Relation among low atmospheric reconnection, shock formation and chromospheric jets

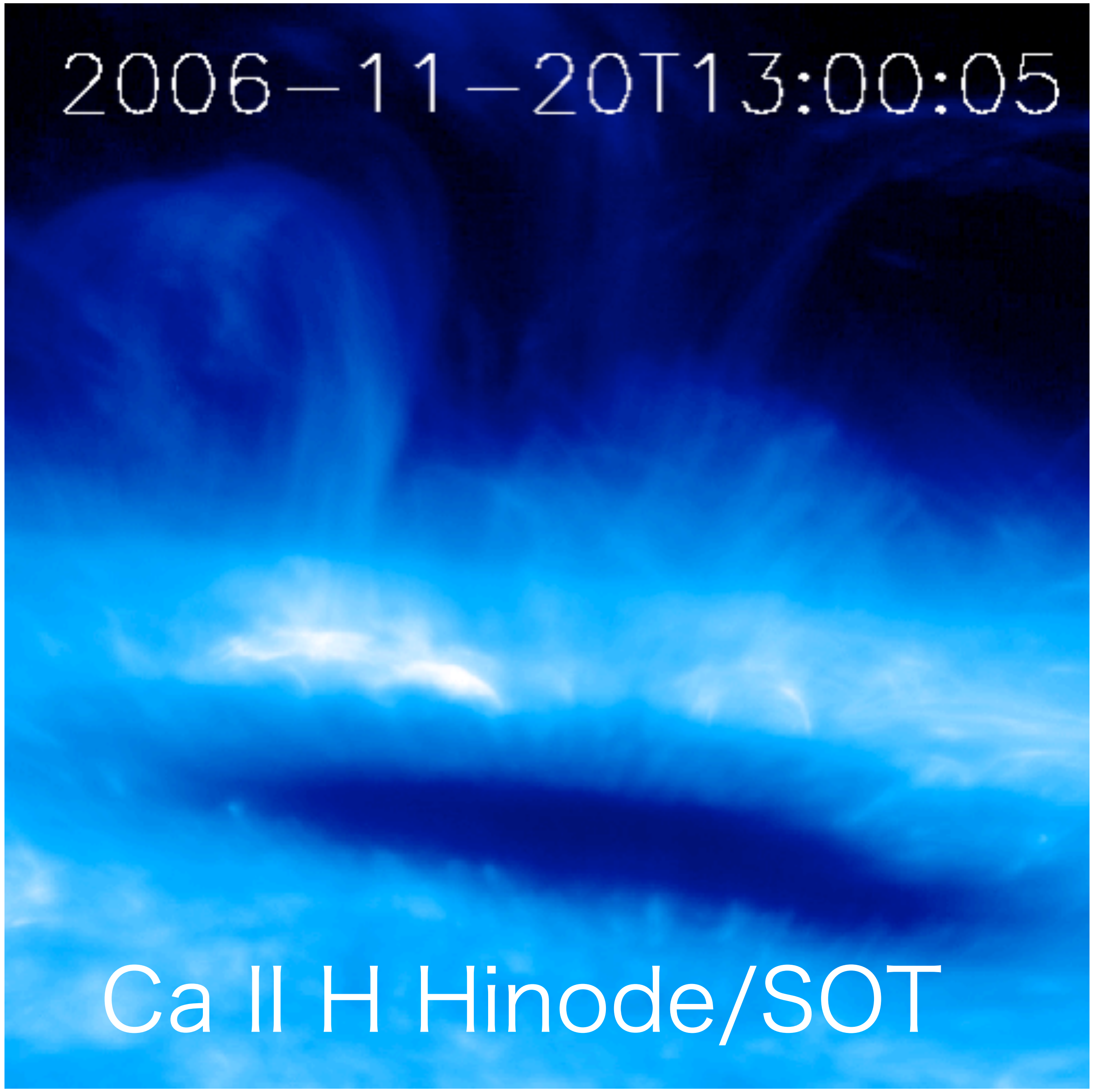
Shinsuke Takasao,
Hiroaki Isobe and Kazunari Shibata (Kyoto Univ.)

Chromospheric Jets of Various Size
Ubiquitous Reconnection

Examples:

- Spicules
- Surges
- Ca anemone jets

Ca anemone jets
time scale:
~a few-10 min.
length scale:
$10^3 - 10^4$ km >> Hp~150km
velocity:
5 - 20 km/s
(Nishizuka+2011)



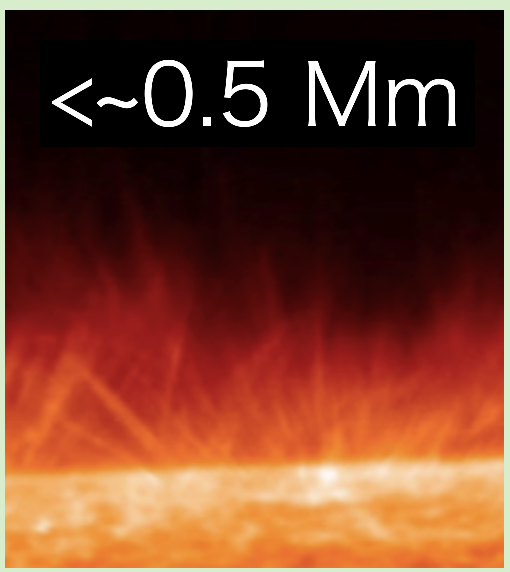
e.g. Sterling + 1993, Shibata + 2007
De Pontieu + 2007, Nishizuka + 2008
Yang + 2013, Kayshap + 2013

Classification by Size of Foot-point Structures of Jets

Size of foot-point structures of jets

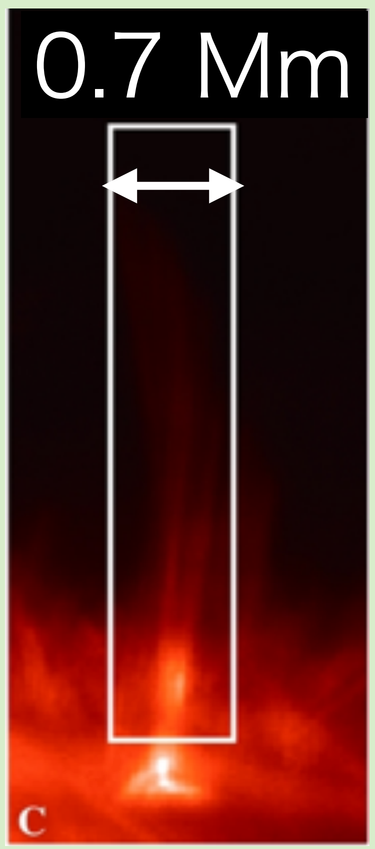
Photo./Low chrom. Upper chrom. TR/corona

Spicules

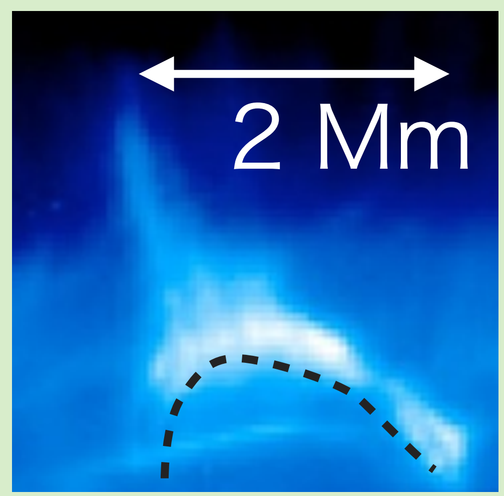


foot-points unresolved...

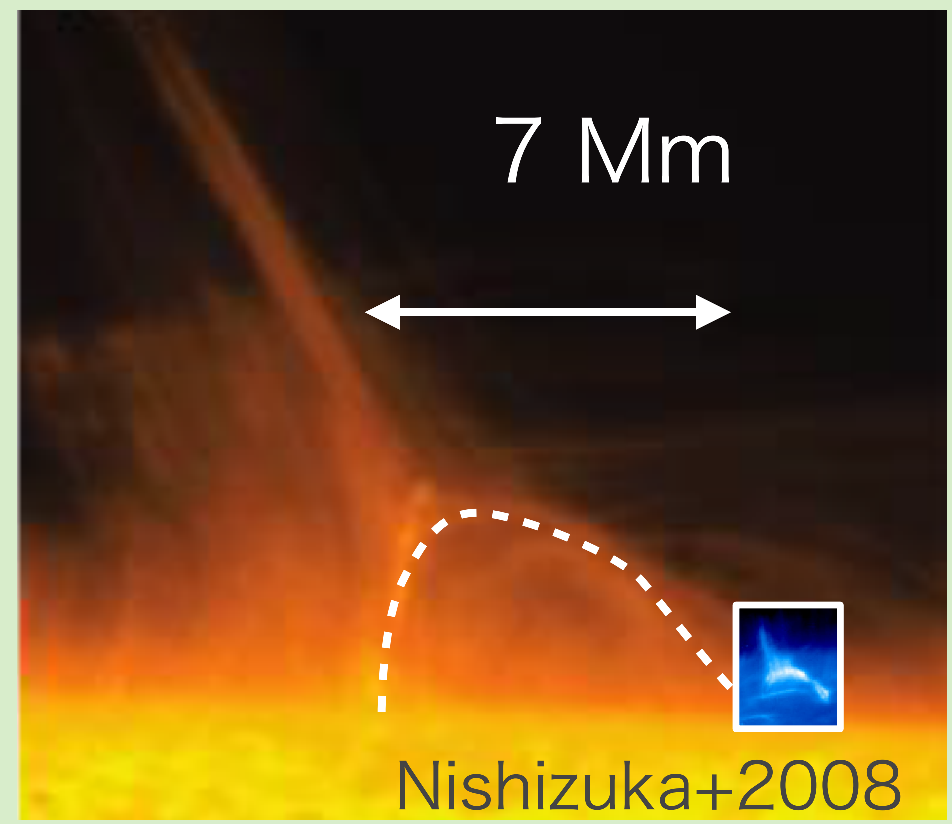
Ca jets



Singh+2012



Giant Ca jets / Surges

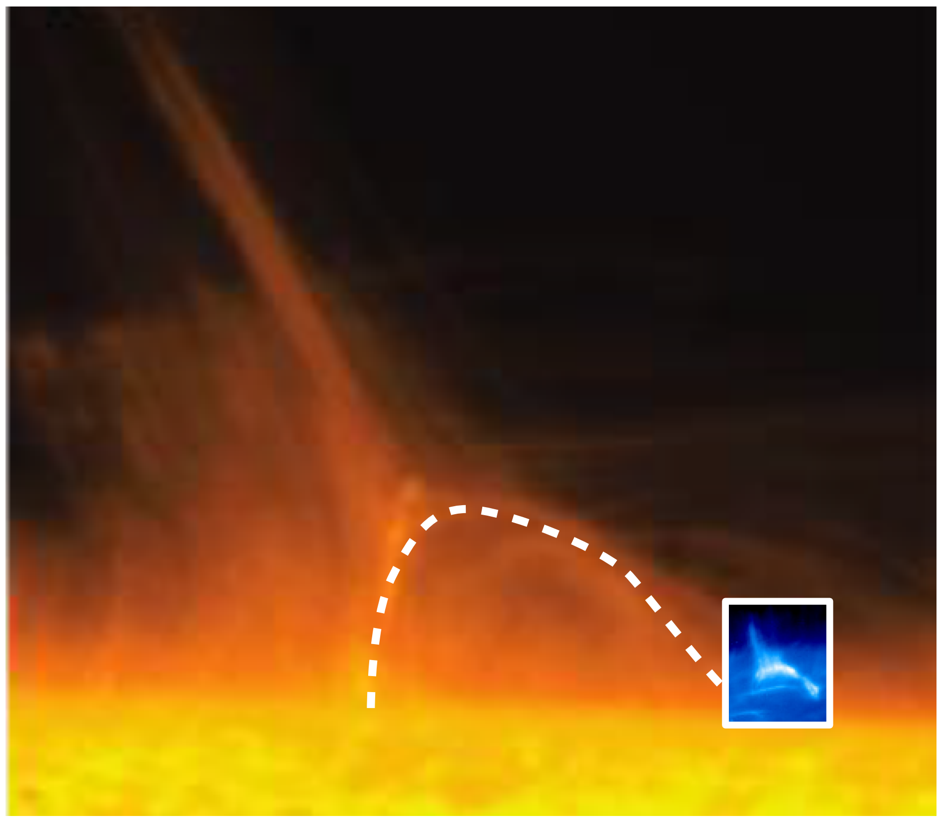


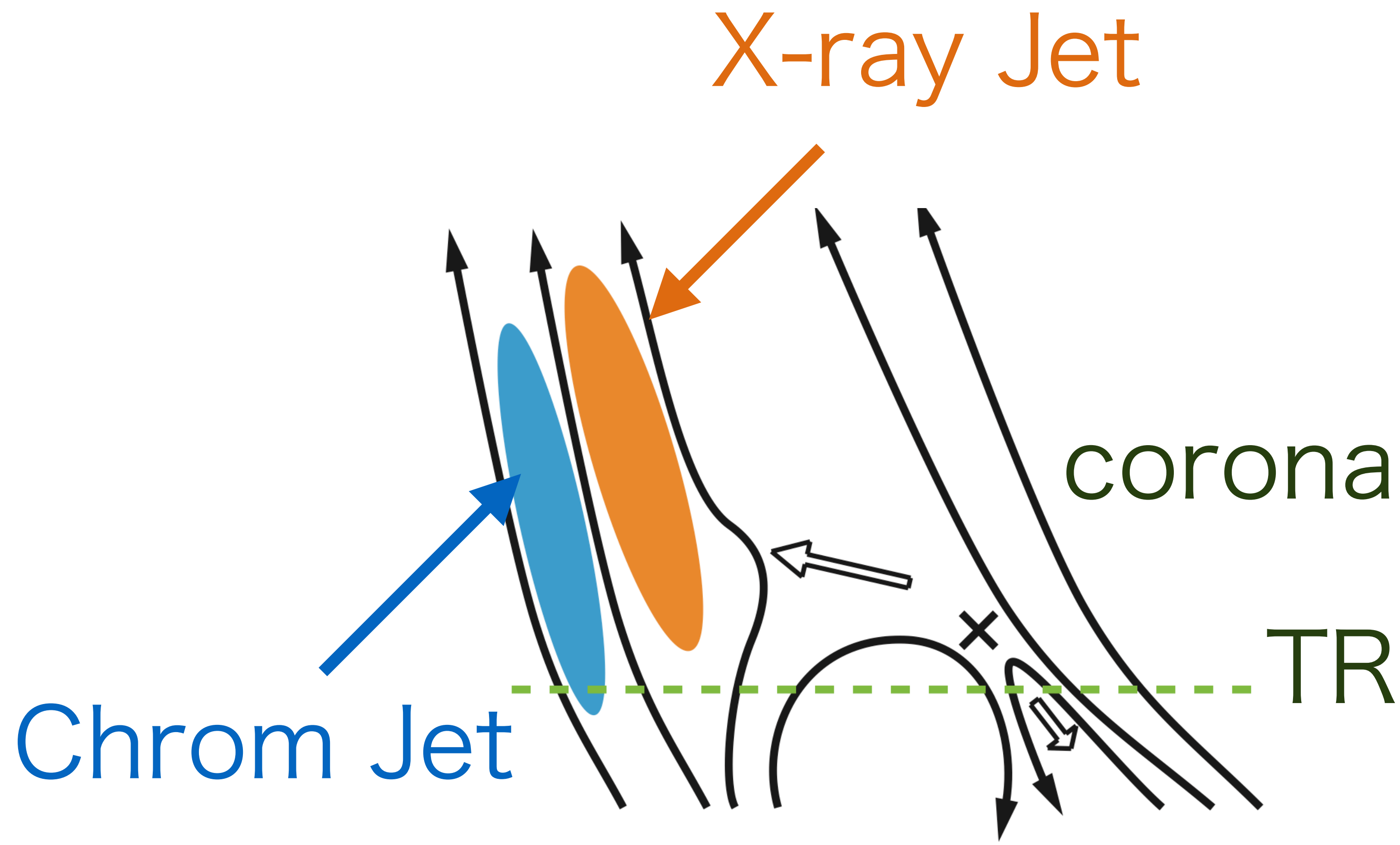
loop- or cusp-shaped foot-points

=> probably emerging flux

Magnetic Reconnection at Coronal Height: Whip-like Acceleration

Surges, giant Ca jets



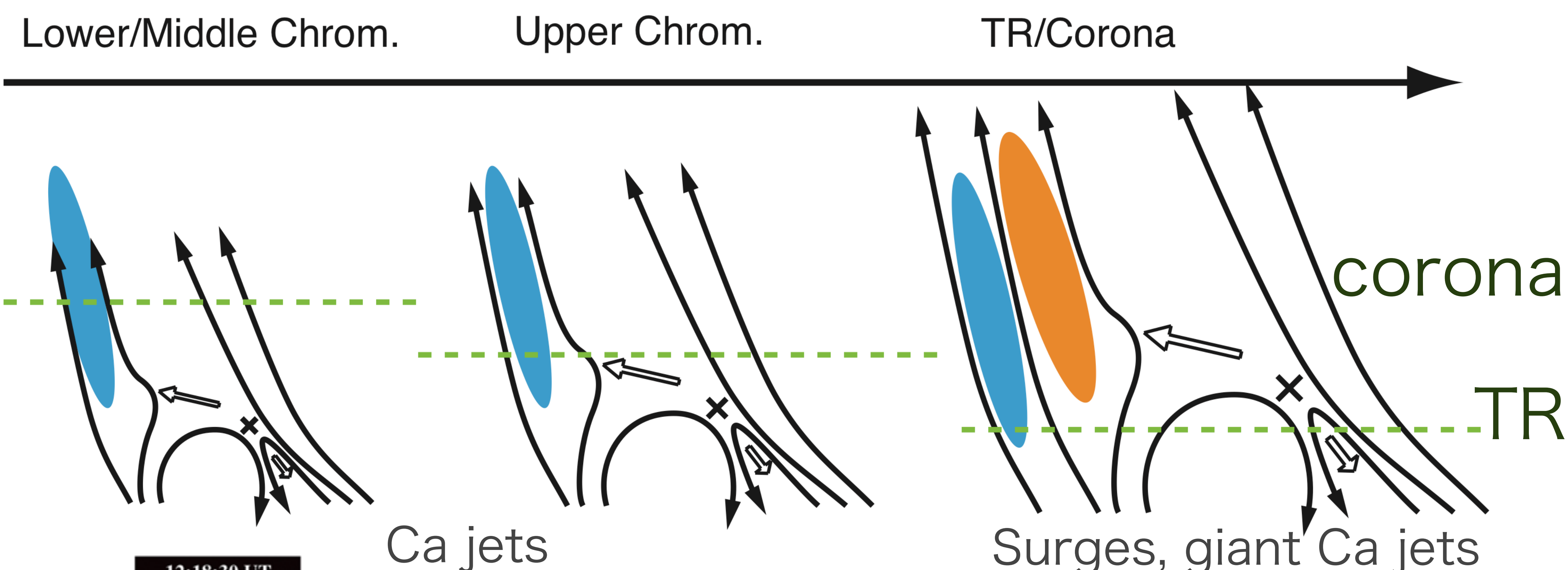


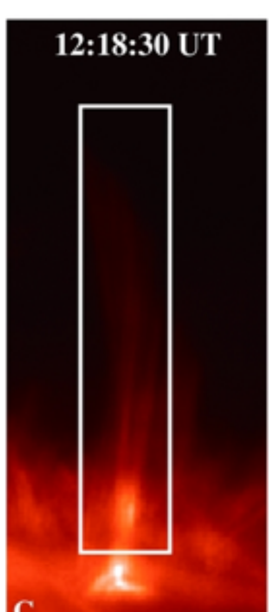
TR: Transition Region
between chrom. and corona

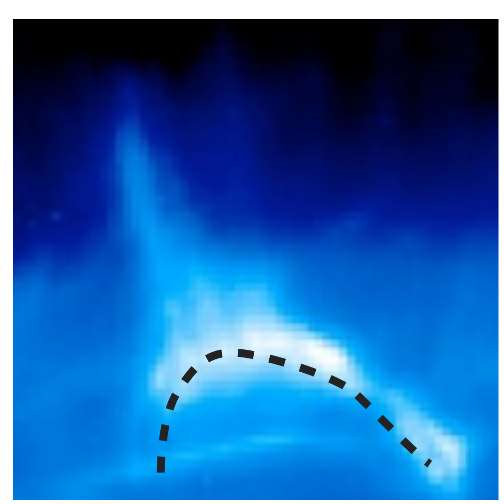
Chrom. jet:
Sling-shot
or whip-like acceleration
e.g. Yokoyama&Shibata 1996,
Moreno-Insertis+ 2013

Magnetic Reconnection can Take Place at Various Heights

Height of Reconnection point







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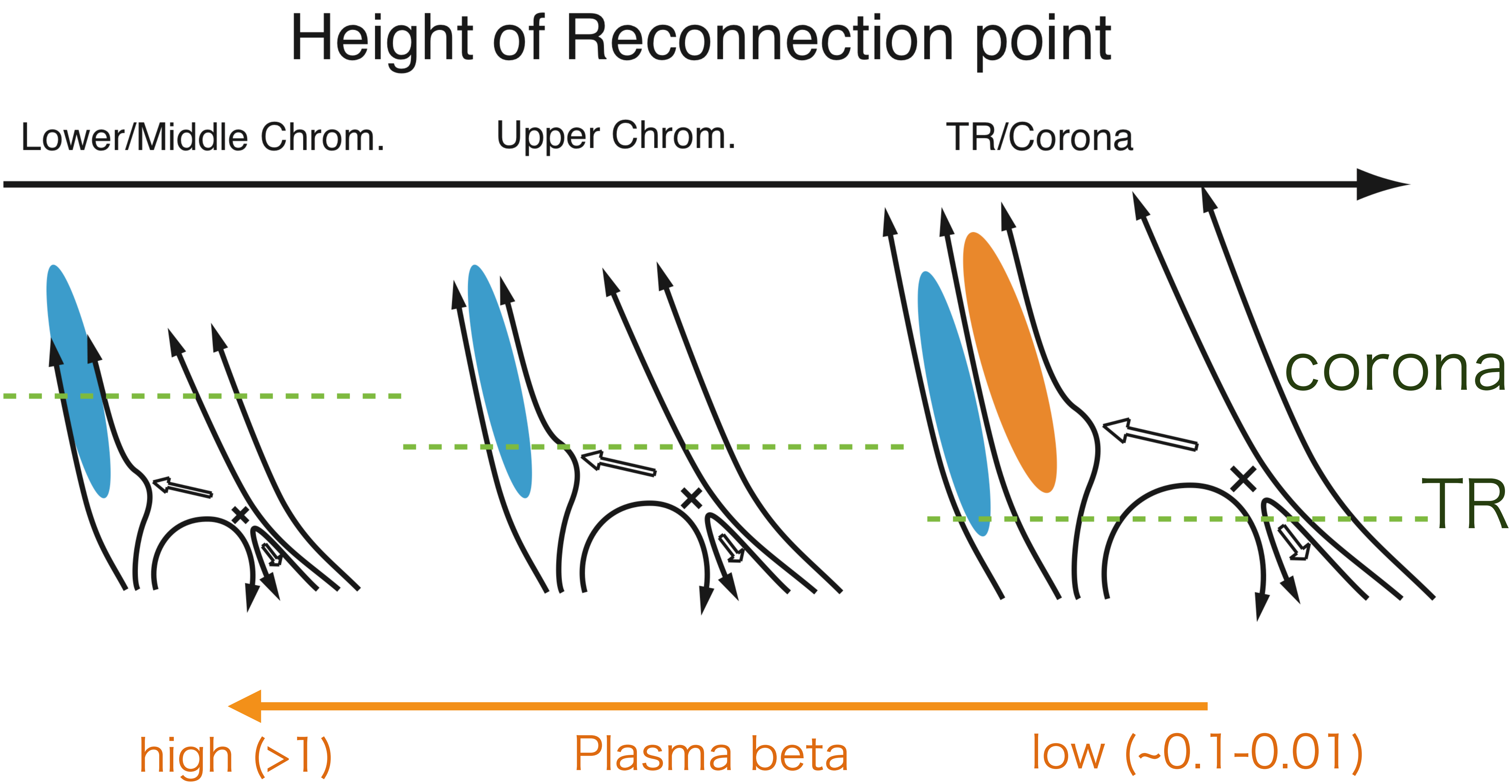
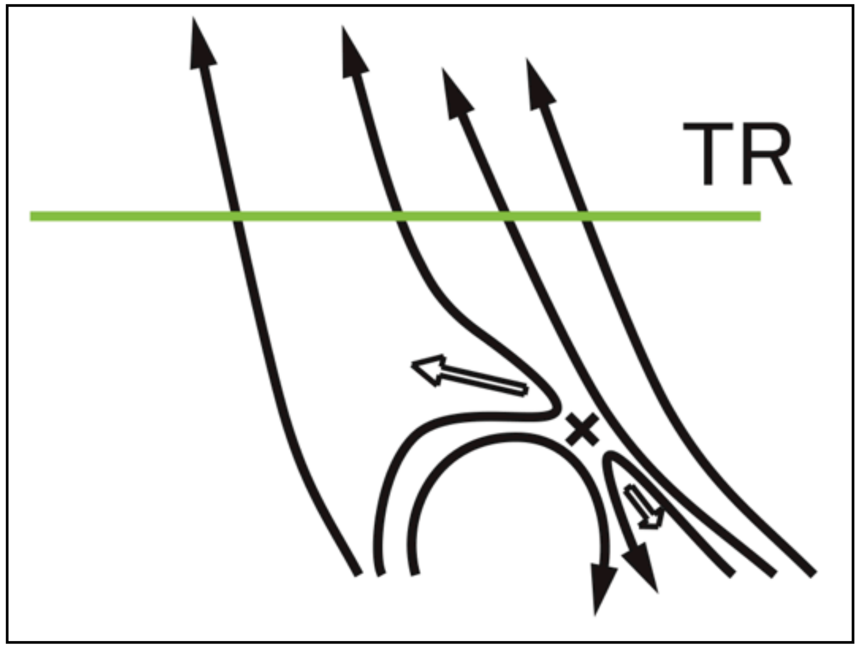


Their apparent structures are quite similar.

=> Their magnetic structures are similar.

=> Same acceleration scenario? NO!

Low Atmospheric Reconnection and Shock



Height of jets driven by the Lorentz force
(sling-shot / whip-like acceleration)

$$h_{jet} \sim H_p/\beta \sim 150/\beta \text{ km}$$

$$h_{jet,obs} \sim 1 - 4 \times 10^3 \text{ km}$$

OK for low-β plasma (corona)

No for high-β plasma (low chrom.)

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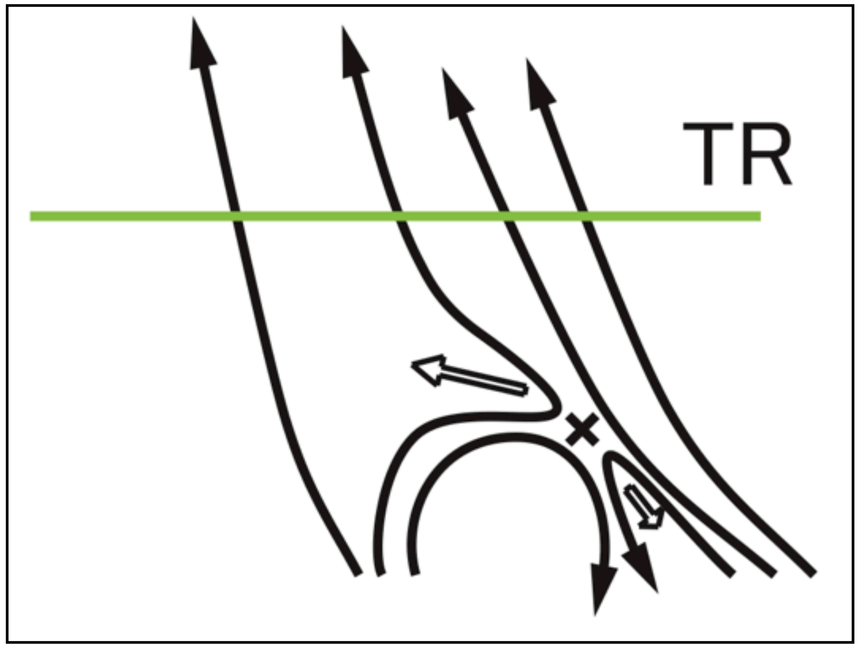

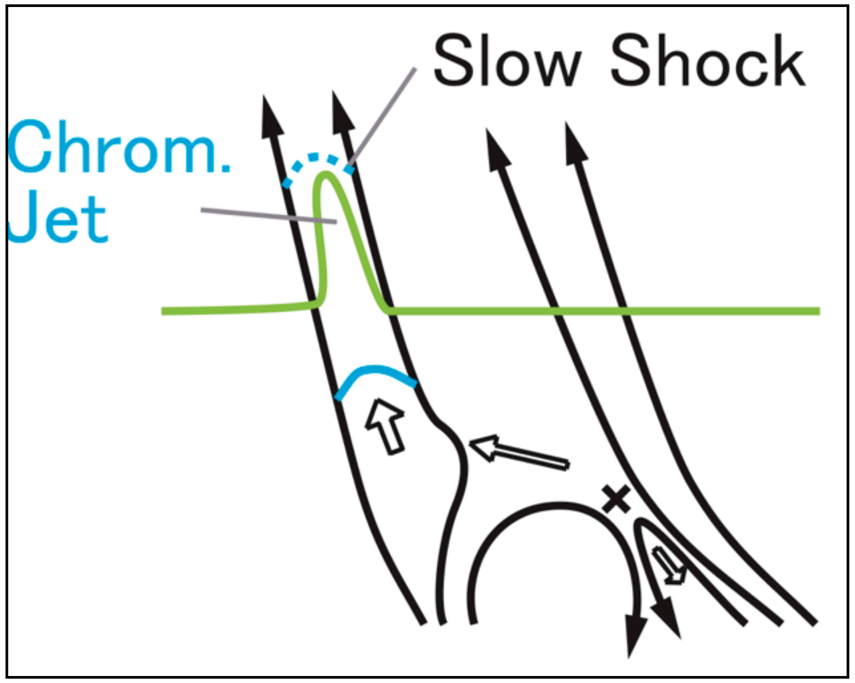

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OK for low-β plasma (corona)

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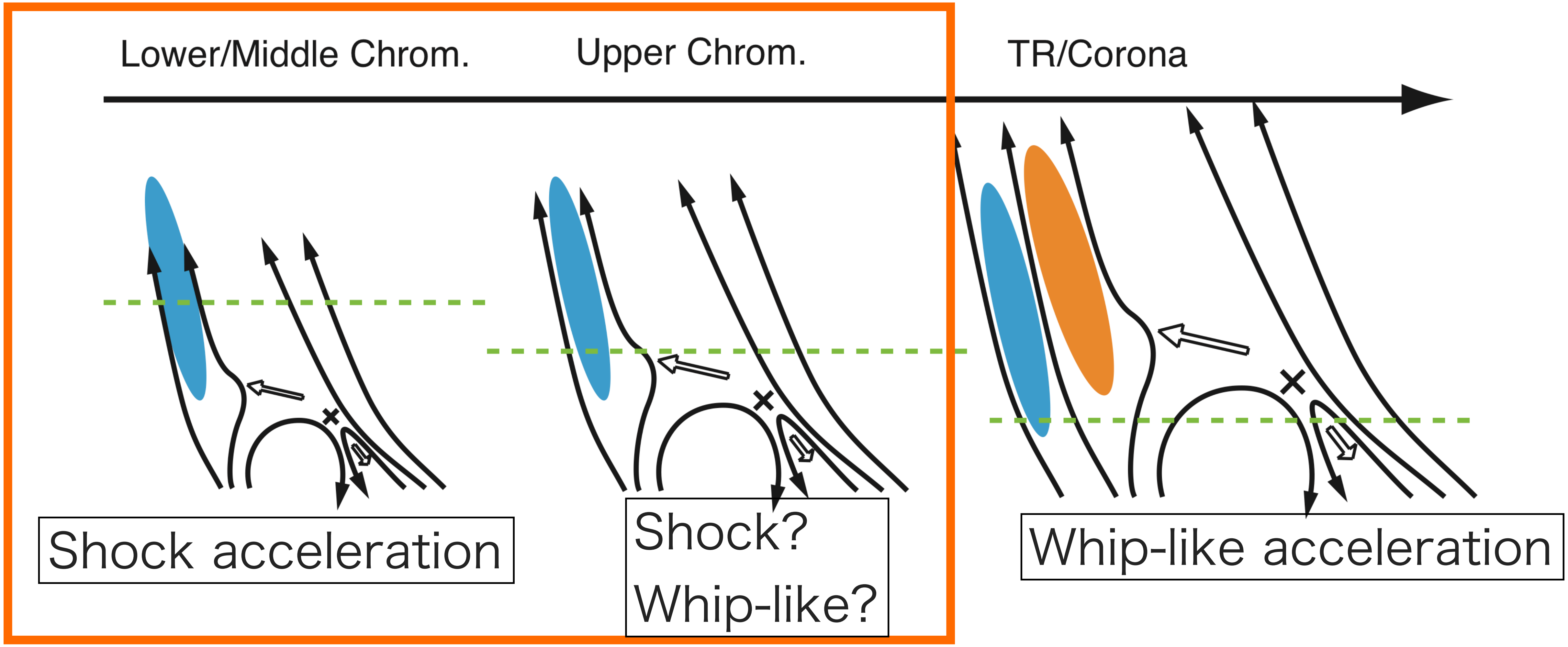
=> Shock acceleration

1. Energy release in the low chrom.
2. Slow mode waves/shocks carry the energy along a magnetic field
3. Only a fraction of the plasma in the upper chrom. (low-density plasma) is accelerated by shocks.

(e.g. Shibata+1982, 2007, Heggland+2007)

Acceleration Mechanism Depends on Height of Reconnection

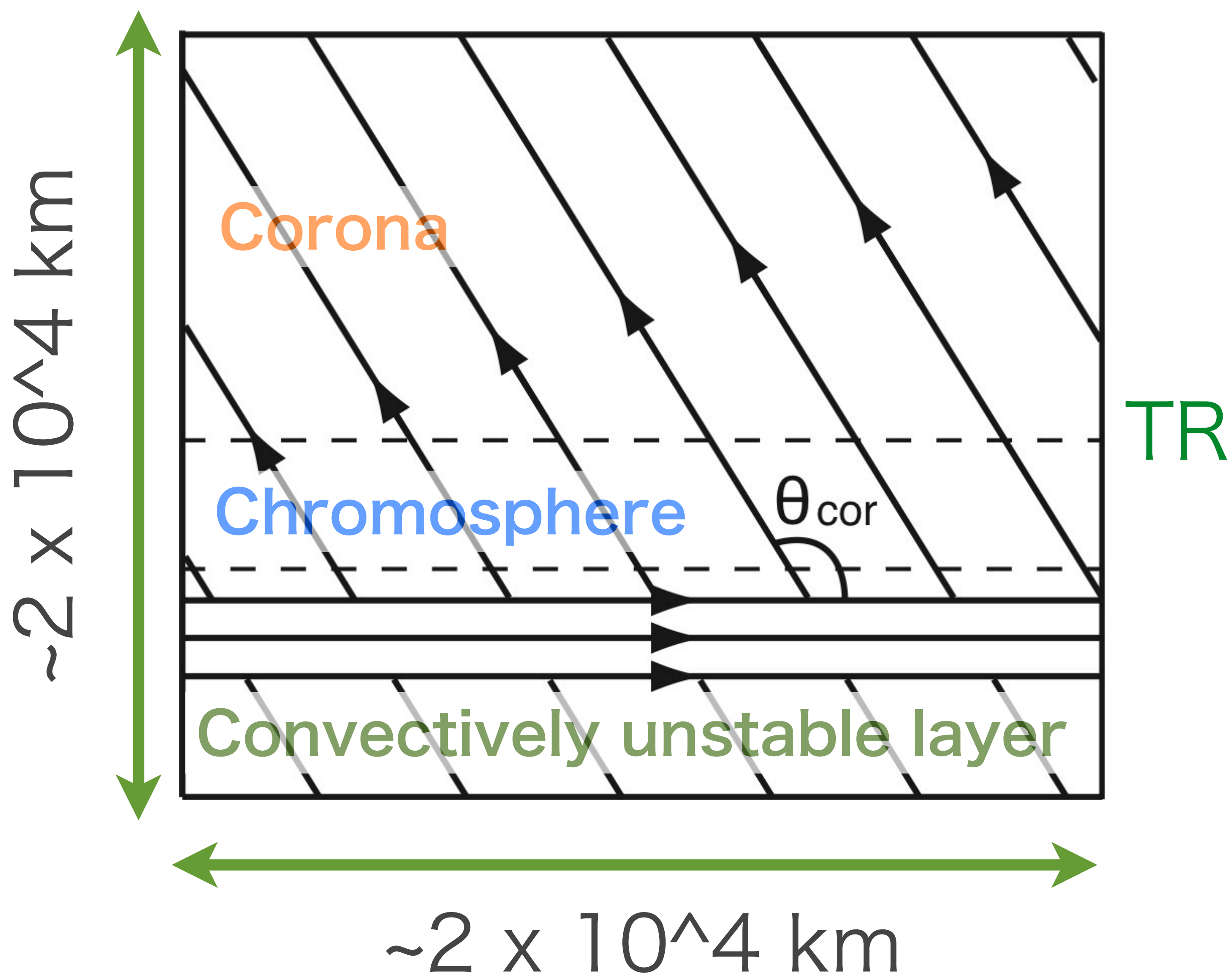
Height of Reconnection point



How shocks form? How shocks accelerate chrom. jets?

→ MHD simulation

Initial Conditions and Assumptions of Simulation

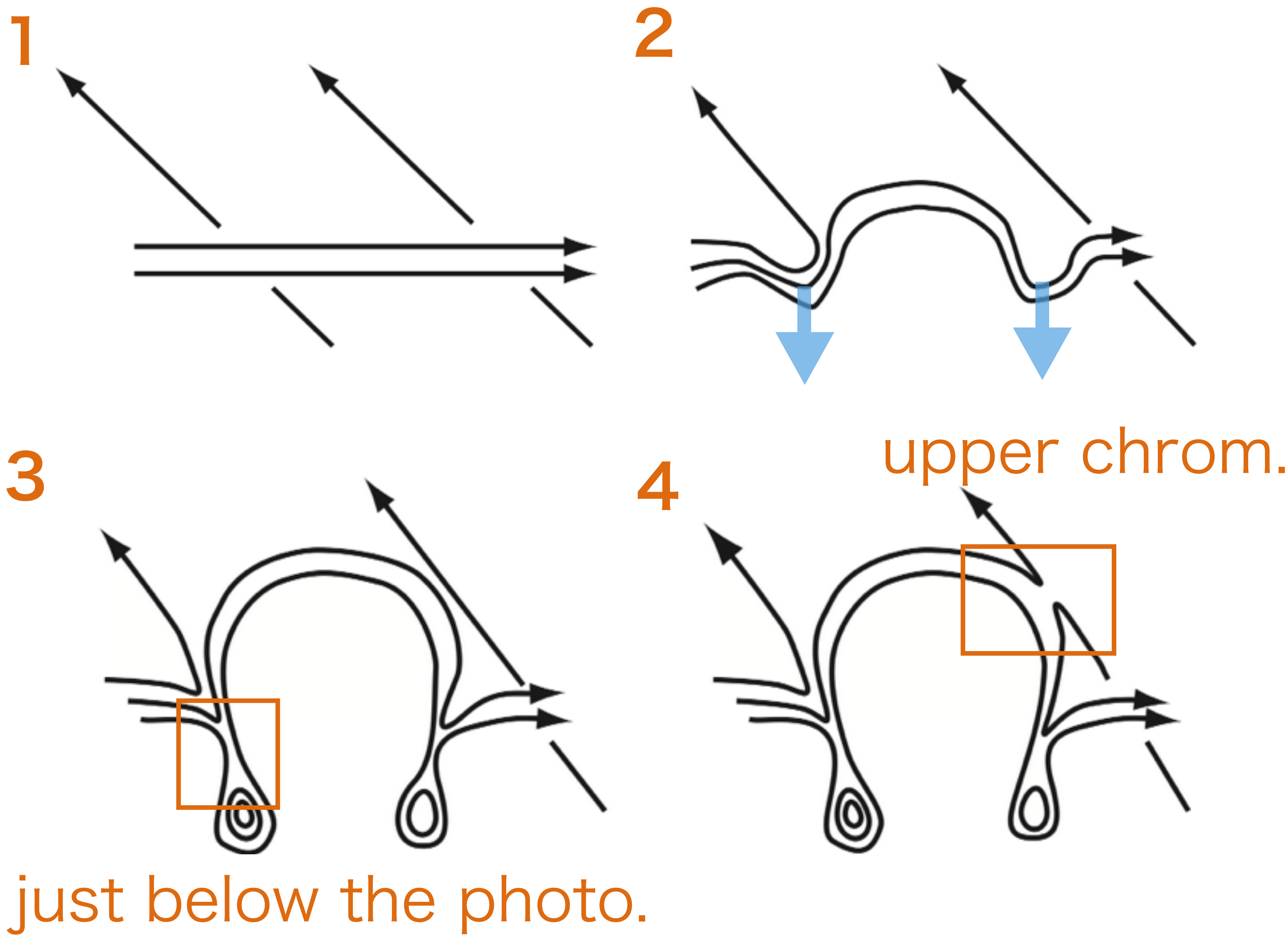


Assumptions:

- uniform gravity
- 2D MHD
- simple radiation cooling func. in the chrom.
- θ cor = $2\pi/3$
- Anomalous resistivity model (a localized resistivity model)

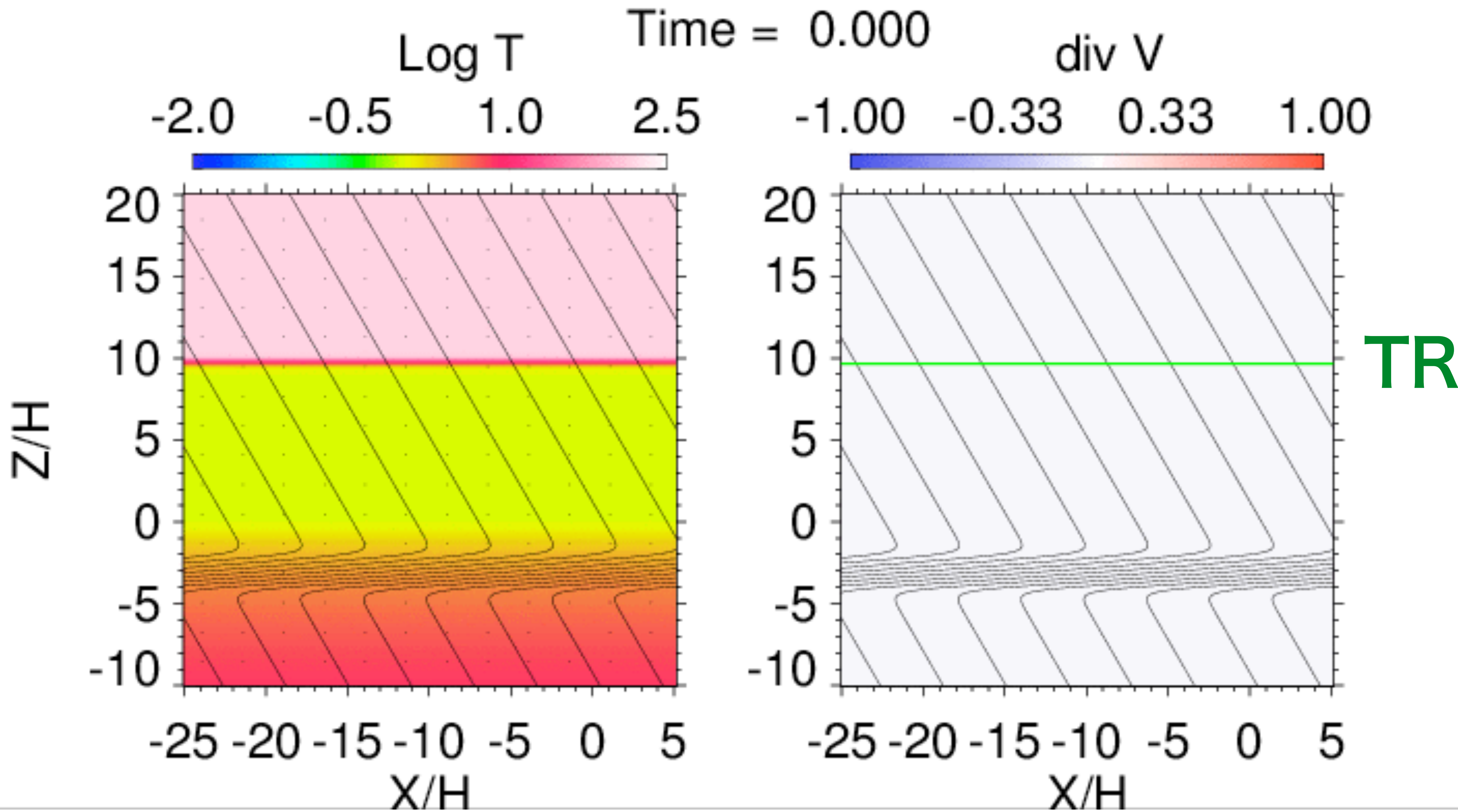
TR: transition region, where the temperature / density drastically vary (density discontinuous layer)

Where Reconnection Takes Place?

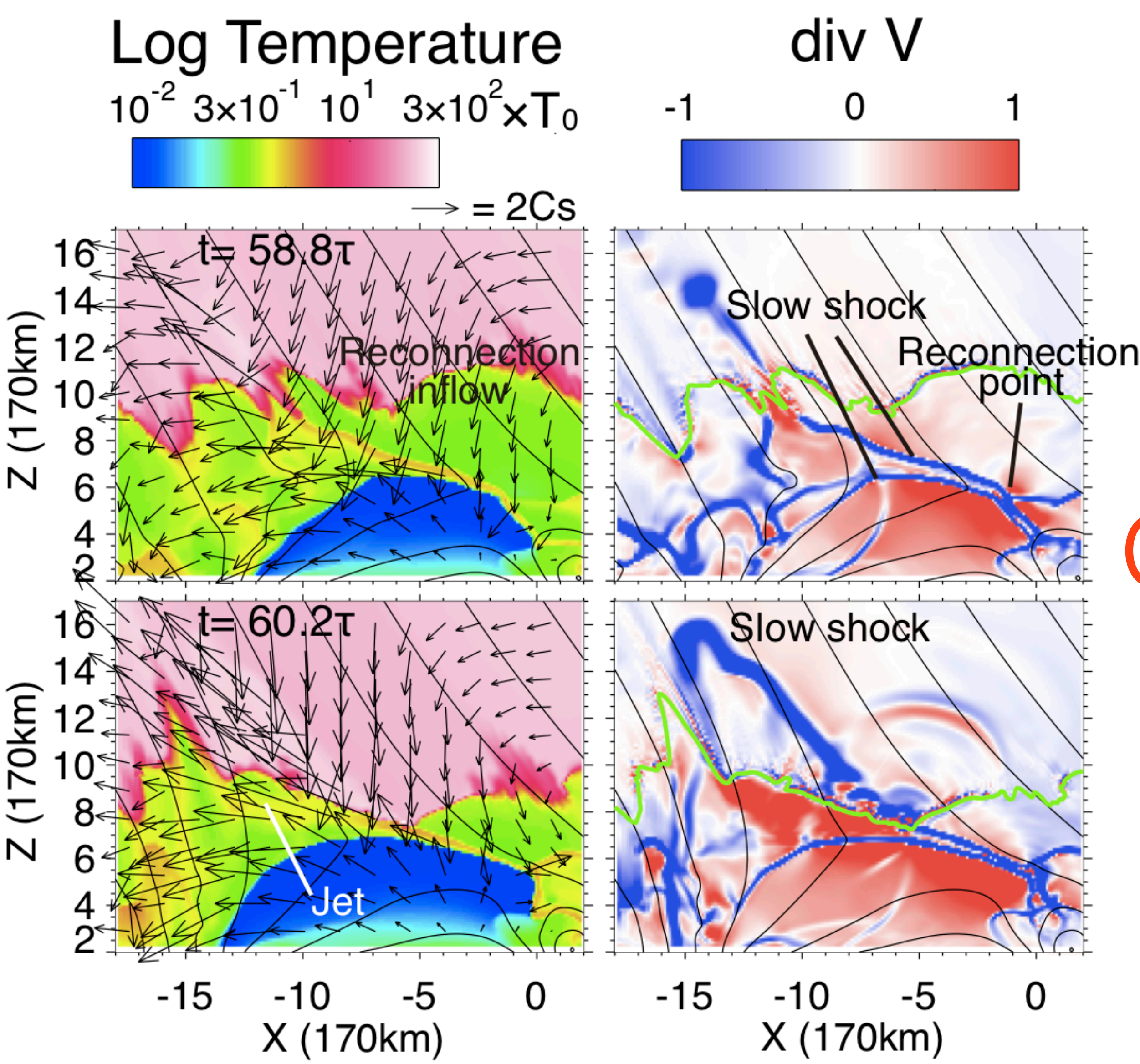


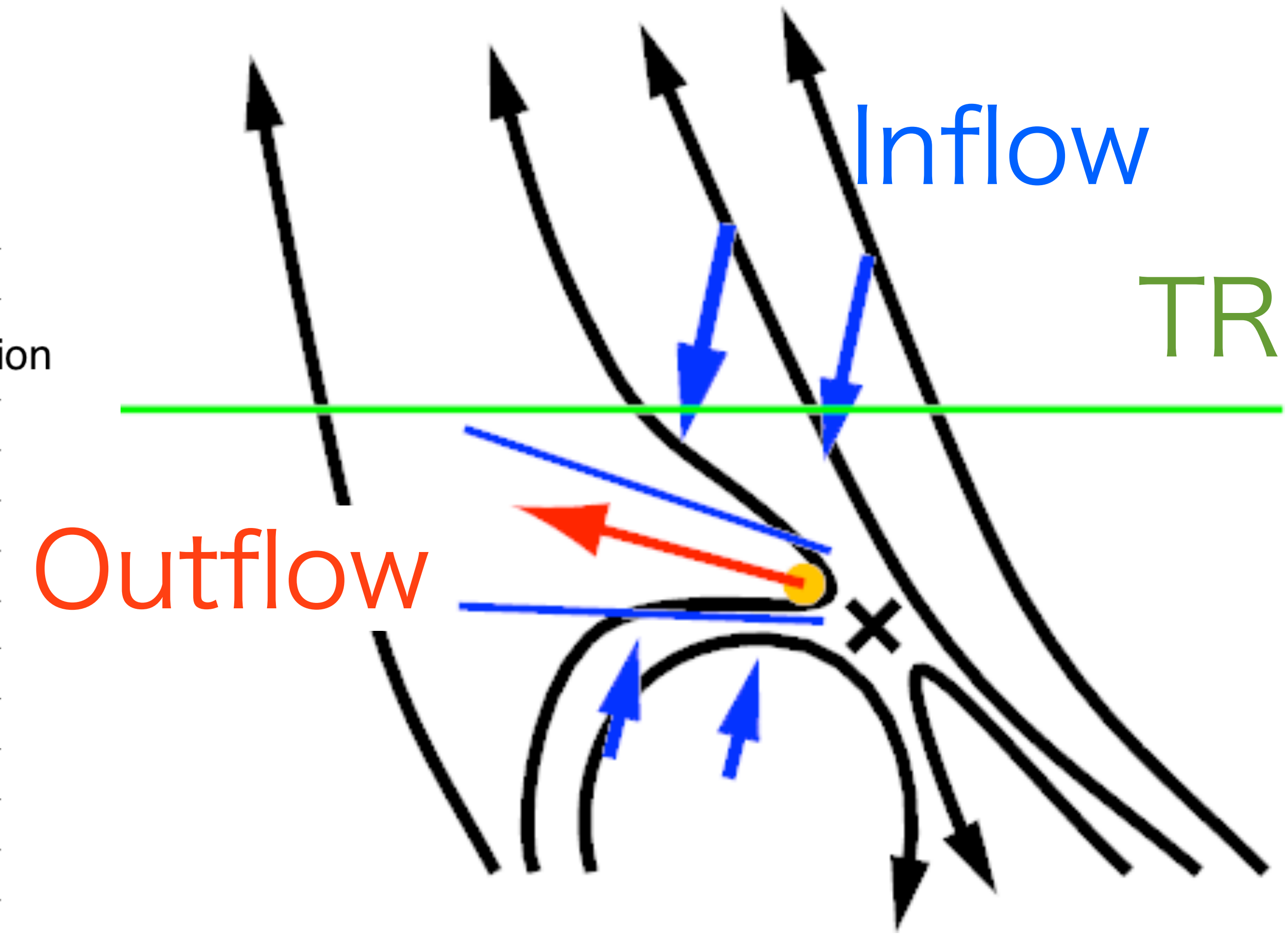
Numerical Results

divergence of the velocity field	Blue : compressed (~shocks) Red : expanded



Upper Chrom. Recon.: Combination of Whip-like and Shock Acceleration

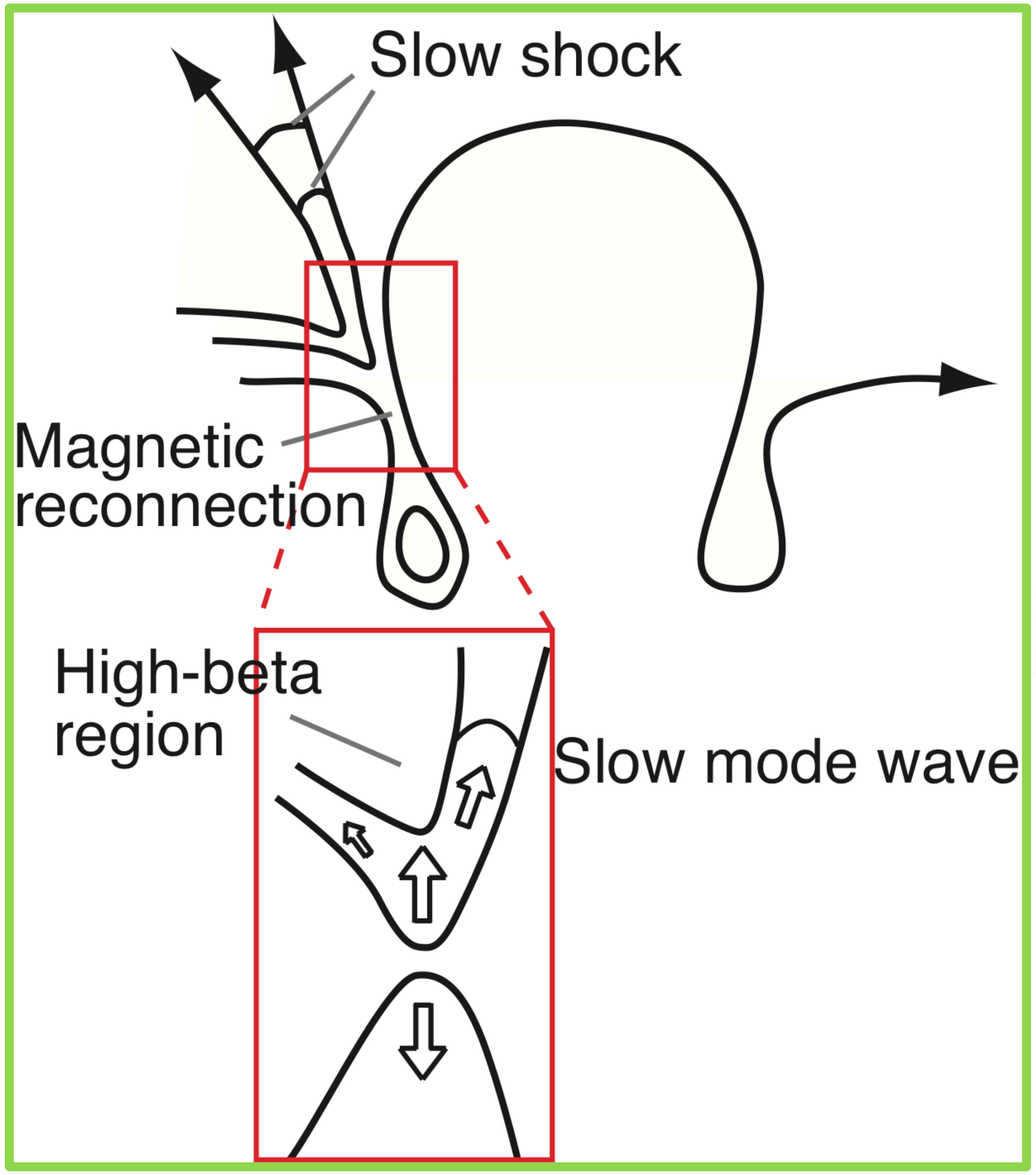


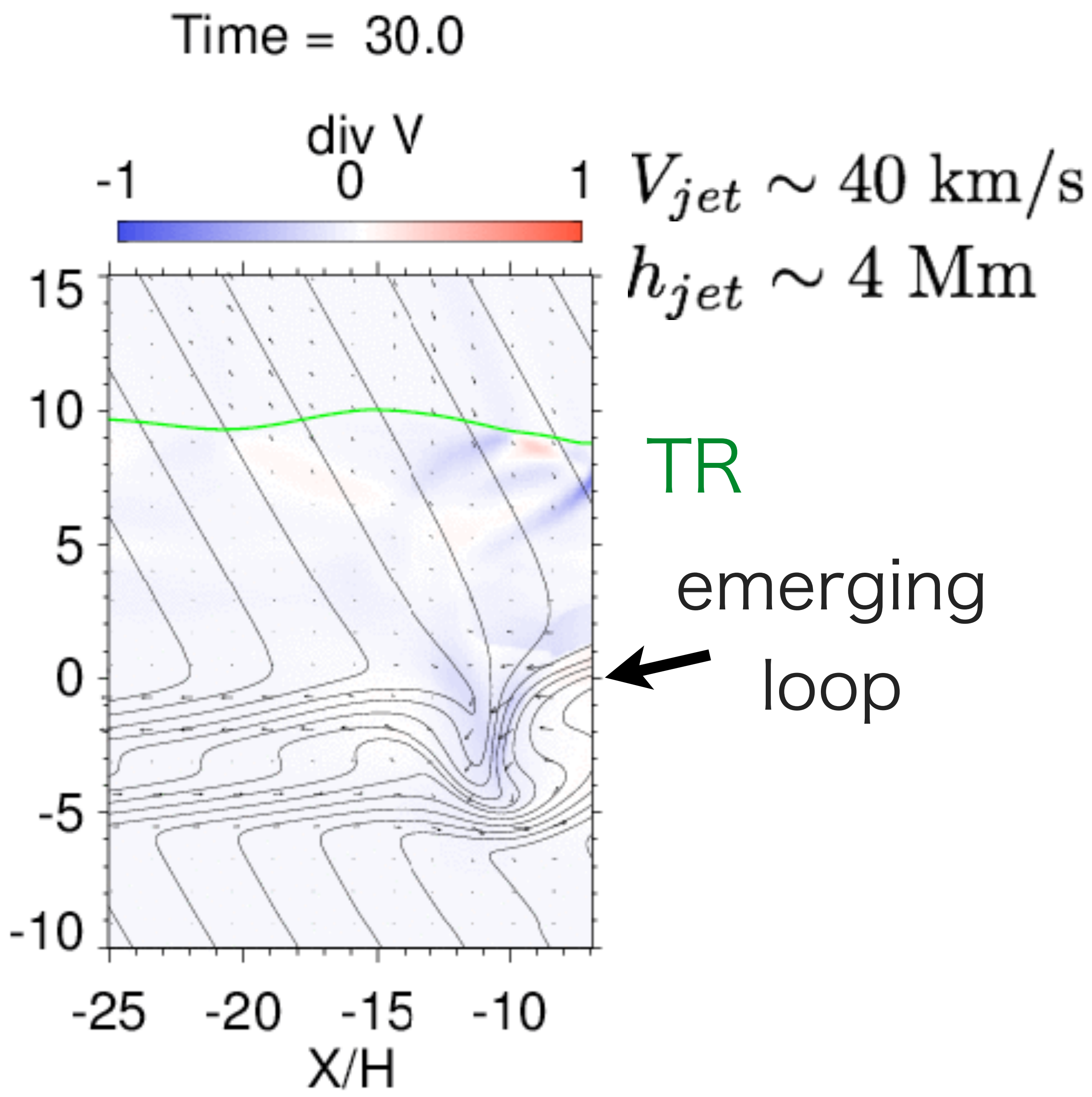


The chrom plasma is accelerated by

1. the magnetic tension (whip-like acceleration)
2. the slow shock (slow shock acceleration)

Lower Atmospheric Recon.: Shock Acceleration

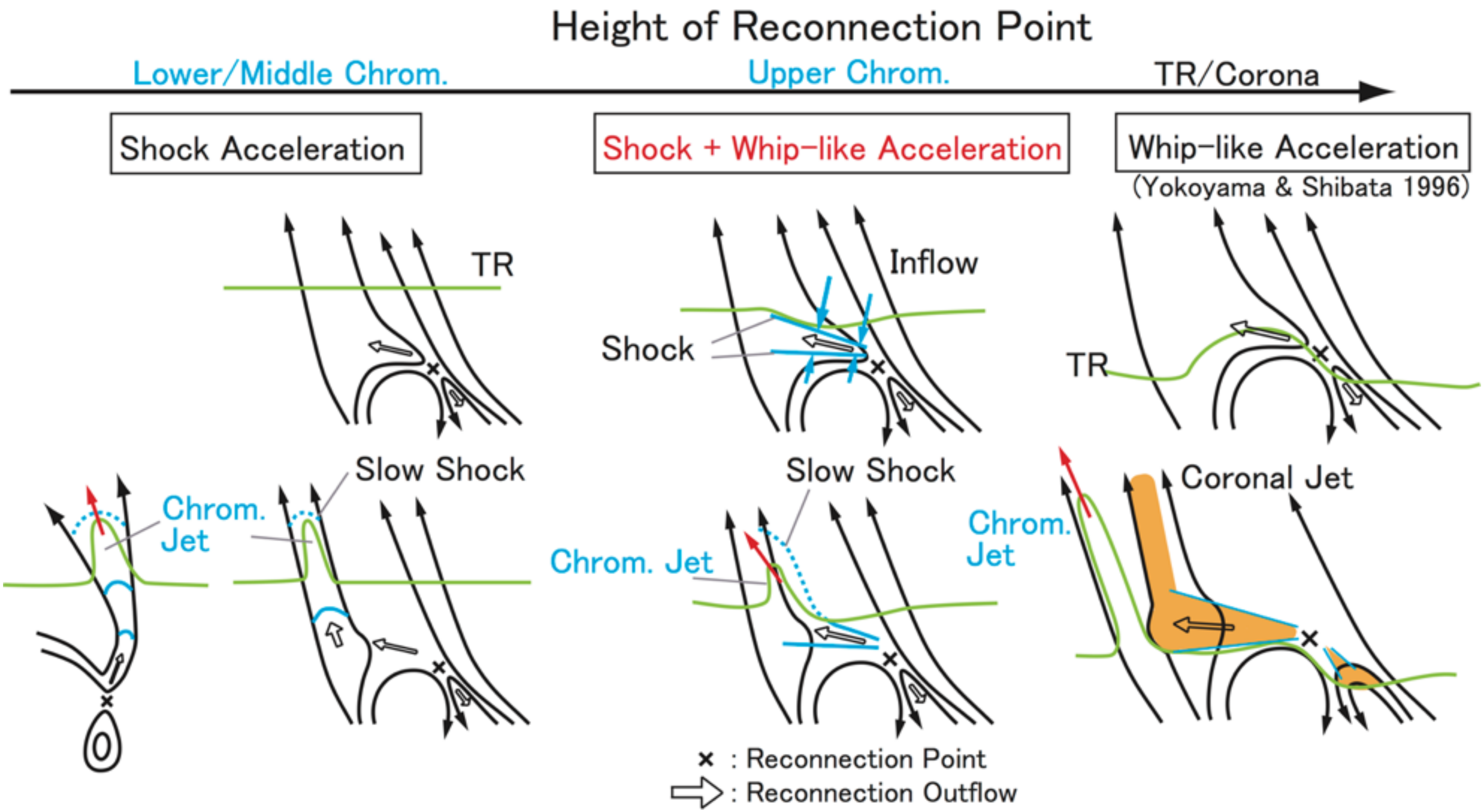




Application:

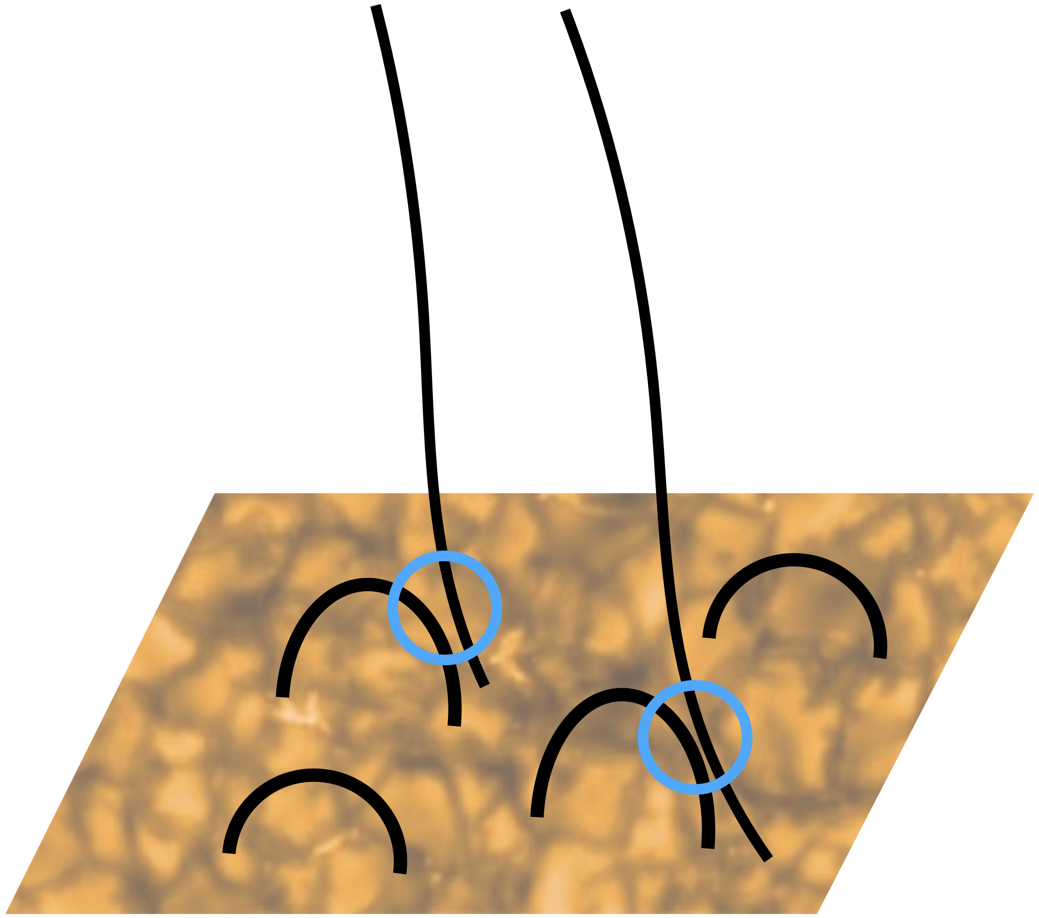
Ellerman bombs => H-alpha Surges (e.g. Pariat+2004)

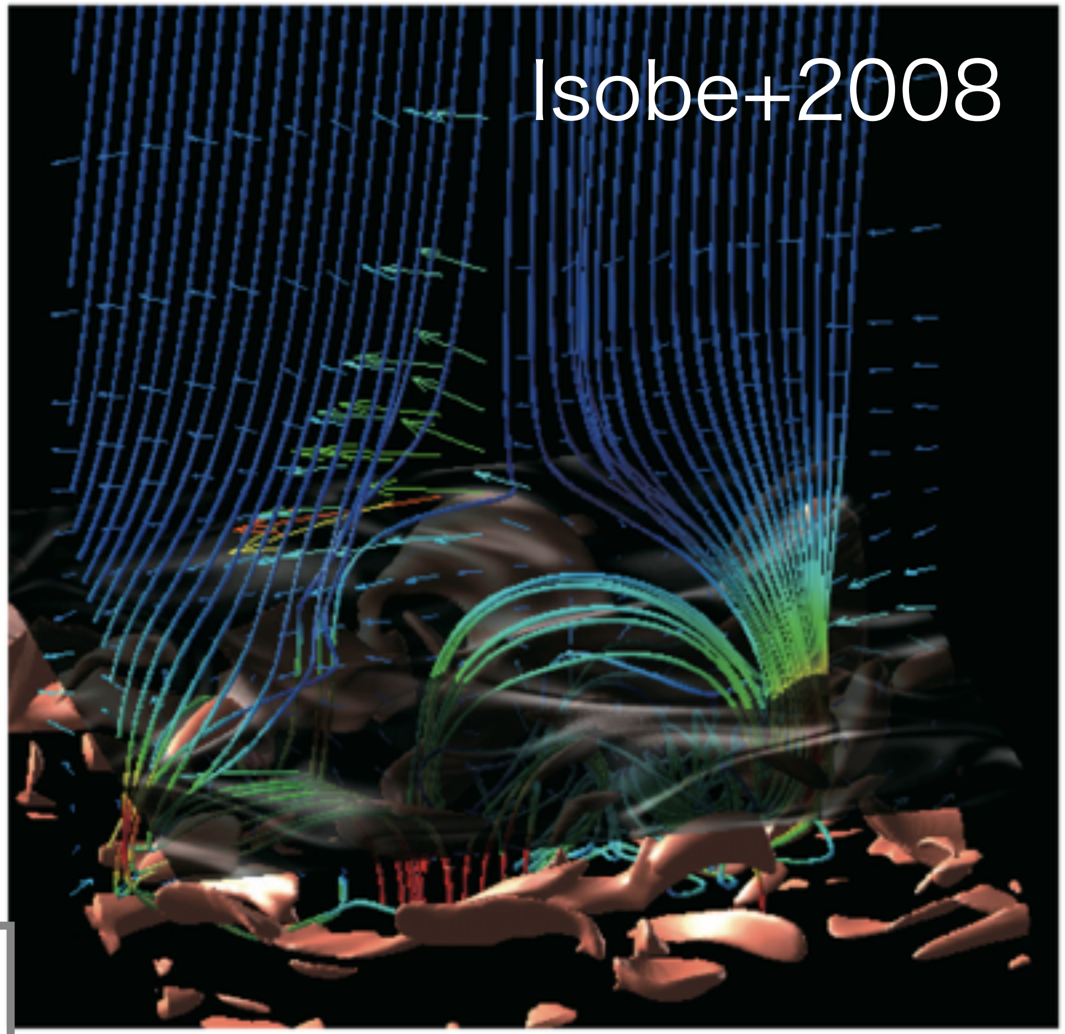
Systematic Understanding of Chromospheric Jets: Classification by the Height of Recon. Points



Takasao+ 2013

Contribution to Chromospheric and Coronal Heating





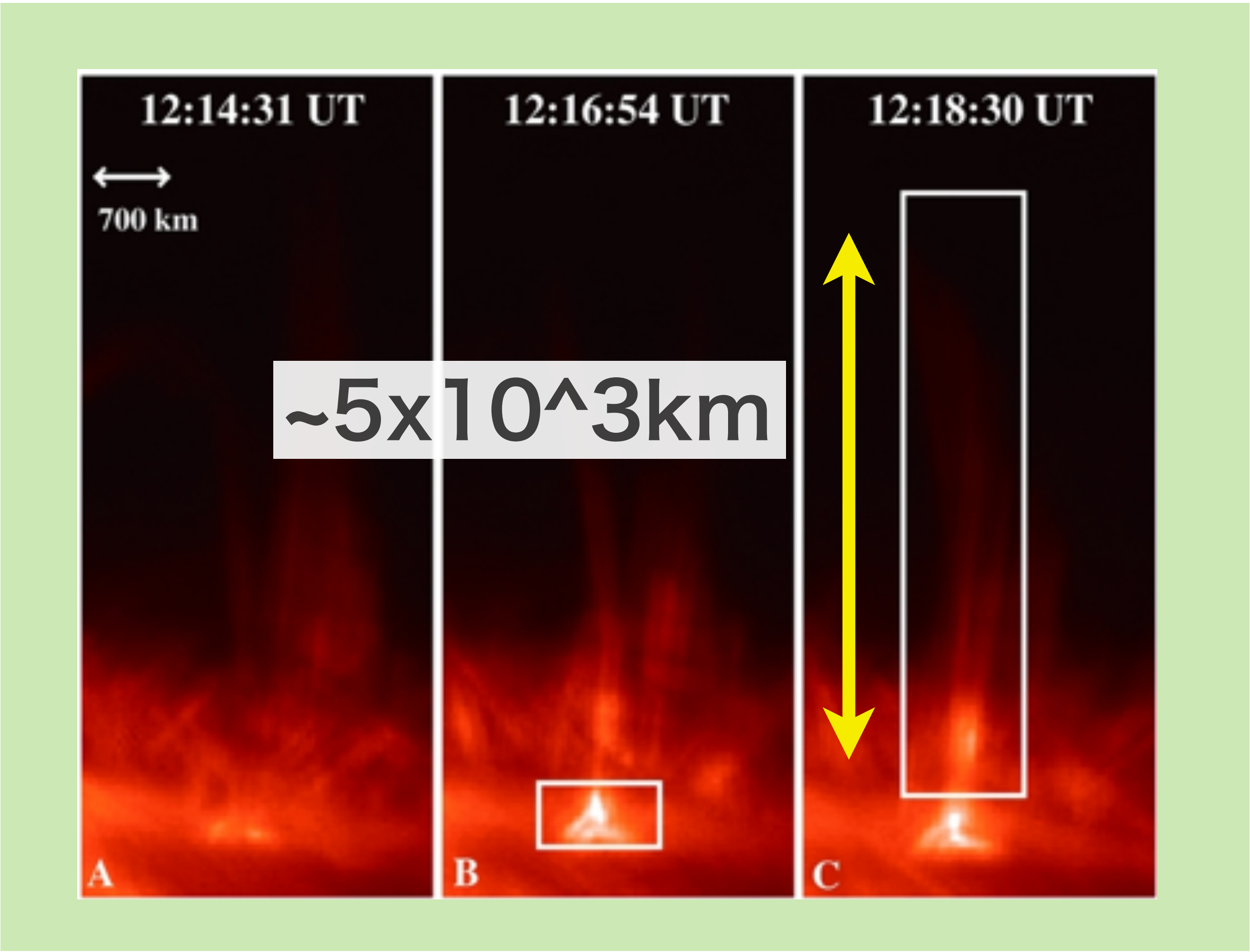
Keys for statistical discussion:
- The rate of the energy release by chrom. reconnection
- the occurrence frequency of chrom. reconnection at various heights

=> Hinode, IRIS, and Solar-C

small scale horizontal field
/granular scale emerging loop
Centeno+2007, Ishikawa+2008
Poynting flux ~ 10^6 erg cm^{-2} s^{-1}
sufficient to heat the chrom

Contribution to the Chromospheric Heating

Can low chromospheric reconnection create tall jets?



(available magnetic energy)

~ (potential energy of jets)

$$\frac{B^2}{8\pi}V \sim \rho g h V$$

V: volume

$$h \sim \frac{B^2}{8\pi}\frac{1}{\rho g}$$

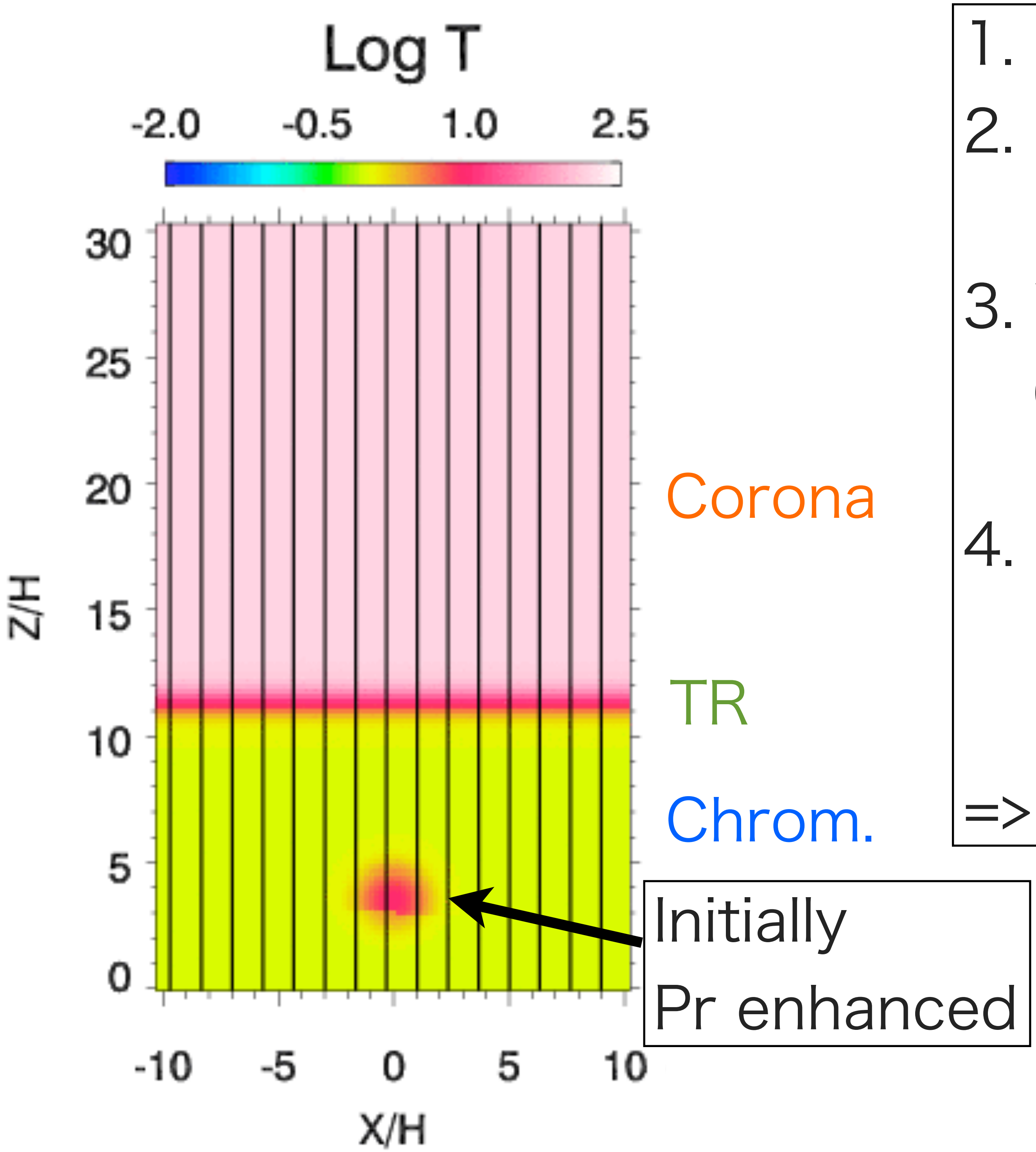
$$= \frac{B^2}{8\pi}\frac{1}{P}\frac{R_g T}{g} = \frac{H_p}{\beta}$$

Hp~200km (pressure scale height in the low chrom.)

If β ~ 1, h ~ Hp~200km << 10^3-10^4 km. Too short!!

Thus the low chrom. plasma cannot be lifted up to the coronal height by the Lorentz force. So how jets are created?

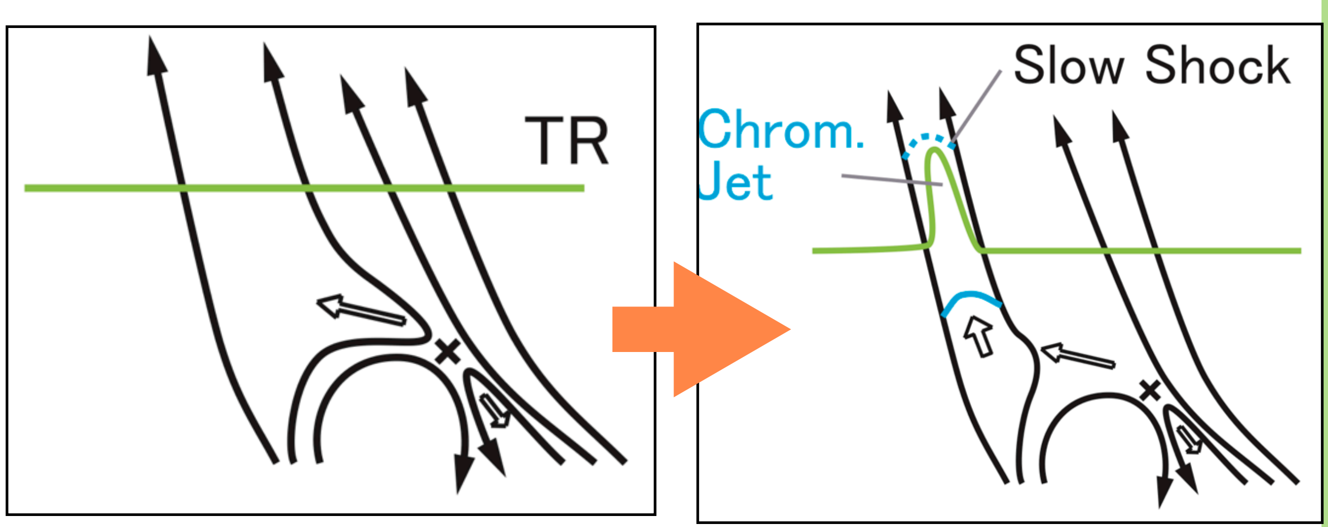
Energy transport by MHD slow-mode waves/shocks



Solid lines: magnetic field lines

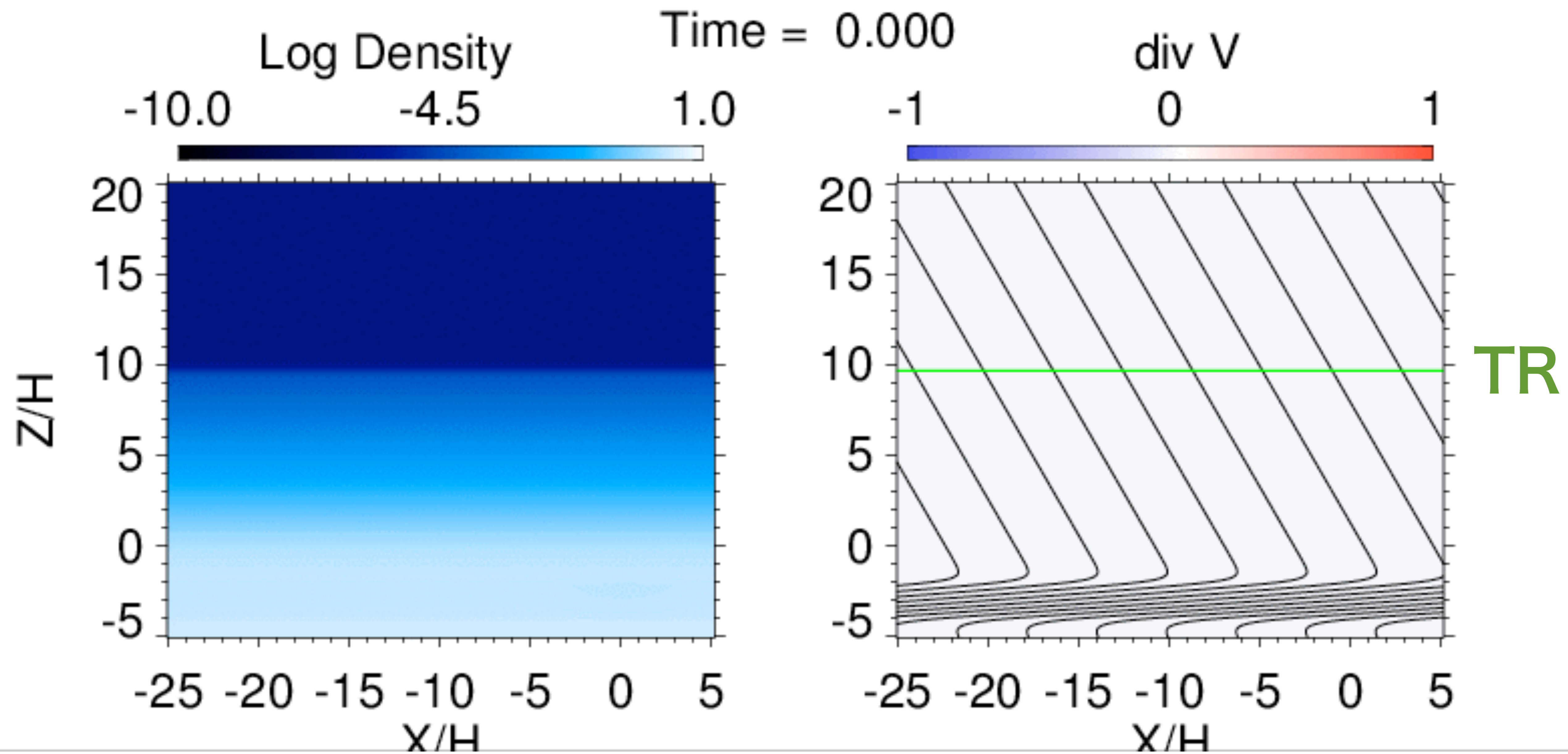
1. Energy release in the low chrom.
2. Slow waves carry the energy along a magnetic field
3. Waves become shocks (e.g. Carlsson and Stein 1997, Centeno + 2009)
4. Only a fraction of the plasma in the upper chrom. (low-density plasma) is accelerated by shocks.

=> spicules, surges, Ca jets...

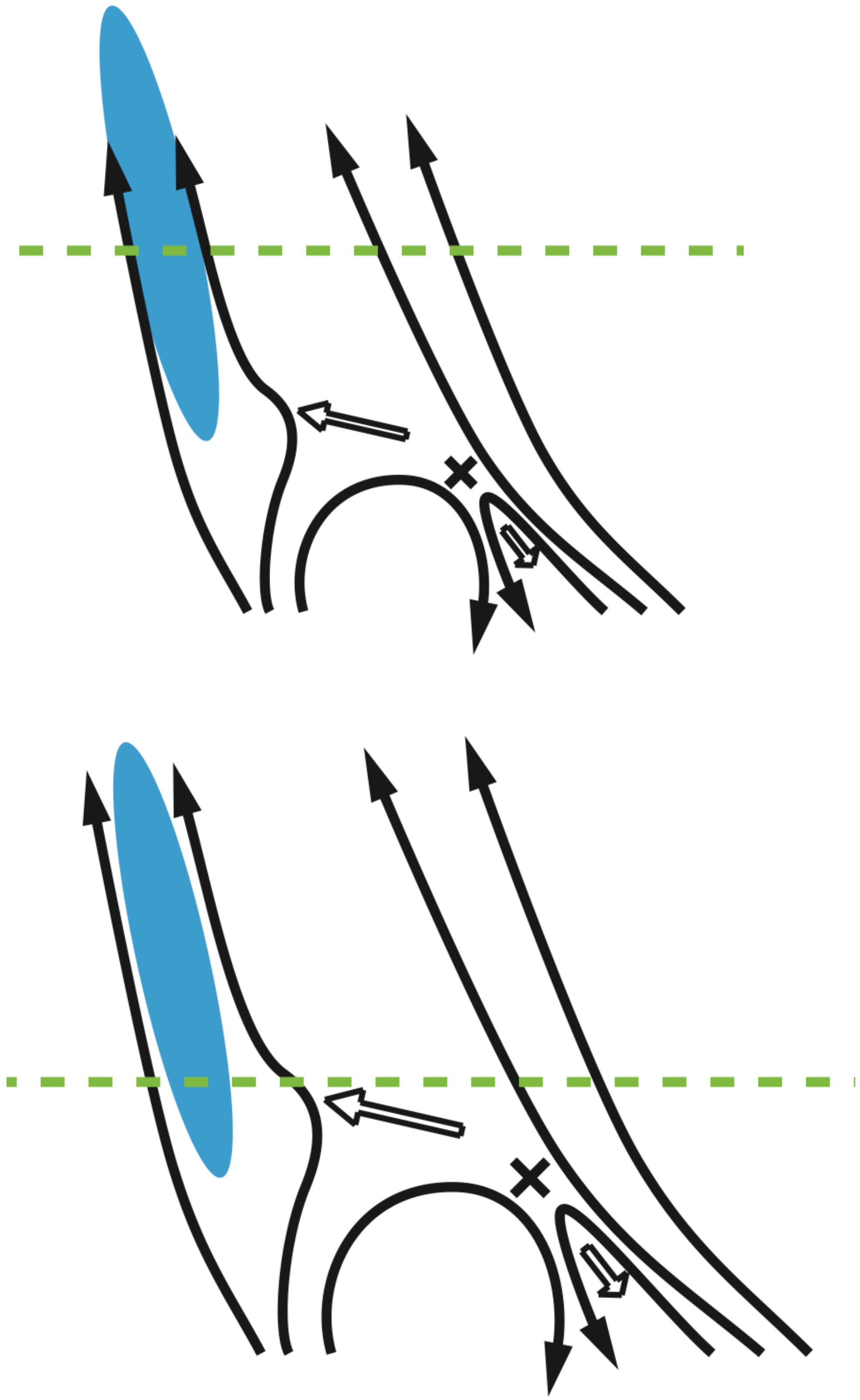


Density and div V distributions

divergence of the velocity field	Blue : compressed (~shocks) Red : expanded



Magnetic reconnection can take place at various heights



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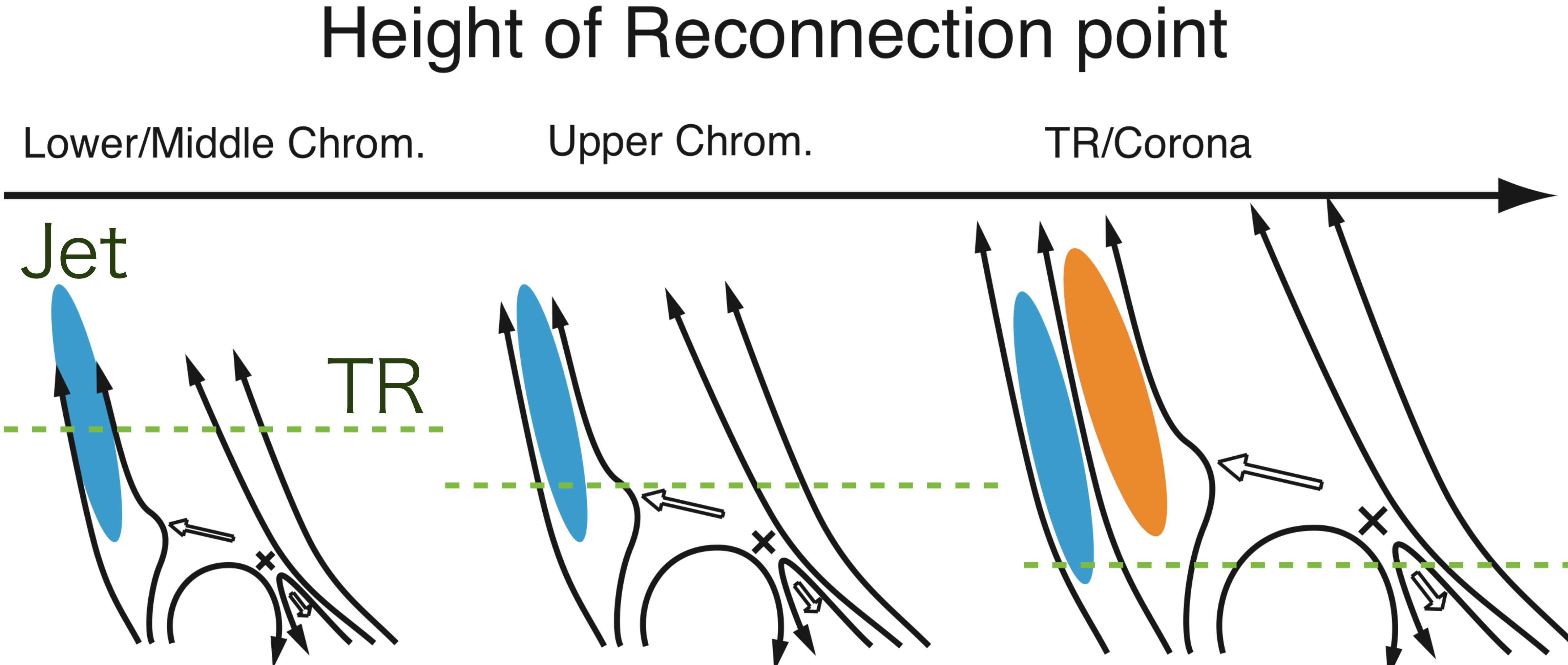

TR: Transition Region between chrom. and corona

Their apparent structures are quite similar.

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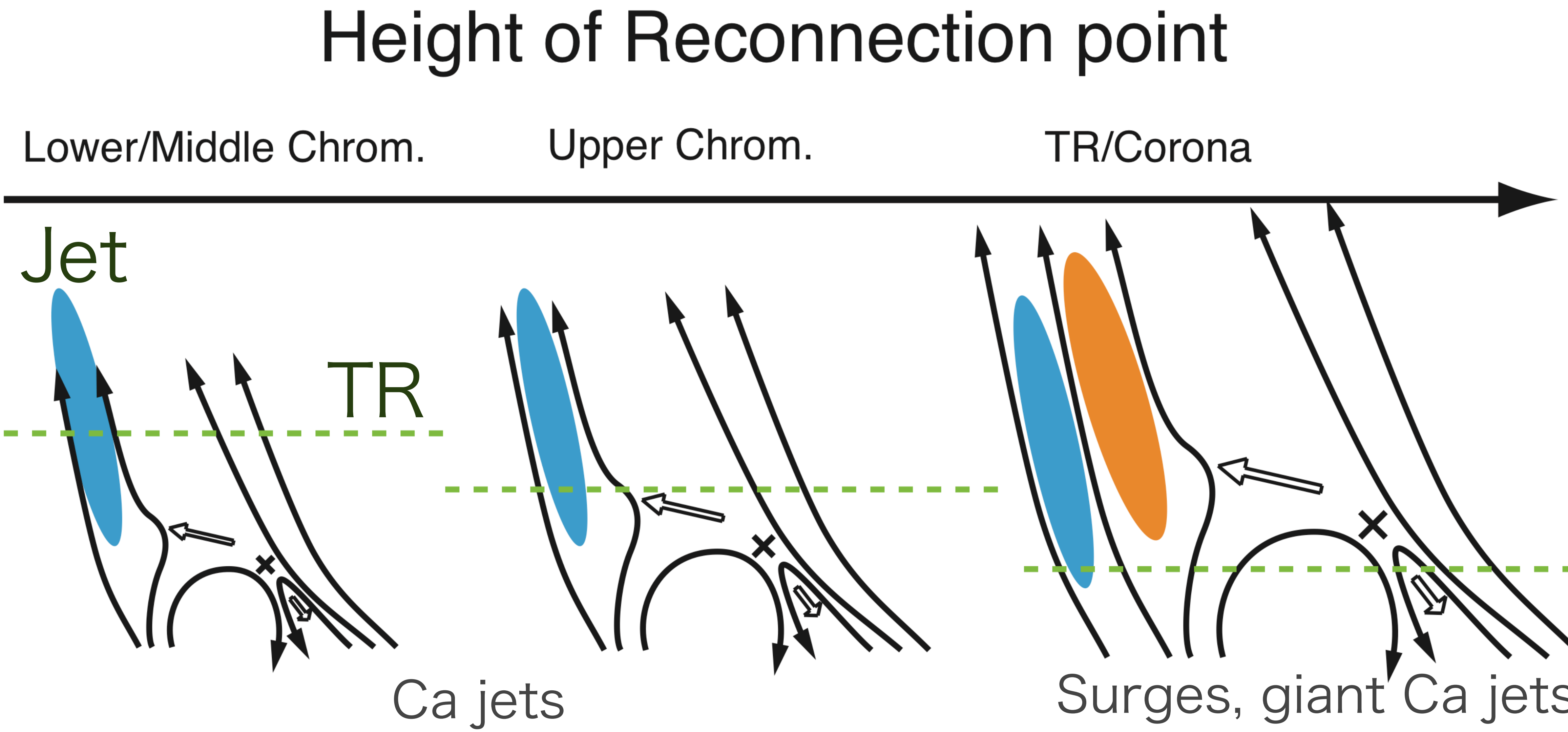

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Sling-shot
or whip-like acceleration
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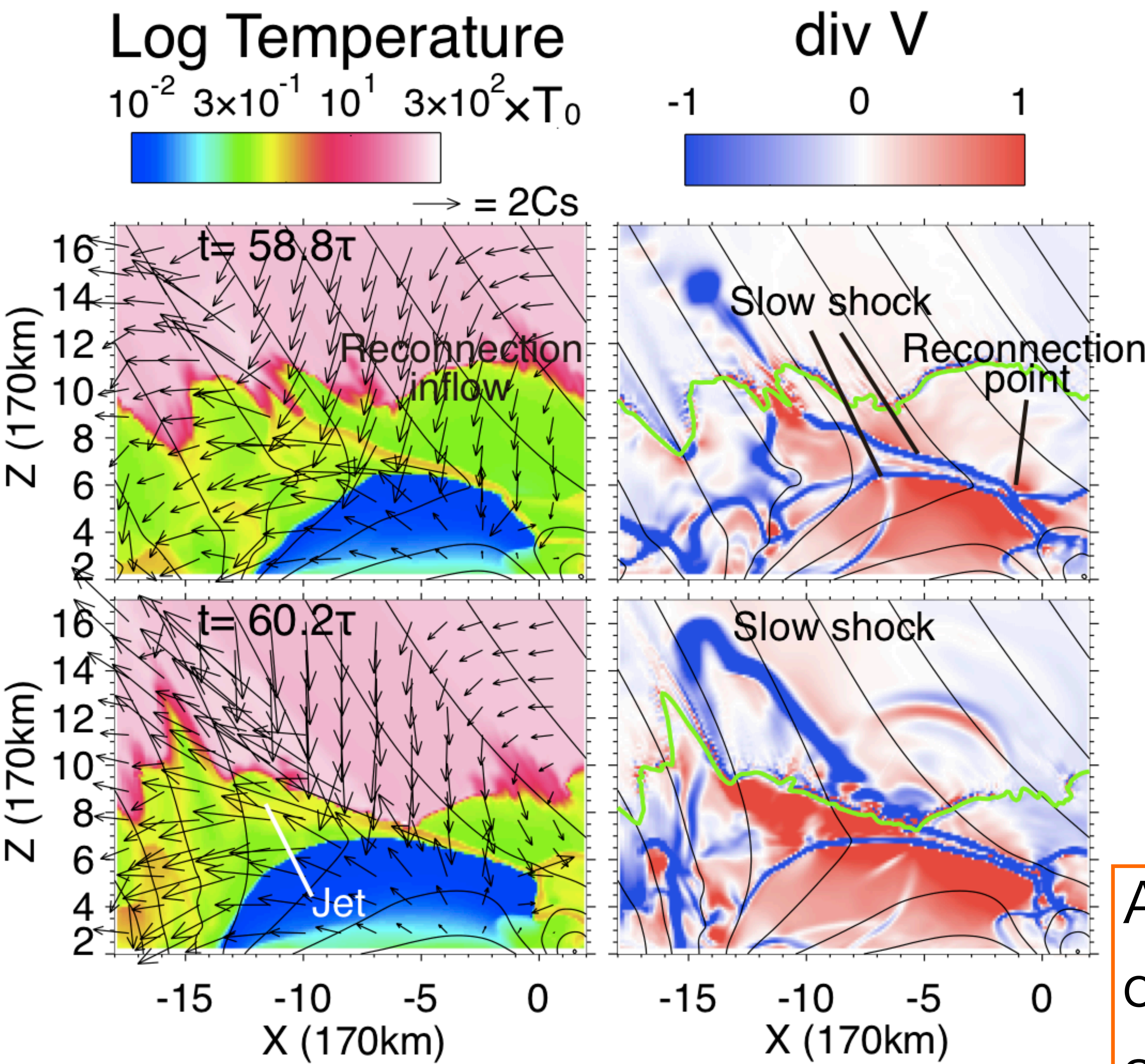
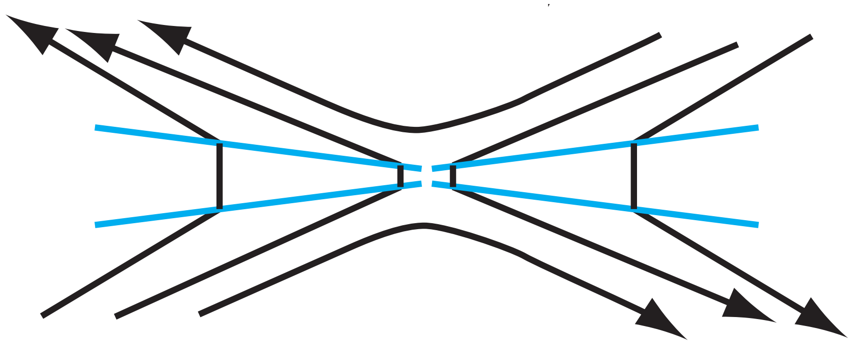
Petschek Slow Shock Contributes to Acceleration of Jet



Before

Shock crosses TR



After

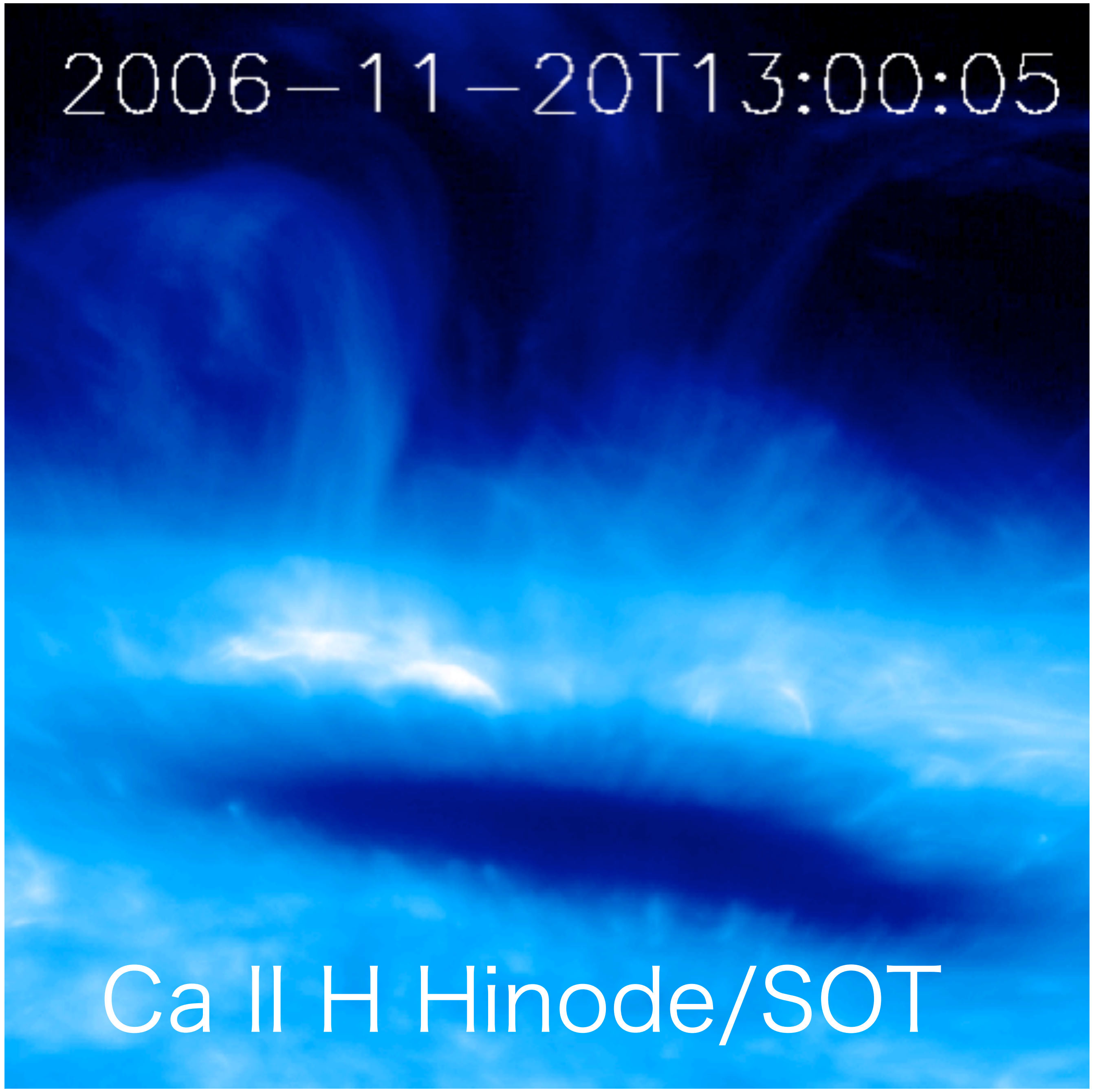
Shock crosses TR

A Petschek shock crosses TR, and then accelerates the plasma.

Chromospheric Jets

- Spicules small
- Ca jets
- Surges large

Ca jets
time scale:
~a few-10 min.
length scale:
$10^3 - 10^4$ km
velocity:
5 - 20 km/s
(Nishizuka+2011)



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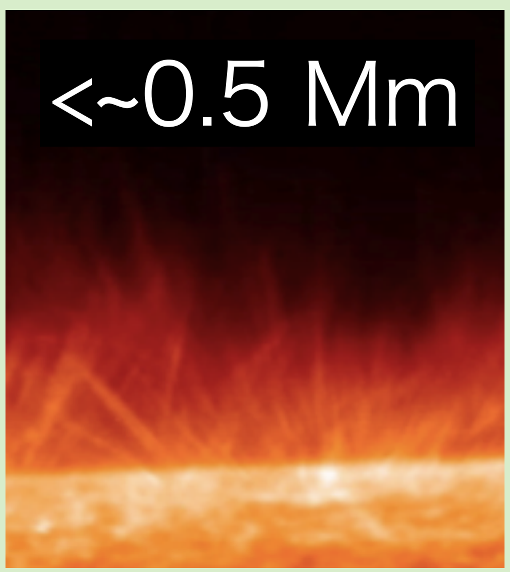
Classification by Height of Drivers of Jets

Height of Drivers of Jets

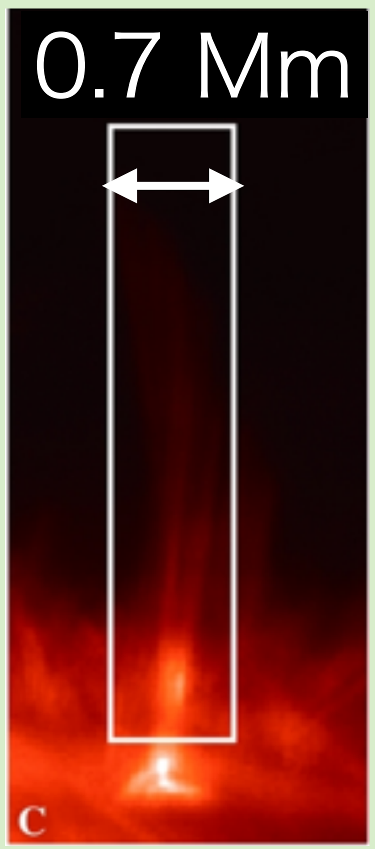
Photo./Low chrom. Upper chrom. TR/corona

Spicules

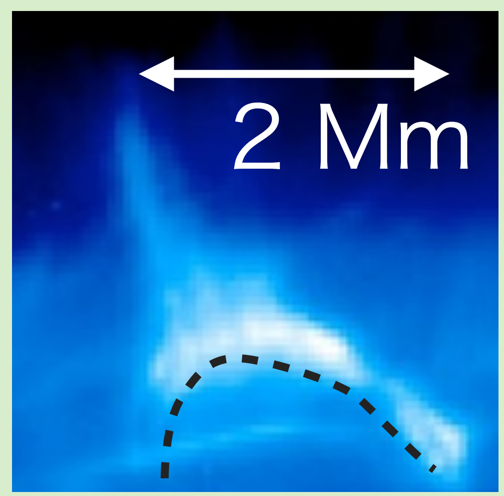


foot-points unresolved...

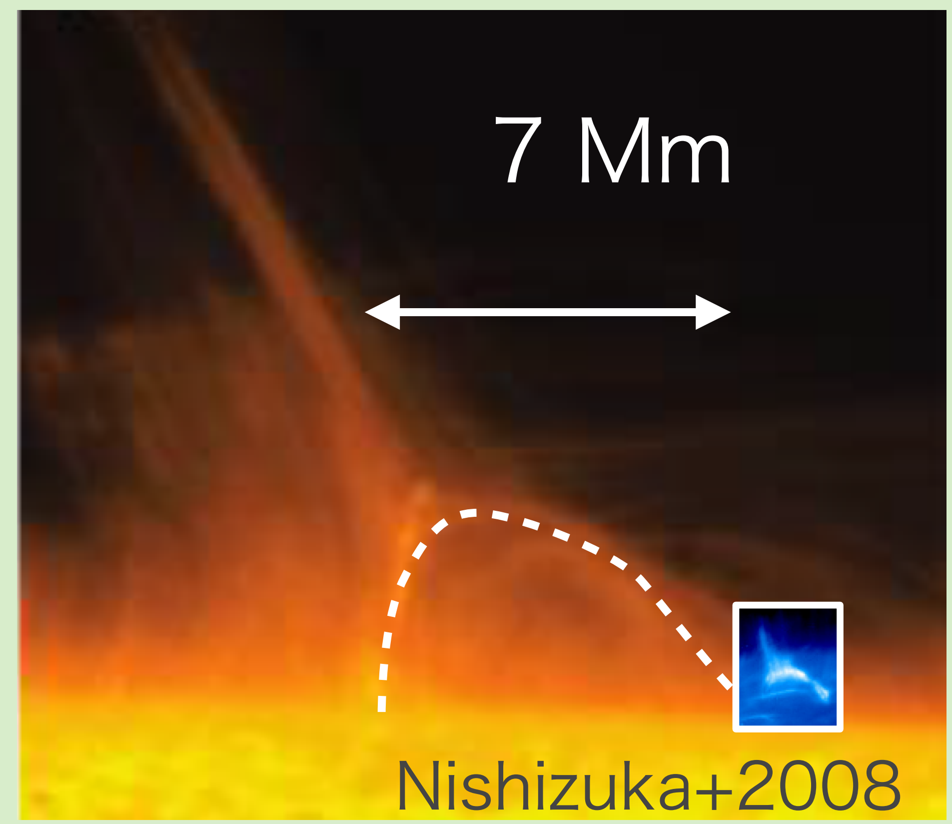
Ca jets



Singh+2012



Giant Ca jets / Surges



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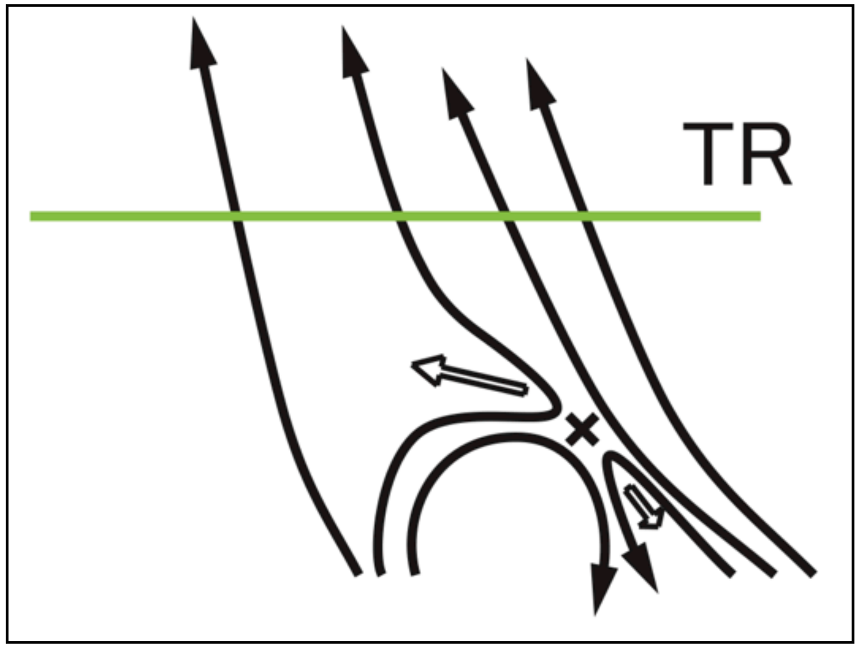
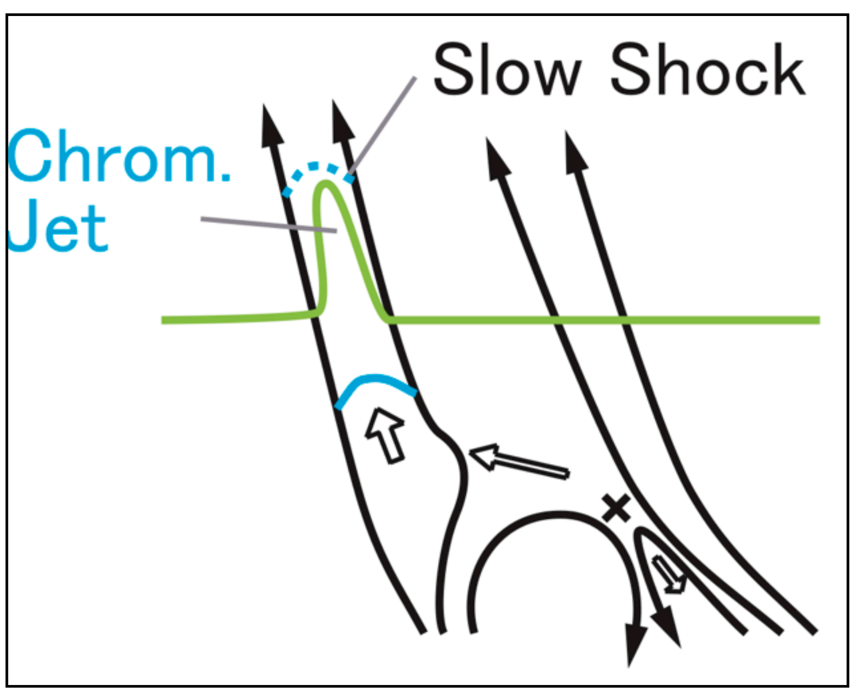
Low Atmospheric Reconnection and Shock





Height of jets driven by the Lorentz force (sling-shot / whip-like acceleration)

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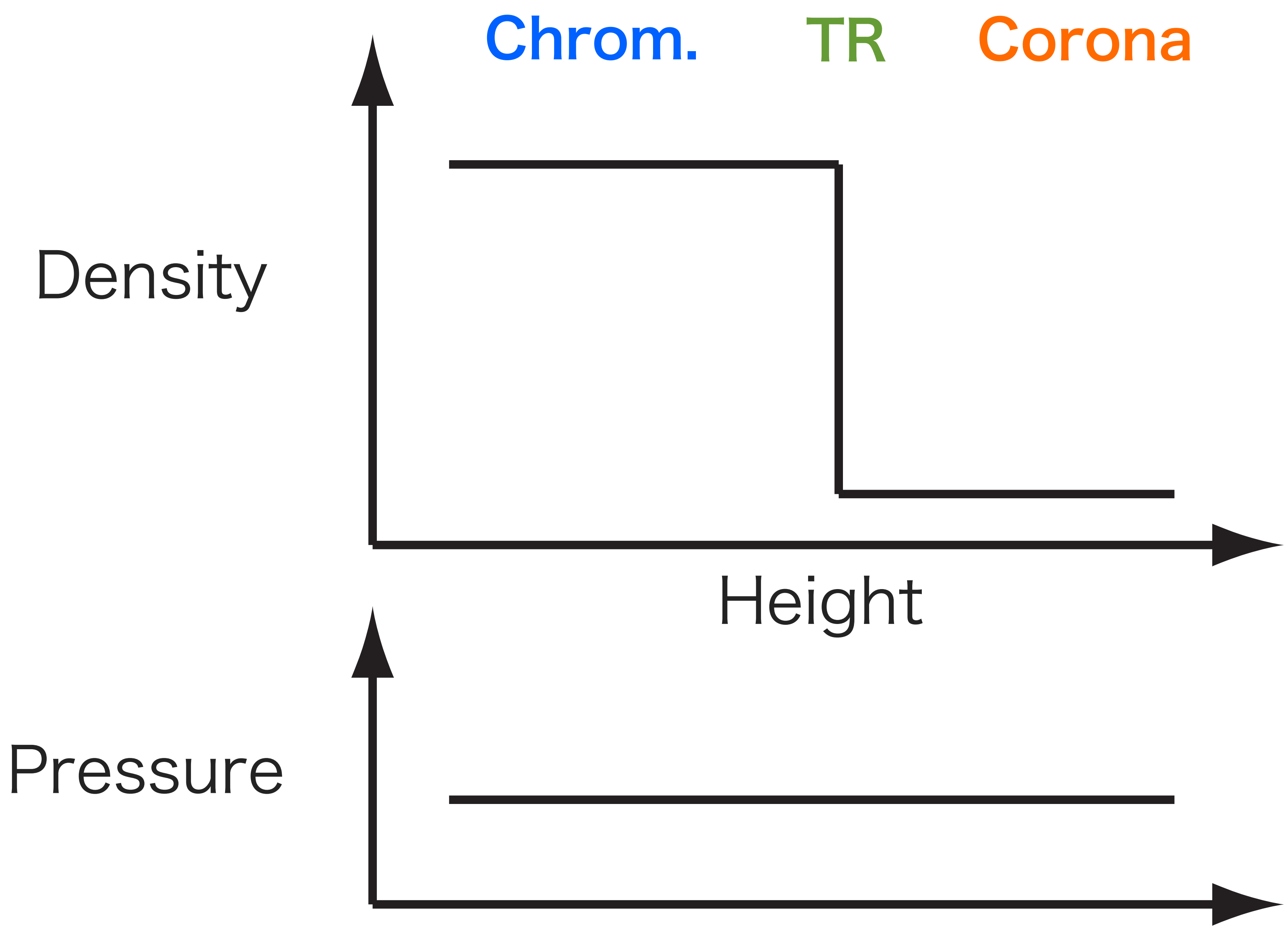
How Shocks Create Jets?
Transition Region - Shock Interaction

When a shock passes through TR, TR is launched to become a chrom. jet.



Note: Here the stratification is neglected

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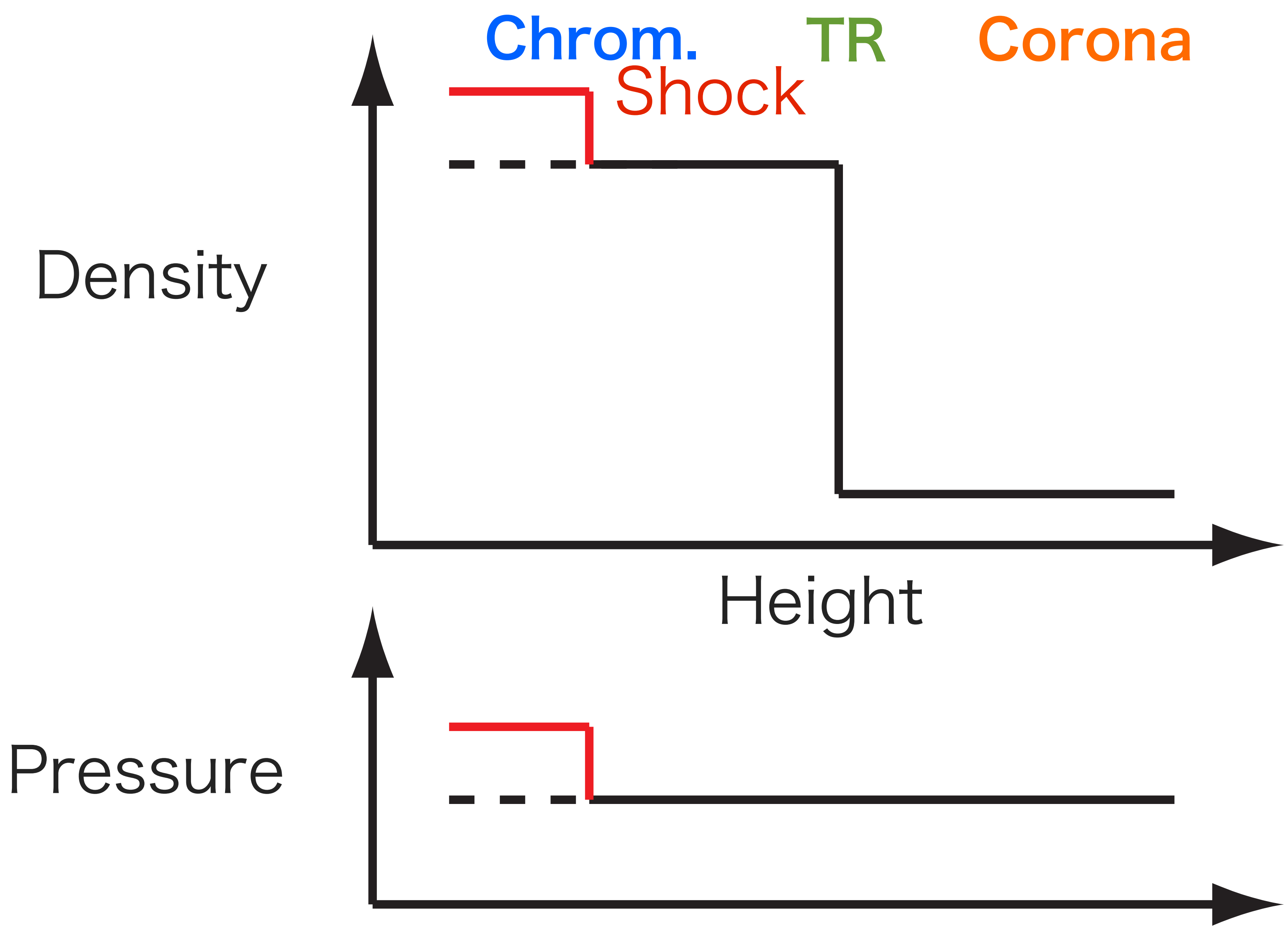

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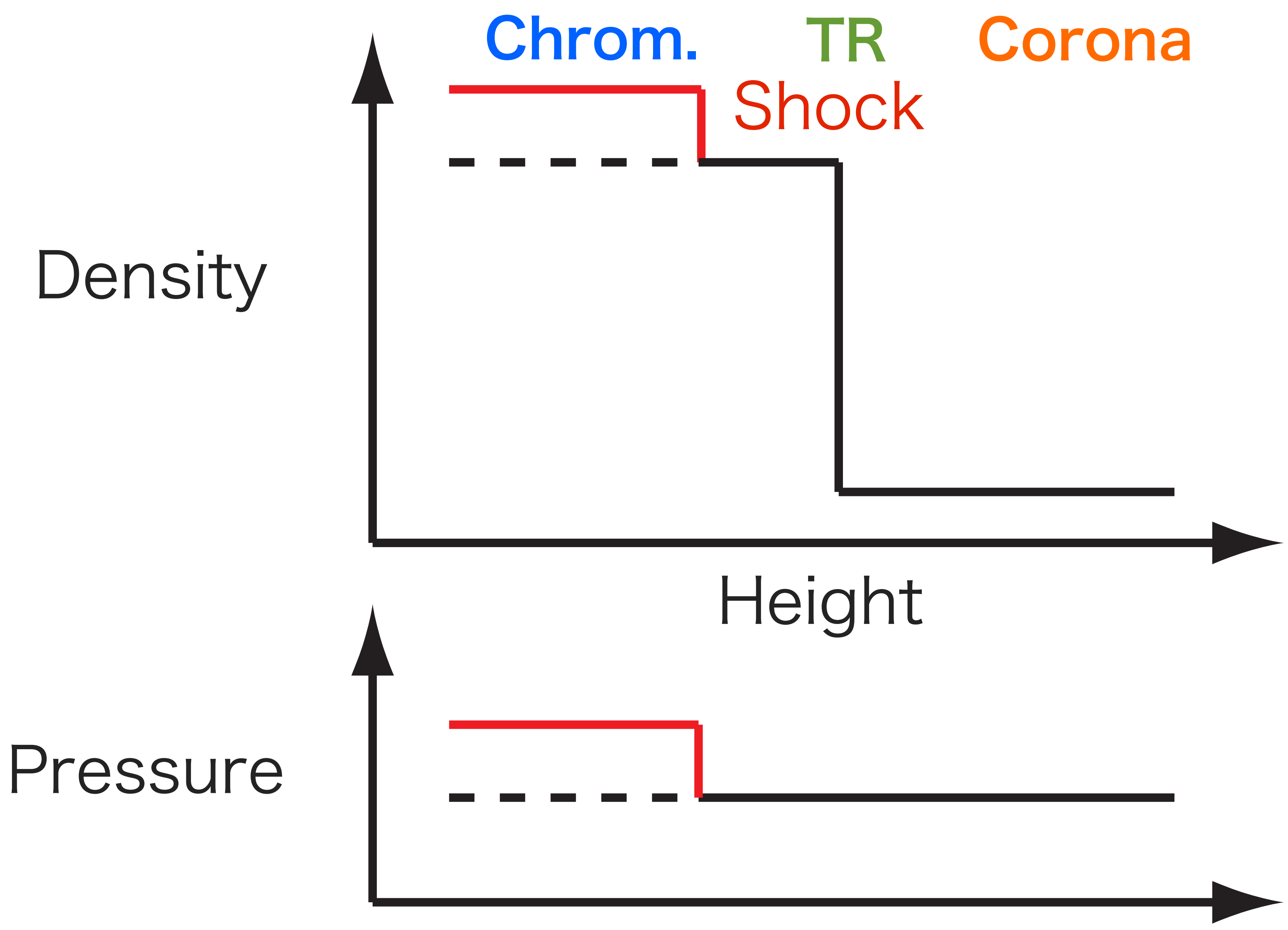

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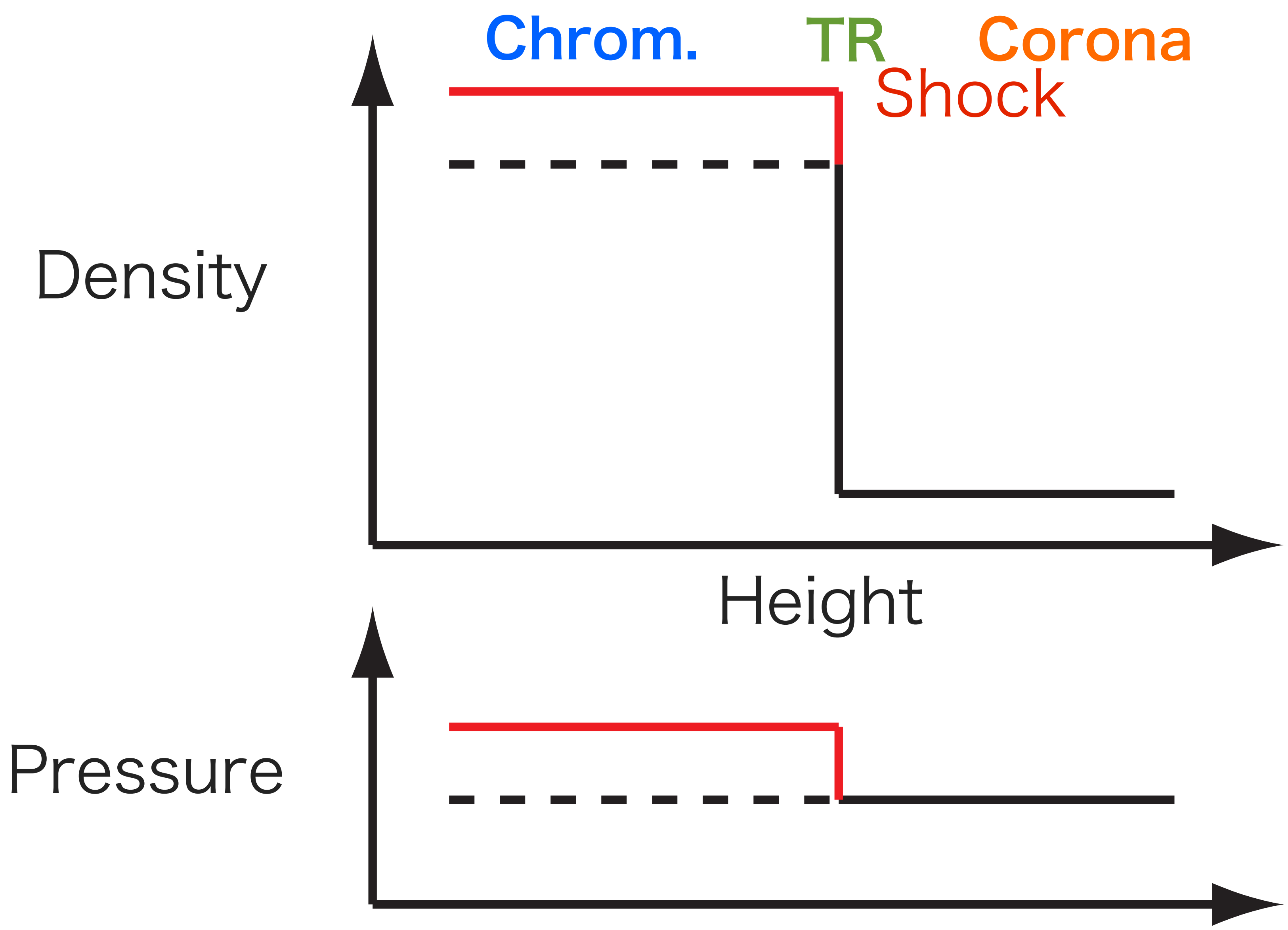

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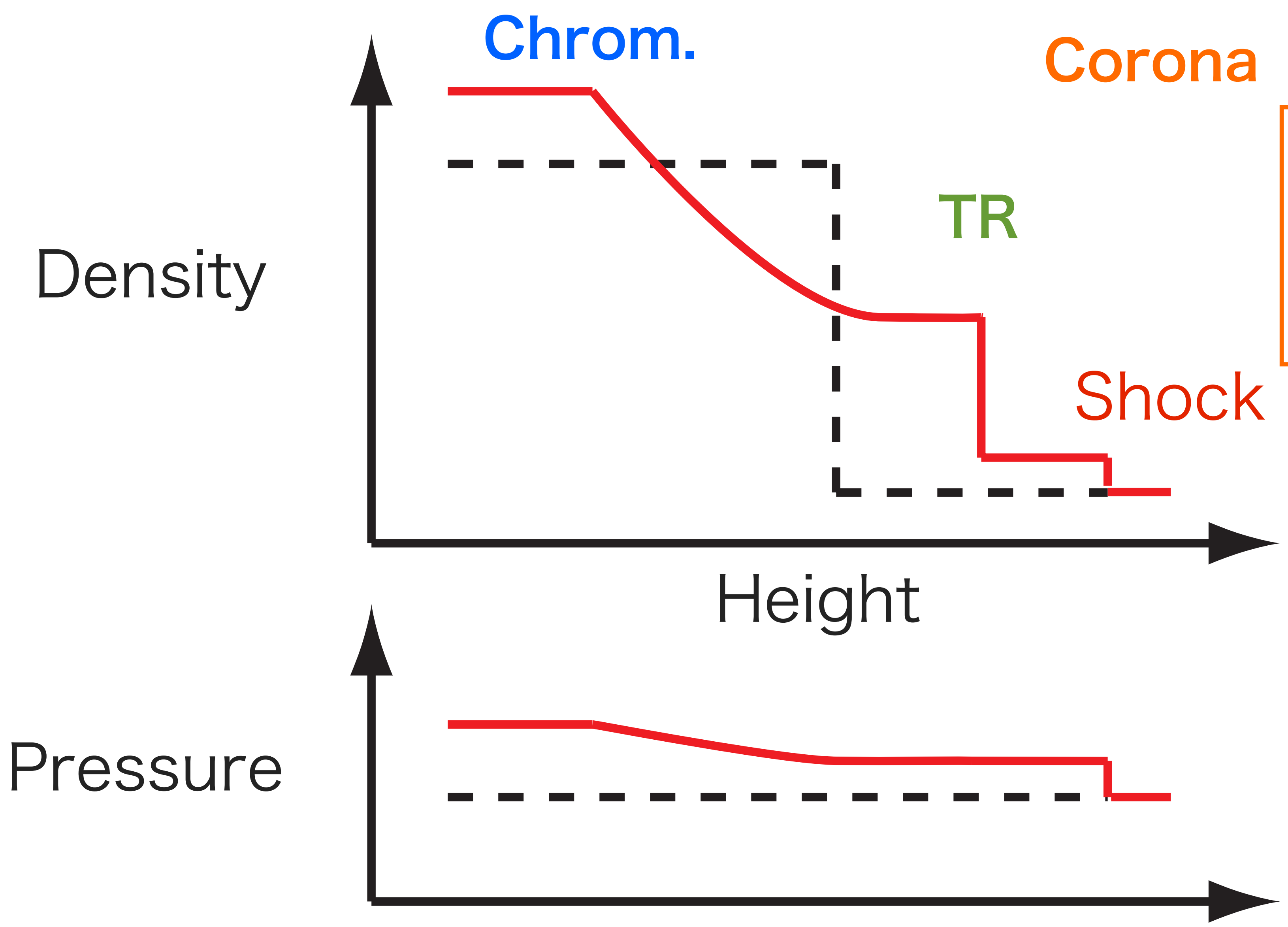
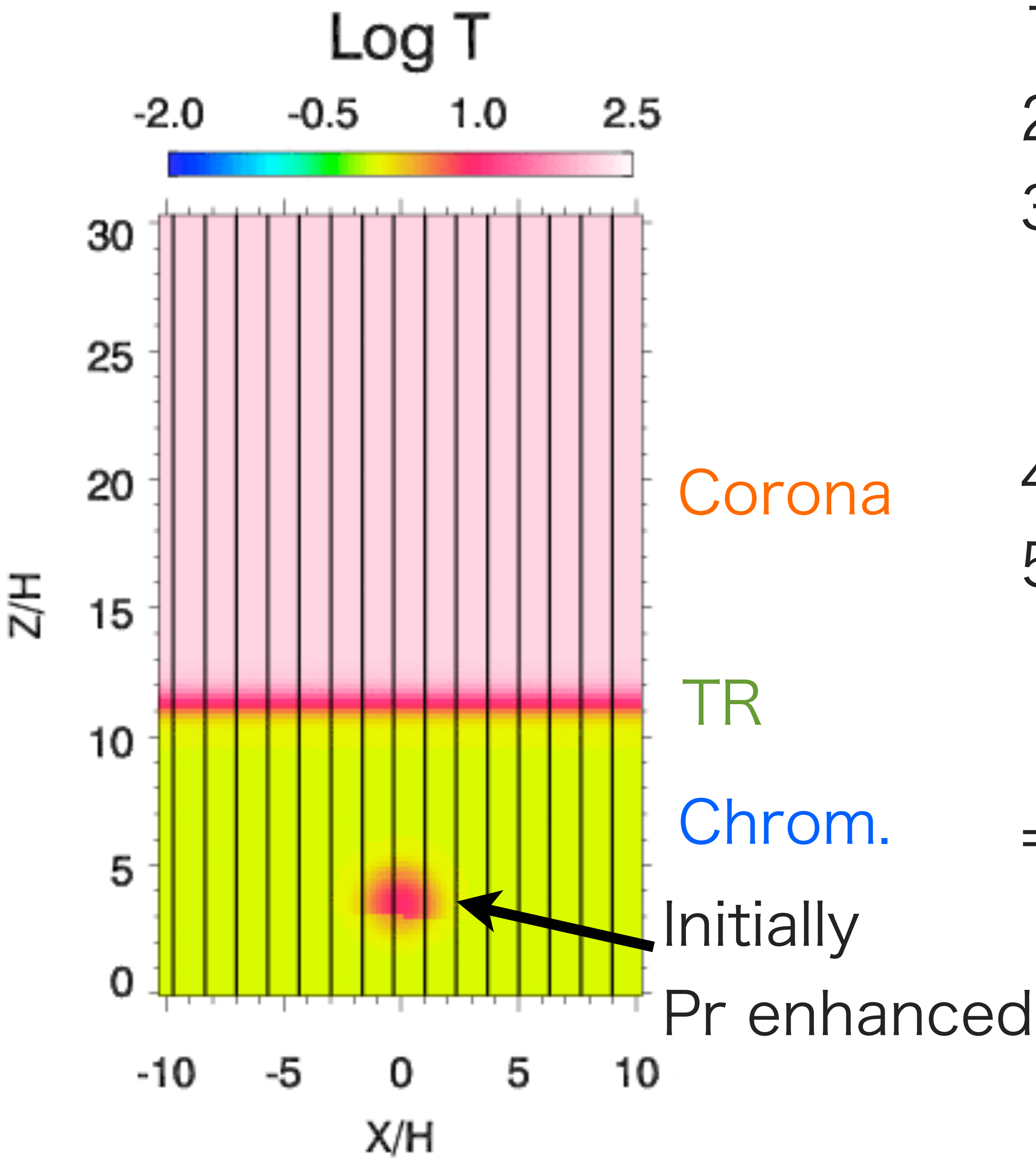


TR launched
due to the enhanced
pressure = Jet

Note: Here the stratification is neglected

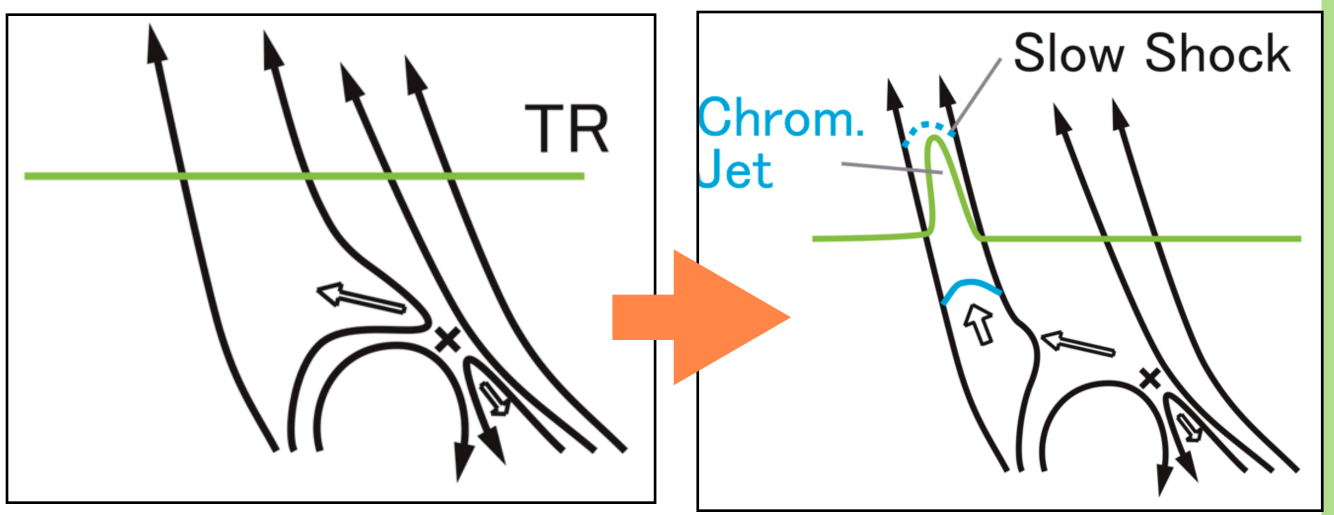
An Example of Jet Created by a Shock (=>Jets due to Reconnection in a Low Chrom.)



Solid lines: magnetic field lines

1. Energy release in the low chrom.
2. Waves carry the energy
3. Due to the stratification, the amplitude of the waves drastically increases
4. Finally waves become shocks
5. Only a fraction of the plasma in the upper chrom. (low-density plasma) is accelerated by shocks.

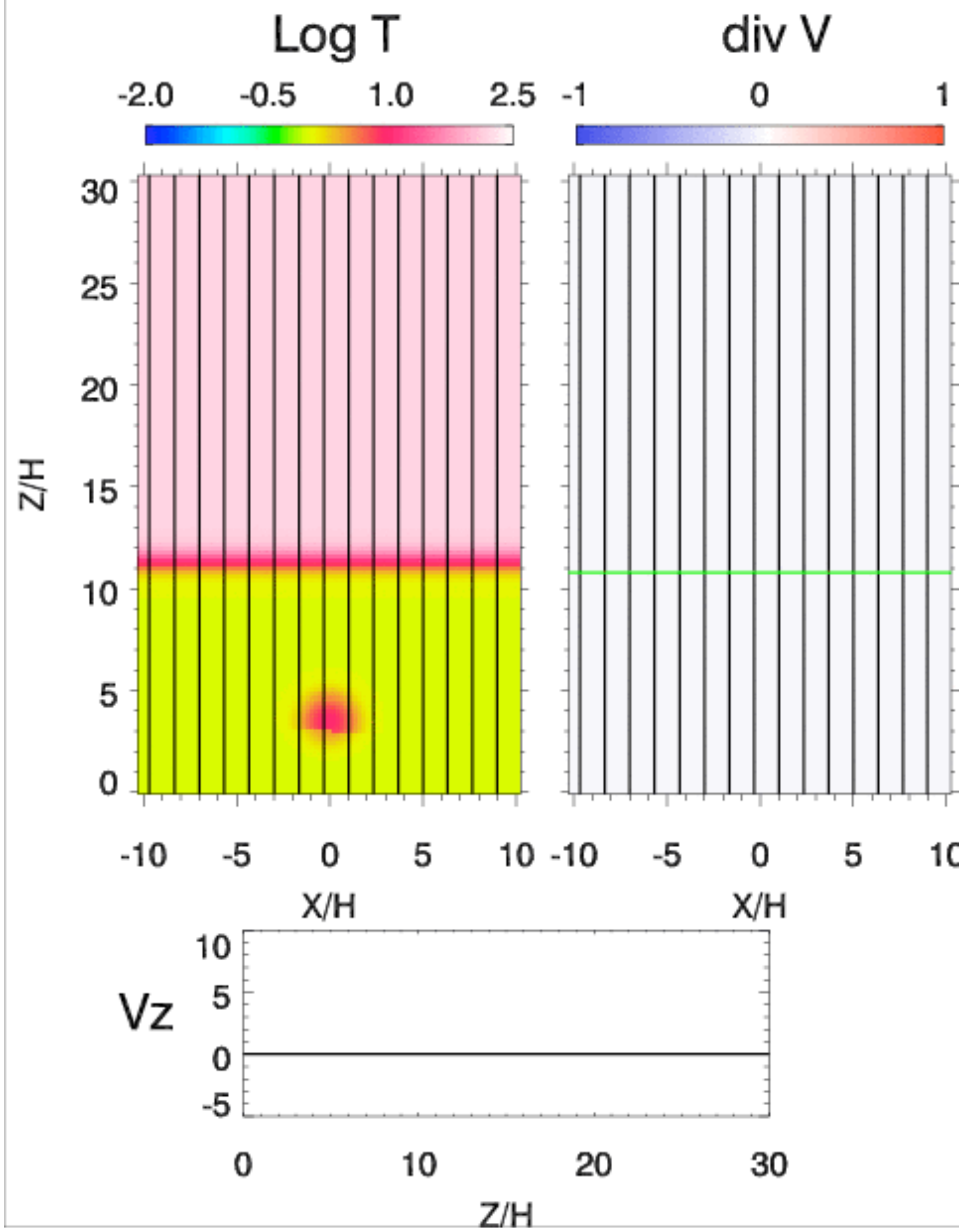
=> spicules, surges, small Ca jets…



$$
\begin{aligned}
\frac{\partial \rho}{\partial t} + (\mathbf{v} \cdot \nabla) &= -\rho \nabla \cdot \mathbf{v} \\
\frac{\partial v}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} &= -\frac{1}{\rho}\nabla p + \frac{1}{4\pi\rho}(\nabla \times \mathbf{B}) \times \mathbf{B} + \mathbf{g} \\
\frac{\partial \mathbf{B}}{\partial t} &= \nabla \times (\mathbf{v} \times \mathbf{B} - \eta \mathbf{J}) \\
\mathbf{J} &= \frac{1}{4\pi} \nabla \times \mathbf{B} \\
\frac{\partial T}{\partial t} + (\mathbf{v} \cdot \nabla) T &= -(\gamma - 1) T \nabla \cdot \mathbf{v} - \frac{T}{\tau_{cooling}} \\
p &= \frac{k_B}{m} \rho T
\end{aligned}
$$

$$
\eta = \begin{cases} 0 & \text{for} \quad v_d < v_c \\ \alpha(v_d/v_c - 1)^2 & \text{for} \quad v_d \geq v_c \end{cases}
\qquad
\tau_{cooling}(z) = \begin{cases} \infty & (z < 0) \\ \frac{\tau_{c1} - \tau_{c0}}{z_{\mathrm{tr}}} z + \tau_{c0} & (0 \leq z \leq z_{\mathrm{tr}}) \\ \tau_{c1} & (z > z_{\mathrm{tr}}), \end{cases}
$$

Point Explosion



Shock acceleration

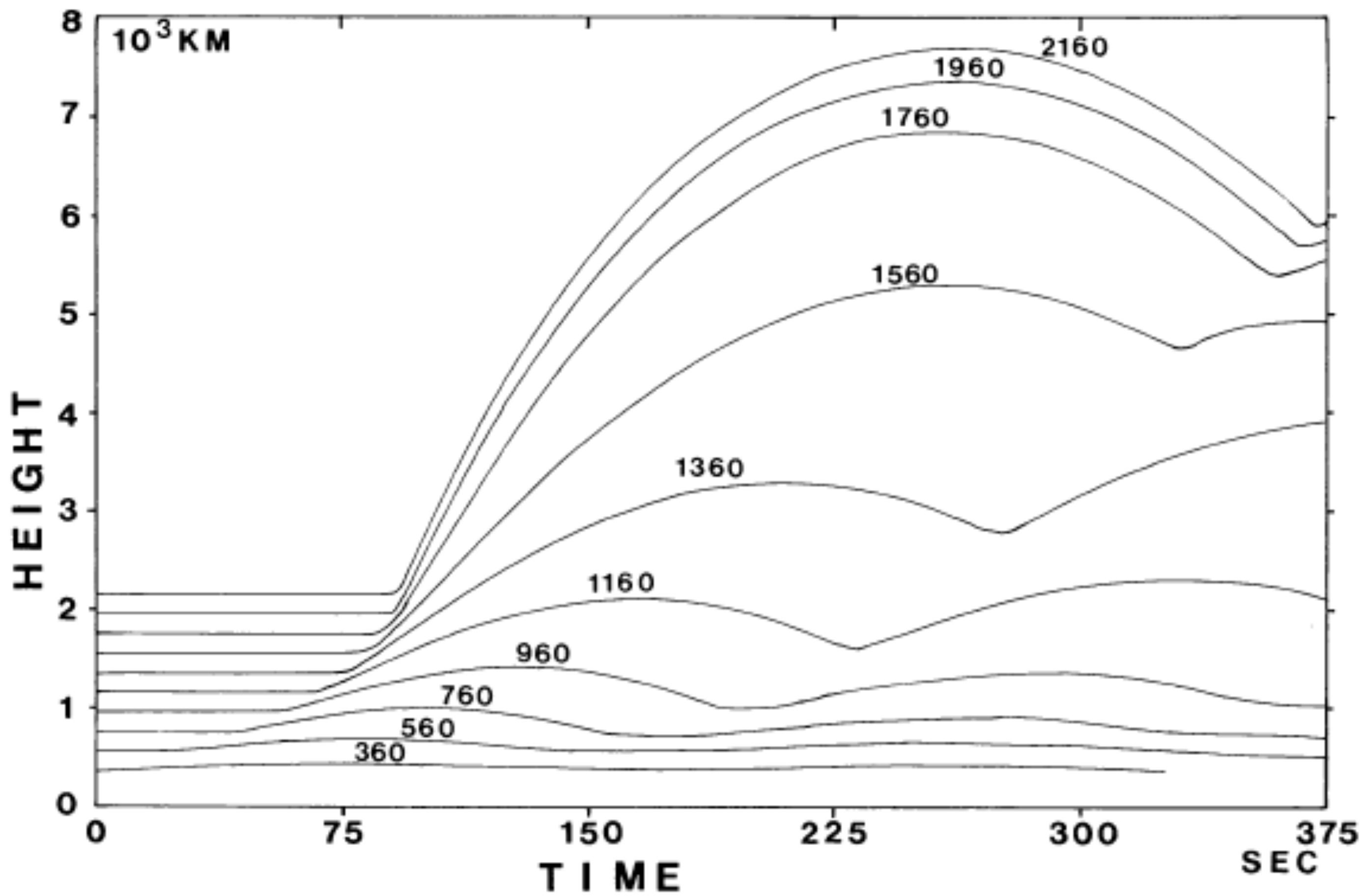
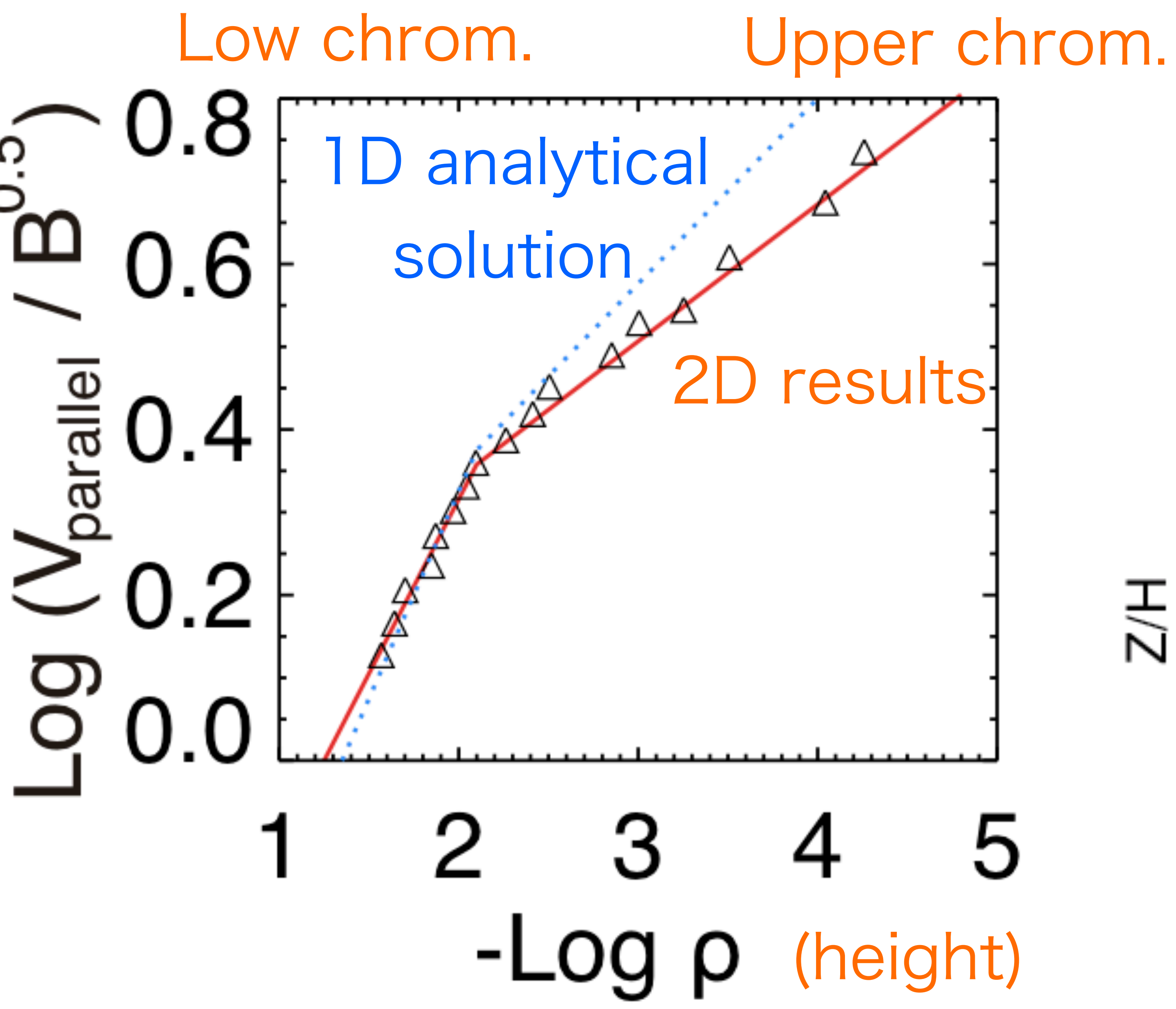


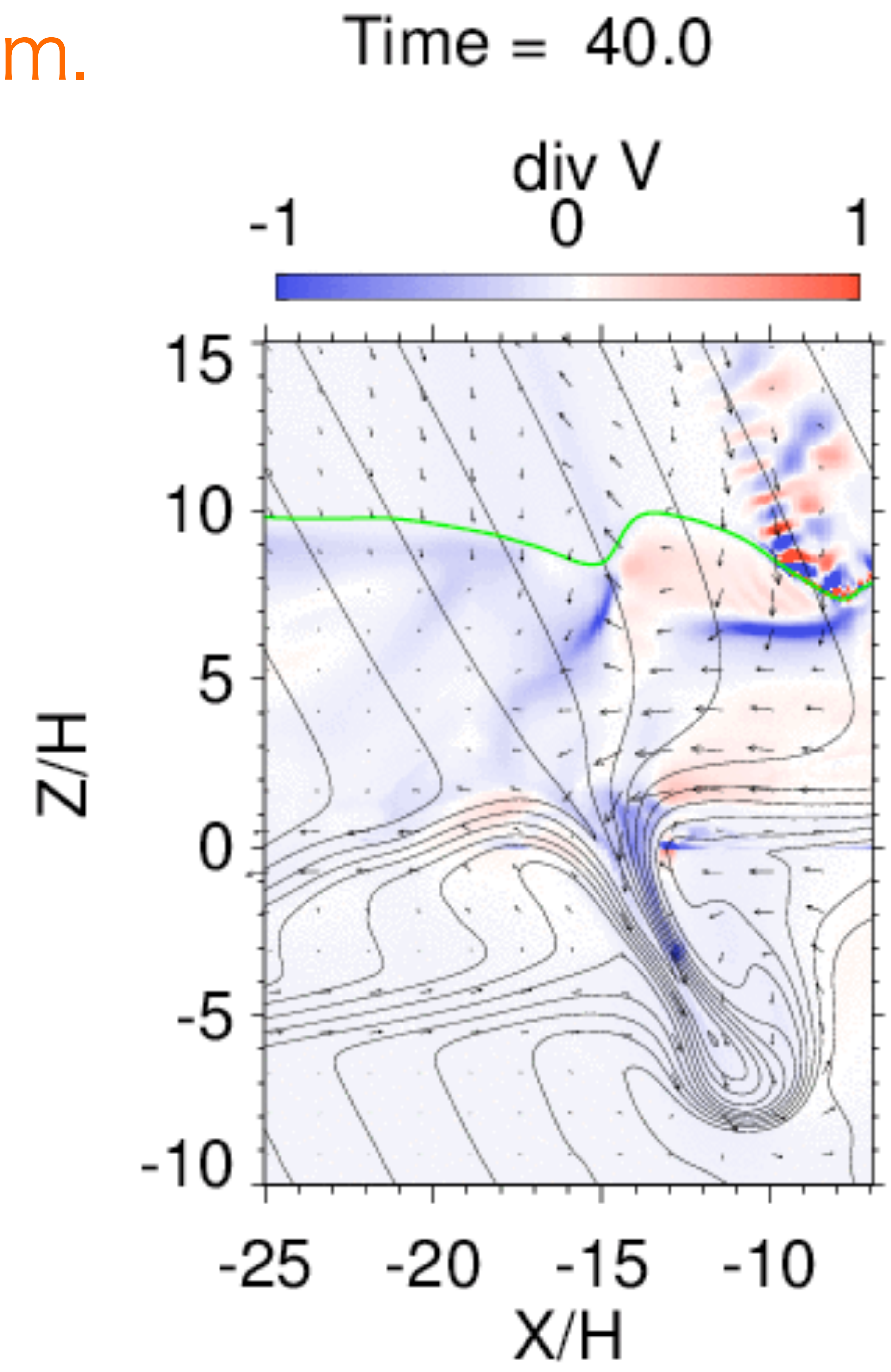
Fig. 2(a). The trajectories of the fluid elements which initially exist at the height of 360, 560, 760, 960, 1160, 1360, 1560, 1760, 1960, and 2160 km. Numerals beside each curve represent the initial heights of the fluid elements.

Suematsu et al. 1982

Trajectories
of Lagrange particles

Growth of the Amplitude of a Shock





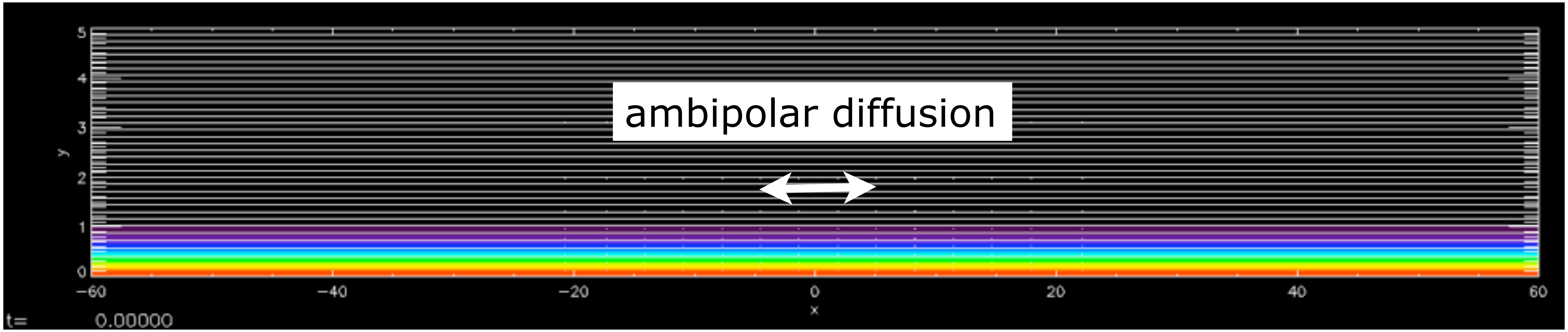
ambipolar diffusion (current sheet thinning)

$$\frac{\partial B}{\partial t} = \nabla \times [V_n \times B - \frac{J \times B}{en_e} + \frac{(J \times B) \times B}{c\nu_{ni}\rho_n} - \eta J]$$

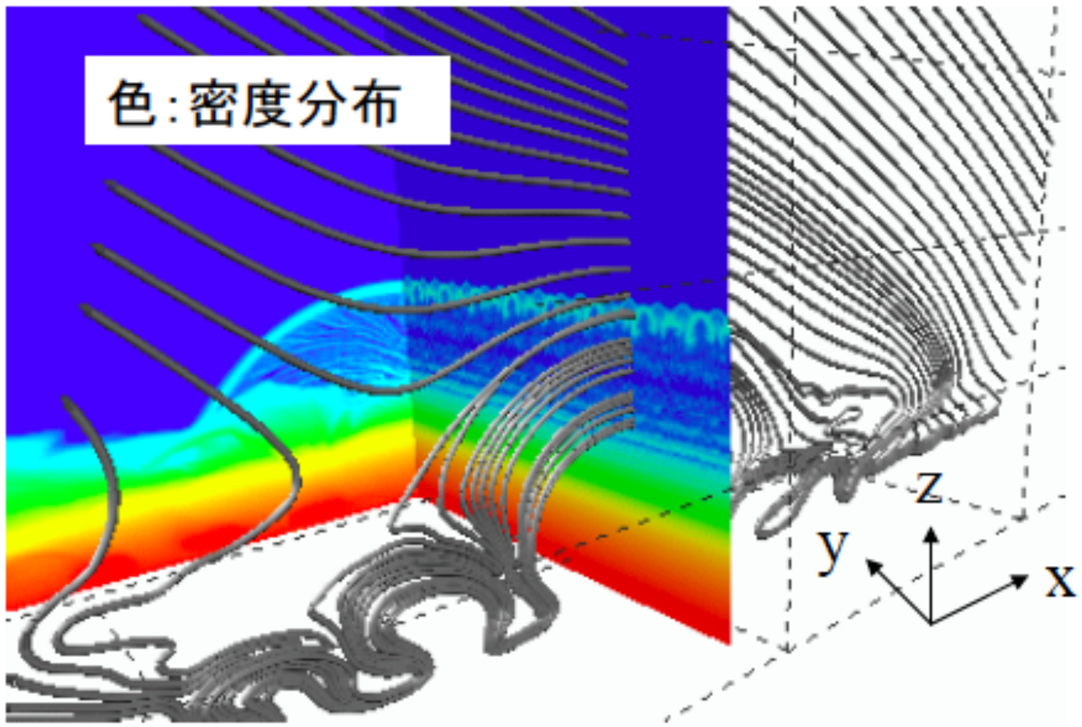
localized distribution of neutrals

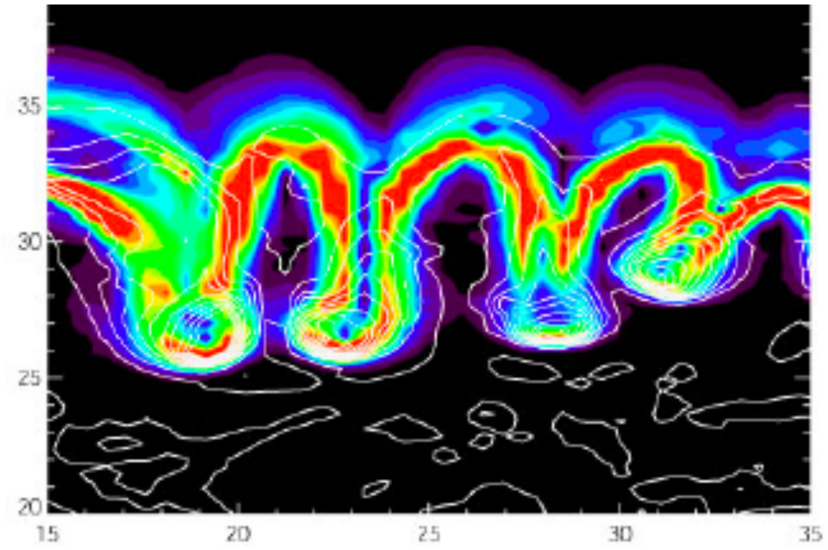
→ local current sheet thinning

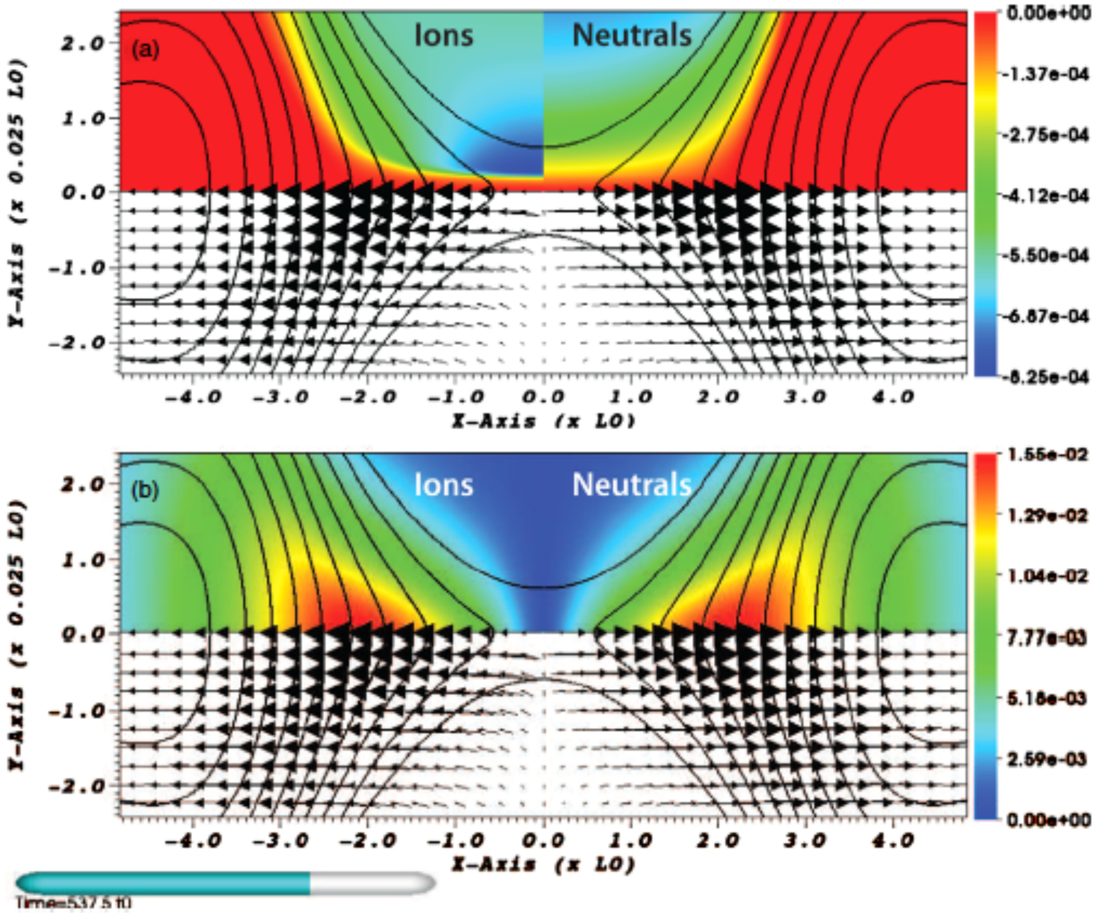
→ Petschek-like reconnection (Isobe in prep.)



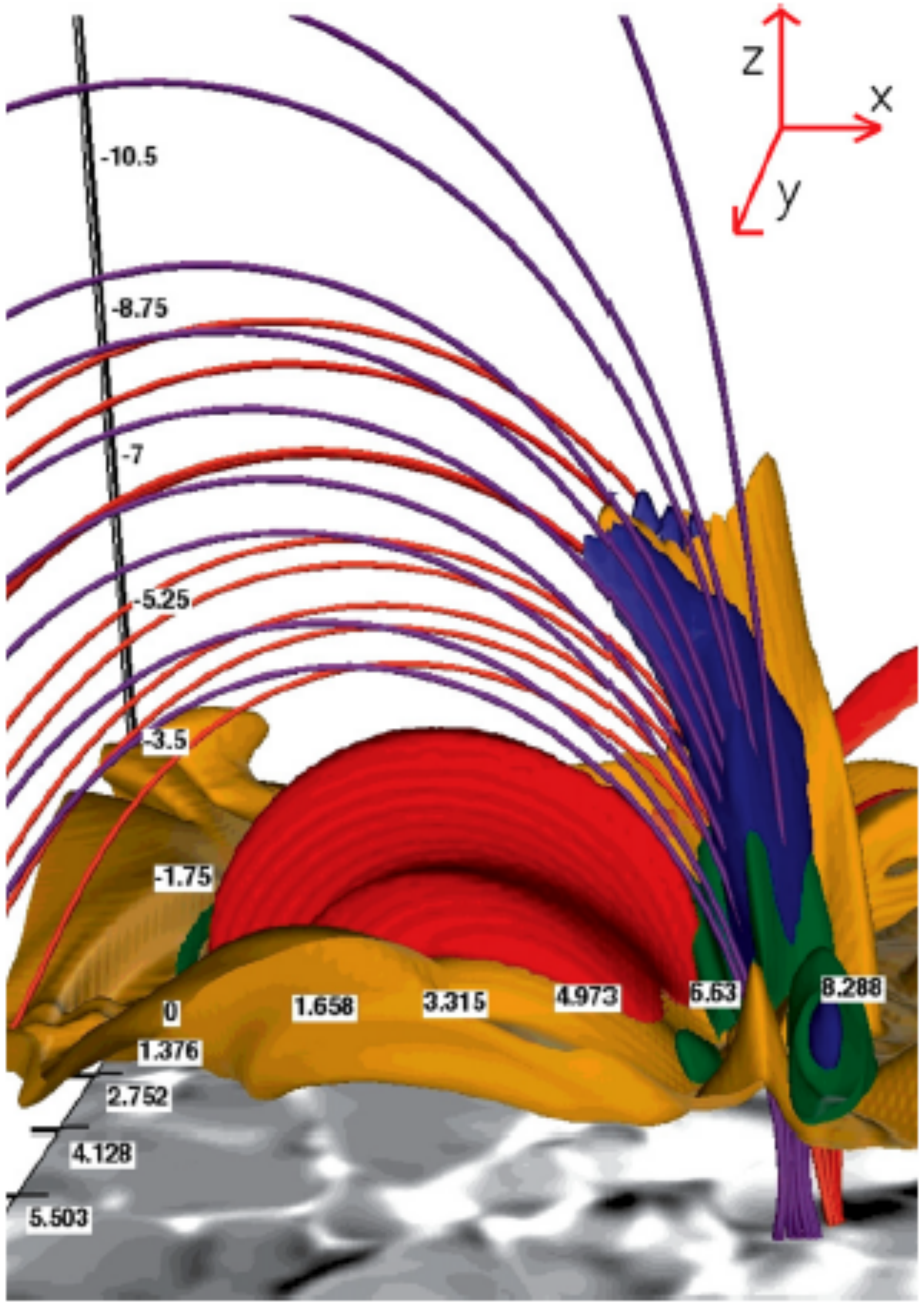
Future Work:
3D Effects and Partially Ionization Effects

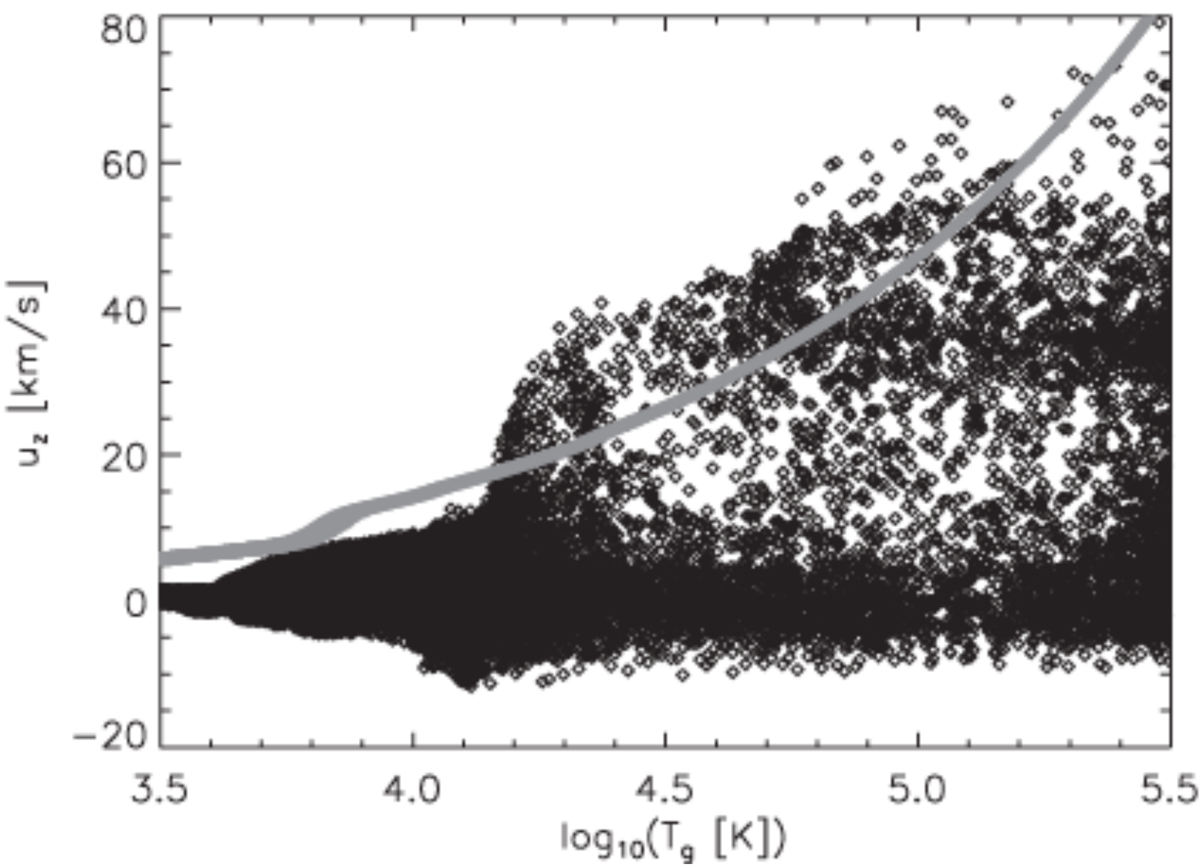






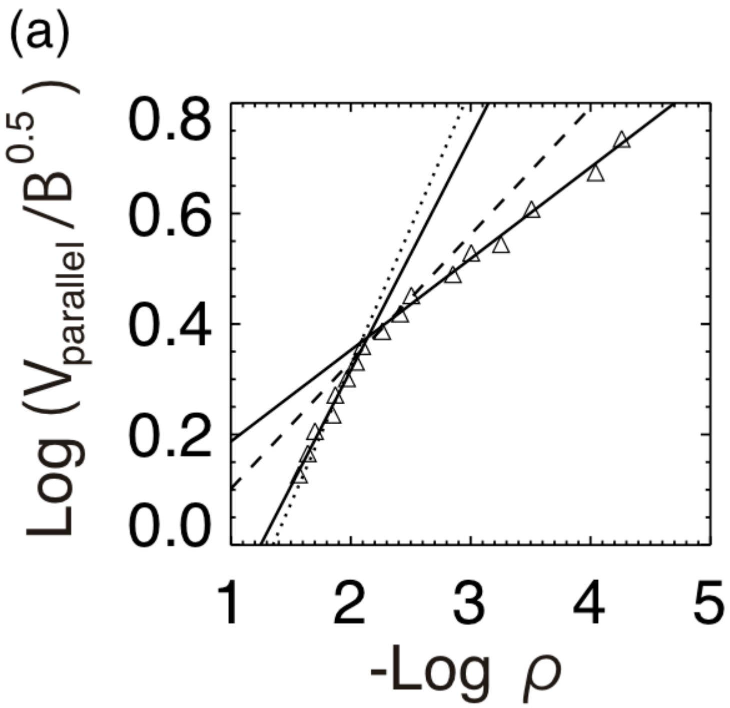
Squeezing Acceleration





Results of the squeezing acceleration by the Lorentz force (Martinez-Sykora + 2012). This cannot be account for jets which is much faster than the sound speed.

Comparison of 2D results with 1D analytical relations

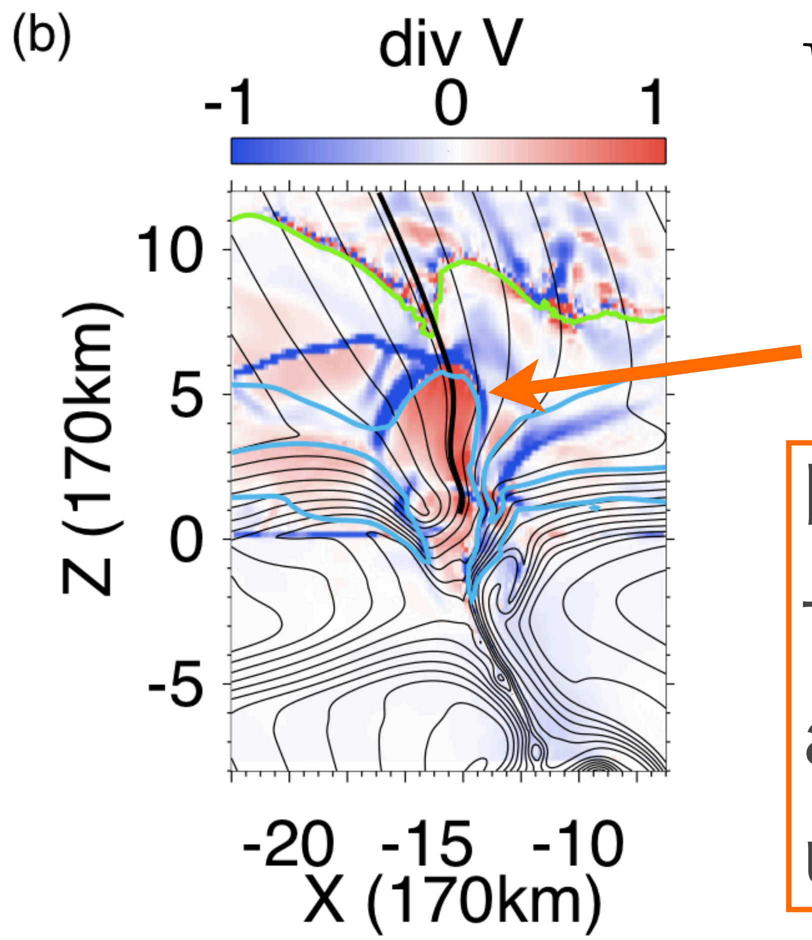


1D analytical relations

$$V_{parallel} B^{-0.5} \propto \begin{cases} \rho^{-0.5} & \text{(linear wave)} \\ \rho^{-0.236} & \text{(strong shock)} \end{cases}$$

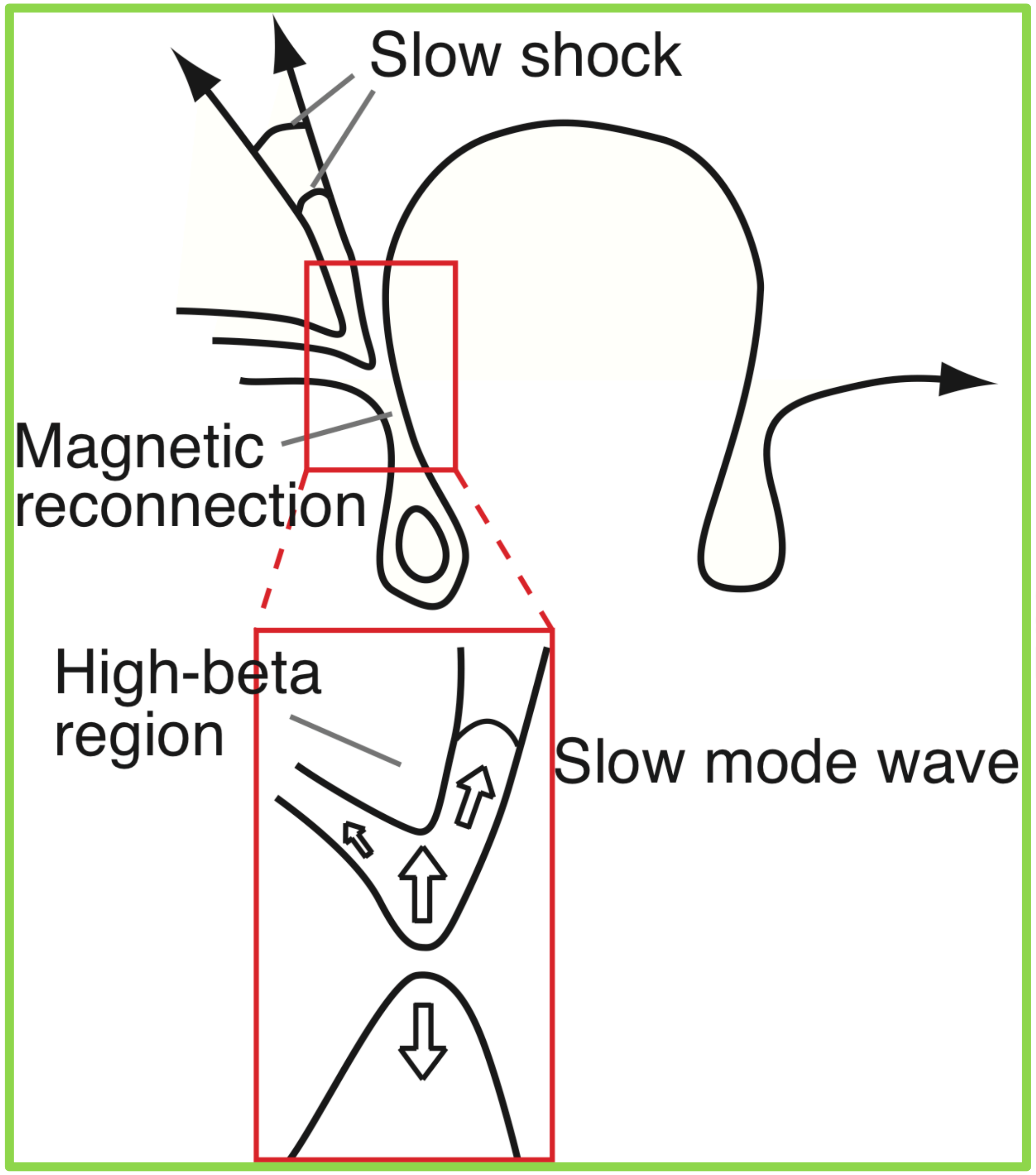
2D simulation results

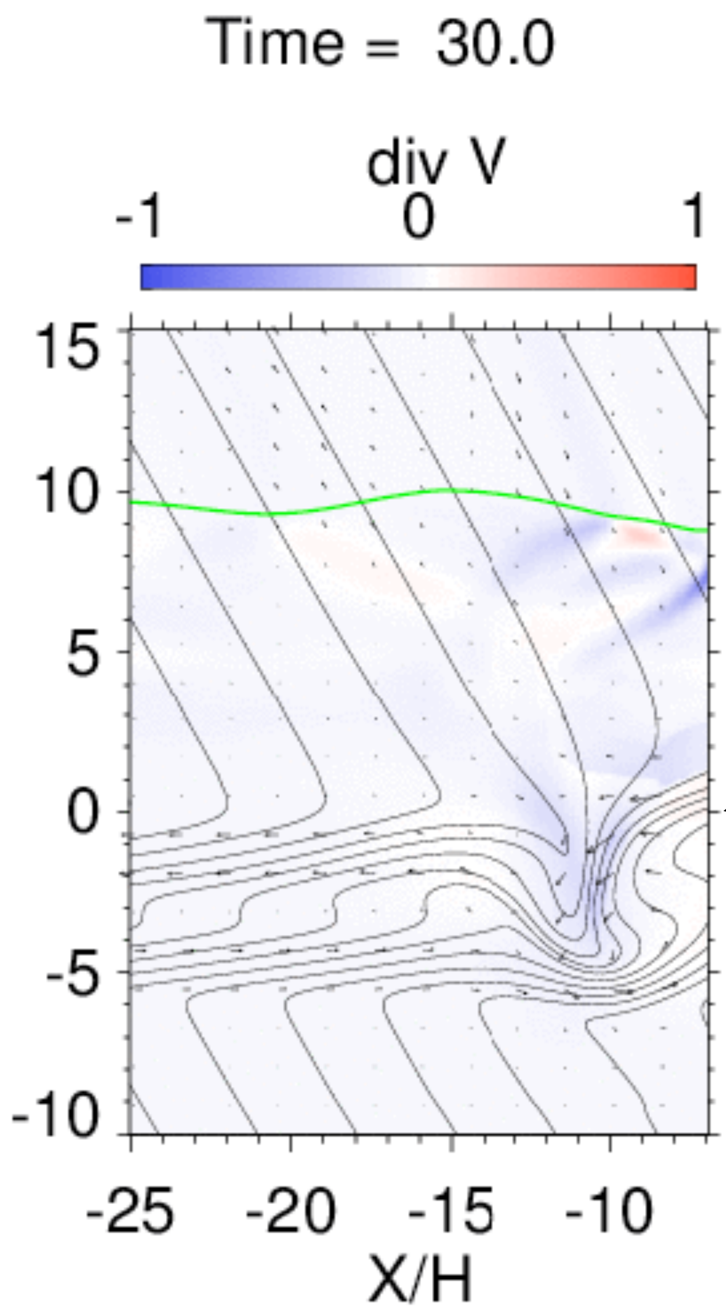
$$V_{parallel} B^{-0.5} \propto \begin{cases} \rho^{-0.36} \\ \rho^{-0.15} \end{cases}$$



Plasma beta behind the shock is close to unity! Therefore the rigid flux tube approximation is broken even in the upper chromosphere.

Lower Atmospheric Recon.: Shock Acceleration





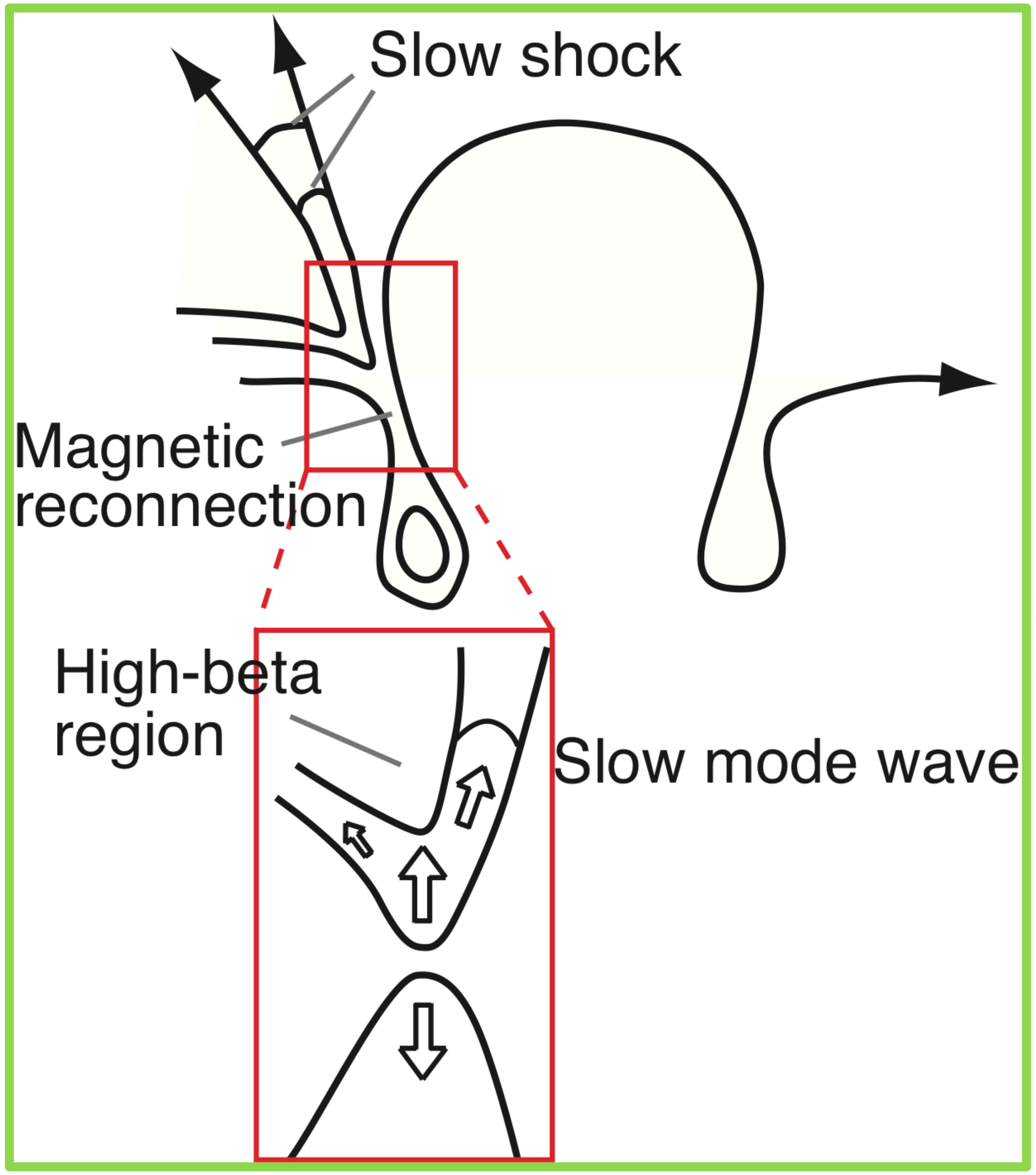
$V_{jet} \sim 40$ km/s
$h_{jet} \sim 4$ Mm

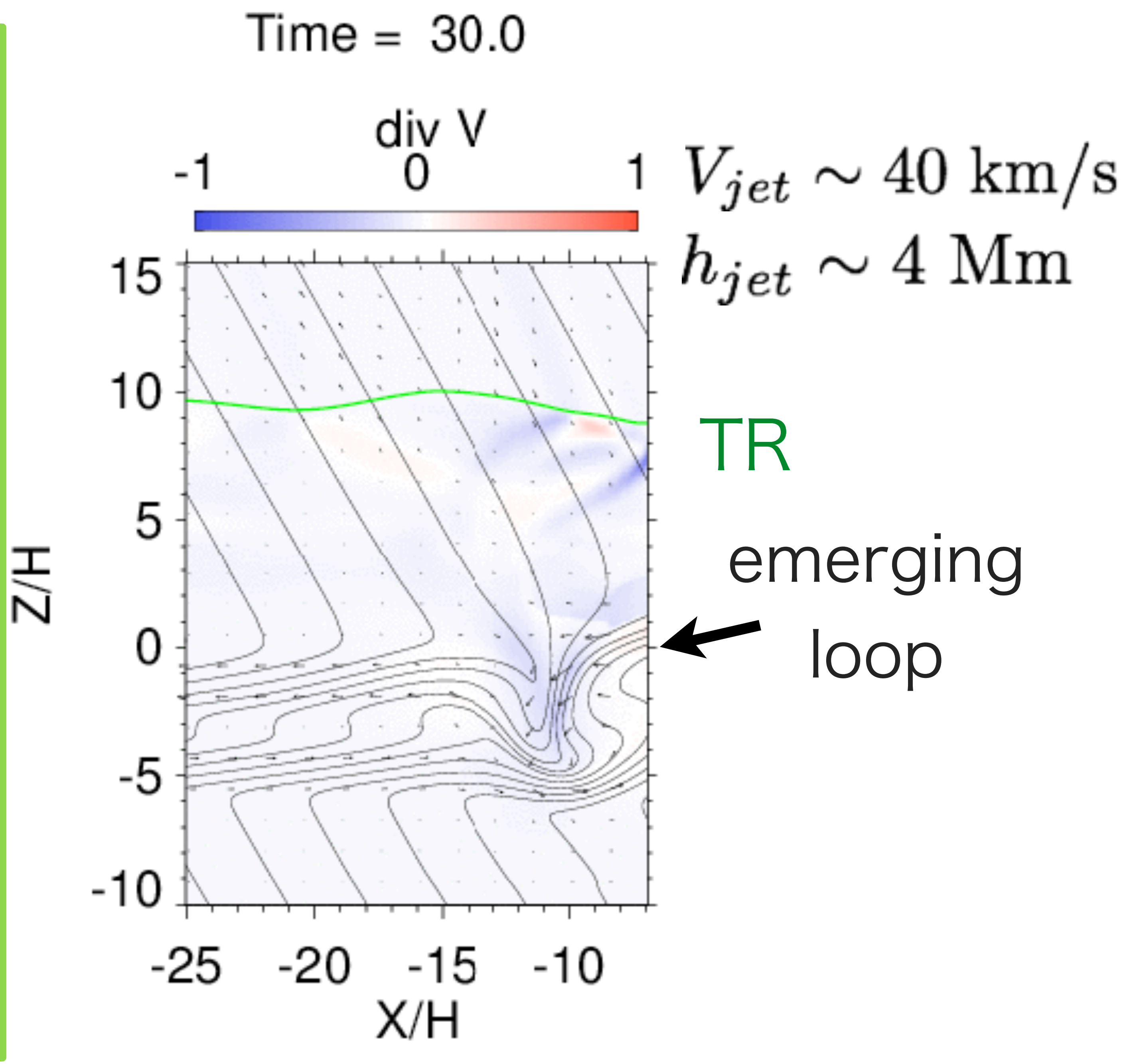
TR

emerging loop

Note: The plasma behind the shock is strongly expanded.
This could be important for decreasing the optical depth, so disappearance of jets

Lower Atmospheric Recon.: Shock Acceleration

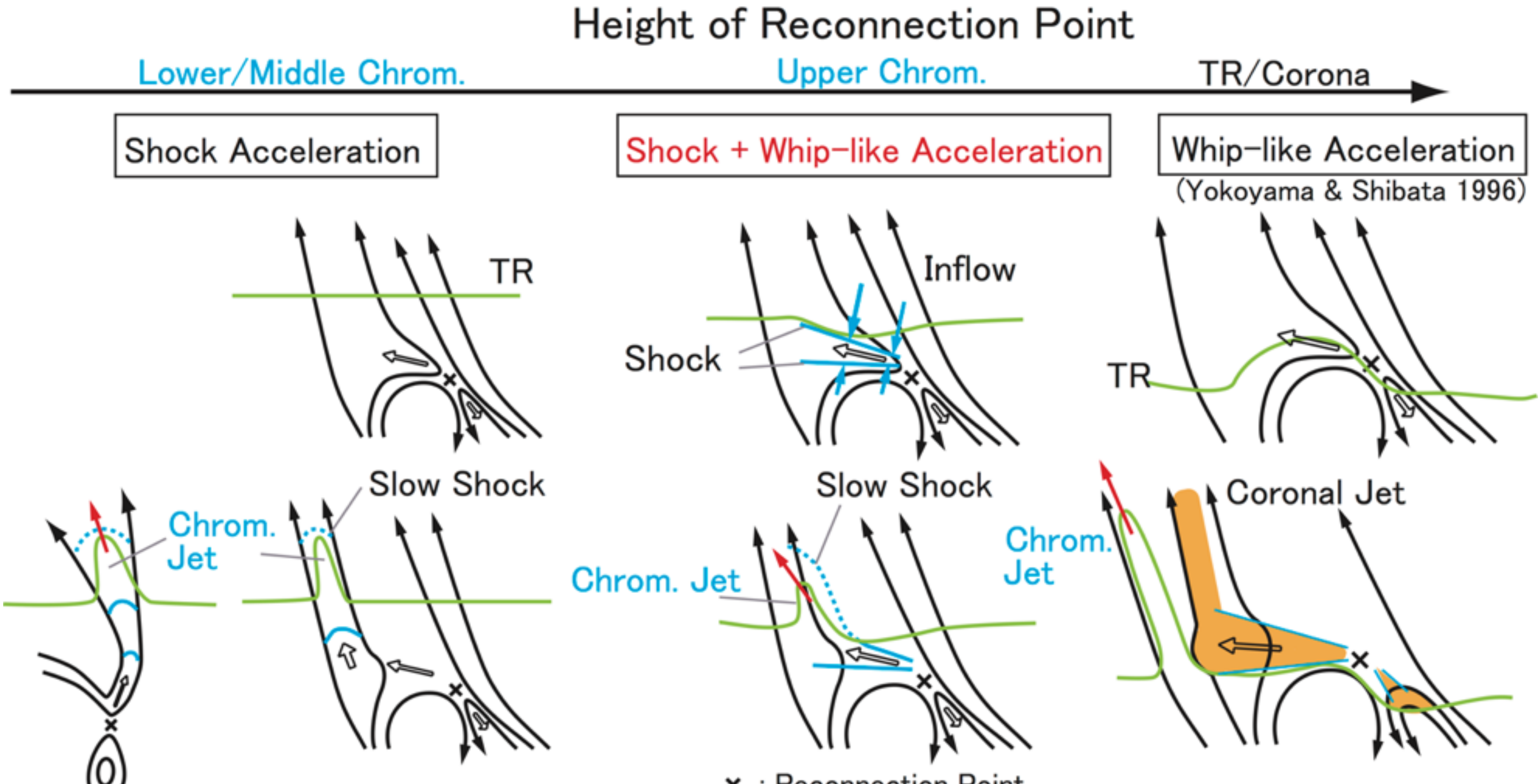




Application:

Ellerman bombs => H-alpha Surges (e.g. Pariat+2004)

Systematic Understanding of Chromospheric Jets: Classification by the Height of Recon. Points



Ellerman bombs => surges
tiny Ca jets
some fraction of spicules?

larger Ca jets
(~2Mm)

H-alpha surges