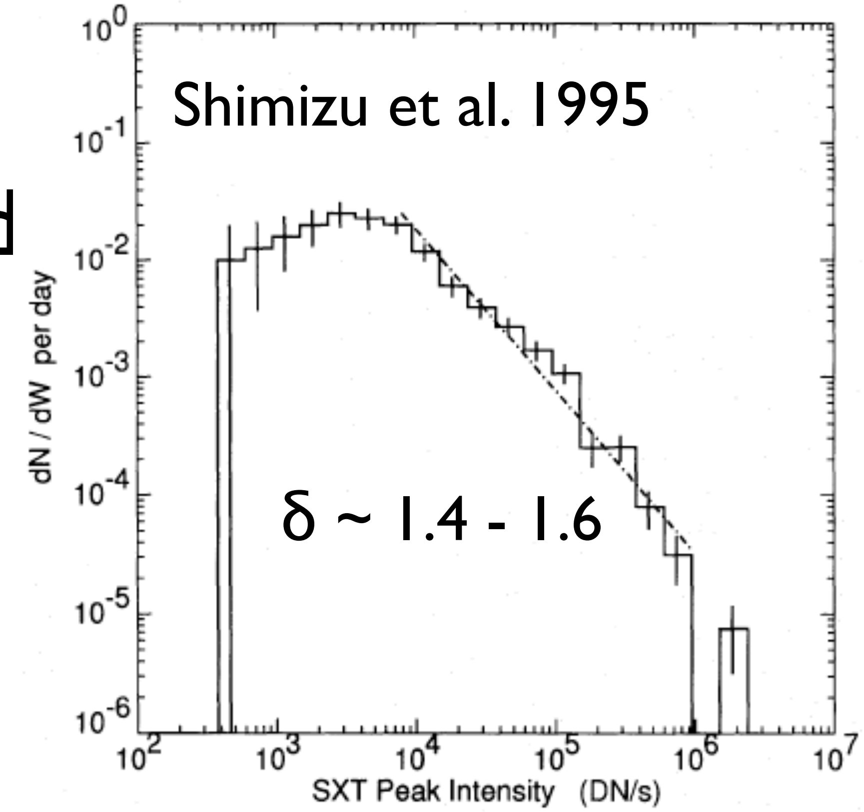
Yohkoh/SXT



- Nanoflare-reconnection model (Porter et al. 1987, Parker 1988).
- Both models may explain observed intermittency and spiky intensity profiles of coronal lines (Parnell & Jupp 2000, Katsukawa & Tsuneta 2001, Moriyasu et al. 2004).

How to recognize both mechanisms when they operate in the corona?

Observational facts



- Energy release processes in the Sun, from solar flares down to microflares are found to follow a power law distribution in frequency (Lin et al. 1984; Dennis 1985).

$$\frac{dN(I)}{dI} \propto I^{-\delta}$$

- Main contribution to the heating may come from smaller energetic events (nanoflares) if these distribute with a power law index $\delta > 2$ (Hudson 1991).

- Studies of small-scale brightenings have shown a power law both steeper and shallower than 2 (Krucker & Benz 1998, Aschwanden & Parnell 2002).

Purpose

- Propose unique observable signatures of Alfvén wave heating and nanoflare-reconnection heating.

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convective motions

reconnection events

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Different characteristics of wave modes along magnetic flux tubes

convective motions

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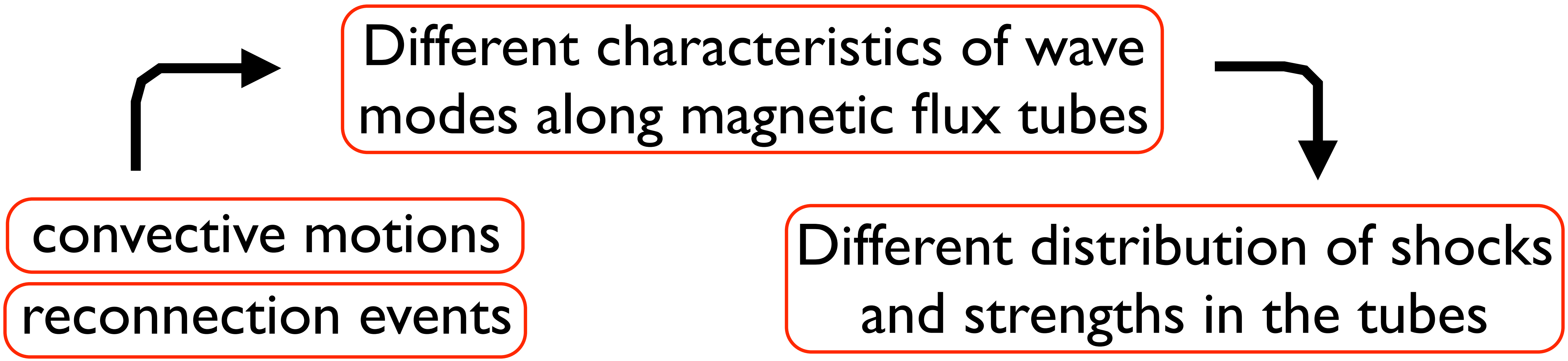

Purpose

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convective motions

reconnection events

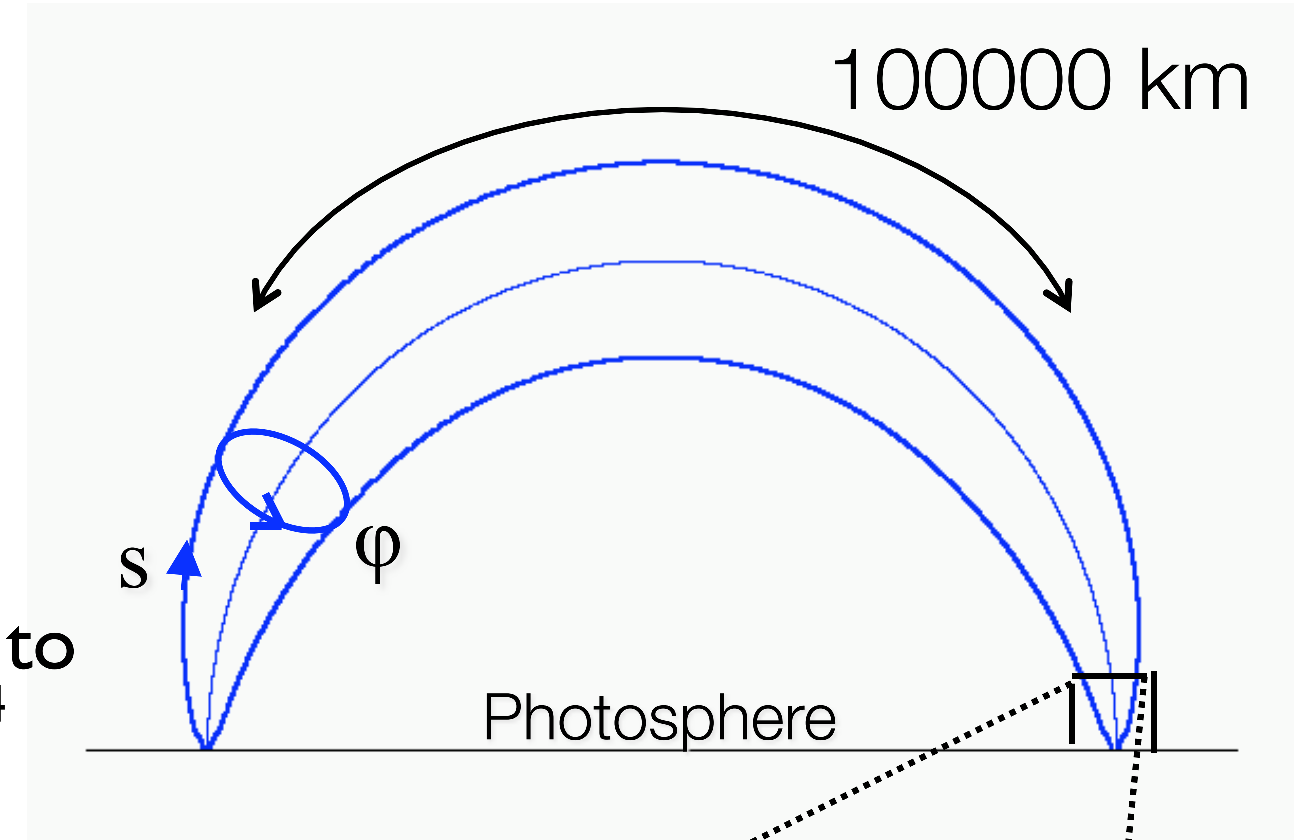
→ Different characteristics of wave modes along magnetic flux tubes

→ Different distribution of shocks and strengths in the tubes

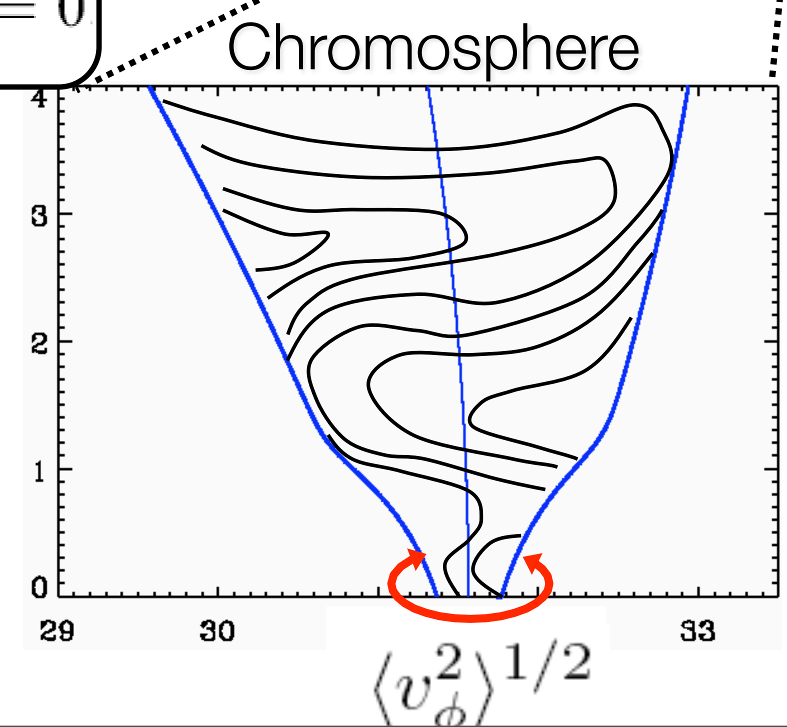
- Distinctive flow patterns along the tubes
- Distinctive X-ray intensity profiles
- Distinctive frequency distribution of heating events between the models: distinctive power law index

Numerical model

- Initial conditions
  - $T_0 = 10^4$ K, constant
  - $\rho_0 = 2.5 \times 10^{-7}$ g cm^{-3}
  - $p_0 = 2 \times 10^5$ dyn cm^{-2}
  - $B_0 = 2300$ G, with apex to base area ratio of 1000
  - Hydrostatic pressure balance up to 800 km height. After $\rho \propto (\text{height})^{-4}$ (Shibata et al. 1989)

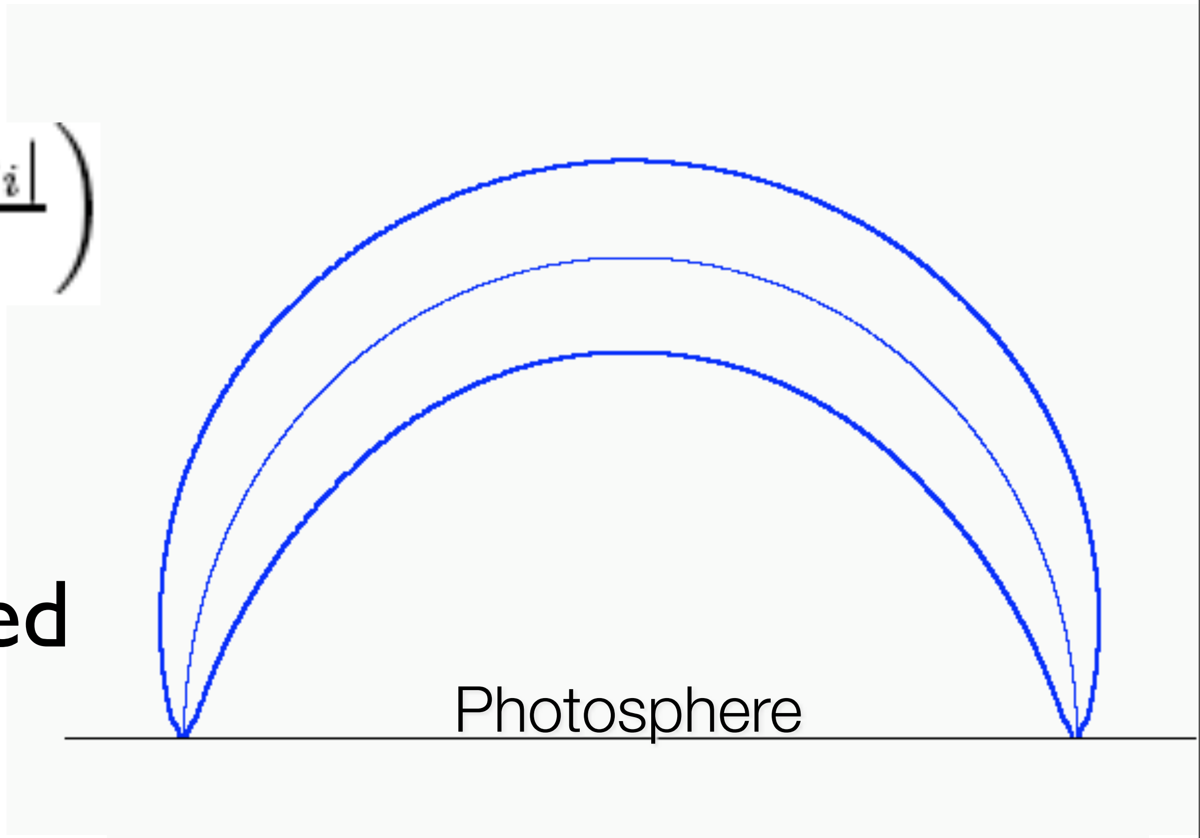


- 1.5-D MHD code $\frac{\partial}{\partial \phi} = 0, \quad \frac{\partial}{\partial r} = 0, \quad v_r = 0, \quad B_r = 0$
- CIP-MOCCT scheme (Yabe & Aoki 1991, Stone & Norman 1992, Kudoh et al. 1999) with conduction + radiative losses (optically thin & thick approximations)
- Torsional Alfvén waves created by a random photospheric driver. Also monochromatic waves

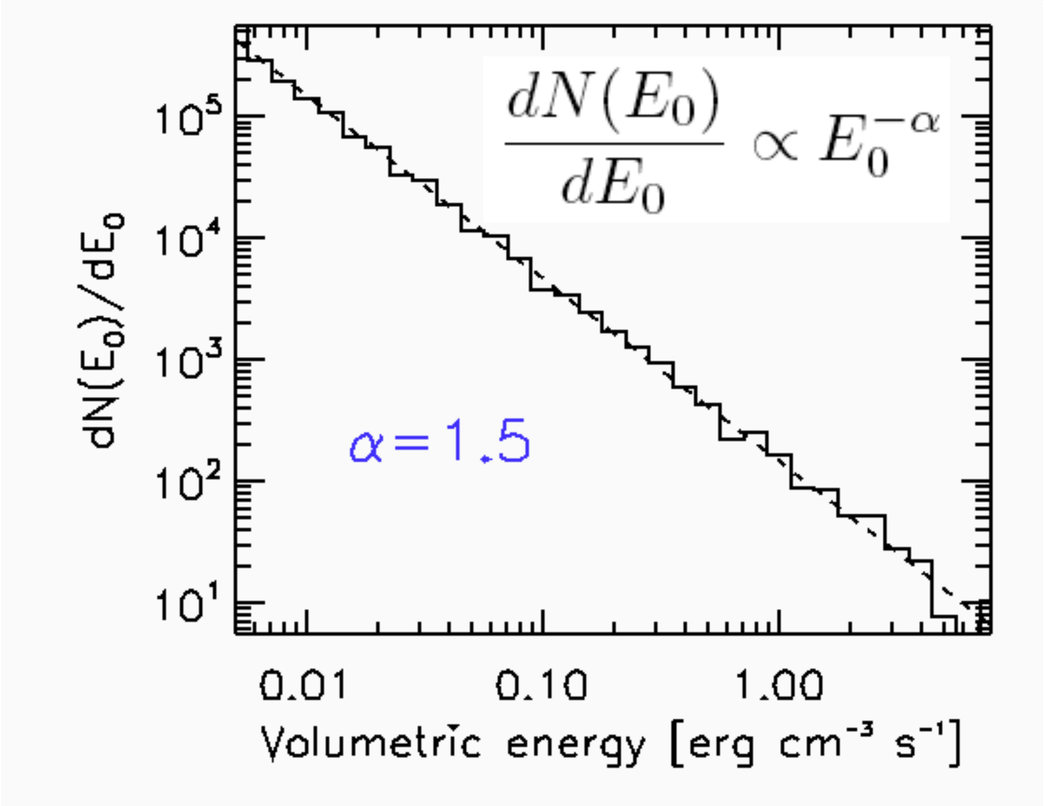


Nanoflare heating function

$$\mathcal{H}_i(t,s) = E_0 \sin\left(\frac{\pi(t-t_i)}{\tau_i}\right) \exp\left(-\frac{|s-s_i|}{s_h}\right)$$
$$(t_i < t < t_i + \tau_i)$$



- Artificial injection of energy: we assume only slow modes are created
- Heating events can be:
  - Uniformly distributed along loop
  - Concentrated towards footpoints
- Energies of heating events can follow
  - A uniform distribution
  - A power law distribution



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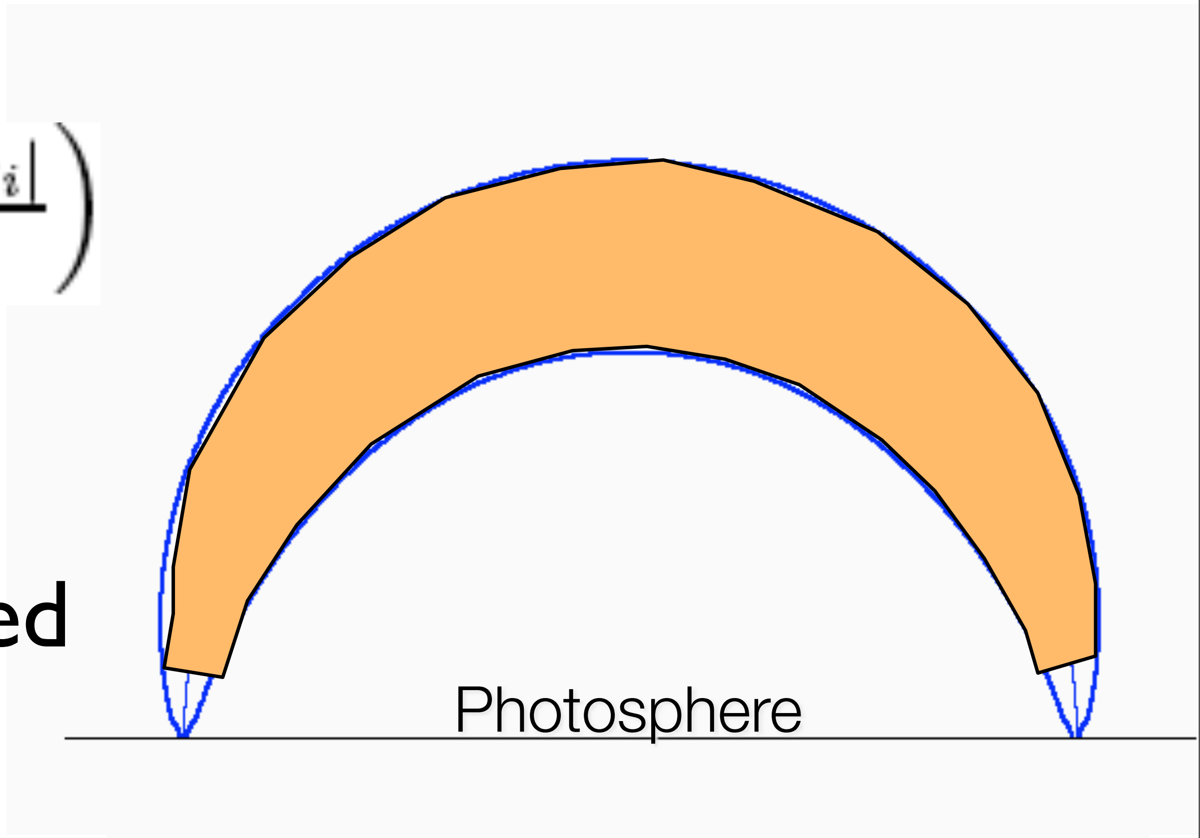

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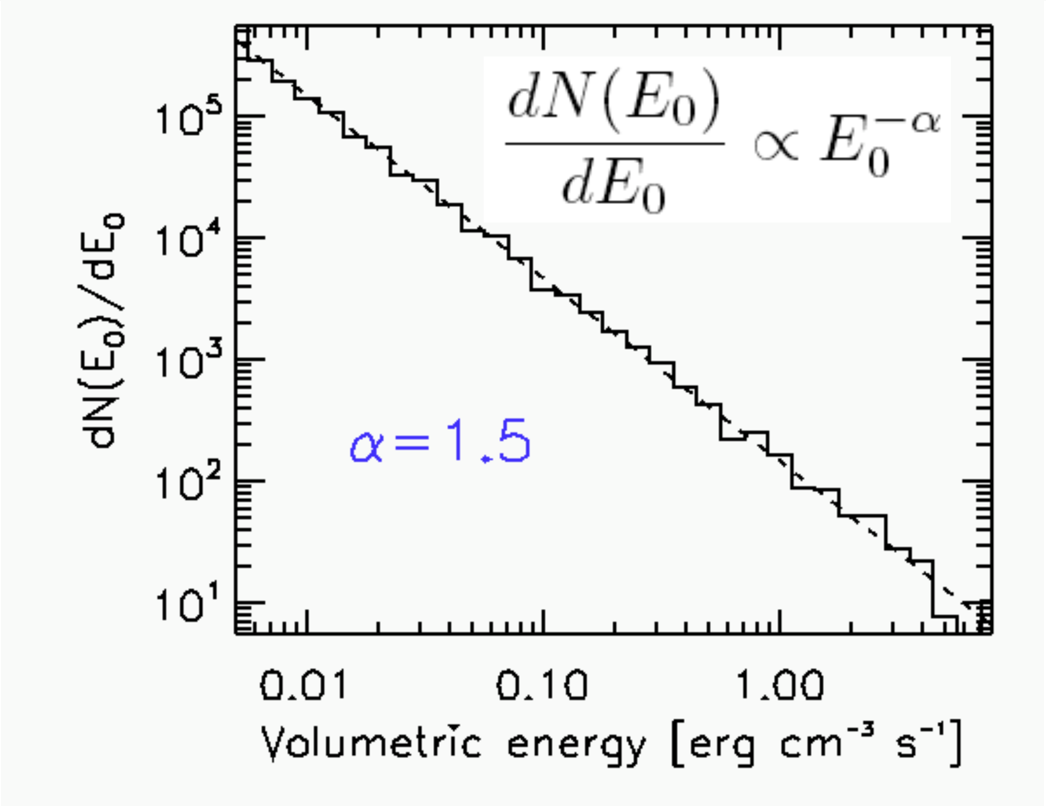

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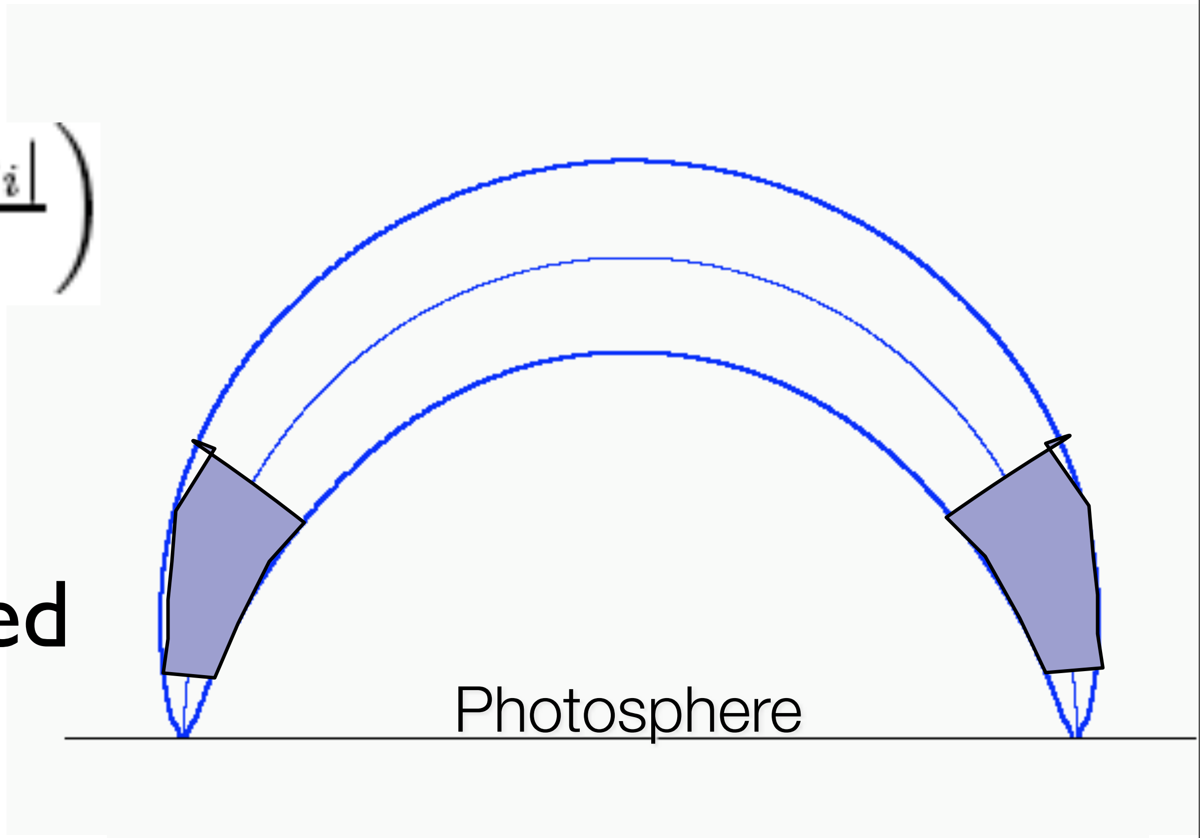

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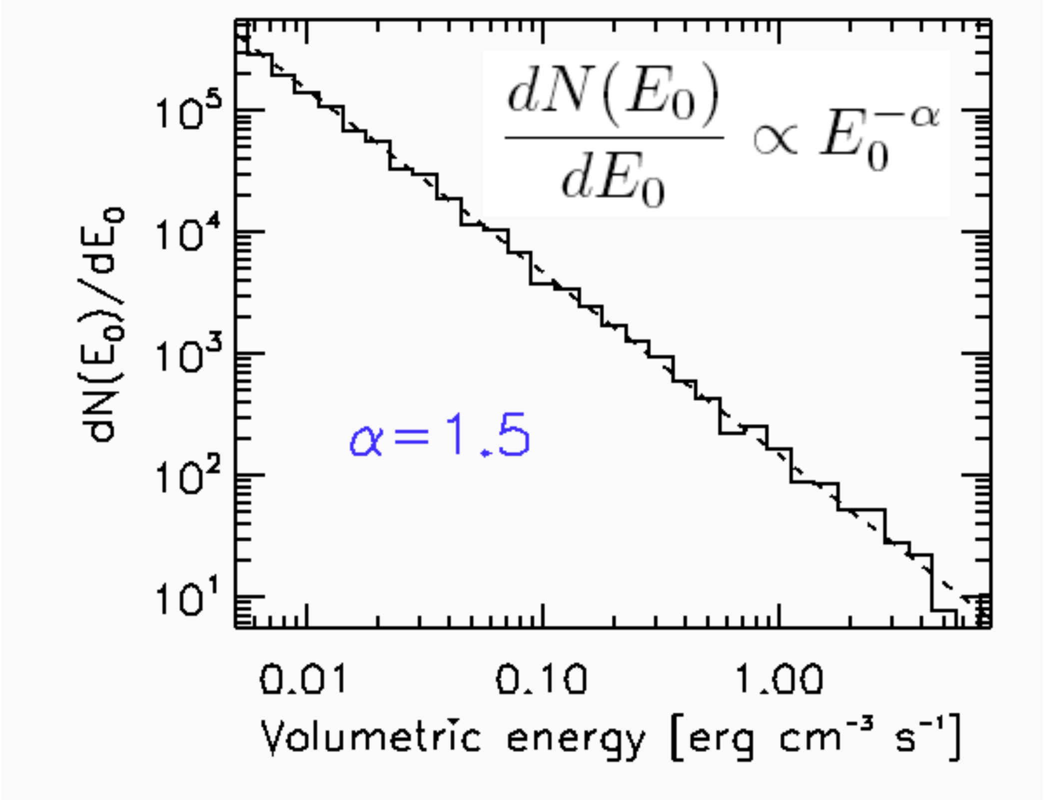

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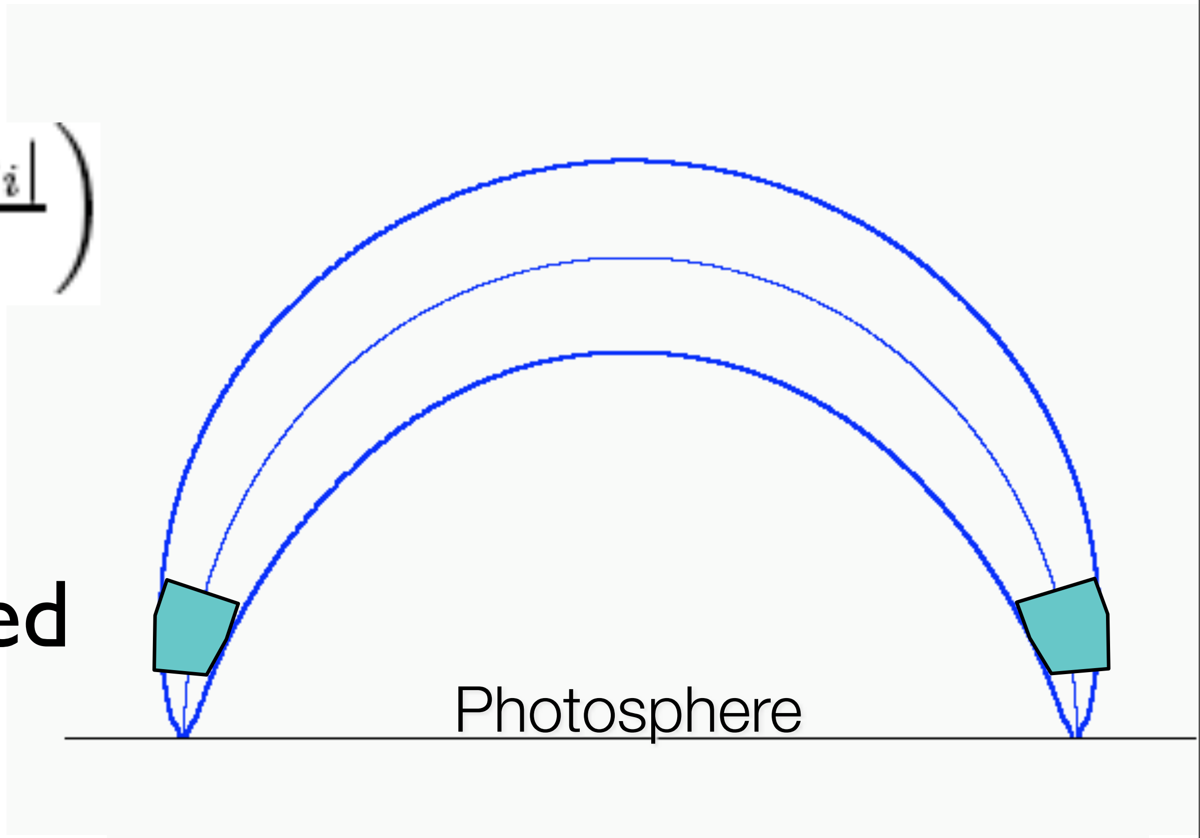
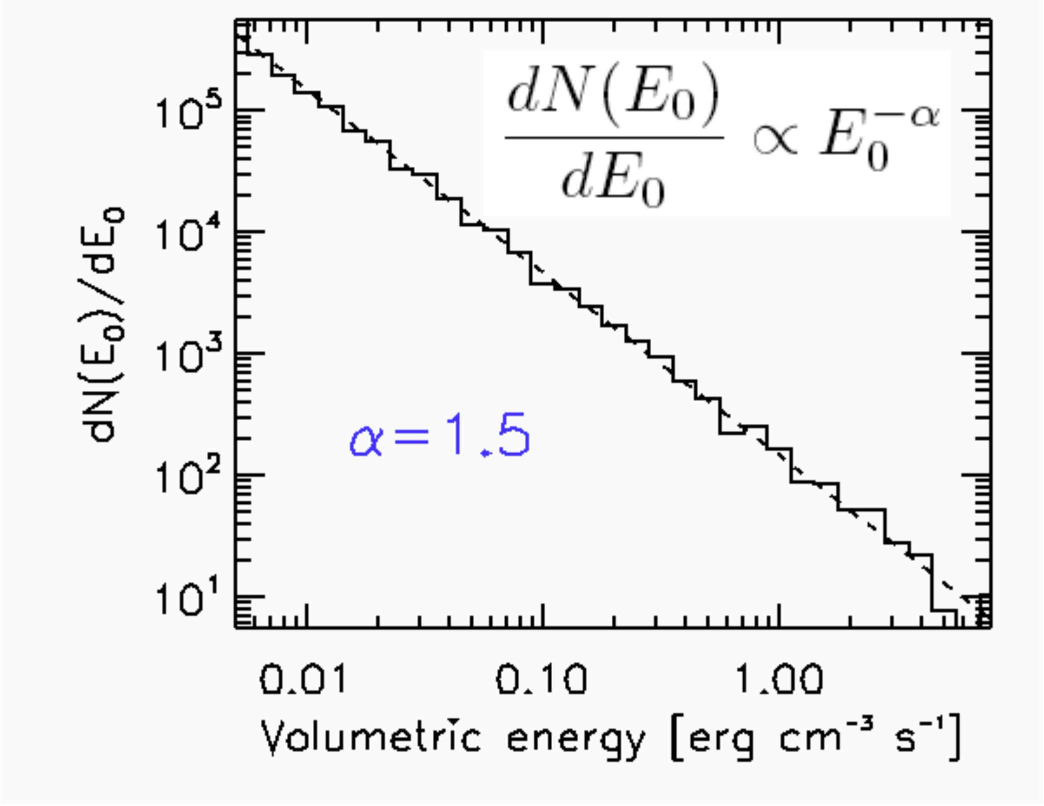
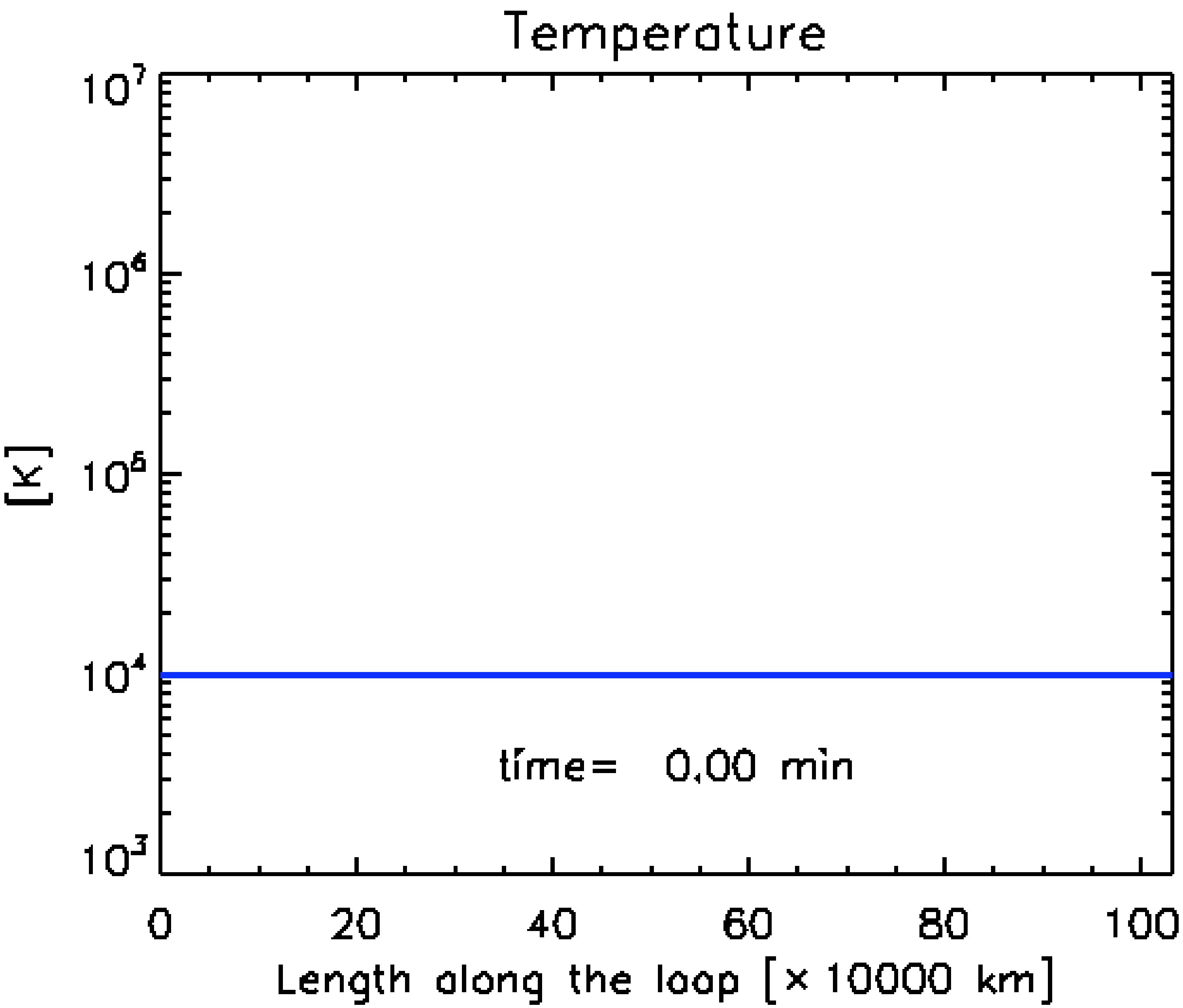
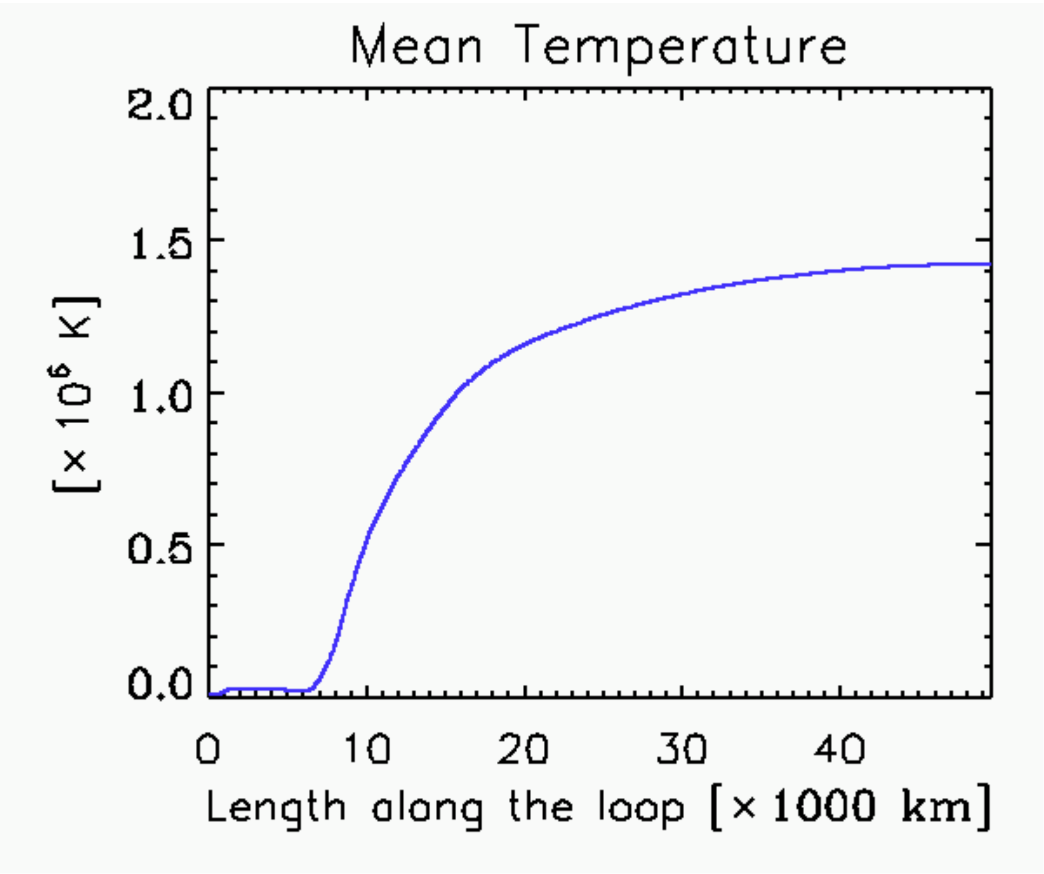




Results

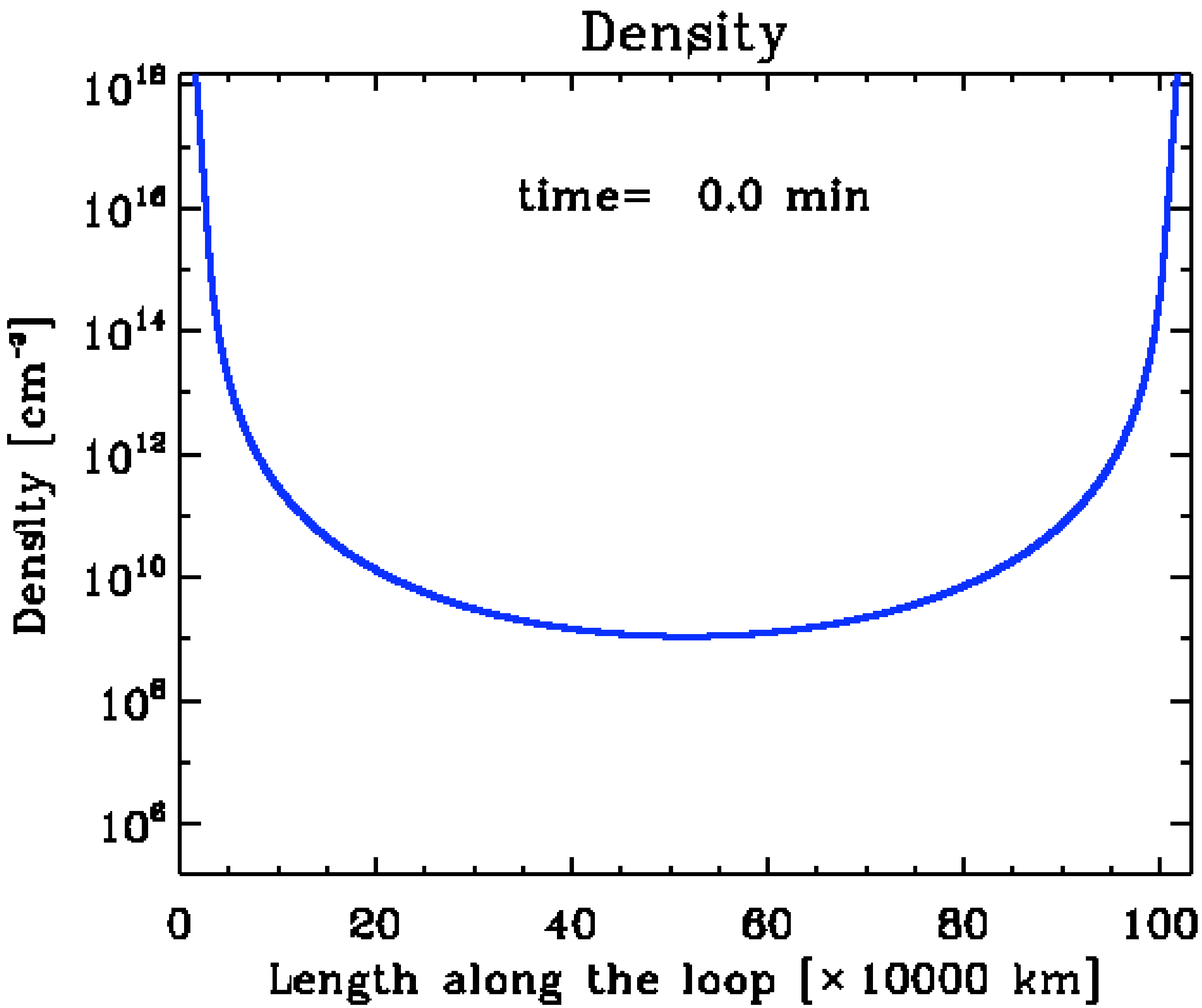
Alfvén wave heating





Loop heated uniformly
Satisfies RTV scaling law
(Moriyasu et al. 2004)

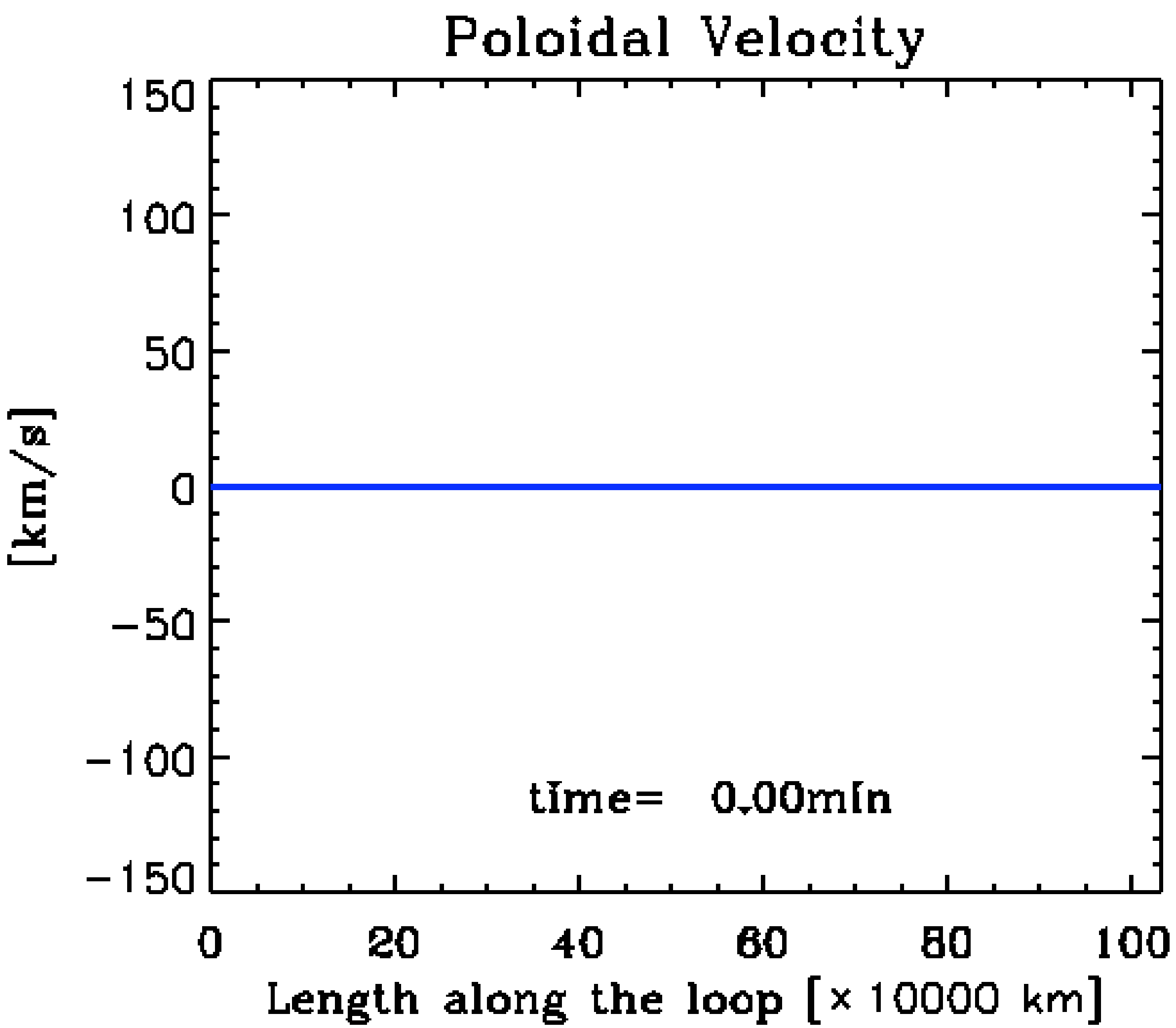
Alfvén wave heating



Strong slow/ fast shocks are ubiquitous in the corona

Spicules easily created (Kudoh & Shibata 1999)

Alfvén wave heating

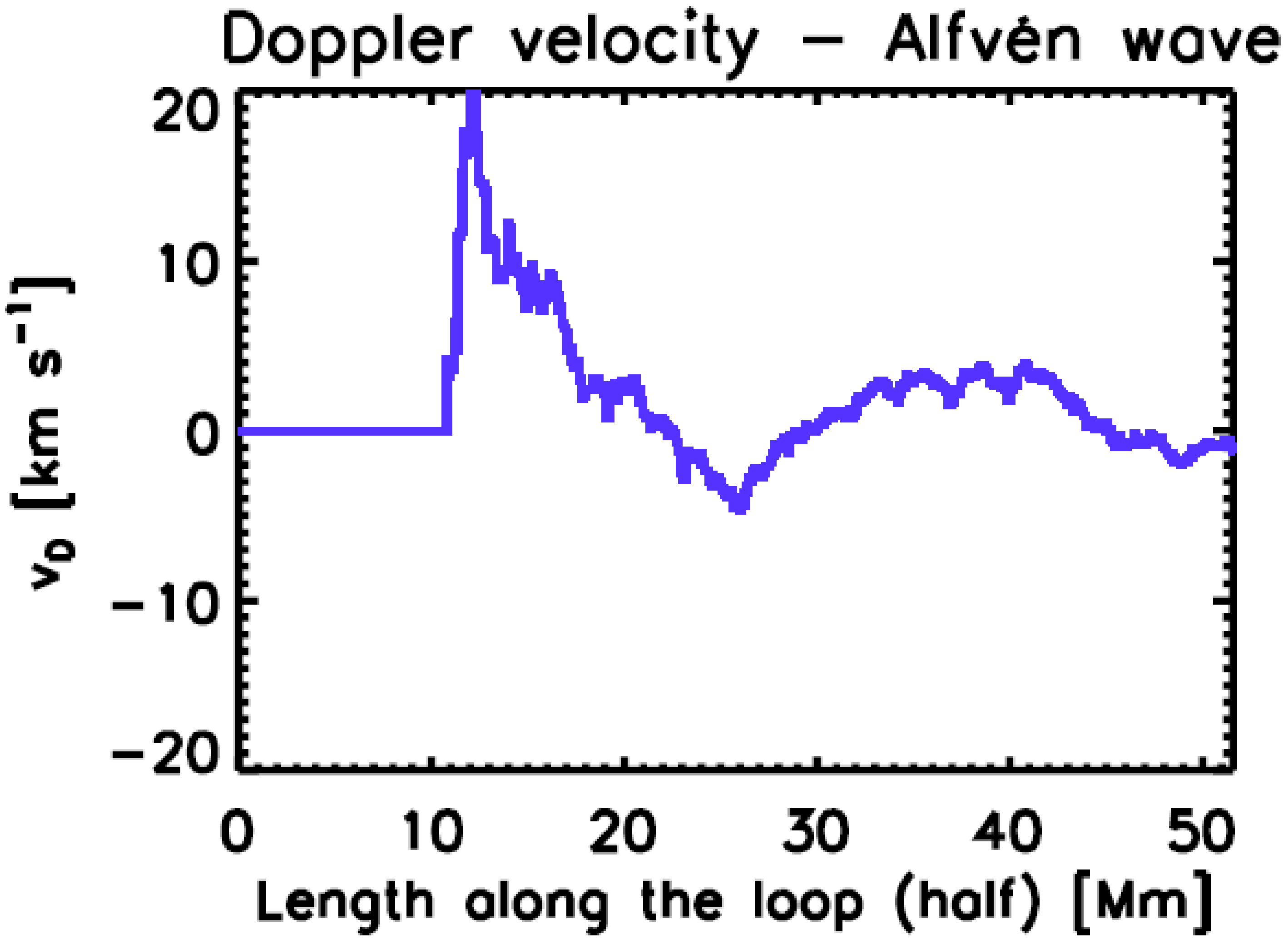


High speed flows are obtained

<v> ~ 50 km/s

v_{max} > 200 km/s

Alfvén wave heating

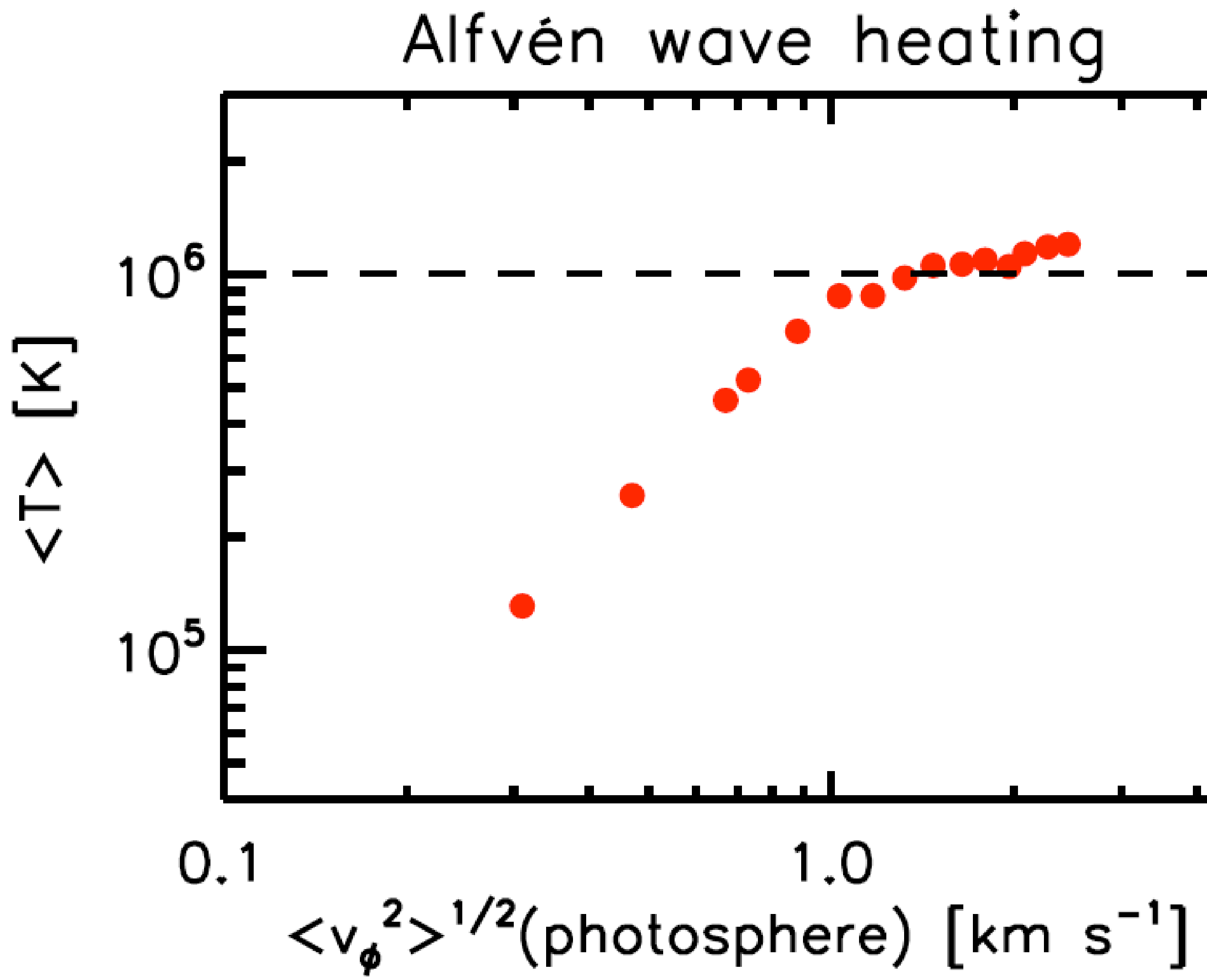


Doppler velocities calculated from Fe XV emission line, using CHIANTI atomic database

Red shifts observed at footpoints

Agreement with observations in QS?

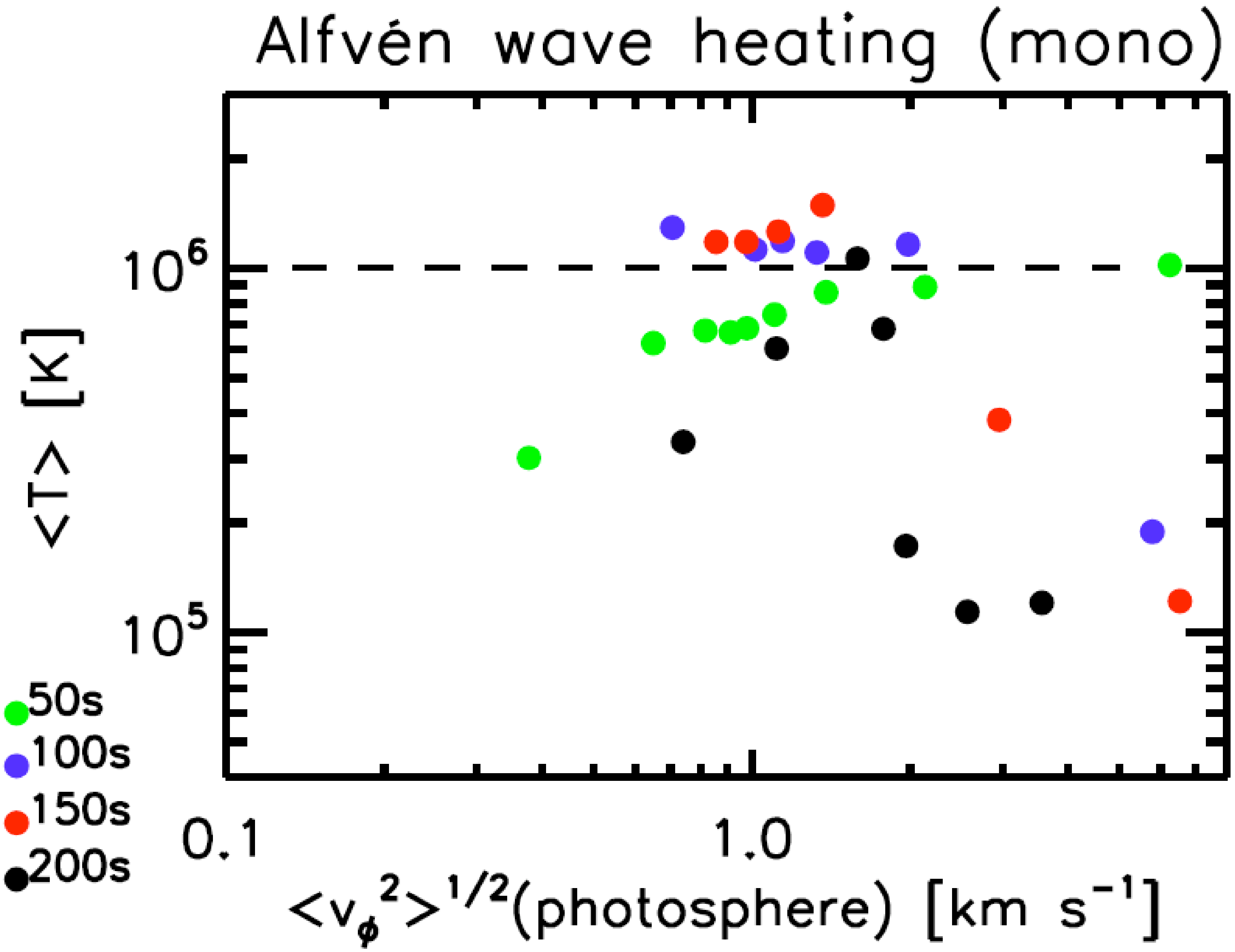
Alfvén wave heating



White noise spectrum

For $<v_\varphi^2>^{1/2} \gtrsim 1.3$ km/s a corona is created

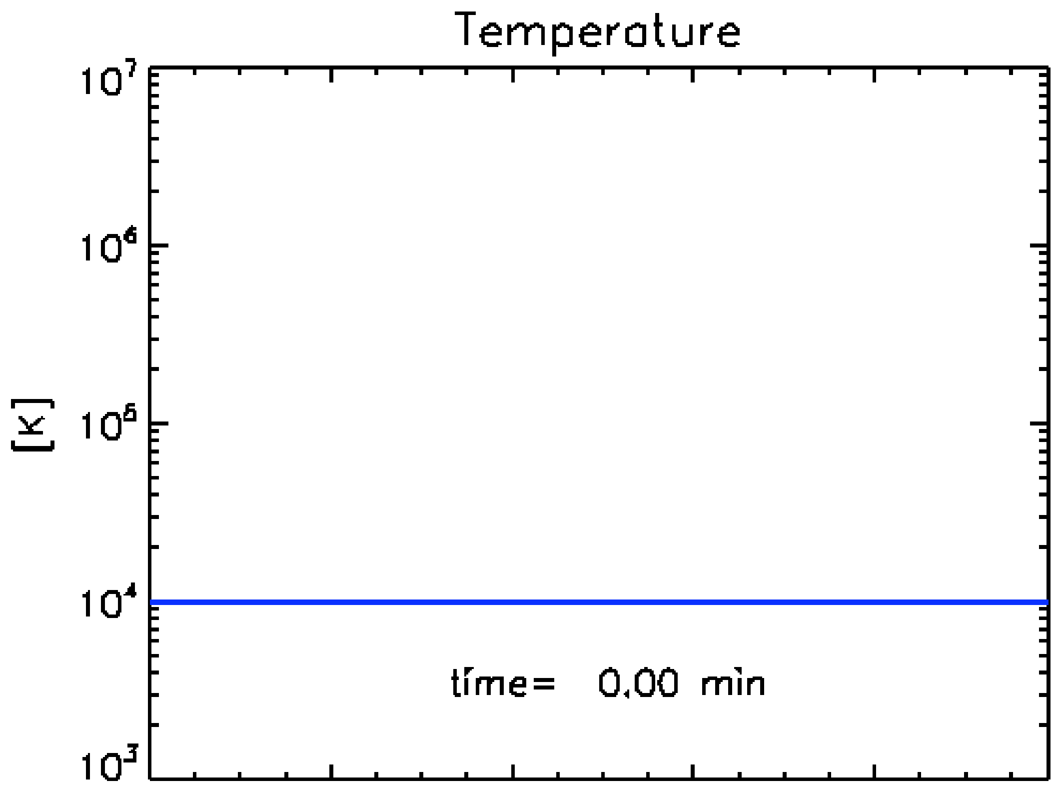
Alfvén wave heating



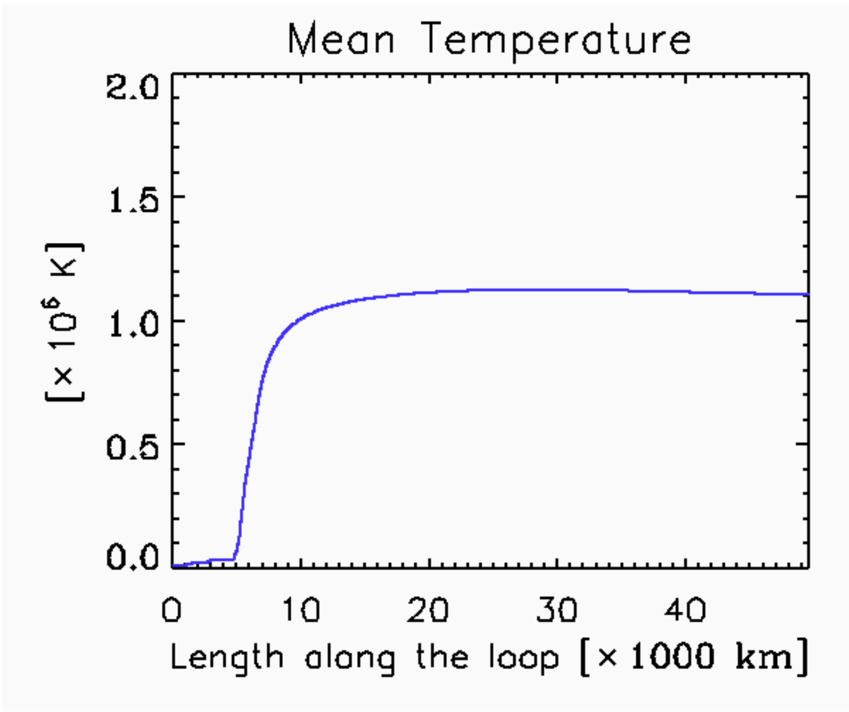
monochromatic waves

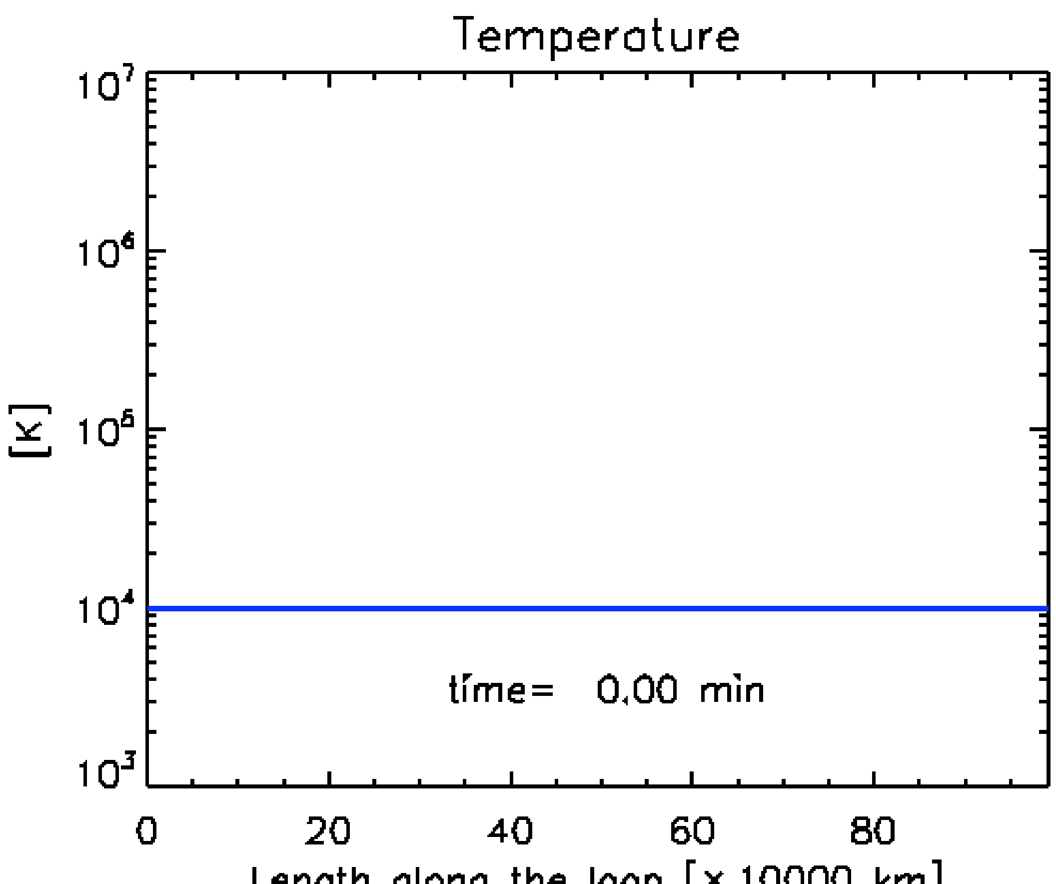
- The 100 - 150 s range is the more efficient
- Shorter periods do not carry sufficient energy into the corona (large dissipation)
- Larger periods produce too strong shocks that disrupt energy balance in the corona

Nanoflare heating

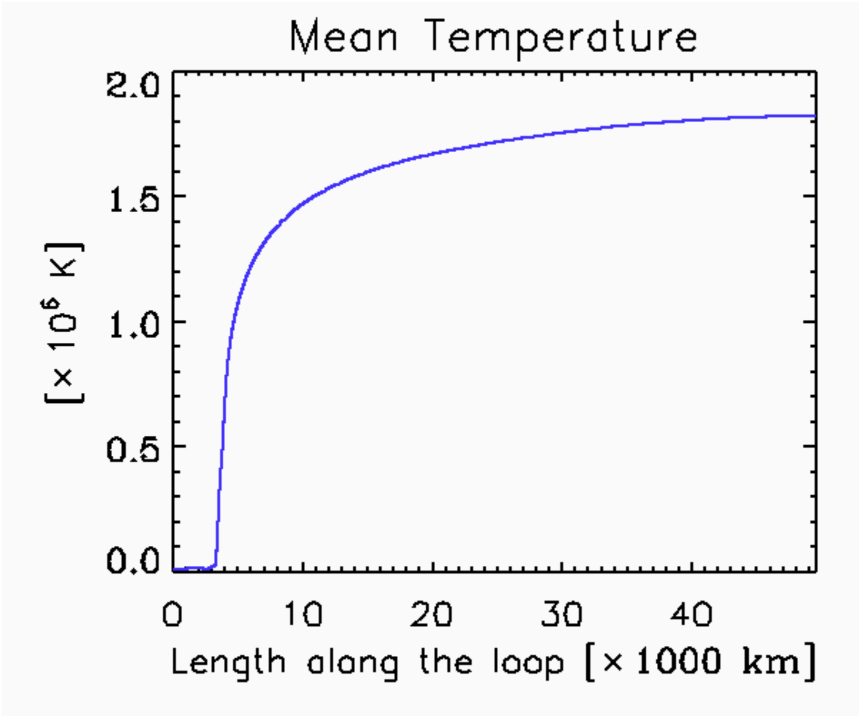


Footpoint

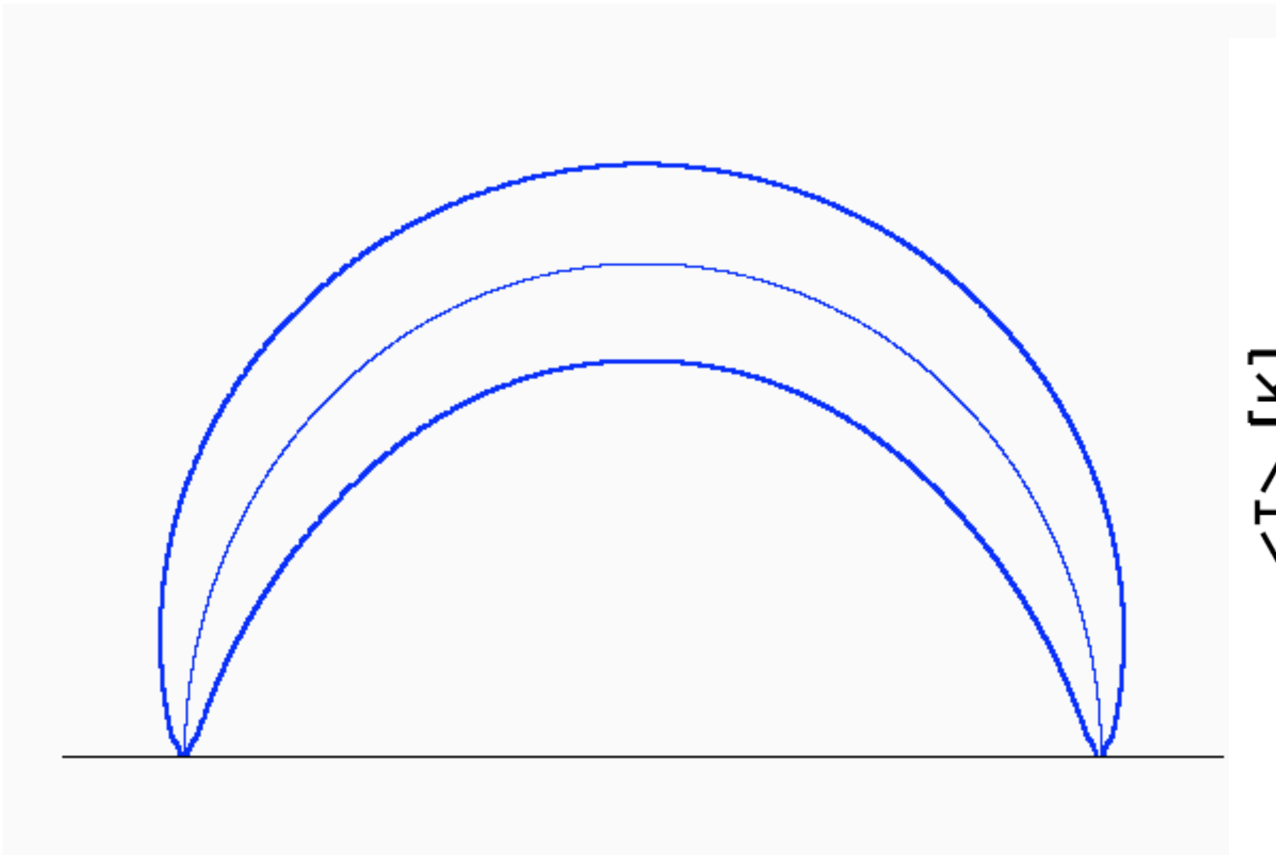


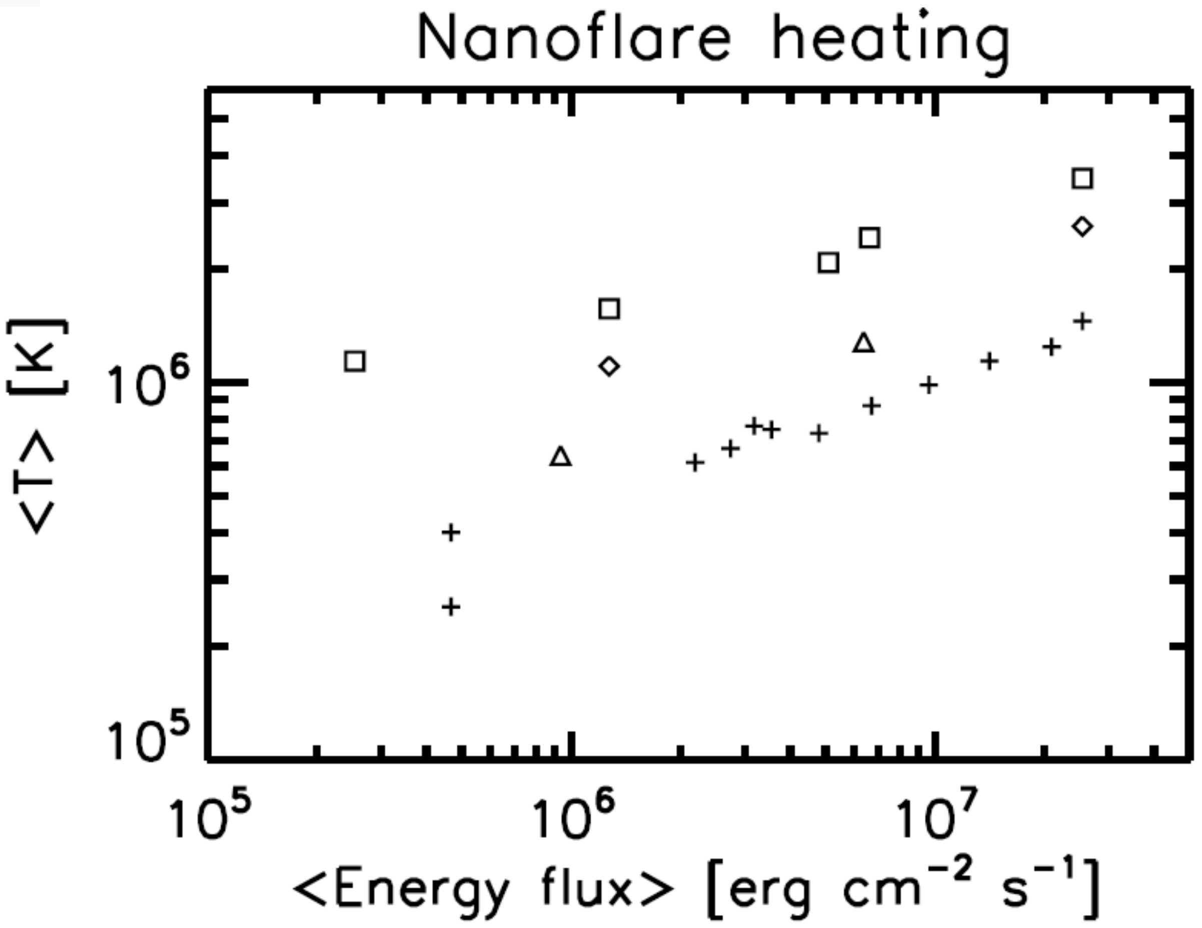


Uniform

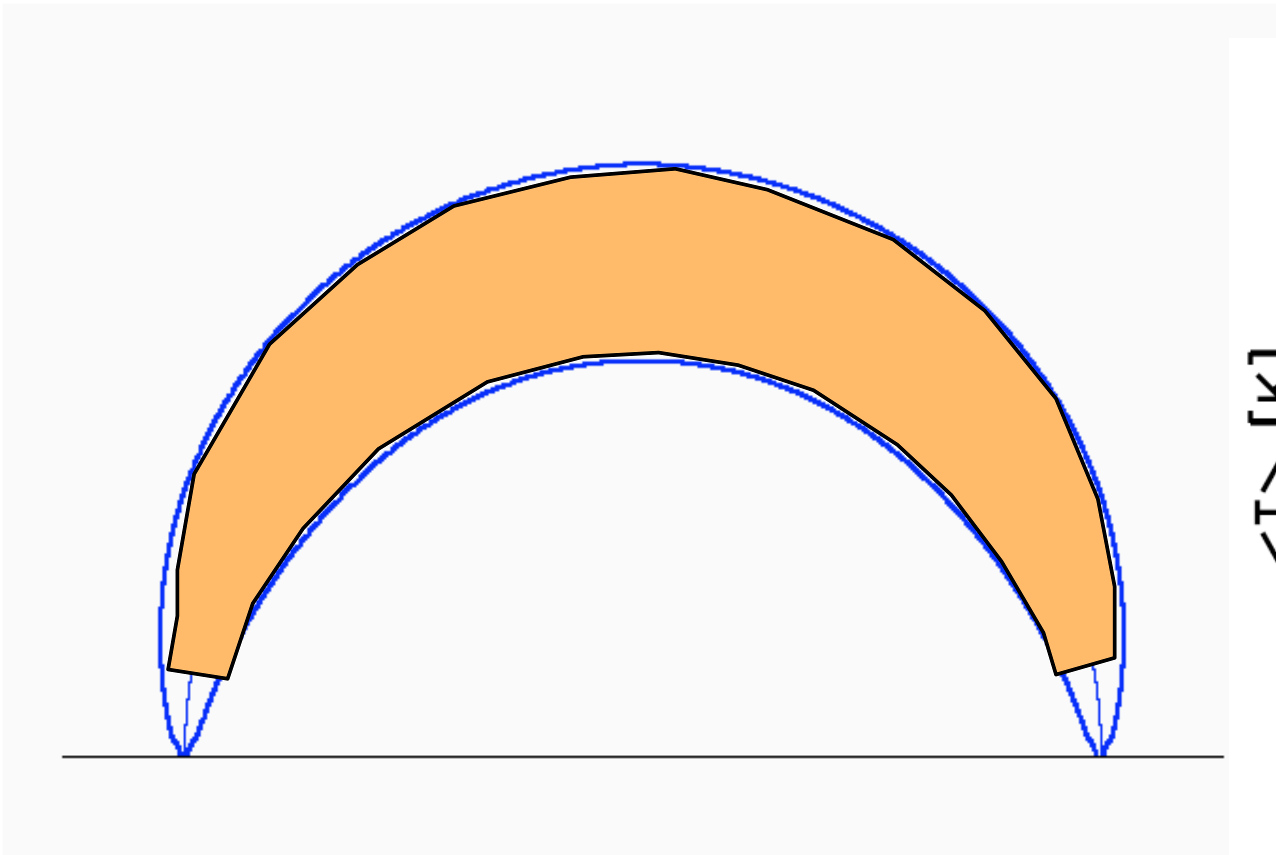


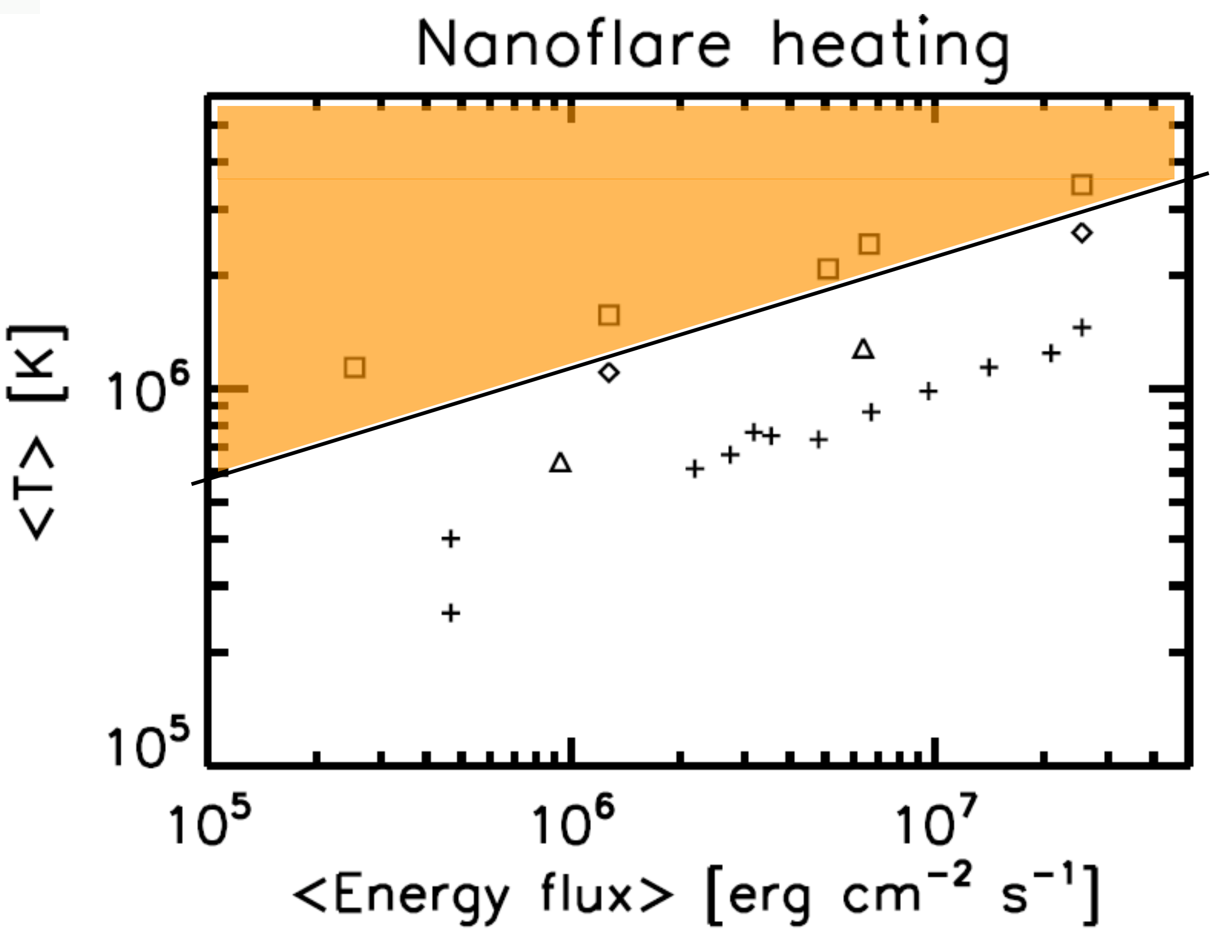
Nanoflare heating



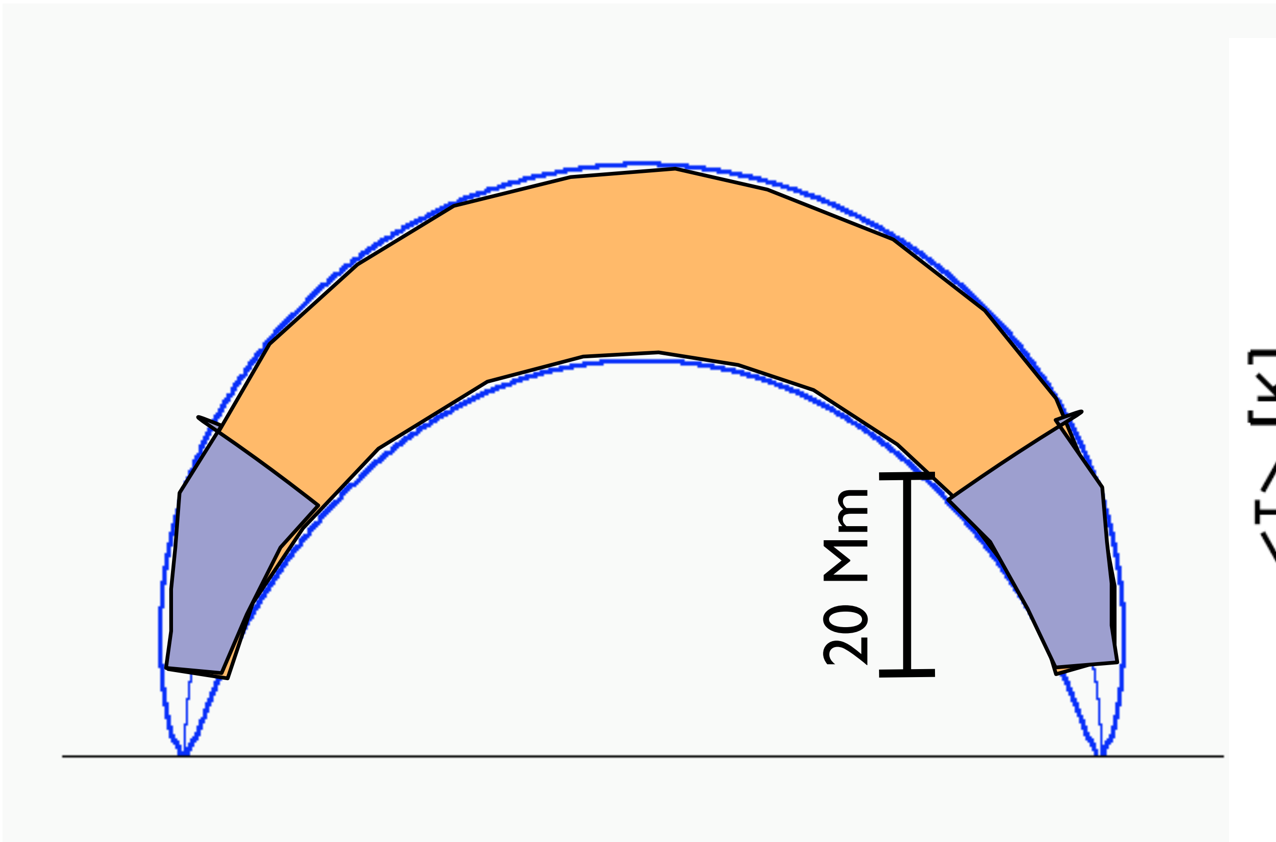


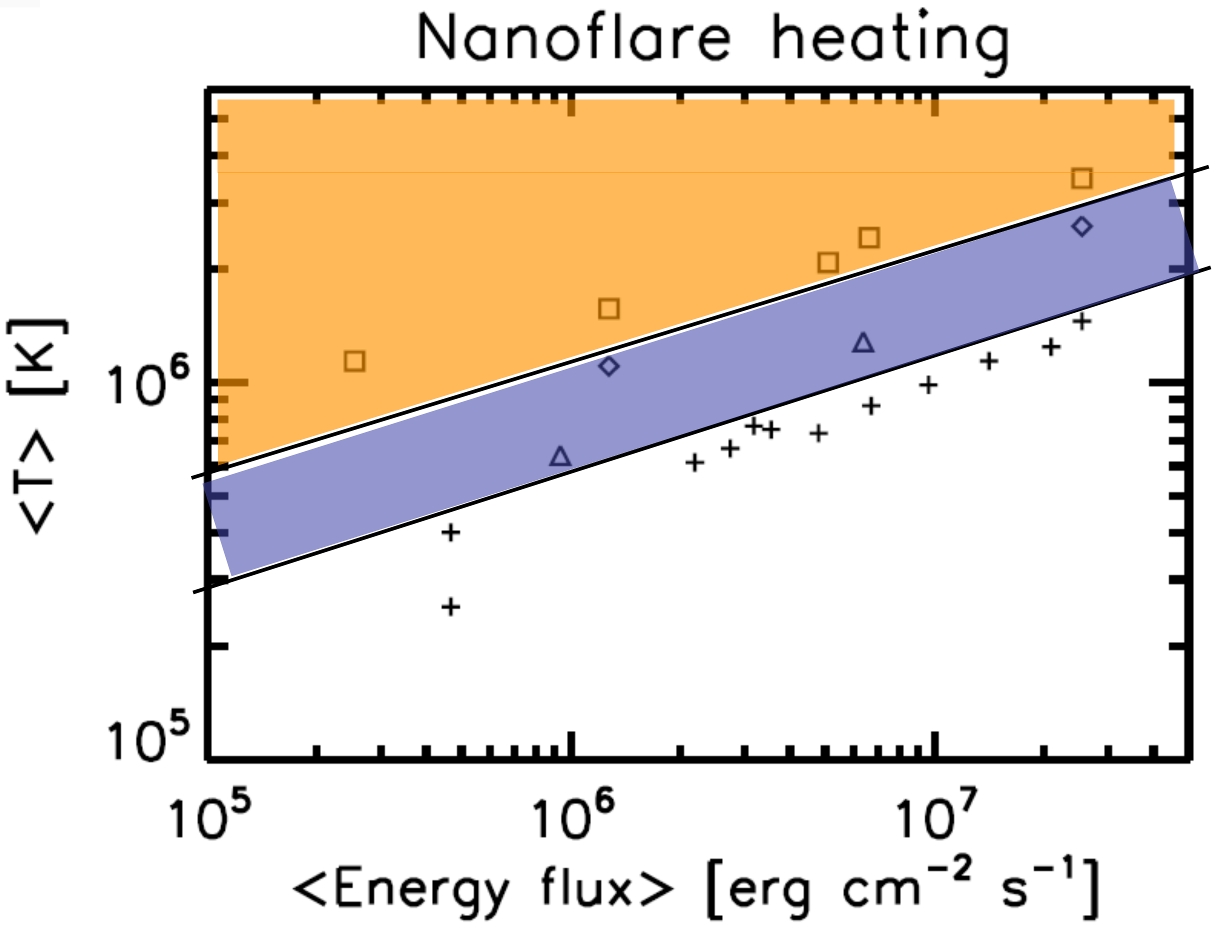
Nanoflare heating



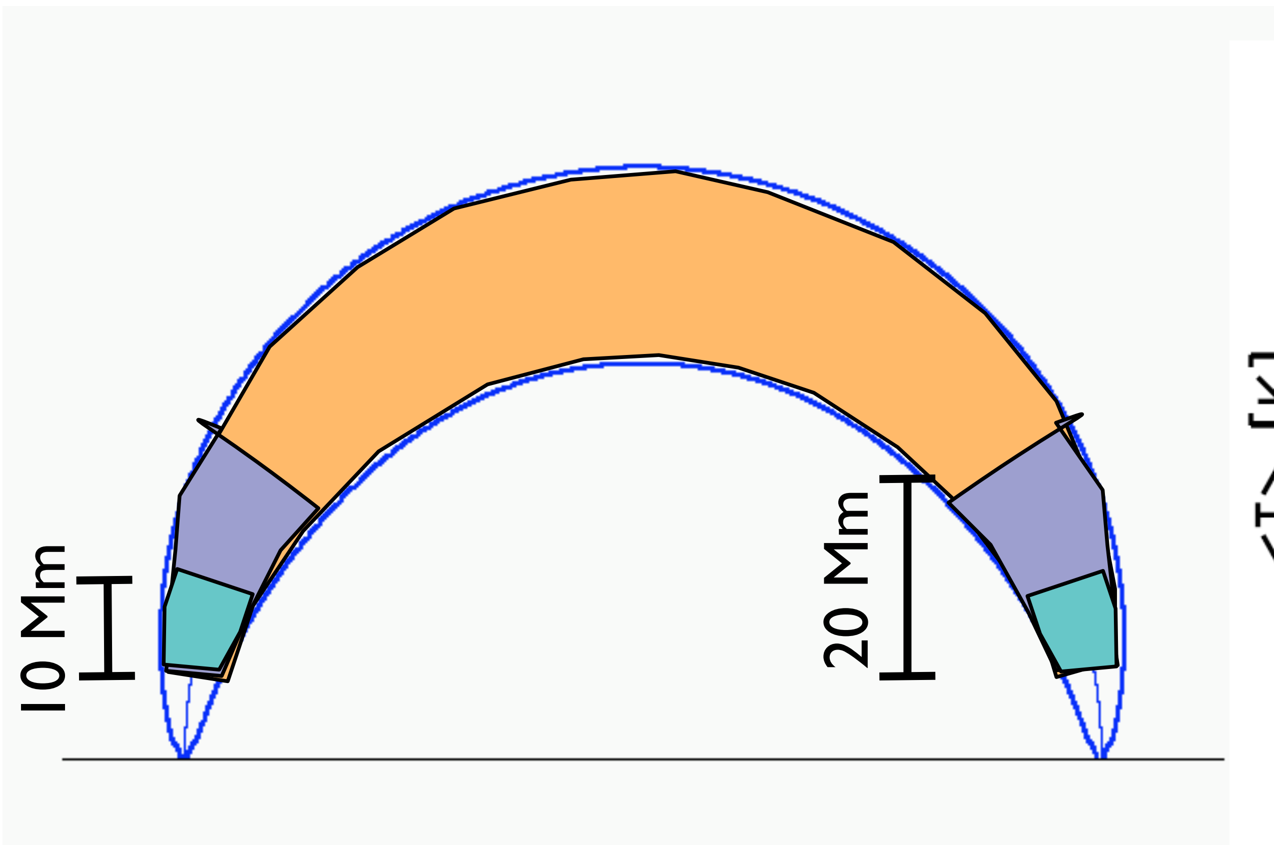


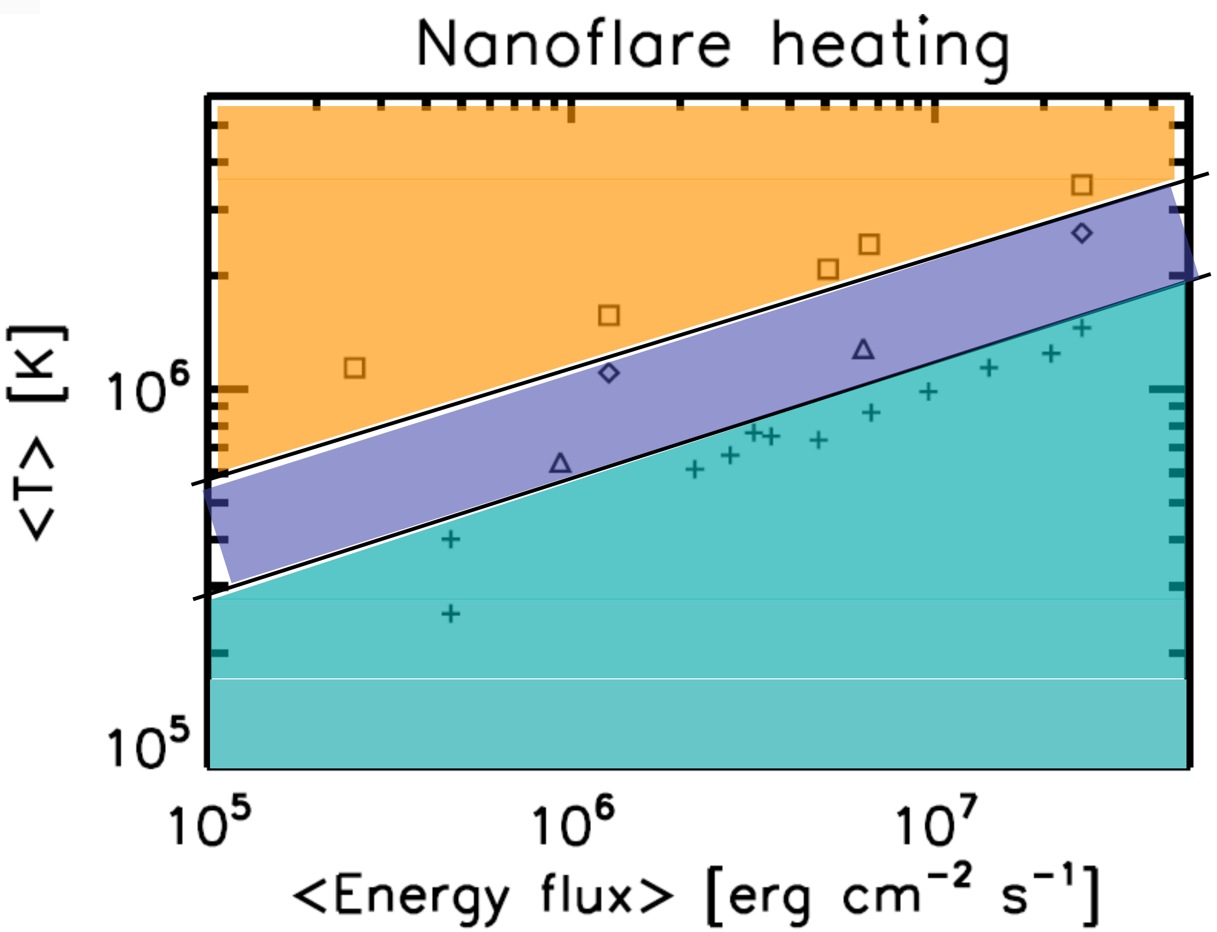
Nanoflare heating





Nanoflare heating





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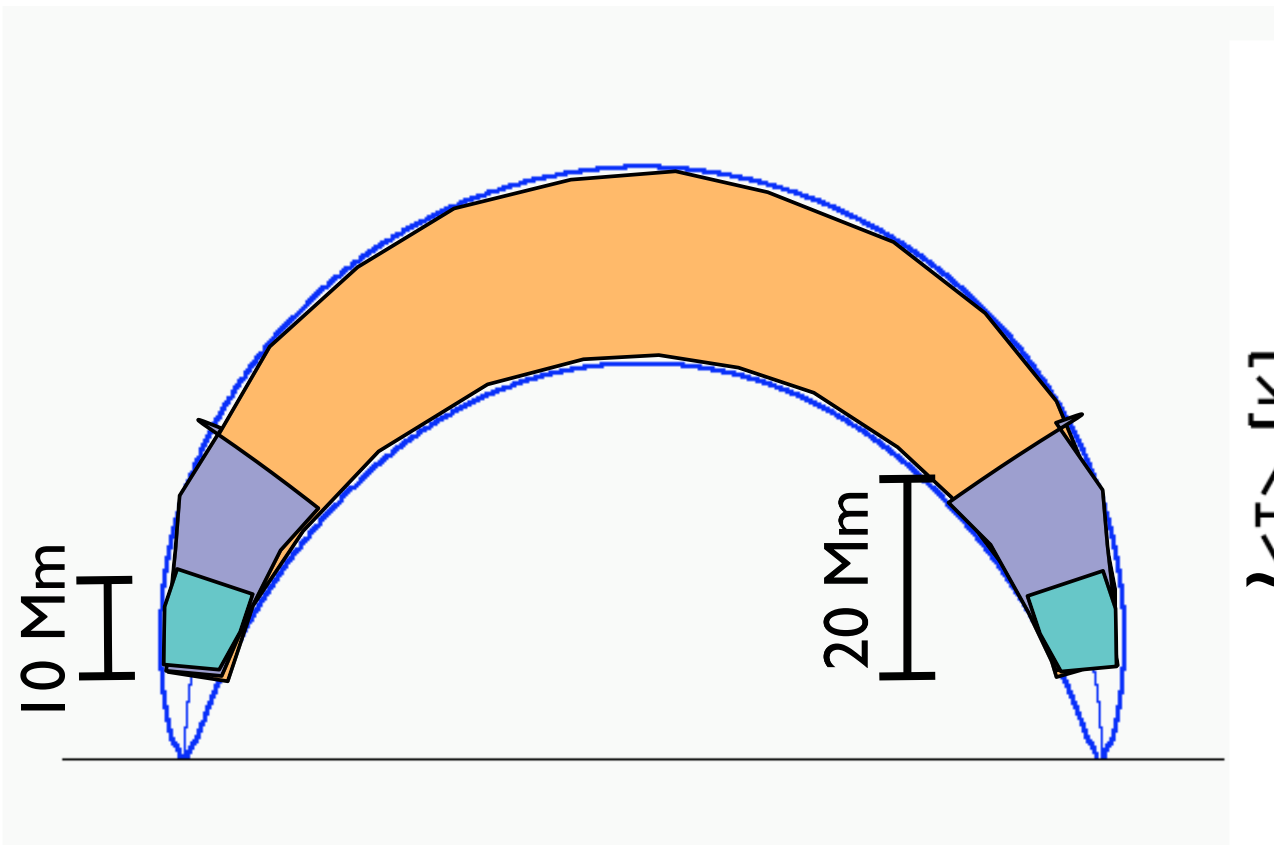
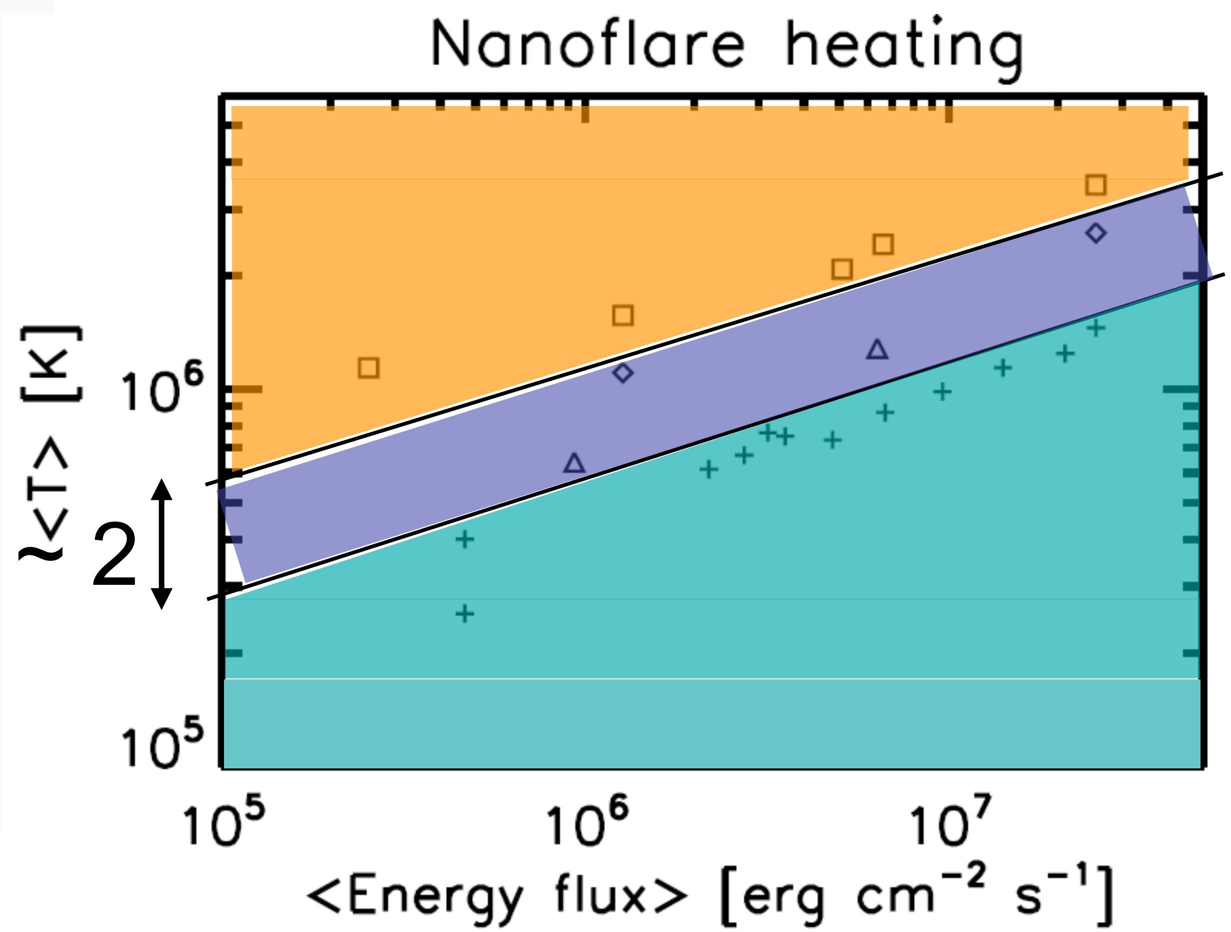
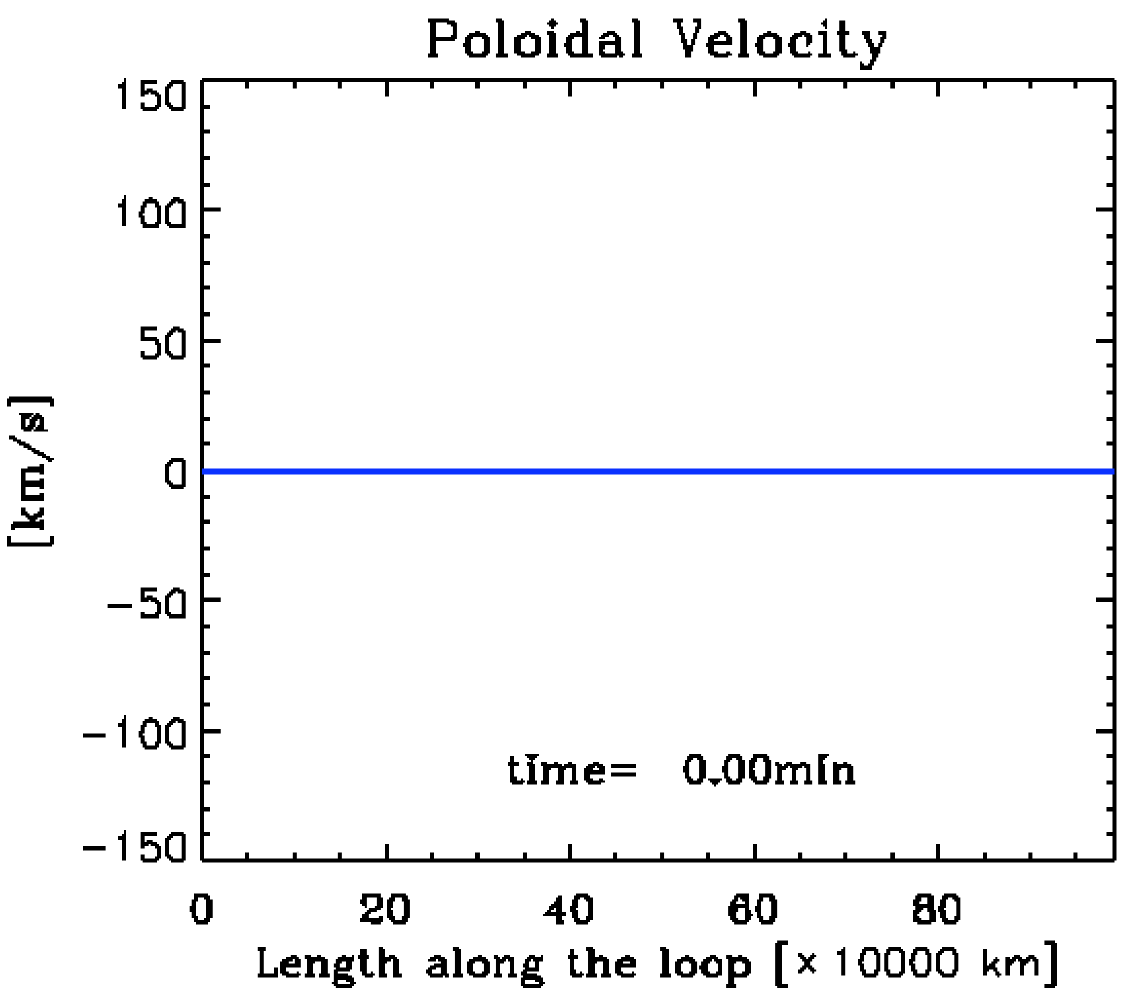




Conductive flux $F \simeq \frac{\kappa_0 T^{7/2}}{S_h} \Rightarrow \frac{T_{\square}}{T_{\square}} = \left(\frac{S_{h\square}}{S_{h\square}}\right)^{2/7} \simeq 2$

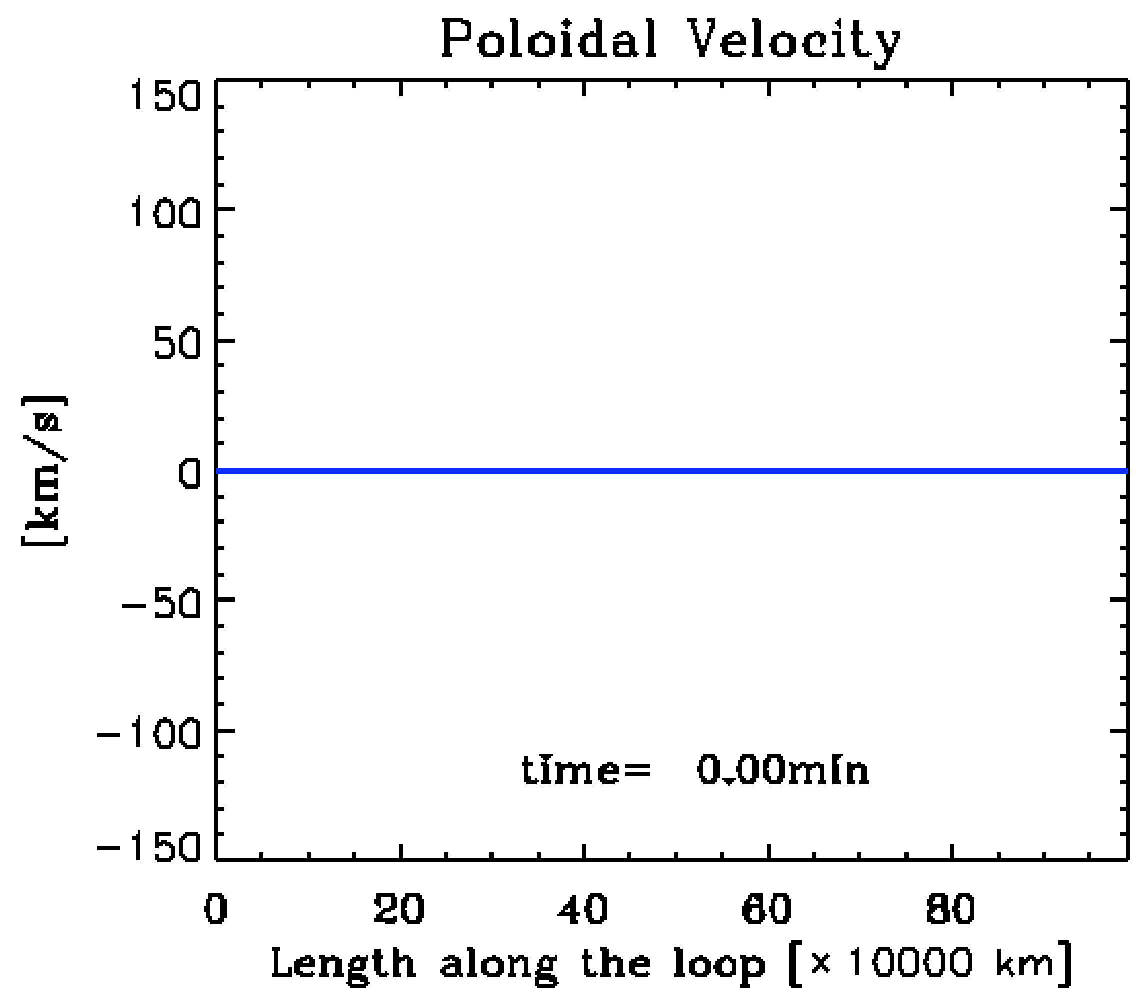
Nanoflare heating



Footpoint

<v> ~ 15 km/s

v_{max} > 200 km/s

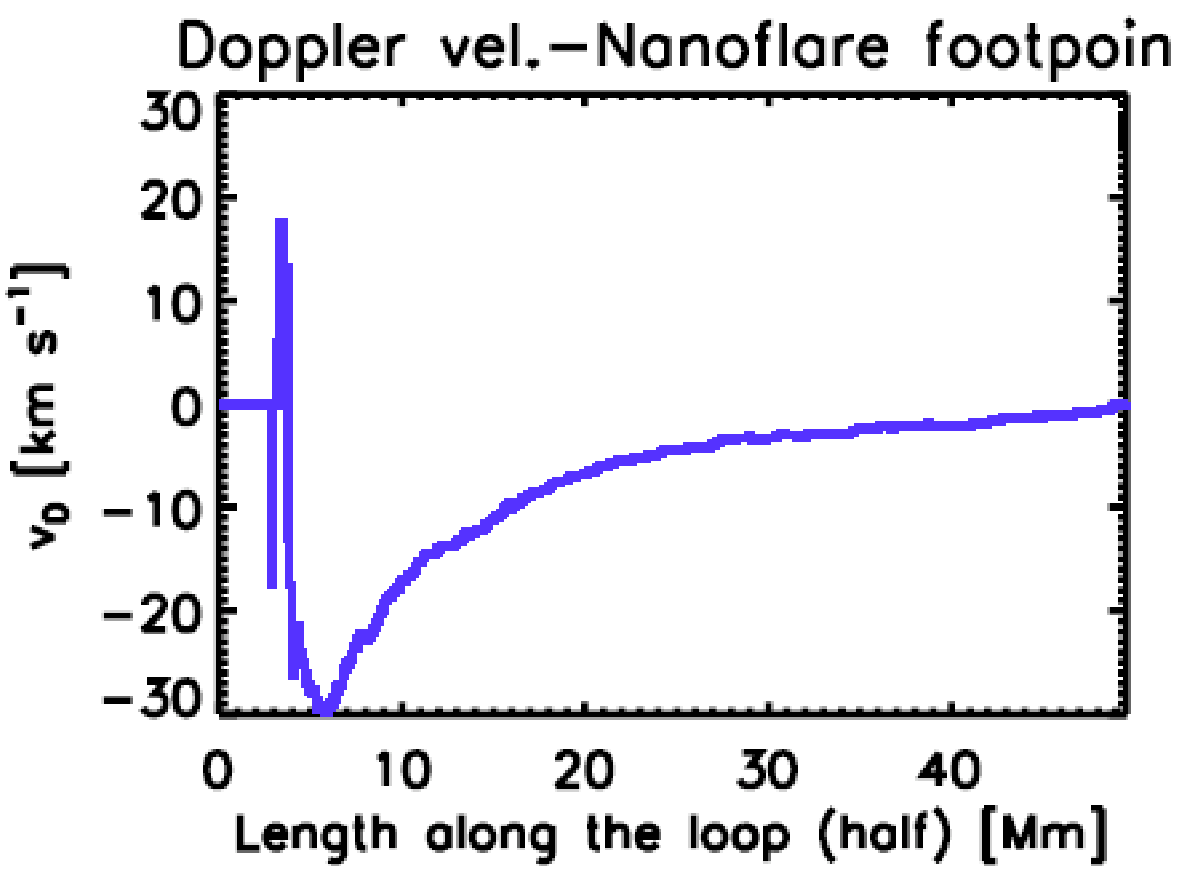


Uniform

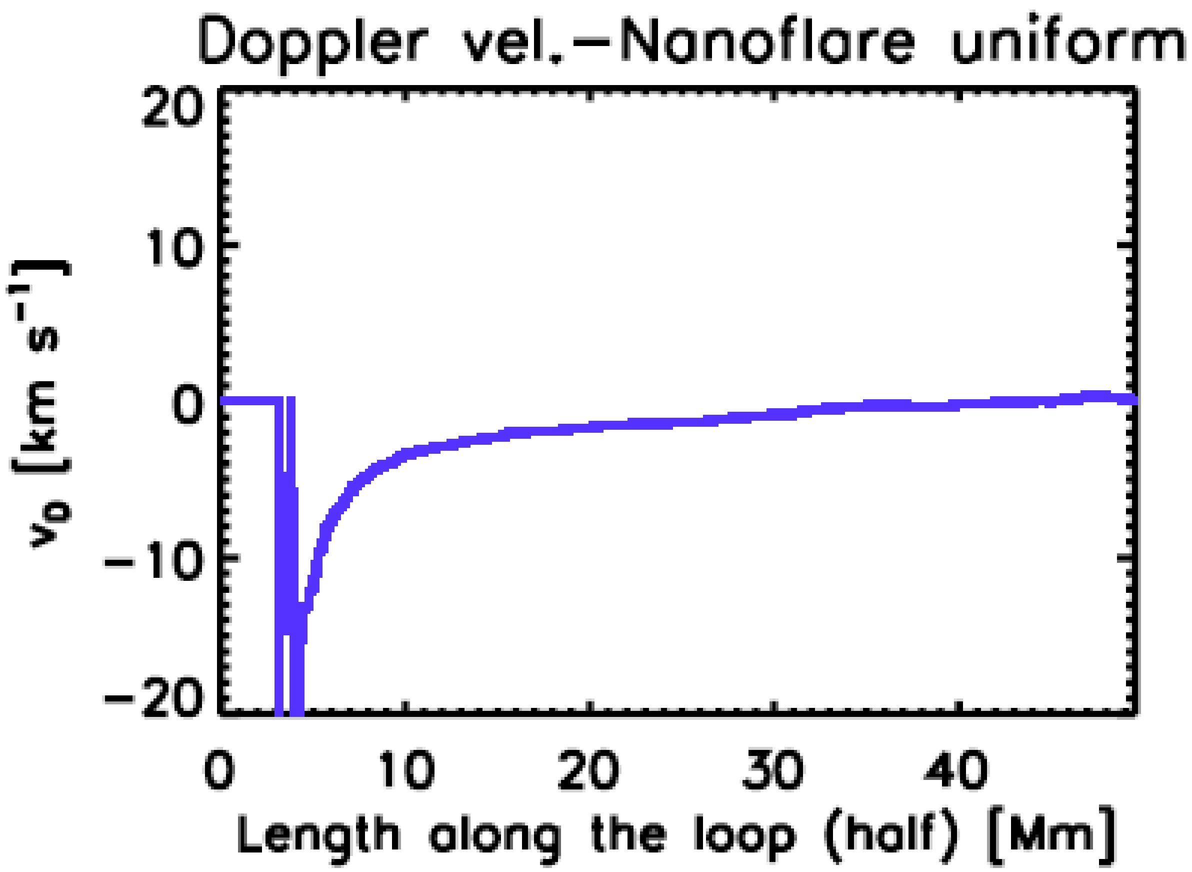
<v> ~ 5 km/s

v_{max} < 40 km/s

Nanoflare heating



Footpoint



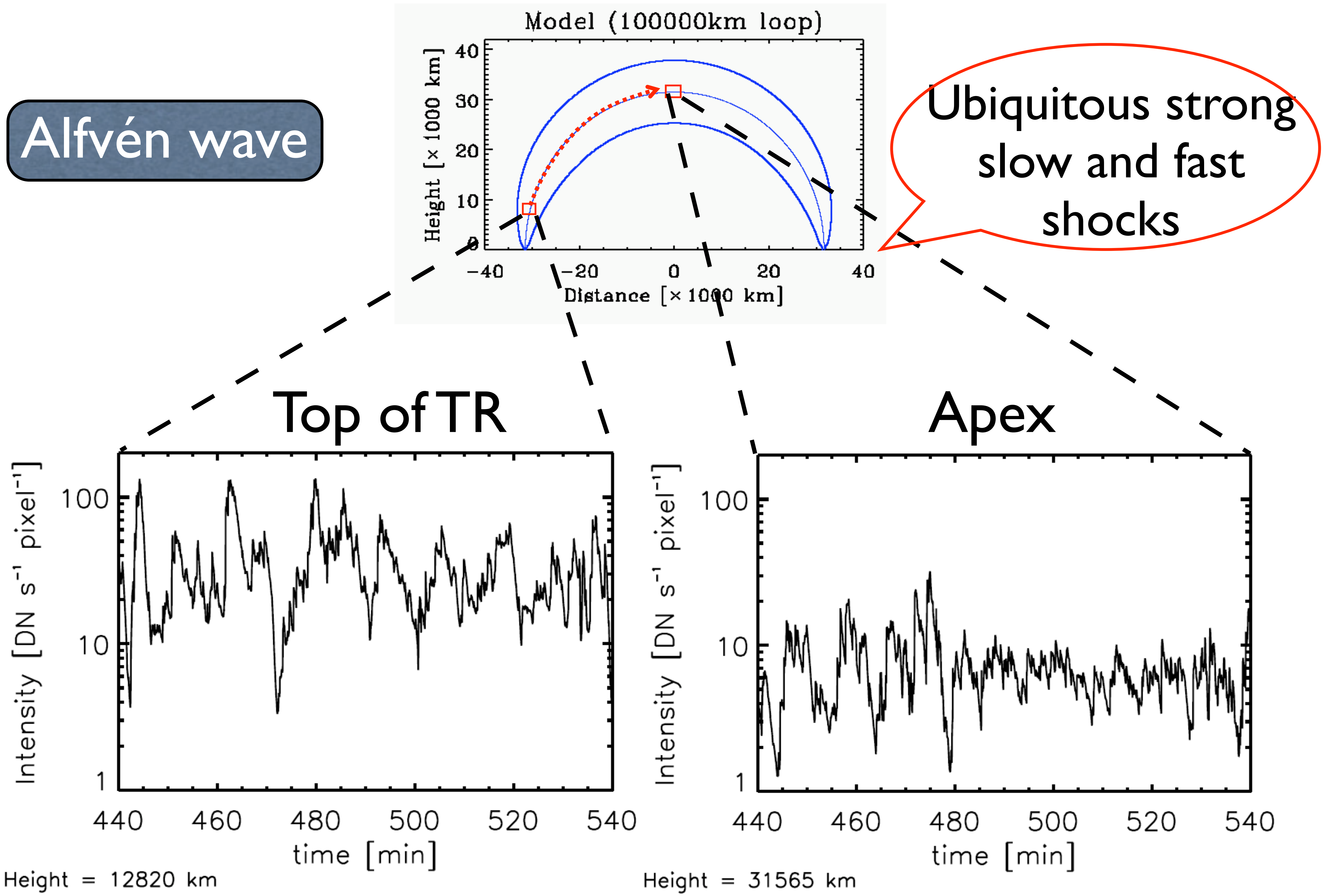
Uniform

Doppler velocities from Fe XV emission line (CHIANTI):

blue shifts at footpoints

Agreement with observations in AR (Hara et al. 2008)

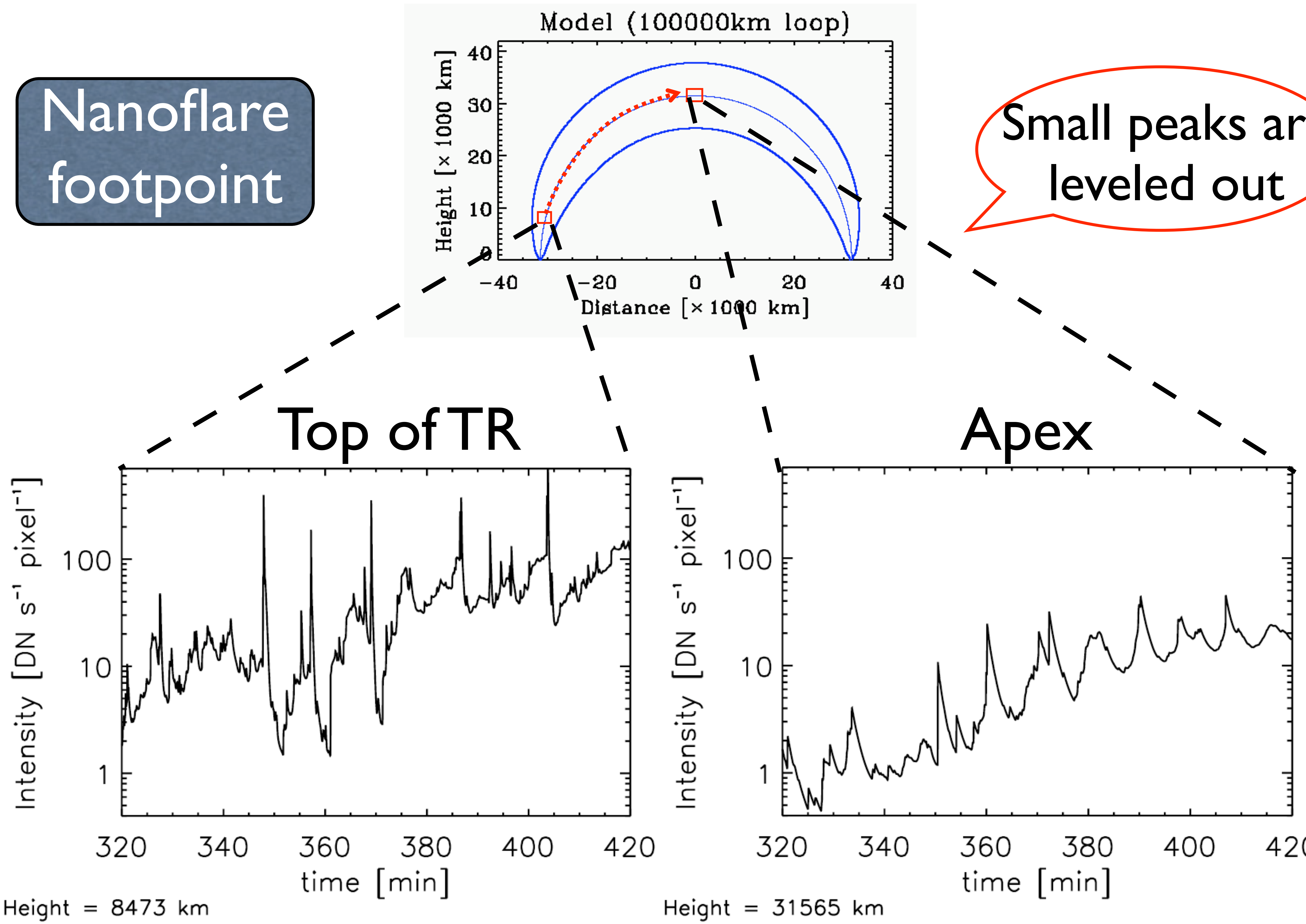
Simulating observations with Hinode/XRT



Simulating observations with Hinode/XRT

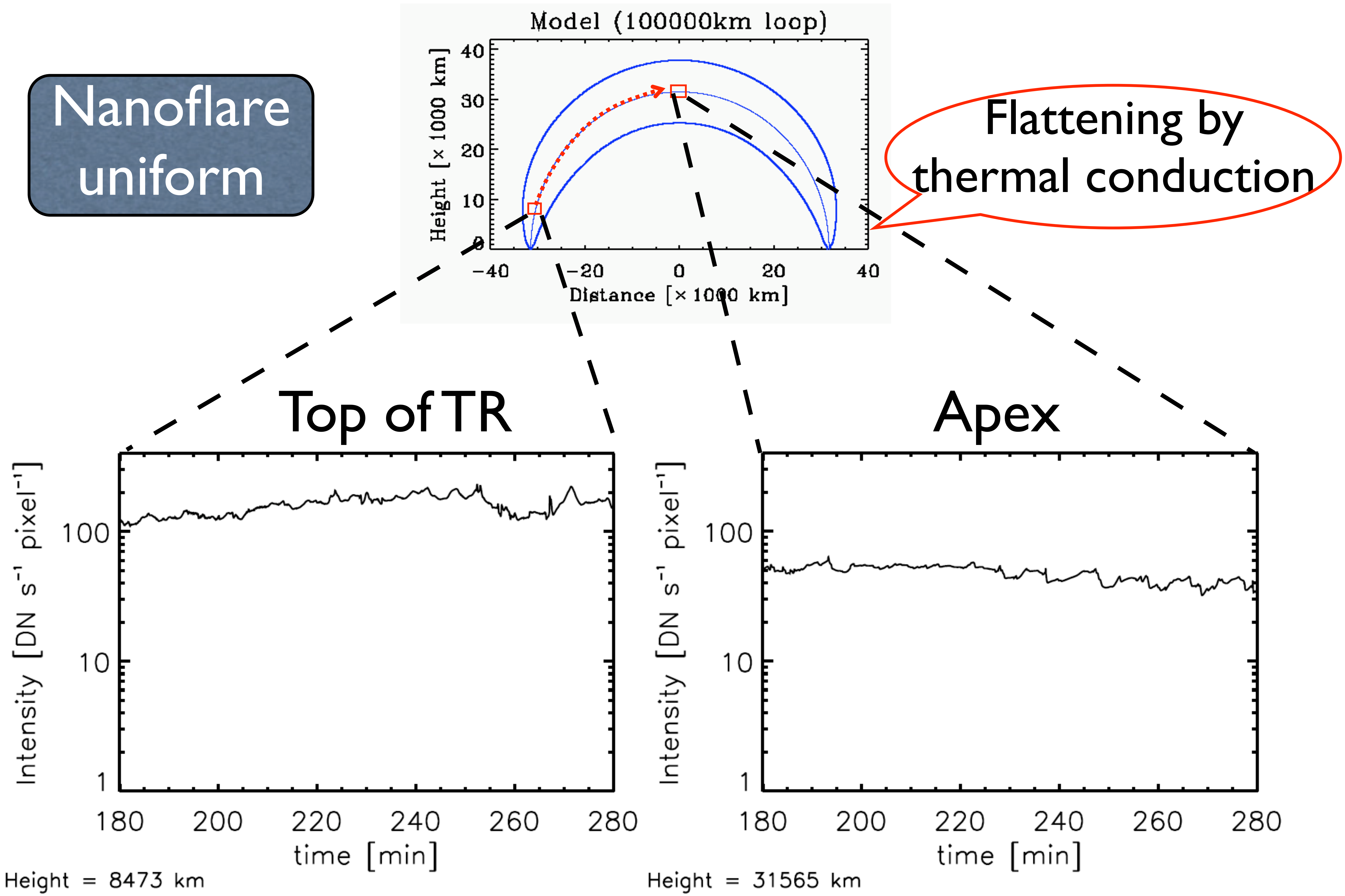
Nanoflare footpoint

Small peaks are leveled out

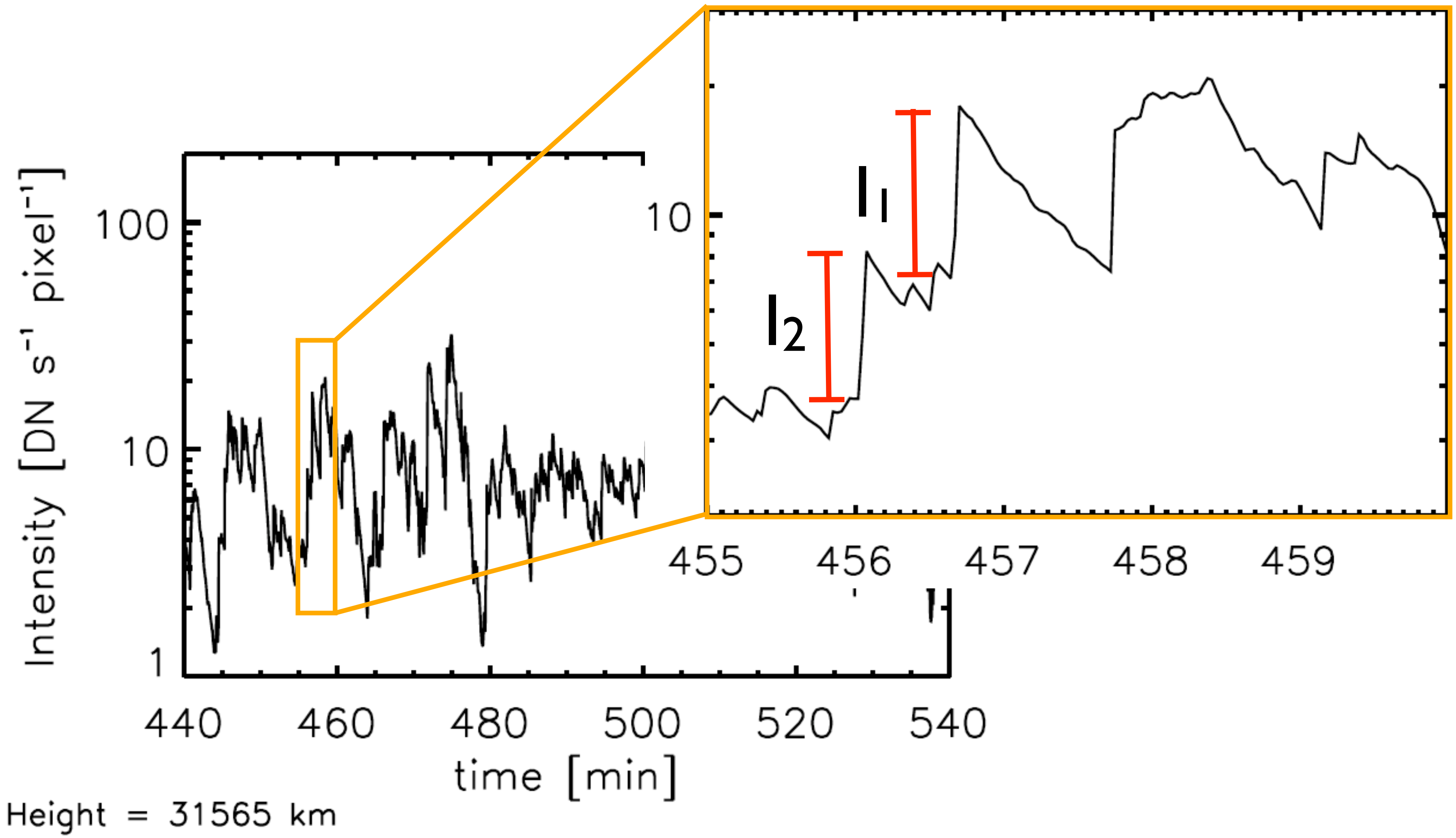


Simulating observations with Hinode/XRT

Nanoflare uniform



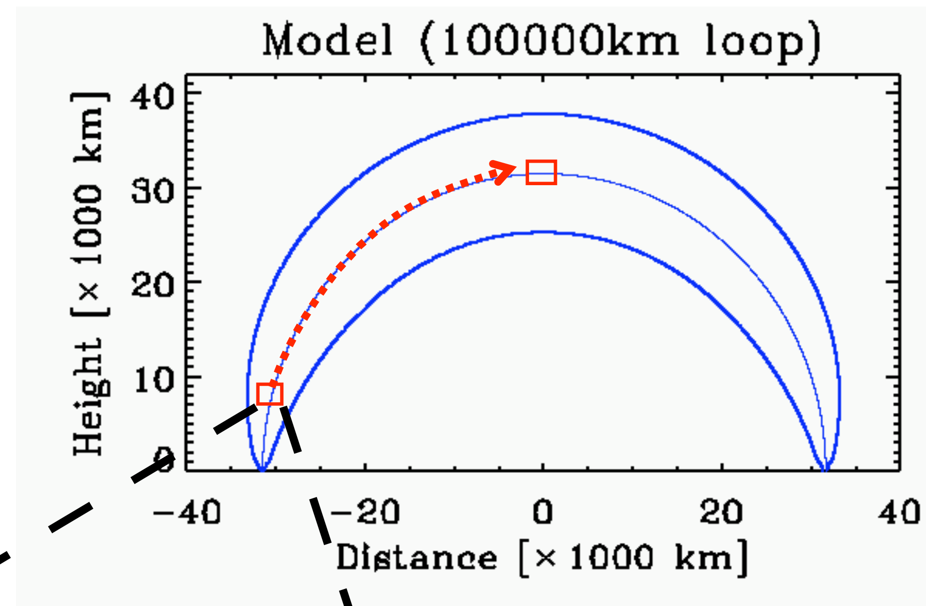
Intensity histograms



Intensity histograms

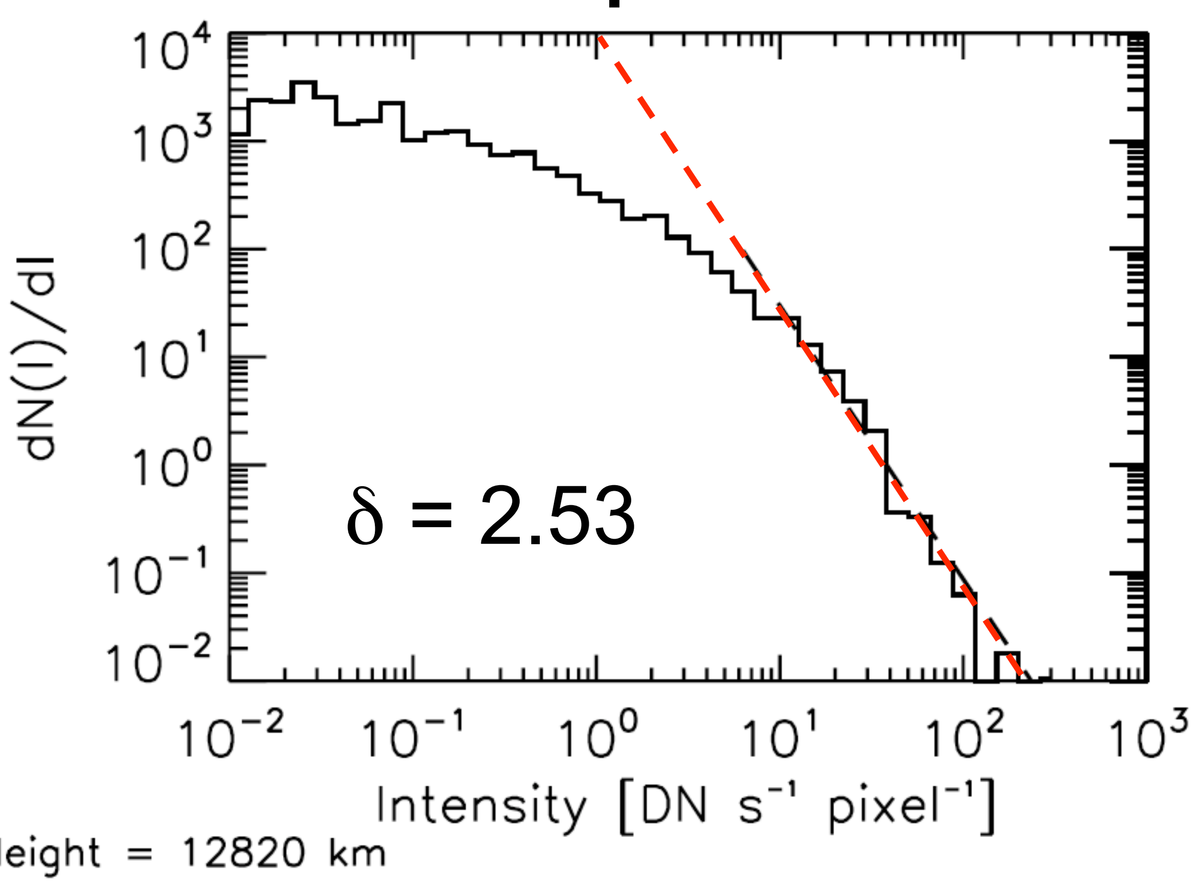
Alfvén wave

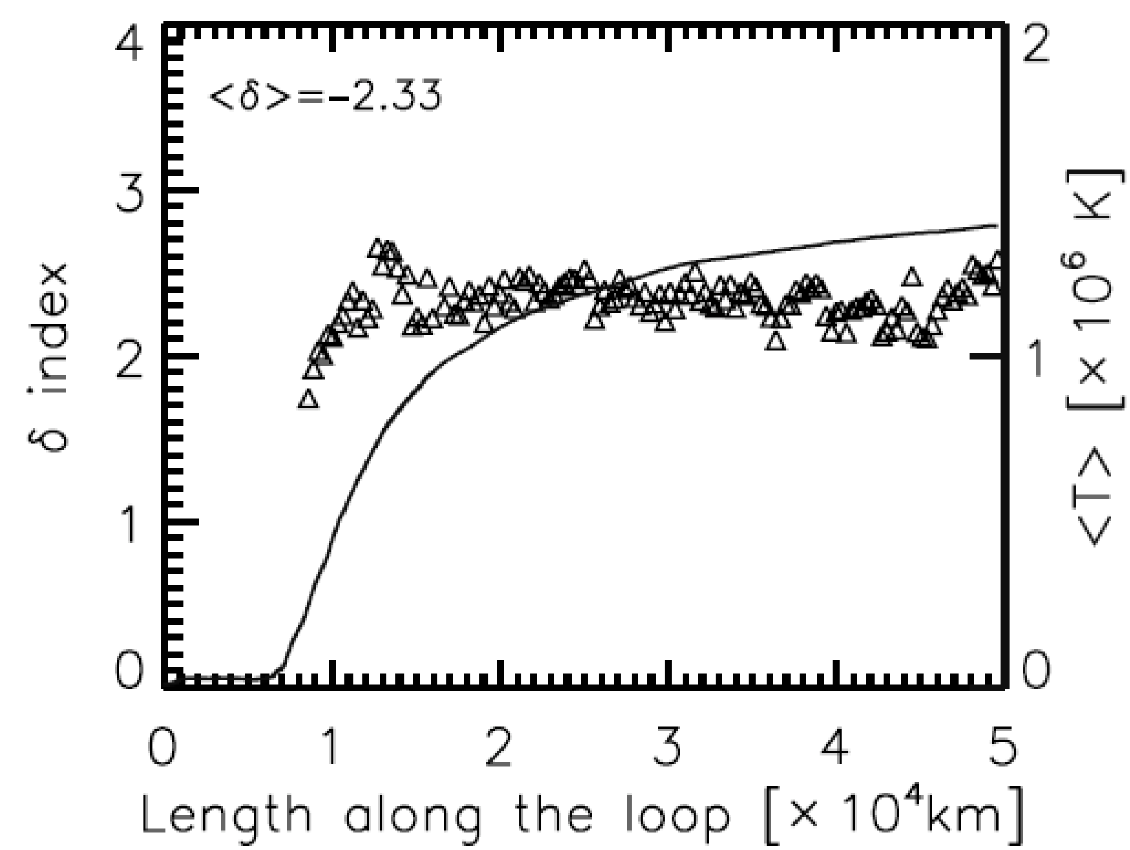
$$\frac{dN(I)}{dI} \propto I^{-\delta}$$



- $\langle\delta\rangle > 2$
  - heating from small dissipative events
- $\delta \sim$ constant in the corona

Top of TR





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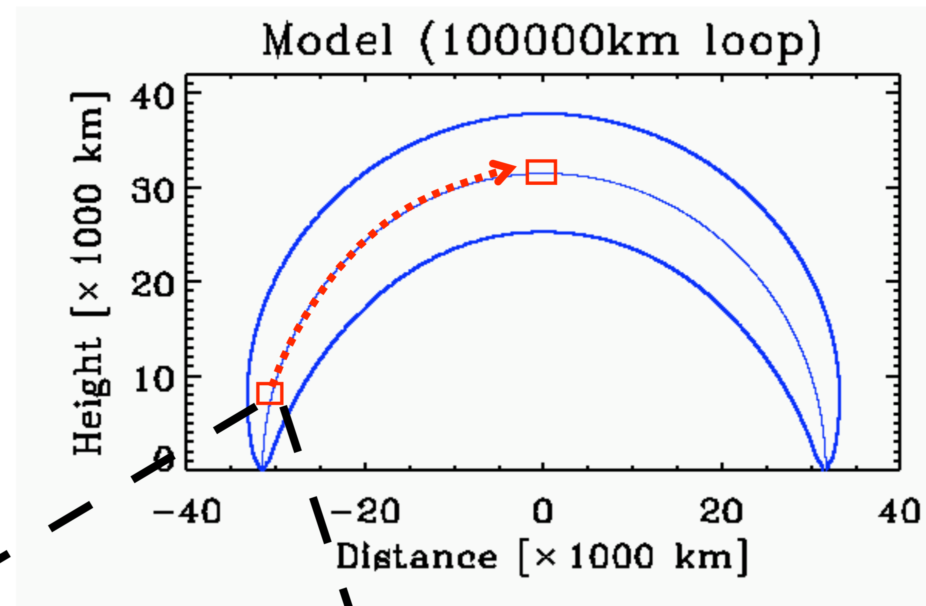


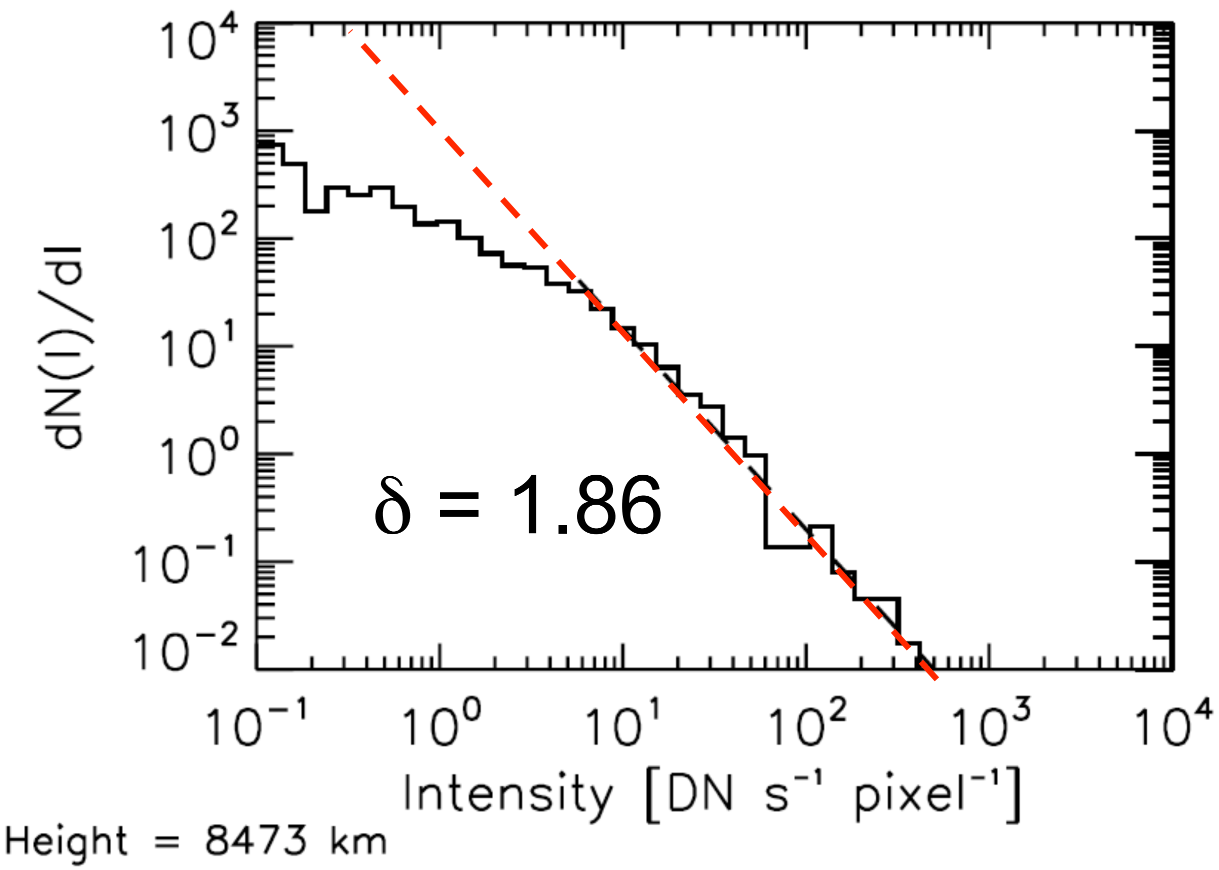
Nanoflare footpoint

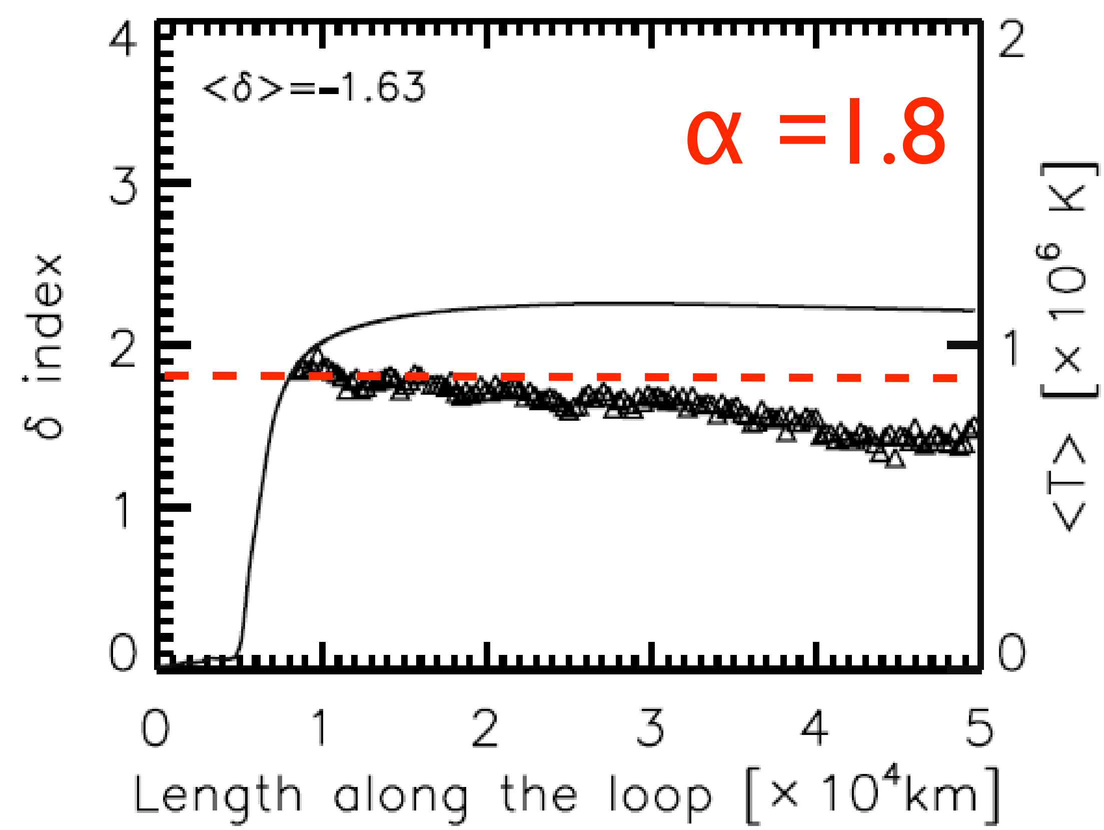
- $1.5 < \langle\delta\rangle < 2$
- $\delta \sim \alpha$ close to footpoints

Output: $\frac{dN(I)}{dI} \propto I^{-\delta}$

Input: $\frac{dN(E)}{dE} \propto E^{-\alpha}$

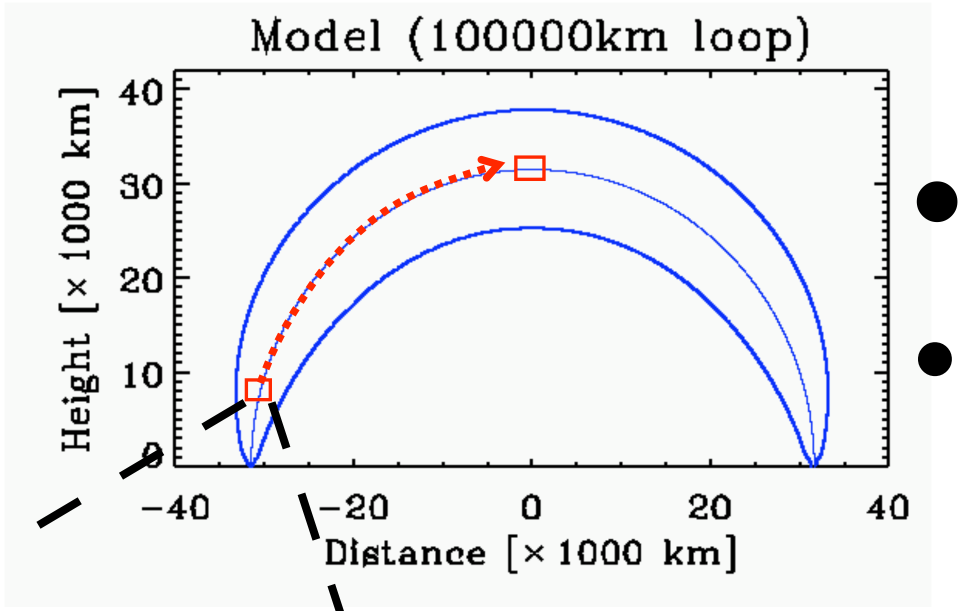
Top of TR





Intensity histograms

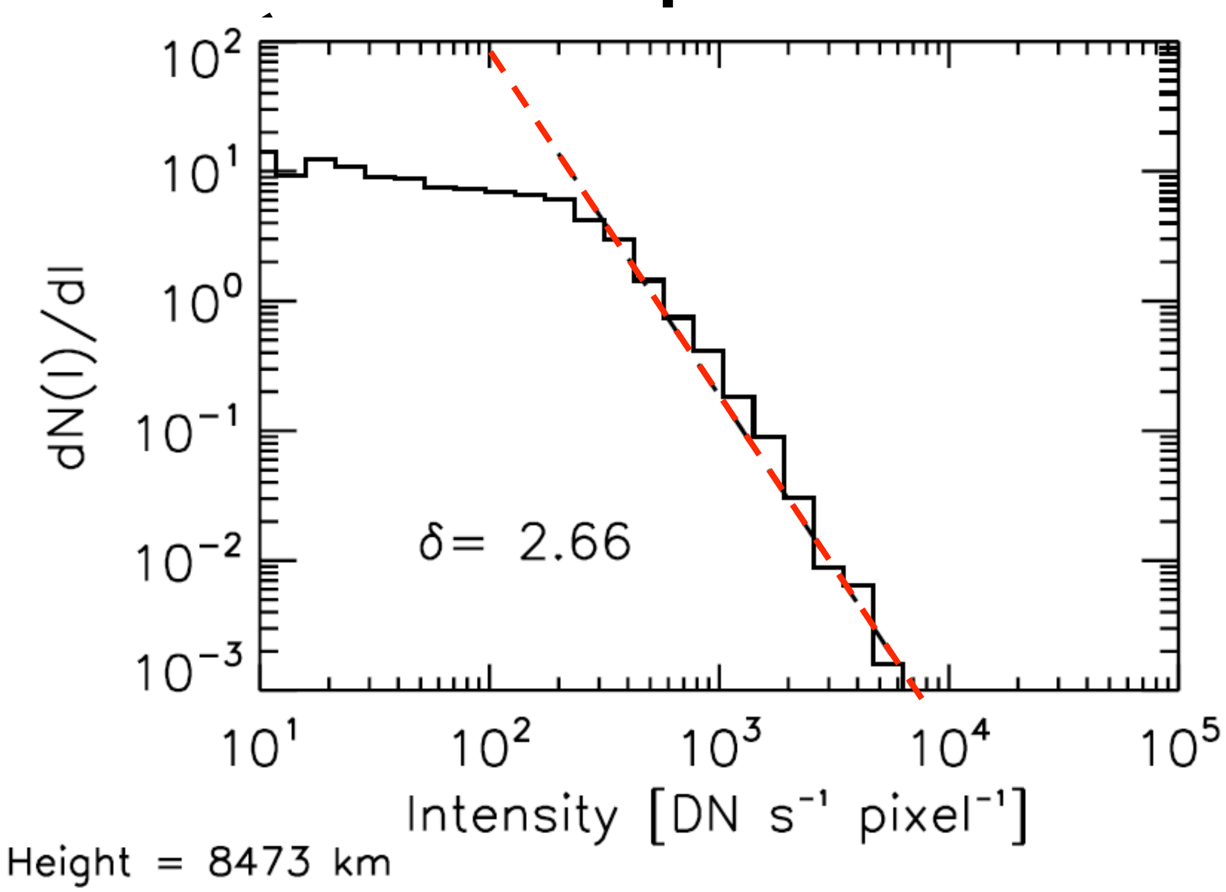
Nanoflare uniform

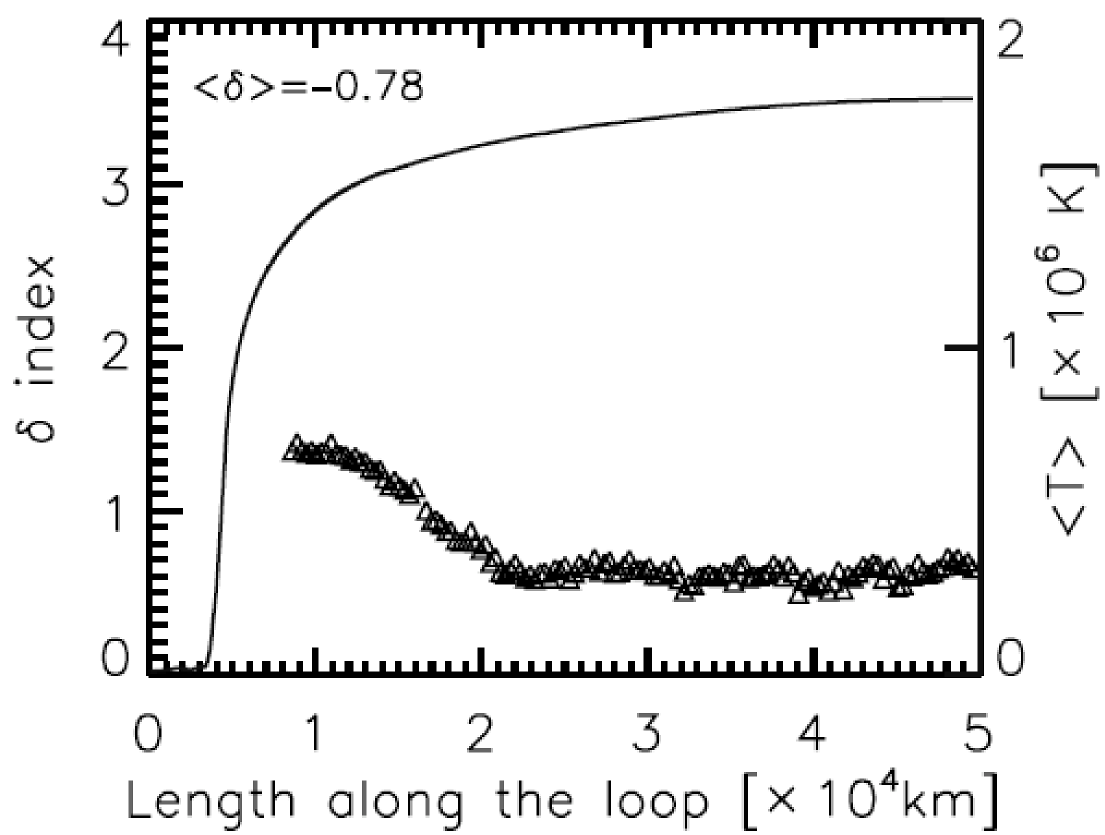


$$\frac{dN(I)}{dI} \propto I^{-\delta}$$

- $<\delta> \sim 1$
- δ decreases approaching apex due to fast dissipation of slow modes & to thermal conduction

Top of TR





Conclusions

Alfvén wave heating / uniform heating ⟶ QS loops?

Nanoflare-footpoint heating ⟶ AR loops?

Observational signatures

Heating model	Mean & max velocities(km/s)	Doppler vel. (Fe XV)	Intensity flux	Mean power law
Alfvén wave	$<v> \sim 50$ $v_{max} > 200$	red shifts ~ 10 km/s	bursty everywhere	$<\delta> > 2$ constant
Nanoflare footpoint	$<v> \sim 15$ $v_{max} > 200$	blue shifts ~ 30 km/s	bursty close to TR	$2 > <\delta> > 1.5$ decreases
Nanoflare uniform	$<v> \sim 5$ $v_{max} < 40$	blue shifts ~ 10 km/s	Flat everywhere	$<\delta> \sim 1$ decreases

Antolin et al.(2008), ApJ 687