# Slow Shock Acceleration Mechanism of Chromospheric Jets on the Sun

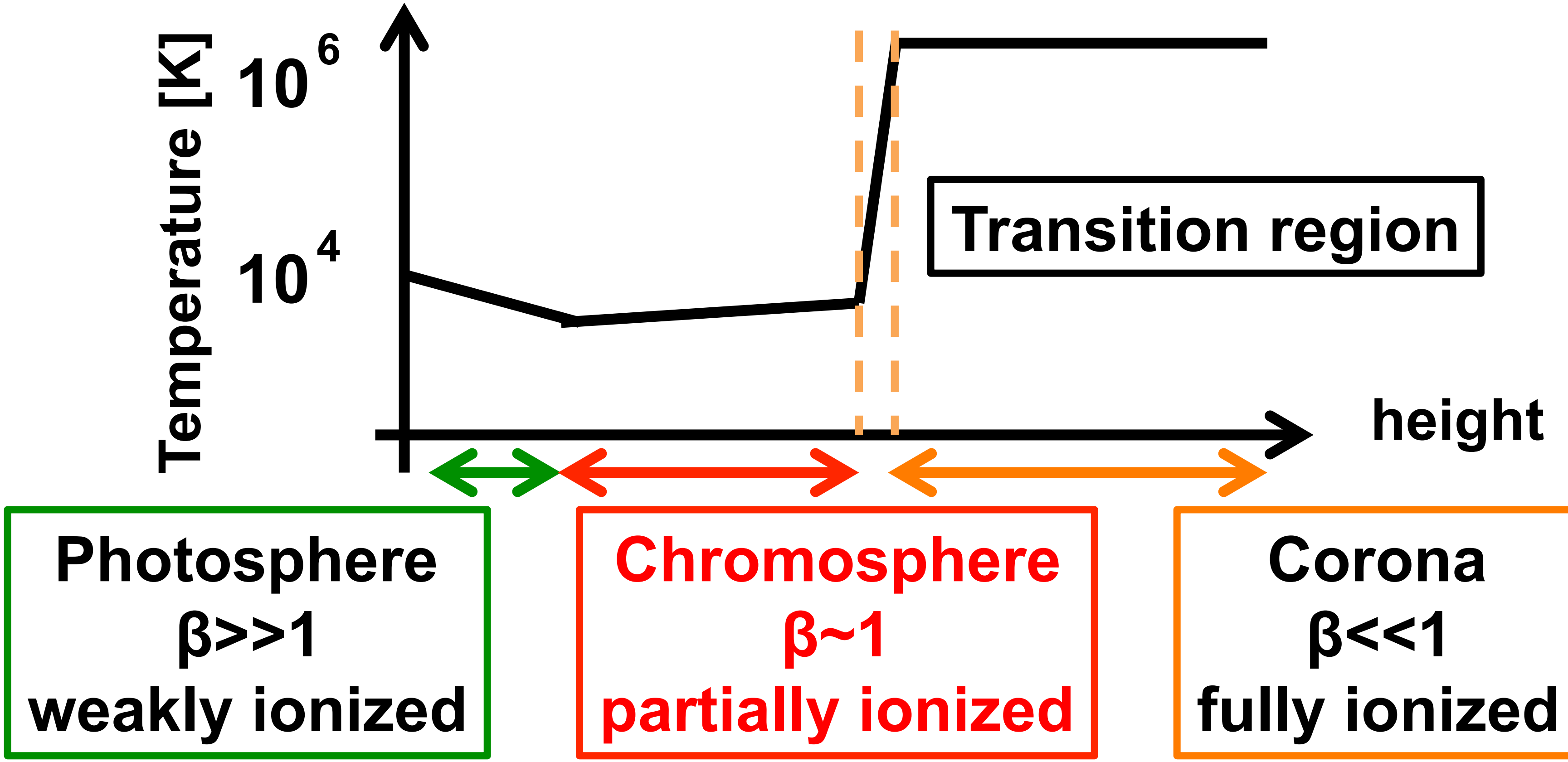

**Shinsuke TAKASAO,**

**Hiroaki ISOBE,**

**and Kazunari SHIBATA**

**(Kyoto University)**

# Chromosphere




Chromosphere:
- Partially ionized plasma
- Energy transportation by waves

These are also important in the ionosphere etc.

# Neutral Effect on Magnetic Reconnection

**ambipolar diffusion** (current sheet thinning)

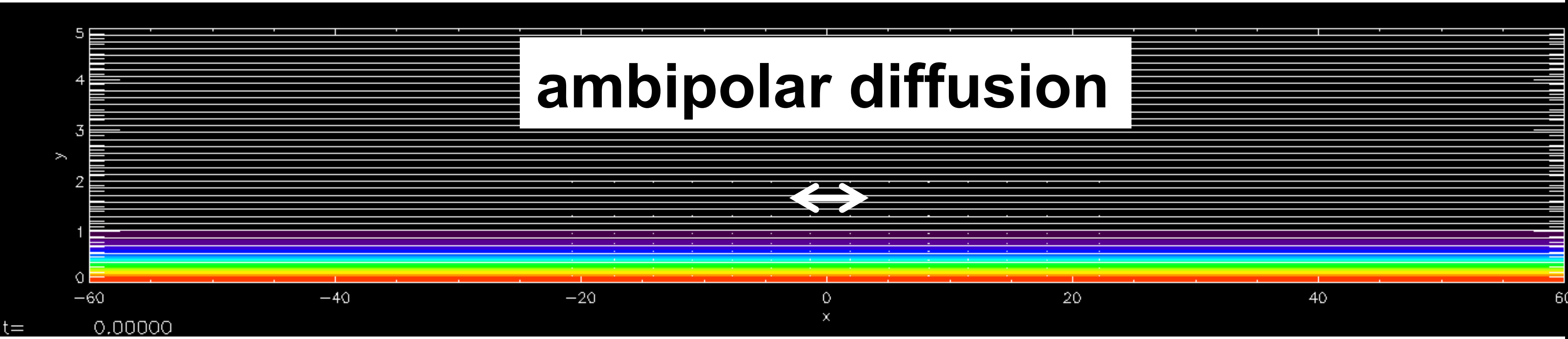
$$\frac{\partial B}{\partial t} = \nabla \times \left[ V_n \times B - \frac{J \times B}{e n_e} + \frac{(J \times B) \times B}{c \nu_{ni} \rho_n} - \eta J \right]$$

**localized** distribution of neutrals

→ **local** current sheet thinning

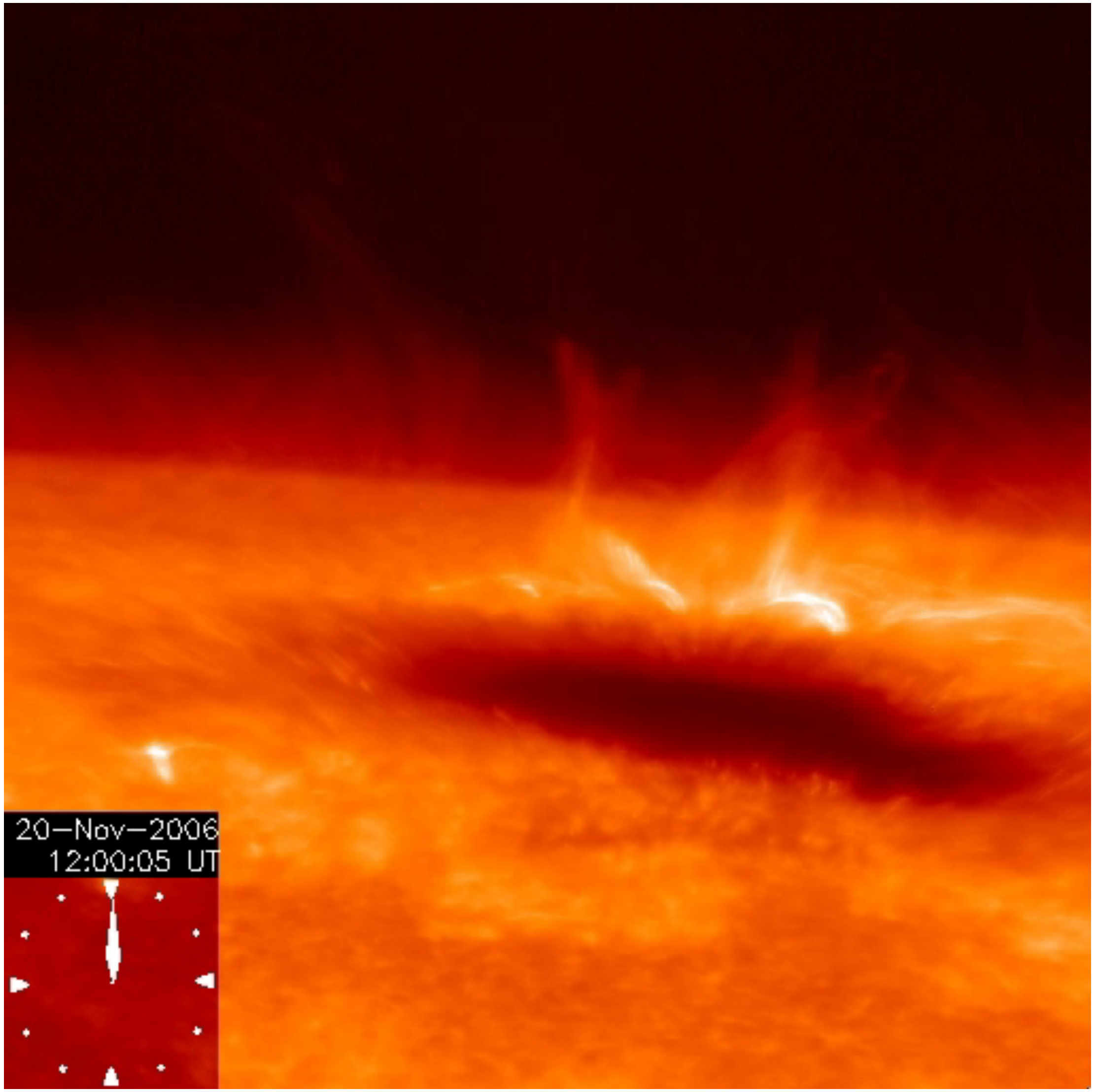
→ **Petschek-like reconnection** (ref. Isobe's talk)

**This fast reconnection might produce the rapid phenomena (e.g. jets) on the Sun.**



# Chromospheric Jets on the Sun

**Many jets near the sunspot!!**



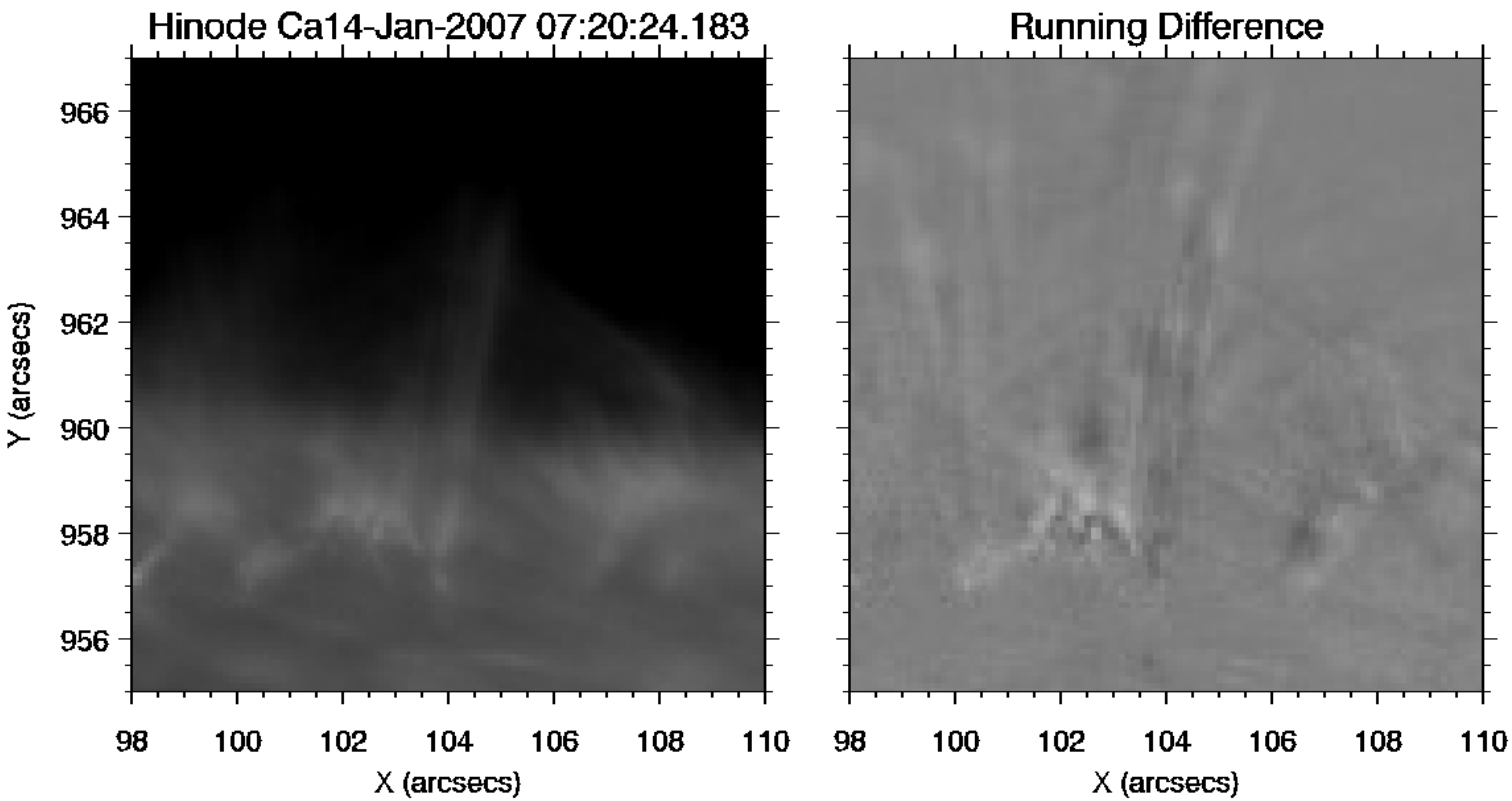

**Hinode/SOT**
**Ca II H, T~10^4K**

**Courtecy Okamoto (ISAS/JAXA)**

**frequent occurrence => waves => coronal heating**

# Chromospheric Anemone Jets

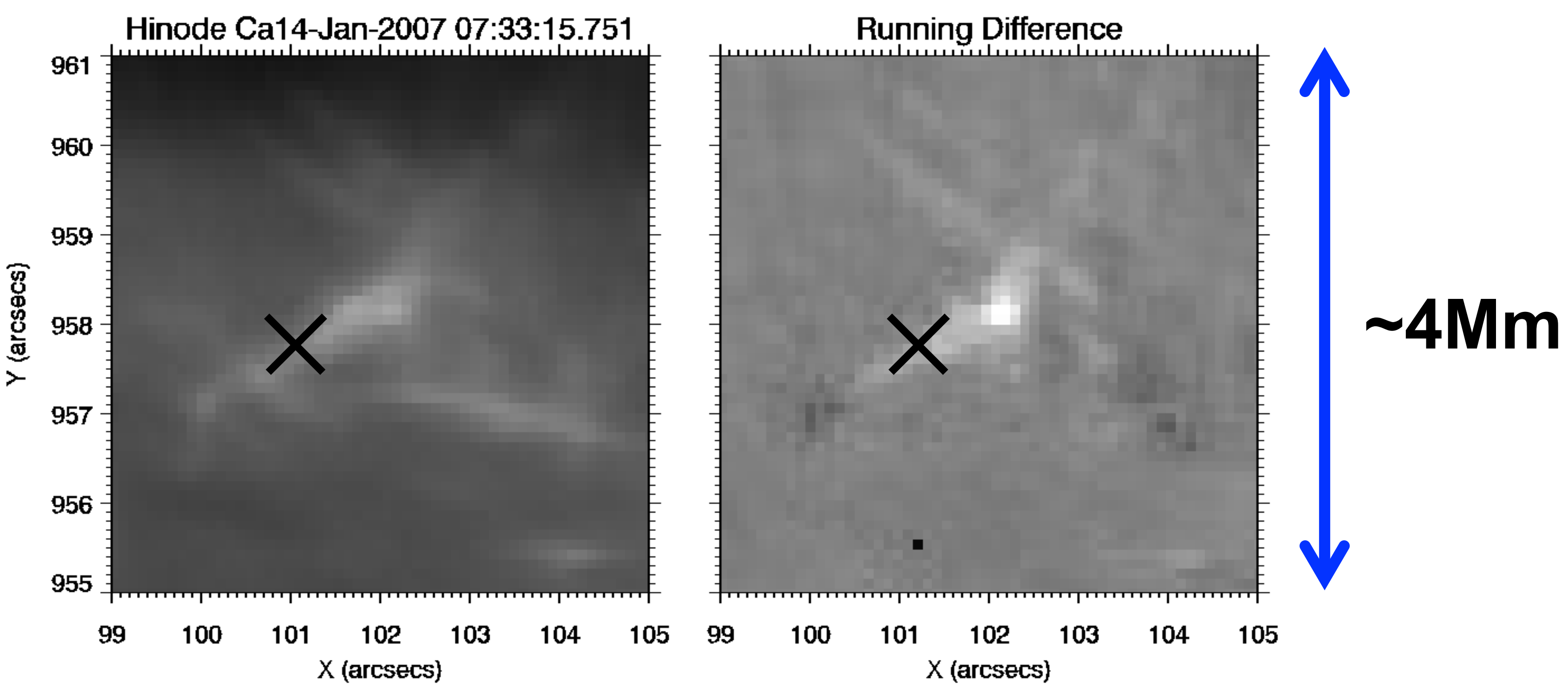
**Anemone jet :**
**Jet with a loop structure at the foot-points**
**(suggesting the existence of the emerging flux)**



# Observational Result Supporting Magnetic Reconnection Model

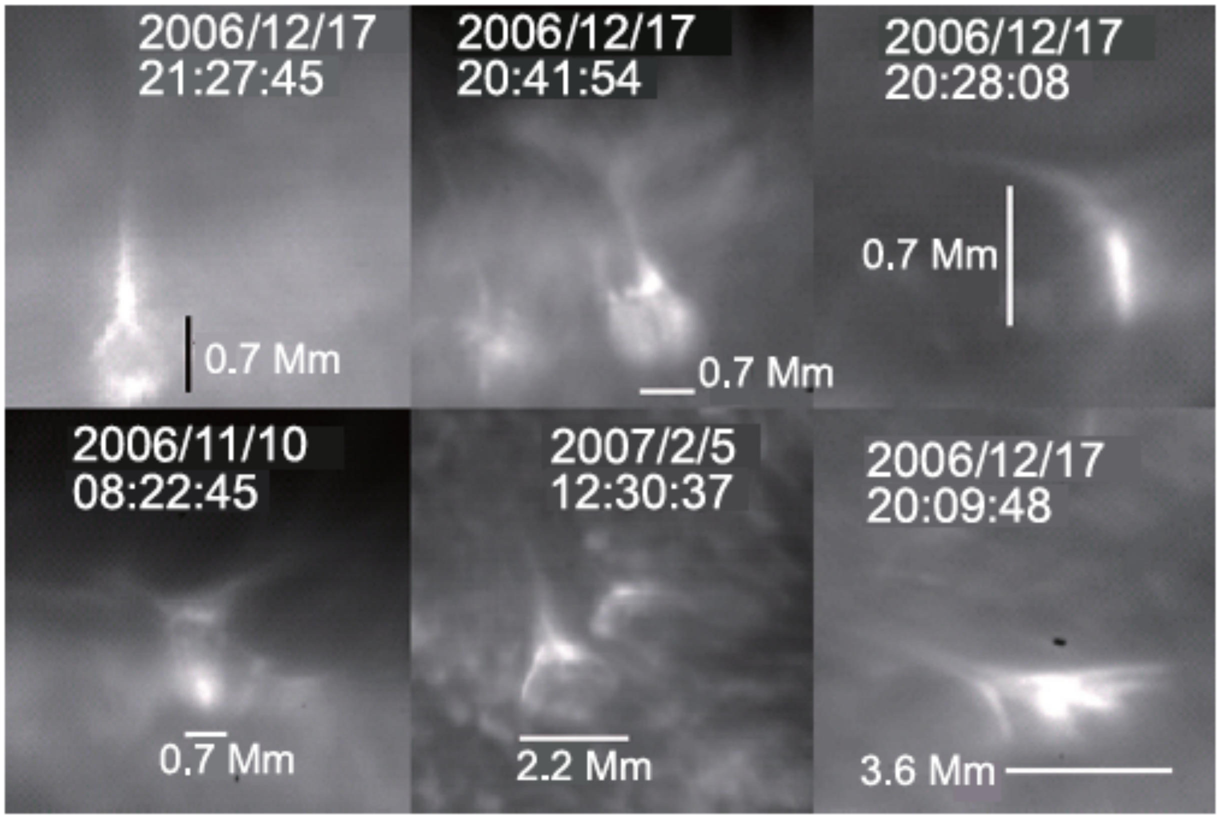
<u>An enlarged movie of the previous one:</u>

- Apparent bidirectional motions.
  This might be the reconnection outflows.
- The direction of the jets is perpendicular to that of the bidirectional motion.



# Observed Physical Values of Chromospheric Anemone Jets

**Anemone jets**
**= jets with loop structures**




**Temperature:**
~10,000 K

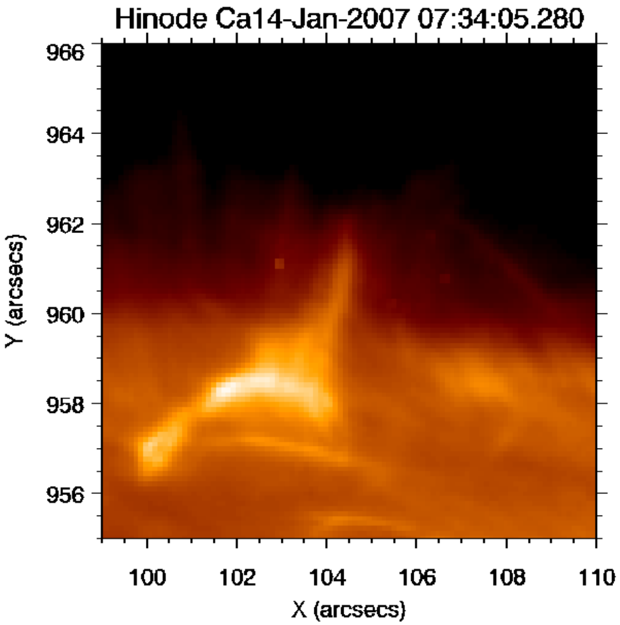
**Velocity:**
~10-100 km/s
( > Cs ~ 10km/s)

**Lifetime:**
>~100 sec

**Size:**
1,000–~5,000km

Shibata et al. 2007
Nishizuka et al. 2011

# Remaining Problem of Magnetic Reconnection Model




**Magnetic reconnection model would be the most promising.**

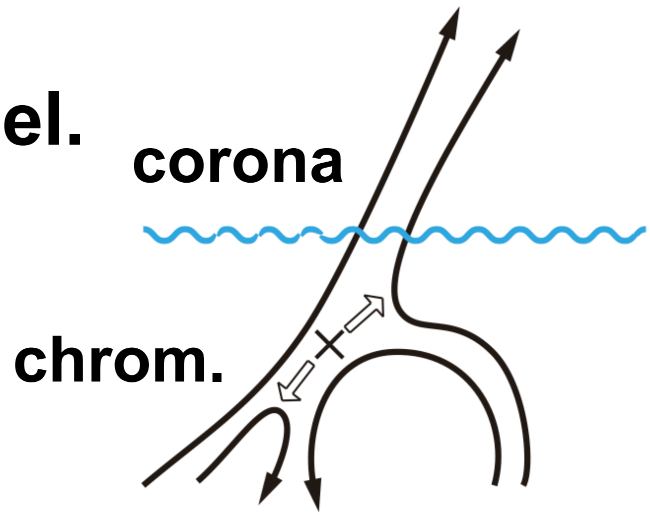
**However,**

**β~1 in the chromosphere.**

$$V_A \approx Cs$$

**It seems difficult to explain the super-Alfvenic jets with a simple reconnection model.**

**Jet ≠ Reconnection outflow**



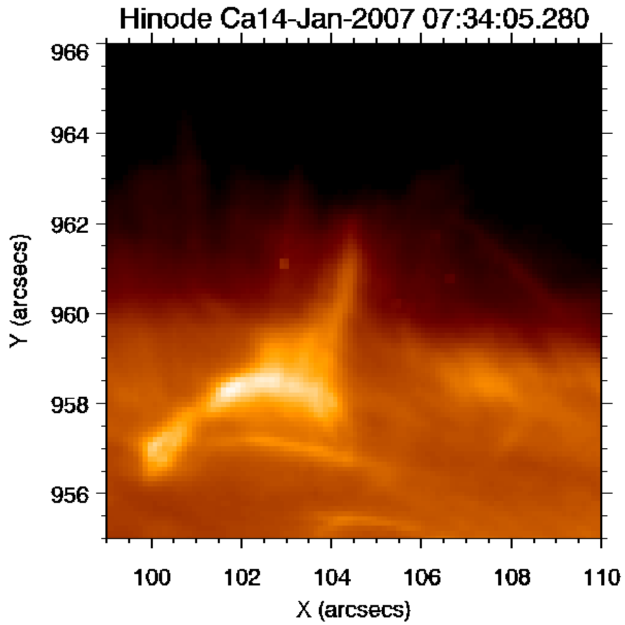
# Model for Chromospheric Anemone Jets: Importance of Slow Shock

**A proposed scenario**

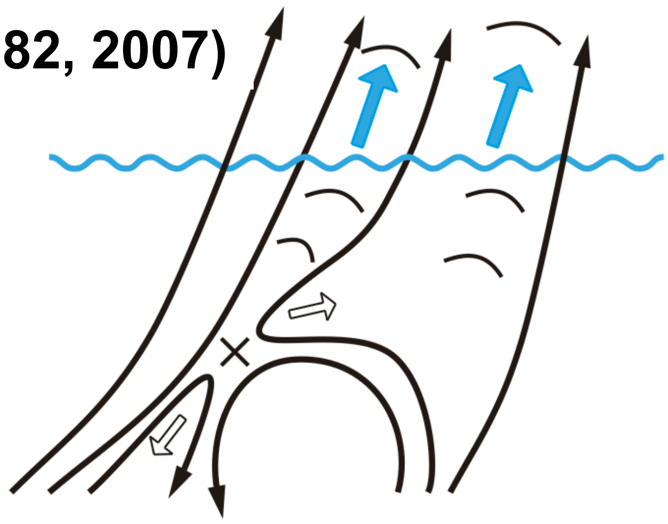
Energy release by reconnection

→ **Waves (Slow Shocks) (energy carrier)**

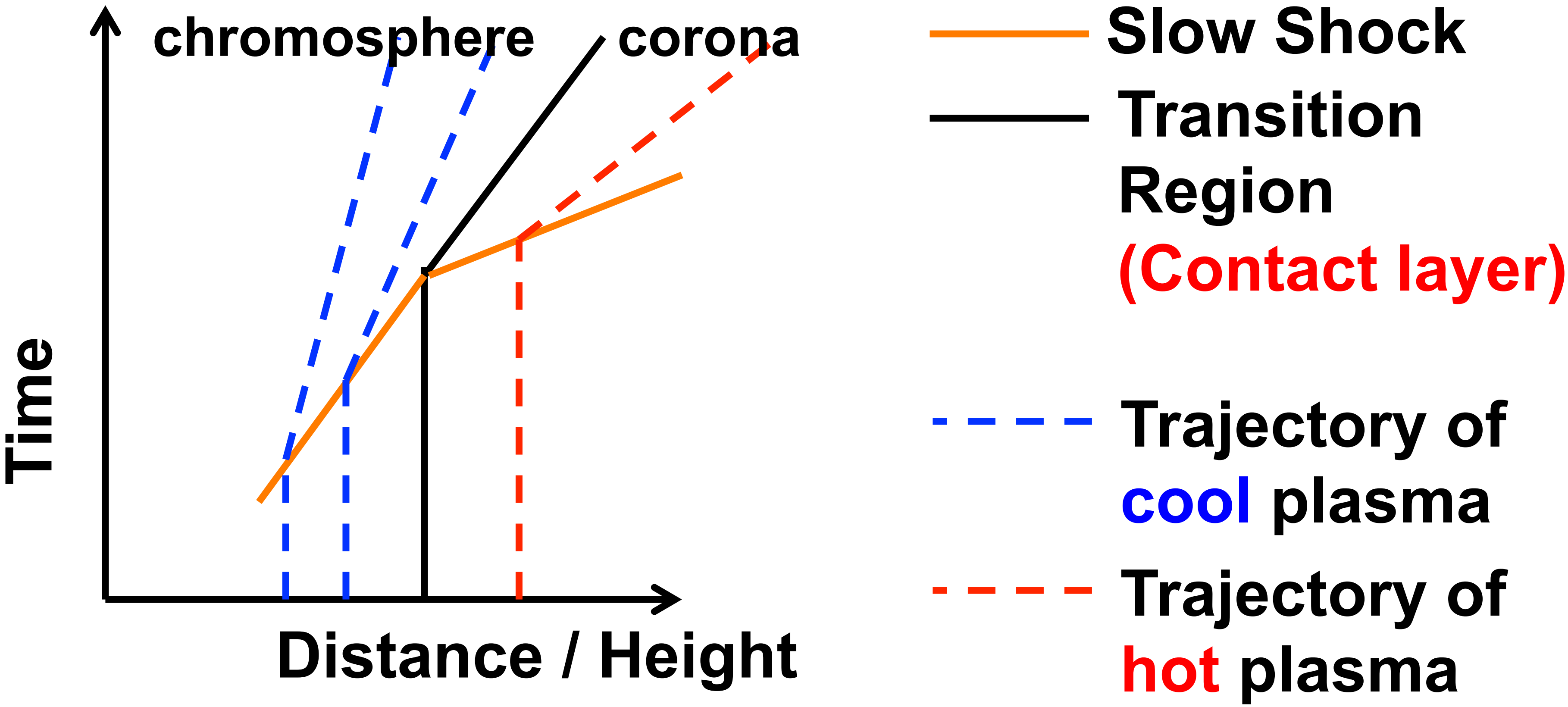
→ **Jets**




(Shibata et al. 1982, 2007)



# Basic Concept of Slow Shock Acceleration Mechanism




Jet
= launched contact discontinuous layer

(e.g. Osterbrock 1961; Suematsu et al. 1982; Shibata et al. 1982)

# Model for Chromospheric Anemone Jets: Importance of Slow Shock

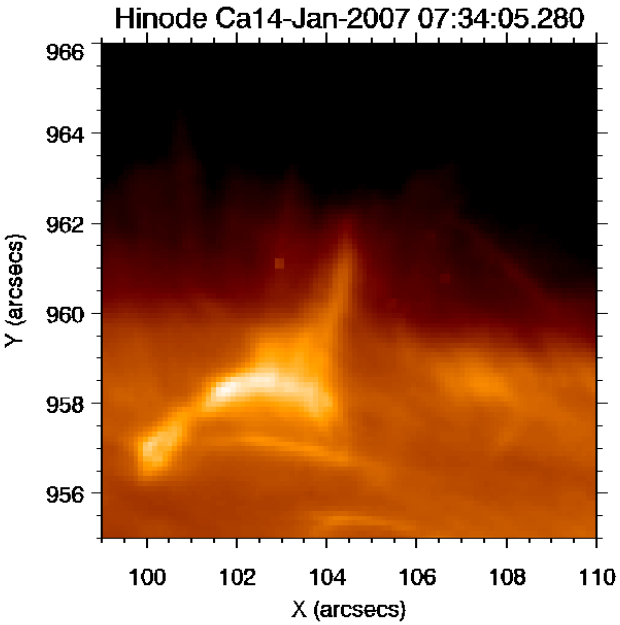
**A proposed scenario**

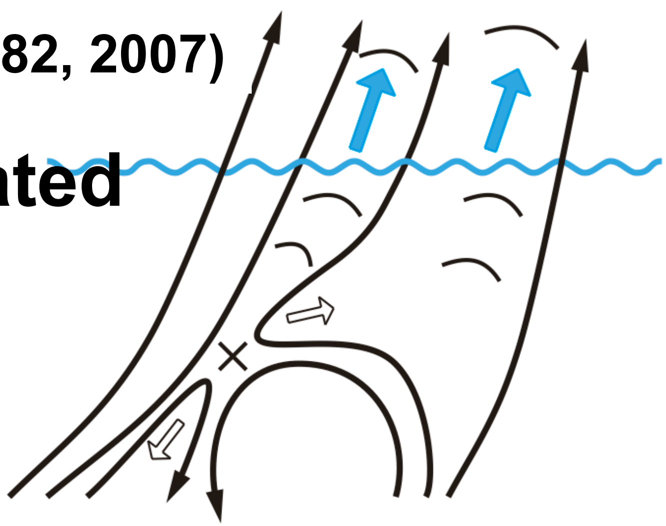
Energy release by reconnection

→ **Waves (Slow Shocks) (energy carrier)**

→ Jets

(Shibata et al. 1982, 2007)



The plasma of the jets is originated from the upper chromosphere.

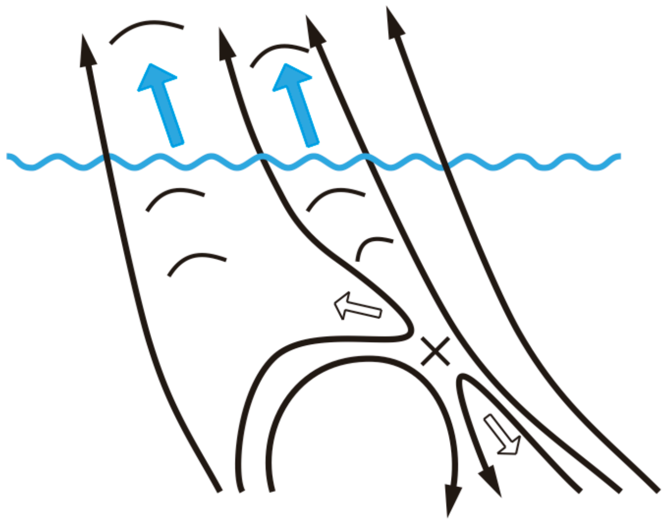
**Not self-consistently confirmed yet!**

# Motivation of This Study

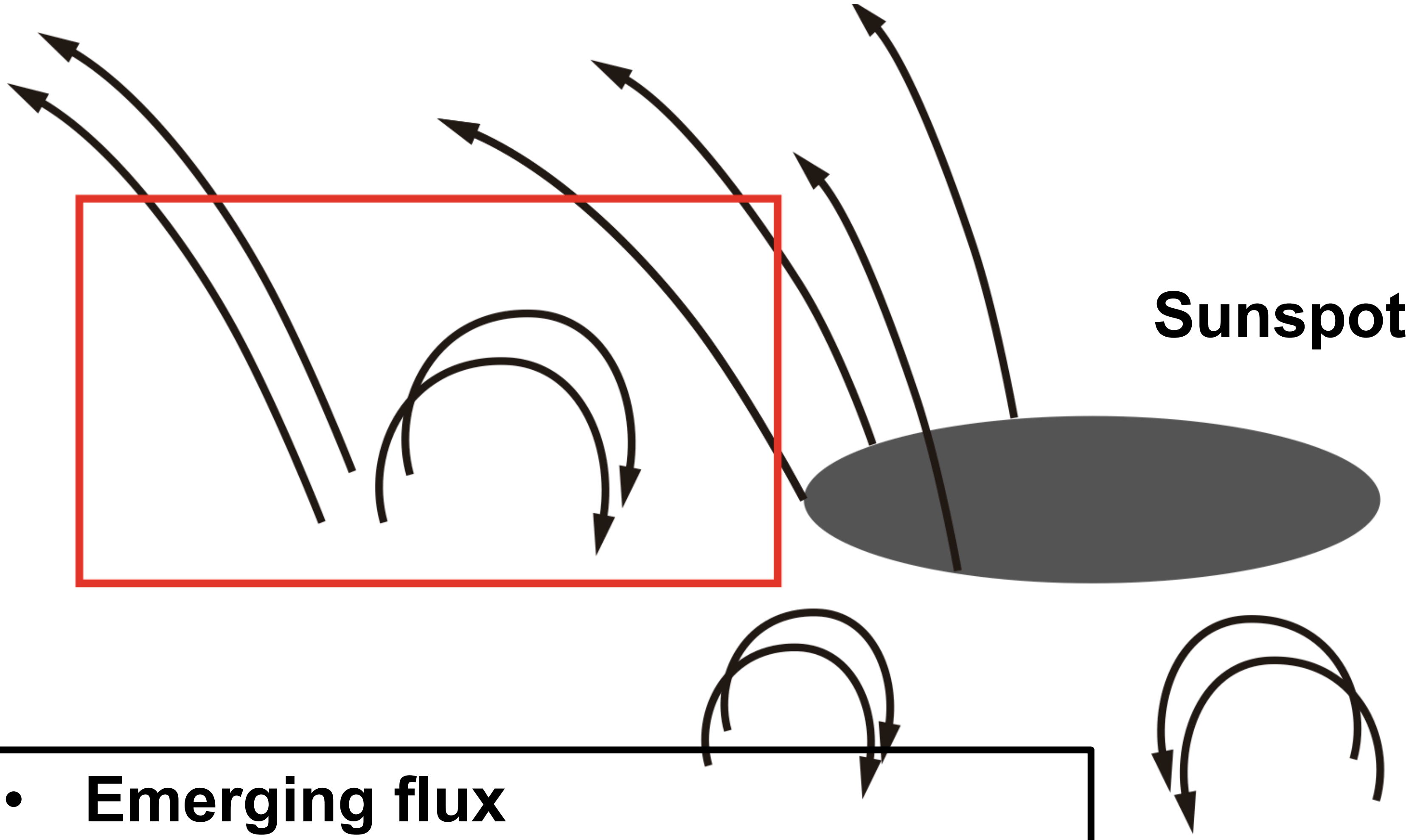
**What is the acceleration mechanism of the chromospheric anemone jets?**

- **Generation mechanism of the slow shocks**

- **Relations between jets and magnetic reconnection**



# Situation: Near a Sunspot



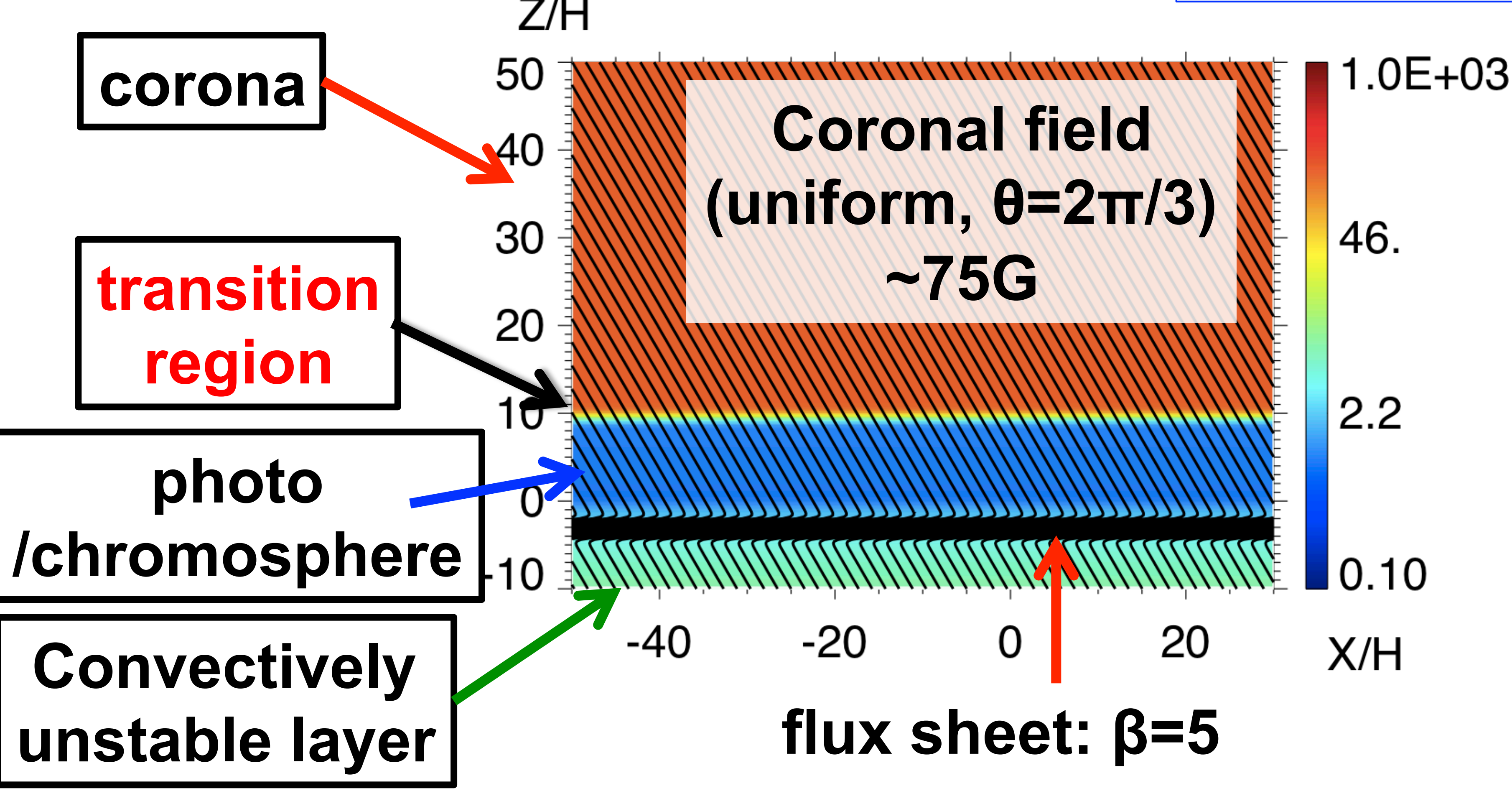

- Emerging flux
- Strong and oblique ambient field
- Low transition region

# Simulation Setup

$H = 170\text{km}$

$T = 5600\text{K}$

uniform gravity




The height of the transition region: Ztr=10H

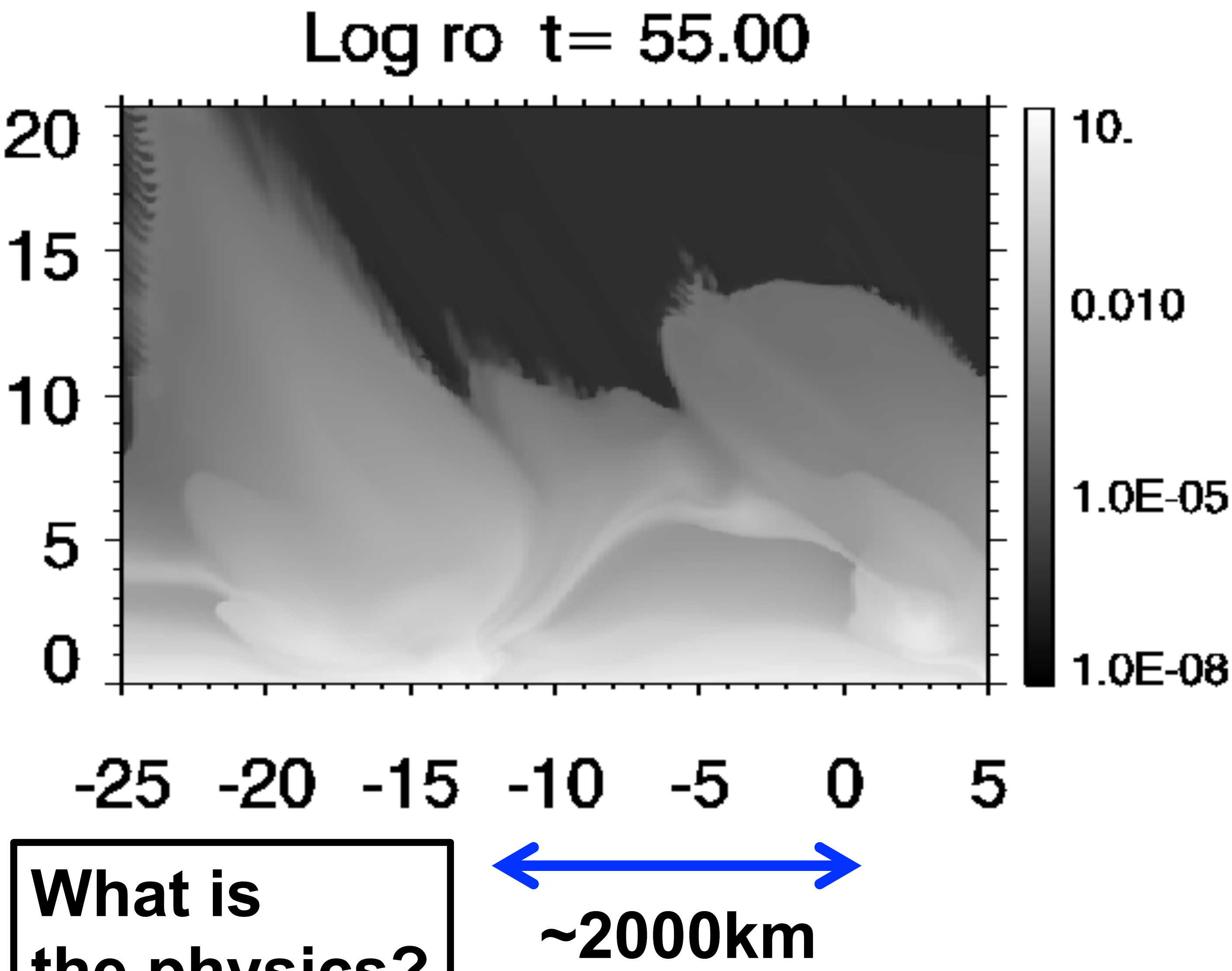
# Simulation Setup

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

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

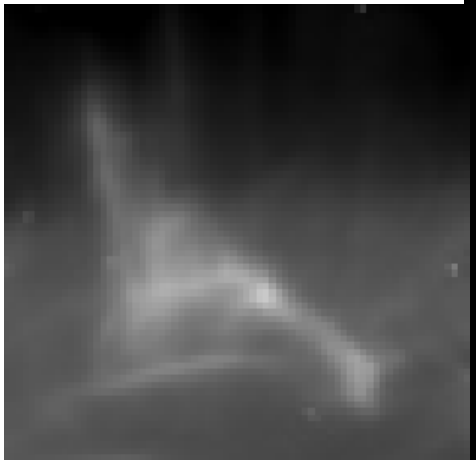
**MHD eqs with**
**the anomalous resistivity (a localized resistivity)**
**and the cooling effect solved by CIP MOC-CT method**

# Density Distribution




What is the physics?

Observation

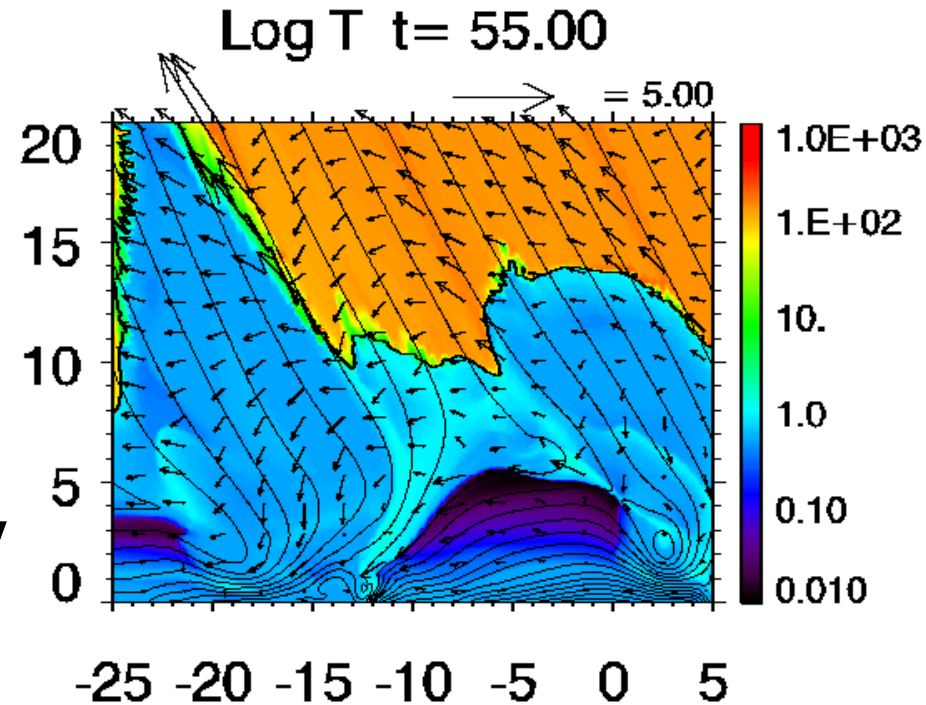


# Temperature and div V distribution

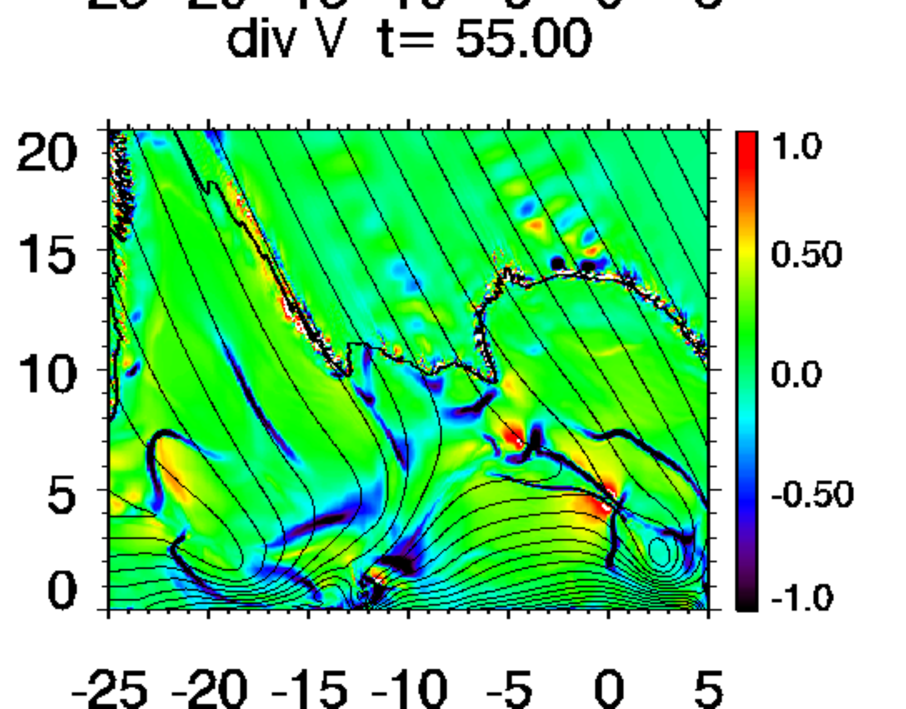
**Thin solid lines**:
field lines

**Thick solid line**:
contact discontinuity

**Arrows**:
velocity vectors

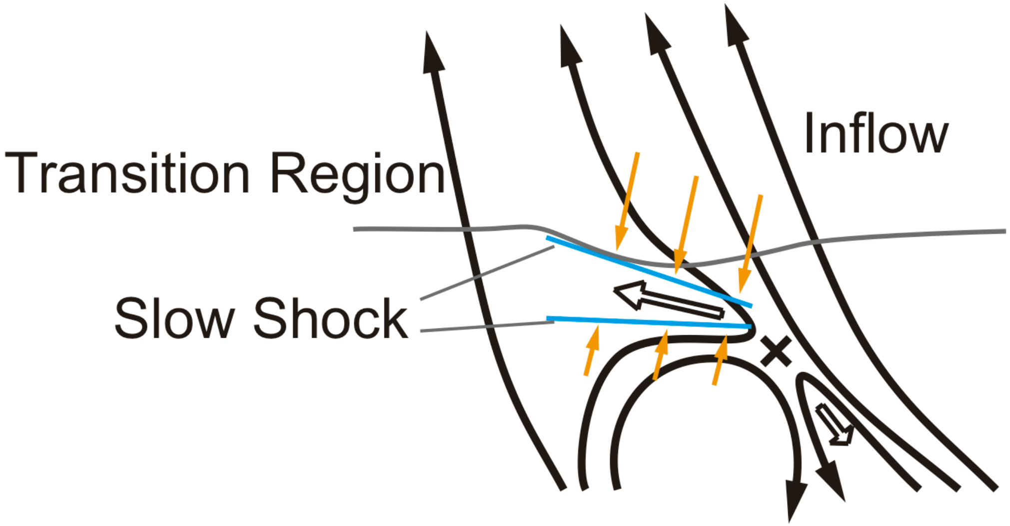



Red:
Expanded region
Blue:
Compressed region
( ~Shock)



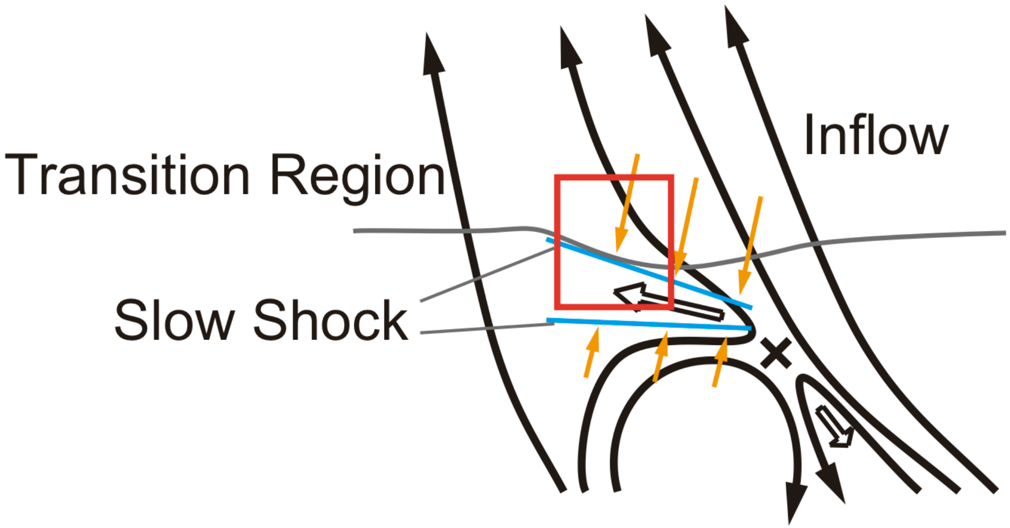
# Schematic Diagrams

**The height of the transition region decreases due to the reconnection inflow.**



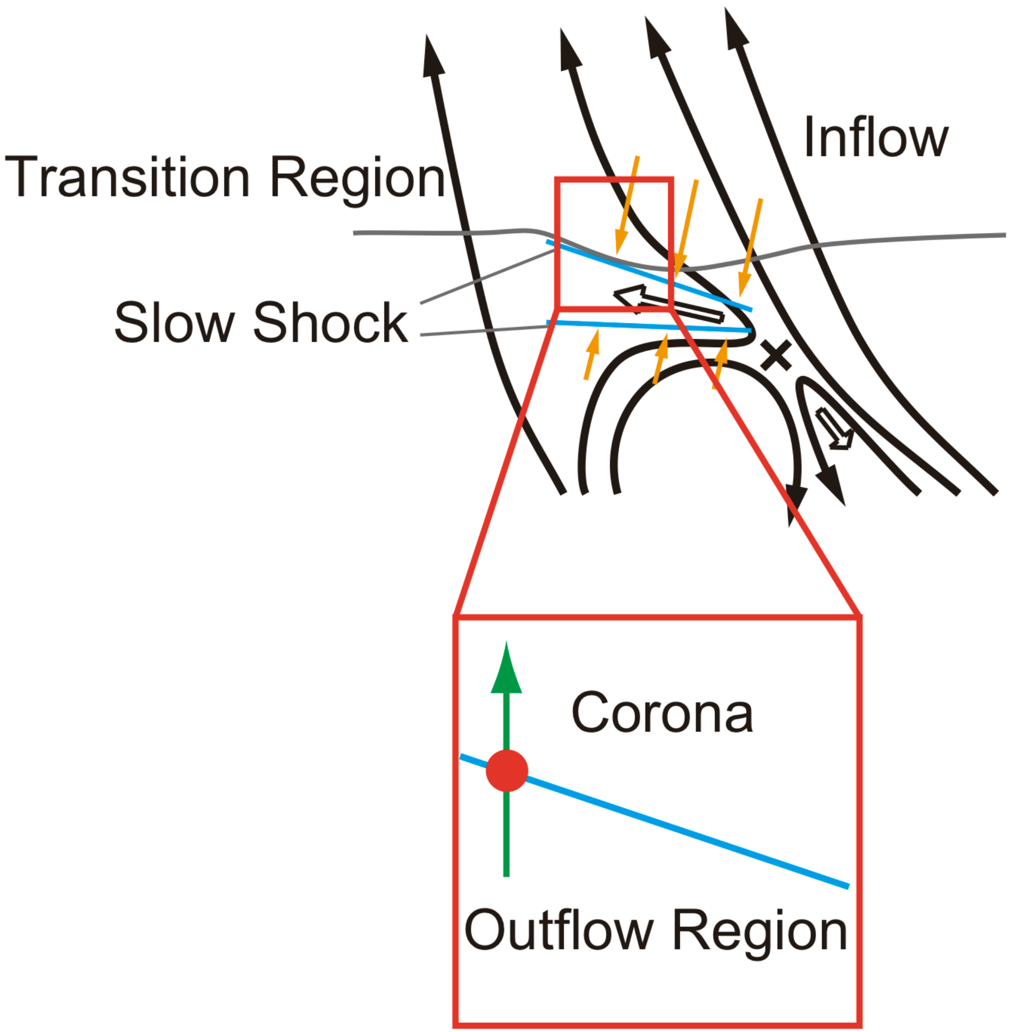
# Schematic Diagrams

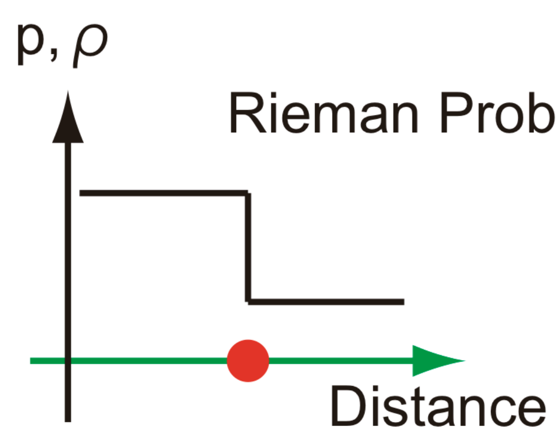
**The transition region collides with the slow shock.**



# Schematic Diagrams

**The transition region collides with the slow shock.** **Riemann (shock tube) problem**



# Schematic Diagrams

**The shock escapes upward and the contact discontinuous layer starts to rise. (chromospheric jet)**