The 10th EAMA
2016. 9. 28. 14:00-14:25 Seoul, Korea

THE UNIVERSITY OF TOKYO

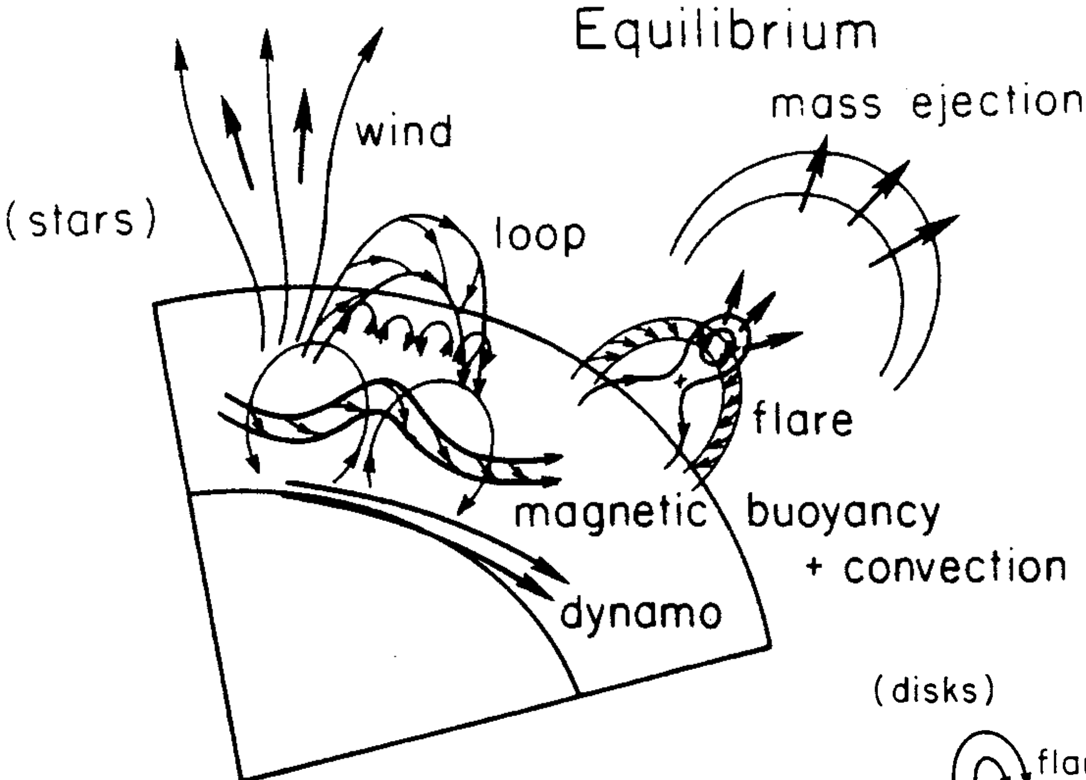
Studies of the Sun with Hinode and Numerical Simulations

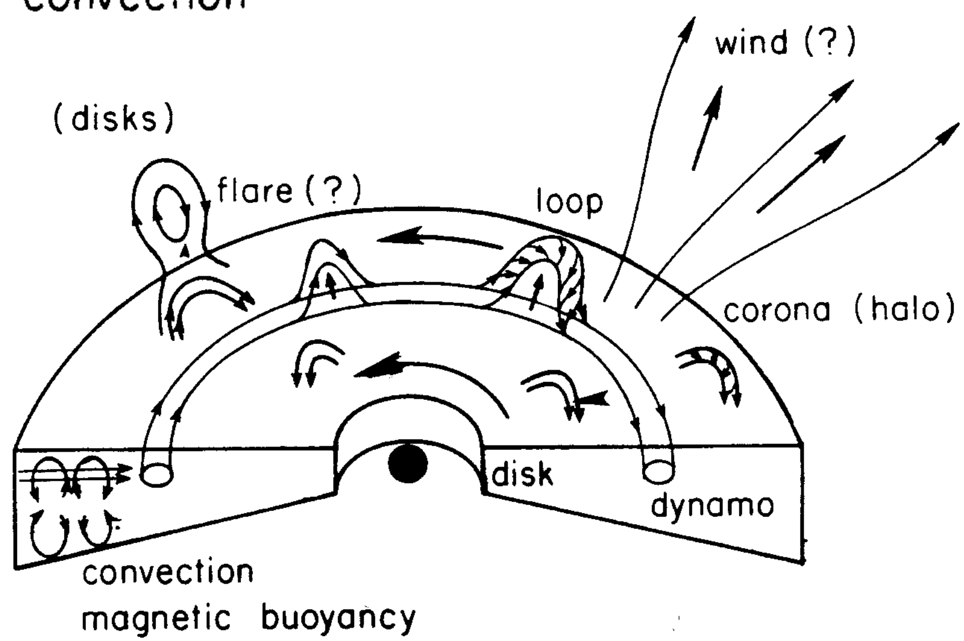
Takaaki Yokoyama
The University of Tokyo

based on
Iijima, H., 2016, DSc thesis, UTokyo
Iijima & TY, 2015, ApJL, 812, L30

1992/01/12

the Sun as a laboratory of plasma astrophysics





From

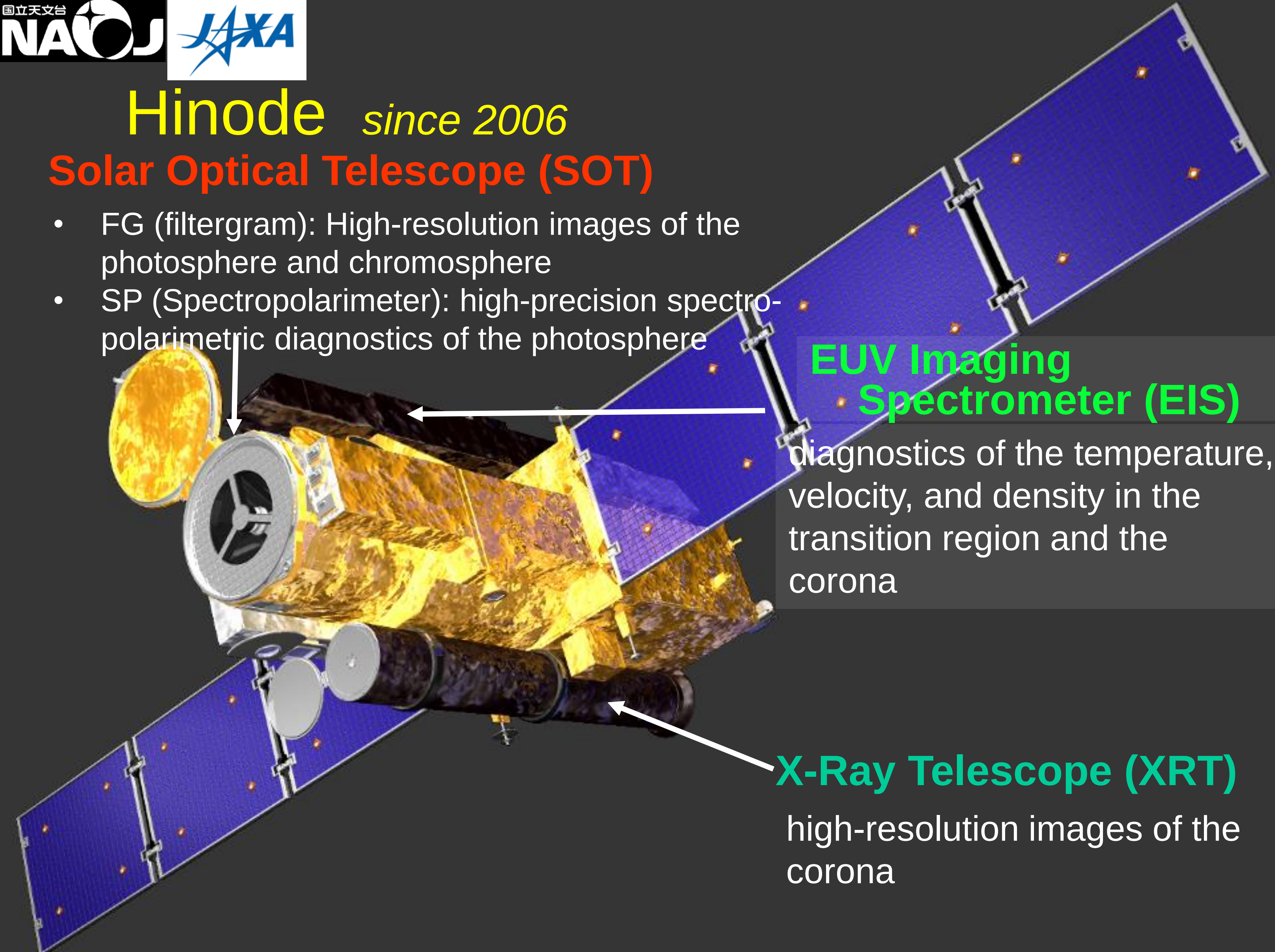
Tajima & Shibata (1997)

“Plasma Astrophysics”

Hinode *since 2006*

Solar Optical Telescope (SOT)

- FG (filtergram): High-resolution images of the photosphere and chromosphere
- SP (Spectropolarimeter): high-precision spectro-polarimetric diagnostics of the photosphere



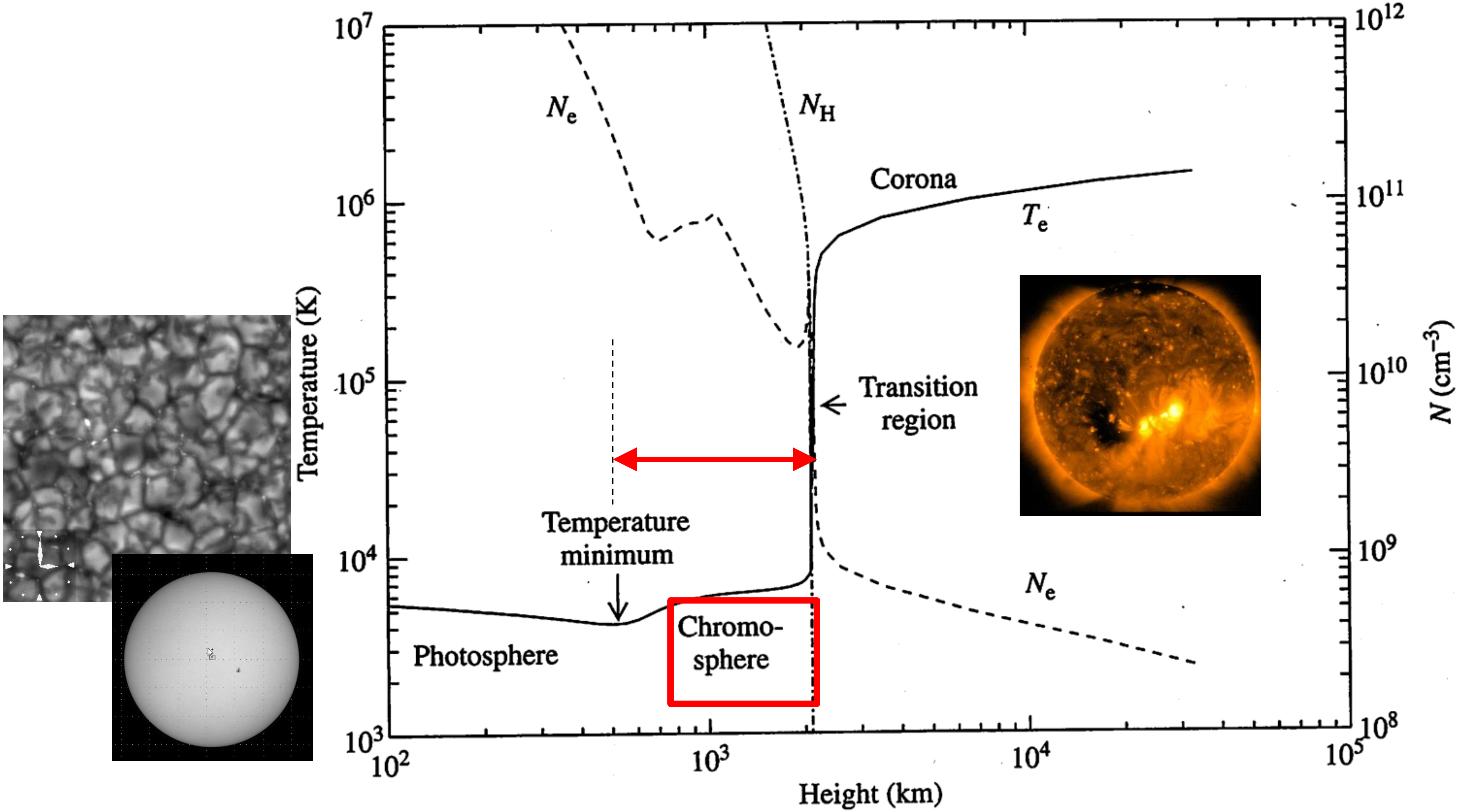
EUV Imaging Spectrometer (EIS)

diagnostics of the temperature, velocity, and density in the transition region and the corona

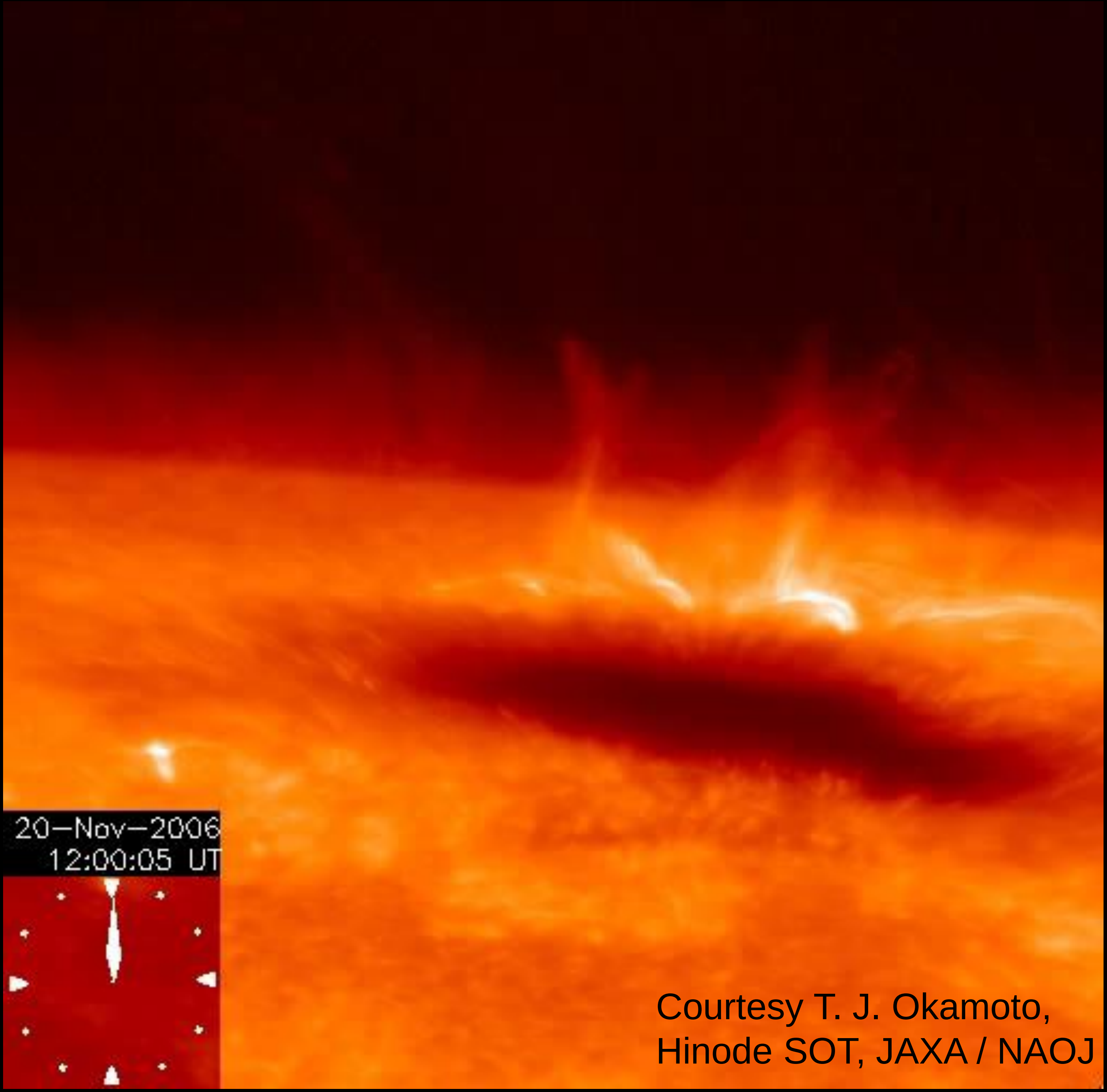
X-Ray Telescope (XRT)

high-resolution images of the corona

The solar atmosphere



(figure from Phillips, Feldman, Landi 2008)


20–Nov–2006
12:00:05 UT
Courtesy T. J. Okamoto,
Hinode SOT, JAXA / NAOJ

Alfvenic waves in the chromosphere

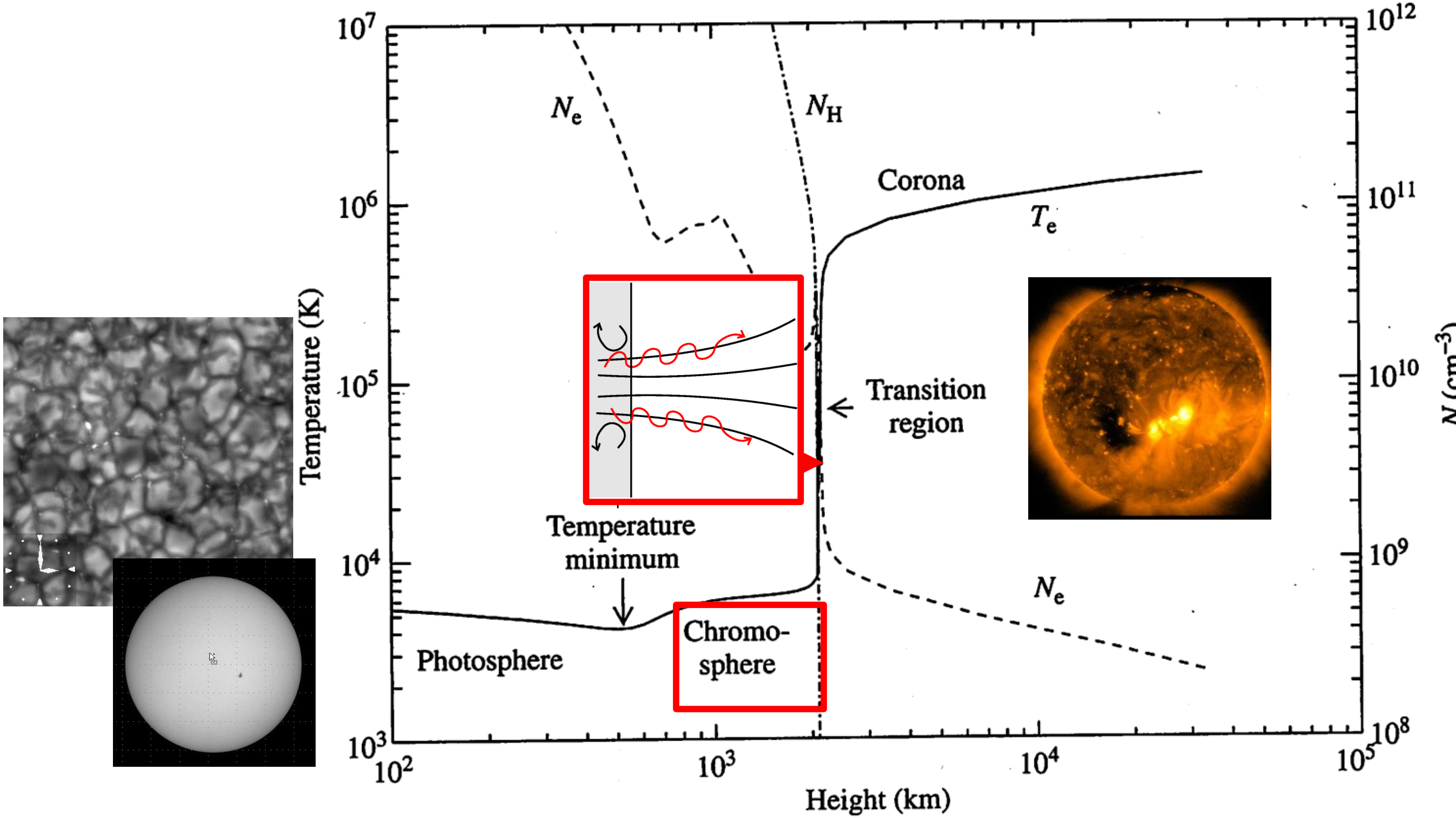
Hinode Observations:

- Okamoto+ (2007), Okamoto+, TY (2015)

Numerical Simulations:

- Antolin, TY, Van Doorsselaere (2014), Antolin+, TY (2015)

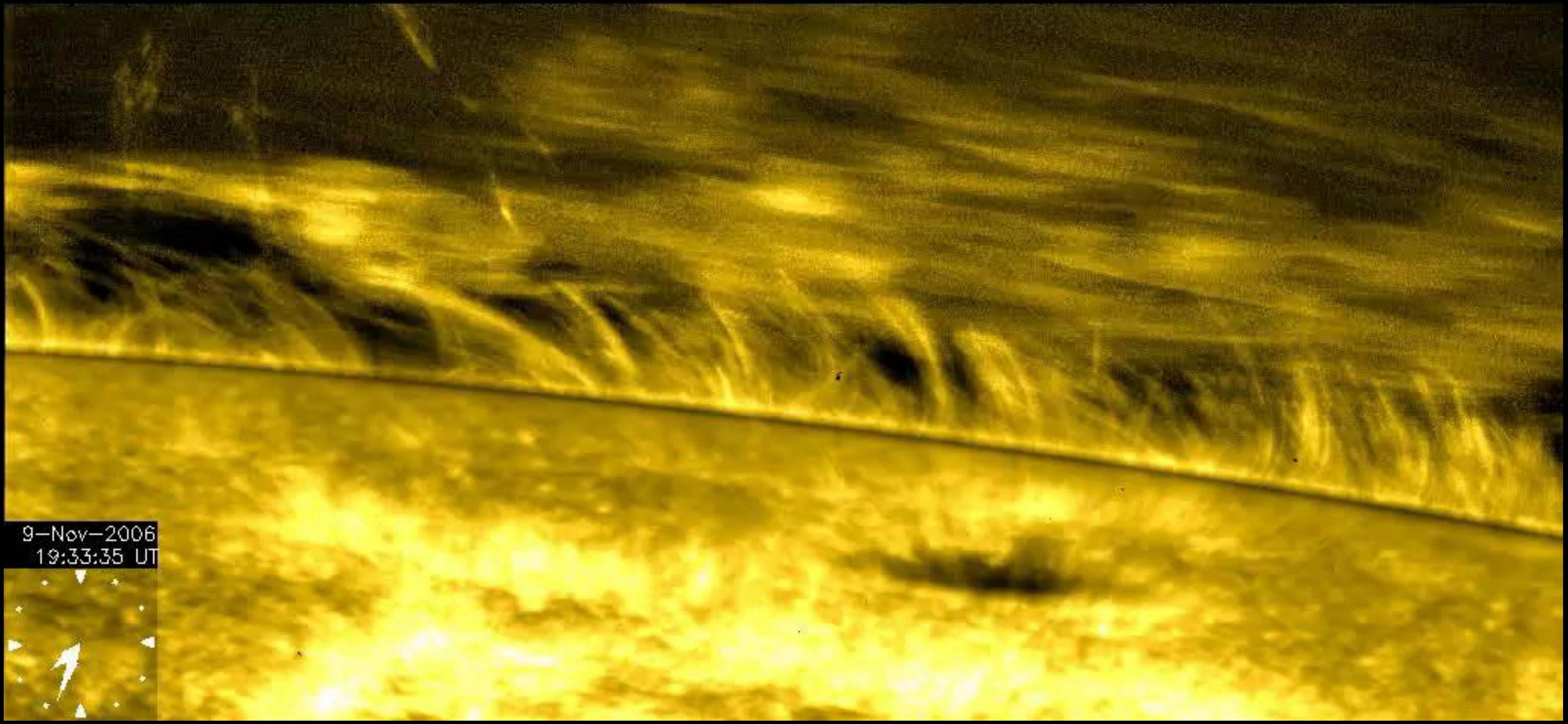
The solar atmosphere



(figure from Phillips, Feldman, Landi 2008)

Coronal transverse waves in a prominence

Okamoto+ 2007



Coronal transverse waves in a prominence

Okamoto+ 2007

fine-scale threadlike structures oscillating in the plane of the sky with periods of several minutes

Alfven waves

(c.f. Ofman & Wang 2008)

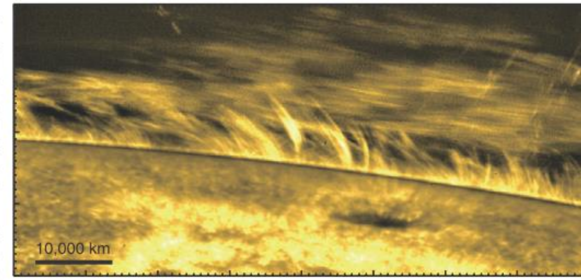


Fig. 1. High-resolution image on the solar limb obtained with SOT aboard Hinode. This observation was performed with a cadence of 15 s from 19:33 to 20:44 UT on 9 November 2006. Tick marks have a spacing of 1000 km on the Sun. A radial density filter is applied to show the brighter photosphere and the fainter coronal structures in the same image. The main sunspot of NOAA AR 10921 as well as the trailing bright plage areas are visible on the disk. Above the limb, ubiquitous vertical spicules are seen below the horizontal threads of the AR prominence. The cloudlike prominence structure is located 10,000 to 20,000 km above the visible limb and exhibits a very complex fine structure with predominant horizontal threadlike features. The intensity of the prominence in Ca II H-line radiation is about 1% of the on-disk photosphere.

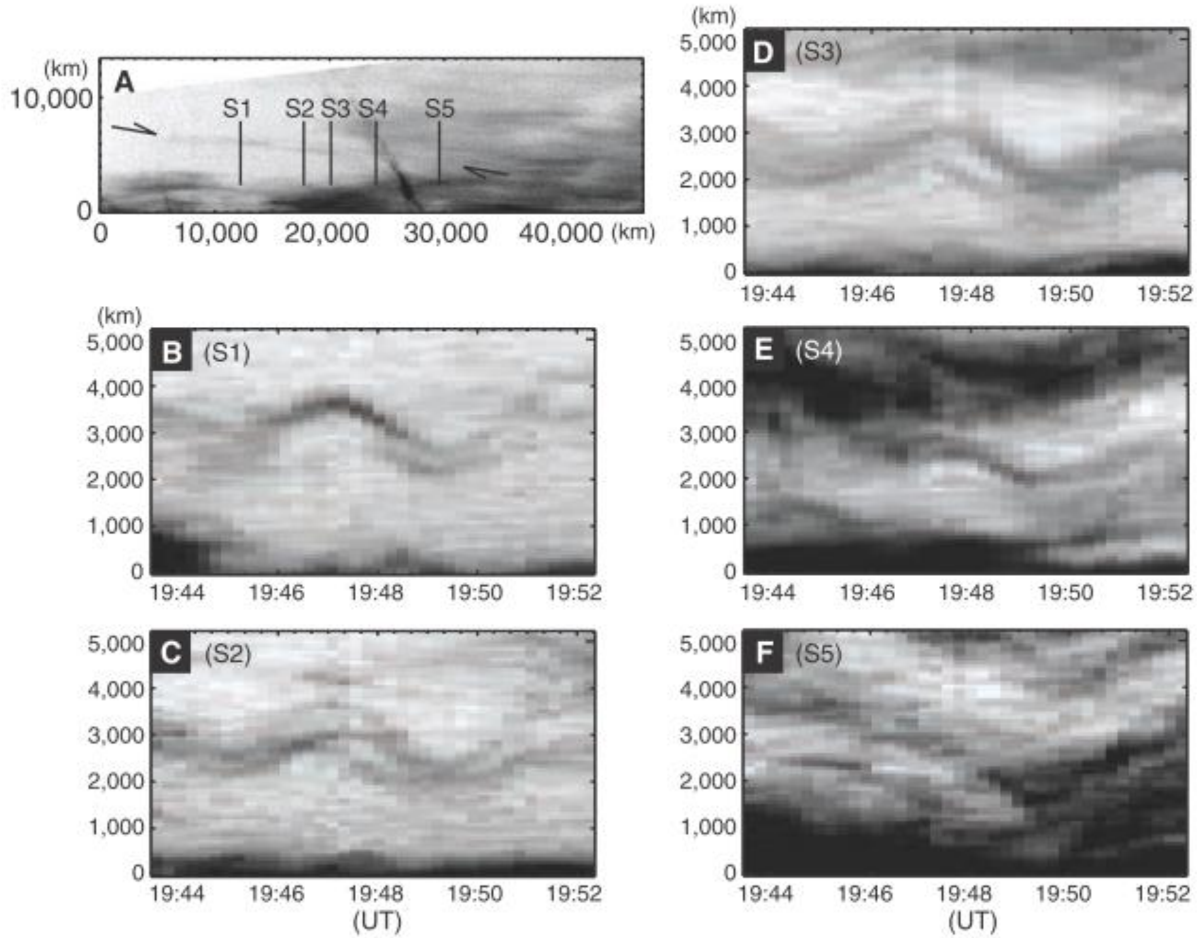
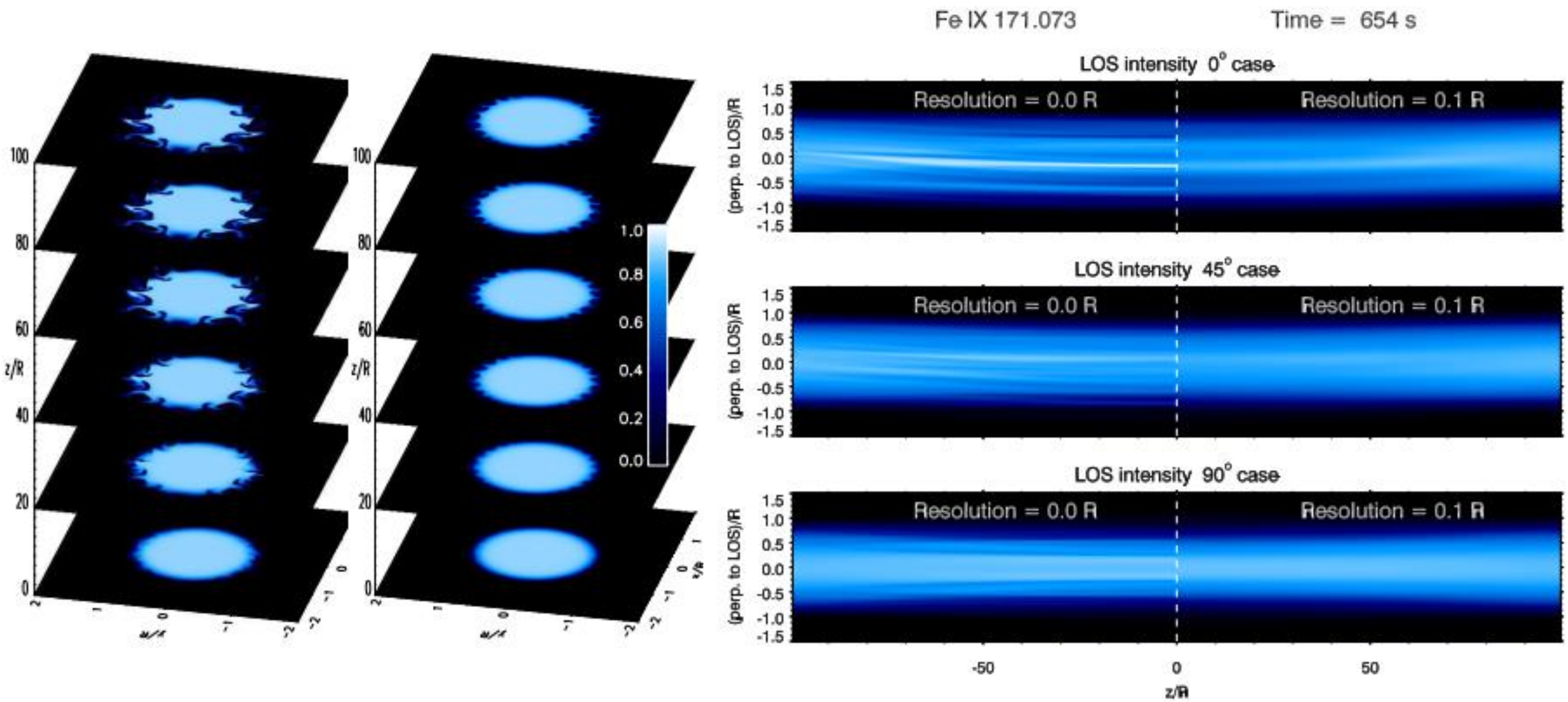


Fig. 3. Example of a prominence thread undergoing synchronous oscillation along its entire length. (**A**) The long thread extending ~16,000 km. Lines S1 to S5 indicate the locations of height versus time plots shown in (B to F). The arrows indicate both sides of the long thread oscillating synchronously. (**B** to **F**) Height-time plots (shown in negative contrast) for the locations indicated in (A). Maximum and minimum amplitudes occur at nearly the same time for all locations.

Fine strand-like structures in the oscillating loop

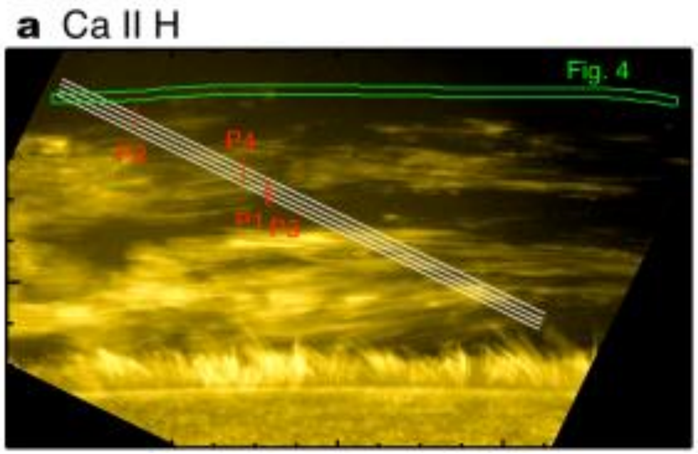
Antolin, TY, Van Doorsselaere, 2014, ApJ

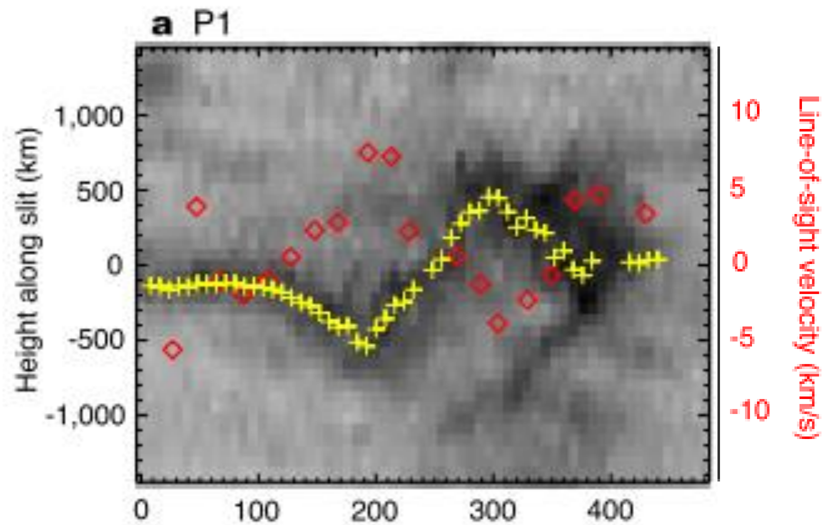
The transverse oscillations can lead to KH instabilities that deform the cross-section area of the loops. The vortices generated from the instability are velocity sheared regions with enhanced emissivity hosting current sheets.

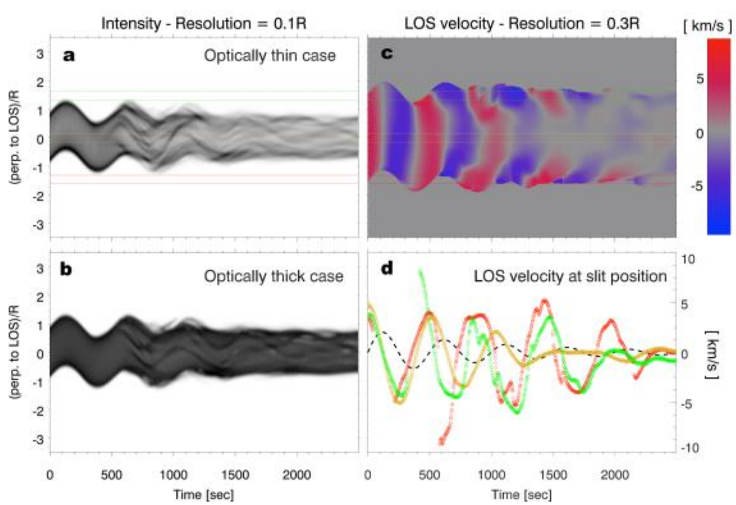


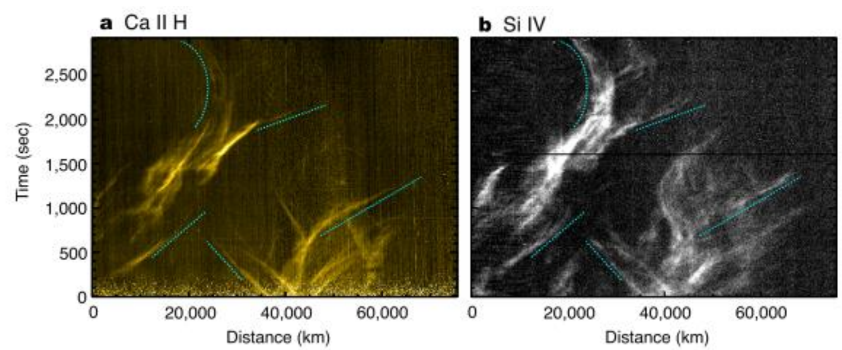
Resonant absorption of transverse oscillation and associated heating in a prominence

Okamoto+, TY 2015; Antolin+, TY 2015









Turbulence in the prominence

Hinode

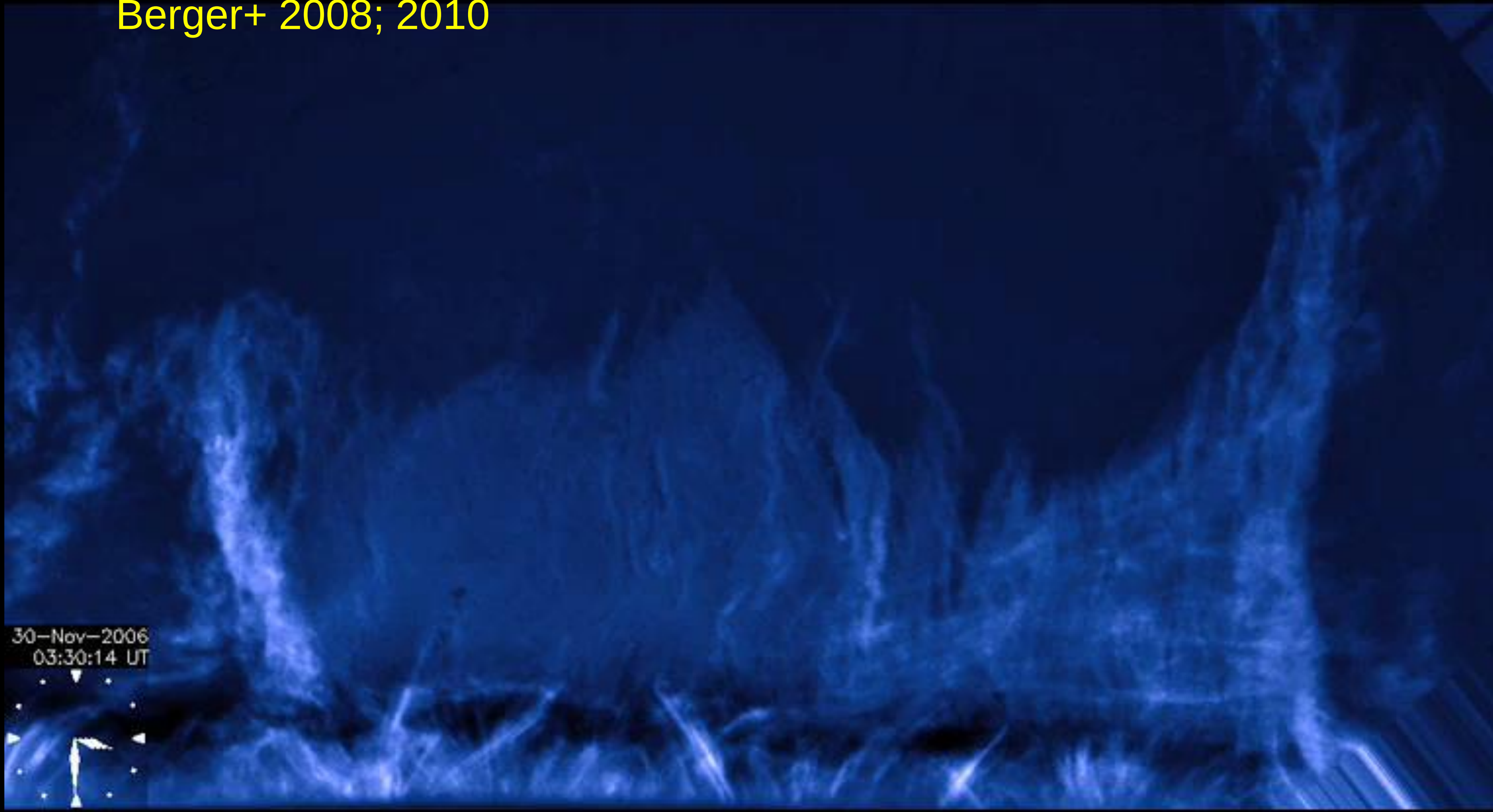
- Berger+ (2008, 2010)

Numerical simulations

- Hillier+ (2012), Kaneko & TY (2016a,b)

Turbulence in a quiescent prominence

Berger+ 2008; 2010

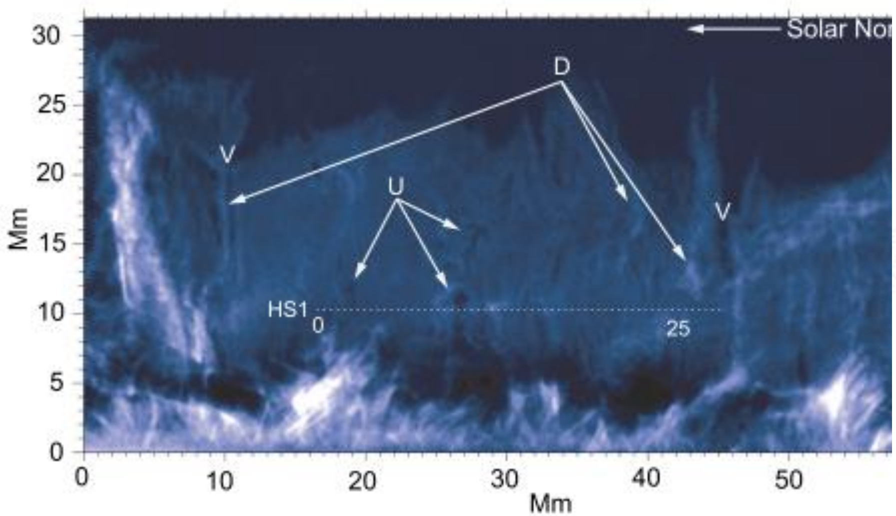


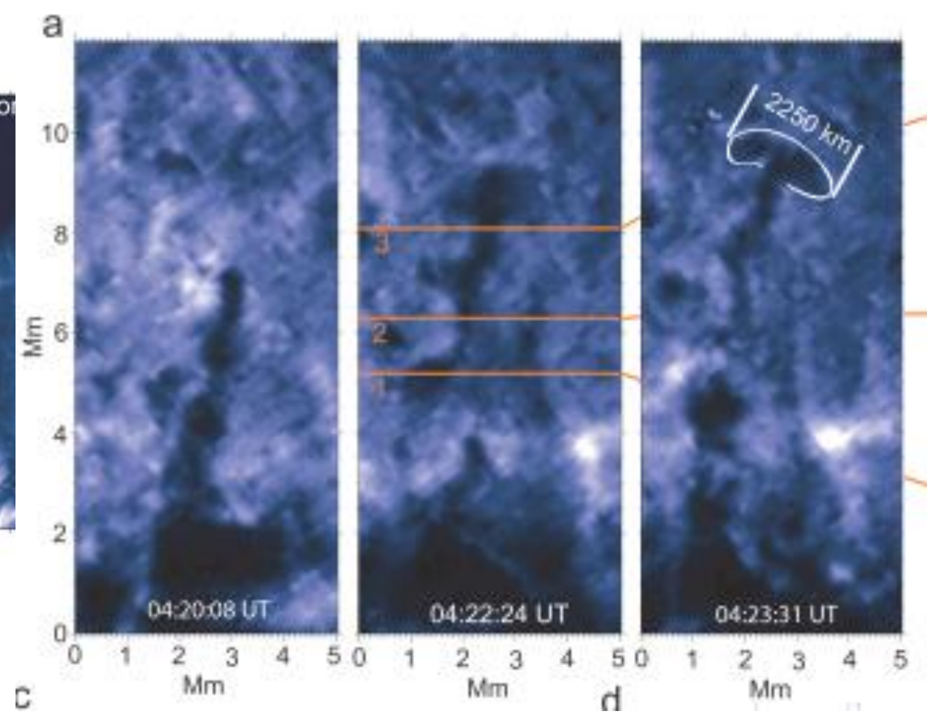
Turbulence in a quiescent prominence

Berger+ 2008; 2010

filamentary downflows and vortices

dark, episodic upflows: 170-700 km in width, exhibit turbulent flow and rise with constant speeds of 20 km/s from the base to heights of 10-20 Mm. resemble buoyant starting plumes

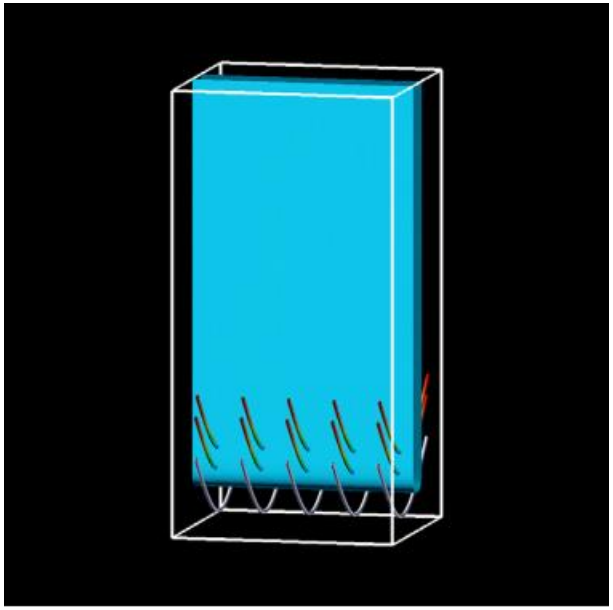


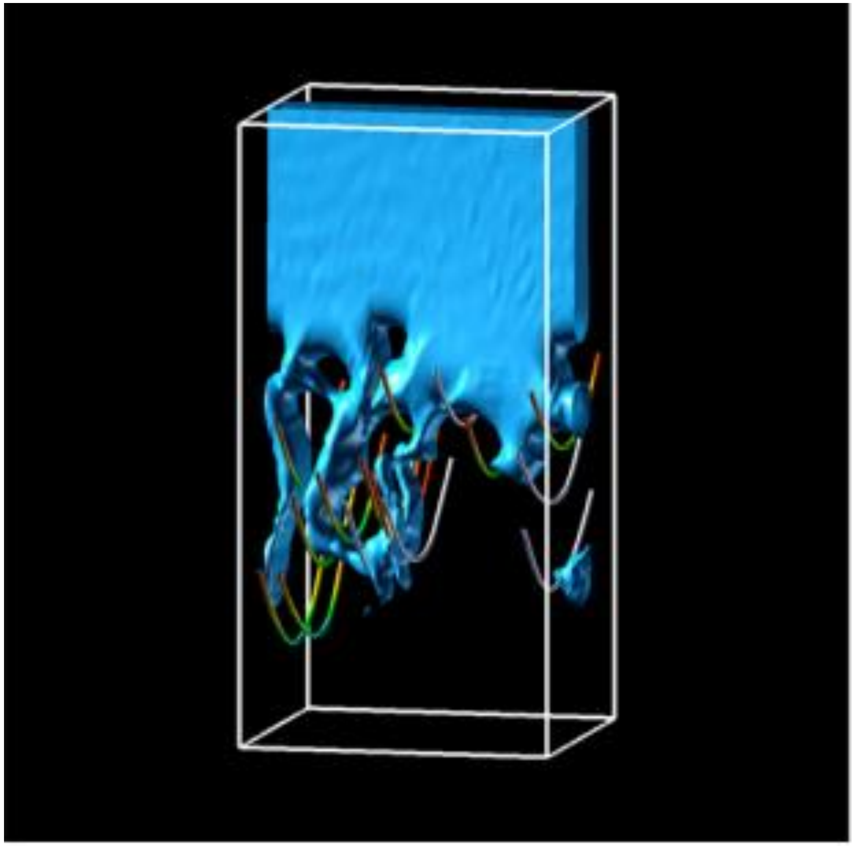


Magnetic Rayleigh-Taylor instability in a prominence

Hillier+ (2012)

Magnetically supported prominence plasma suffers from the RT instability. It may evolve into the turbulence state in the nonlinear phase. Demonstration by MHD simulations.



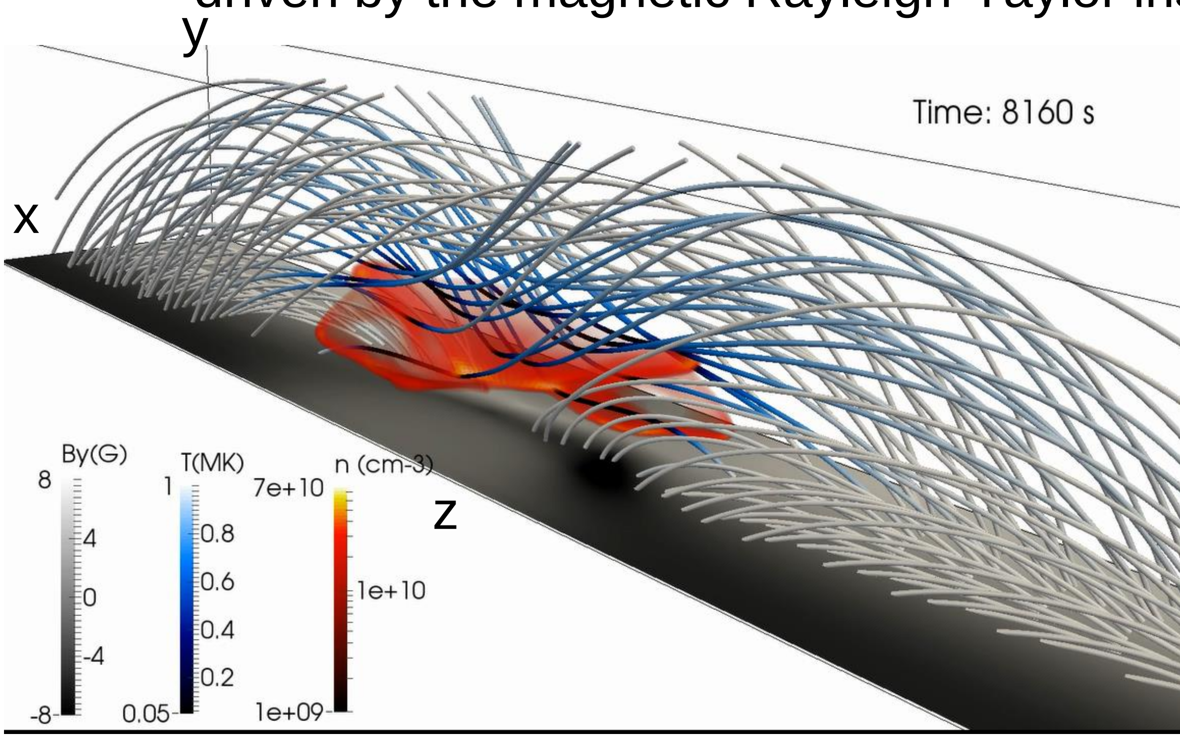


Magnetic RT instability in a prominence

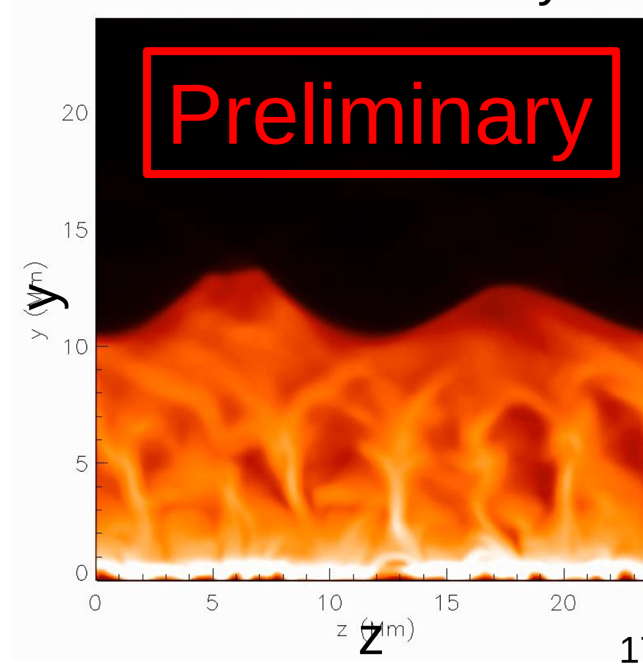
Kaneko & TY (2016a, b in prep.)

3D MHD simulations based on the newly proposed "reconnection condensation" model. The simulation includes the optically-thin radiative cooling and thermal conduction effects.

The formed prominence shows a turbulent structure probably driven by the magnetic Rayleigh-Taylor instability.



Column density



Studies on chromospheric jets

Hinode Observations:

- De Pontieu+ (2007), Pereira+ (2012)

Numerical Simulations:

- Iijima & TY (2015), Iijima (2016, PhD thesis UTokyo)

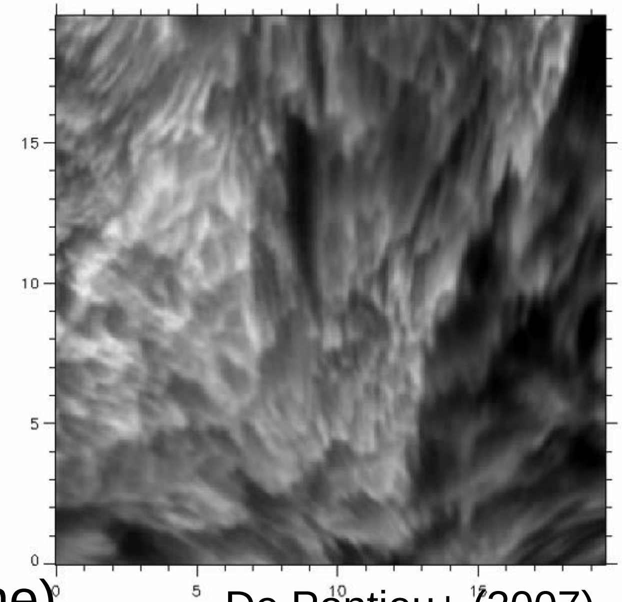
Chromospheric jets

- Spicules in quiet regions and coronal holes
- Dynamic fibrils in active regions

...

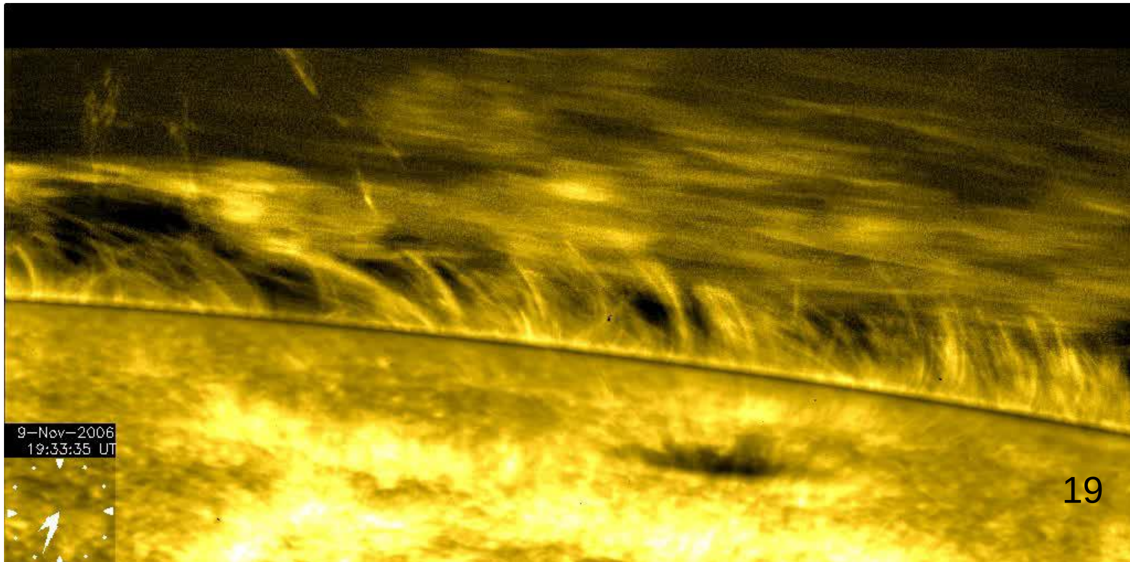
Manifestation of dynamic plasma processes

- Plasma flows (super-sonic speed)
- Magnetic fields (from high- to low-beta regime)
- MHD waves, Shock waves (mode conversion, non-linear procs.)
- Thermal processes: Radiative cooling, shock heating
- Ionization, recombination ...



De Pontieu+ (2007)

Clue for understanding the transport of energies to the corona

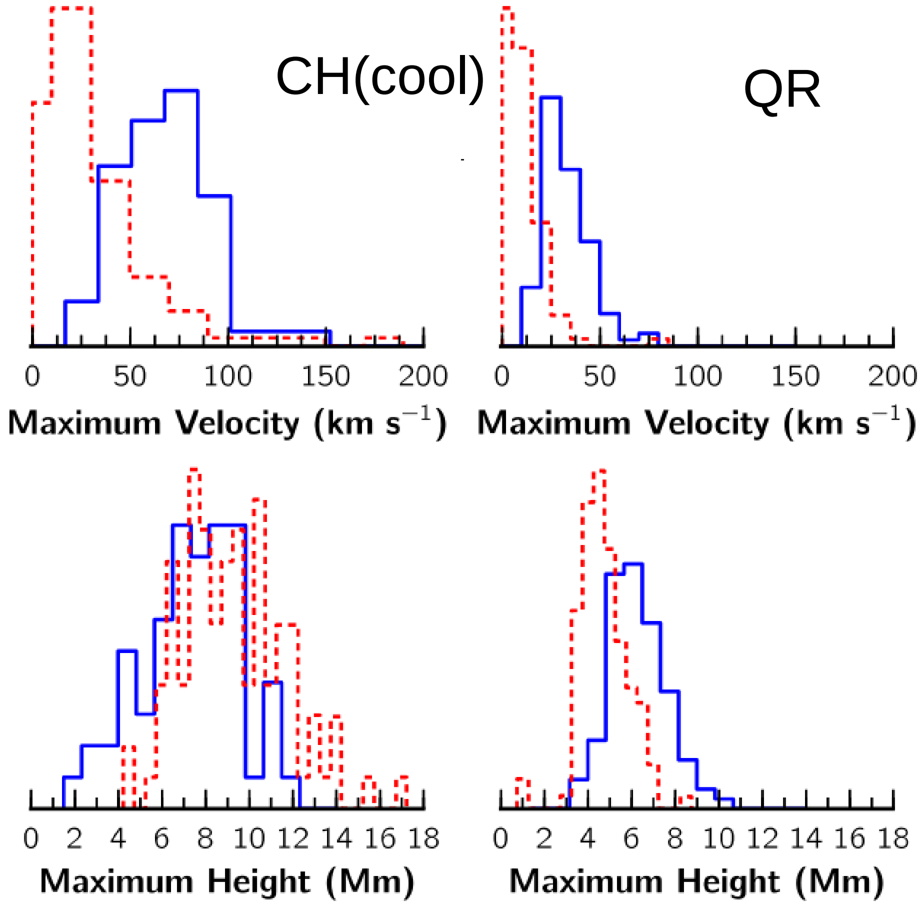


Courtesy T. J. Okamoto, Hinode SOT, JAXA / NAOJ

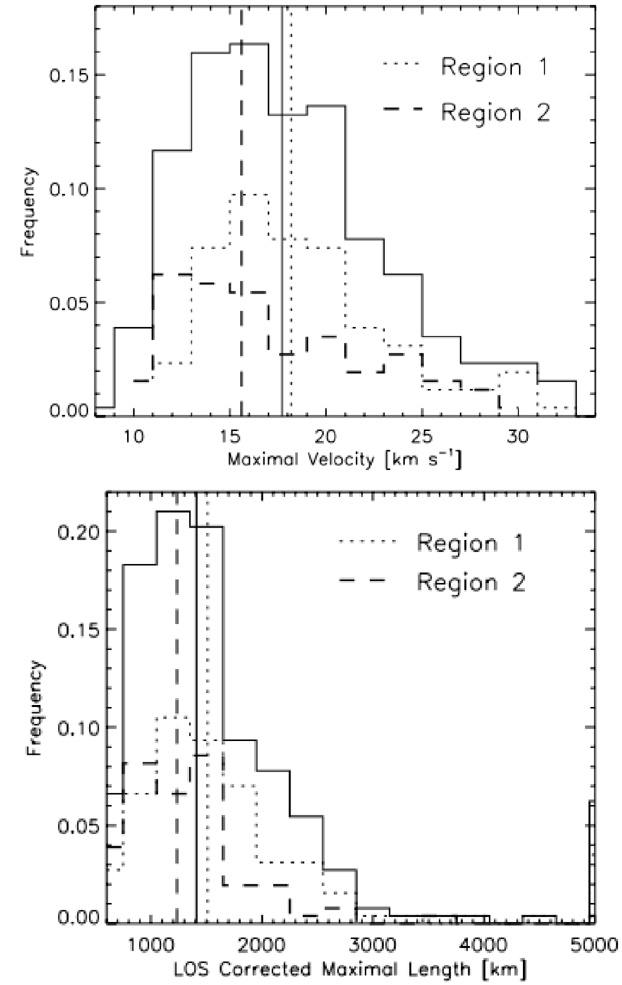
Statistical studies of chromospheric jets

Lengths, velocities, lifetimes are different among different classes of jets.

Spicules (Pereira+ 2012)



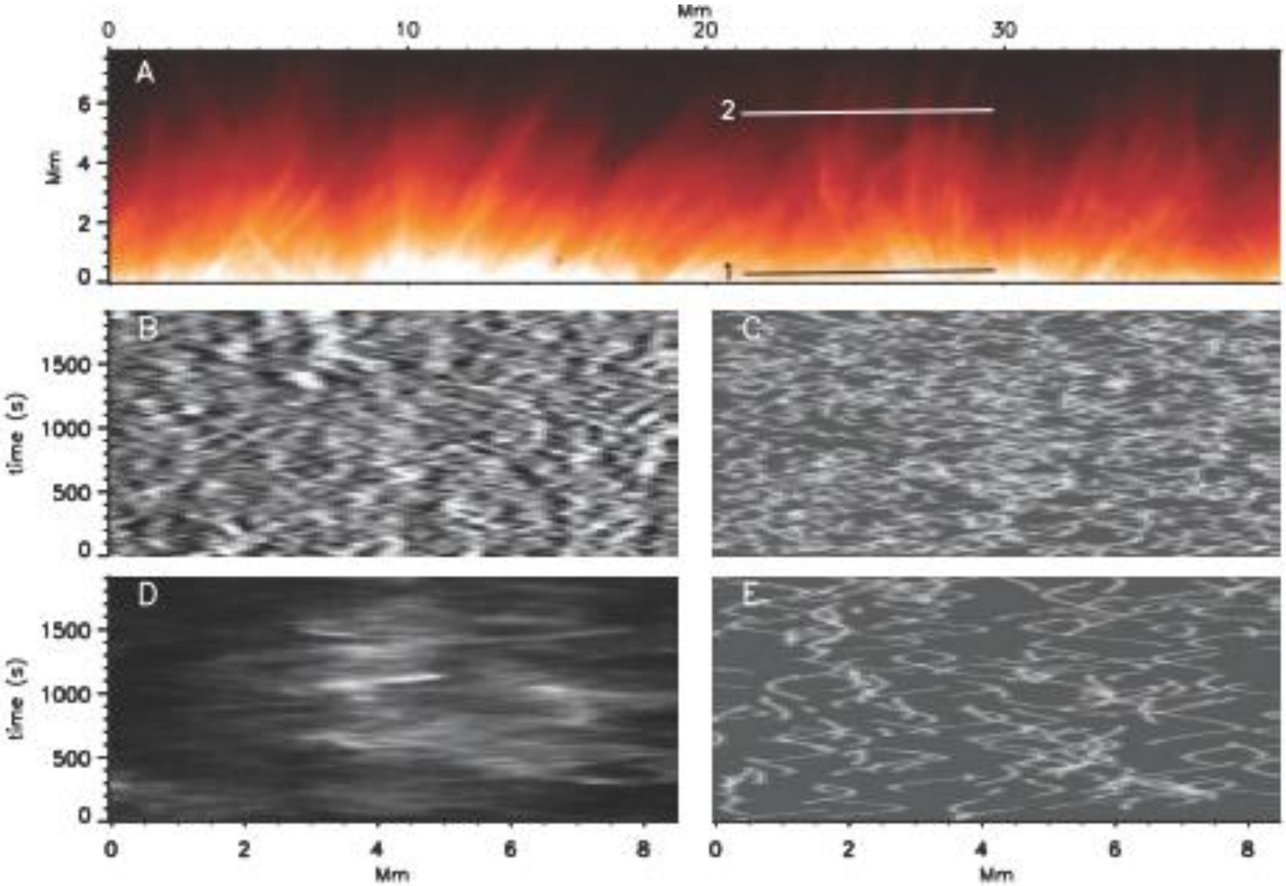
AR(hot) dynamic fibrils
(De Pontieu+ 2007)



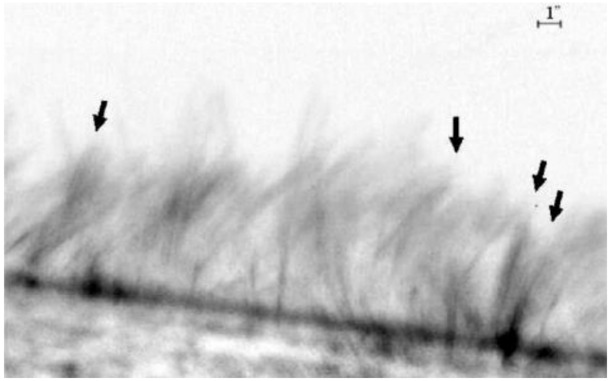
Chromospheric Alfvenic Waves

De Pontieu+ 2007

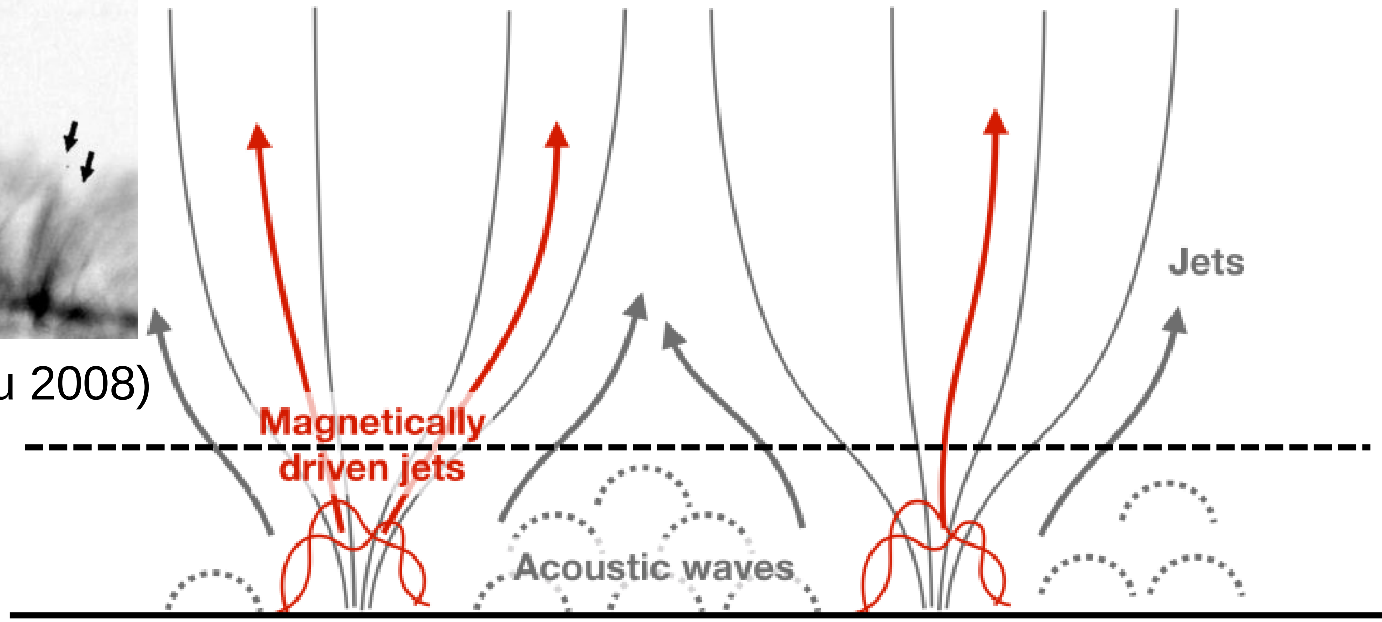
Alfven waves with amplitudes in the order of 10 to 25 km/s and periods of 100 to 500 sec. energetic enough to accelerate the solar wind and possibly to heat the quiet corona (c.f. Okamoto & De Pontieu 2011)



Chromospheric jets: model



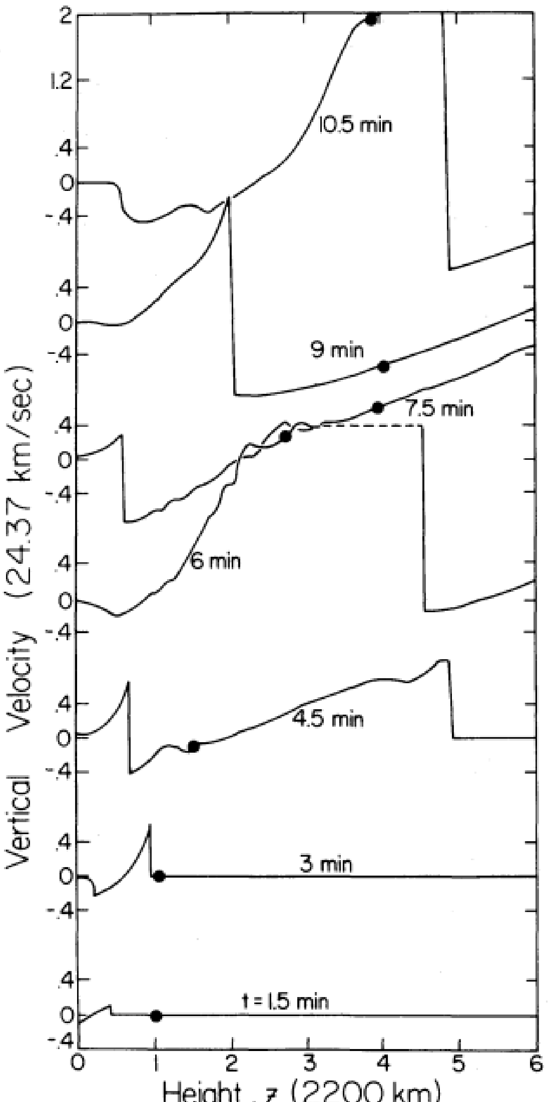
(figure from Suematsu 2008)



(figure from Iijima 2016, PhD UTokyo)

The dense cool chromospheric plasma is lifted by unknown mechanism(s) into the relatively tenuous corona. It is guided by a vertical magnetic field and is observed as an elongated jet.

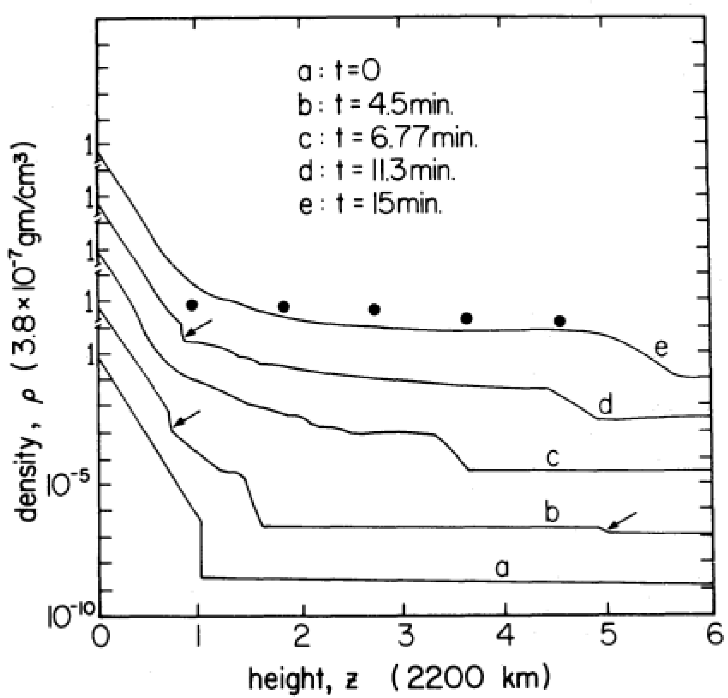
The rebound shock model for jet driving



Hollweg (1982)

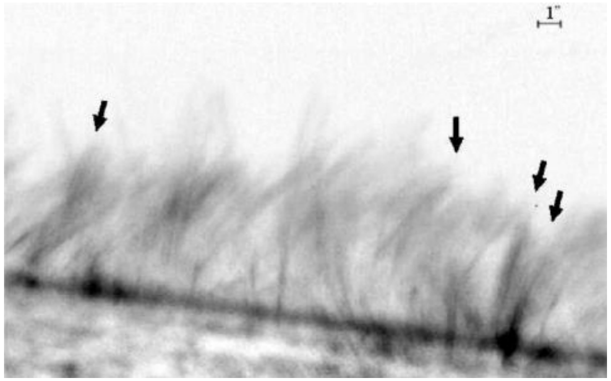
(also Hollweg+ 1982; Sterling & Hollweg 1988; Suematsu+ 1982, Kudoh & Shibata 1999, Takasao+ 2013, etc.)

The transition region (contact discontinuity) is lifted up by interactions with the rebound shock trains propagating in the chromosphere.



The shock trains can be generated by various processes: from convective overshoot, Alfven waves, reconnection events etc.

Chromospheric jets: model



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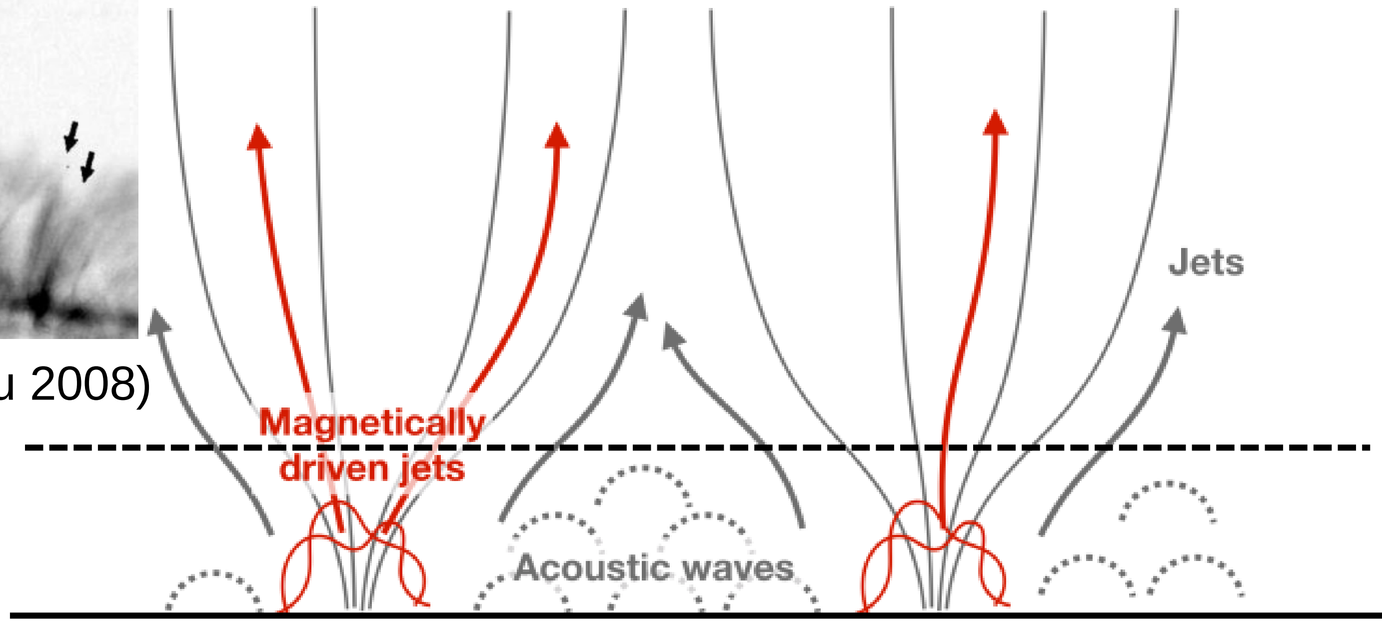

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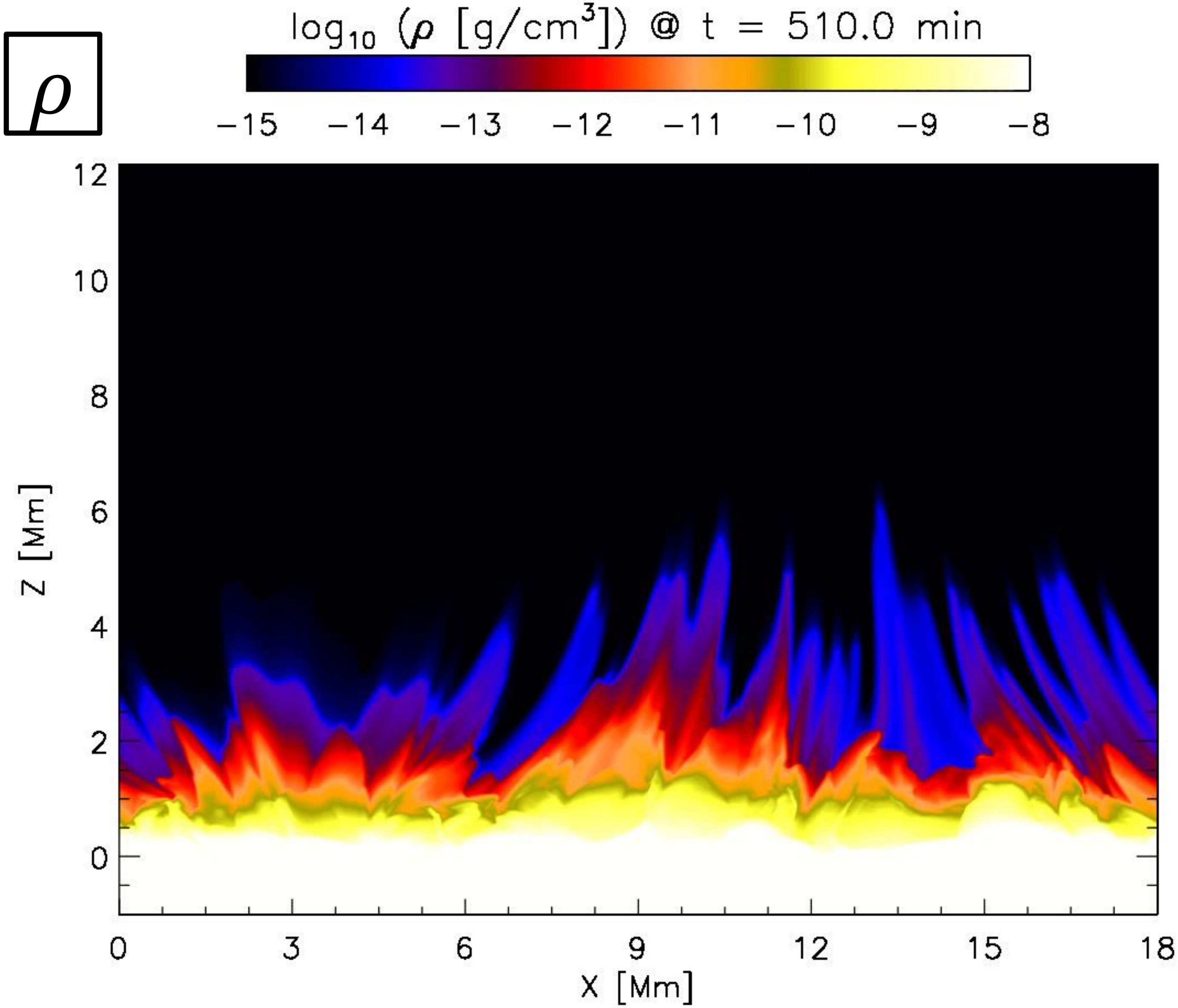
Radiative MHD simulations of chromospheric jets

Iijima & TY (2015); Iijima (2016, PhD UTokyo)

Typical case: T_c = 0.4 MK, B_0 = 30 G



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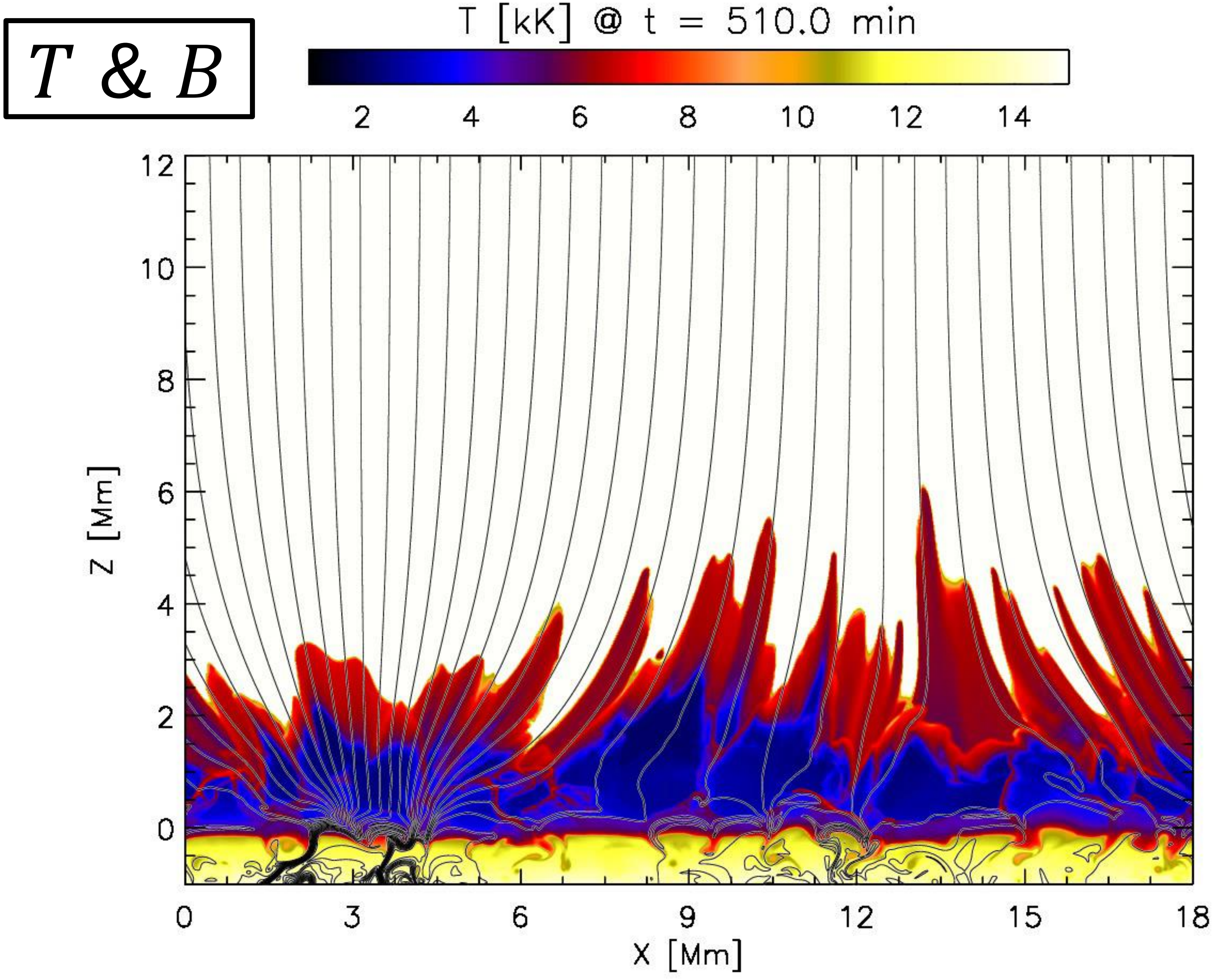

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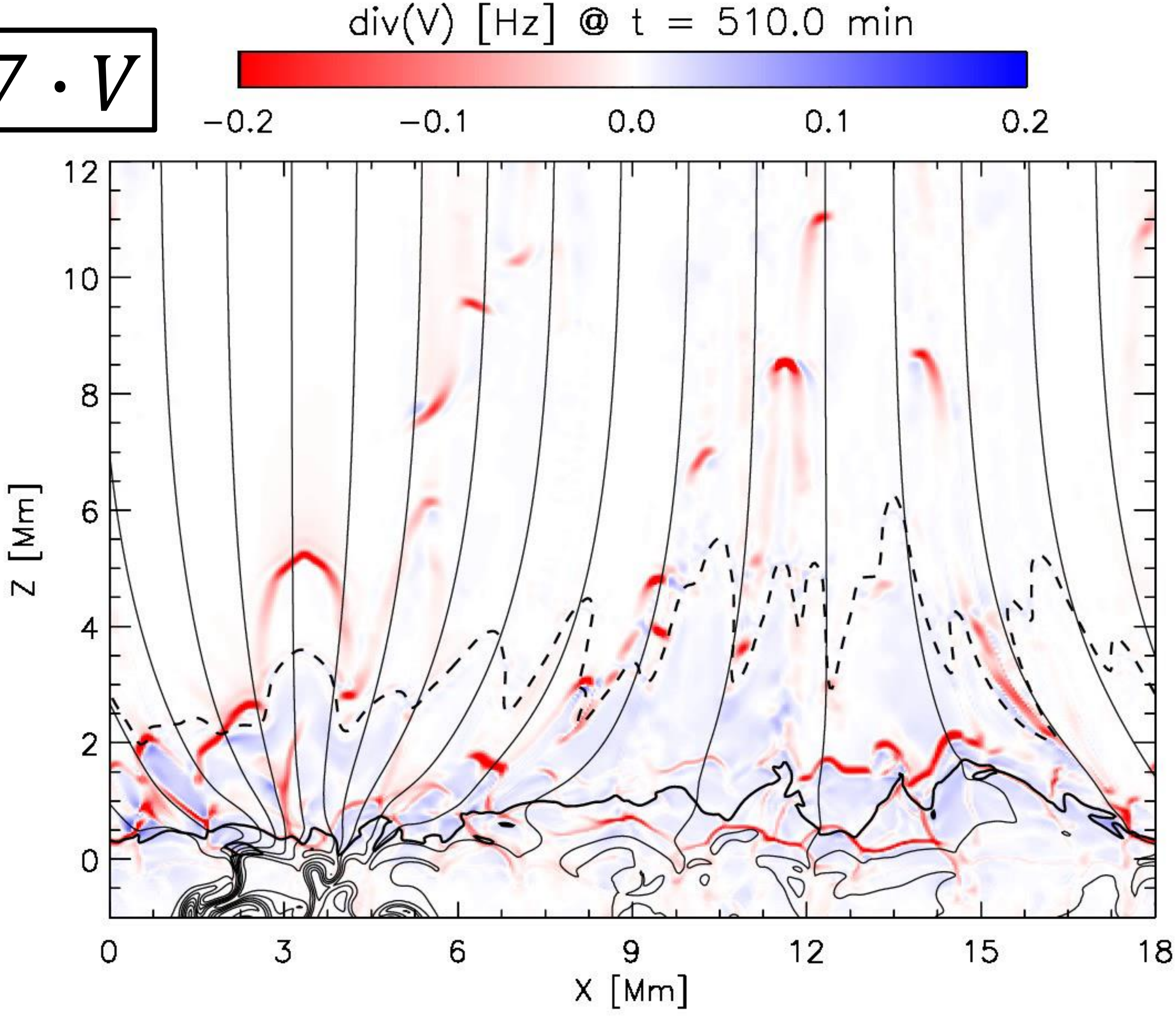
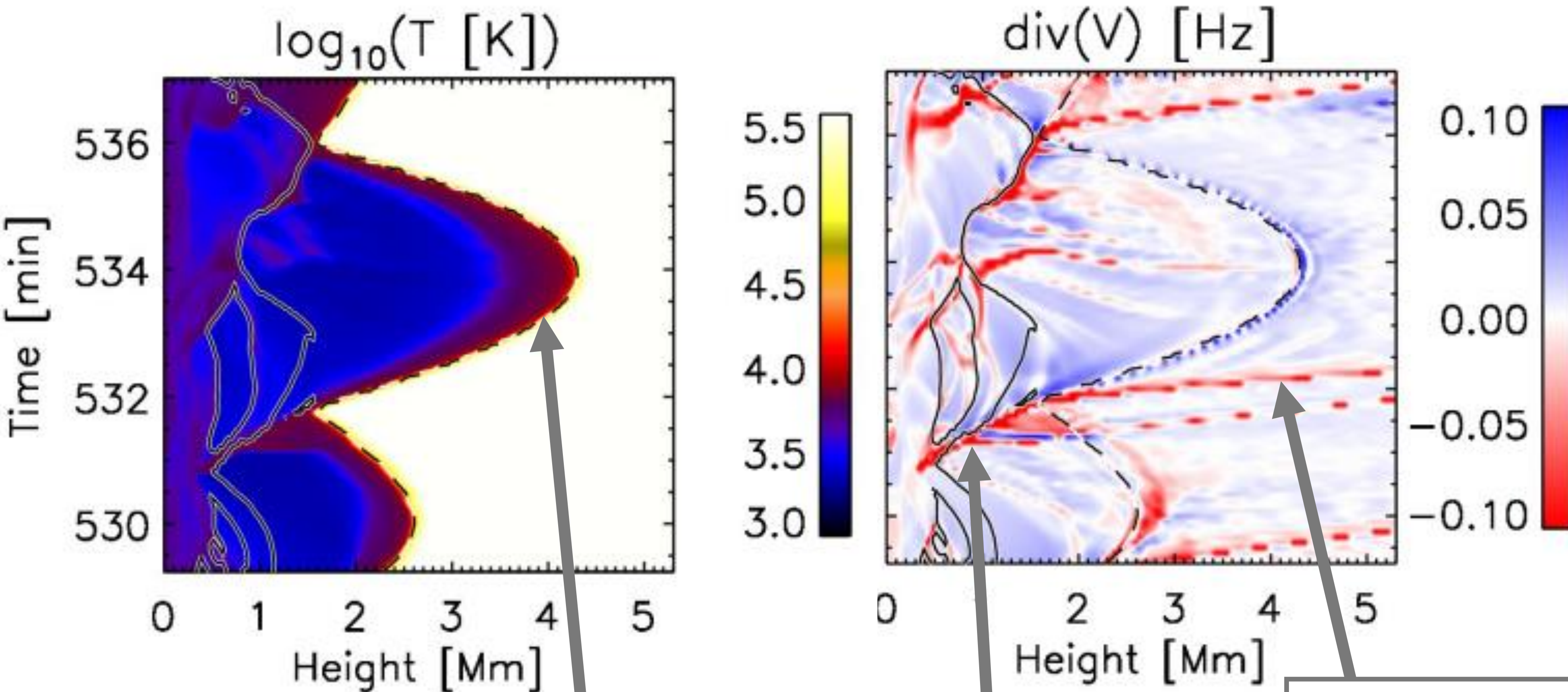
$\nabla \cdot V$



Rebound-shock ejection of jets

Iijima & TY (2015); Iijima (2016, PhD UTokyo)

1D distribution along a field line passing through the top of a jet



shock in corona

shock in chromosphere

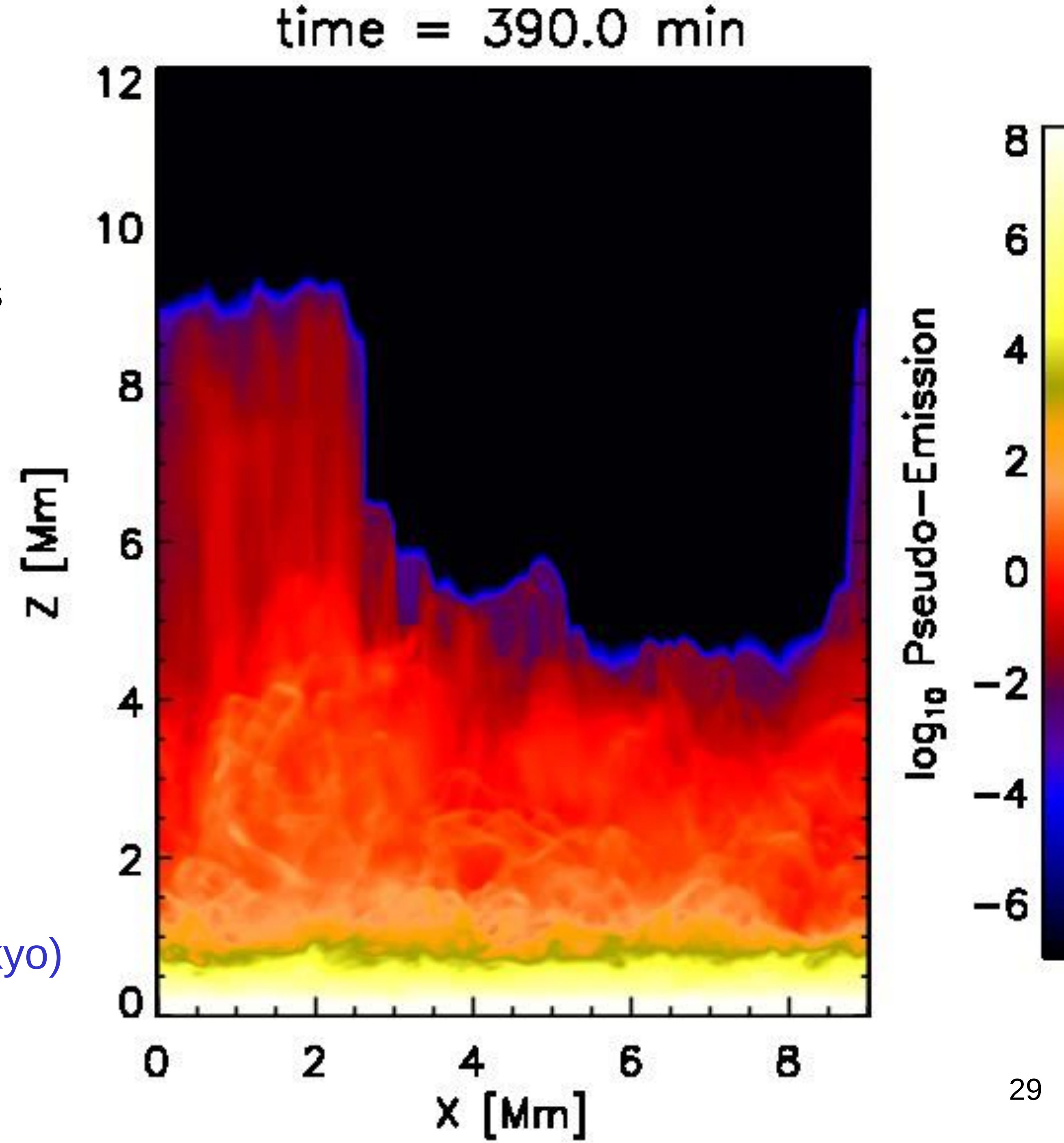
Jet "front":
contact discontinuity between
chromospheric and coronal plasmas

Results

Preliminary

Synthesized brightness

$$\epsilon = \int n_{\mathrm{e}} n_{\mathrm{H}} G(T) \mathrm{d}l$$



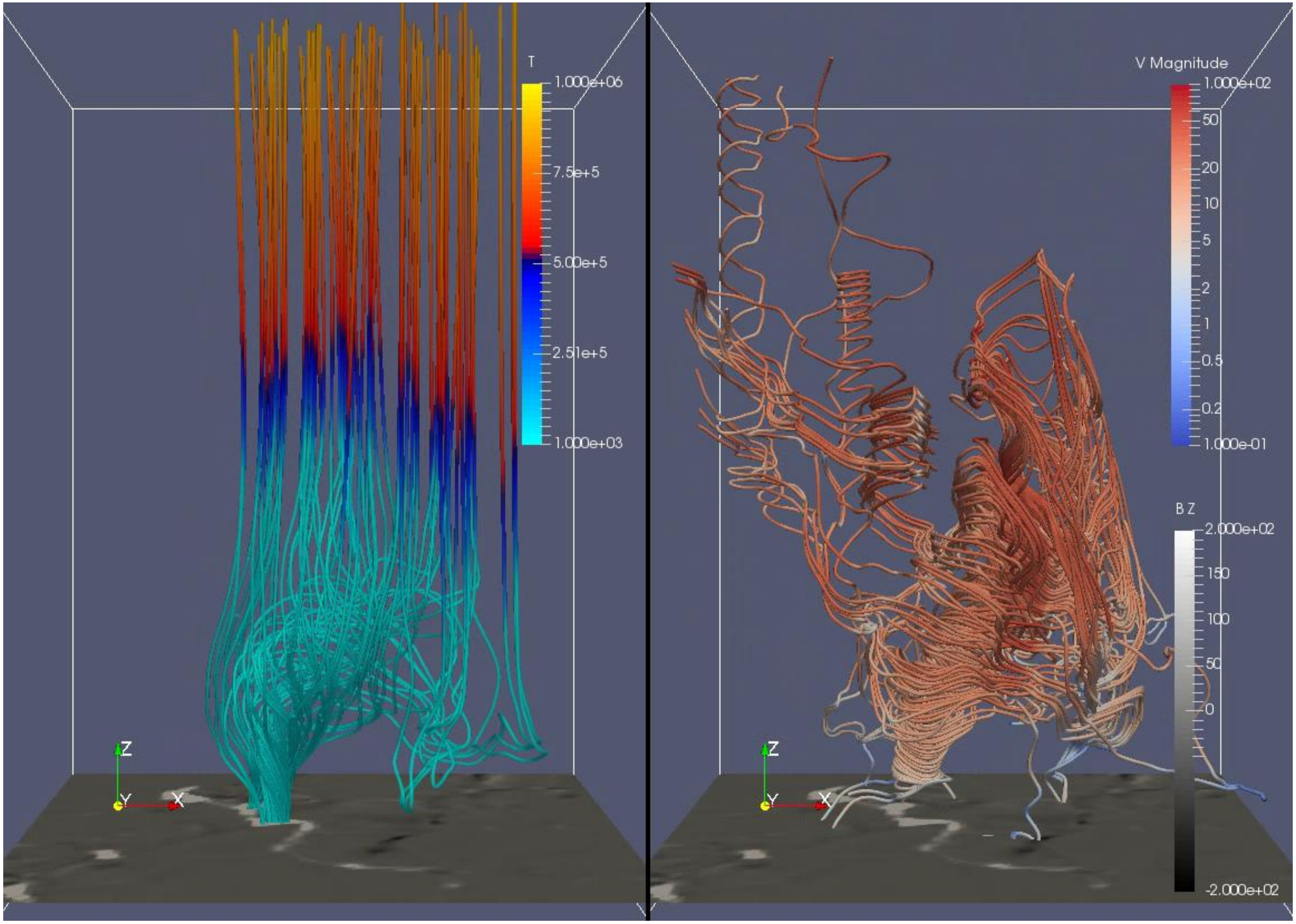
Iijima & TY (2016);
Iijima (2016, PhD UTokyo)

Iijima & TY (2016); Iijima (2016, PhD UTokyo)

Preliminary

magnetic field lines & T color

stream lines & |V| color



Hinode results on chromospheric dynamics

Waves

Transverse waves found in prominences (Okamoto+ 2007), spicules (De Pontieu+ 2007), evidence of the resonant-absorption thermalization (Okamoto+ 2007)

Prominence internal flows

Turbulent flows inside (Berger+ 2008; 2010)

Chromospheric jets (Spicules)

Extensive statistical studies are carried out.

→ By combination with radiative MHD simulations, understanding of the driving mechanisms are going to be achieved.

Chromospheric reconnection

Anemone jets (Shibata+ 2007), penumbral micro-jets (Katsukawa+ 2007)

→ Ubiquitous magnetic reconnection

End

Basic equations

Iijima & TY (2015); Iijima (2016, PhD UTokyo)

Magnetohydrodynamic equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{V}) = 0$$

$$\frac{\partial (\rho \boldsymbol{V})}{\partial t} + \nabla \cdot \left[\rho \boldsymbol{V} \otimes \boldsymbol{V} + \left(p + \frac{B^2}{8\pi} \right) \boldsymbol{I} - \frac{\boldsymbol{B} \otimes \boldsymbol{B}}{4\pi} \right] = \rho \boldsymbol{g}$$

$$\frac{\partial e_{\mathrm{tot}}}{\partial t} + \nabla \cdot \left[\left(e_{\mathrm{tot}} + p + \frac{B^2}{8\pi} \right) \boldsymbol{V} - \frac{1}{4\pi} \boldsymbol{B} (\boldsymbol{V} \cdot \boldsymbol{B}) \right] = \rho (\boldsymbol{g} \cdot \boldsymbol{V}) + Q_{\mathrm{cnd}} + Q_{\mathrm{rad}}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} + \nabla \cdot (\boldsymbol{V} \otimes \boldsymbol{B} - \boldsymbol{B} \otimes \boldsymbol{V}) = 0$$

EoS for LTE plasma (tabulated)

Radiative cooling Iijima & TY (2015); Iijima (2016, PhD UTokyo)

Total cooling term is switched according to the vertical column density

$$Q_{\mathrm{rad}} = \left[1 - \xi\left(m_c\right)\right] Q_{\mathrm{thick}} + \xi\left(m_c\right) Q_{\mathrm{thin}}$$

$$Q_{\mathrm{thick}} = \mathrm{e}^{-(\tau/\tau_0)^2} Q_{\mathrm{J}} + \left[1 - \mathrm{e}^{-(\tau/\tau_0)^2}\right] Q_{\mathrm{F}}.$$

$$Q_{\mathrm{F}} = -\nabla \cdot \boldsymbol{F}, \quad \boldsymbol{F} = \int_{4\pi} \boldsymbol{n} I(\boldsymbol{n}) d\boldsymbol{n}$$

$$Q_{\mathrm{J}} = 4\pi\alpha_{\mathrm{R}}\left(J - S\right), \quad J = \frac{1}{4\pi}\int_{4\pi} I(\boldsymbol{n}) d\boldsymbol{n}.$$

Intensity I (w/ gray approx.) is obtained by solving radiative transfer eq.

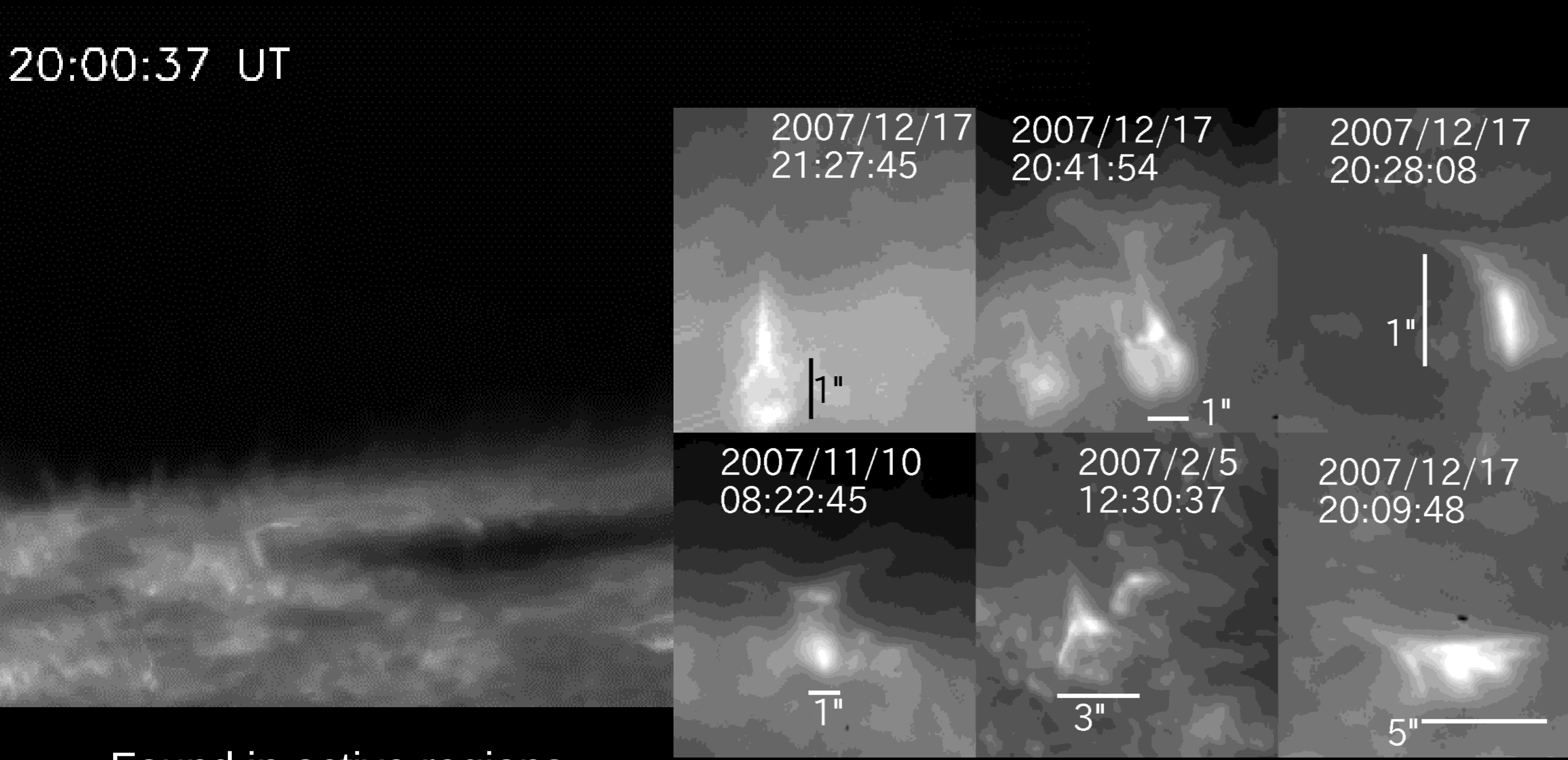
$$\frac{dI}{ds} = \alpha\left(B - I\right)$$

$$Q_{\mathrm{thin}} = -n_H n_e \Lambda(T)$$

radiative loss function:
CHIANTI database
with extension by Goodman & Judge (2012) for low temperature plasma

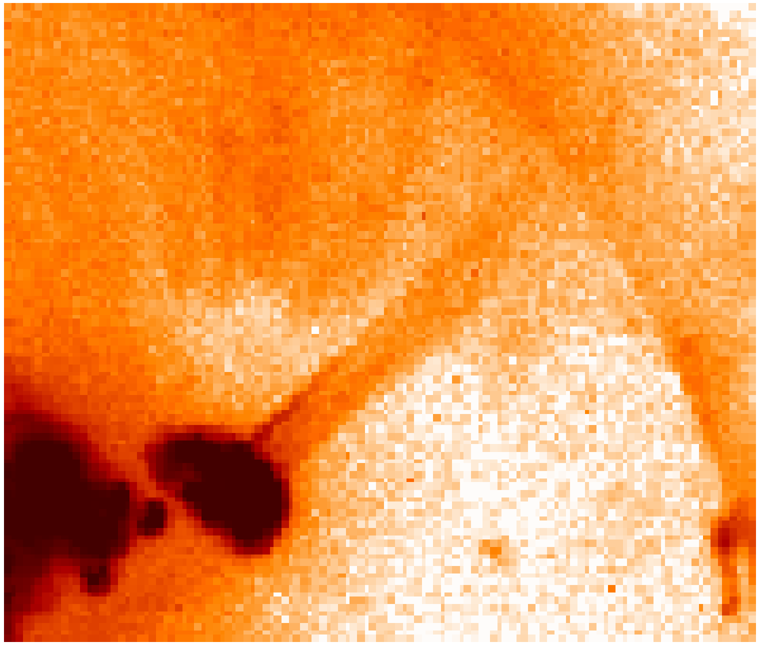
Chromospheric Anemone Jets

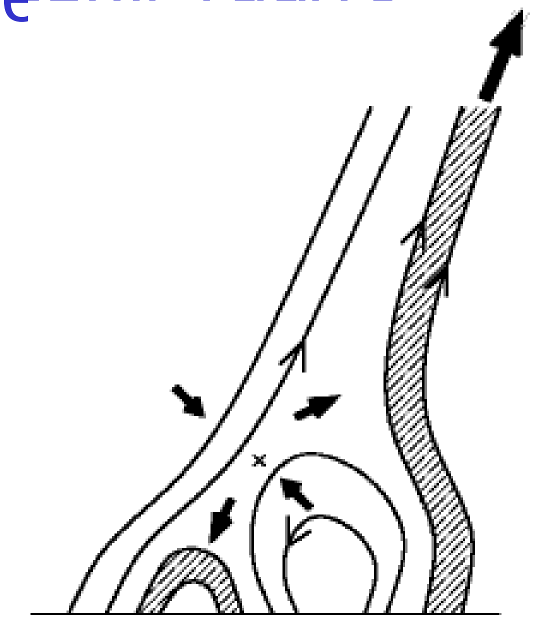
(Shibata et al. 2007;
Nishizuka et al. 2011)



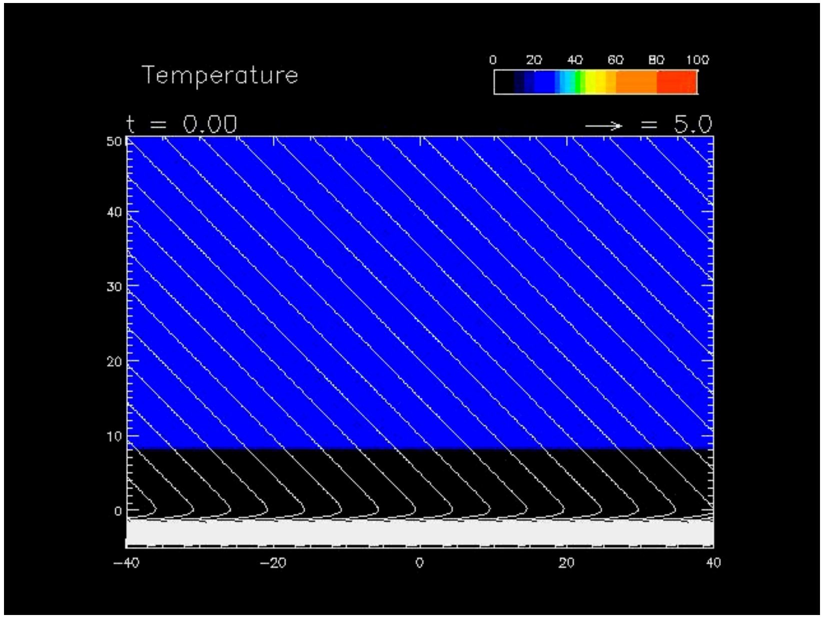
Found in active regions
Cusp-shaped structure and bright footpoint
length 1-4 Mm, lifetime 100-500s
velocity 5-20km/s ~local Alfven speed

Coronal X-ray Jets found in early 1990's



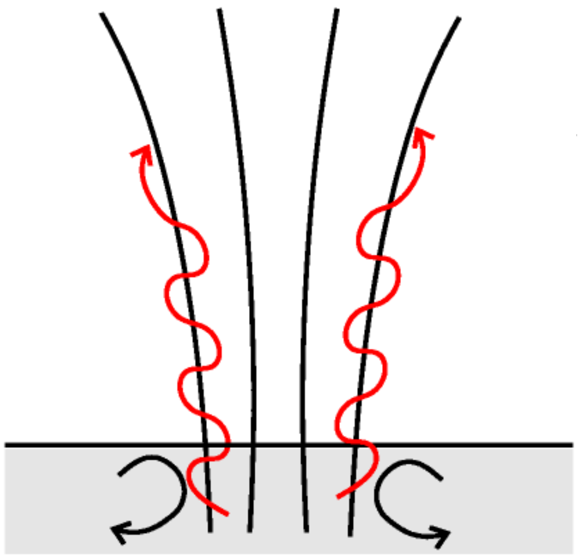


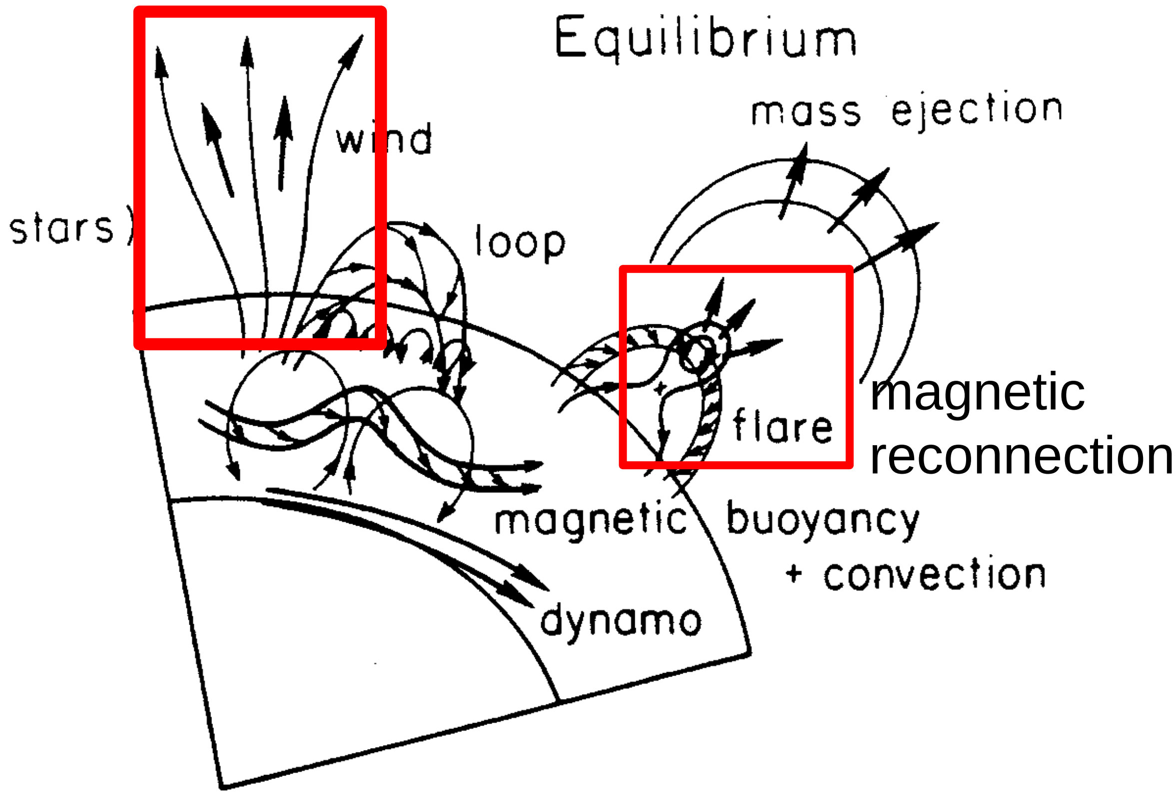
Shibata et al. 1992



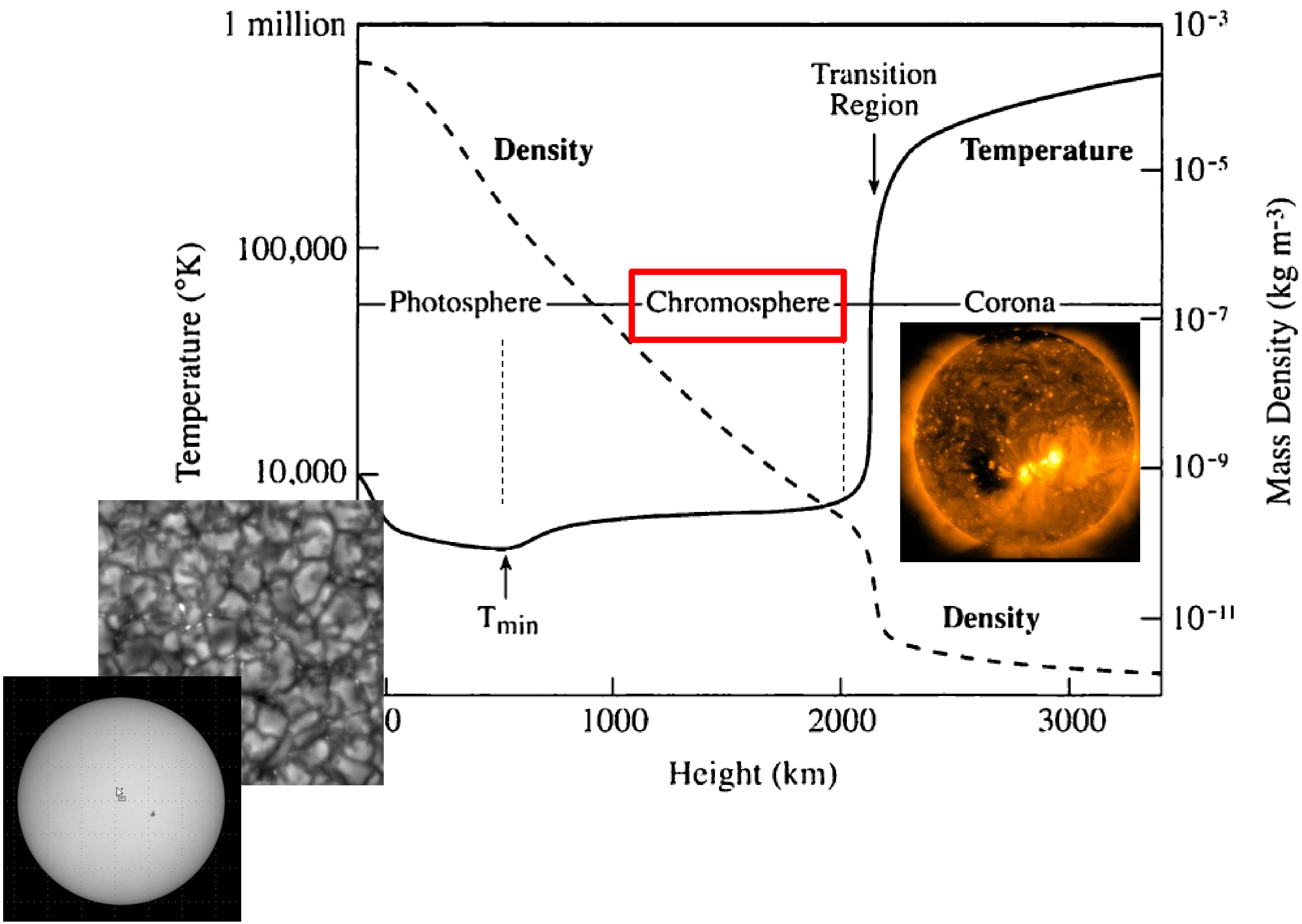
TY & Shibata (1995, 1996)

Waves as a carrier of energy





The solar atmosphere



Wave as a carrier of the energy