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FMSP

Three-dimensional MHD Simulation of Prominence Formation by Radiative Condensation

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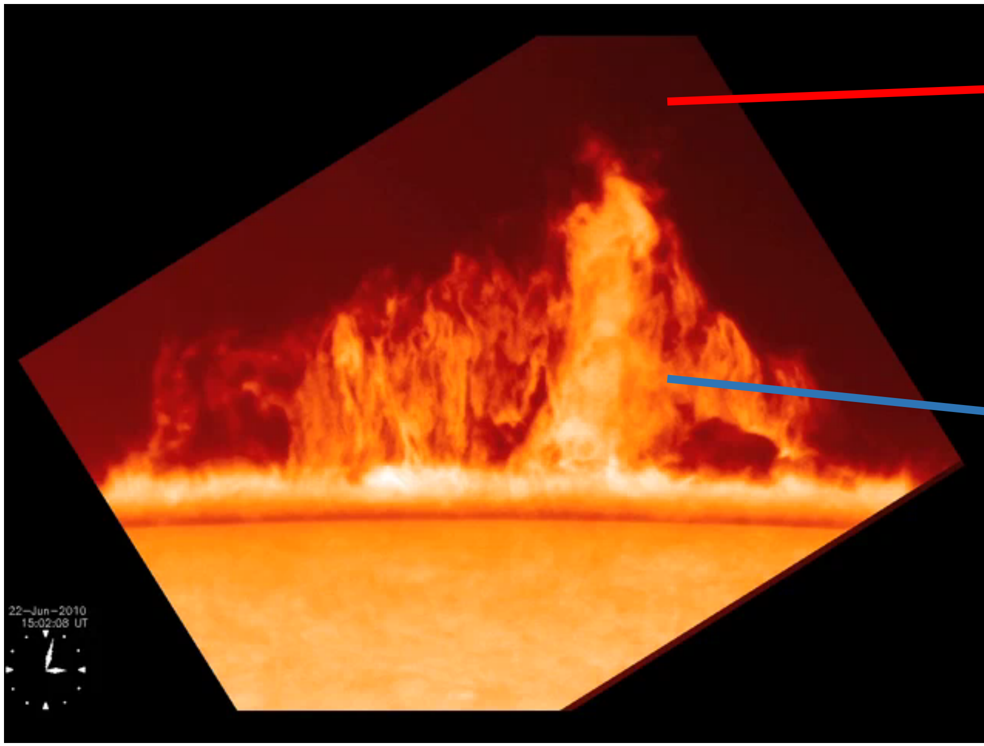
Solar Prominence



Berger et al., 2011, 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}

Mechanism of Prominence Formation

What is the origin of cool dense plasmas ?

<u>Radiative condensation/Thermal nonequilibrium (instability):</u>
Coronal plasmas are cooled down and condensed by radiative cooling. (Karpen et al., 2007; Luna et al., 2012; Xia et al.,2012; Kaneko & Yokoyama,2015; Xia & Keppens, 2016)

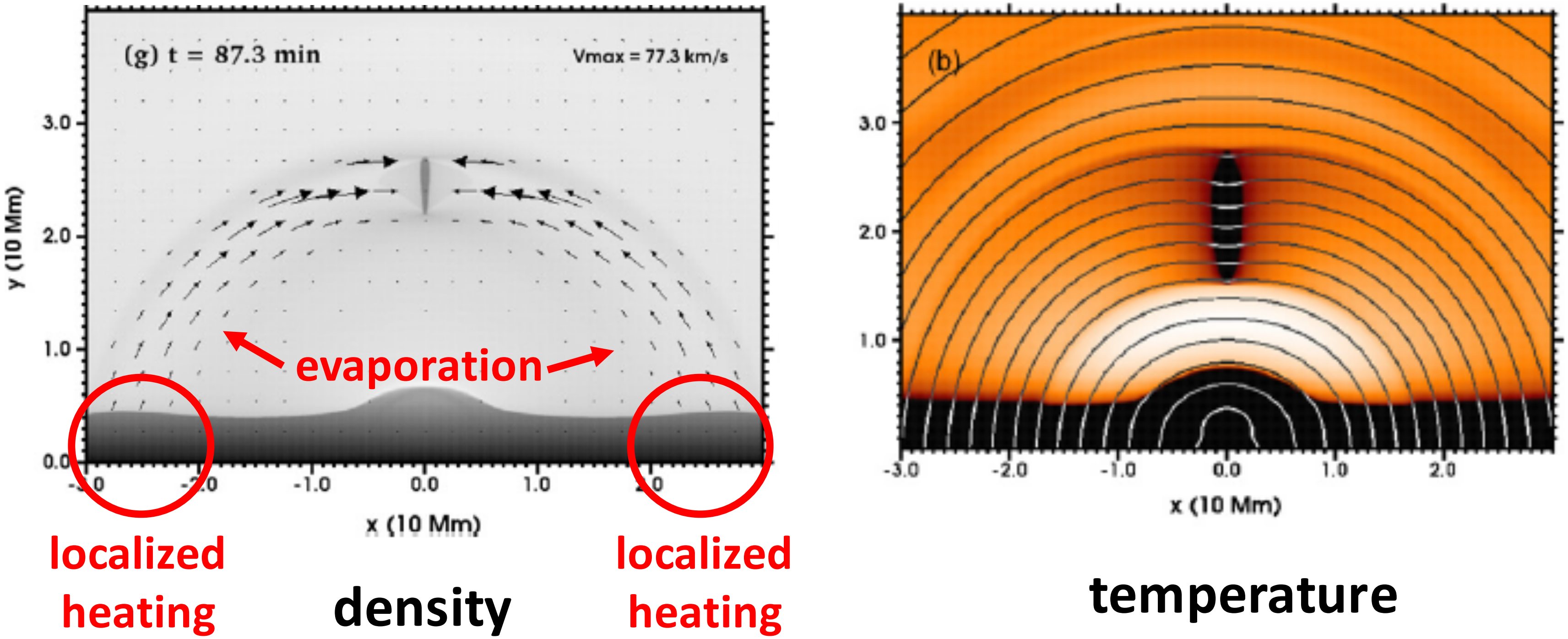
<u>Injection, Levitaion:</u>
Chromospheric plasmas are lifted up to coronal height by jet or emerging flux.
(Chae et al., 2003; Okamoto et al.,2007,2008; Deng et al.,2000)

Evaporation-condensation model

Chromospheric evaporation by Localized footpoint heating

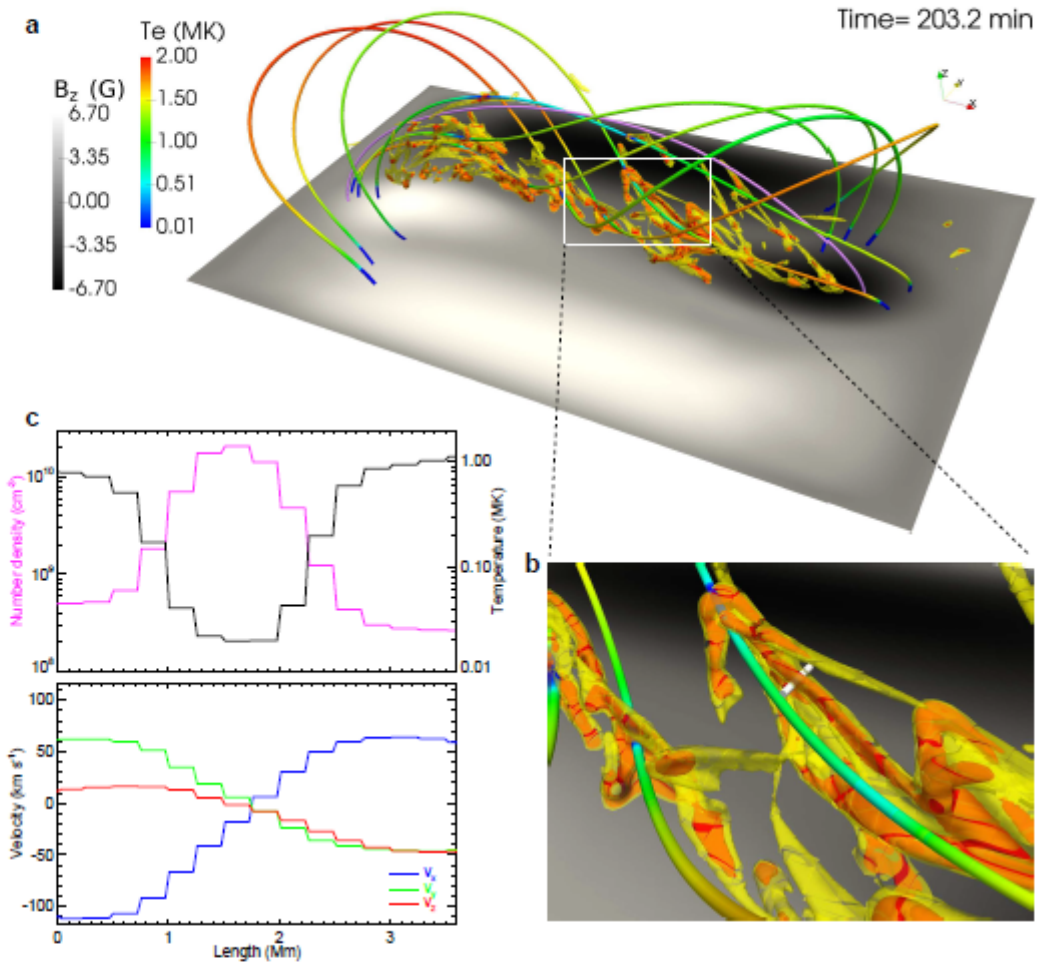
➡ Radiative condensation

Xia et al. (2012)



Evaporation-condensation model (3D)

Xia & Keppens (2016)



Chromospheric evaporation by footpoint heating

↓

Enhancement of radiative cooling inside flux rope by injection of high density plasmas

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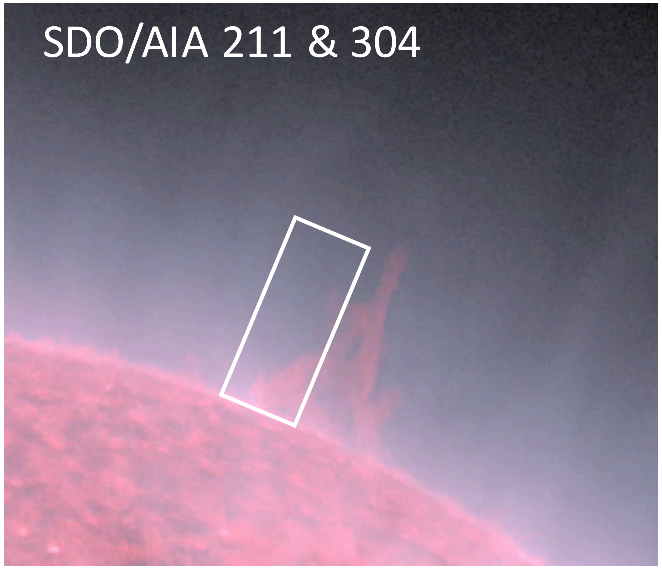
prominence formation by radiative condensation

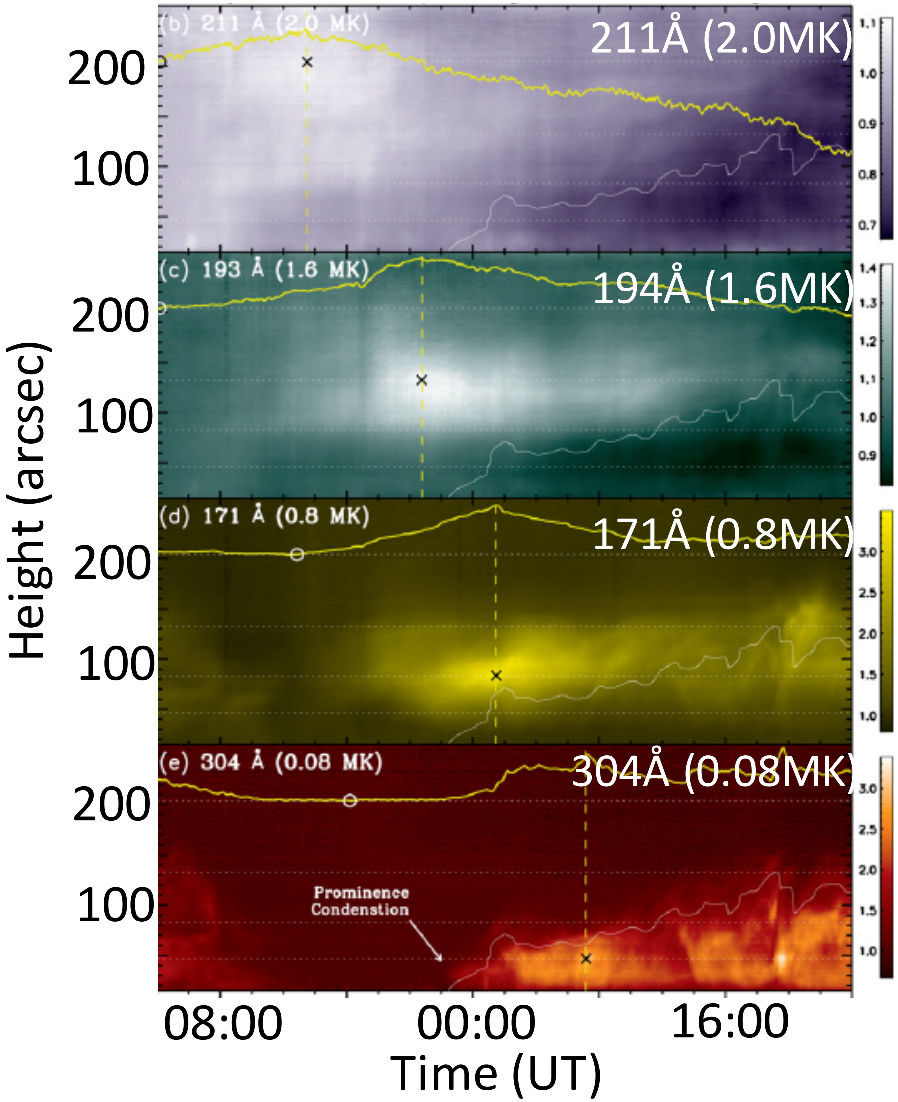
↓

drainage of prominence to chromosphere

Observation of in-situ condensation

Berger et al. (2012)





- Temporal intensity shift from high temperature to low temperature
->Radiative condensation
- Evaporated flows had not detected.
->In-situ condensation in the corona

Key steps to radiative condensation

Evaporation-condensation model

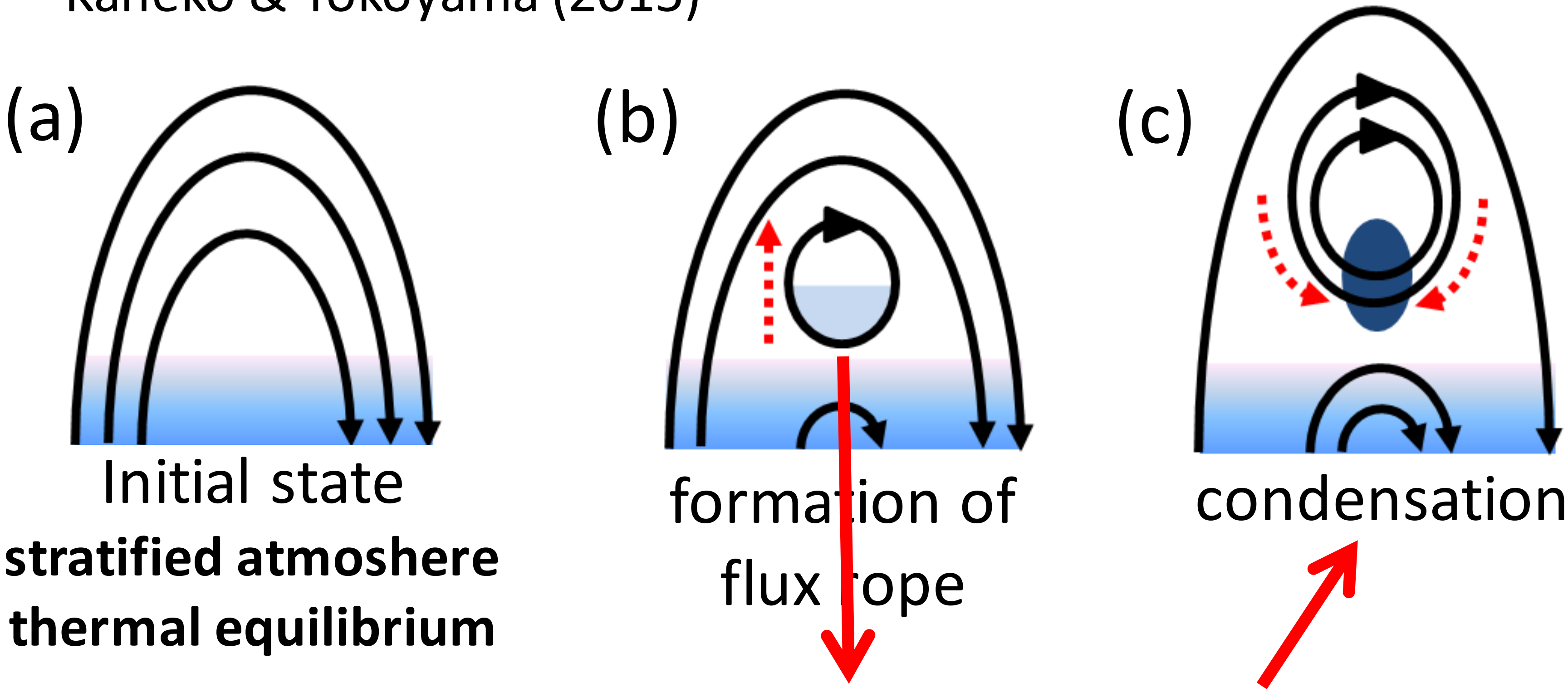
- Enhancement of radiation by deposition of high density plasmas
- Limiting thermal conduction by changing the direction of thermal flux (in long magnetic loop)

Reconnection-Condensation Model

Reconnection and subsequent topological change of magnetic field can also trigger radiative condensation.

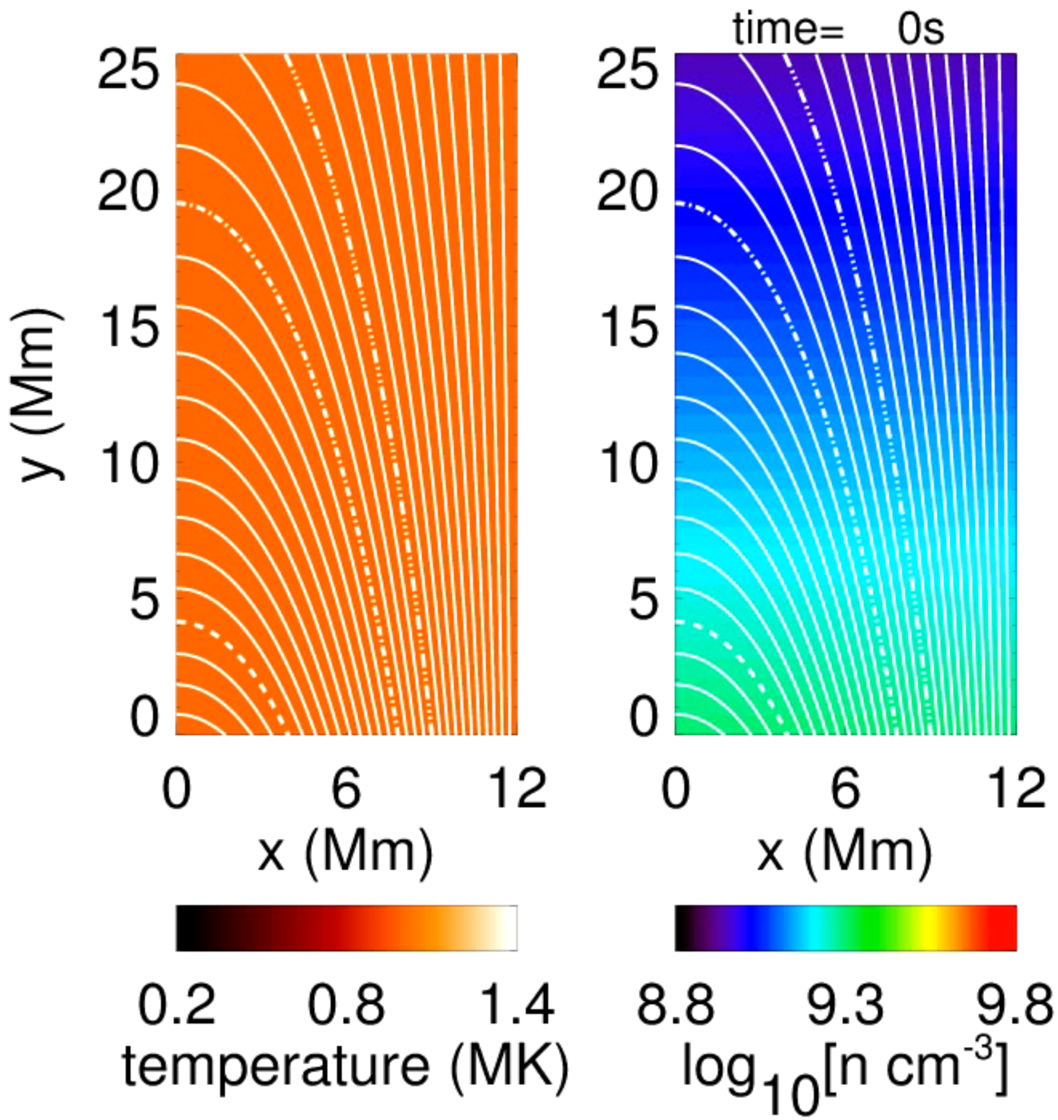
Reconnection-condensation model (2D)

Kaneko & Yokoyama (2015)



- relatively dense plasmas at the bottom (strong radiation)
- closed field line (limiting thermal conduction)

Demonstration by 2D simulation



flux rope formation

↓

thermal imbalance
in thermally isolated
closed loops

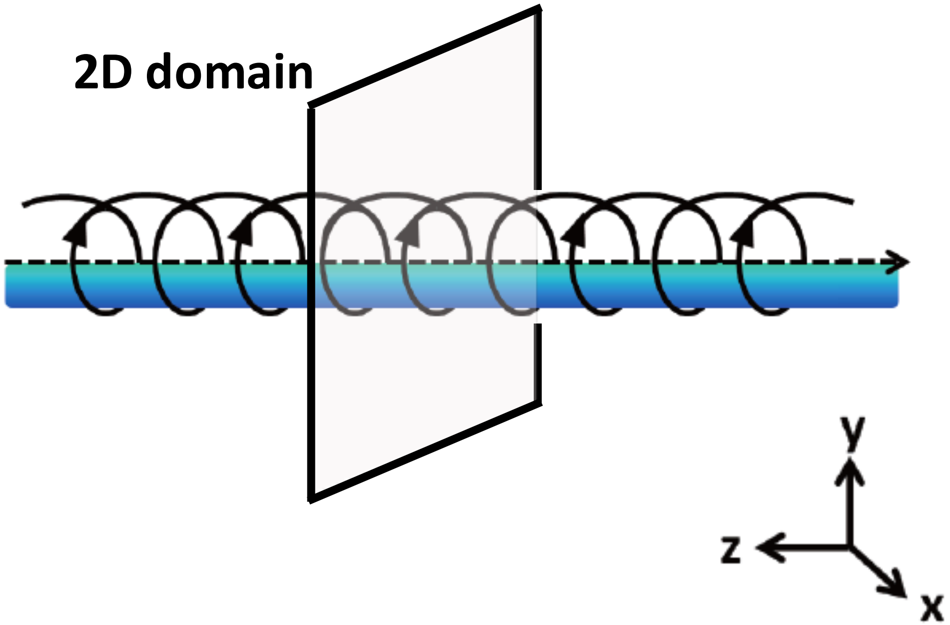
↓

radiative condensation

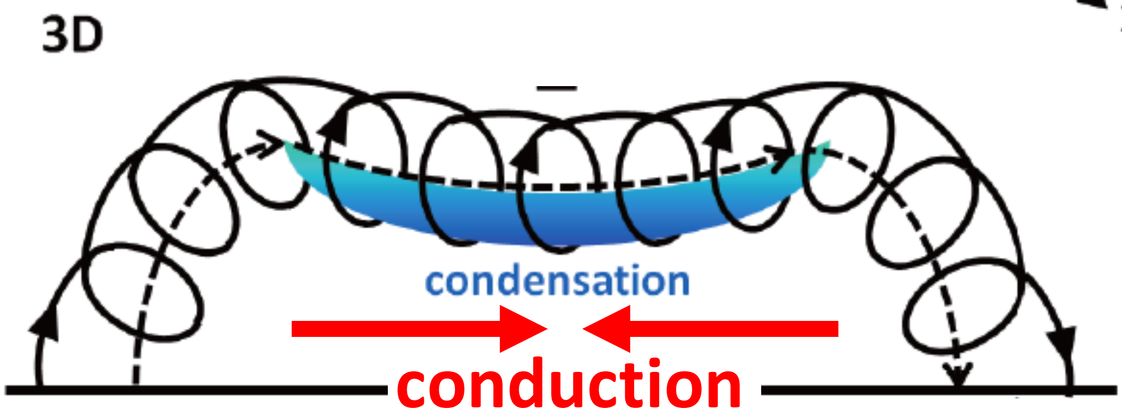
Kaneko & Yokoyama (2015)

Feasibility of the model in 3D

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

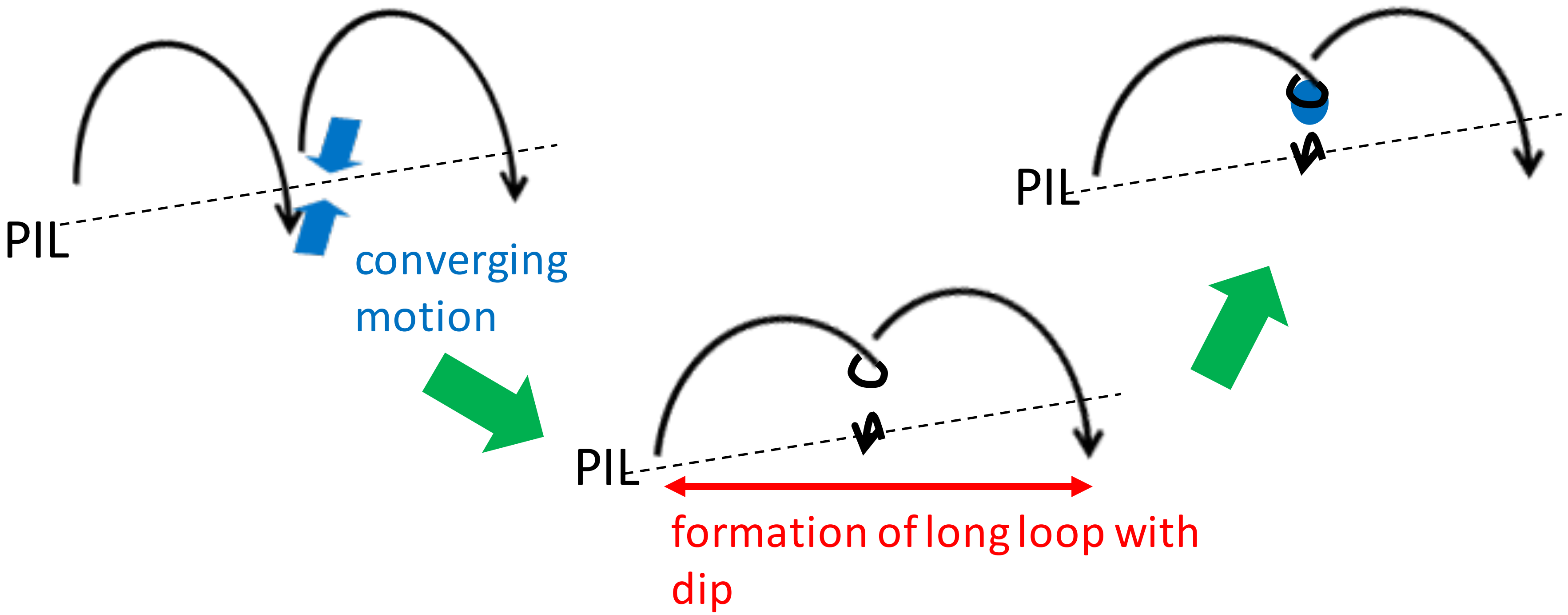


3D
→Conduction along toroidal magnetic field may suppress thermal instability.



Extension to 3D model

Aim:
Demonstration of reconnection-condensation model by 3D MHD simulation including radiative cooling & thermal conduction



Numerical setting 1/5

Basic equations:

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

radiative cooling

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

thermal conduction

heating

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

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

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

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

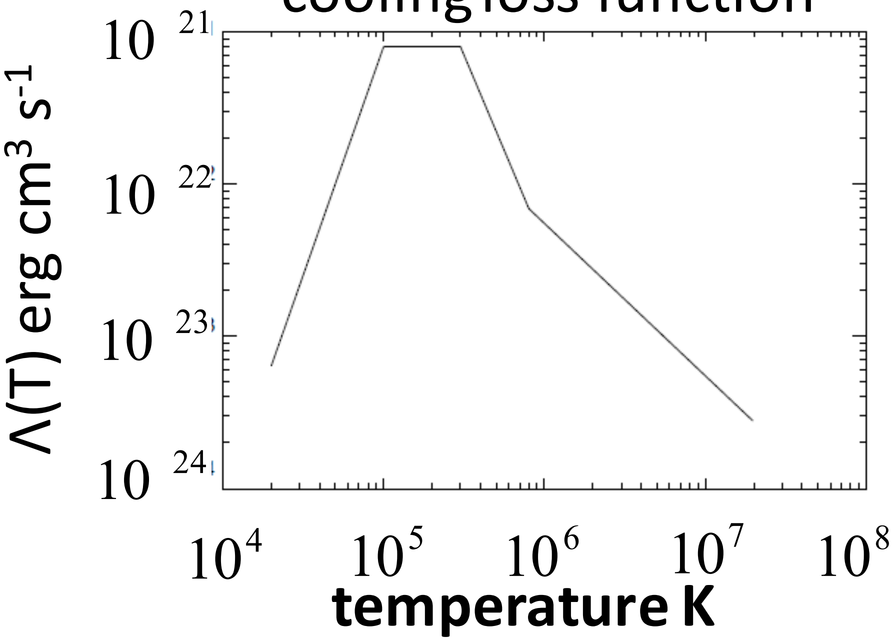
Numerical setting 2/5

Energy equation:

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

radiative cooling background heating

cooling loss function



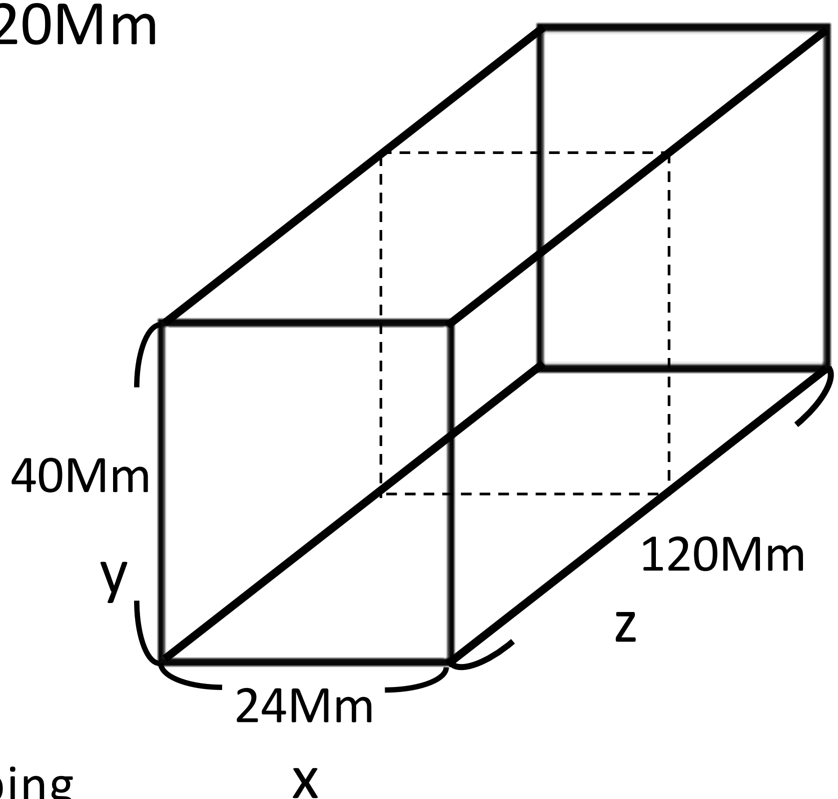
$$H \propto P_m$$

coronal heating related to magnetic energy density (e.g. Parker, 1983)

Numerical setting 3/5

Simulation box: 24Mm x 40Mm x 120Mm
(point-symmetry at z=60Mm)

Grid size: 120km (uniform)



Scheme

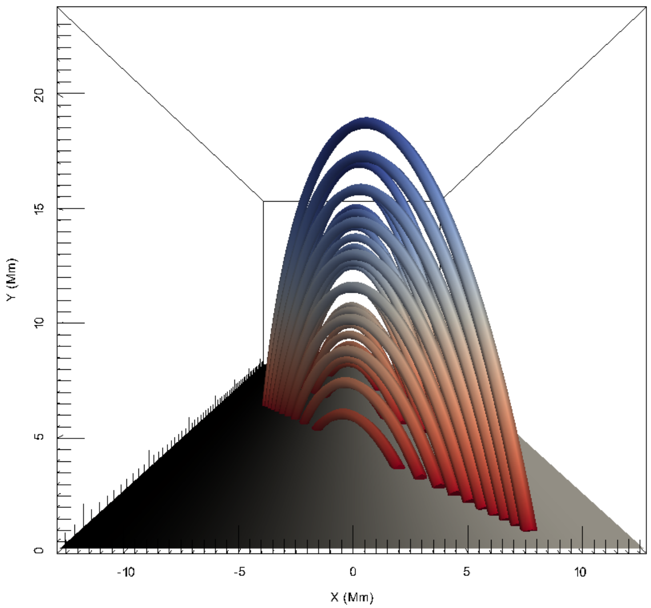
- 4th order Runge-Kutta
- 4th order central difference
- Artificial viscosity (Rempel, 2012)
- Hyperbolic divergence cleaning (Dedner, 2002)
- Thermal conduction: Super Time Stepping (RKL 2nd order, Meyer et al.2012,2014)

Numerical setting 4/5

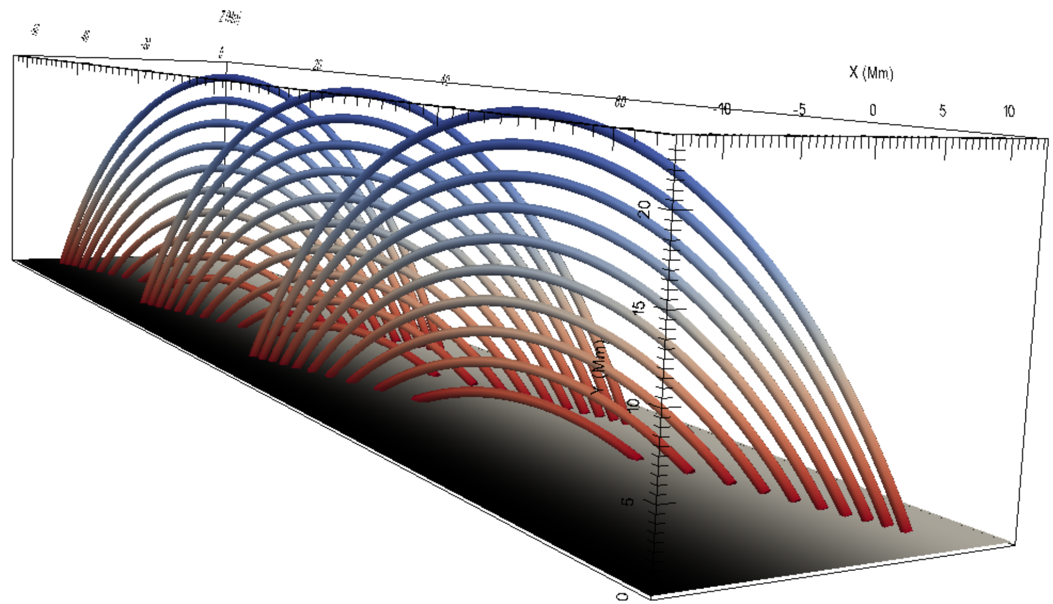
Initial condition

- magnetic field: linear force-free arcade field (< 6 G)
- stratified under uniform temperature & gravity
  ($T = 1$MK, $n < 2{\times}10^{9}$ cm^{-3})

front view



side view



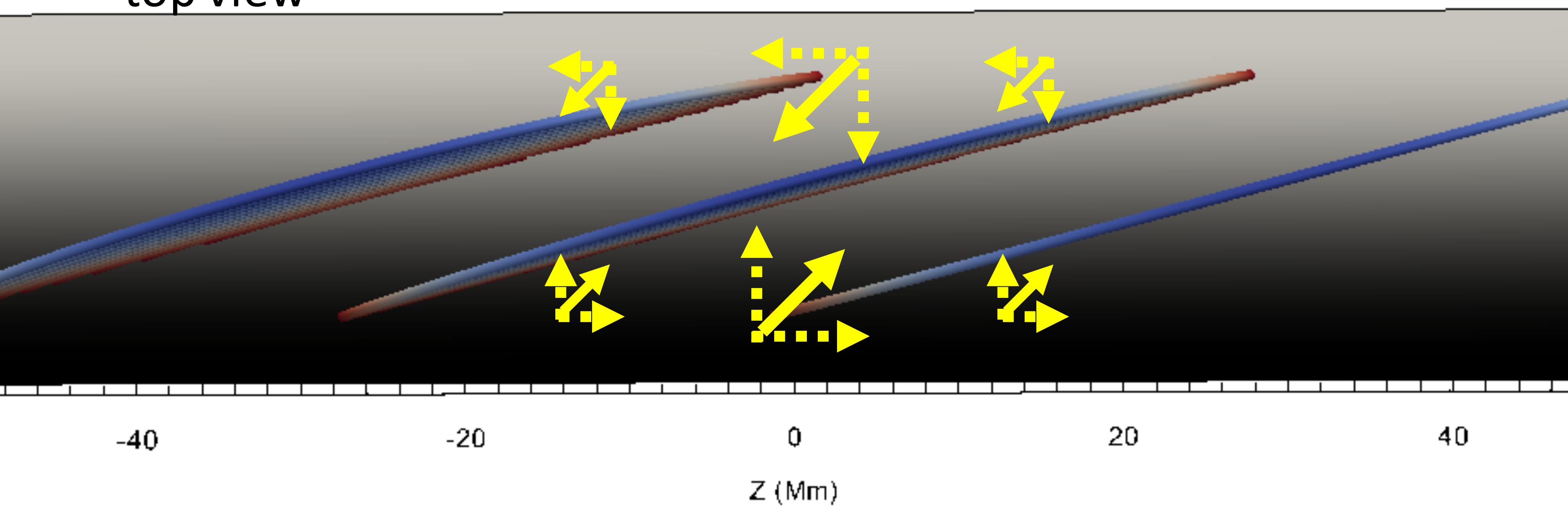
Numerical setting 5/5

Footpoint motion

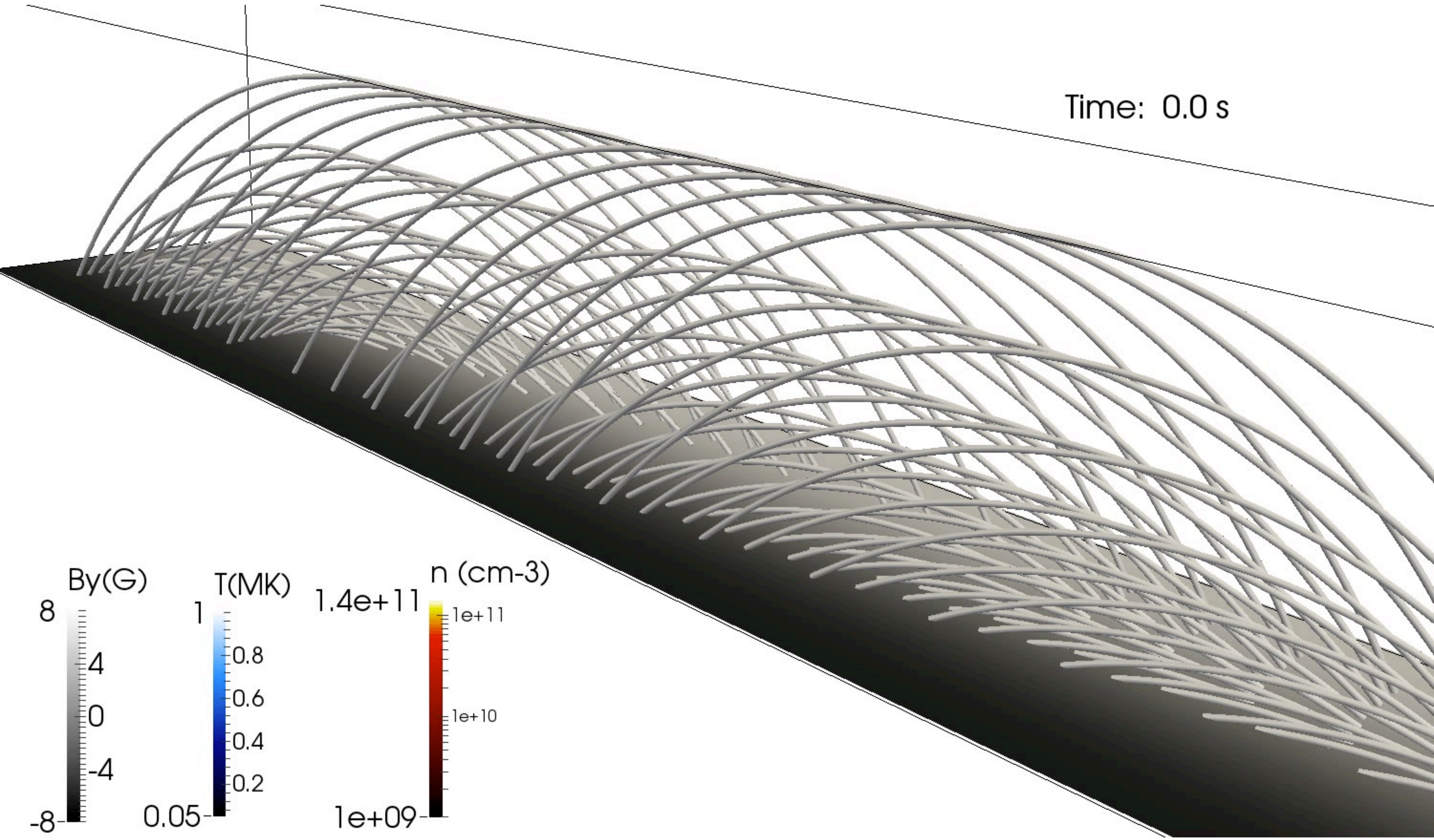
converging & anti-shearing motion

the direction in which magnetic shear is reduced
(toroidal component is reduced)

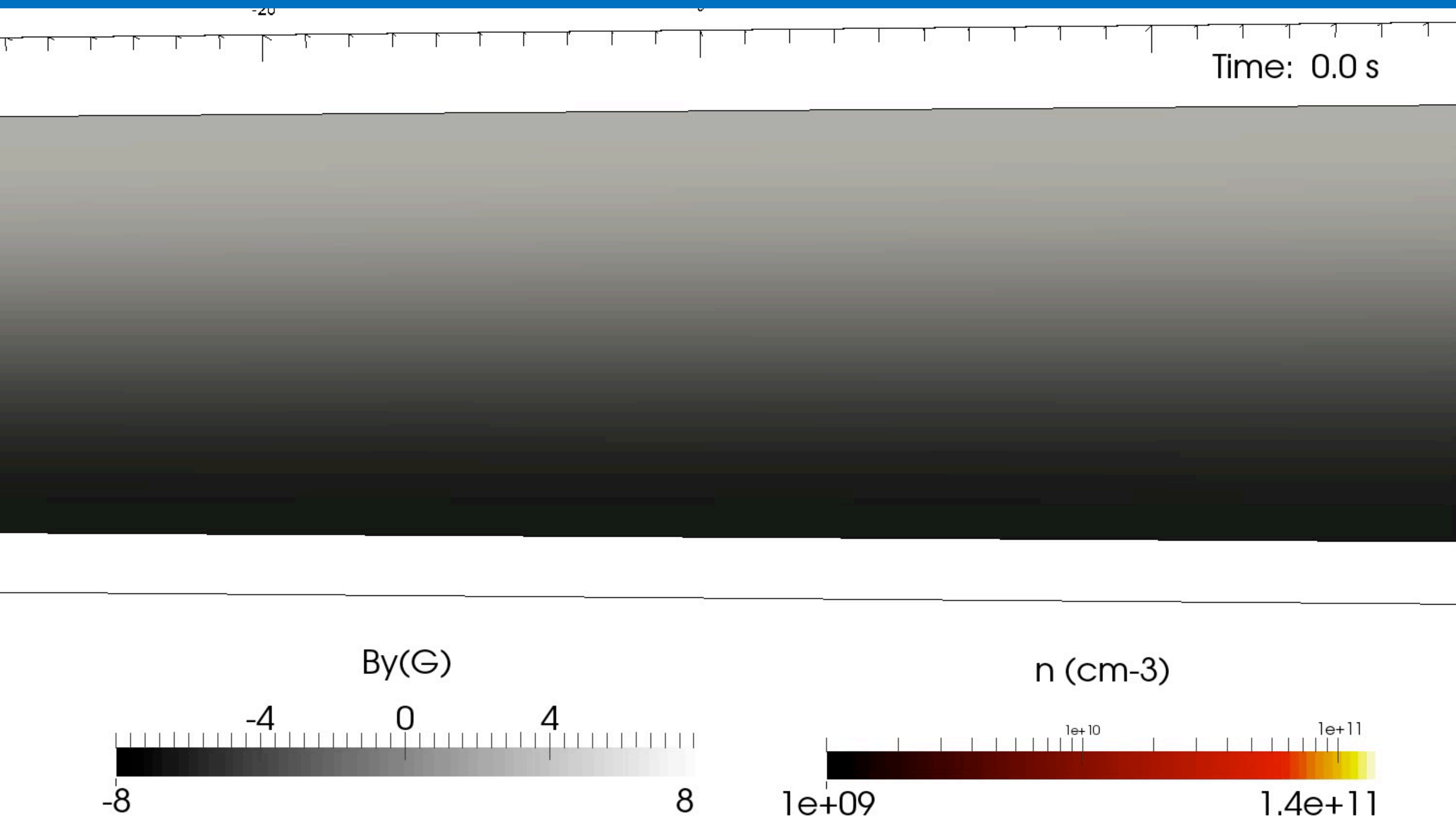
top view



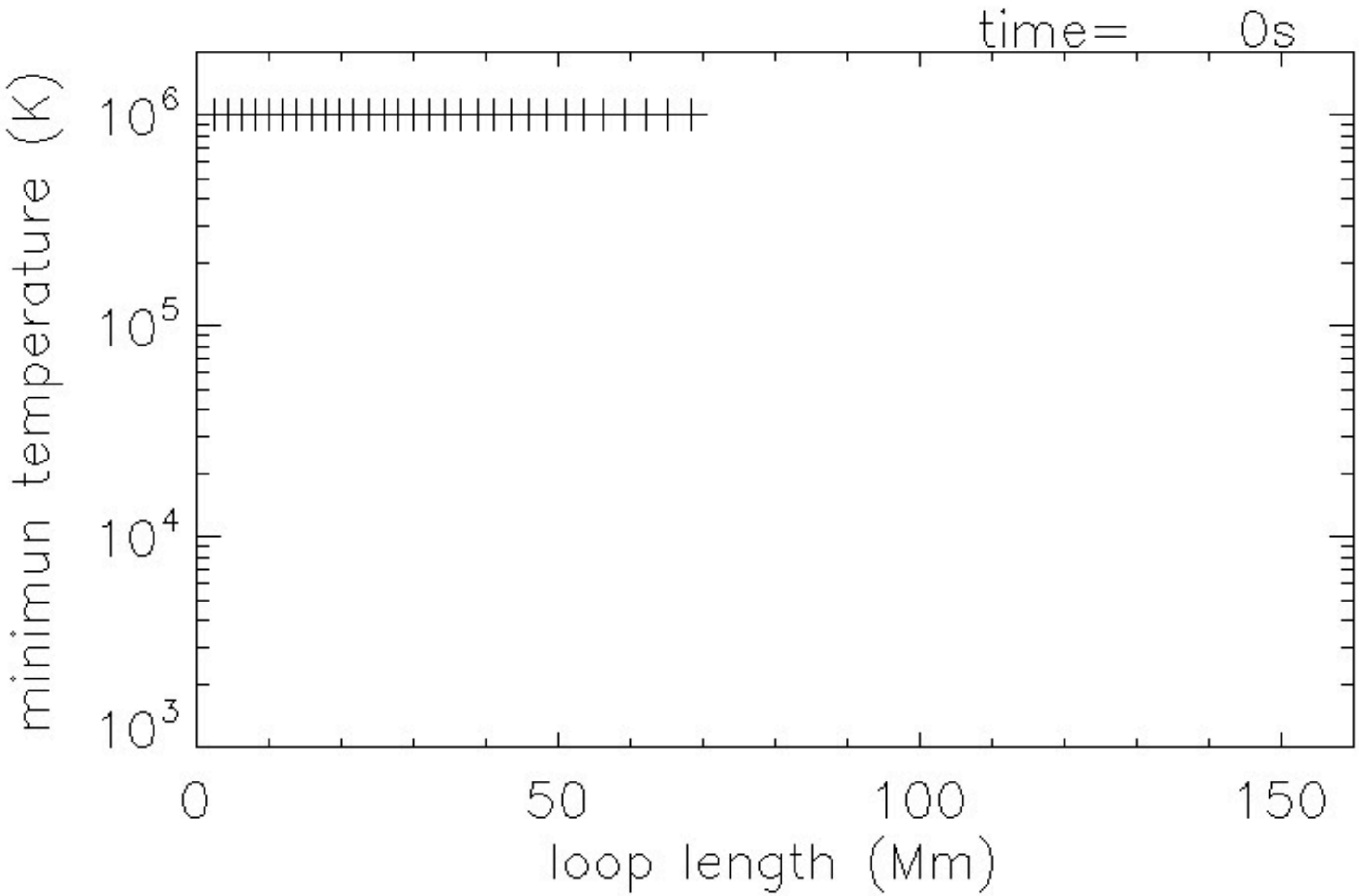
Result: side view



Result: top view

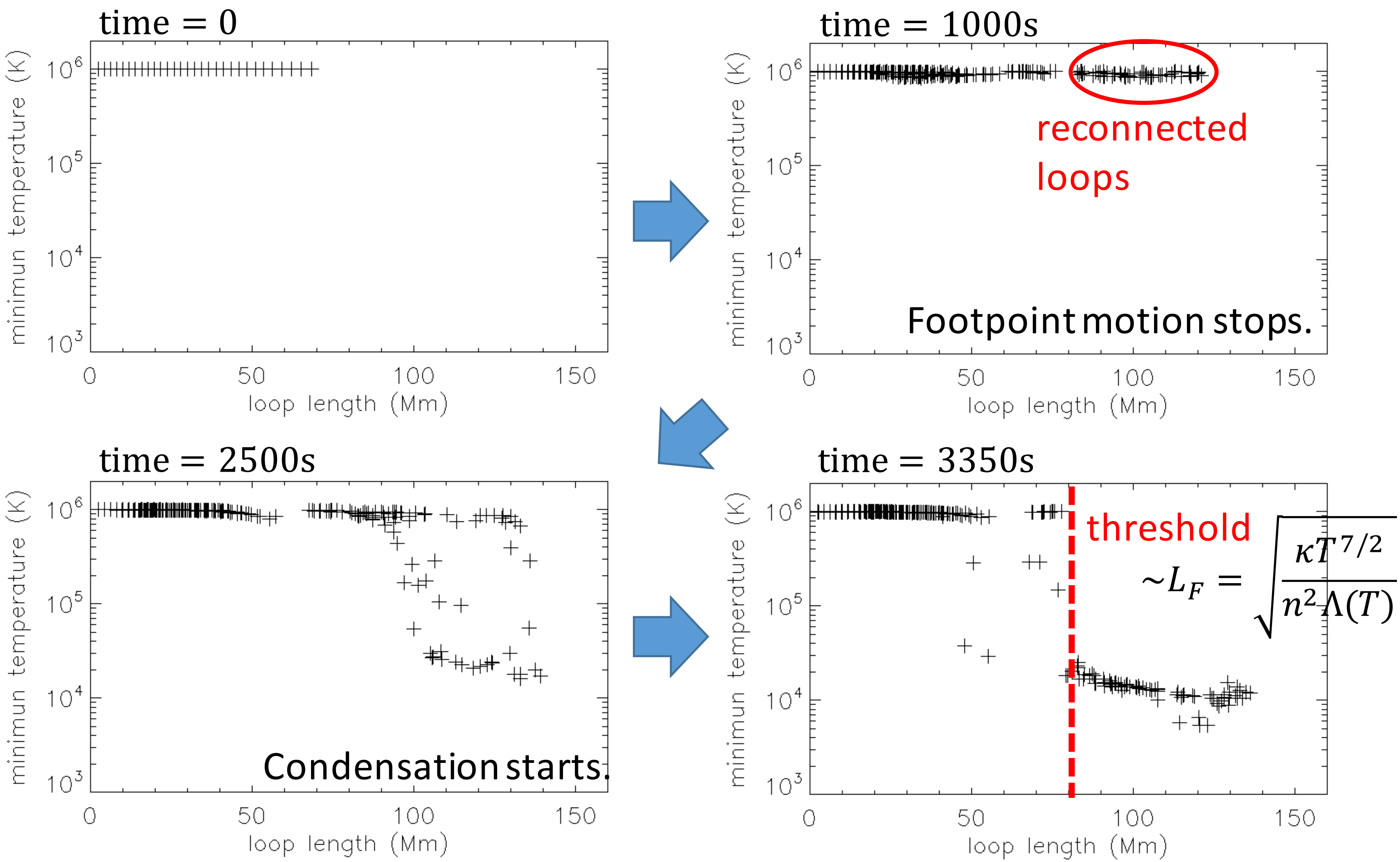


Loop length & temperature



Sufficiently long loop ➡ Radiative cooling is not compensated by conduction.

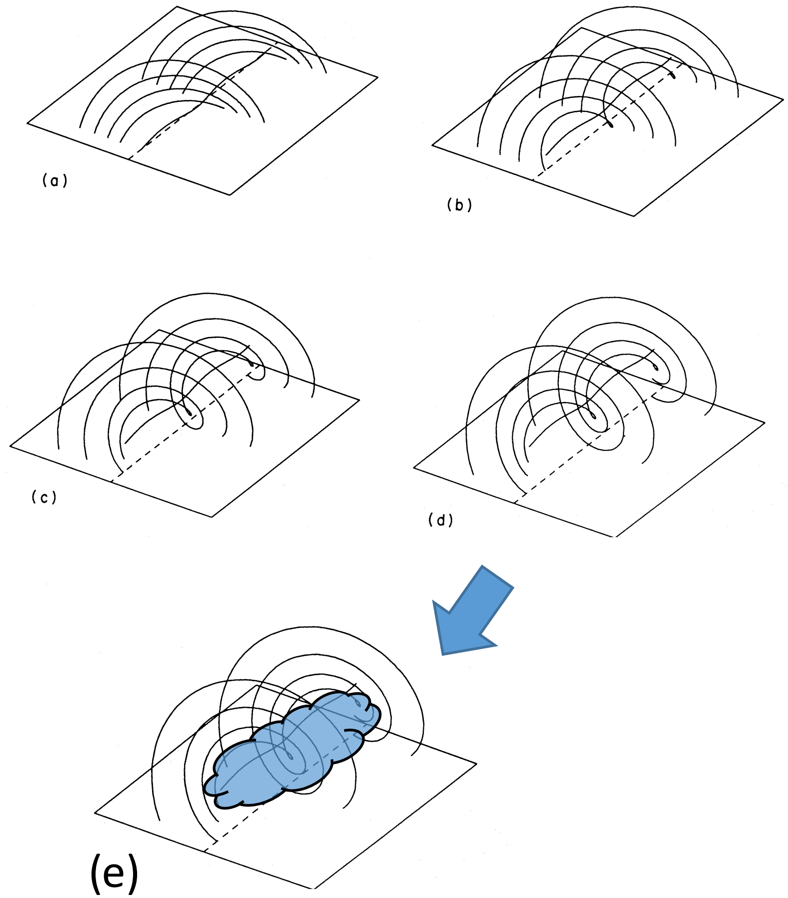
Loop length & temperature



Summary of our results

- Reconnection-condensation scenario has been demonstrated, in which radiative condensation is caused by the topological change of magnetic field due to reconnection, not evaporation.
- Sufficiently long reconnected loops suffer from radiative condensation.
- Converging motion can lead not only the formation of flux rope but also the radiative condensation.

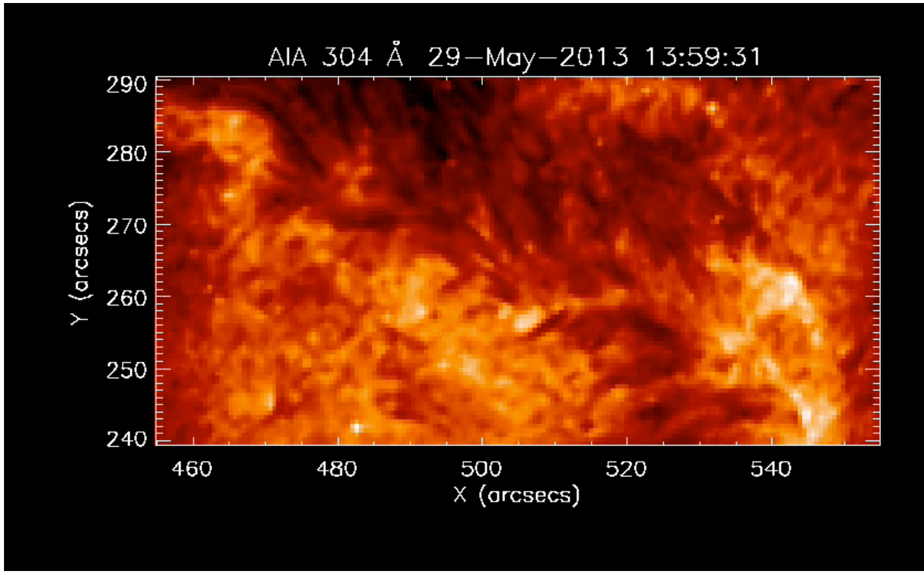
Van Ballegooijen & Martens (1989)
converging motion



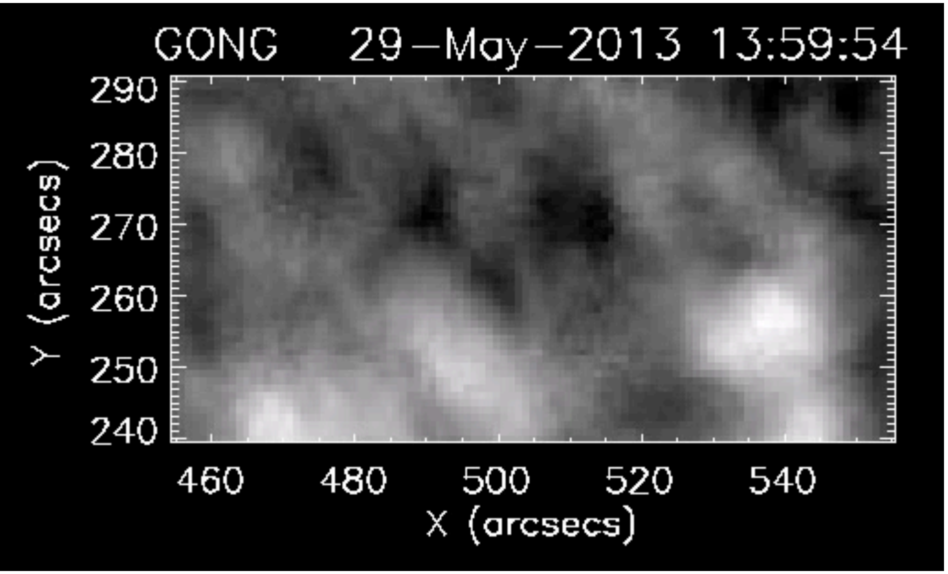
Observation of filament formation 1/2

Yang et al. (2016)

SDO/AIA 304 Å



GONG Hα

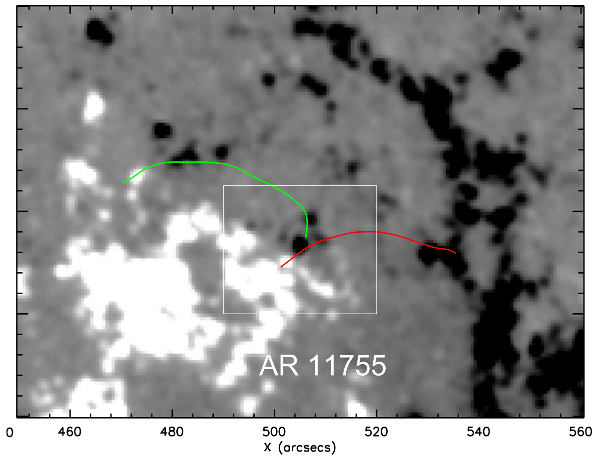


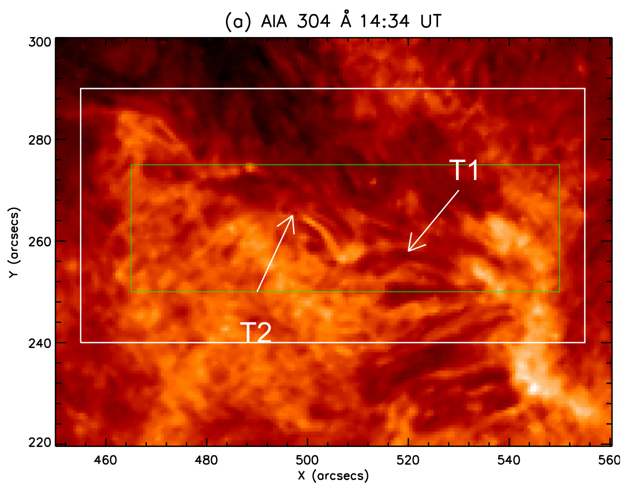
Reconnection ➡ Condensation

Observation of filament formation 2/2

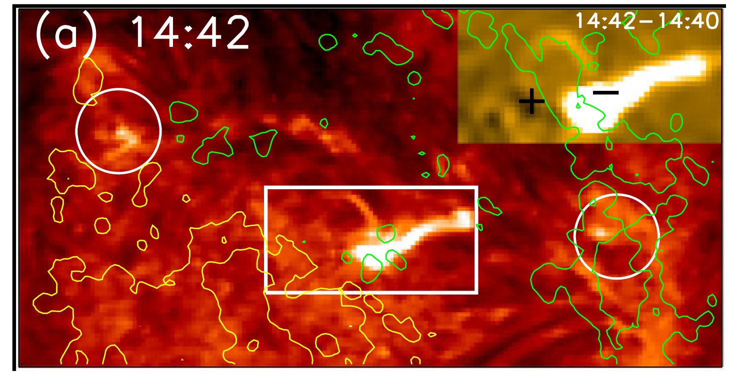
Yang et al. (2016) SDO/AIA 304 & HMI

Cancellation

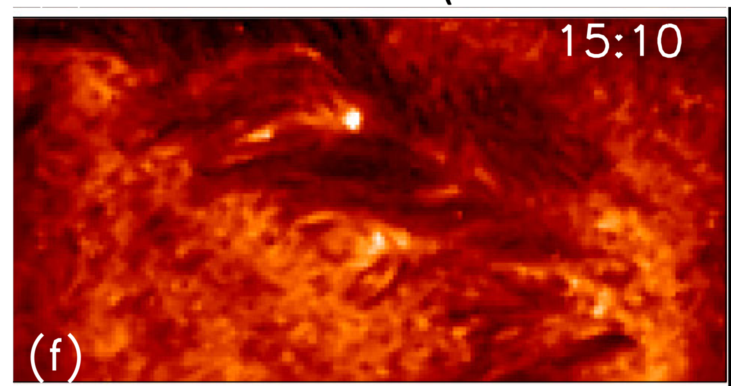




Reconnection

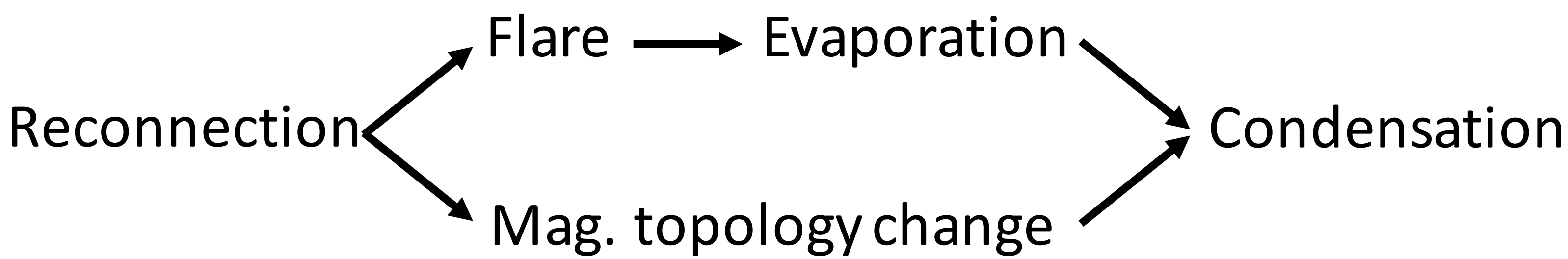


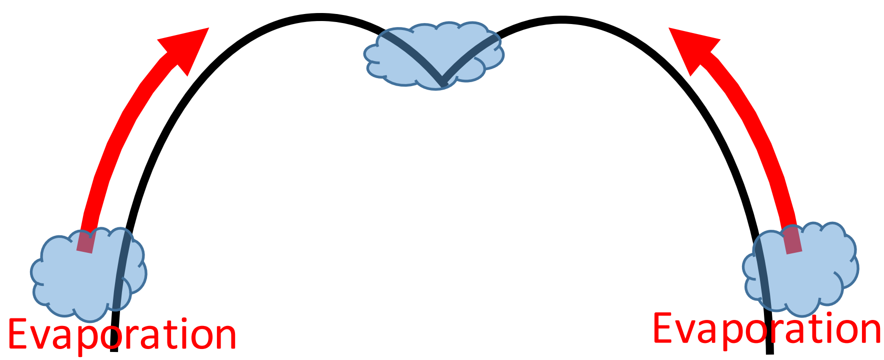
Filament formation (condensation)

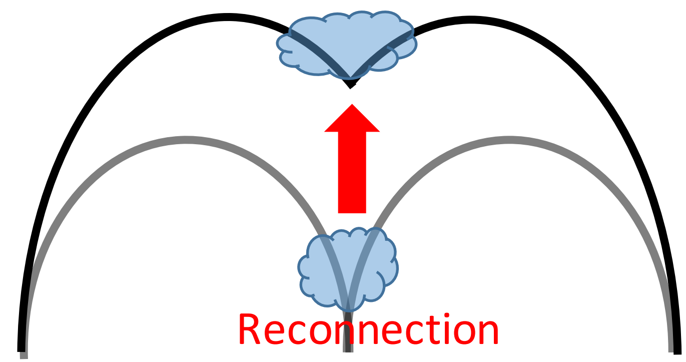


Discrimination of models by observation

- From which route does the high density plasmas come ?
- How is the thermal evolution ?







Phase-mixing in Prominence 1/2

Cross-field waves

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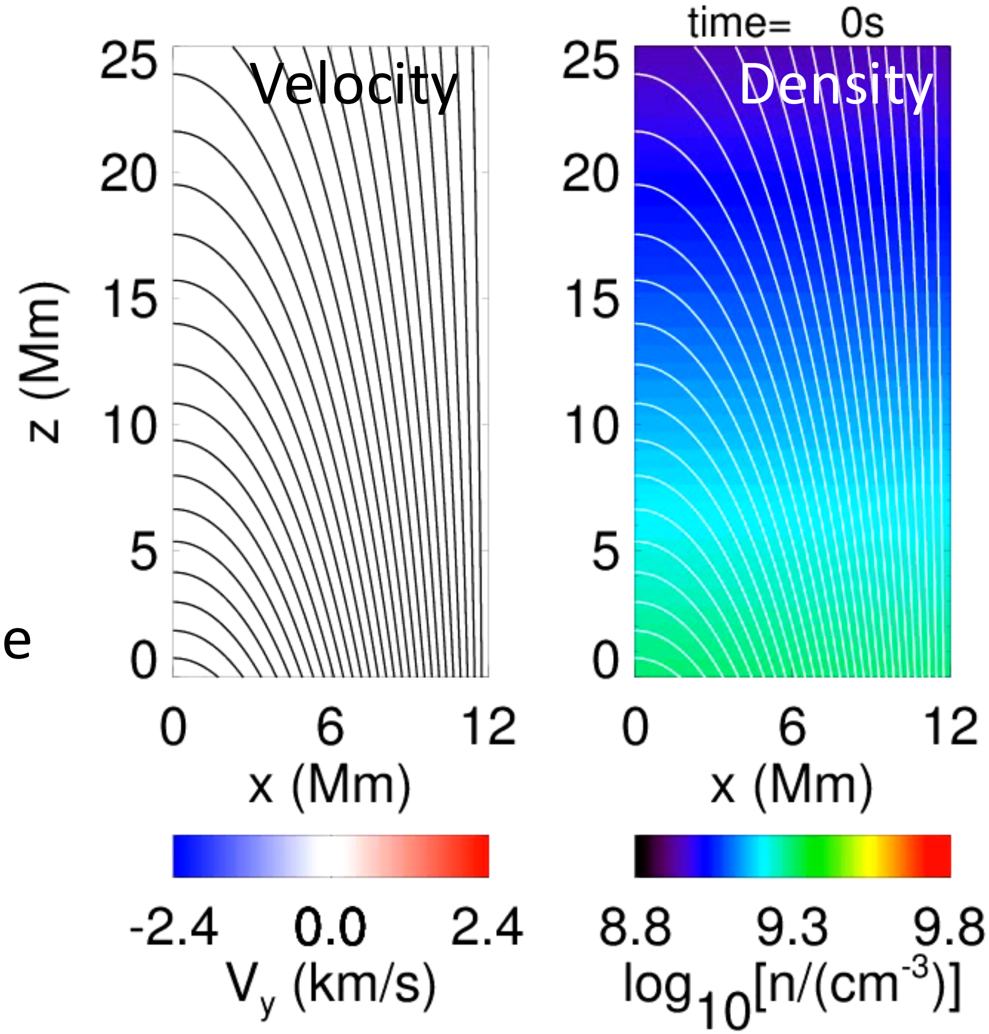
~~Fast mode ?~~

↓

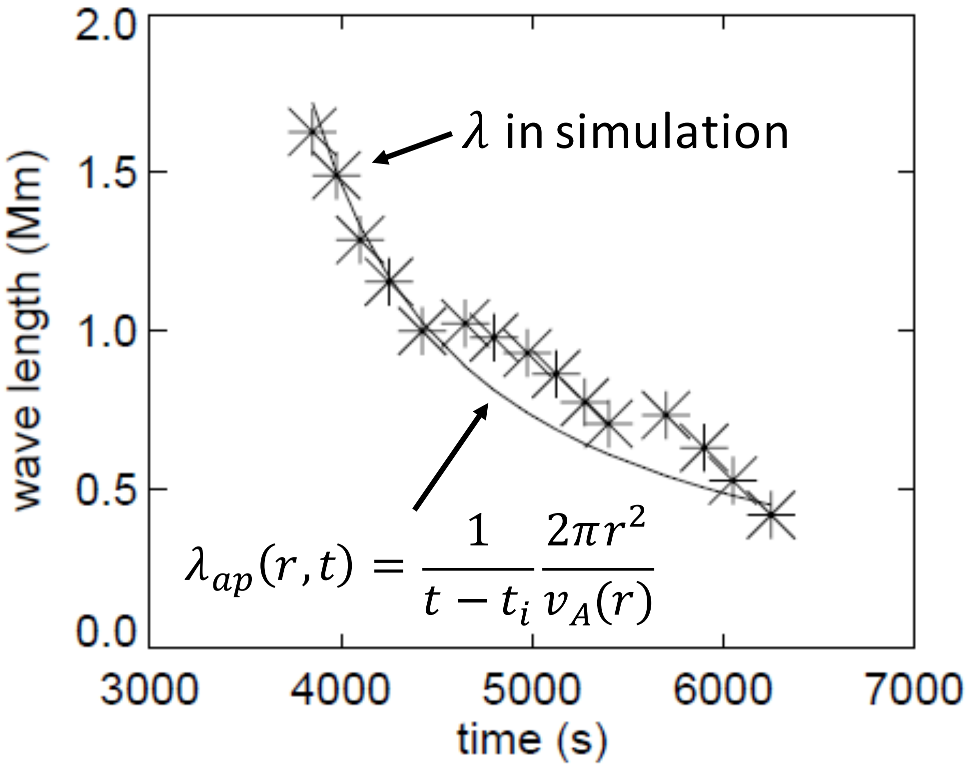
Phase mixing of standing Alfven waves in the flux rope

Kaneko et al. (2015)



Phase-mixing in Prominence

wavelength @ r=4 Mm



Kaneko et al. (2015)

Phase-mixing

- Cross-field wavelength decreases with time.
- Eigen frequencies vary across magnetic field.

High spatiotemporal resolution of IRIS has advantage to detect phase-mixing.

Conclusion

- We demonstrate reconnection-condensation model by 2D & 3D MHD simulation including radiative cooling & thermal conduction
- In 3D simulation, although thermal conduction along toroidal magnetic components are effective, radiative condensation is triggered in the dip of sufficiently long helical magnetic field.
- IRIS multiwavelength observation with high spatiotemporal resolution has advantage for detect the flows & waves associated with prominence condensations.

Papers:

✓ T. Kaneko & T. Yokoyama (2015), ApJ, 806, 115

✓ T. Kaneko, M. Goossens, R. Soler, J. Terradas, T, Van Doorsselaere, T. Yokoyama & A. N. Wright (2015), ApJ, 812, 121