MHD simulations of prominence formation and oscillation

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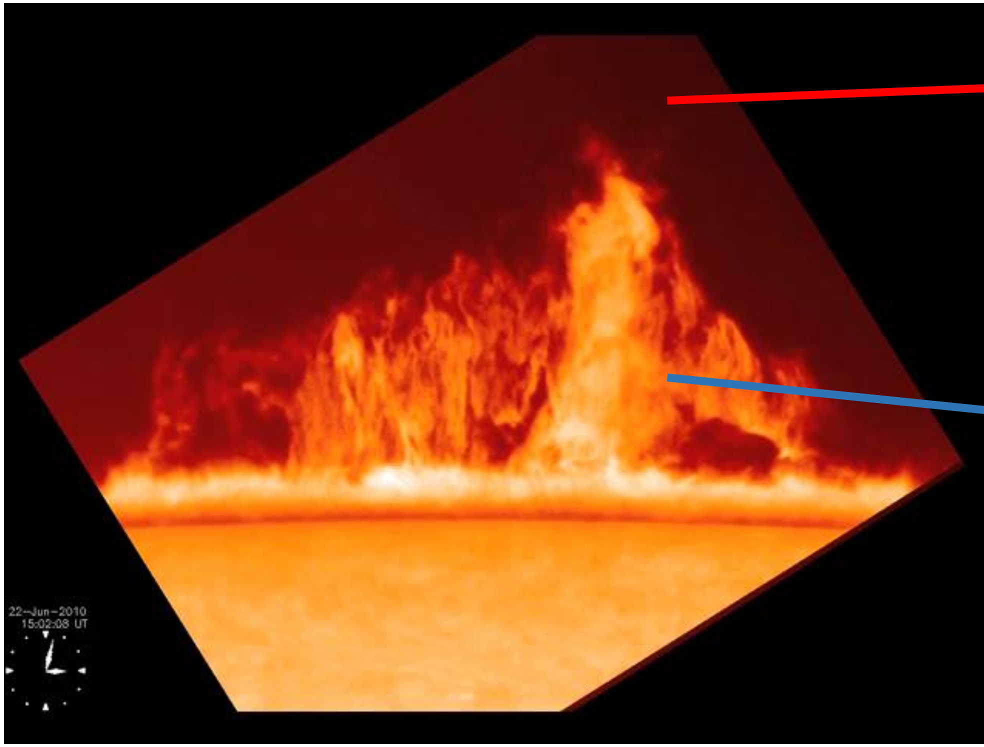
Based on

Kaneko, T., 2017, PhD thesis, UTokyo

Kaneko & Yokoyama, 2015, ApJ, 806, 115

Kaneko et al., 2015, ApJ, 812, 121

Solar Prominence



Berger et al., 2010, Hinode/SOT, Hα

Corona
temperature $\sim 10^6$K
density $10^8 \sim 10^9$ cm^{-3}

Prominence
Cool dense plasma cloud
temperature $< 10^4$K
density $10^9 \sim 10^{11}$ cm^{-3}

- The formation model has not been established.
- Associated with studies of MHD waves, eruptions etc.

Outline of this talk

1. Prominence Formation by Radiative Condensation
   - Kaneko & Yokoyama (2015) demonstrated a new prominence formation model by MHD simulation.
   - Reconnection-Condensation model

2. Cross-field superslow propagation inside prominence
   - The superslow waves inside prominence have been reproduced in our simulations.
   - We revealed that the superslow waves are apparent propagation due to phase mixing of Alfven/slow mode wave, not fast mode wave.

Prominence Formation

Kaneko & Yokoyama, 2015, ApJ, 806, 115
Kaneko, 2017, PhD thesis, UTokyo

Previous studies: Evaporation–condensation model

Mok 1990; Antiochos & Klimchuk, 1991; Müler et al., 2003, 2004, 2005; Karpen et al., 2001, 2003, 2005, 2006; Karpen & Antiochos, 2008; Luna et al., 2012; Xia, Chen, Keppens et al. 2011, 2012; Xia & Keppens, 2016

Localized heating at footpoints

↓

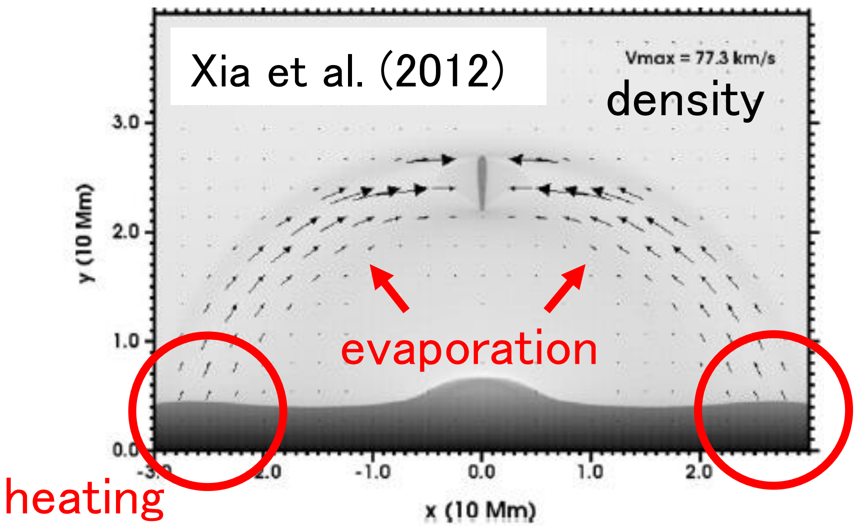
Chromospheric evaporation

↓

Enhancement of radiative cooling by increase in density

↓

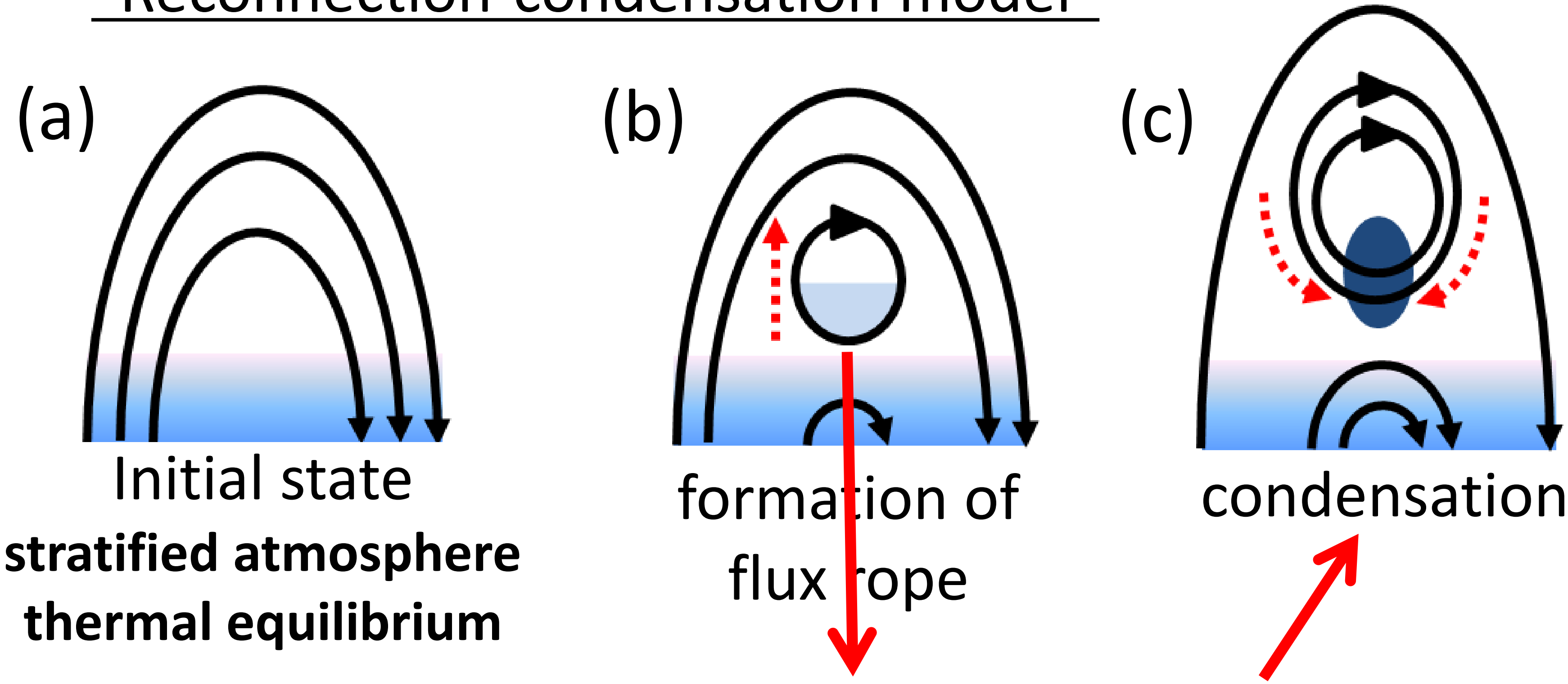
Condensation



Observational and theoretical justification for the footpoint long-term heating is necessary.

Our proposed model

<u>“Reconnection-condensation model”</u>



•**relatively dense plasmas at the bottom (strong cooling)**
•**closed field line (reduction of conduction effect)**

Numerical setting 1/4

Basic equations:

$$\frac{\partial \rho}{\partial t} + \boldsymbol{v} \cdot \nabla \rho = -\rho \nabla \cdot \boldsymbol{v},$$

$$\frac{\partial e}{\partial t} + \boldsymbol{v} \cdot \nabla e = -(e+p) \nabla \cdot \boldsymbol{v} + \nabla \cdot \left(\kappa T^{\frac{5}{2}} \boldsymbol{b}\boldsymbol{b} \cdot \nabla T\right) - n^2 \Lambda(T) + H + \eta J^2,$$

radiative cooling

thermal conduction

heating

$$e = \frac{p}{\gamma - 1}, \qquad T = \frac{m}{k_B} \frac{p}{\rho},$$

$$\frac{\partial \boldsymbol{v}}{\partial t} + \boldsymbol{v} \cdot \nabla \boldsymbol{v} = -\frac{1}{\rho} \nabla p + \frac{1}{4\pi\rho} (\nabla \times \boldsymbol{B}) \times \boldsymbol{B} + \mathbf{g},$$

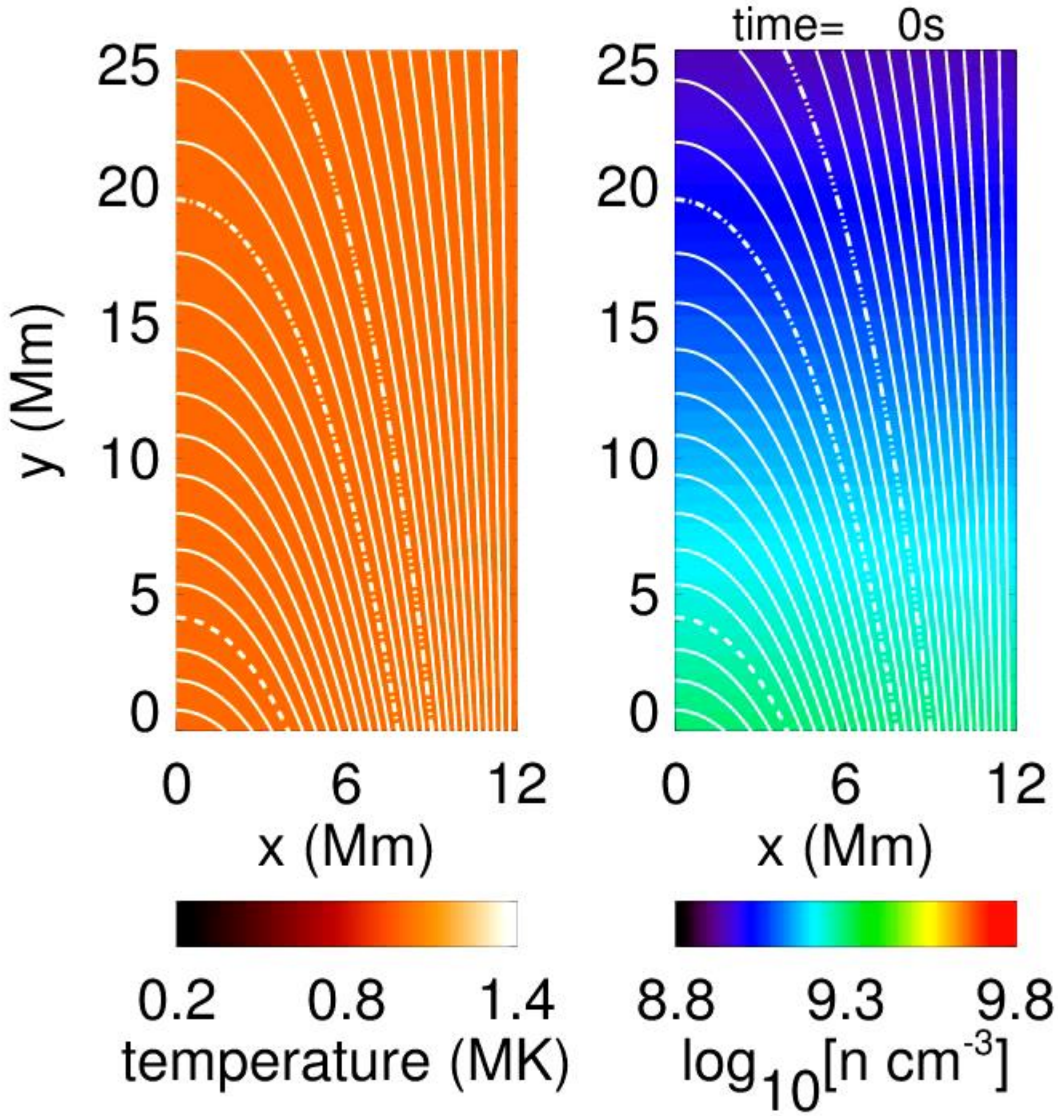
$$\frac{\partial \boldsymbol{B}}{\partial t} = -c \nabla \times \boldsymbol{E},$$

$$\boldsymbol{E} = -\frac{1}{c} \boldsymbol{v} \times \boldsymbol{B} + \frac{4\pi\eta}{c^2} \boldsymbol{J}, \qquad \boldsymbol{J} = \frac{c}{4\pi} \nabla \times \boldsymbol{B}.$$

$$\eta = 0, \quad (J < J_c)$$

$$\eta = \eta_0 (J/J_c - 1)^2, \quad (J \geqslant J_c)$$

Result



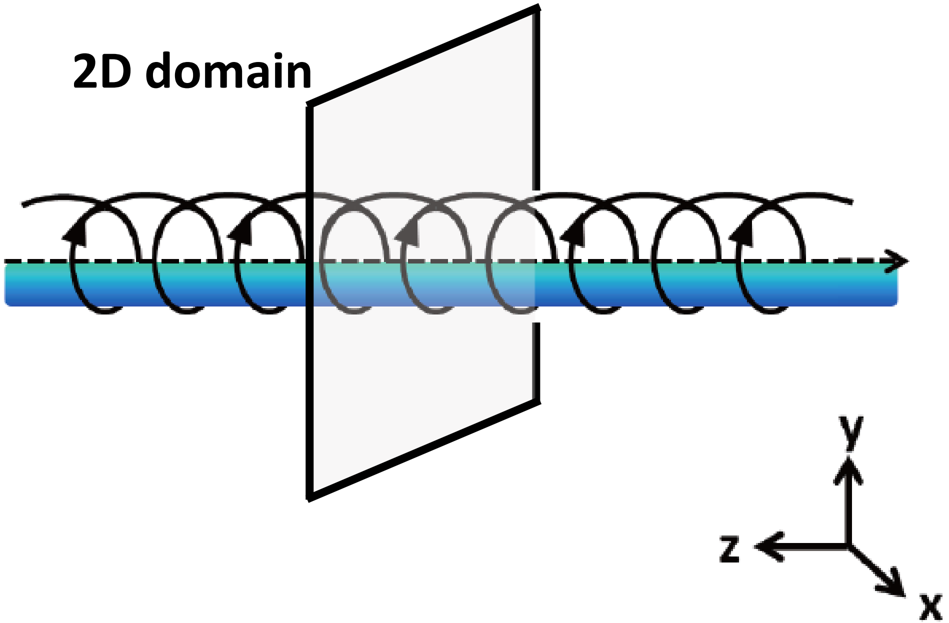
flux rope formation

thermal imbalance
in thermally isolated
closed loops

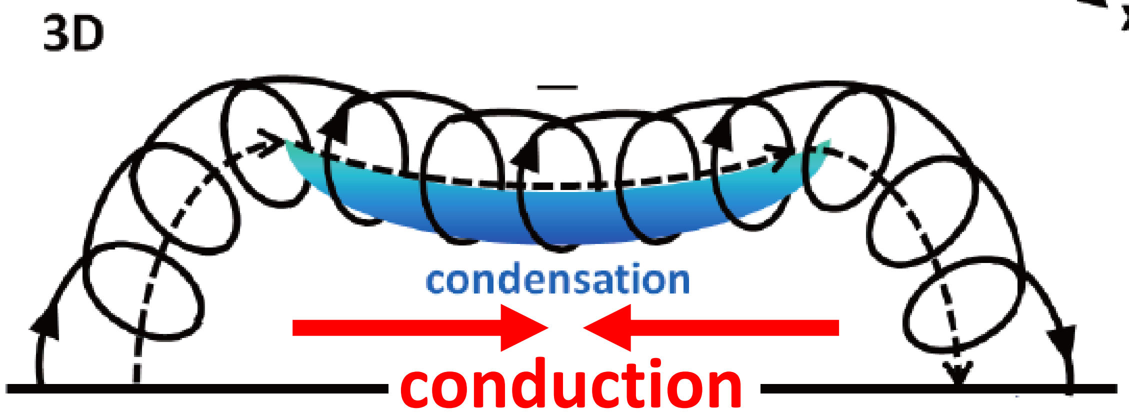
radiative condensation

Feasibility of the model in 3D

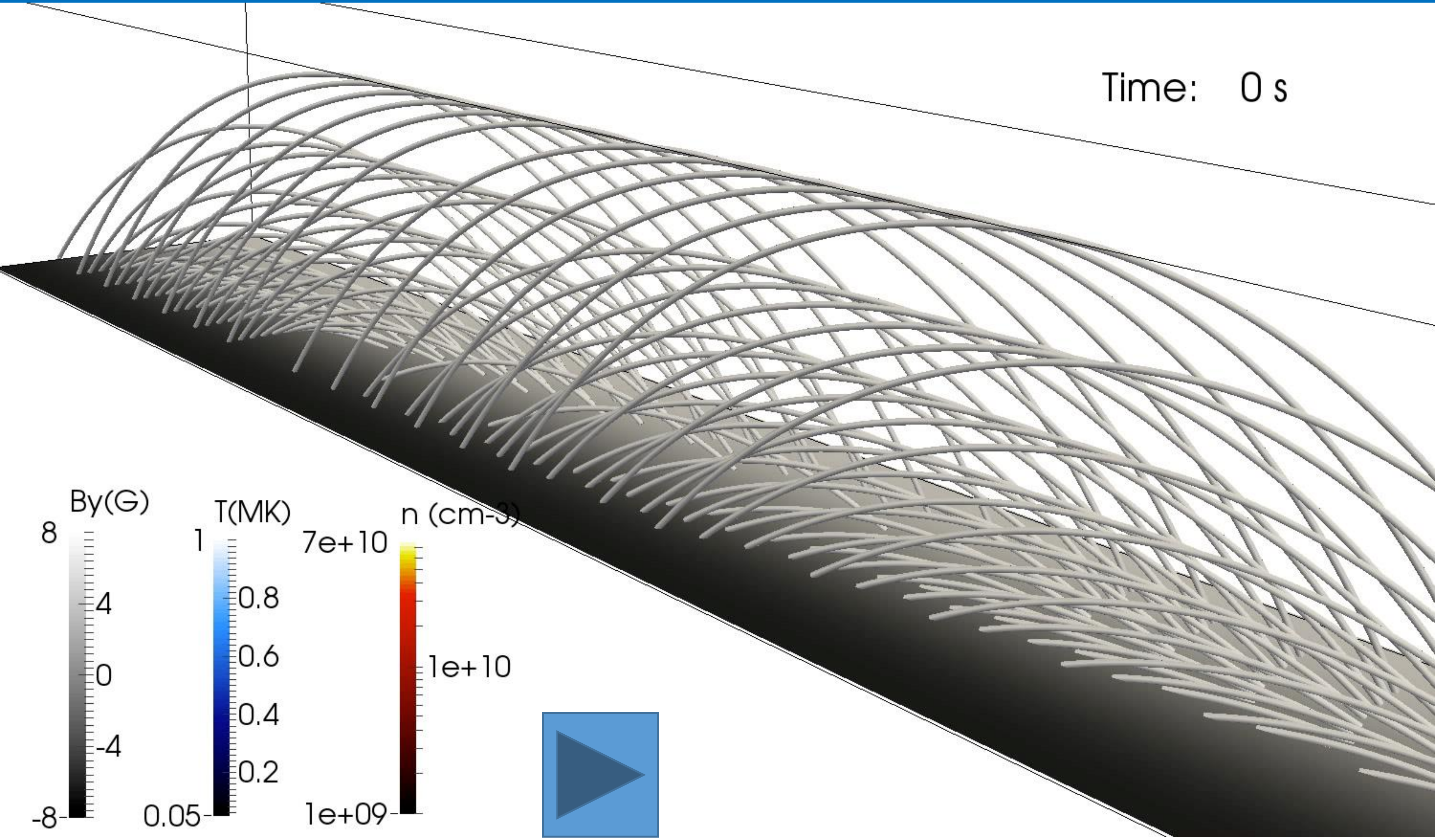
2.5D
->Temperature is uniform perpendicular to 2D plane
=>Conduction along toroidal components is ineffective.



3D
→Conduction along toroidal magnetic field may suppress thermal instability.



Result: side view ($n_{\rm init} = 8 \times 10^8\ {\rm cm}^{-3}$)



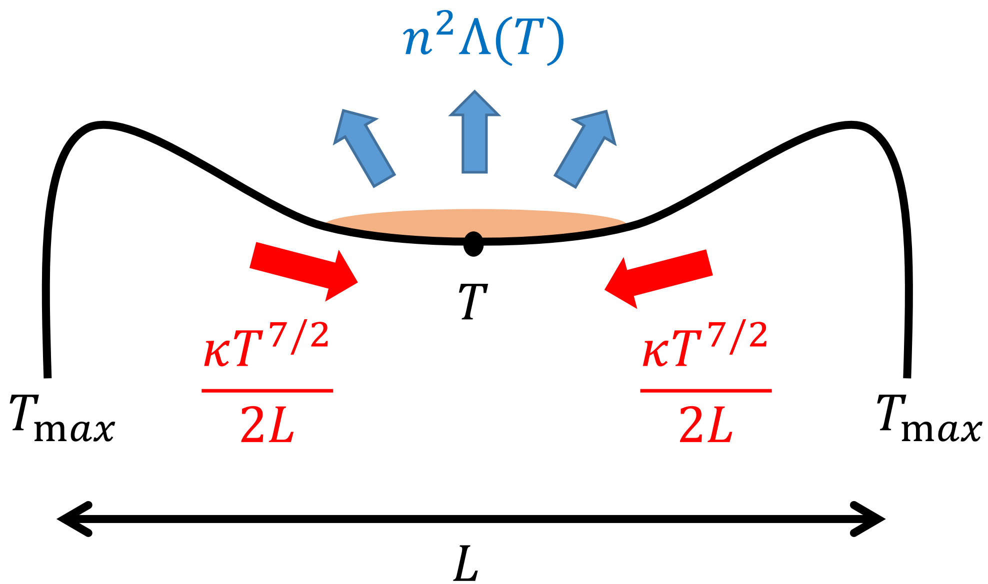
Threshold for radiative condensation

conduction ≪ radiation

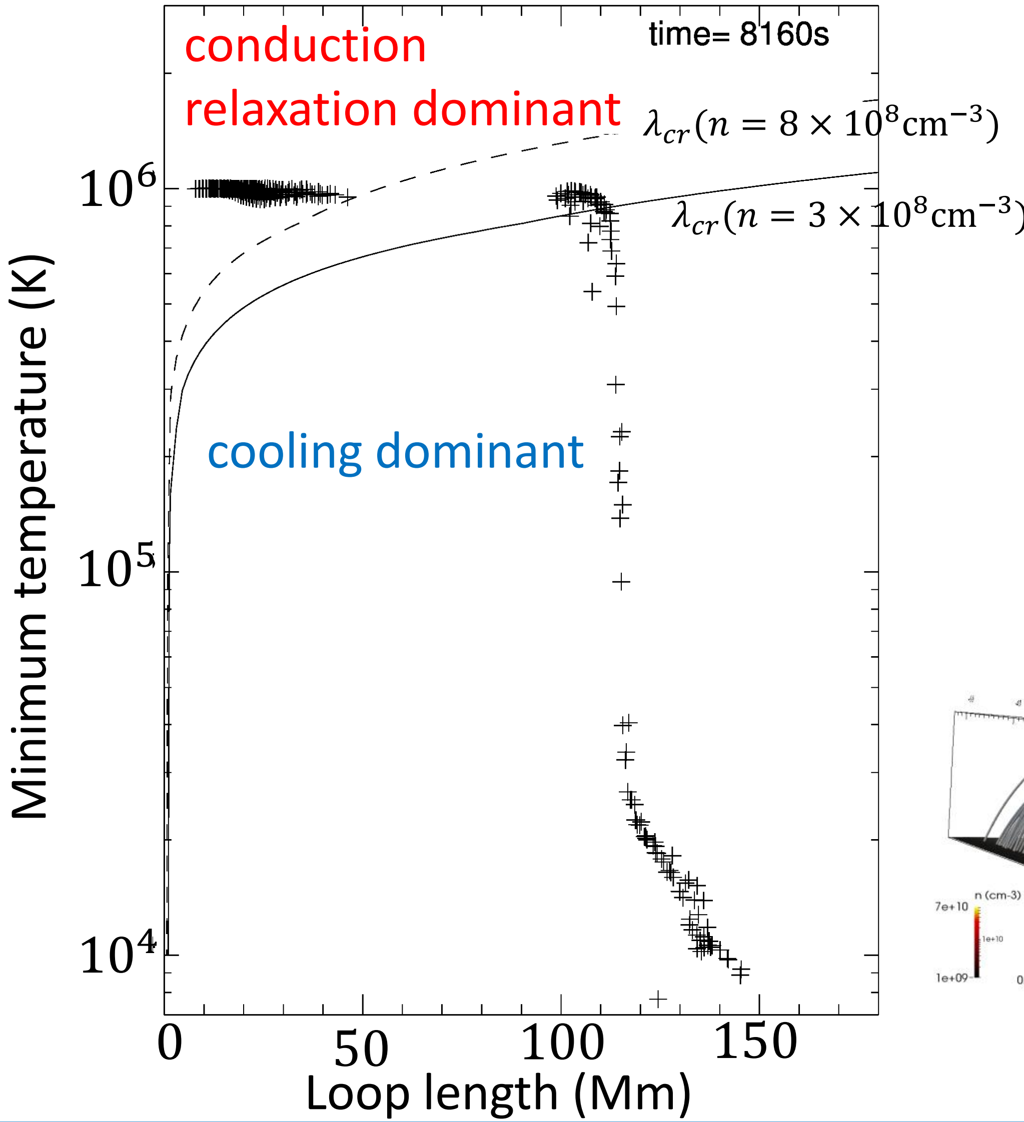
$$\frac{\kappa T^{7/2}}{L^2} \ll n^2 \Lambda(T)$$

Radiative condensation

Field length: $\lambda_{cr} \approx \sqrt{\frac{\kappa T^{7/2}}{n^2 \Lambda(T)}}$



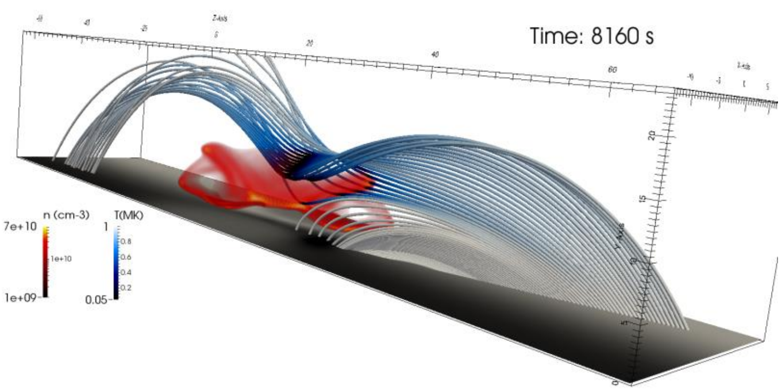
Loop length & temperature ($n_{\text{init}} = 8 \times 10^8\ \text{cm}^{-3}$)



conduction ≪ radiation

$$\frac{\kappa T^{7/2}}{L^2} \ll n^2 \Lambda(T)$$

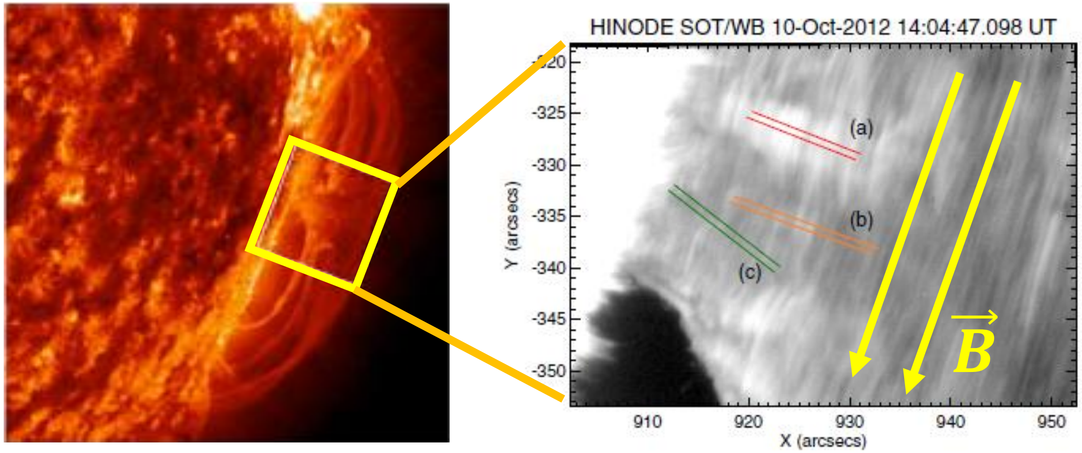
Field length: $\lambda_F \approx \sqrt{\dfrac{\kappa T^{7/2}}{n^2 \Lambda(T)}}$



Cross-field Superslow Waves in Prominence

Kaneko, Goossens, Soler, Terradas, Van Doorsselaere, Yokoyama, Wright, 2015, ApJ, in press (arXiv:1509.03042)

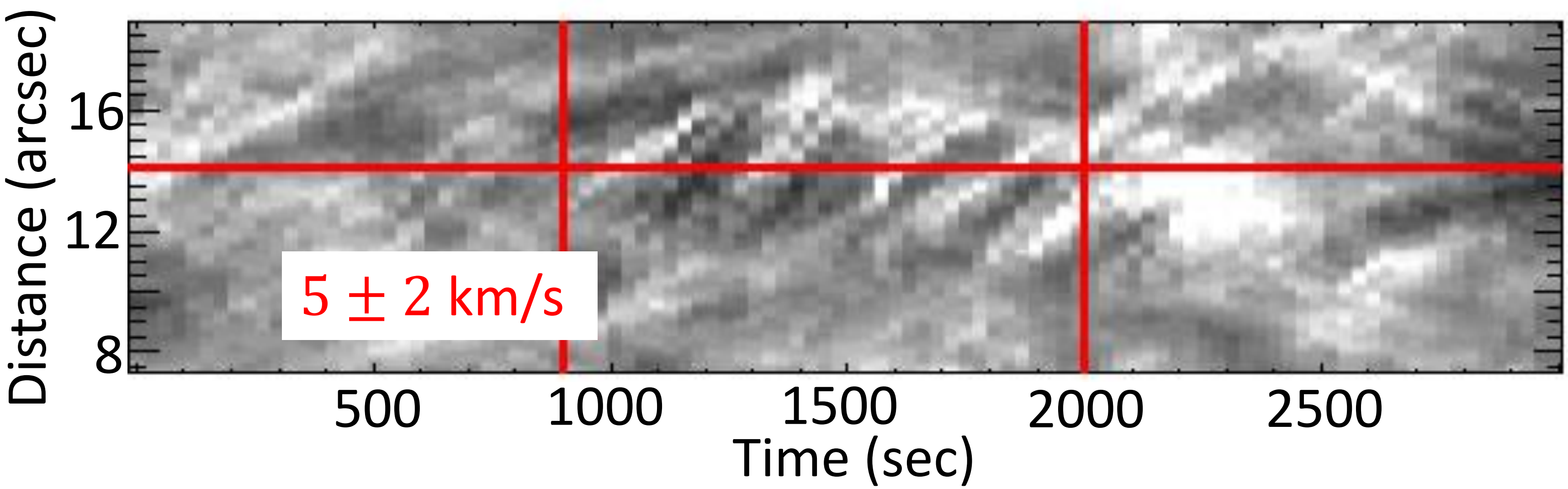
Superslow MHD Waves in Prominence: Observation
(Schmieder et al., 2013)



SDO/AIA 304Å

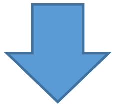
Hinode/SOT Ca II H line

Fast-mode speed is generally 100-1000 km/s in the corona.



Cross-field Superslow Waves: Simulation

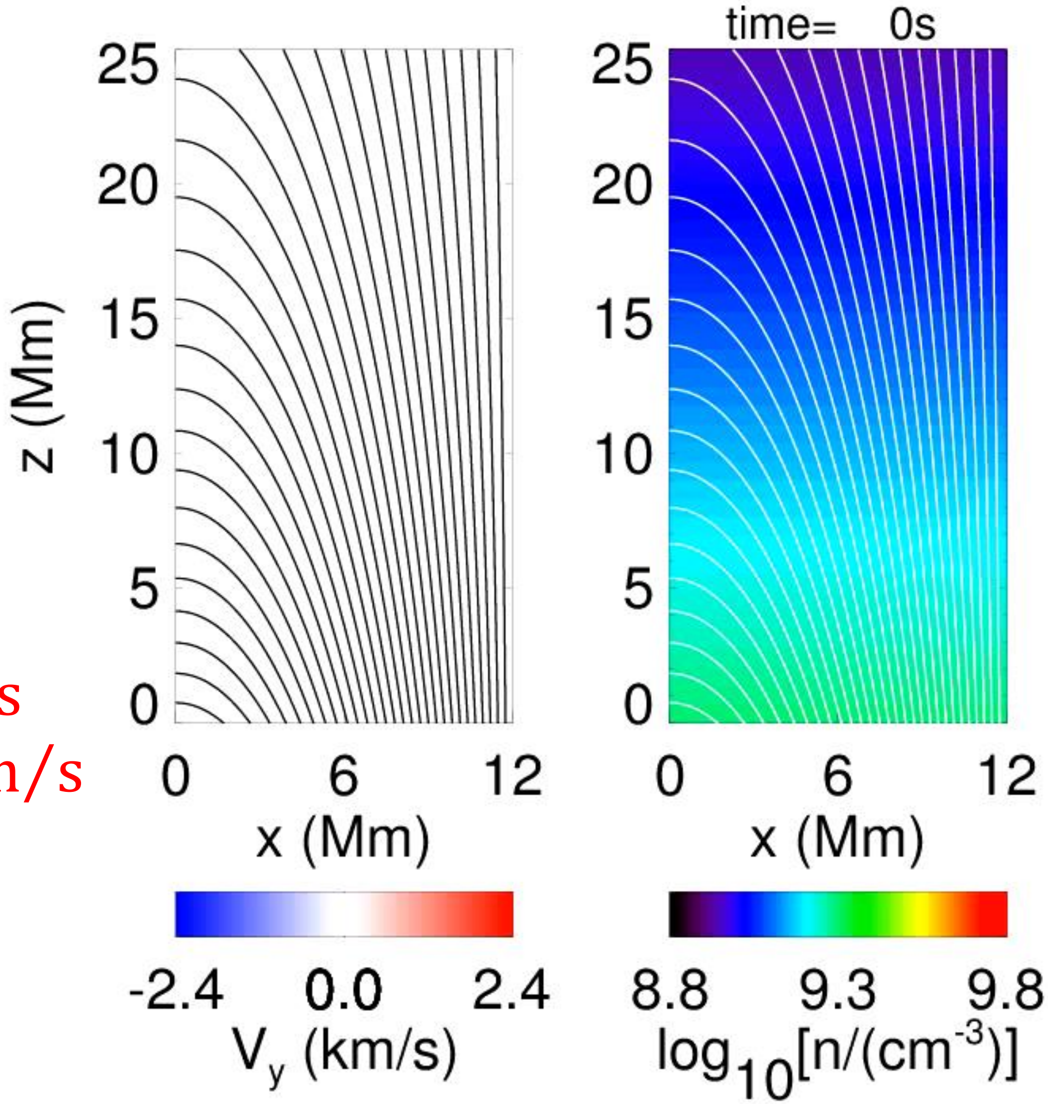
Radiative condensation



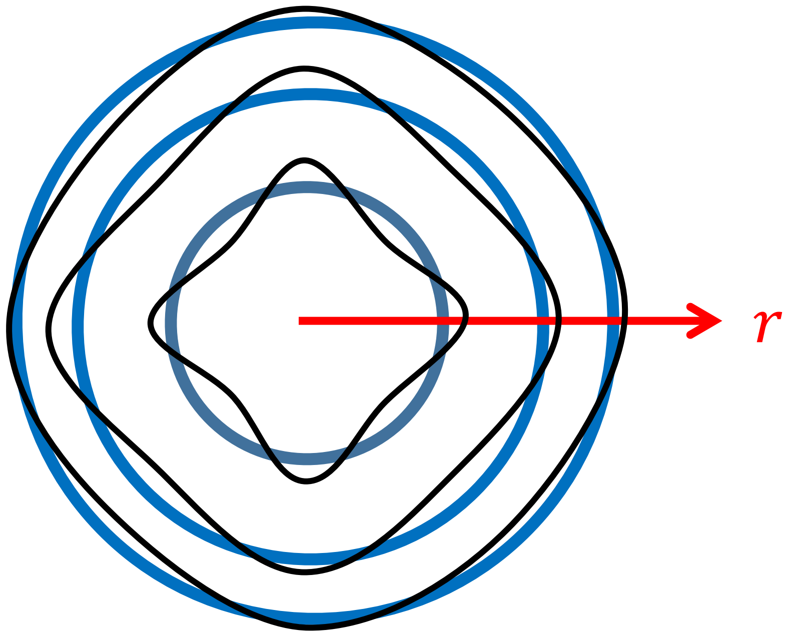
Excitation of waves

- Cross-field propagation

- Propagation speed$\sim$3 km/s
  $\ll$ fast-mode speed$\sim$160 km/s



Mechanism of Apparent Propagation 1/2



Each magnetic loop oscillates independently.

Alfven/slow standing wave on each magnetic loop with individual frequency

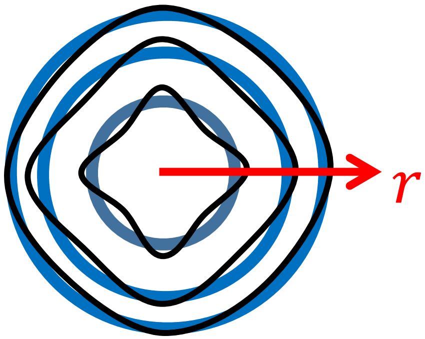
e.g.
Alfven velocity: $v_A = \text{const.}$
Alfven frequency: σ_A

$$\sigma_A = n \frac{v_A}{2\pi r}$$

$$\sigma(r - \Delta r) > \sigma(r) > \sigma(r + \Delta r)$$

n (=1,2,3, ...) : harmonic number

Mechanism of Apparent Propagation 2/2

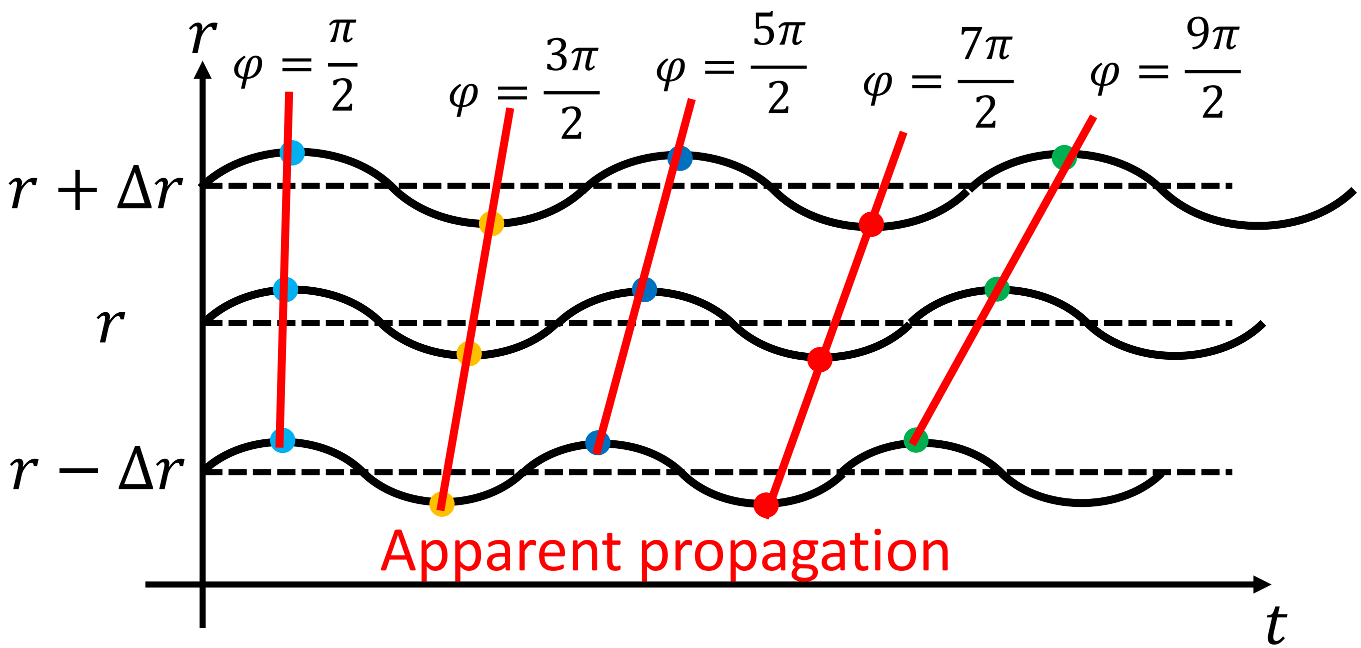


Each magnetic loop oscillates independently.

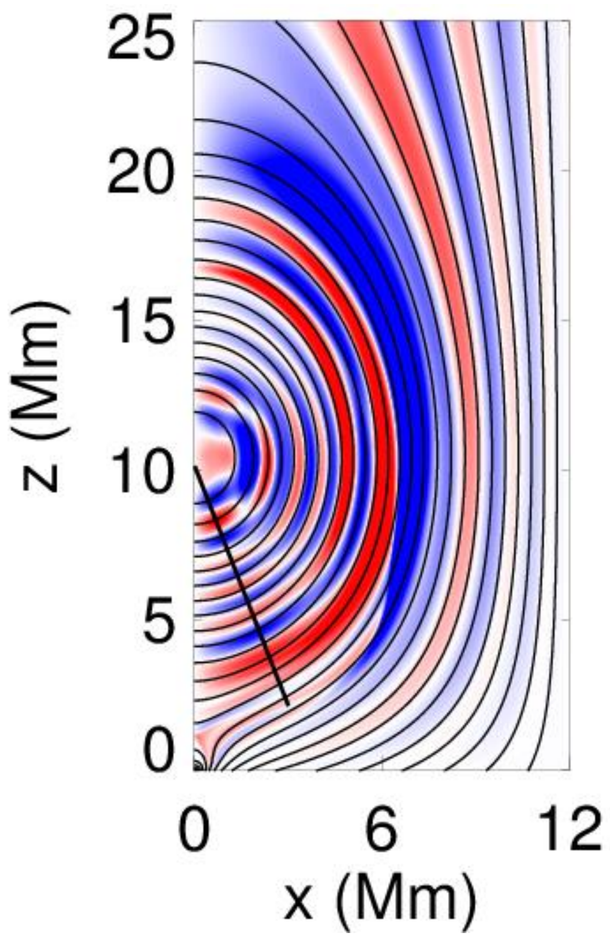
e.g. $\sigma(r-\Delta r) > \sigma(r) > \sigma(r+\Delta r)$

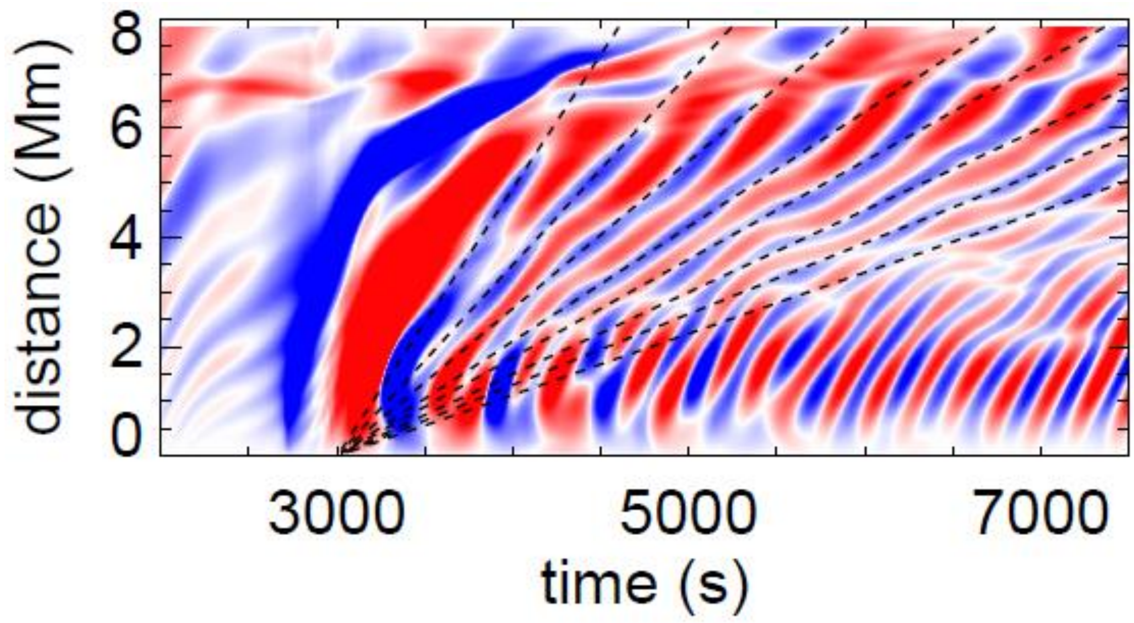
Phase lag is generated among magnetic surfaces.

⇨ phase mixing



Application to Simulation Result 4/5

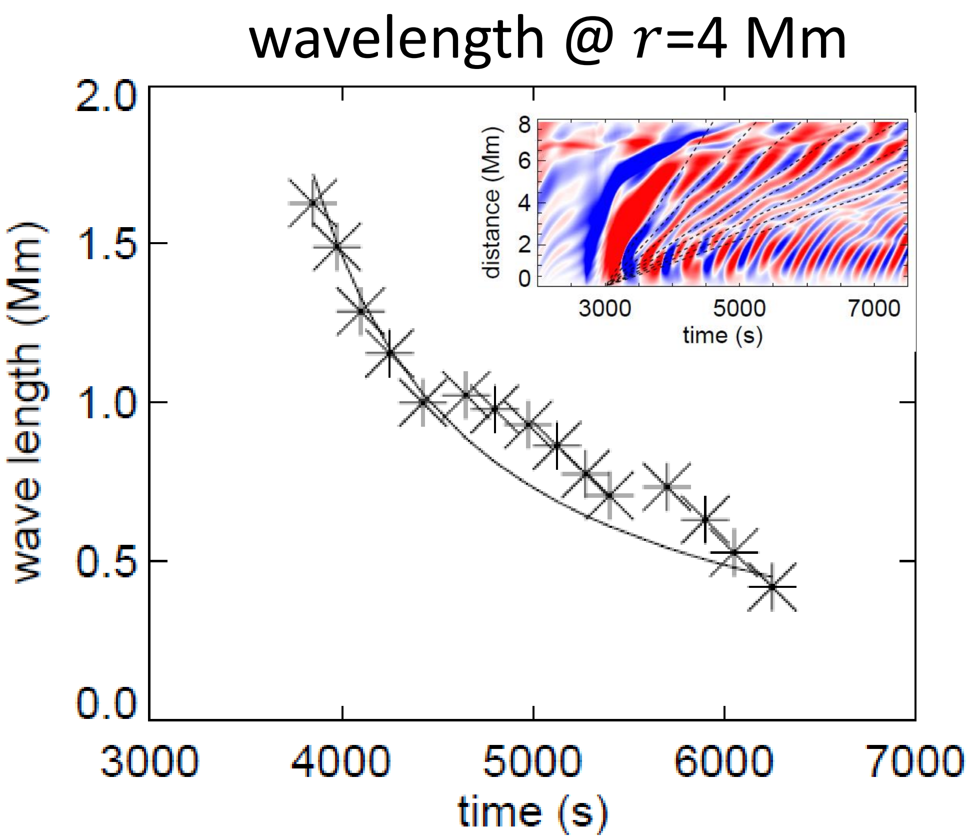




dashed lines: $\frac{r}{t - t_i} = v_{ap}$,

$v_{ap} = 1 - 5$ km/s $\quad t_i = 3000$ s

Application to Simulation Result 5/5



Dots:
wave length in r-direction

Solid line:
apparent wavelength computed by

$$\lambda_{ap}(r,t) = \frac{2\pi}{k_{ap}} = \frac{1}{t - t_i}\frac{2\pi r^2}{v_A(r)}$$

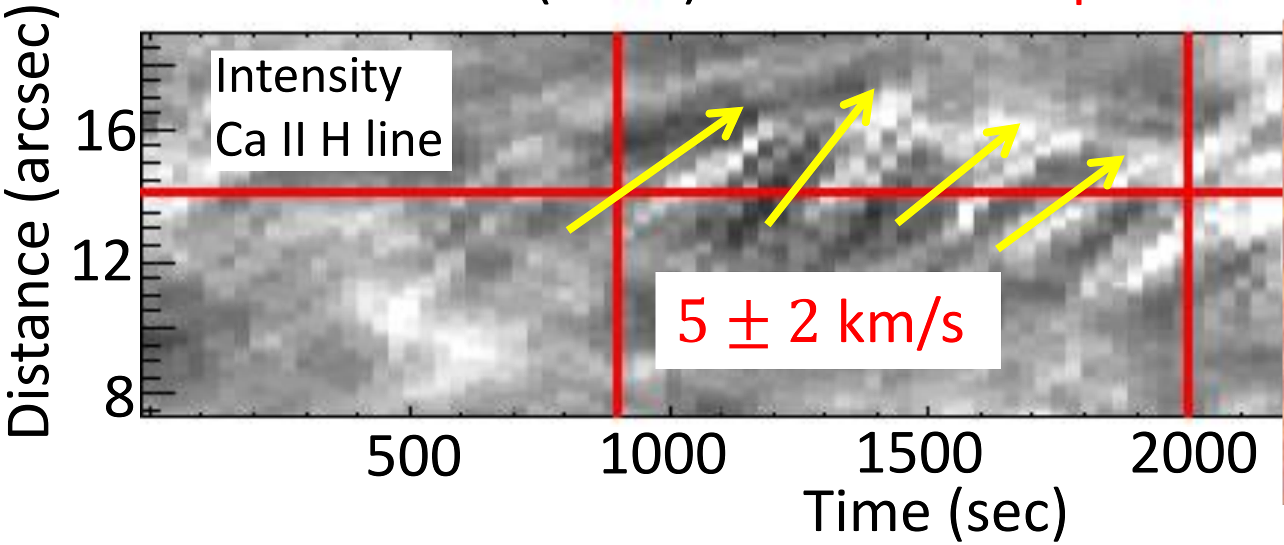
where

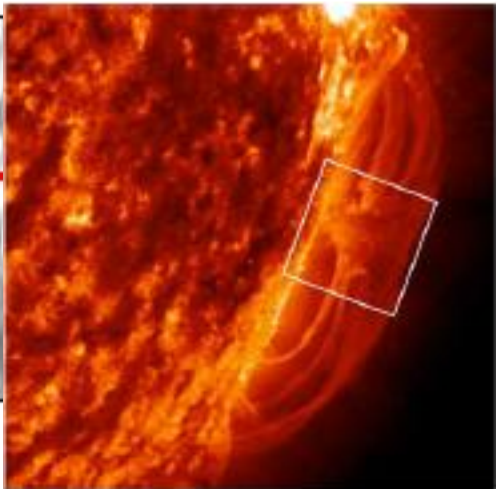
$$r = 4\ \mathrm{Mm}, \qquad t_i = 3000\ \mathrm{s},$$

$$v_A = 70\ \mathrm{km/s}$$

Applicability to Observation

Schmieder et al. (2013): cross-field superslow propagation





Fast-mode model:

$$v_f = \sqrt{C_s^2 + V_A^2} \approx 75 \sim 750\ \mathrm{km/s}$$

$C_s = 10\ \mathrm{km/s}\ \ (T = 8000\mathrm{K})$

$V_A = 70{\sim}750\ \mathrm{km/s}$

$(B = 7.5\ \mathrm{G}, n_e = 10^{9-11}\ \mathrm{cm}^{-3})$

Apparent propagation model:

$$v_{ap} = \frac{\sigma}{t\dfrac{d\sigma}{dr}} \approx \frac{r}{t} = 3 \sim 6\ \mathrm{km/s}$$

$r = 4\ \mathrm{arcsec},\ \ t = 500{\sim}1000\ \mathrm{s}$

Agrees with the observation.

Conclusion

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