ISSI Team - coronal rain

23-27 February 2015

1-D & 1.5-D MHD simulations of thermal instability

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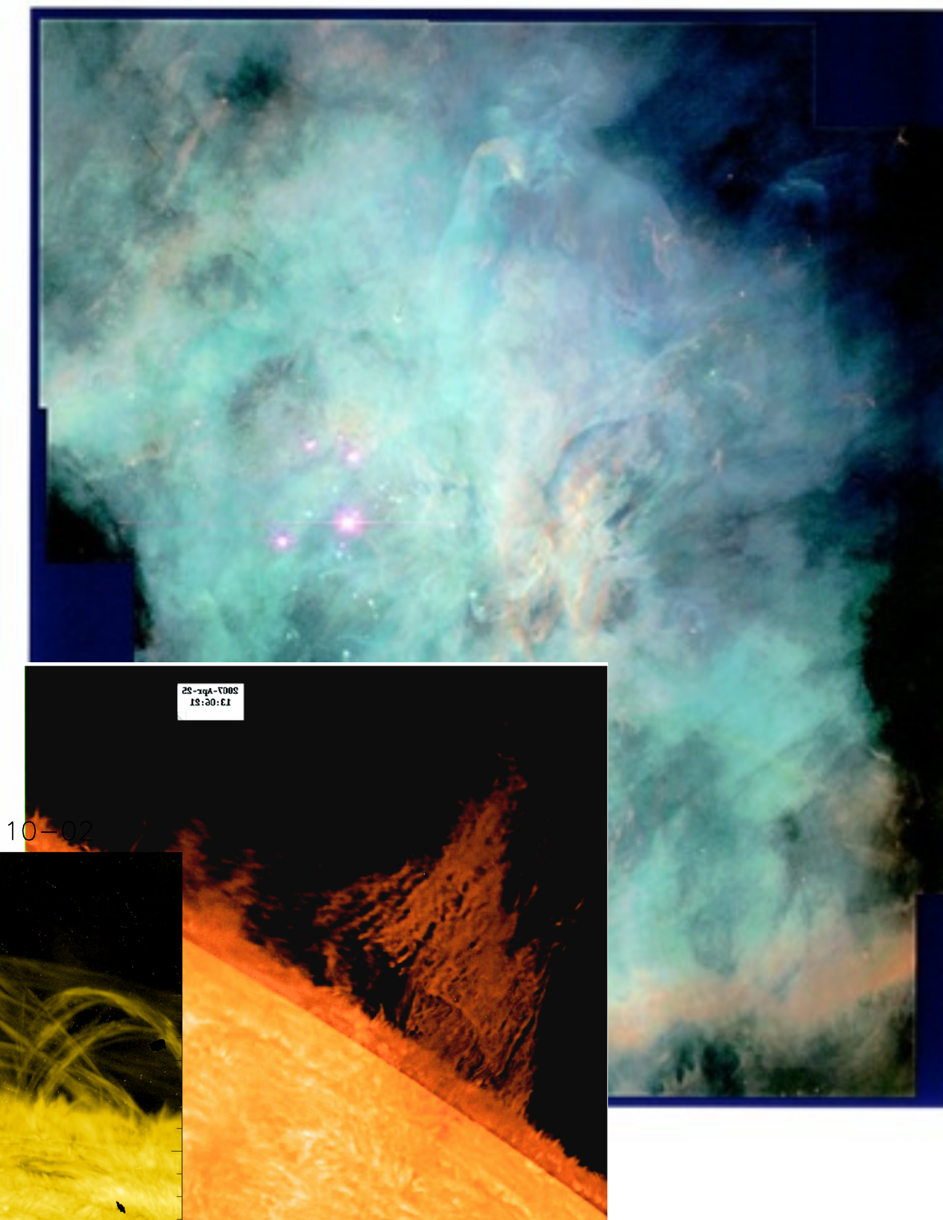
NAOJ

Plasma condensations in the universe

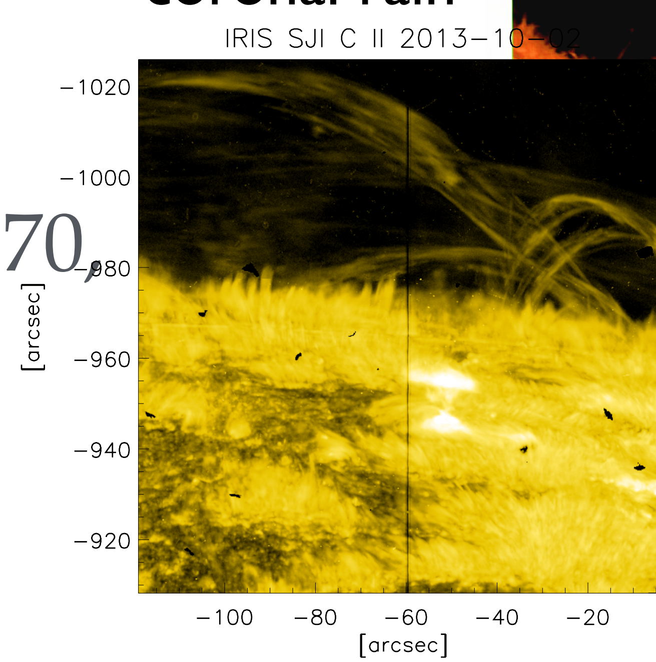
- Filamentary structure in interstellar medium (Cox 1972)
- Planetary nebulae (Zanstra 1955)
- Spiral arms of galaxies (Spitzer 1956)
- Prominences (Parker 1953)
- Coronal rain (Kawaguchi 1970, Leroy 1972)

Orion Nebula



QS prominence

coronal rain



Thermal instability

- Parker (1953), Field (1965), Goldsmith (1971), Hildner (1974), Heyvaerts (1974), Heasley & Mihalas (1976),...

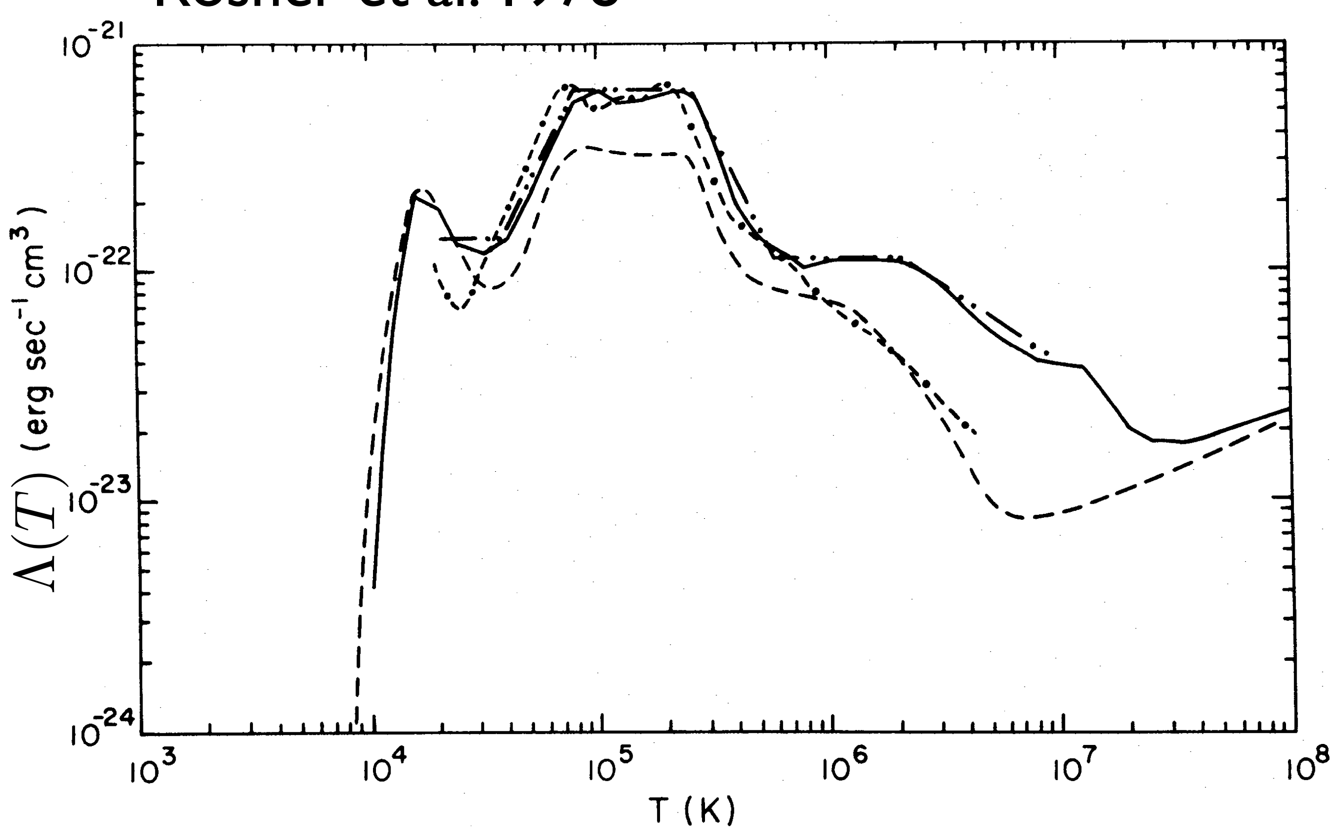
$$\frac{de}{dt} - \frac{\gamma e}{\rho}\frac{d\rho}{dt} = -n_e n_i \Lambda(T) - \nabla \cdot \boldsymbol{Q} + H(t),$$

radiative cooling

conductive heating

background (coronal) heating

Rosner et al. 1978



If radiative cooling > heating, runaway cooling can occur

$\Delta p < 0$

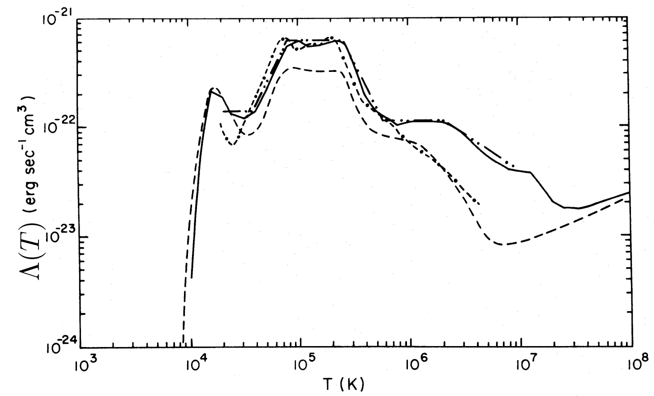
condensation - thermal mode (entropy mode)

Thermal instability in coronal loops

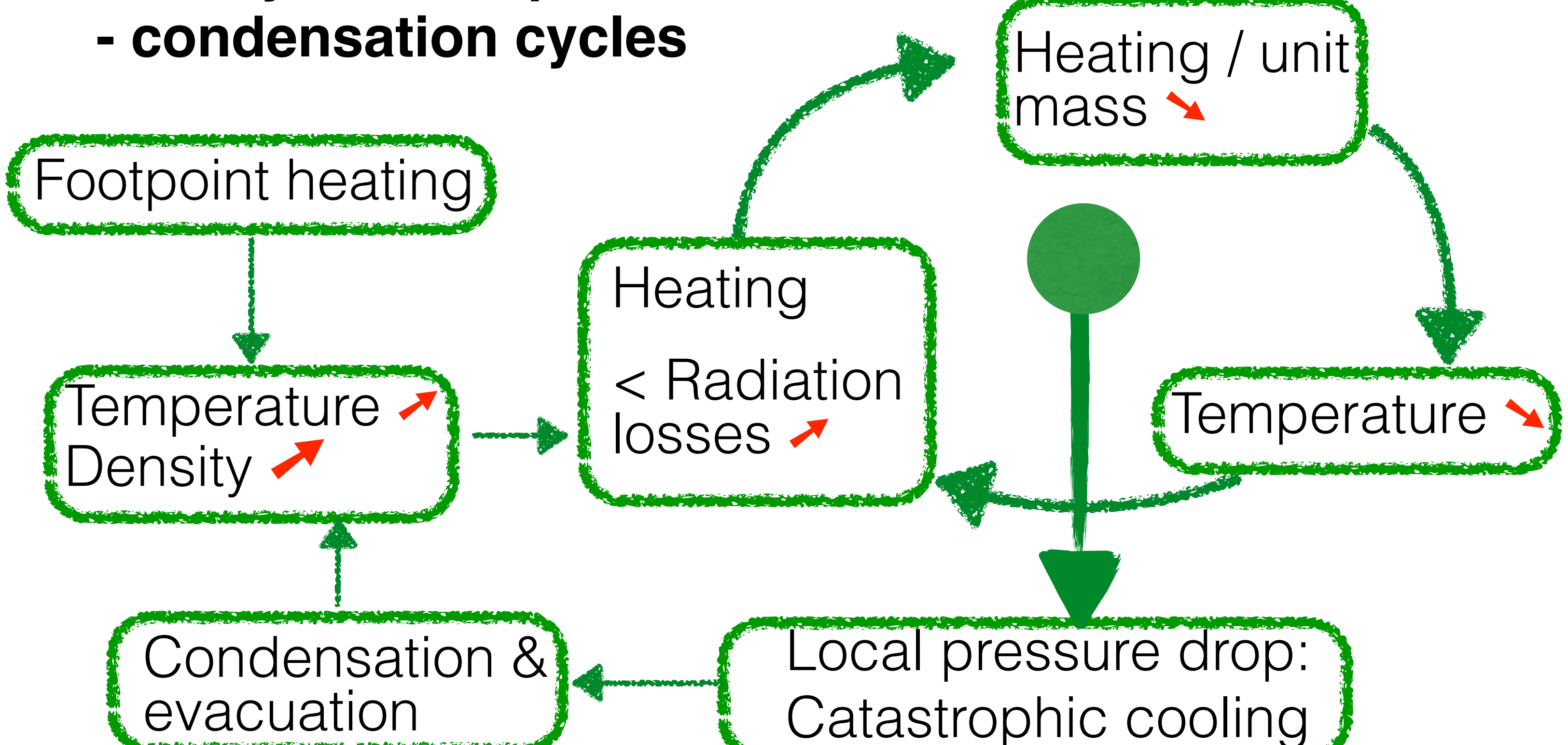
State of thermal non-equilibrium: A coronal loop subject to footpoint heating can be thermally unstable (Mok+ 1990, Antiochos & Klimchuk 1991, van der Linden & Goosens 1991, Wiik+ 1996, Antiochos+ 1999, Karpen+ 2001, Müller+ 2003-4, Mendoza-Briceño+ 2005, Reale+1996-97, Mok+ 2008, Xia+ 2011)

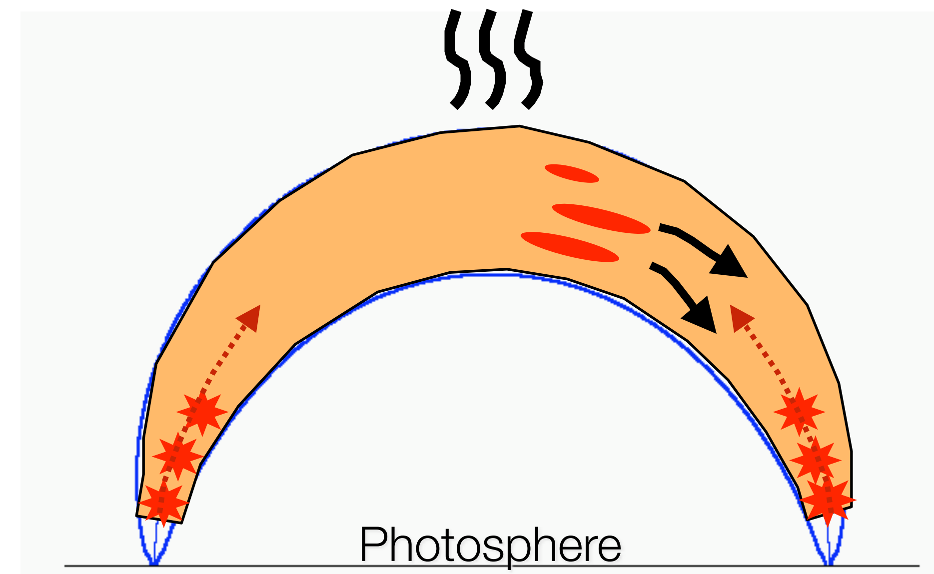
Parker (1953), Field (1965), Goldsmith (1971), Hildner (1974), Heyvaerts (1974), Heasley & Mihalas (1976),…

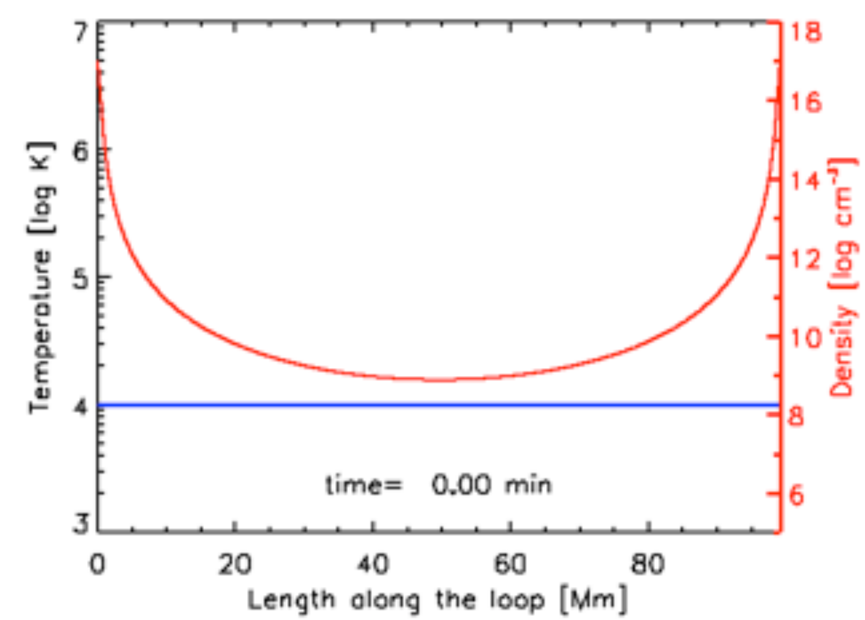
Rosner et al. 1978



limit cycles, evaporation - condensation cycles







Thermal instability in coronal loops

Parameter space?

$$\frac{\partial \varepsilon}{\partial t}+\frac{\partial}{\partial s}(\varepsilon v+p v)=\rho g_{\parallel} v+H(s)-n_{\mathrm{H}} n_{\mathrm{e}} \Lambda(T)+\frac{\partial}{\partial s}\left(\kappa \frac{\partial T}{\partial s}\right)$$

$$H_0(s)=\begin{cases} E_0 \exp(-s/H_m), & s < L/2; \\ E_0 \exp[-(L-s)/H_m], & L/2 \leqslant s < L \end{cases}$$

$$H_l(s)=\begin{cases} E_1, & s \leqslant s_{tr}; \\ E_1 \exp[-(s-s_{tr})/\lambda], & s_{tr} < s \leqslant L/2; \\ f E_1 \exp[-(L-s_{tr}-s)/\lambda], & L/2 < s \leqslant L-s_{tr} \\ f E_1, & s > L-s_{tr}, \end{cases}$$

- Loop geometry: length, area (cross-section, asymmetry), dips
- Heating: volumetric rate, scale length, timescale (steady, impulsive, finite), asymmetry
- Radiative loss function

Xia+ (2011)

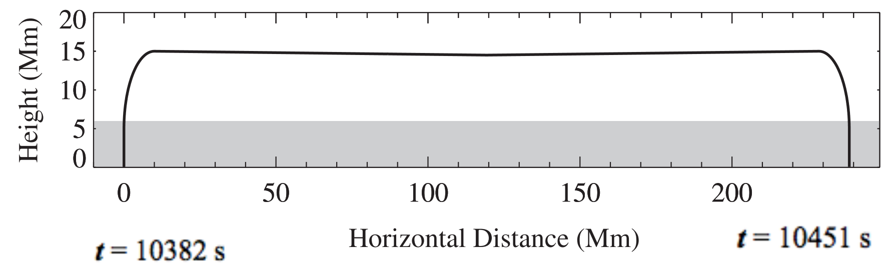
List of Parameters in Simulations of Radiative Condensation

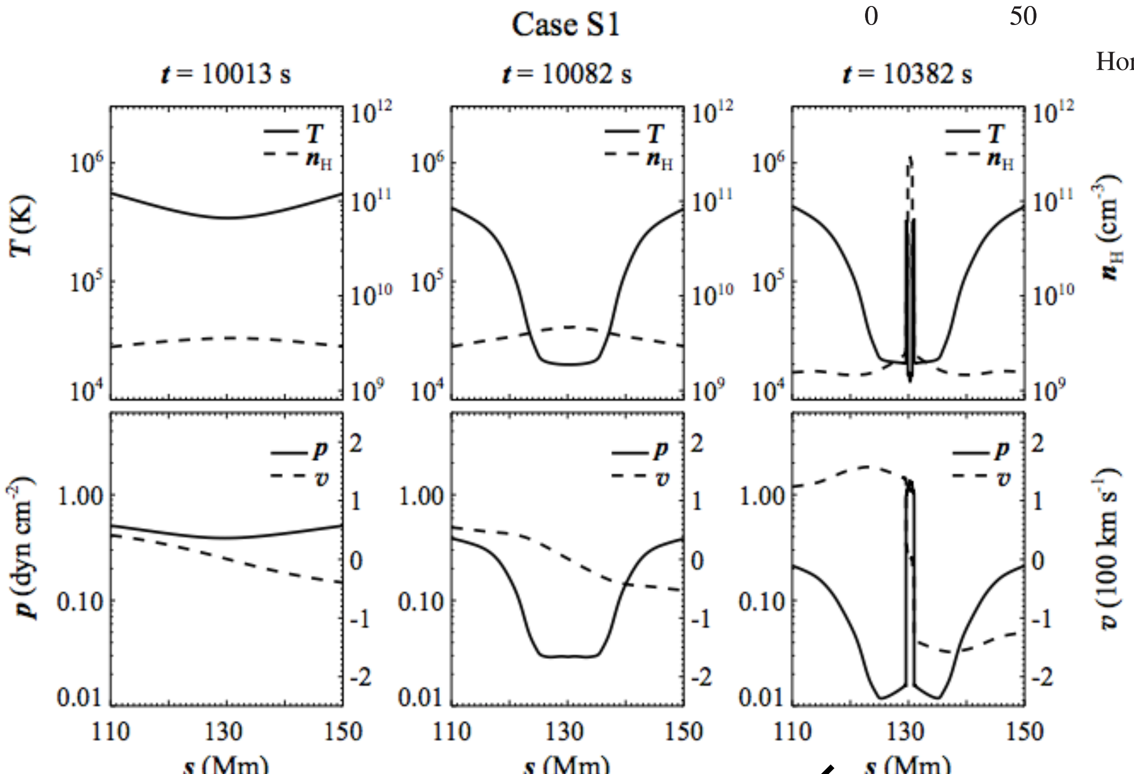
Reference	L (Mm)	D (Mm)	Vertical Leg (Mm)	s_{tr} (Mm)	Cross Section (Non)Uniform
Antiochos et al. (1999)	220	5	10	10	U
Antiochos et al. (2000)	320	5	60	50	U
Karpen et al. (2001)	340	no	60	60	U
Karpen et al. (2003)	420	15,10	75	60	U
Müller et al. (2003)	10	no	1	1.6	U
Müller et al. (2004)	100	no	1	1.6	U
Karpen et al. (2005)	405	20	60	60	N
Karpen et al. (2006)	405	20	75	60	U
Karpen & Antiochos (2008)	405	20	75	60	U
Klimchuk et al. (2010)	205	no	50	50	U
Our cases	260	0.5	5	6	U

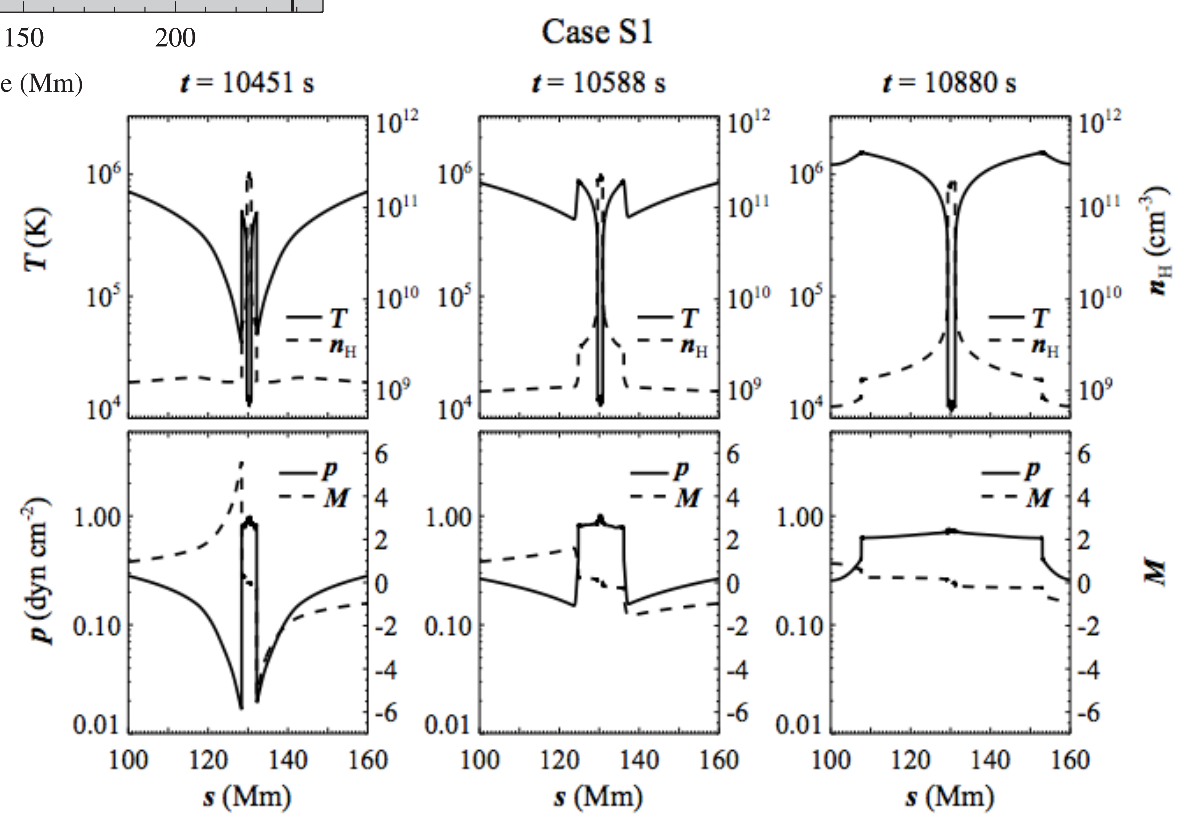
Reference	E_0 (erg cm^{-3} s^{-1})	E_1 (erg cm^{-3} s^{-1})	f	λ (Mm)	Type S/I/F[a]	Radiation
Antiochos et al. (1999)	1.5e-5	1.e-3	1	10	S	Old[b]
Antiochos et al. (2000)	1.5e-5	1.e-3	0.75	10	S	Old
Karpen et al. (2001)	1.5e-4	1.e-3	0.75	10	S	Old
Karpen et al. (2003)	1.5e-4	1.e-2	0.75	10	S	Old
Müller et al. (2003)	no	1.2e-3	1	1.25	S	IE[c]
Müller et al. (2004)	no	1.2e-3	1	5,3,2	S	IE
Karpen et al. (2005)	1.5e-4	1.e-2	0.75	10	S	KR
Karpen et al. (2006)	1.5e-4	2.e-2,1.e-2	0.75	5,10	S	KR
Karpen & Antiochos (2008)	1.5e-4	1.e-2	0.75	5,1	I	KR
Klimchuk et al. (2010)	6.e-4	8.e-2	0.5,0.75,0.9	5	S	KR
Symmetric cases	3.e-4	5.e-3 ∼ 0.2	1	3 ∼ 20	S/F	Colgan
Asymmetric cases	3.e-4	1.e-2	0.4,0.75	5,10	S	Colgan

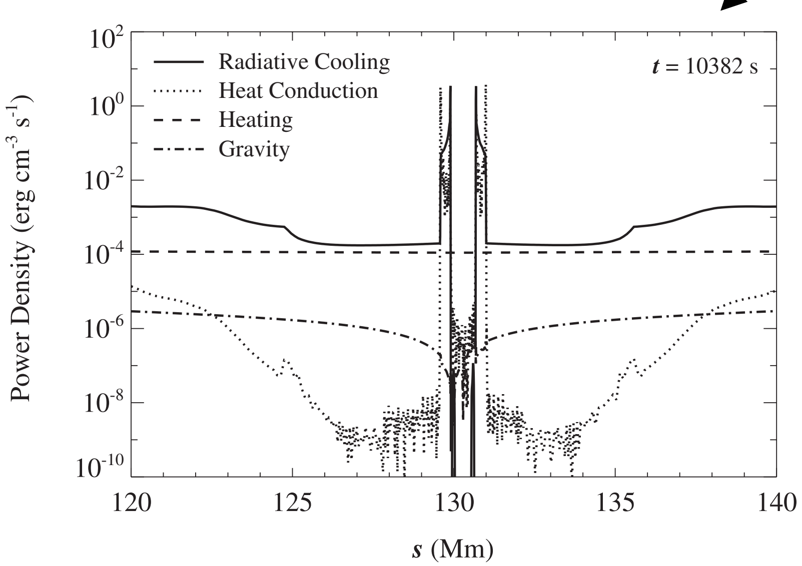
Thermal instability in coronal loops

Xia+ (2011)





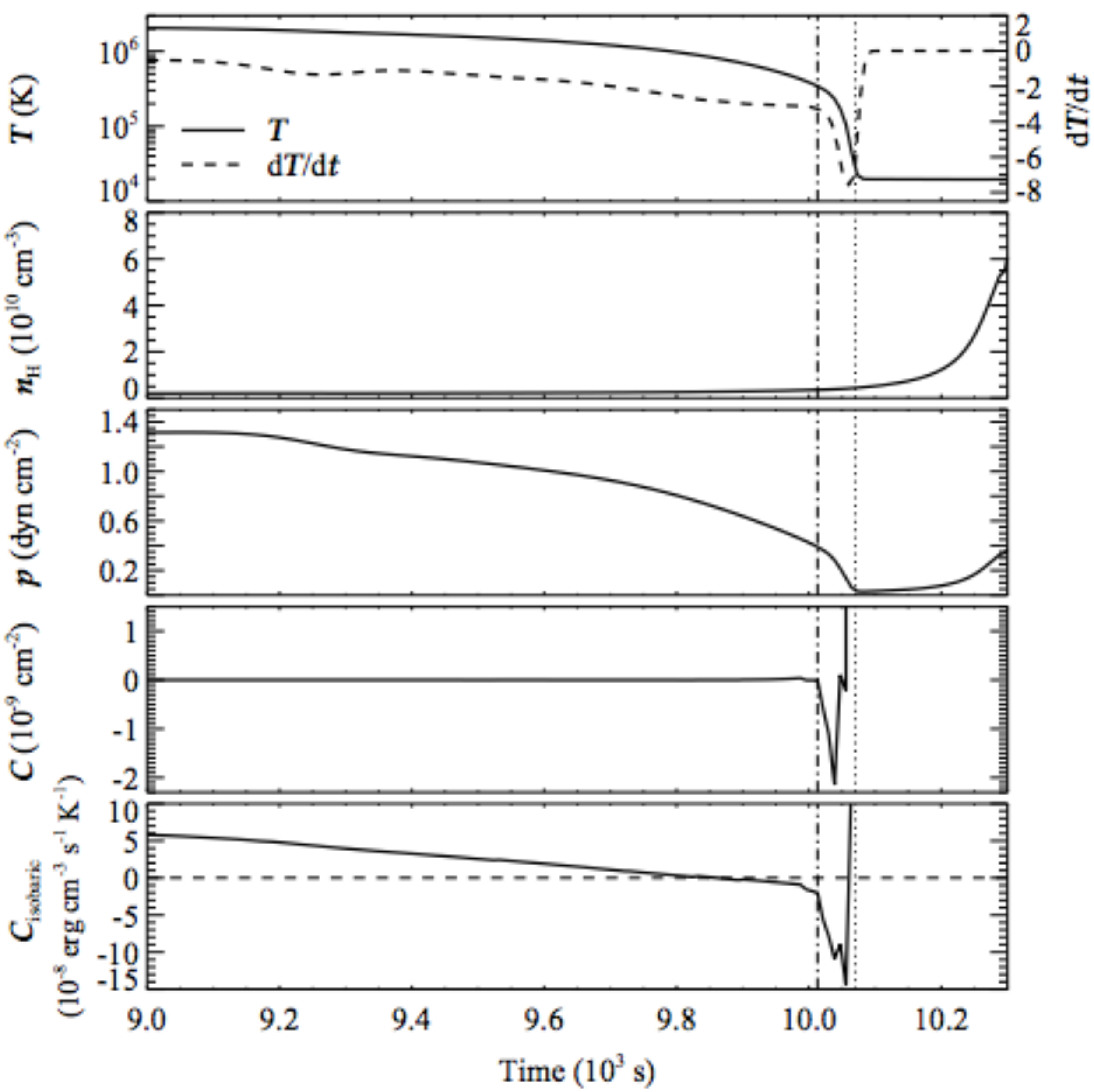




- Loss of pressure accompanied by loss of temperature
- Strong radiative losses at ChTR boundary maintains the clump
- Strong siphon flows are produced, feeding the clump

Thermal instability in coronal loops

Xia+ (2011)



- Parker's criterion (1953) for thermal instability: isochoric

$$C \equiv k^2 - \frac{1}{\kappa}\left(\frac{\partial H(s)}{\partial T} - \frac{\partial R}{\partial T}\right) < 0$$

k: wavenumber of perturbations
κ: thermal conduction coeff.
R=$n_e n_H \Lambda(T)$

- Field's criterion (1965): isobaric

$$C_{\text{isobaric}} \equiv \rho\left(\frac{\partial \mathcal{L}}{\partial T}\right)_\rho - \frac{\rho^2}{T}\left(\frac{\partial \mathcal{L}}{\partial \rho}\right)_T + k^2\kappa < 0$$

$$\mathcal{L} = (n_H n_e \Lambda(T) - H(s))/\rho$$

- Isochoric condition follows closely the runaway catastrophic cooling: sharp temperature decrease, roughly constant density
- Condensation (high density) takes a few more minutes (kinematic timescale driven by pressure gradient)
- Isobaric condition may not be appropriate

Morphology

- Unstable modes have a specific wavelength: Field's length

$$\sigma\gamma = -\chi_\| k_\|^2 - t_{\rm cool}^{-1}\frac{d\ln(\Lambda/T^2)}{d\ln T} \longrightarrow \lambda_F \equiv 2\pi\left[\frac{\chi_\| t_{\rm cool}}{d\ln(T^2/\Lambda)/d\ln T}\right]^{1/2}$$

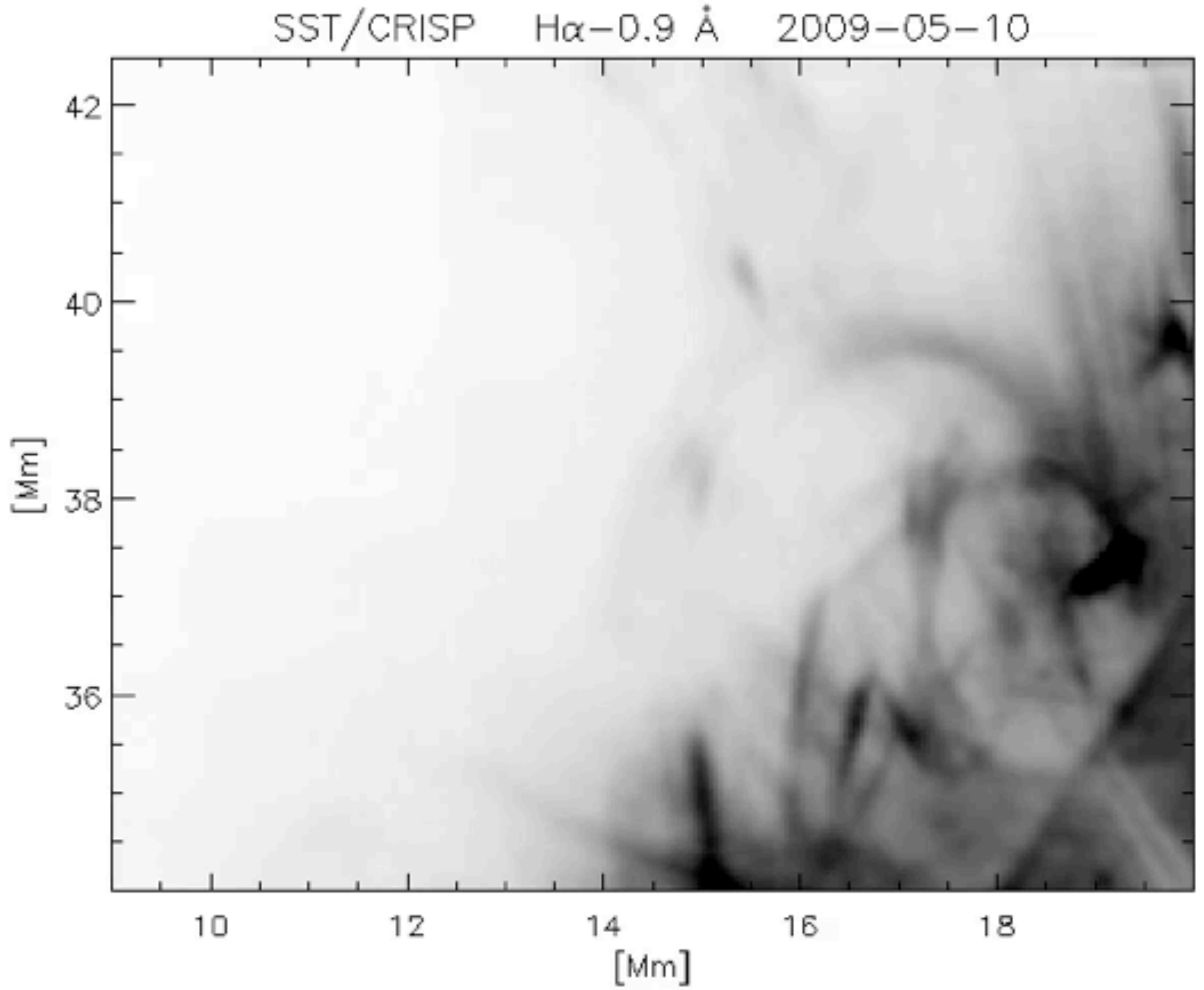
➡May define the longitudinal scales found in rain (clumpy structure) and in prominences

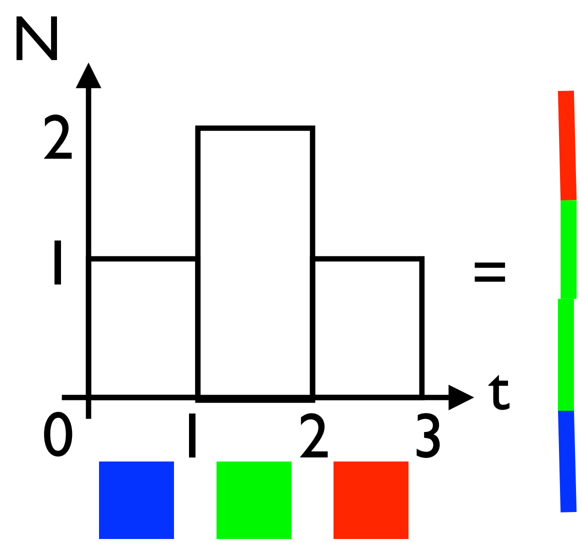
- For the strand-like structure we need 2D-3D

Constraint for coronal heating

Strands may not evolve always independently

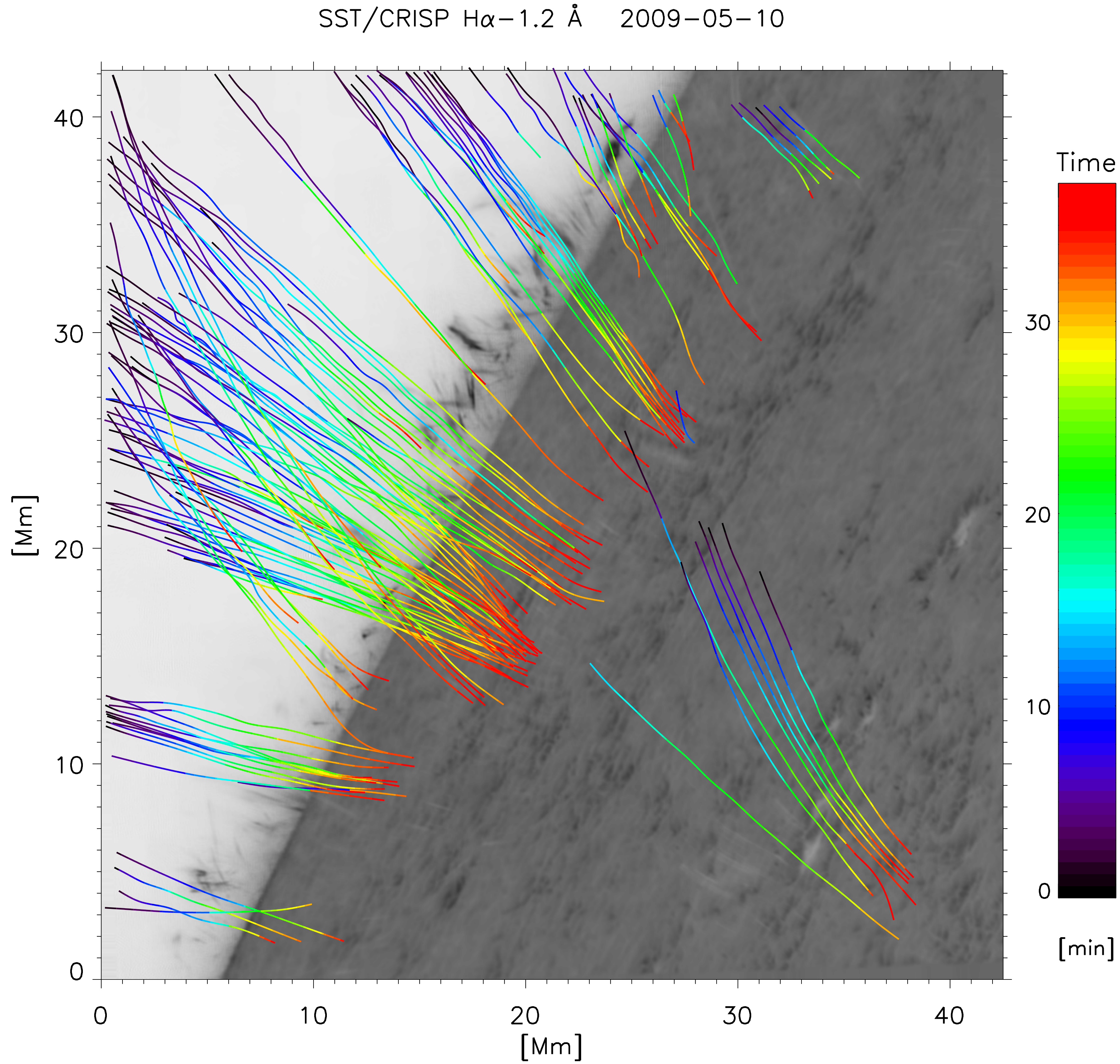
existence of coherent thermodynamic transverse scale





Neighboring strands cool generally at the same time

- coherent footpoint heating transverse scale ~ 2 Mm



with random distribution in time

Relation to coronal heating?

ARE MAGNETIC DIPS NECESSARY FOR PROMINENCE FORMATION?

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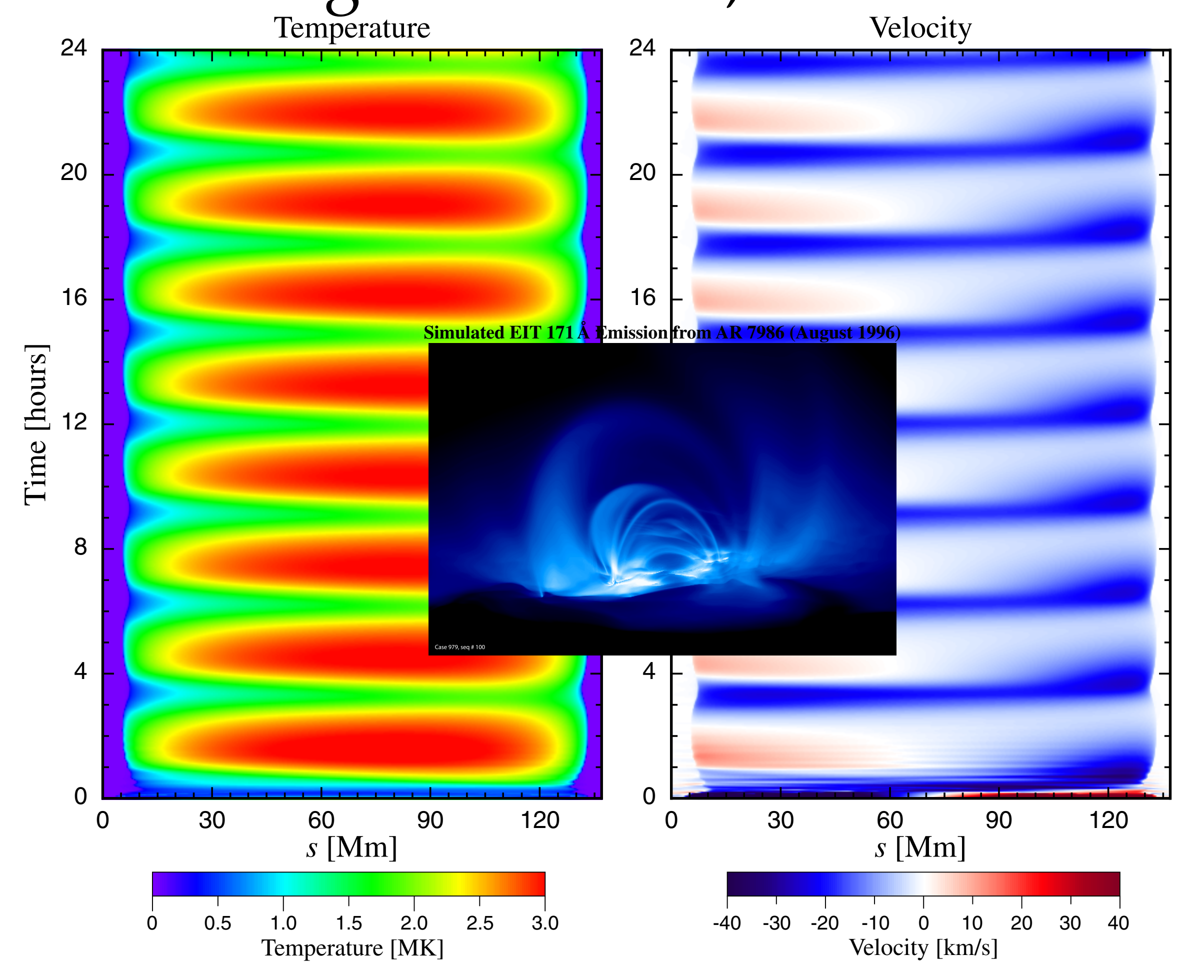
ABSTRACT

The short answer: No.

- Thermally unstable corona produced when heating scale length is small compared to loop length & heating timescale small compared to radiative cooling timescales (Müller+ 2003-4, Mendoza-Briceño+ 2005, Susino 2010, Peter+ 2011)
- Complex parameter space: Spatial and temporal heating distribution, volumetric energy, loop geometry (length and area)

➡Important information about the spatial (and temporal) heating scales

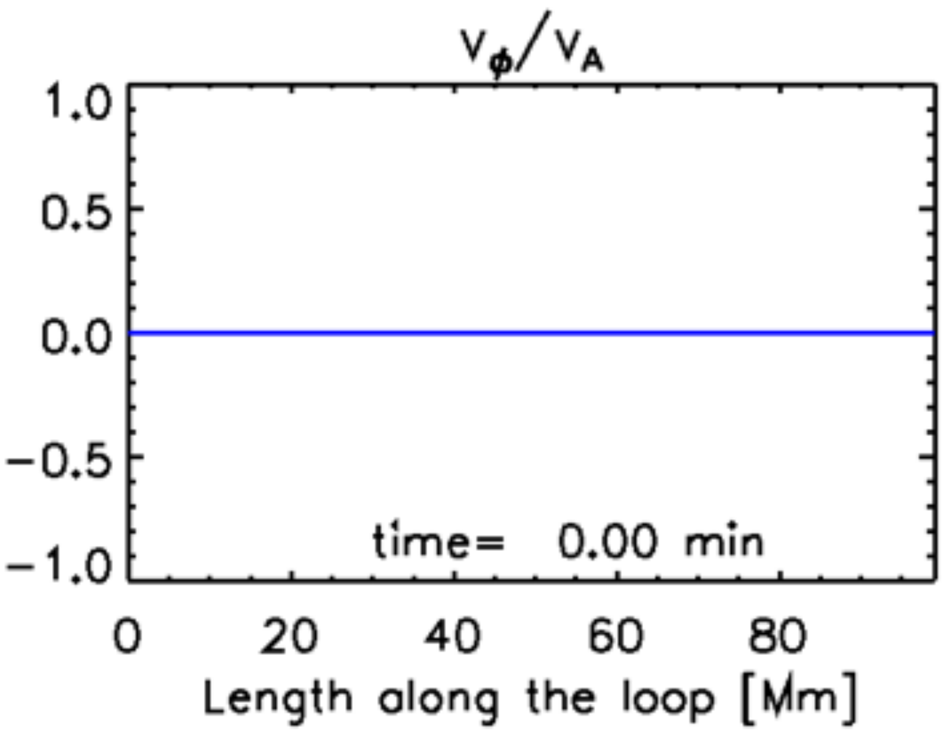


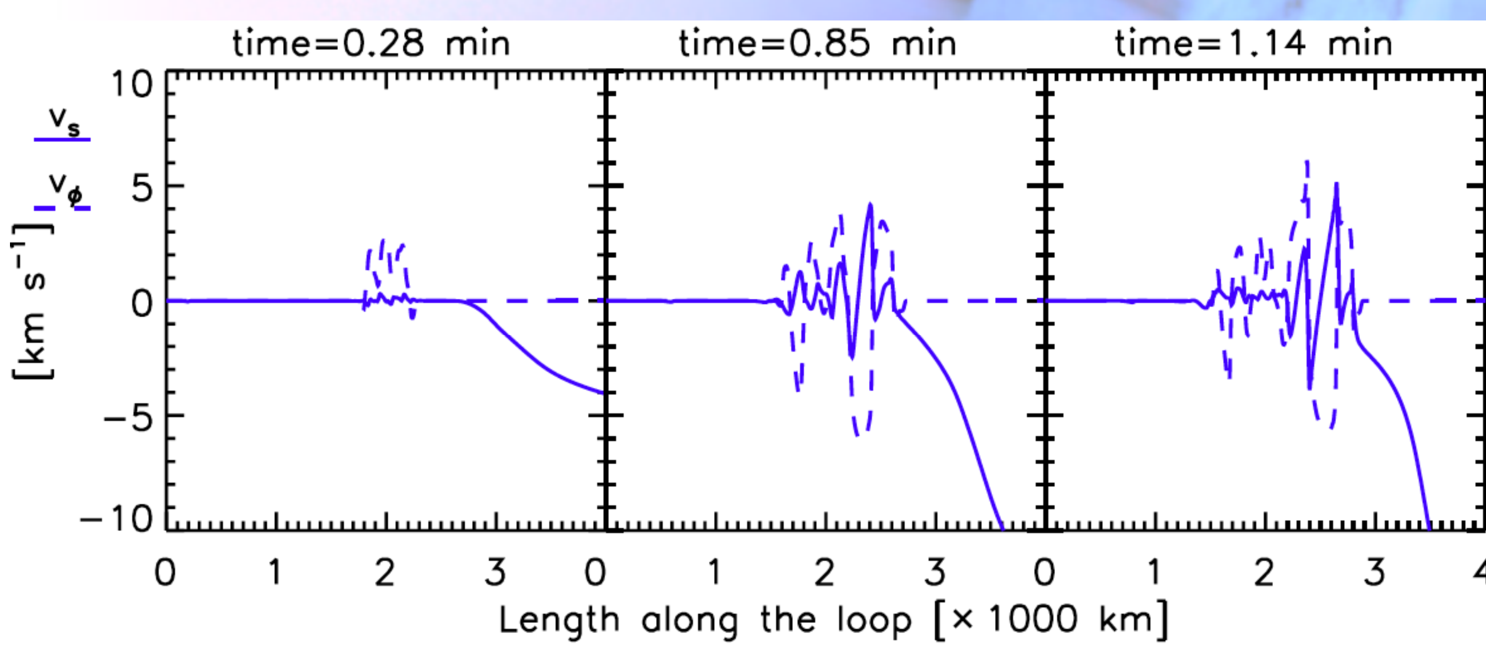
- Non-uniformity and asymmetry in area and heating can lead to incomplete thermal instability (condensations do not reach chromospheric temperatures): Lionello+ 2013, Mikiç+ 2013

Alfvén wave heating

- Heating mechanism

torsional Alfvén waves → non-linear effects → slow/fast modes → develop into shocks → shock heating



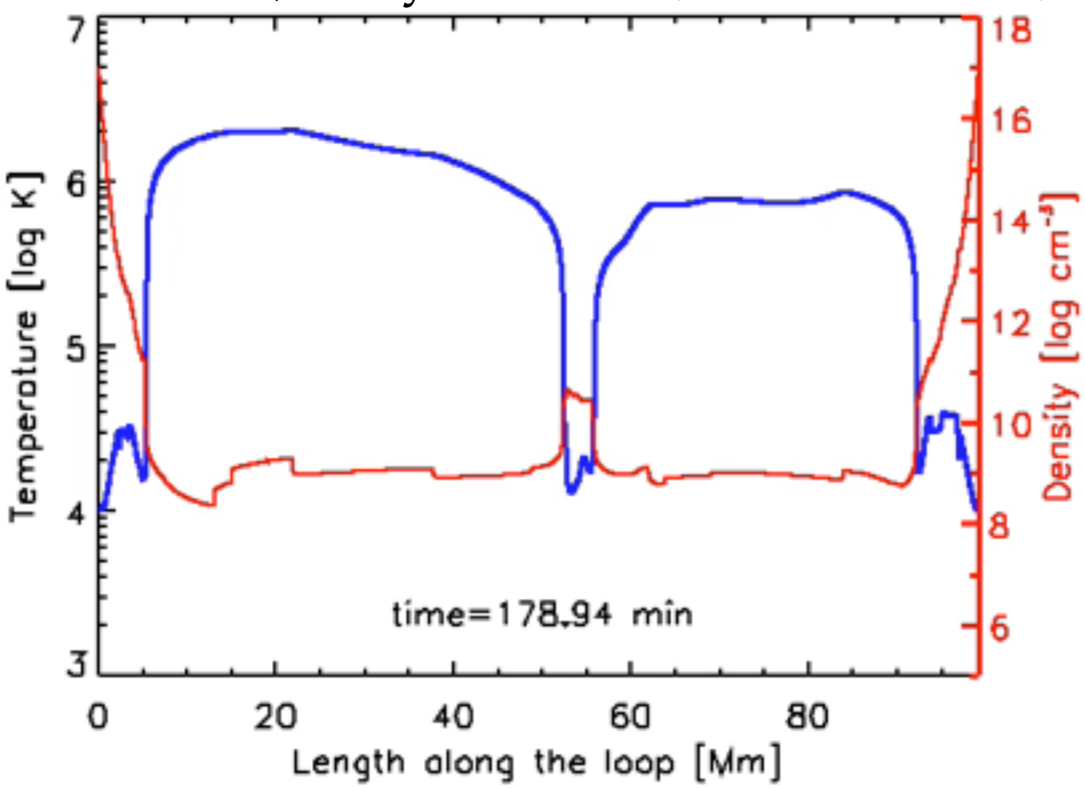


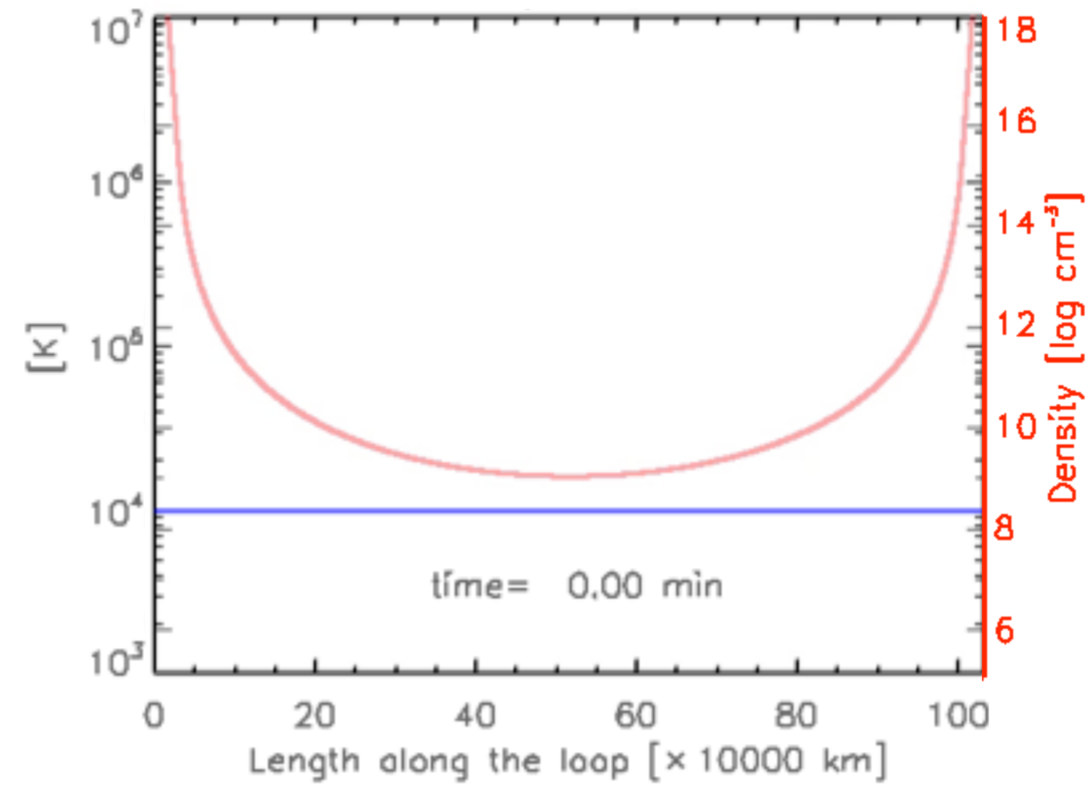
Relation to coronal heating?

- Heating mechanisms may have characteristic spatial and temporal scales

footpoint heating | nonlinear Alfvén waves: uniform heating

(Moriyasu+ 2004, Antolin+2008, Antolin+ 2010, Antolin & Shibata 2010)

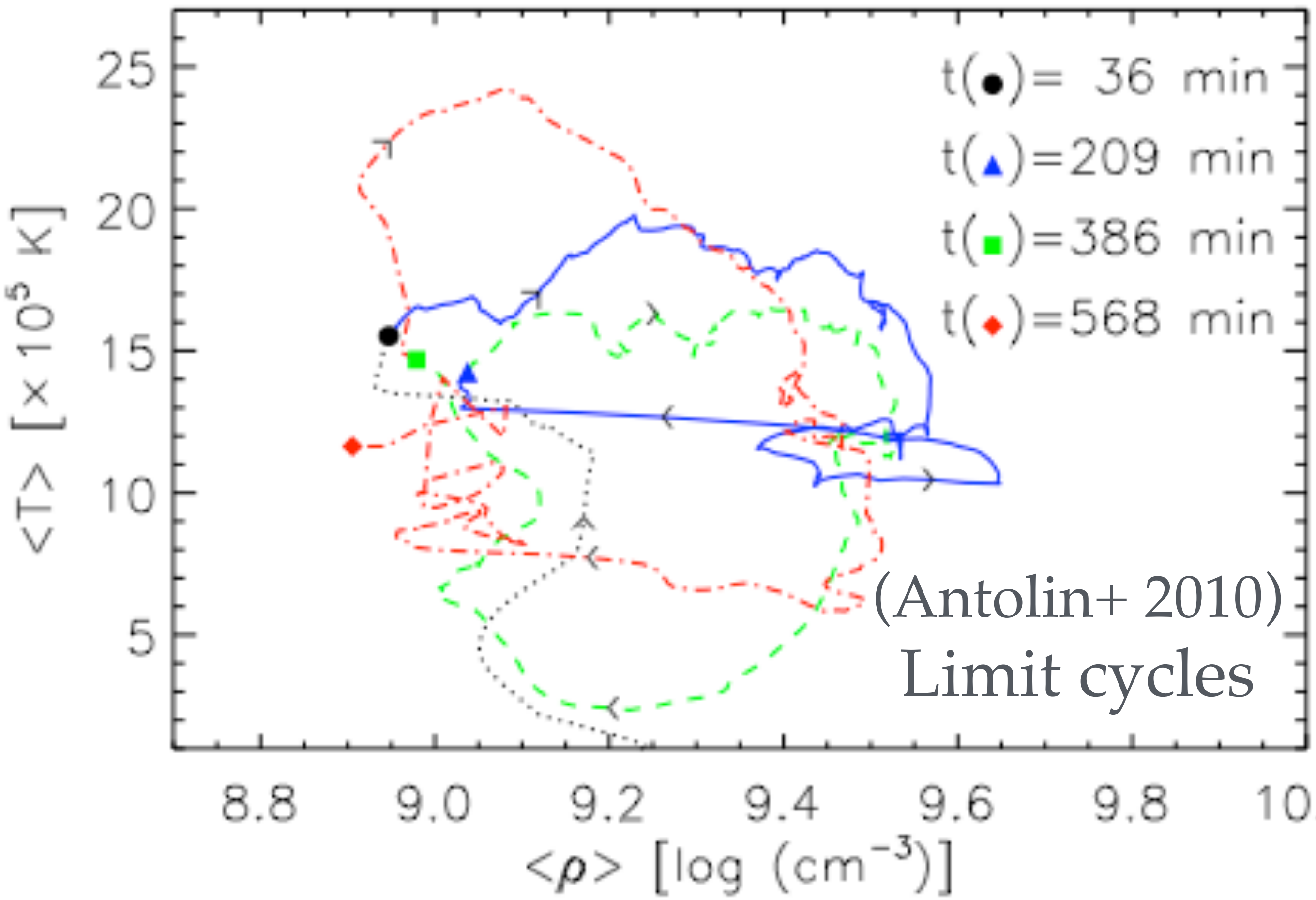




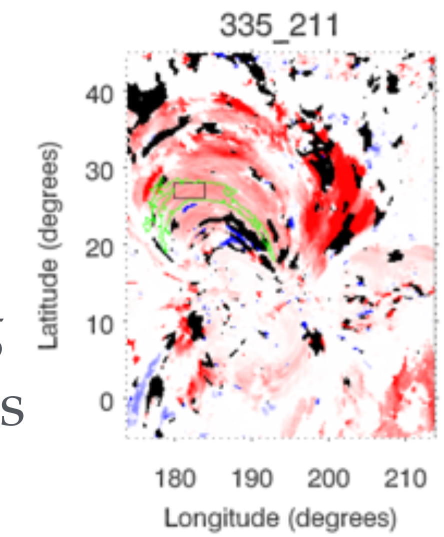
Important information about the heating mechanism

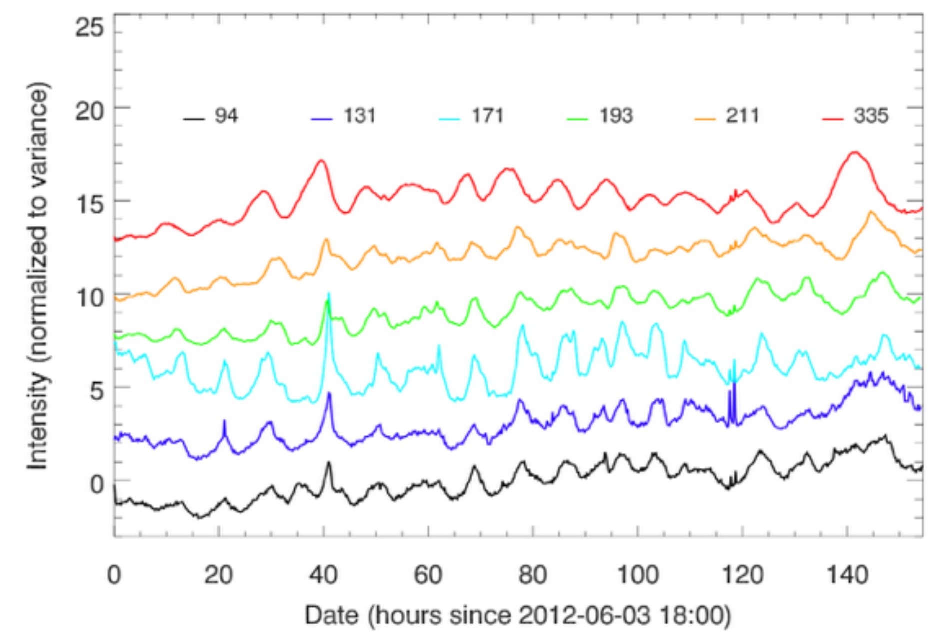
Relation to coronal heating?

(Antiochos+ 1999, Karpen+ 2001, Müller+ 2003, 2004, Antolin+ 2010, Susino+ 2010, Mikiç+ 2013)



Froment+ (in prep.): long period intensity pulsations in loops (2-16 hrs)





Periodicity in the occurrence of coronal rain: link to heating parameters

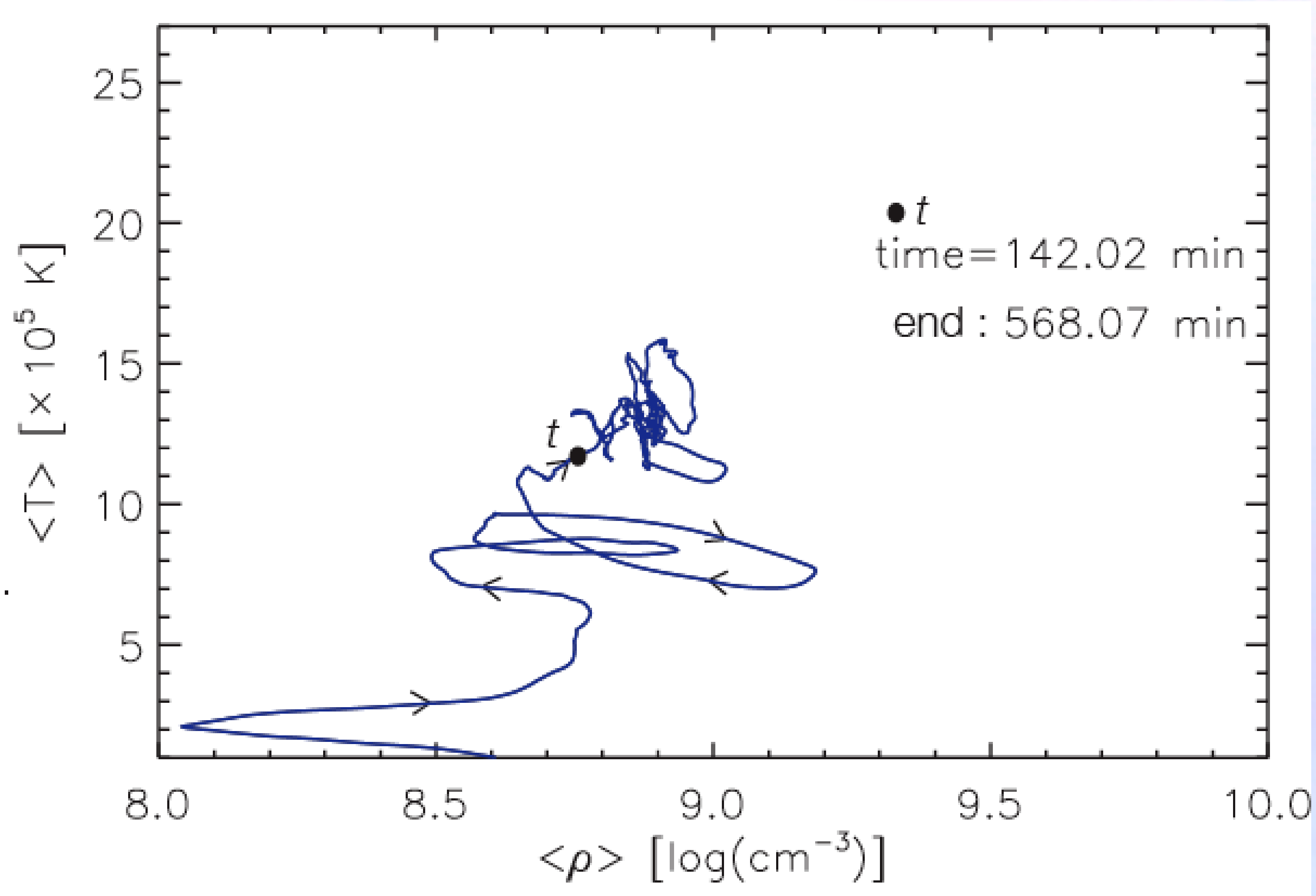
What is the observed periodicity for coronal rain?

Schrijver (2001): once each 2 days for an AR,

Antolin & Rouppe van der Voort (2012): once each 5-20 hrs

Alfvén wave heating

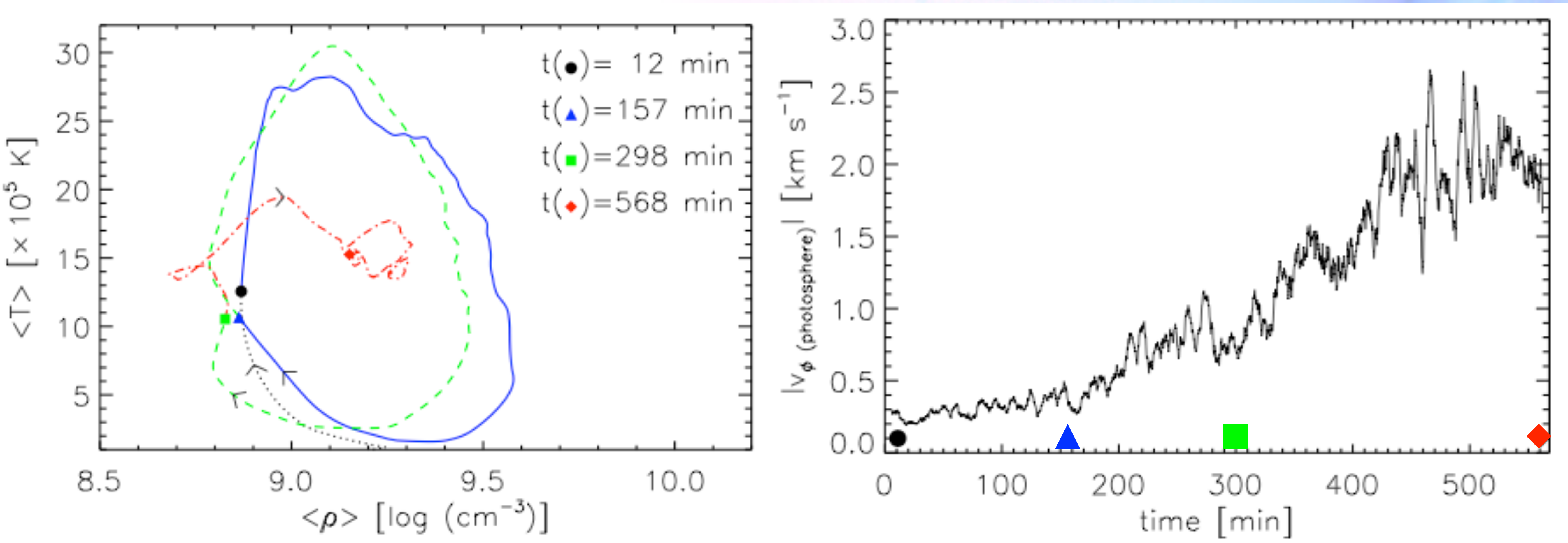
Temperature vs. density in the corona



Loop reaches thermodynamic equilibrium: attractor in the temperature-density diagram

- No thermal instability in this case due to uniform heating from the waves

Footpoint heating + Alfvén waves

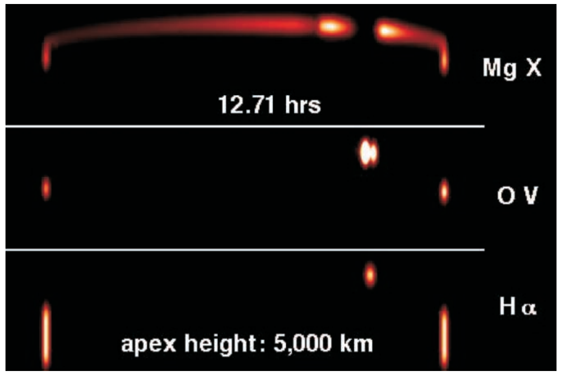


If Alfvén wave heating is significant the loop is thermally stable → marker of coronal heating mechanisms

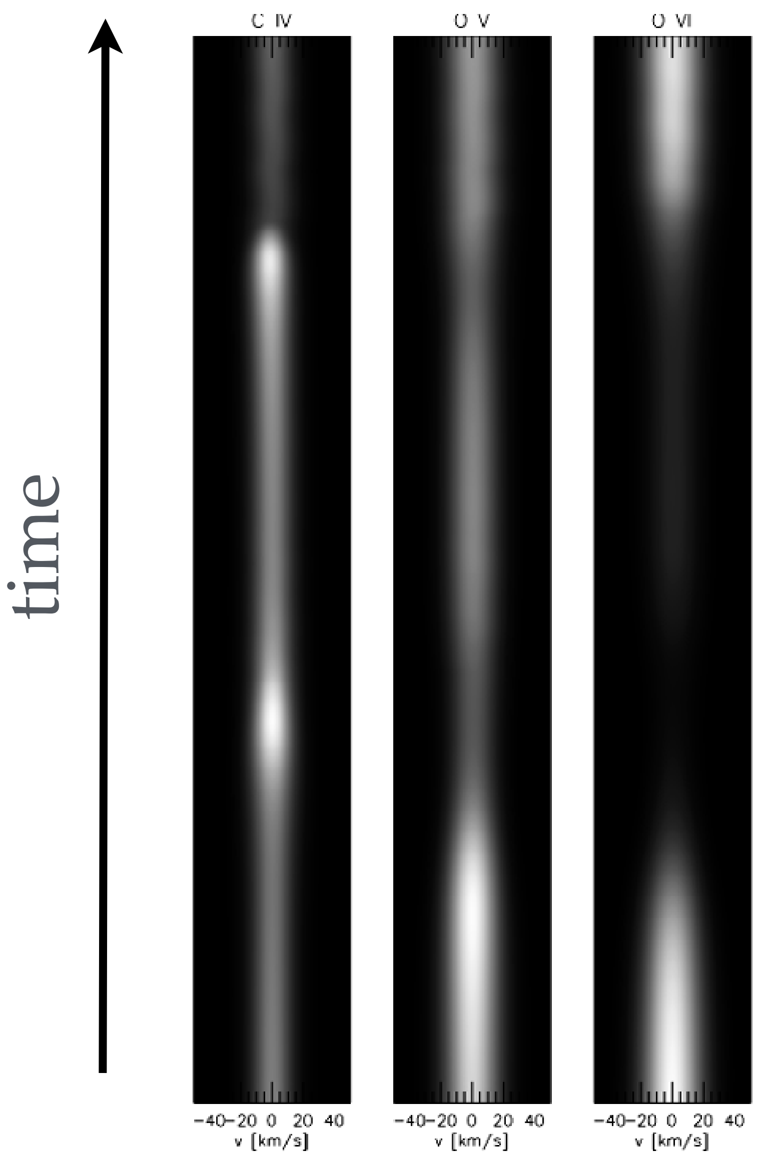
Antolin, Shibata & Vissers, ApJ 716, 2010

Match with observations?

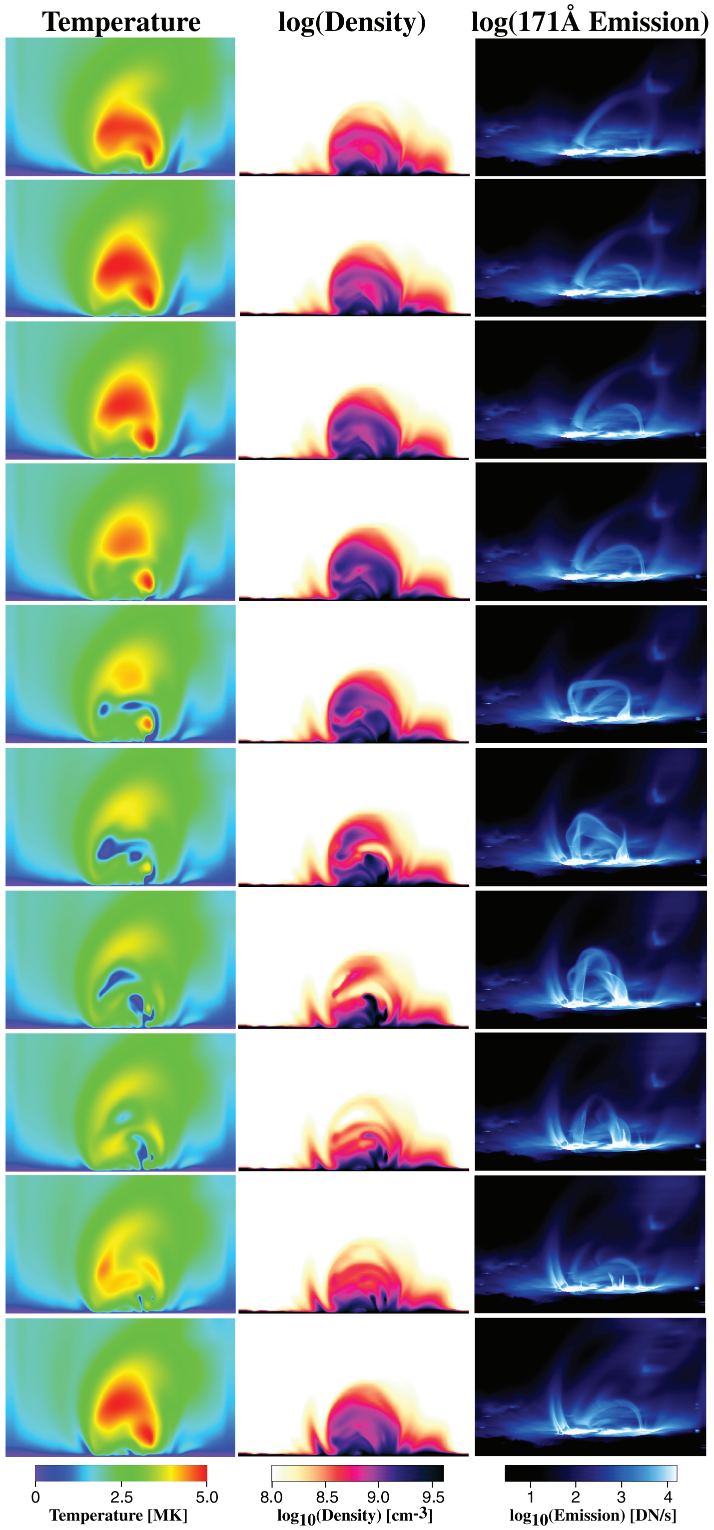
Karpen+ 2001



Müller 2003



Mok+ 2008



Debate:

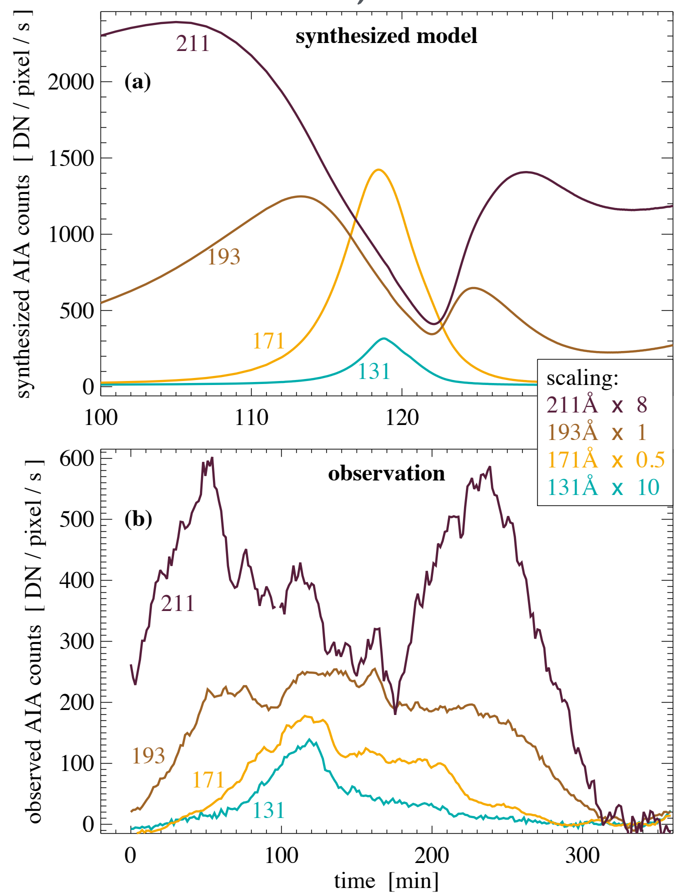
Do EUV light curves of loops in thermal non-equilibrium state match observations?

No: Klimchuk+ (2010)

Yes: Peter + (2012), Mikiç + (2013)

…

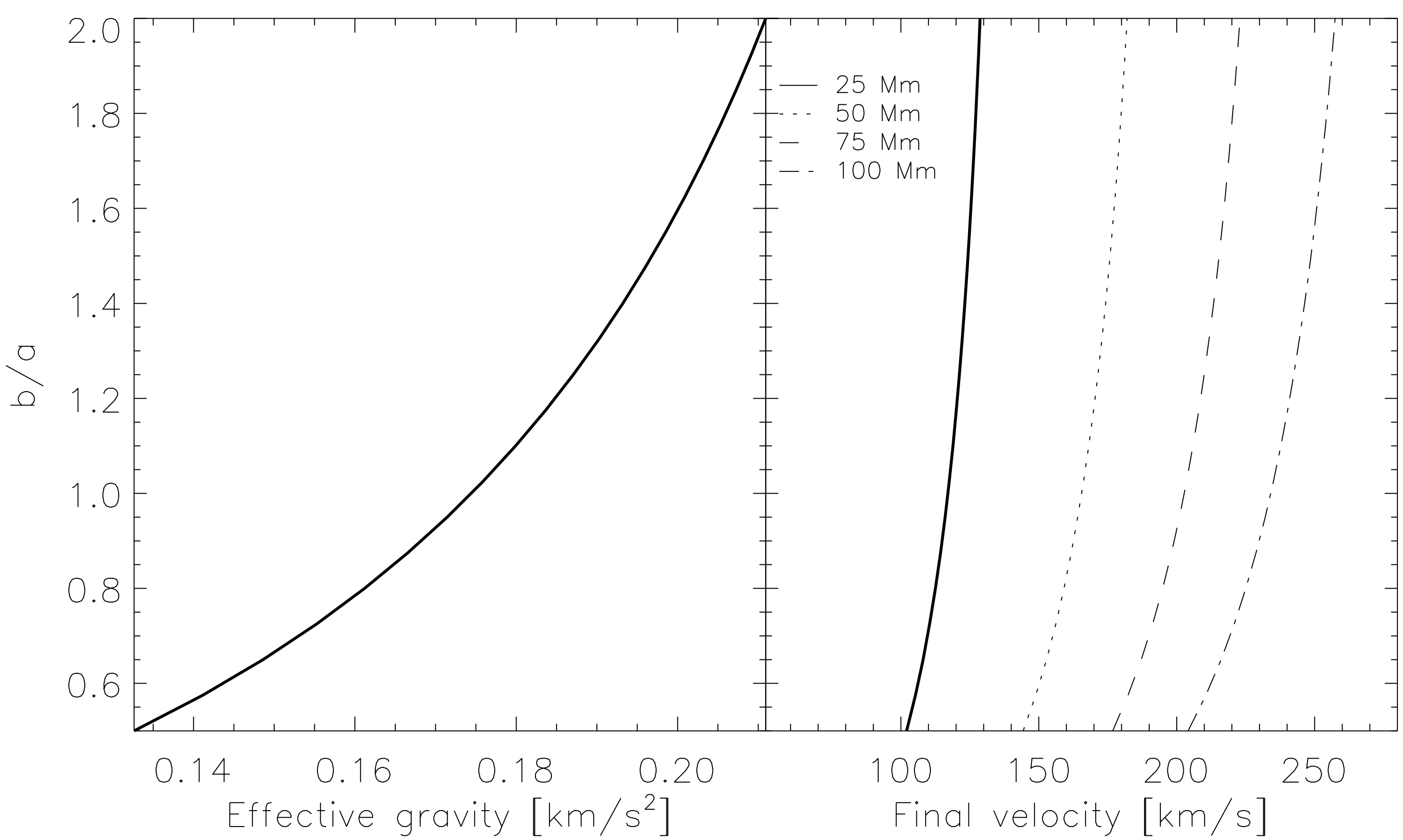
Kamio+ 2011, Peter+ 2011

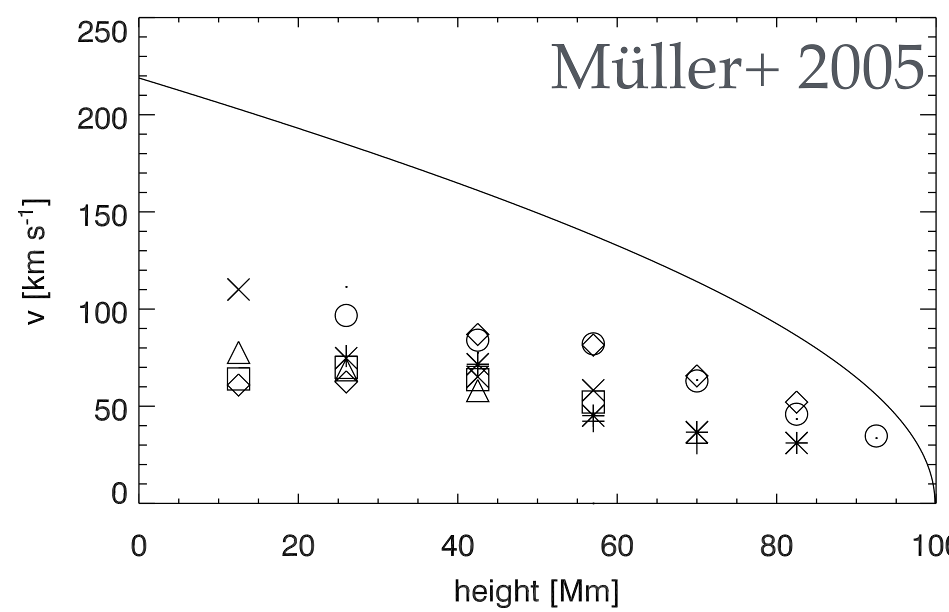


Dynamics

$$\langle g_{\text{eff}} \rangle = \frac{2}{\pi} \int_0^{\pi/2} g_\odot \cos\theta(s) ds$$

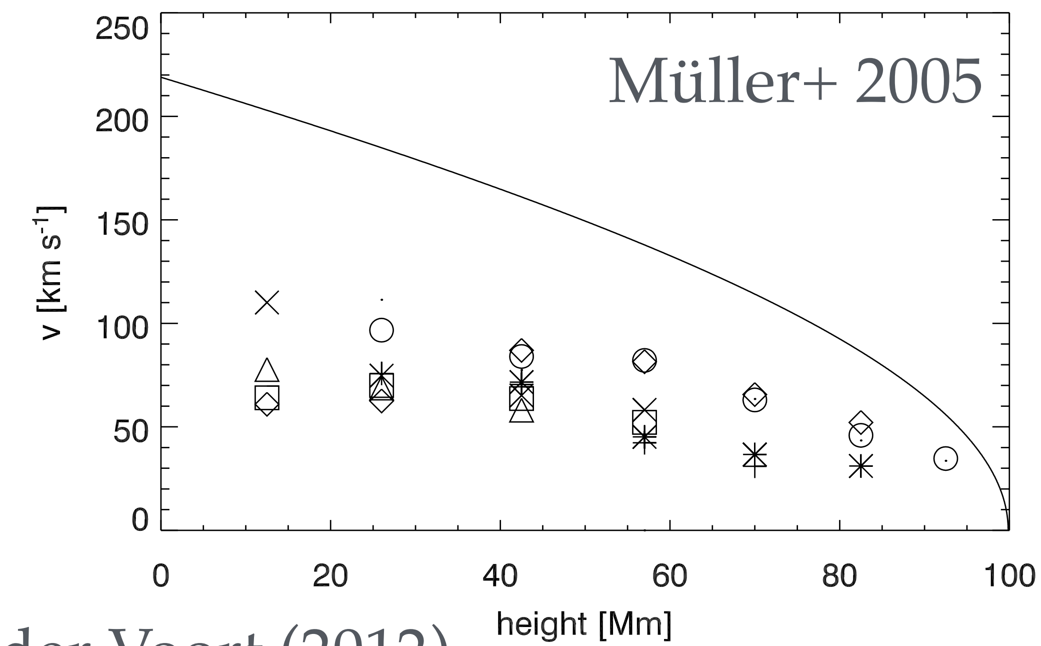
How fast can coronal rain be under effects of gravity alone?





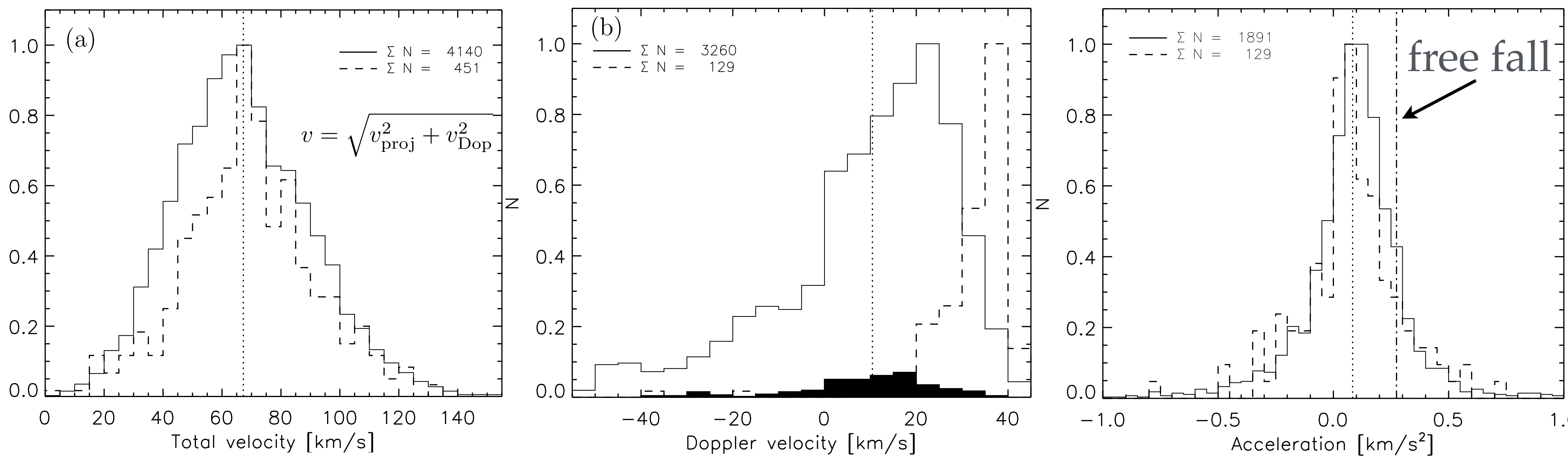
Dynamics

Acceleration << effective gravity along loops (Wiik+ 1996, De Groof et al. 2004, 2005, Müller+ 2005, Antolin+ 2010, 2012)



off-limb ------ on-disc

Antolin & Rouppe van der Voort (2012)



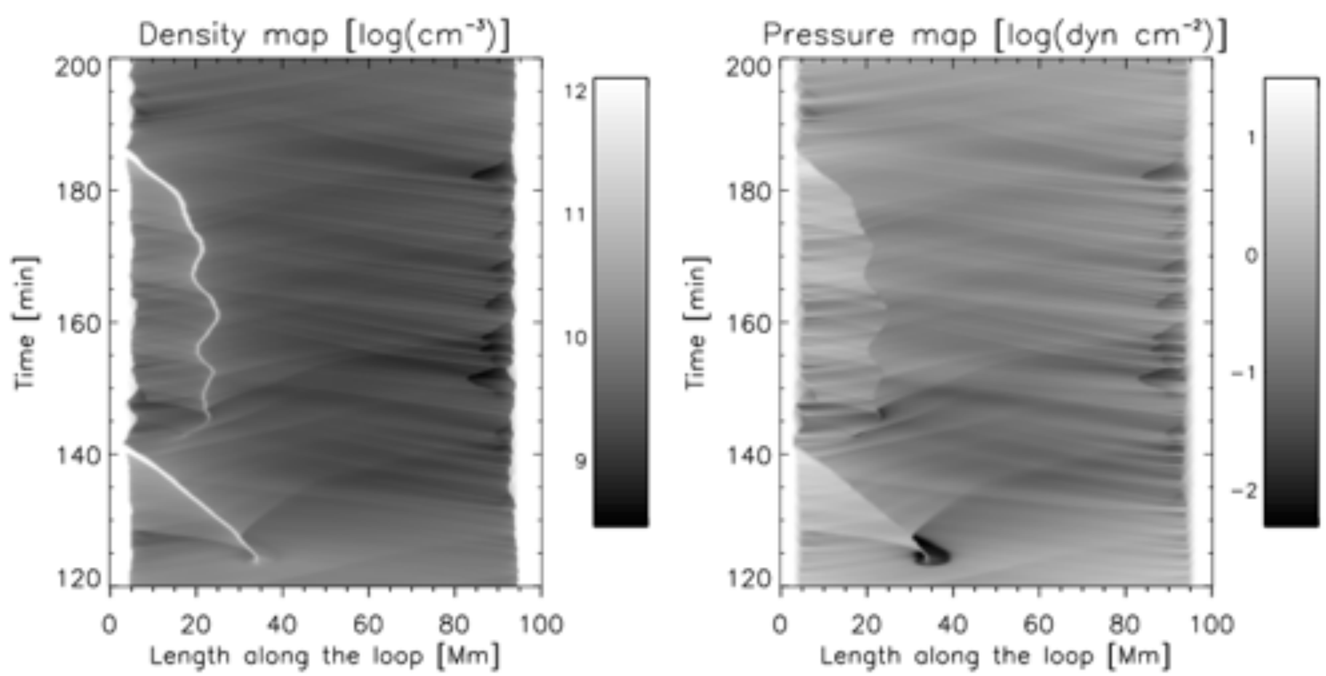
$\langle g_{\rm eff}\rangle = \frac{2}{\pi}\int_0^{\pi/2} g_\odot \cos\theta(s)ds$ ~(0.13, 0.21) km s^{-2} for elliptic path with semi-axes ratio between 0.5 and 2

→ Other important forces exist inside loops

Dynamics

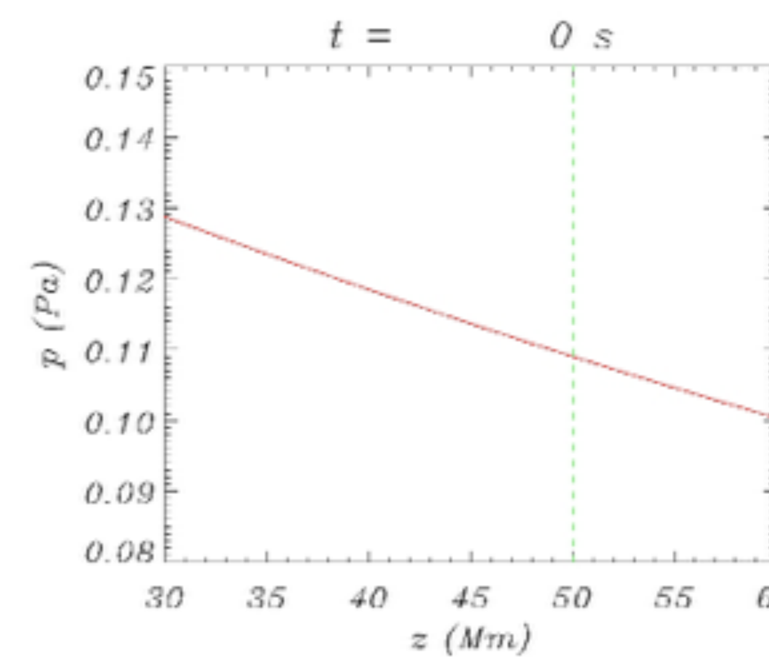
- Gas pressure driven? (Antiochos+ 1999, Karpen+ 2001, Müller+ 2003-4, Antolin+ 2010)

Antolin+ 2010



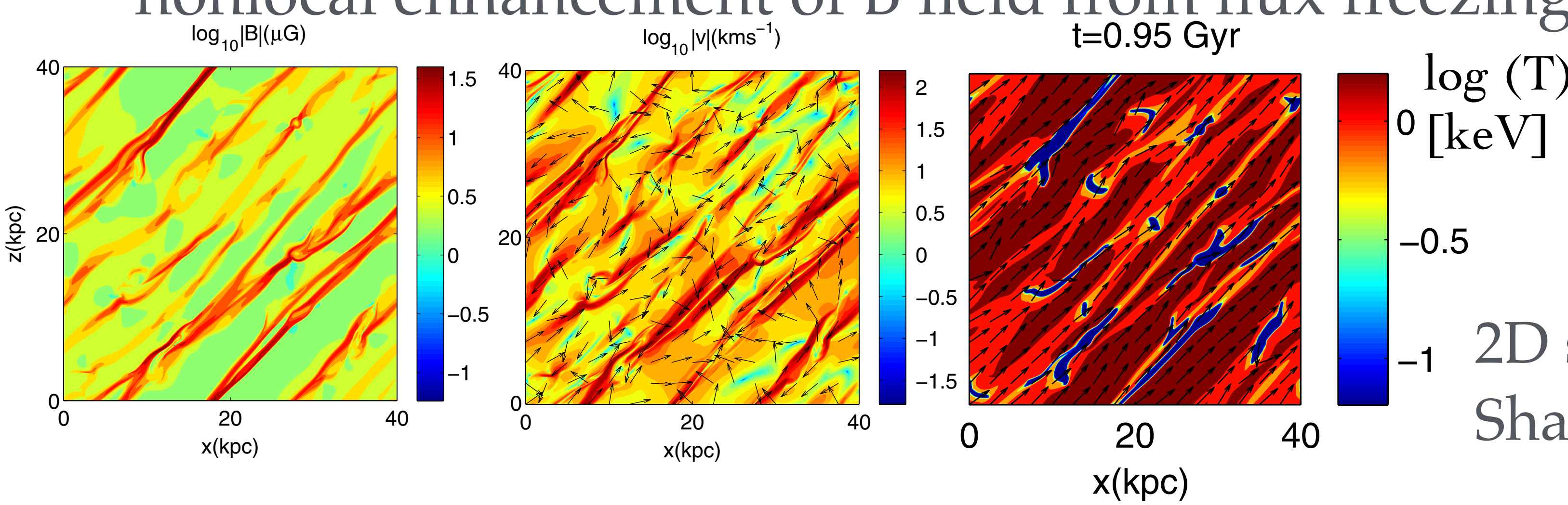
- Condensation generates acoustic shocks: pressure below is reset leading to constant downward speeds (Oliver+ 2014)

- Generation of leaky sound waves: prospects for seismology applications



Oliver+ 2014

- Magnetic pressure driven? condensations generate nonlocal enhancement of B field from flux freezing



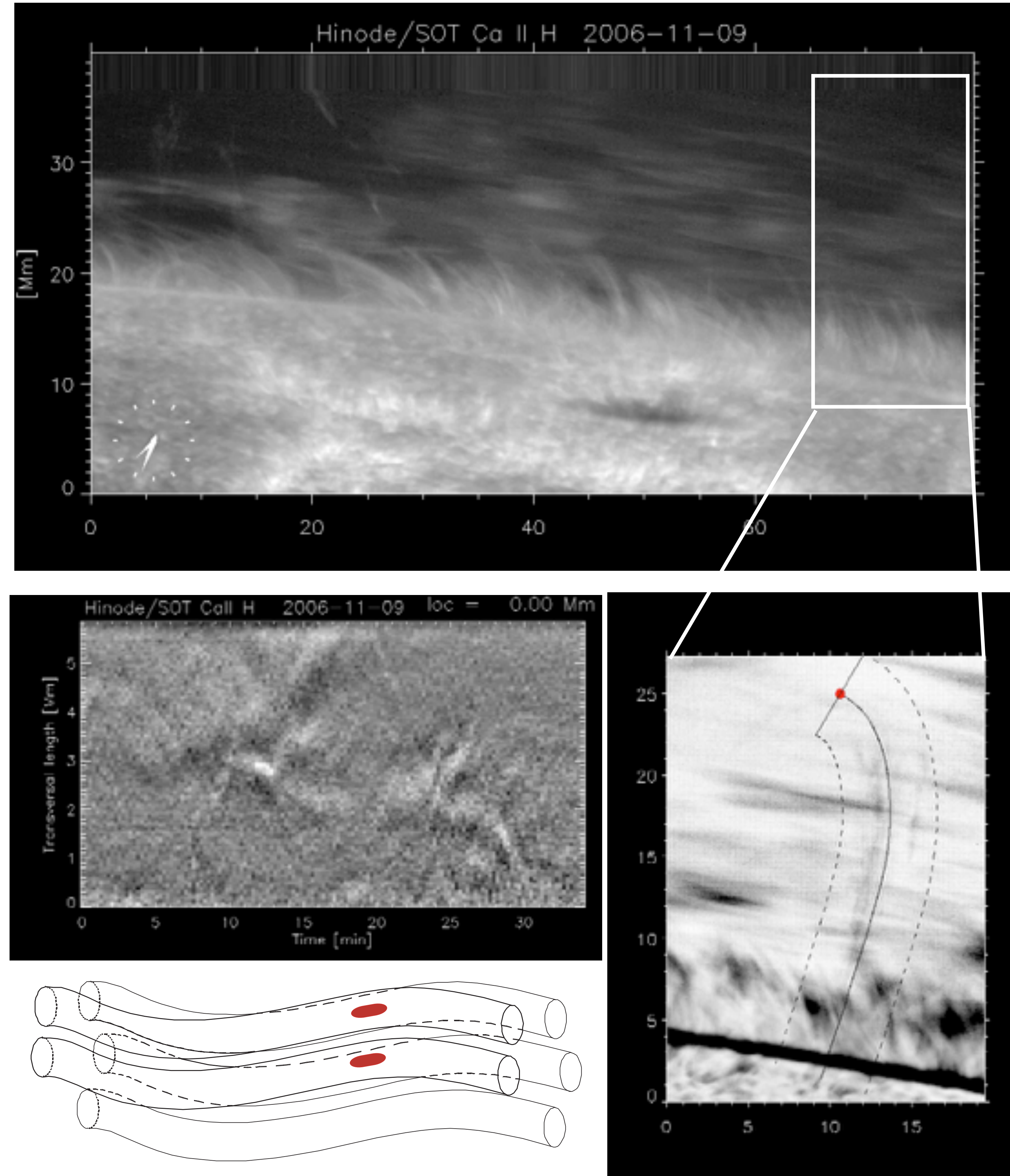
2D sims from Sharma+ 2010

Dynamics

Antolin & Verwichte 2011

- Magnetic driven - transverse MHD waves?

Okamoto+ 2007, Tomczyk+ 2007 Erdélyi & Taroyan 2008, Van Doorsselaere+ 2008; Terradas+ 2008, Jess+ 2009; Lin 2011; McIntosh+ 2011, Tian+ 2012; Hillier+ 2013



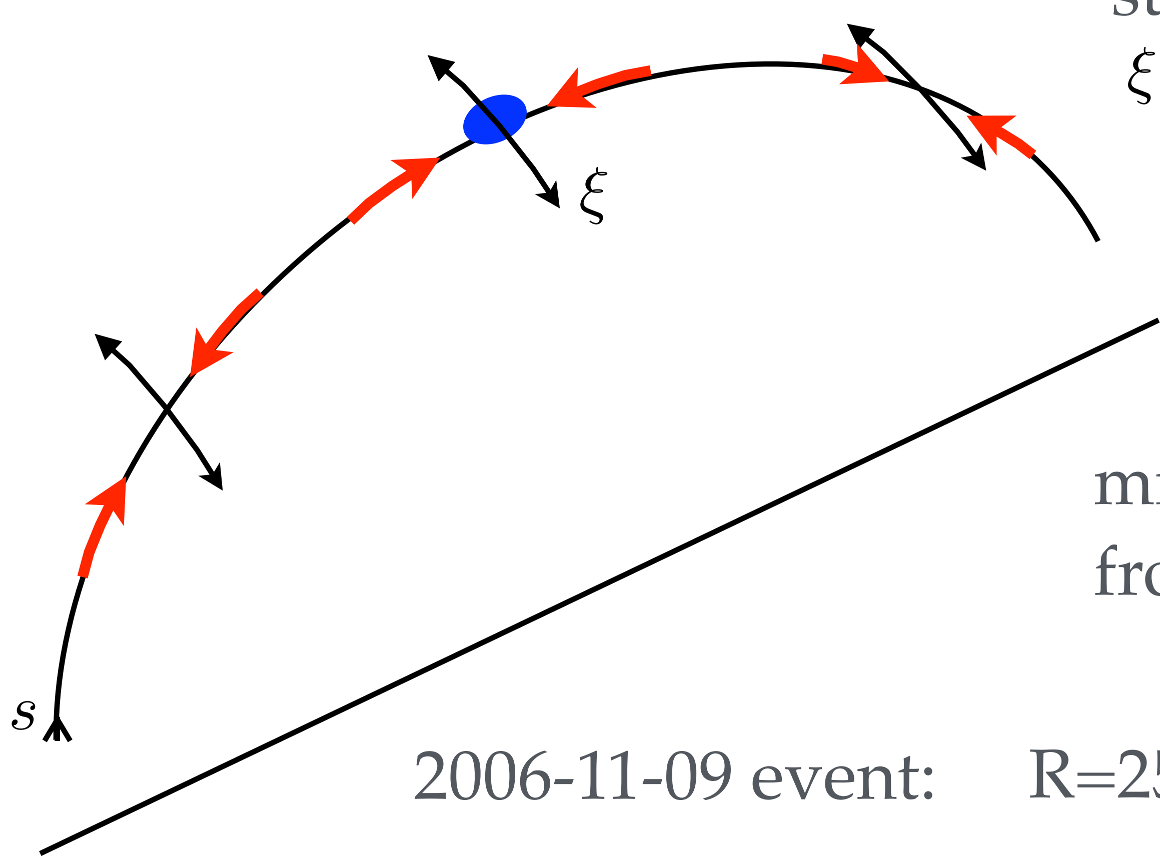
In phase oscillations
Periods: 100 - 200 s
Amplitudes: <500 km

→ dynamic effect from ponderomotive force? (Terradas & Ofman 2004, Antolin & Verwichte 2011)

Dynamics

Coronal rain blob modelled as a bead on a string:
→ dynamical system

$$\mathcal{L} = \int_0^{\pi R} \left[\frac{\rho}{2} \left(\frac{\partial \xi}{\partial t} \right)^2 - \frac{B^2}{2\mu_0} \left(\frac{\partial \xi}{\partial s} \right)^2 \right] S \mathrm{d}s + \frac{m}{2} \left[\left(\frac{\mathrm{d}s_\mathrm{p}}{\mathrm{d}t} \right)^2 + \left(\frac{\mathrm{d}x_\mathrm{p}}{\mathrm{d}t} \right)^2 \right] - m \int_0^{s_\mathrm{p}} g(s') ds'$$



string:

$$\xi(s,t) = \frac{a}{k} \sin(ks) \cos(\omega t), \qquad k = n/R, \ \omega = v_\mathrm{A} k$$

blob:

$$\frac{\mathrm{d}^2 s_\mathrm{p}}{\mathrm{d}t^2} = a_0 \frac{\omega^2}{k} + a_1 \omega \frac{\mathrm{d}s_\mathrm{p}}{\mathrm{d}t} + a_2 k \left(\frac{\mathrm{d}s_\mathrm{p}}{\mathrm{d}t} \right)^2$$

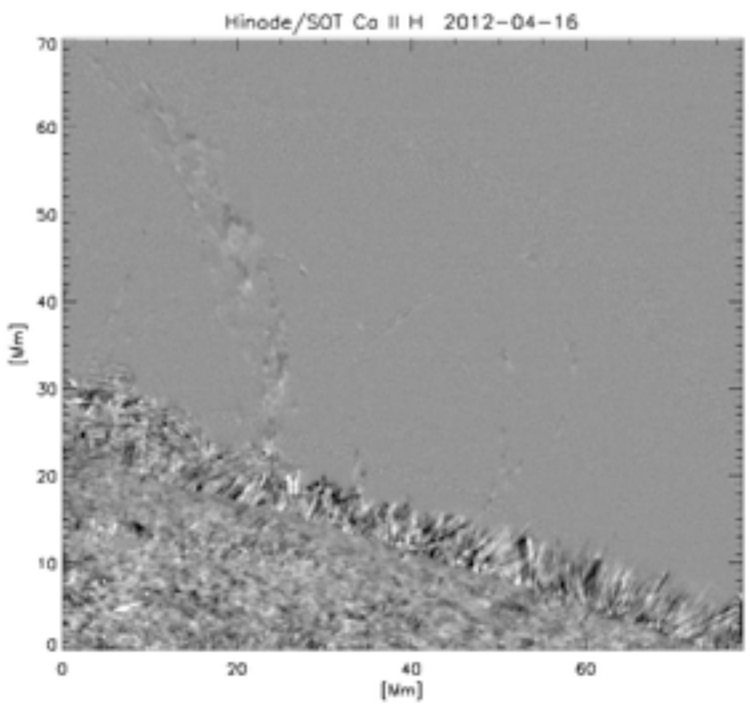
minimum amplitude required to prevent blob from falling:

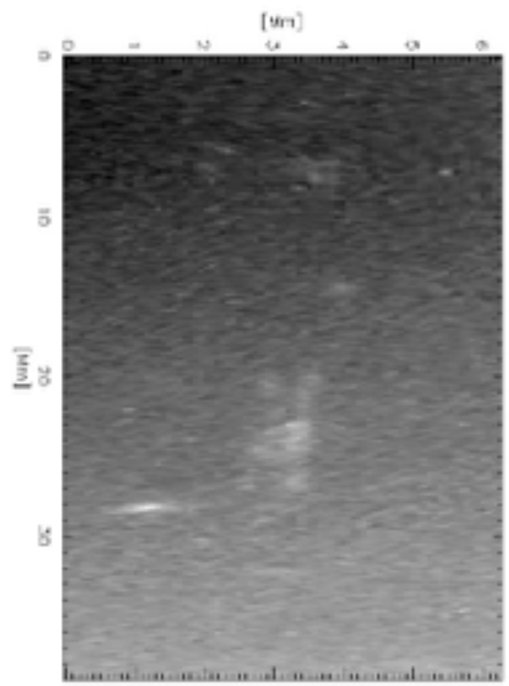
$$a_\mathrm{min} = \frac{\sqrt{2 g_\odot R}}{v_\mathrm{A} n}$$

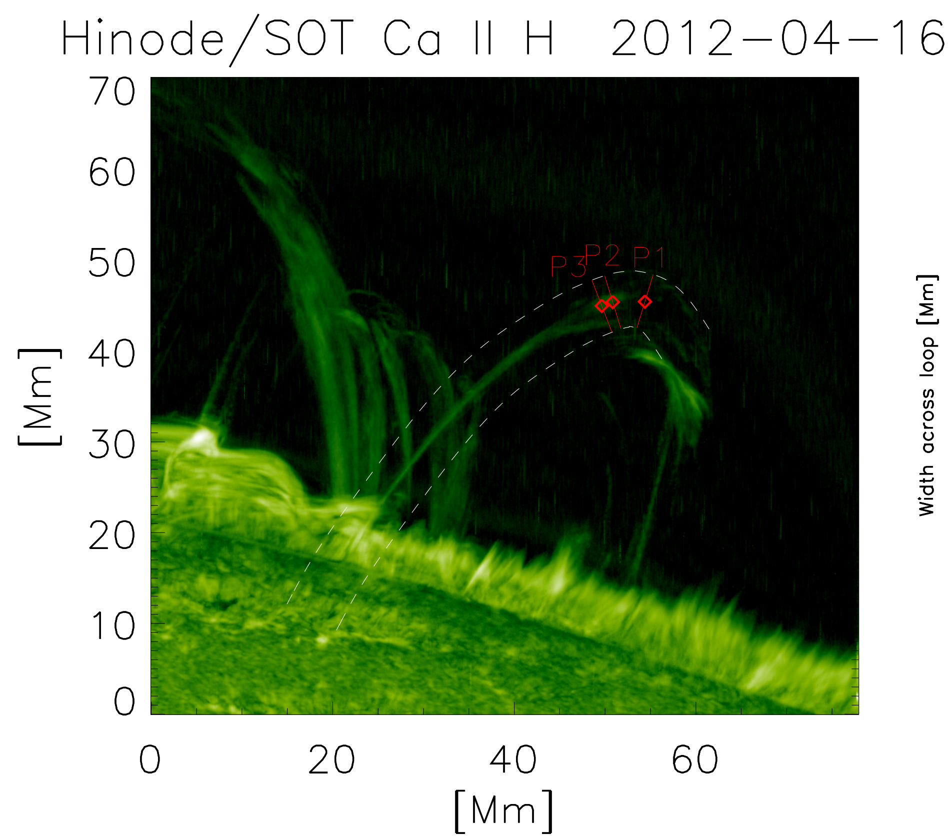
2006-11-09 event: R=25 Mm, v_A = 710 km/s → a_min = 2.7 Mm

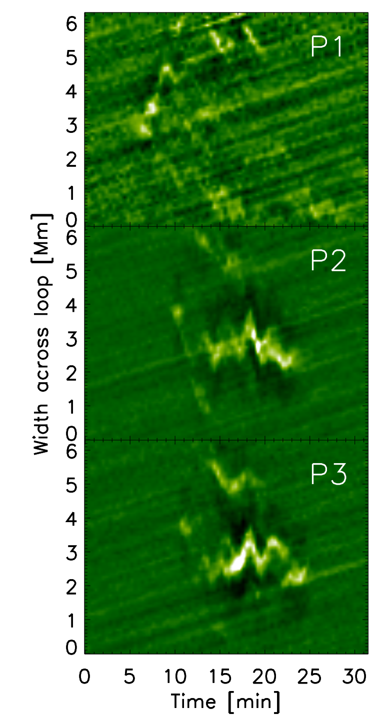
Verwichte, Antolin, Rowlands, Neukirch (2014, in prep.)

Dynamics

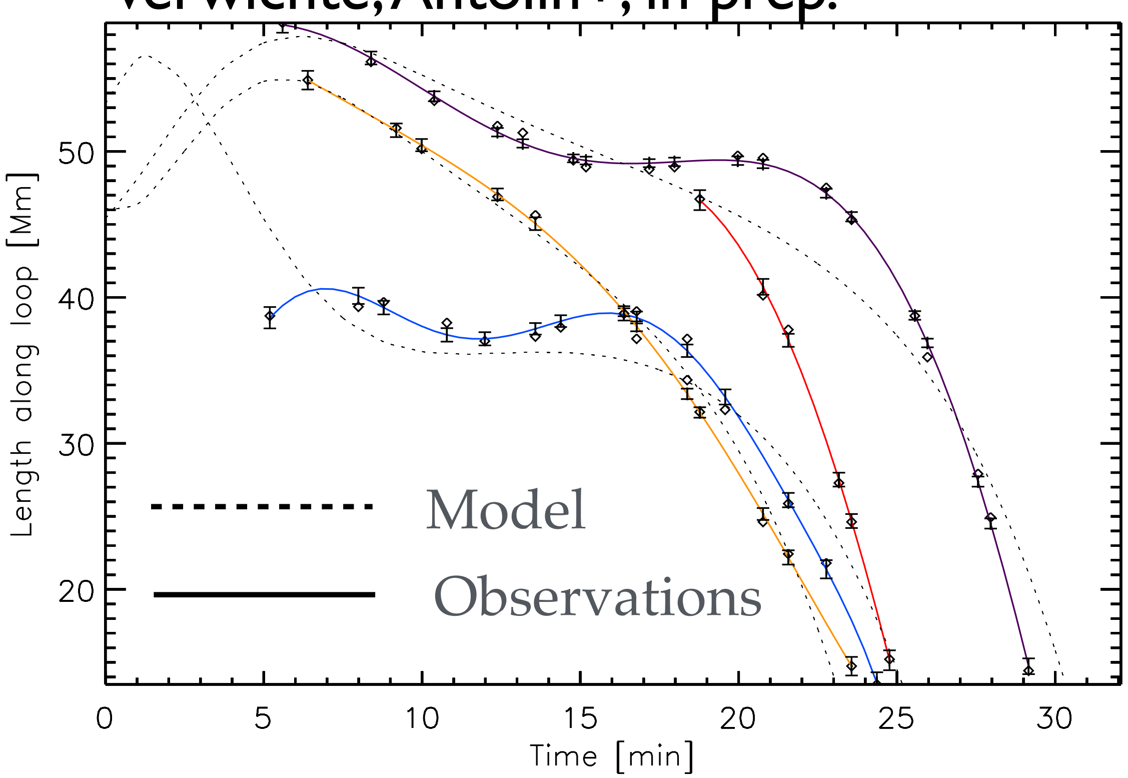








Verwichte, Antolin+, in prep.



Radius: 41 Mm,
Period: 154 s,
Amplitude <2 Mm,
loop plane angle ~30°

$$v_A = \frac{\omega}{k} \approx 1180 \text{ km/s}$$

Multi-dimensional modelling of coronal rain

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