2018.02.27 DKIST CSP WS @ Nagoya-U

Insight on chromosphere dynamics from numerical simulations

Expected signatures of spicule formation and evolution

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(ISEE, Nagoya-U)

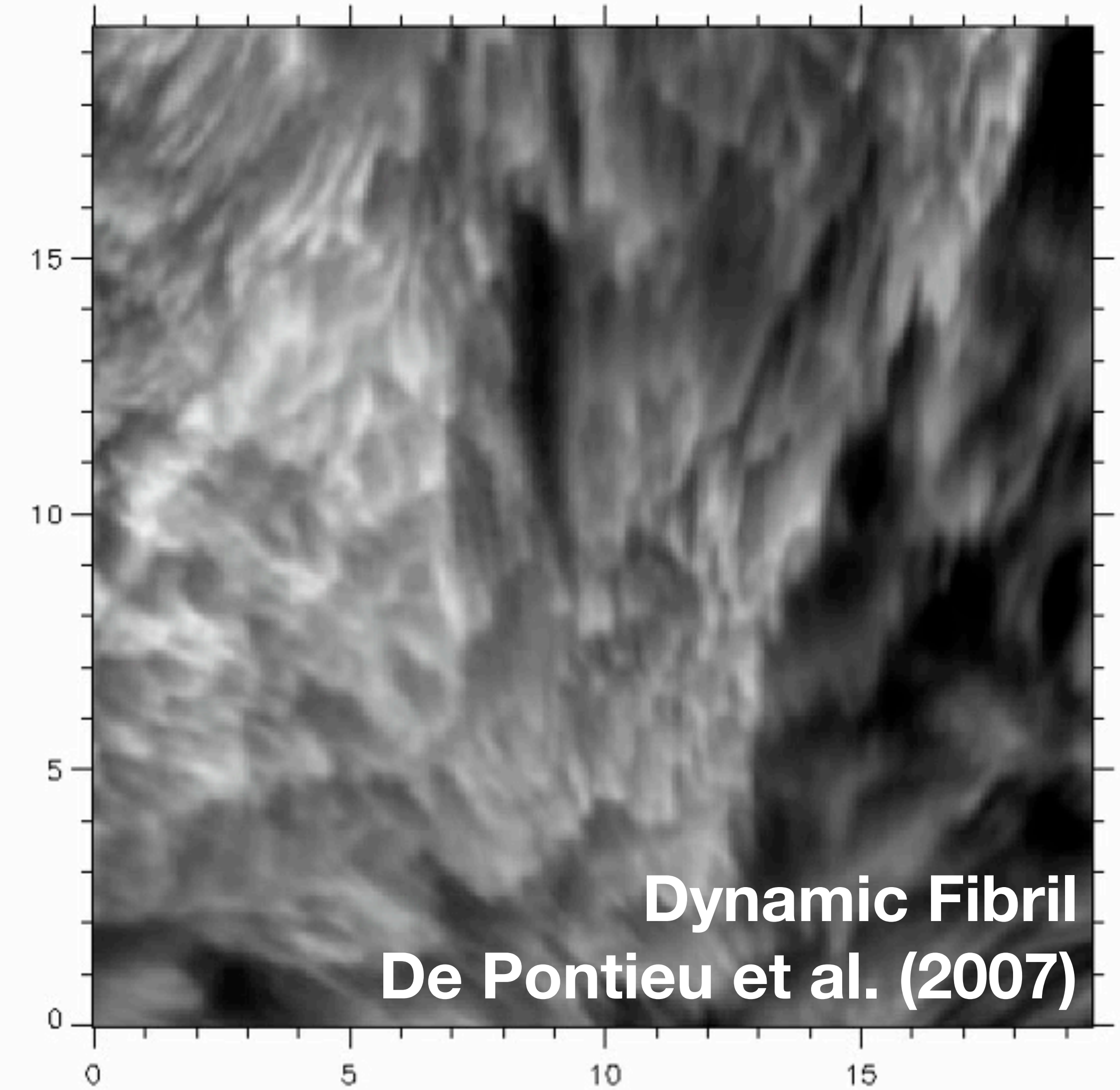
Chromospheric jets

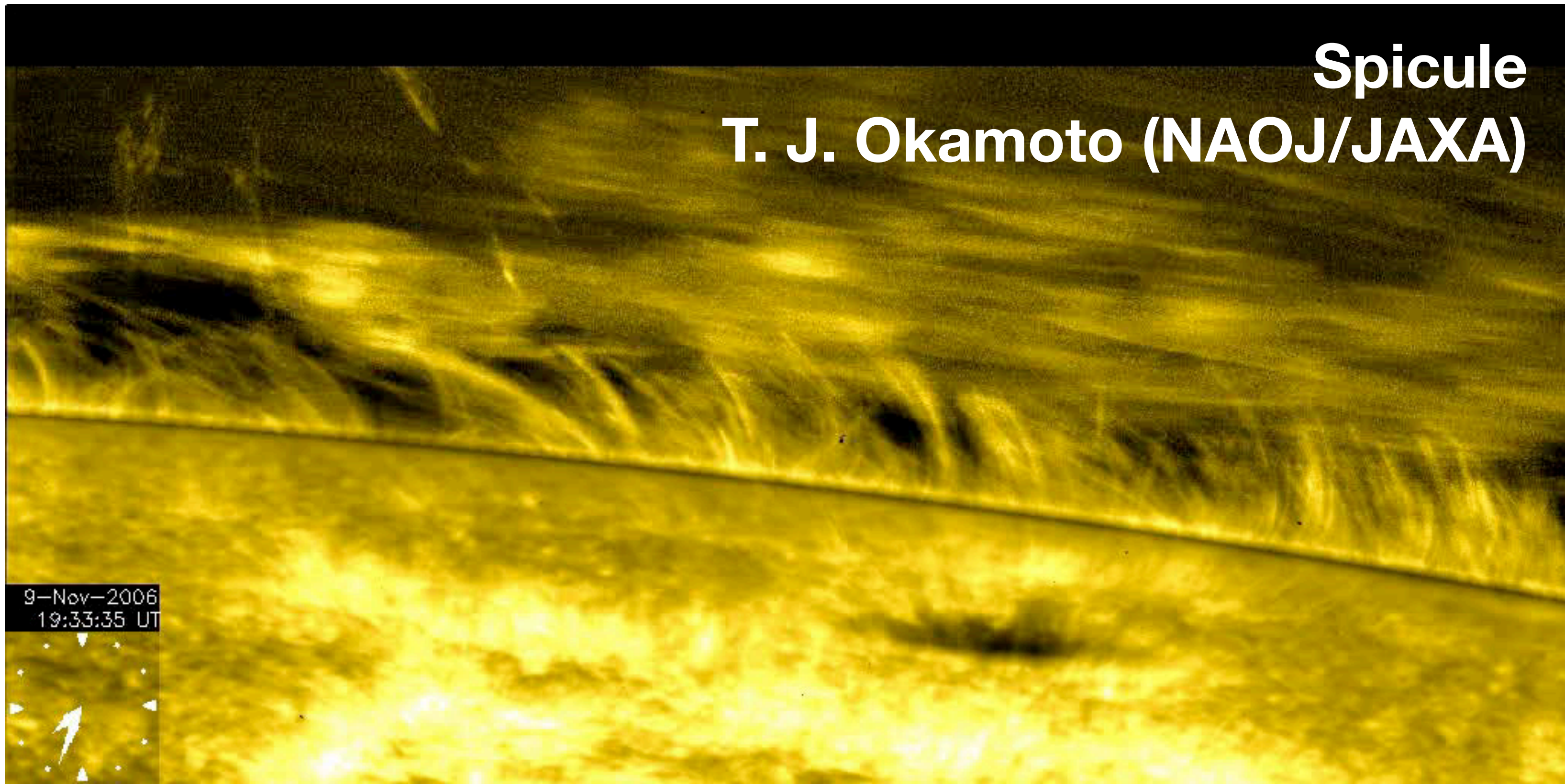
Chromospheric jets

- **Spicules** in quiet regions and coronal holes (length ~ 5–15 Mm)
- **Dynamic fibrils** in active regions (length ~ 3 Mm)
- Penumbral microjets, umbral dynamic fibrils, Hα-surges, Ellerman bomb,…

Involved physical processes

- **MHD shocks and waves**: mode conversion, nonlinear amplification
- **Strong stratification**: high β -> very low β
- **Partial ionization**
- **Radiation**





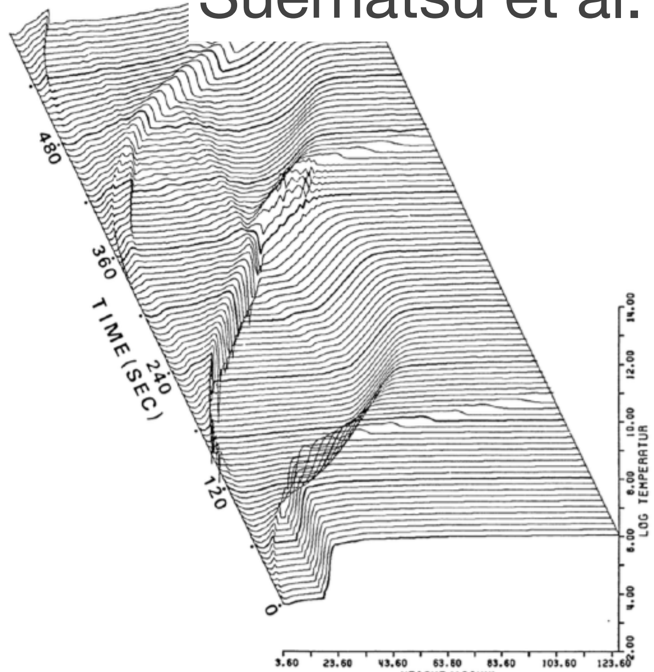
In this presentation

- DKIST
  - Very high spatial resolution (source region ~ sub-arcsec?) chromospheric magnetic field
- Main question
  - **What is the formation mechanism of spicules?**
    Is it possible to distinguish formation mechanisms for each spicule from observation?
- To reach this goal
  - Summarize possible formation mechanisms and expected signatures to distinguish them from the observation.

Possible drivers of spicules

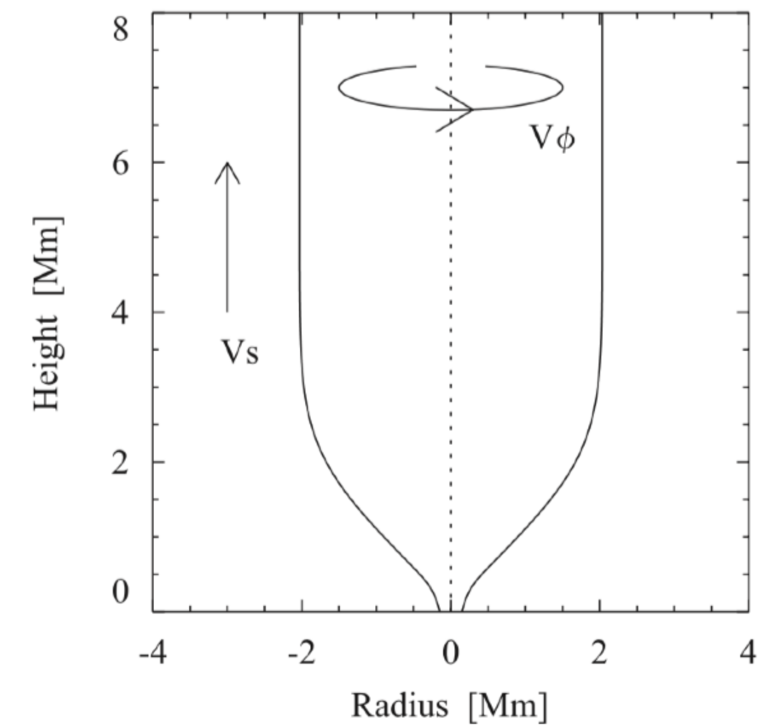
Acoustic wave

Suematsu et al. (1982)



Alfvén wave

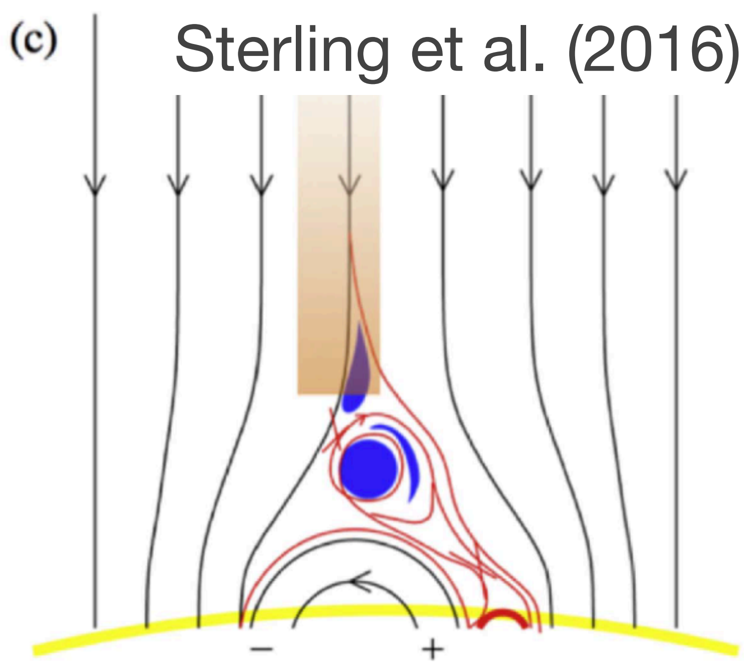
Alfvén wave
 -> Sound wave

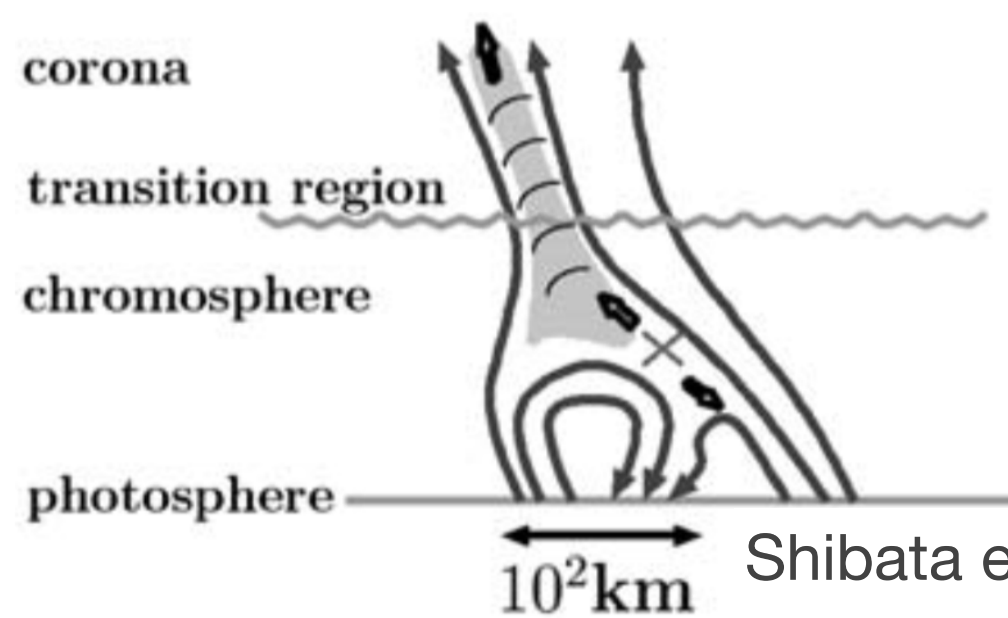


Matsumoto & Shibata (2010)

Magnetic reconnection

Sterling et al. (2016)





Shibata et al. (2007)

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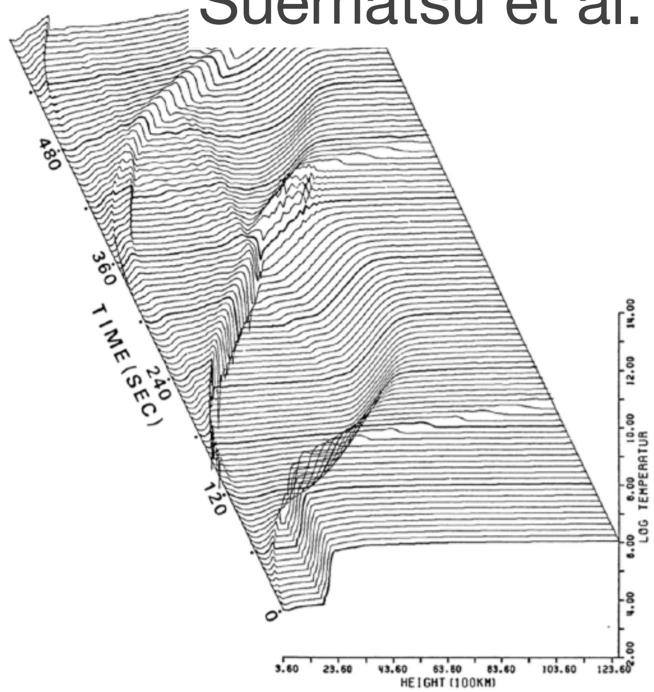

Alfvén wave

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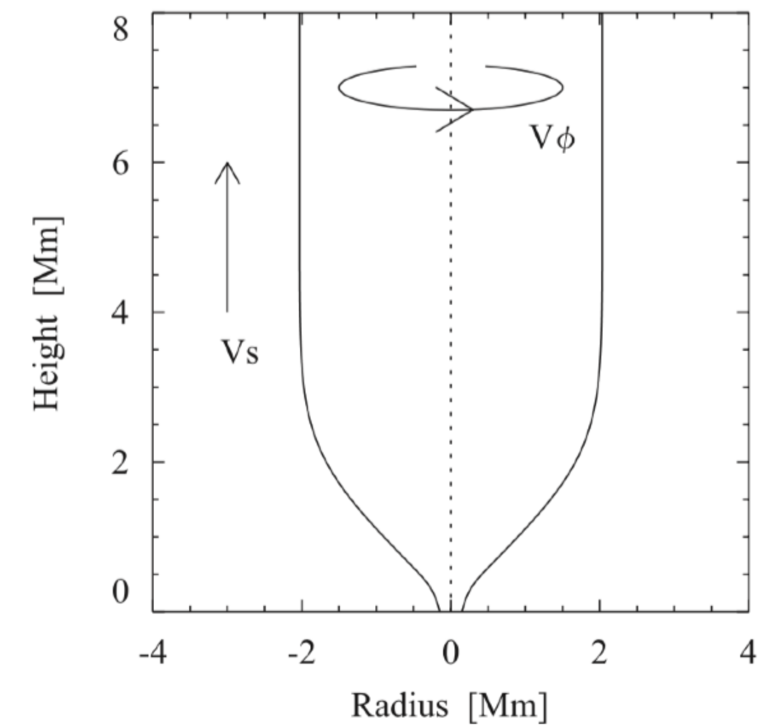

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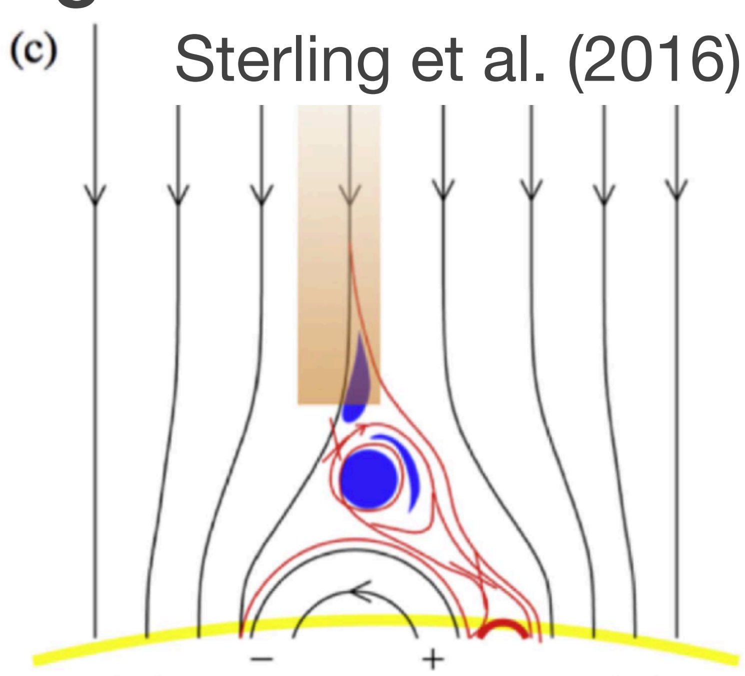
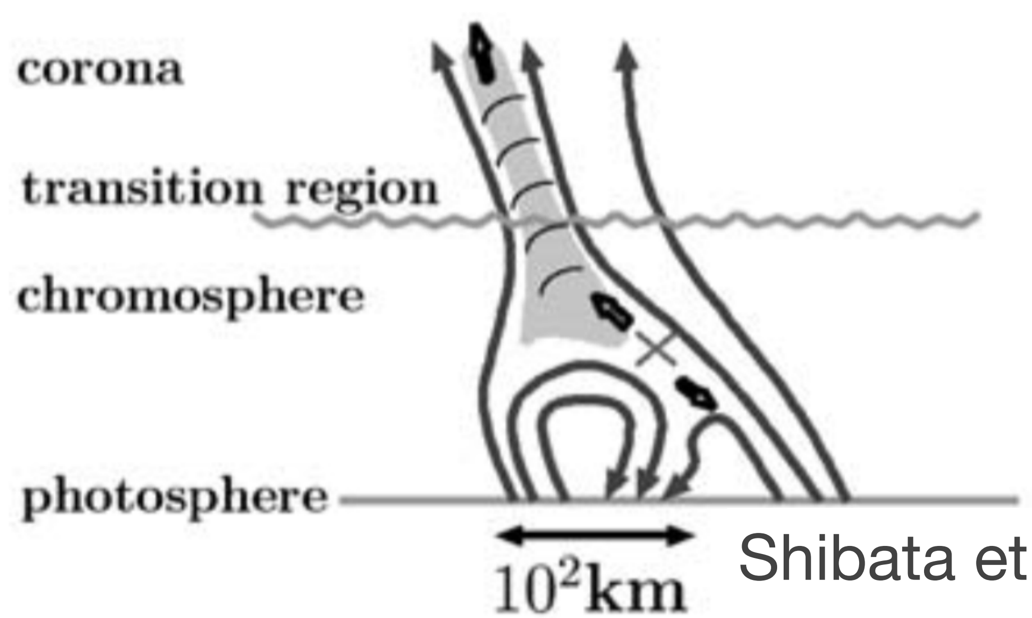




Shibata et al. (2007)

Sound wave model

Acoustic wave (driver)

P-mode oscillation

Granular collapse

Flux tube pumping

Amplification by stratification

Shock wave

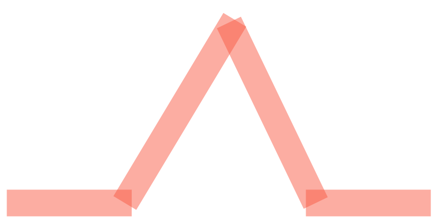
Shock-TR interaction

Jet formation

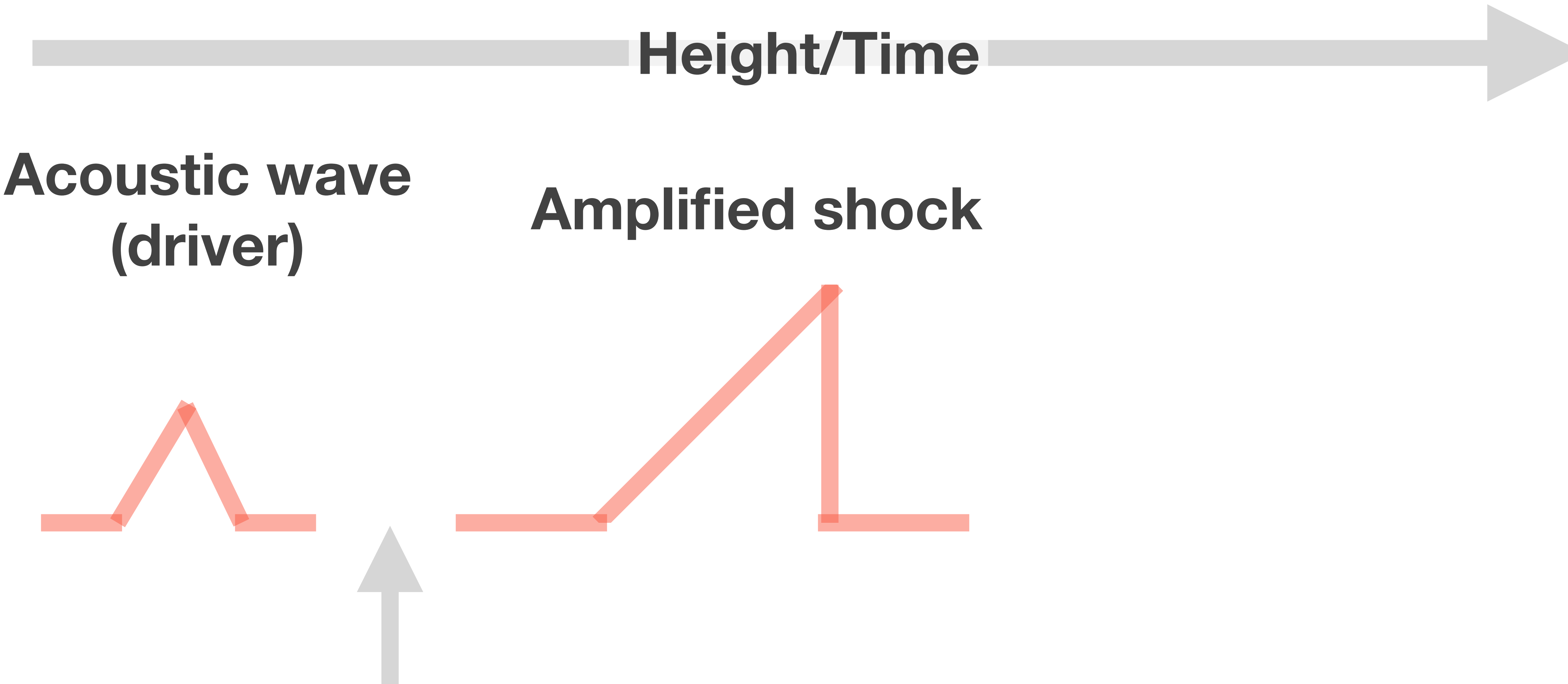
Formation process | Sound wave model

Height/Time

Acoustic wave (driver)



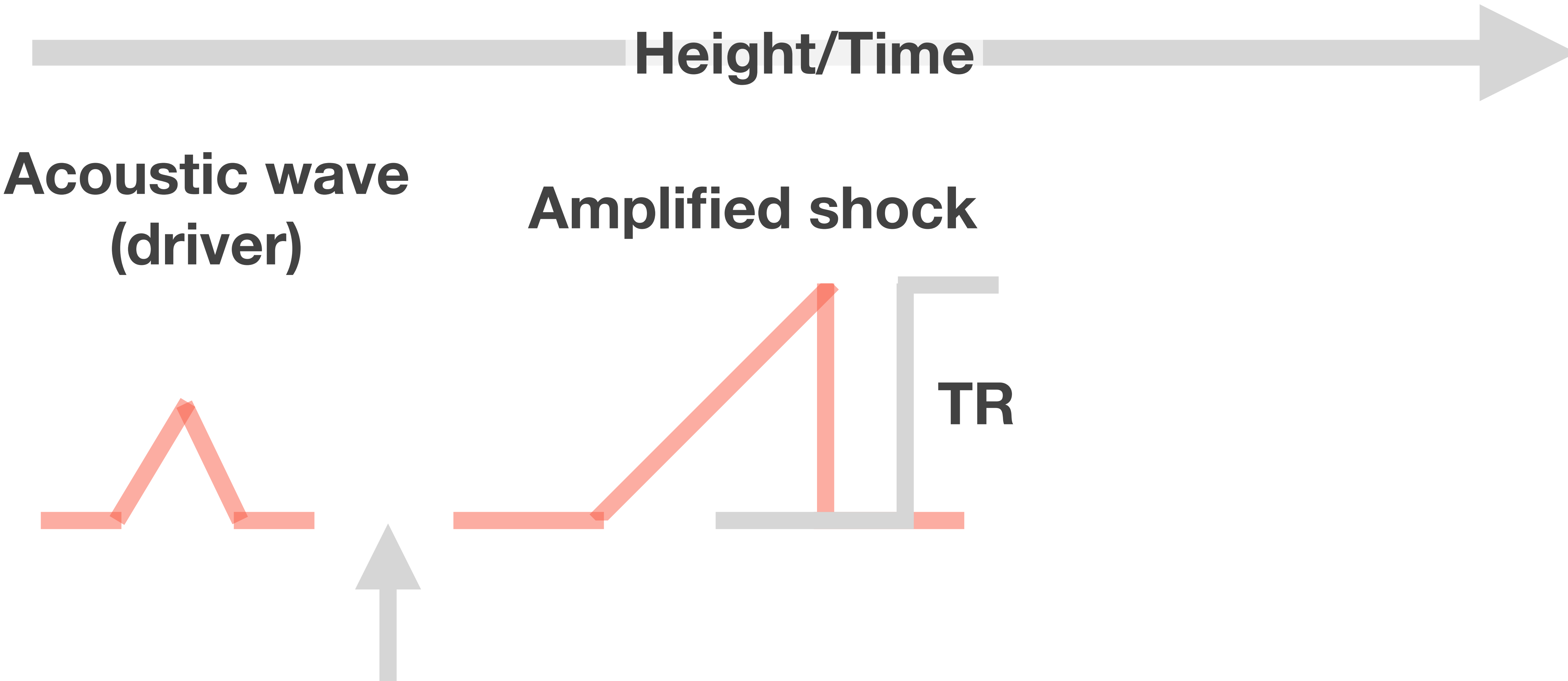
Formation process | Sound wave model



Amplification by stratification

Brinkley & Kirkwood (1947)
Ohno et al. (1960, 1961)
Shibata & Suematsu (1982)

Formation process | Sound wave model



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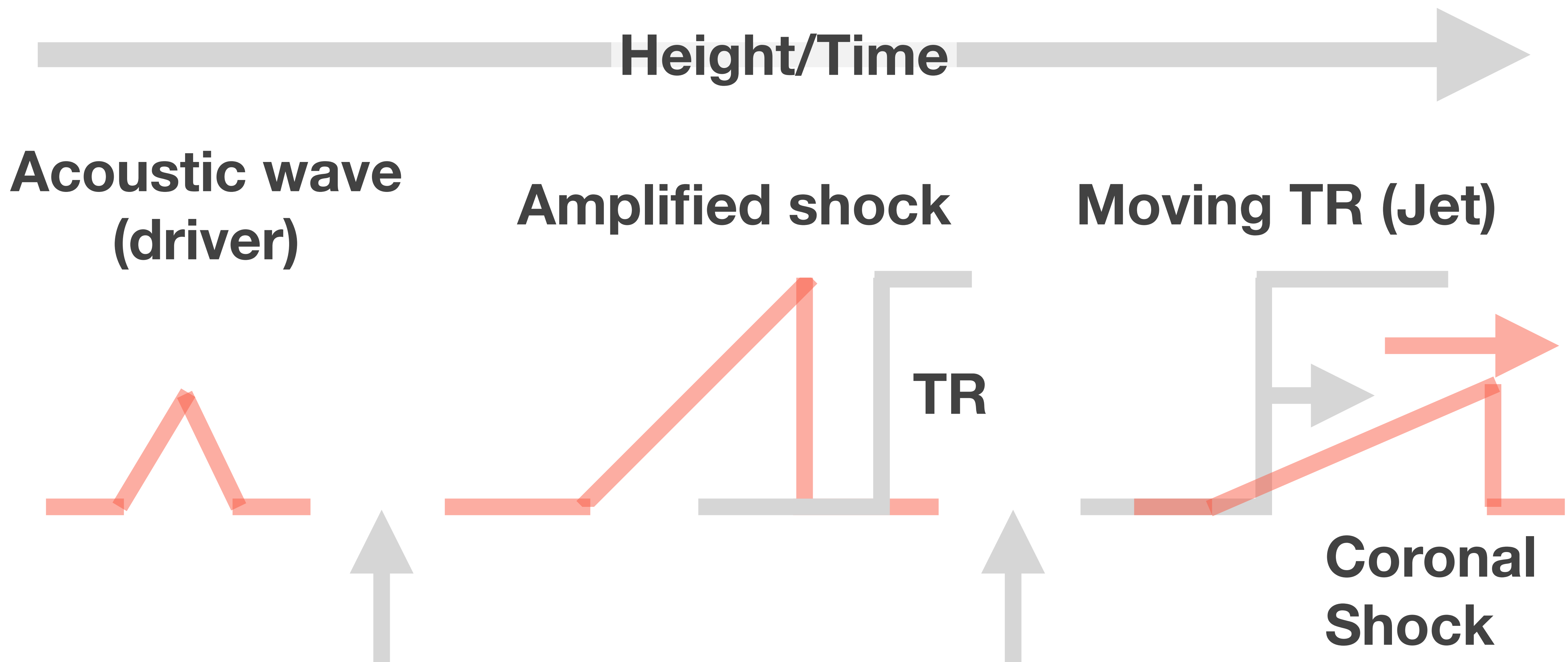
Brinkley & Kirkwood (1947)
Ohno et al. (1960, 1961)
Shibata & Suematsu (1982)

Formation process | Sound wave model



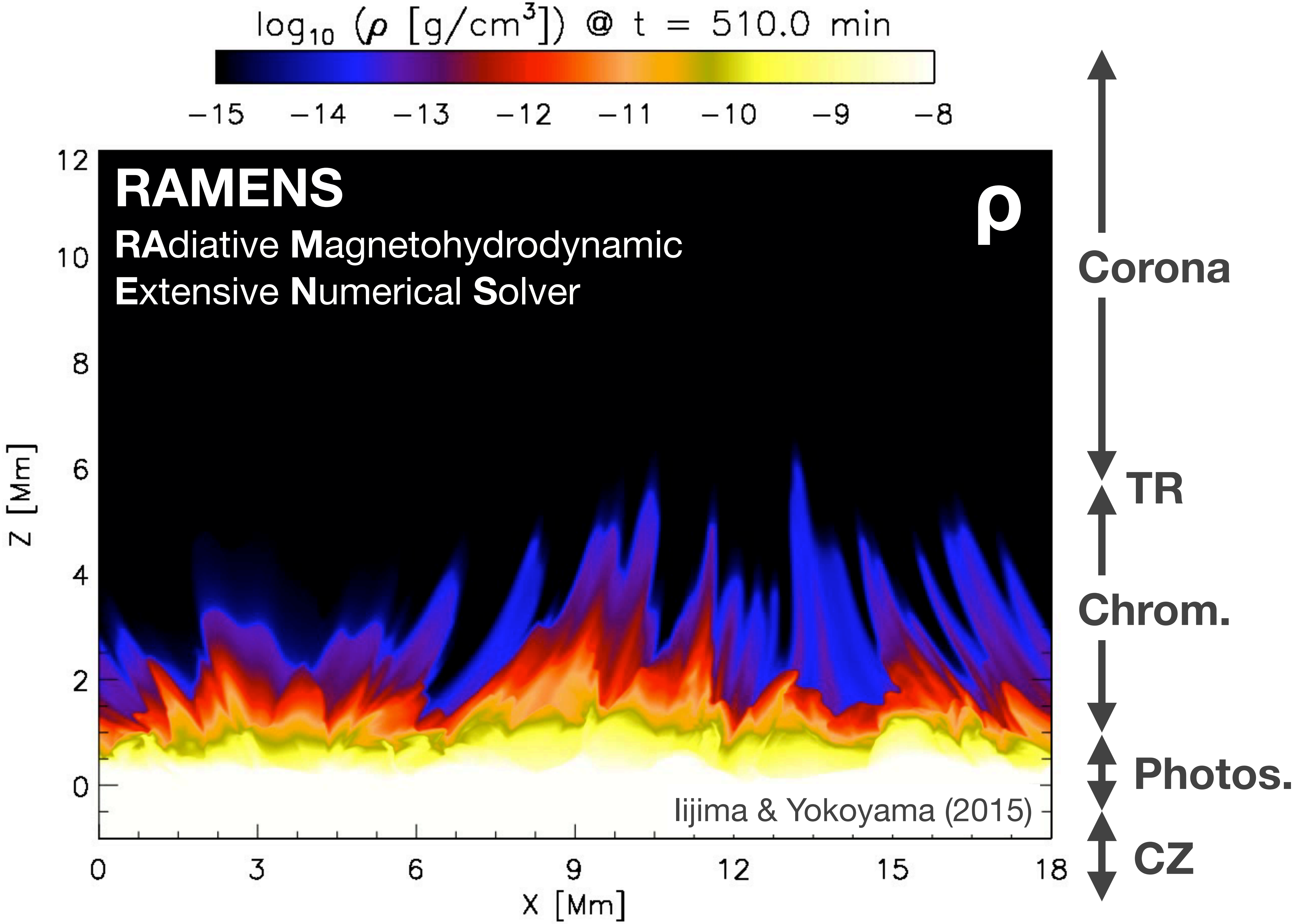
Amplification by stratification

Brinkley & Kirkwood (1947)
Ohno et al. (1960, 1961)
Shibata & Suematsu (1982)

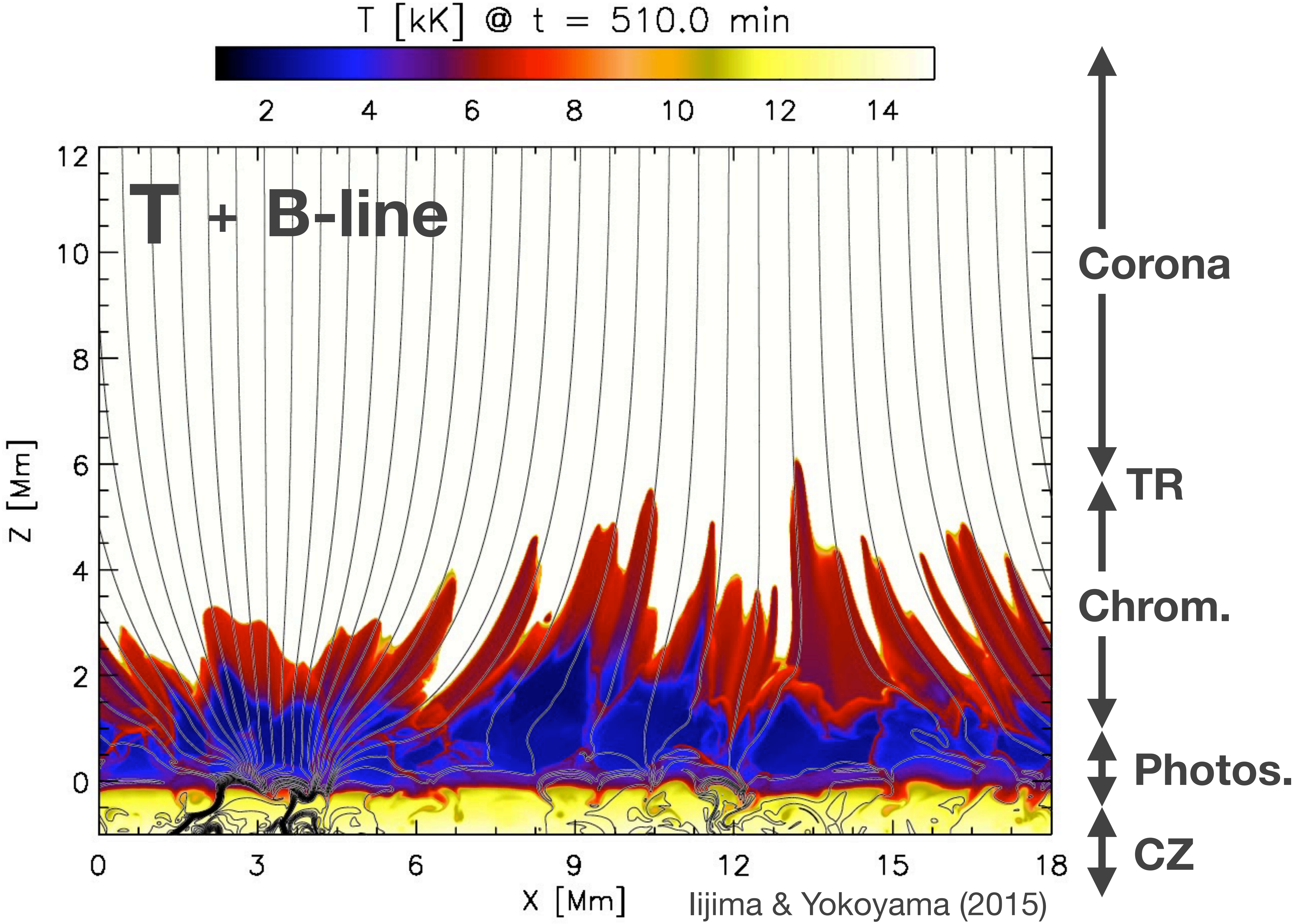
Shock-TR interaction

Landau & Lifschitz (1959)
Osterbrock (1961)
Hollweg (1982)

Sound wave driven jets | density

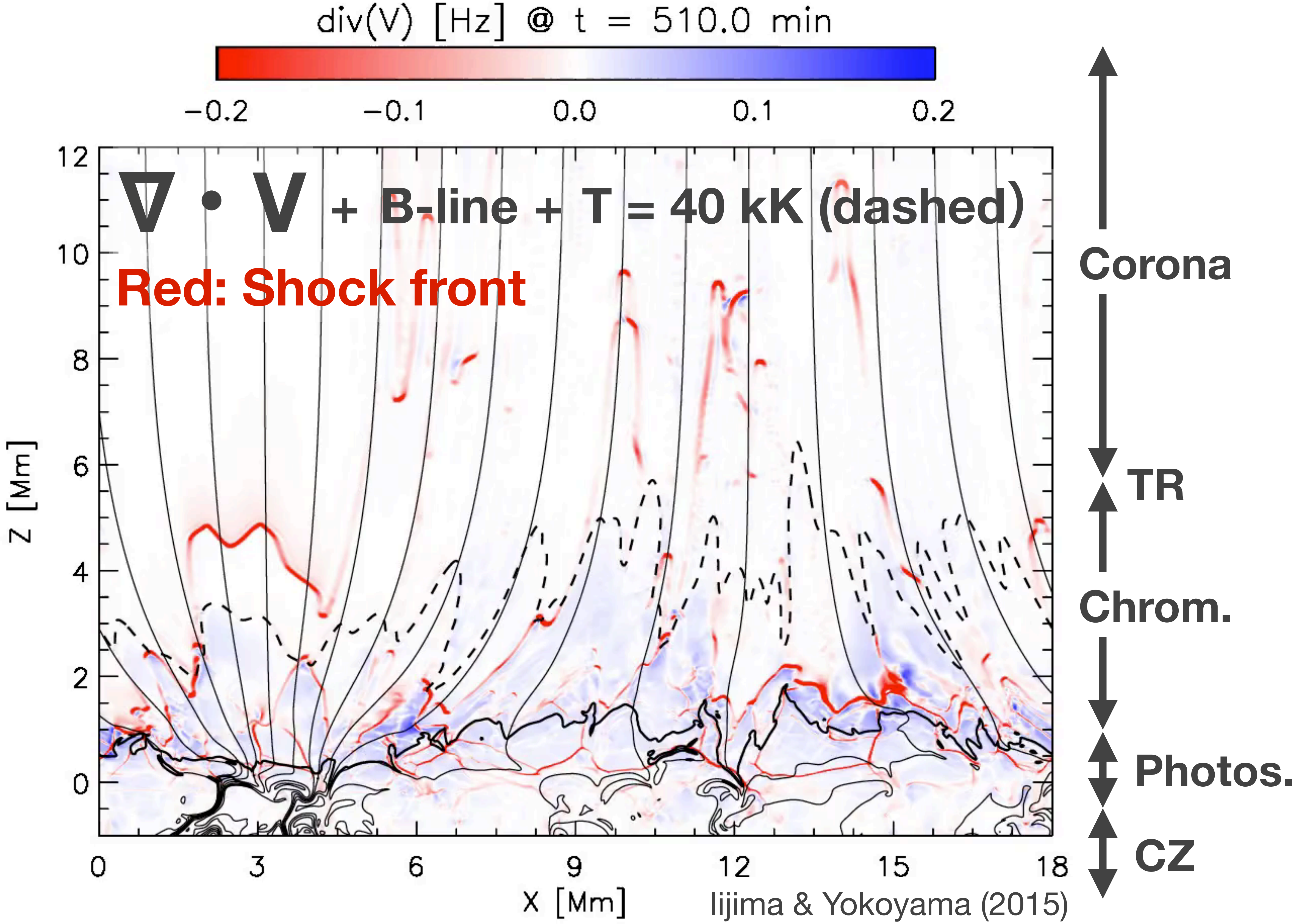


Sound wave driven jets | temperature



Iijima & Yokoyama (2015)

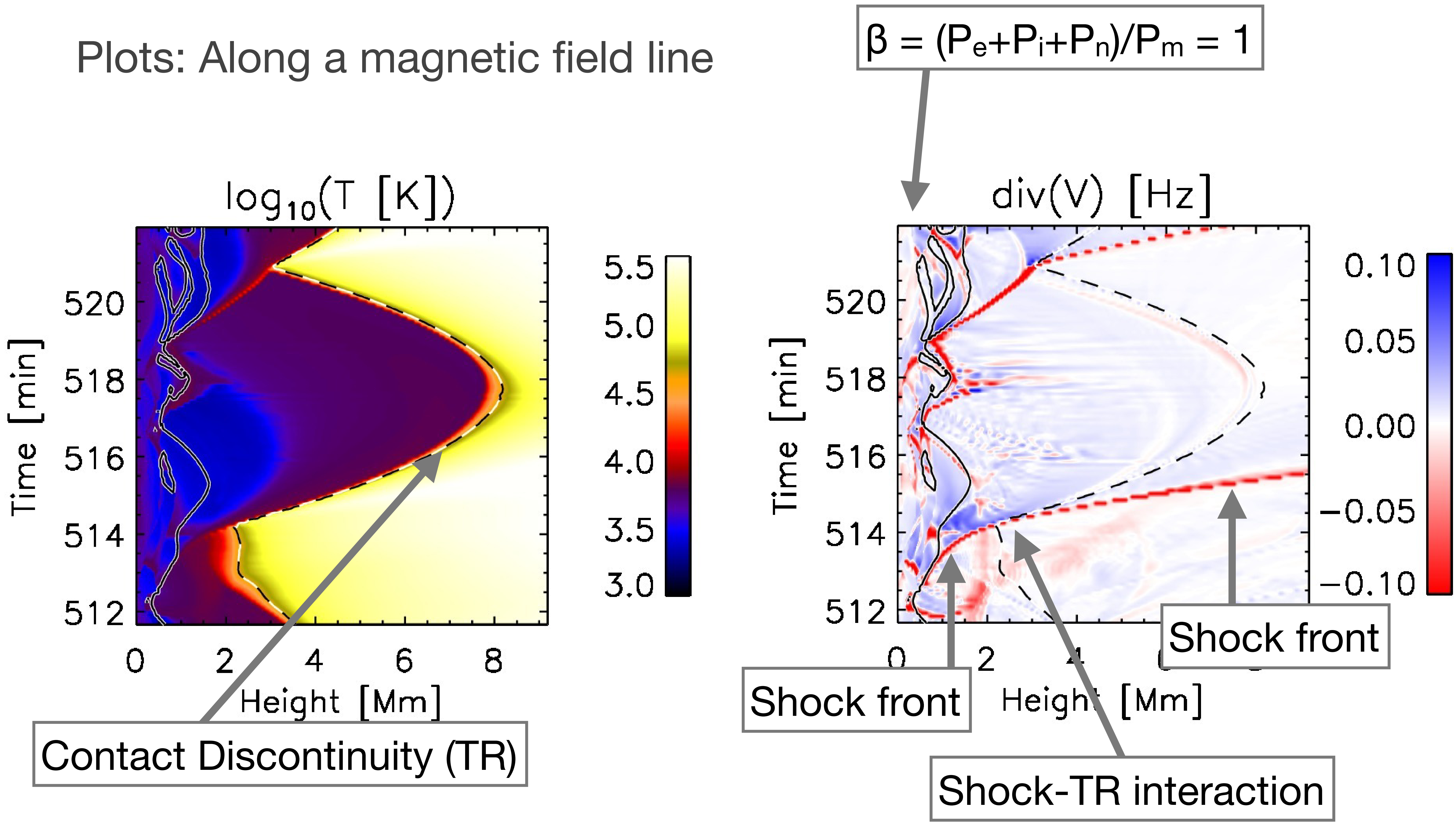
Sound wave driven jets | div(V)



Iijima & Yokoyama (2015)

Sound wave driven jets | evolution

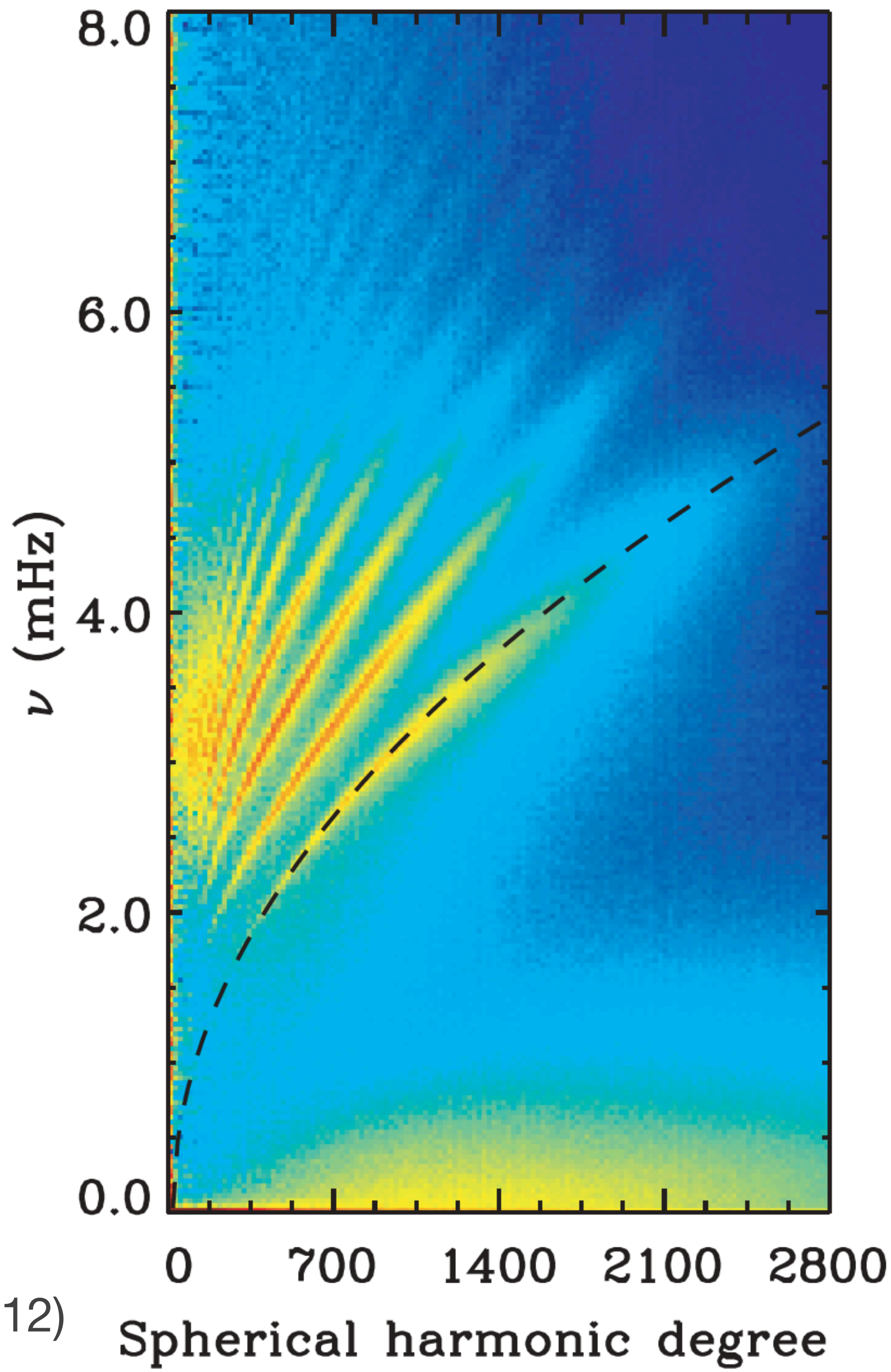
Plots: Along a magnetic field line



Possible source of acoustic waves

Possible source of acoustic waves

P-mode oscillation



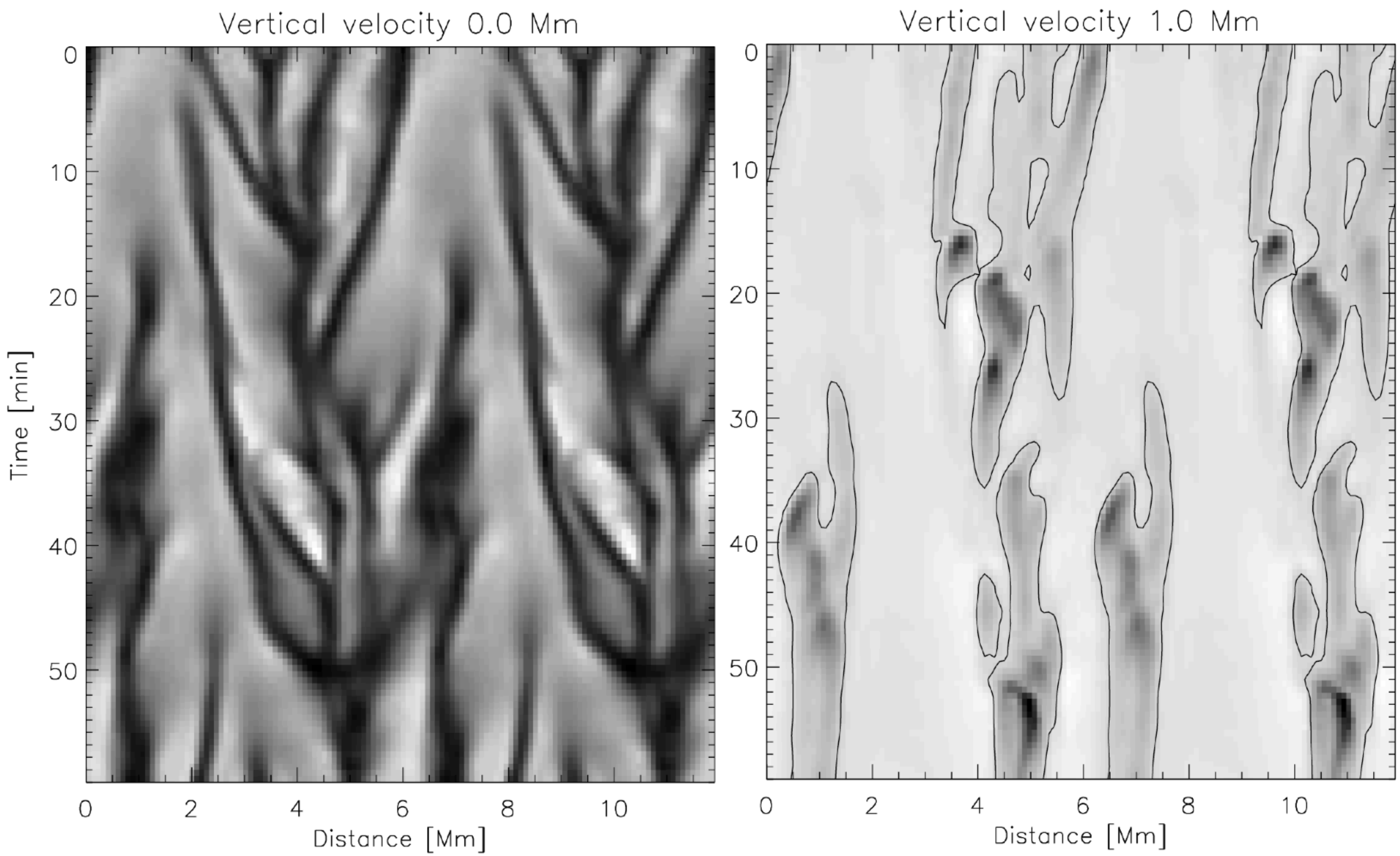
Georgobiani et al. (2012)

Possible source of acoustic waves

P-mode oscillation

Collapsing granule

Skartlien et al. (2000)



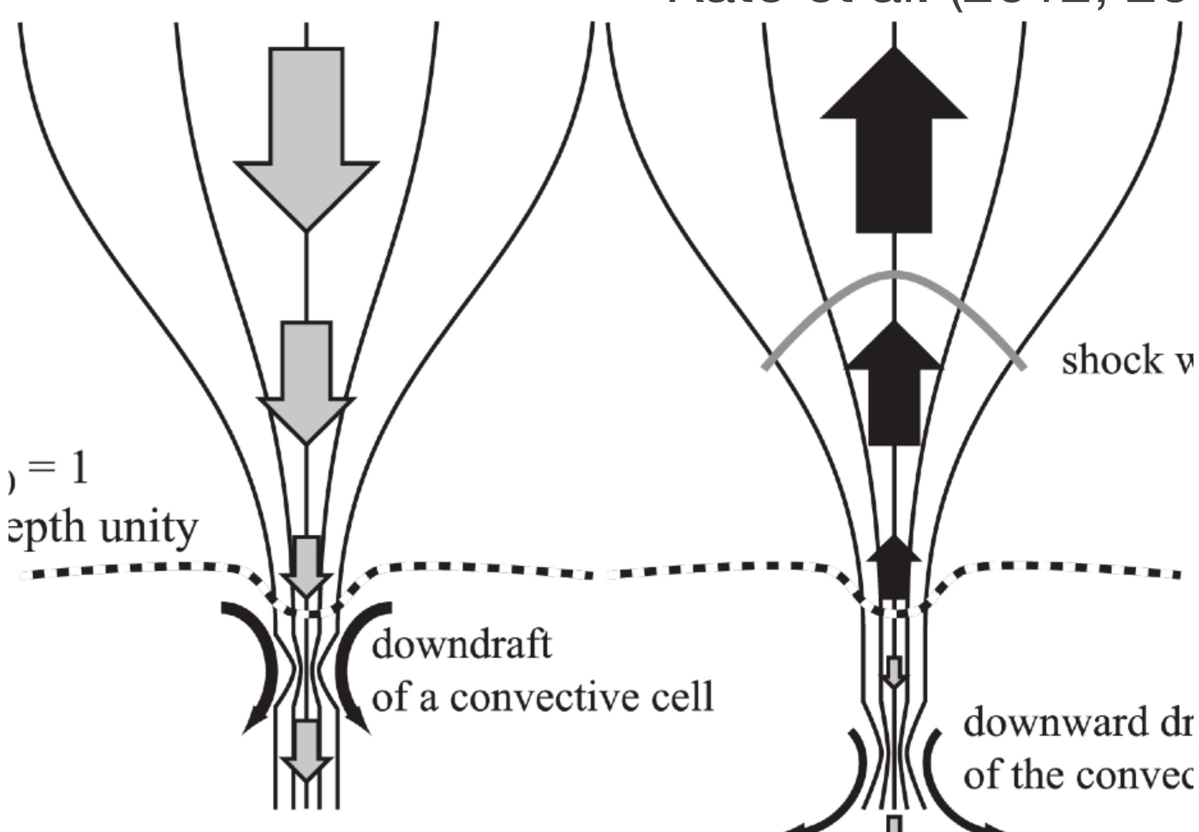
Possible source of acoustic waves

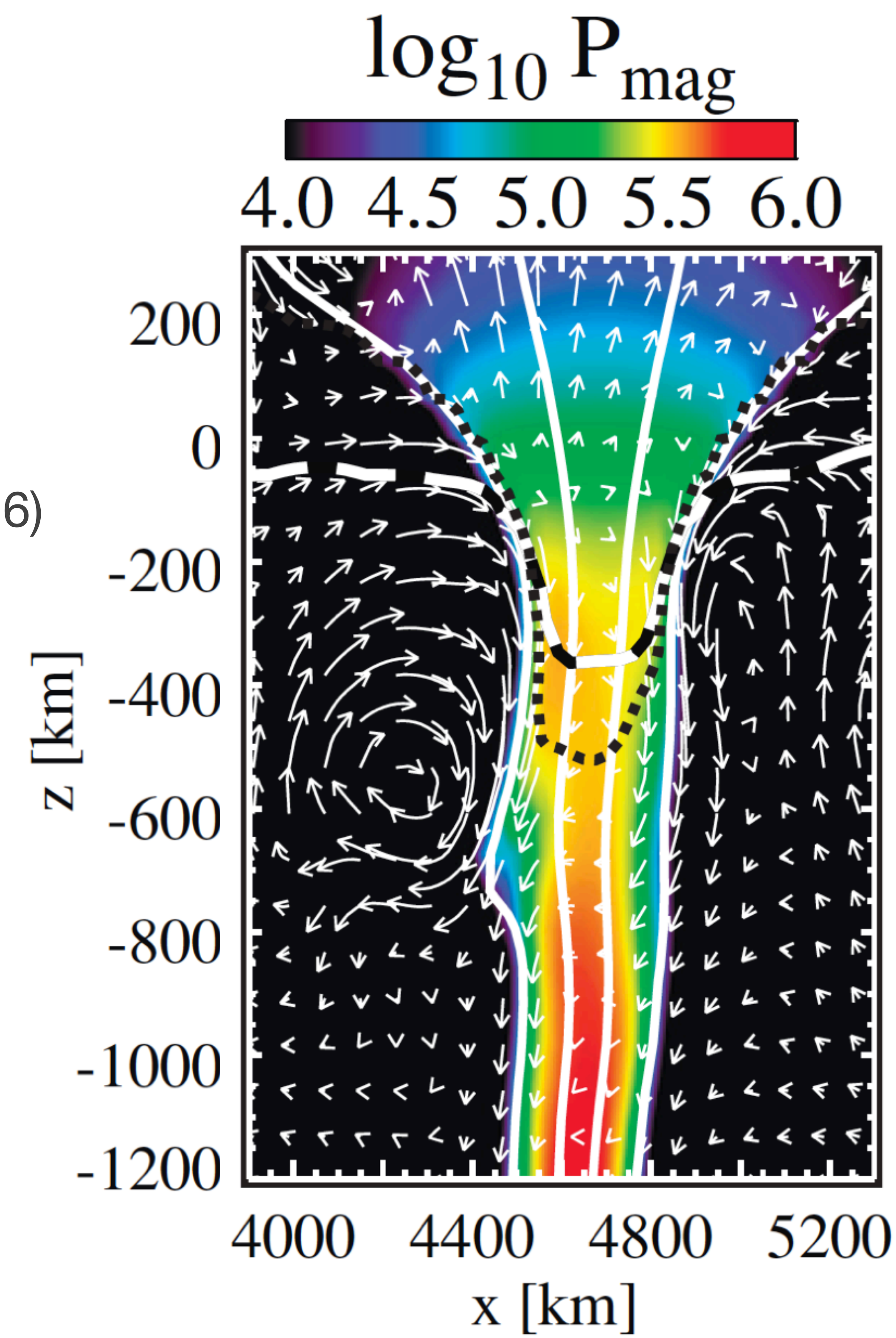
P-mode oscillation

Collapsing granule

Flux tube pumping

Kato et al. (2012, 2016)





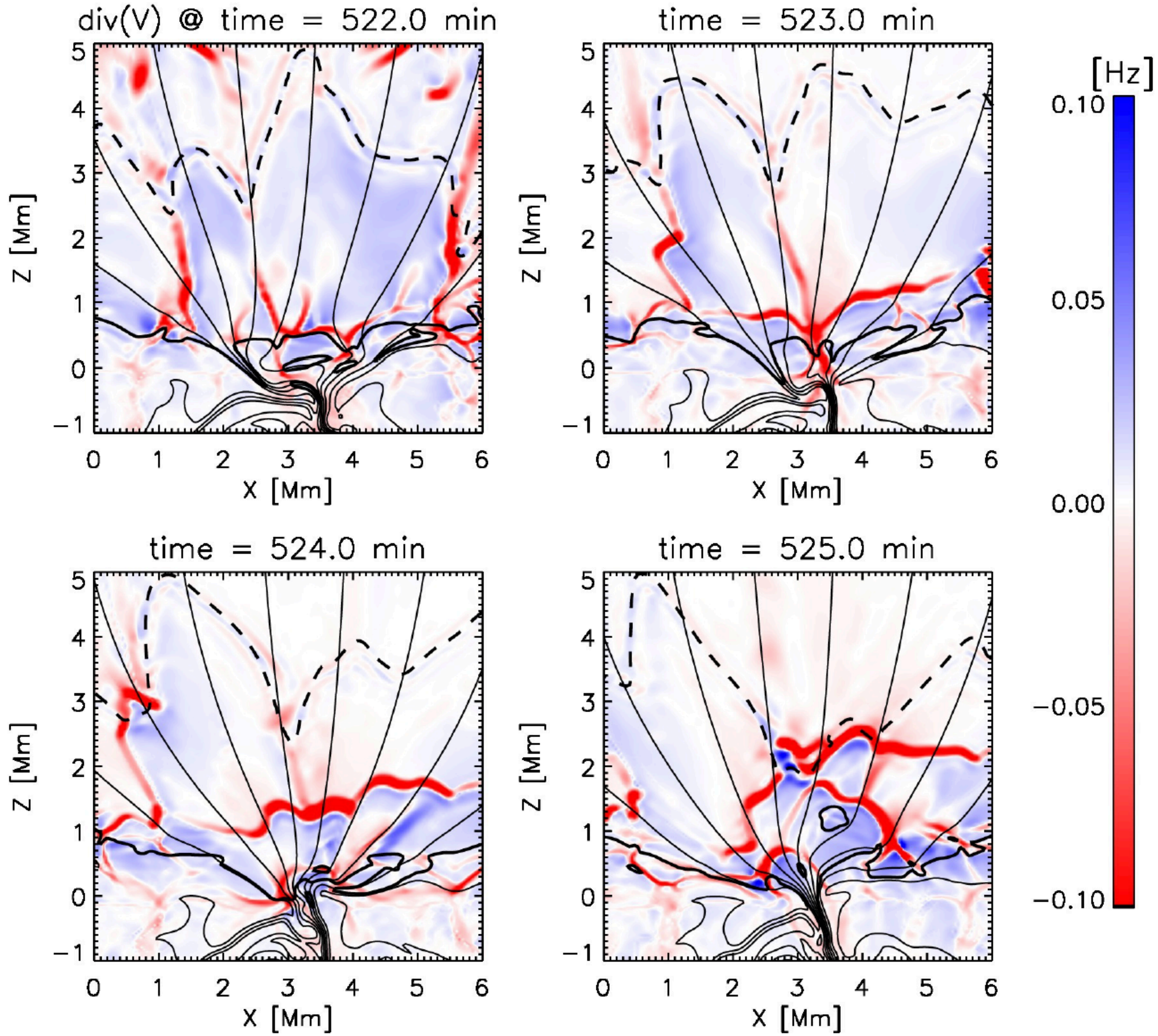
Possible source of acoustic waves

P-mode oscillation

Collapsing granule

Flux tube pumping

Colliding flux tubes



Possible source of acoustic waves

P-mode oscillation

Collapsing granule

Flux tube pumping

Colliding flux tubes

Other more indirect sources
which can be observed in upper layer.
=> Alfvén wave models, Reconnection models, …

Sound wave model

Acoustic wave (driver)

P-mode oscillation

Granular collapse

Flux tube pumping

Shock wave

Jet formation

Amplification by stratification

$$V_{||} \propto \rho^{-\alpha} B^{1/2}$$

$$\alpha \sim 0.1 - 0.5$$

depending on energy loss
by shock and/or radiation.

Shock-TR interaction

$$V_{\rm jet} \propto V_{||}$$

Importance of the density diagnostics

How can we argue that the observed sound wave has enough power to drive the observed spicule?

=> From the information of density and magnetic field.

Amplification by stratification

$$V_{||} \propto \rho^{-\alpha} B^{1/2}$$

$$\alpha \sim 0.1 - 0.5$$

depending on energy loss by shock and/or radiation.

Example 1: high velocity at upper chromosphere.

$$V_{||} \sim 40 \ [\mathrm{km/s}], \ \rho \sim 10^{-12} \ [\mathrm{g/cm^3}]$$

Example 2: low velocity at lower chromosphere

$$V_{||} \sim 10 \ [\mathrm{km/s}], \ \rho \sim 10^{-9} \ [\mathrm{g/cm^3}]$$

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Same amplitude for $\alpha = 0.2$

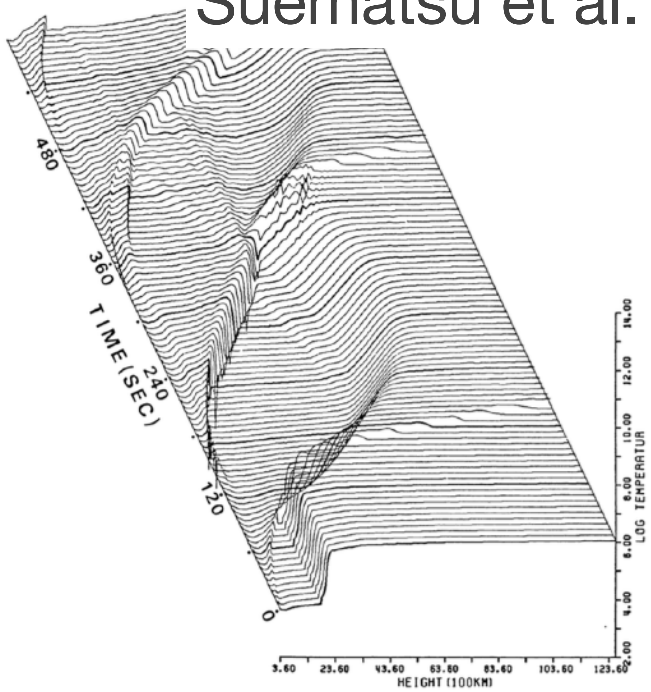
Sound wave model

- Source
    - P-mode, granule collapse, flux tube pumping, flux tube collision, etc.
- Expected signatures
    - **Photospheric counterpart of acoustic source**
      (Although some mechanisms will be inside the convection zone.)
    - **Amplification of longitudinal velocity**
      (**multi-wavelength** observation with **density** and longitudinal velocity diagnostics)
    - No need of cancellation nor complex magnetic field configuration
- Note
    - Amplification process of shock is also appeared in other models.
      It is critical to provide the quantitative tracking of each acoustic wave from the photospheric layer.

Possible drivers of spicules

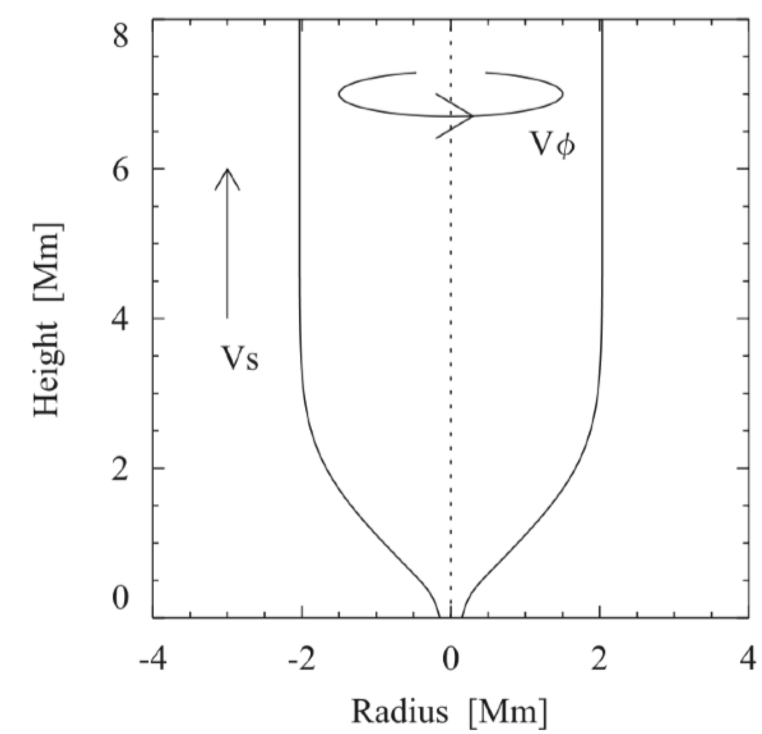
Acoustic wave

Suematsu et al. (1982)



Alfvén wave

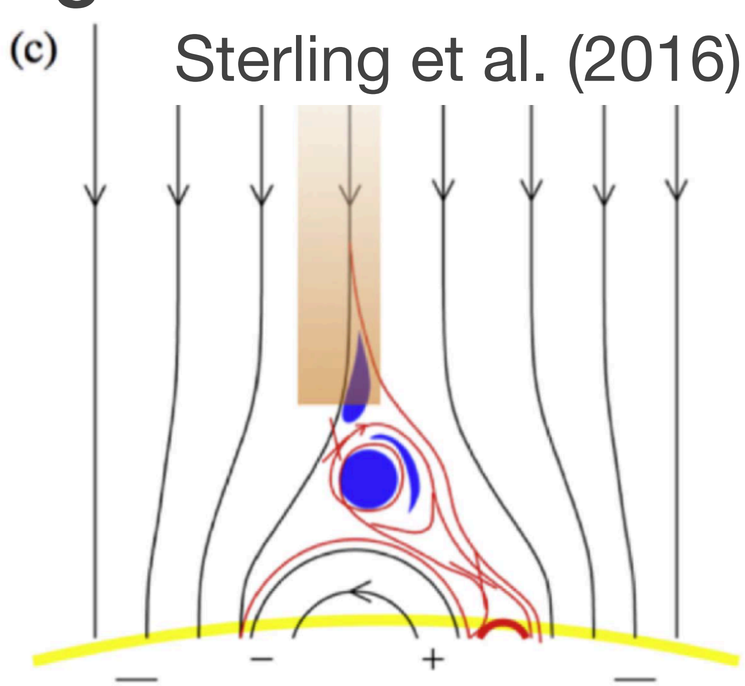
Alfvén wave
-> Sound wave

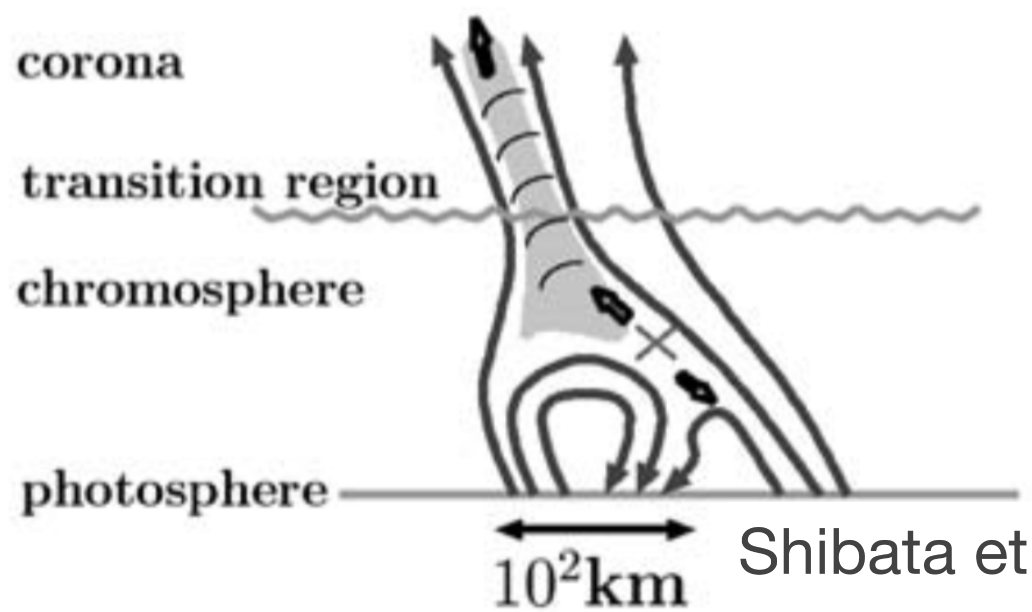


Matsumoto & Shibata (2010)

Magnetic reconnection

Sterling et al. (2016)





Shibata et al. (2007)

Reconnection heating model

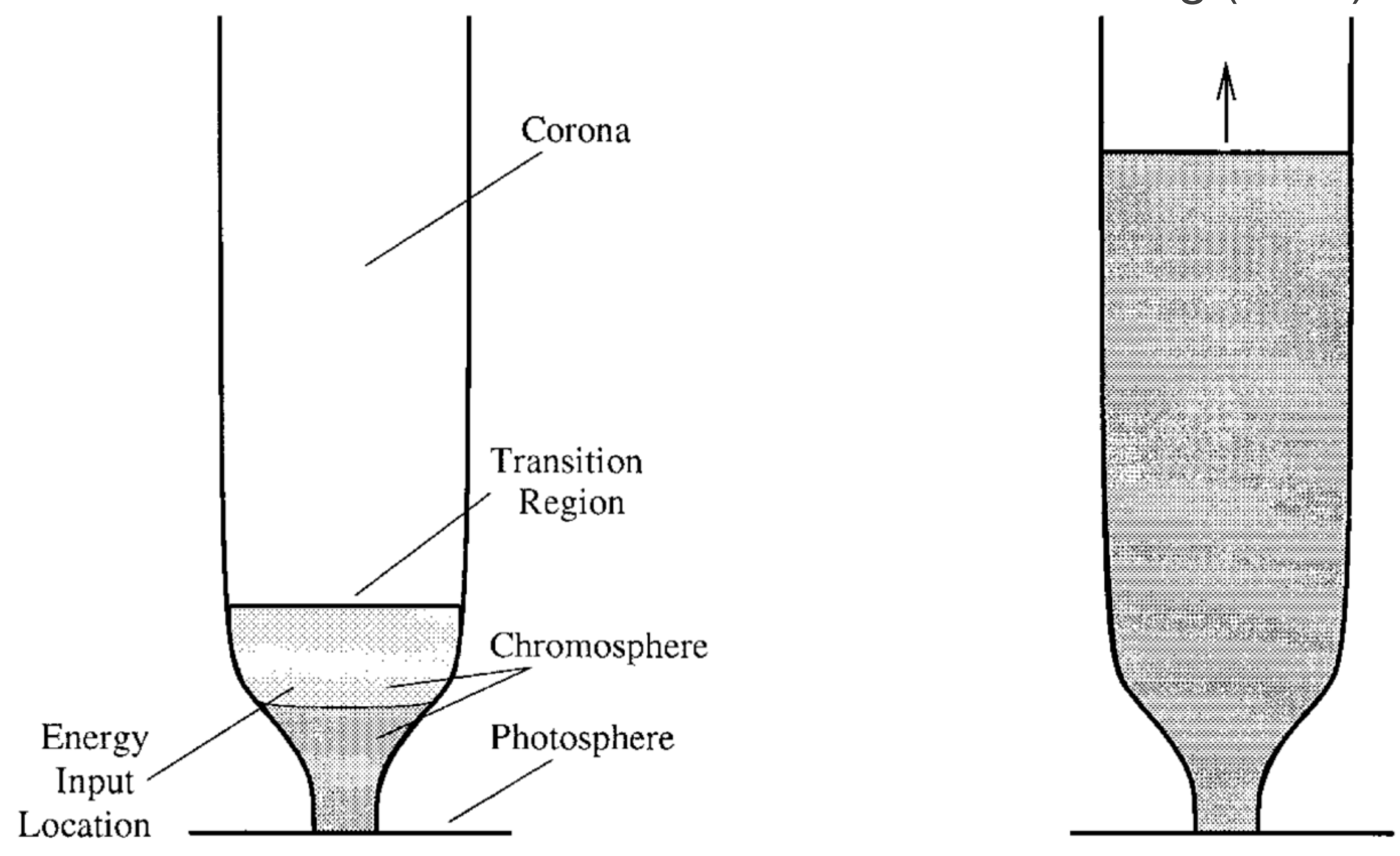
Reconnection (driver)

Joule heating/Pressure pulse

Shock wave

Jet formation

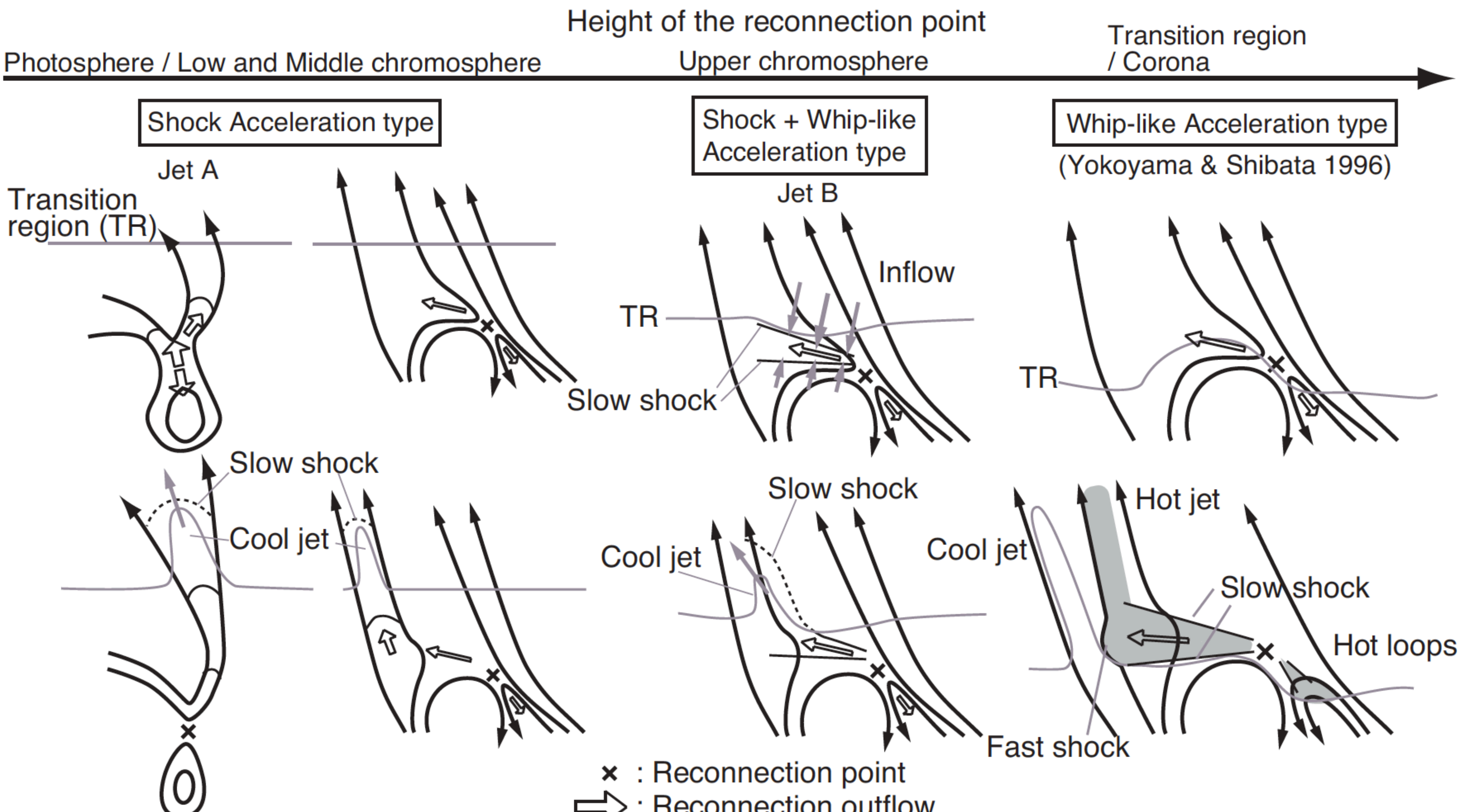
Sterling (2000)



(a) Initial Setup

(b) Late Phase

Guid-field reconnection models



Takasao et al. (2013)

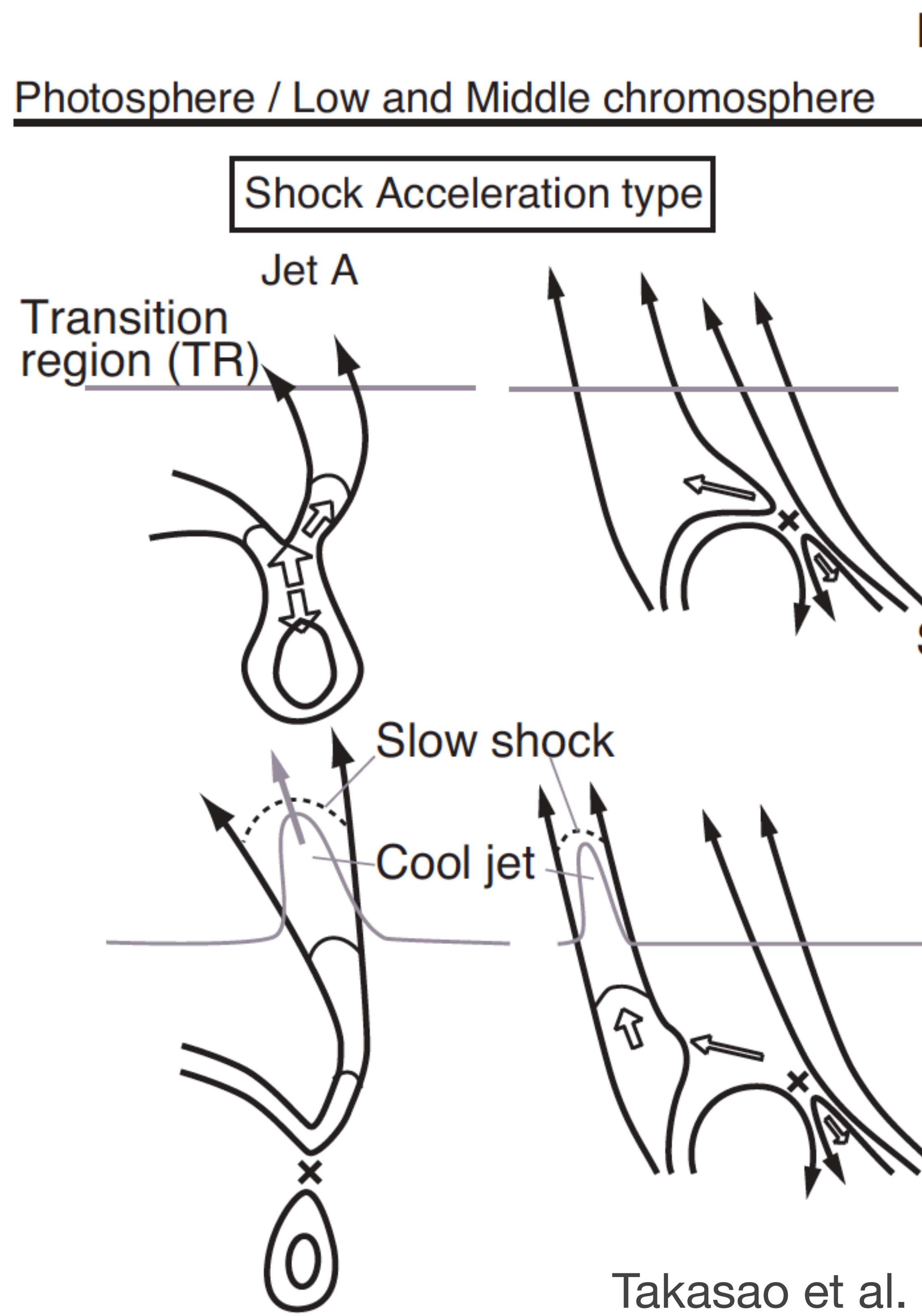
Guid-field reconnection model

Reconnection (driver)

Reconnection outflow

Shock wave

Jet formation

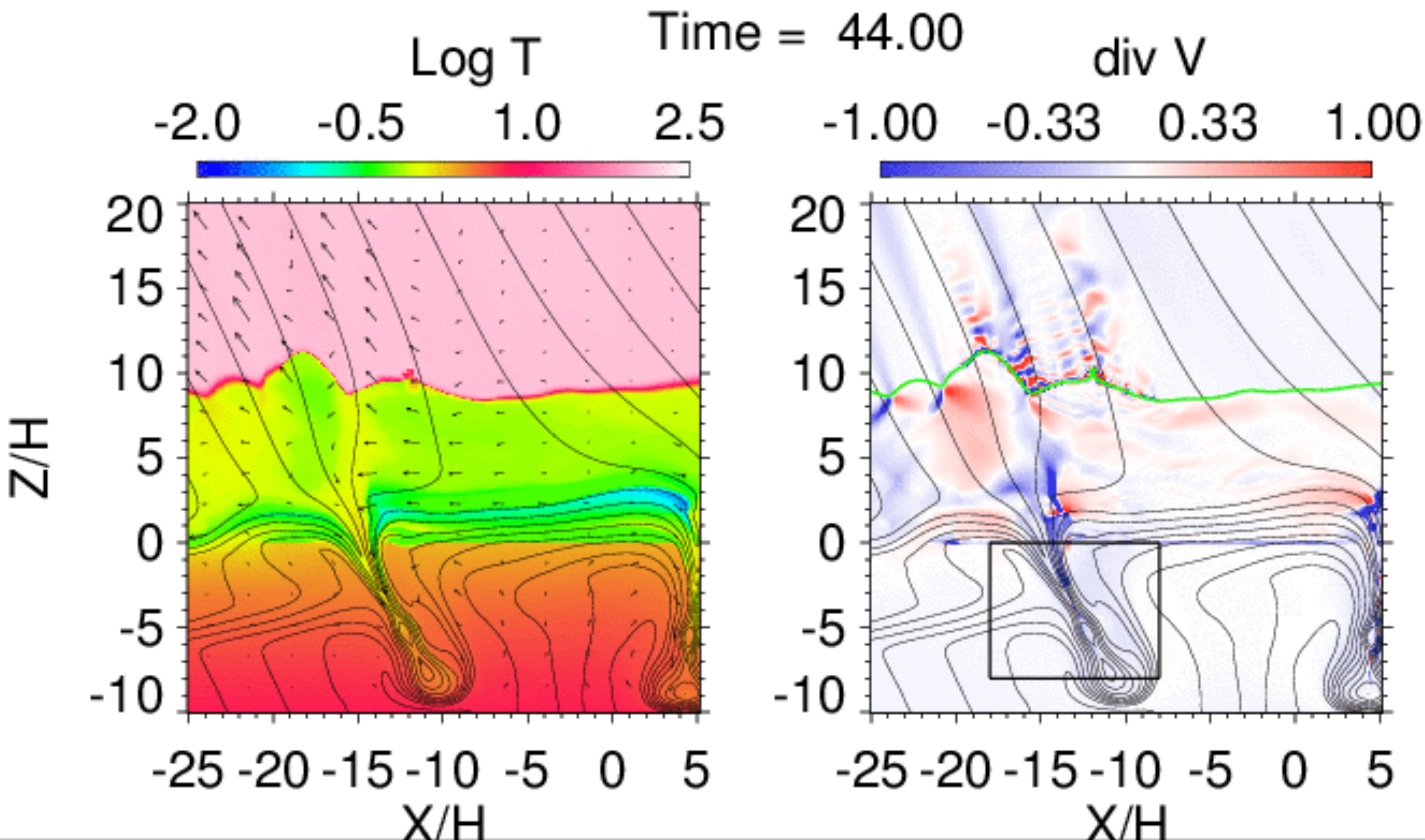


Takasao et al. (2013)

Guid-field reconnection model

Reconnection (driver)

Photosphere / Low and Middle chromosphere



Takasao et al. (2013)

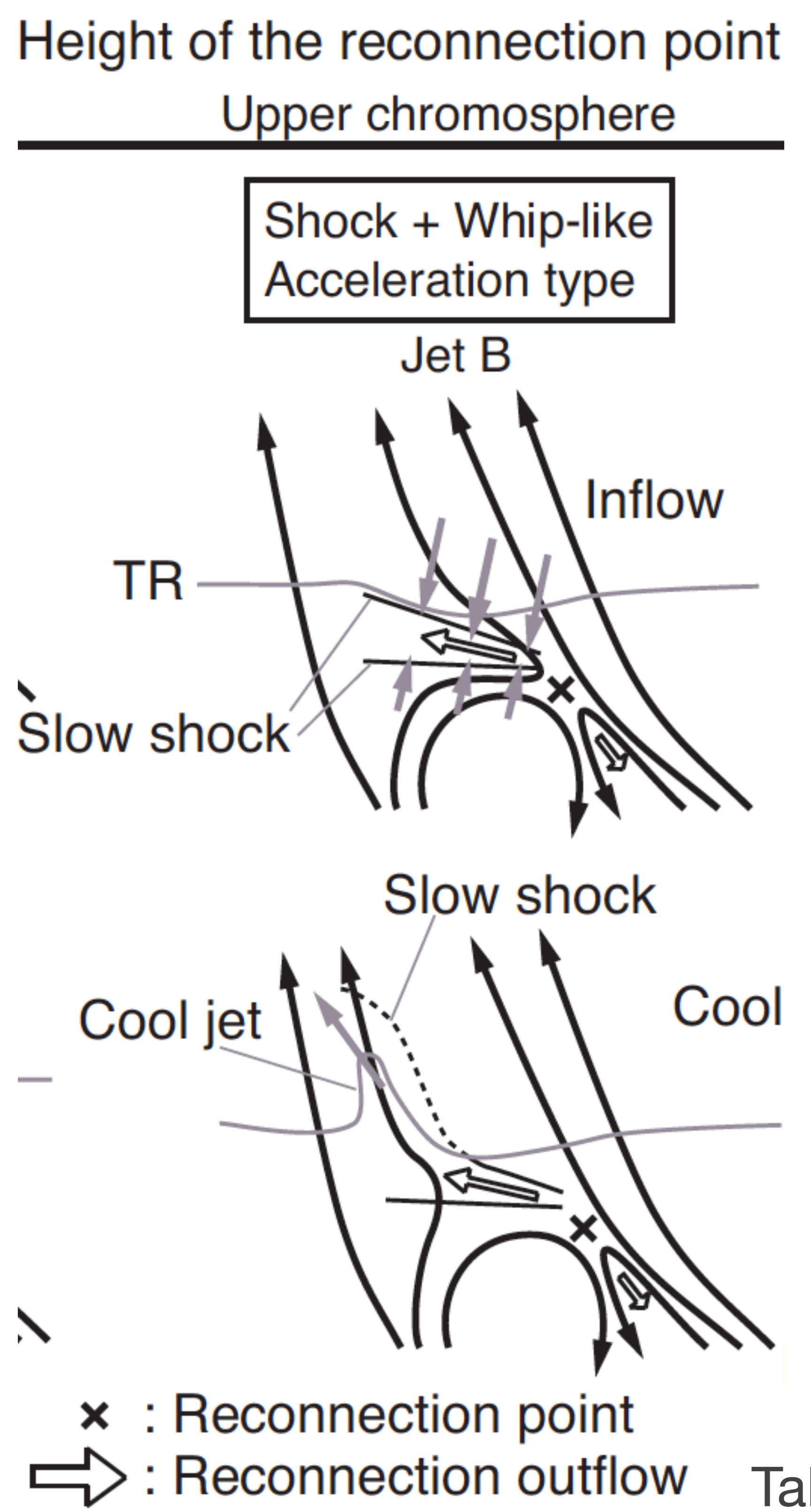
Guid-field reconnection model

Reconnection (driver)

Reconnection outflow

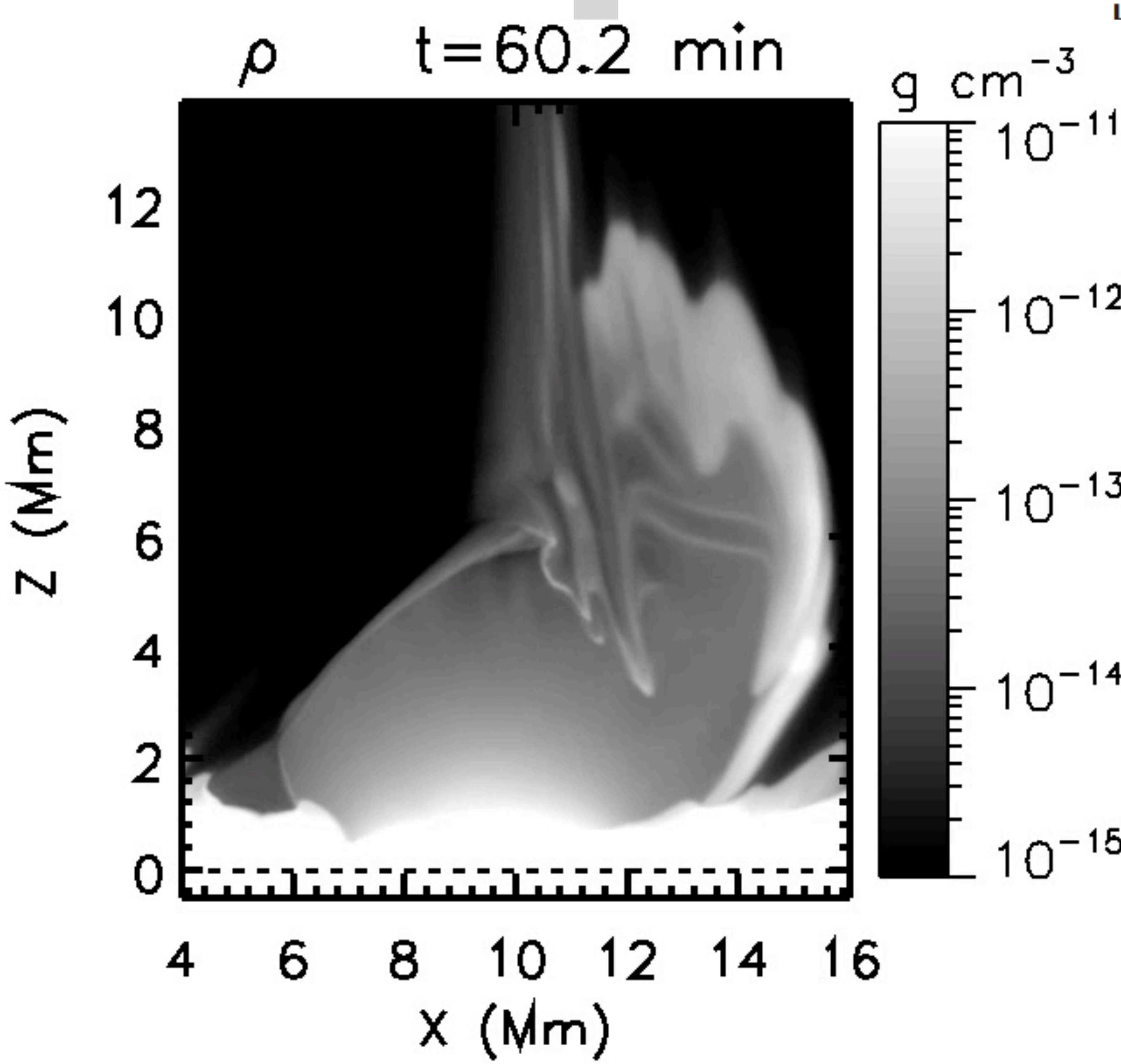
Slow-mode shock
(with tension force)

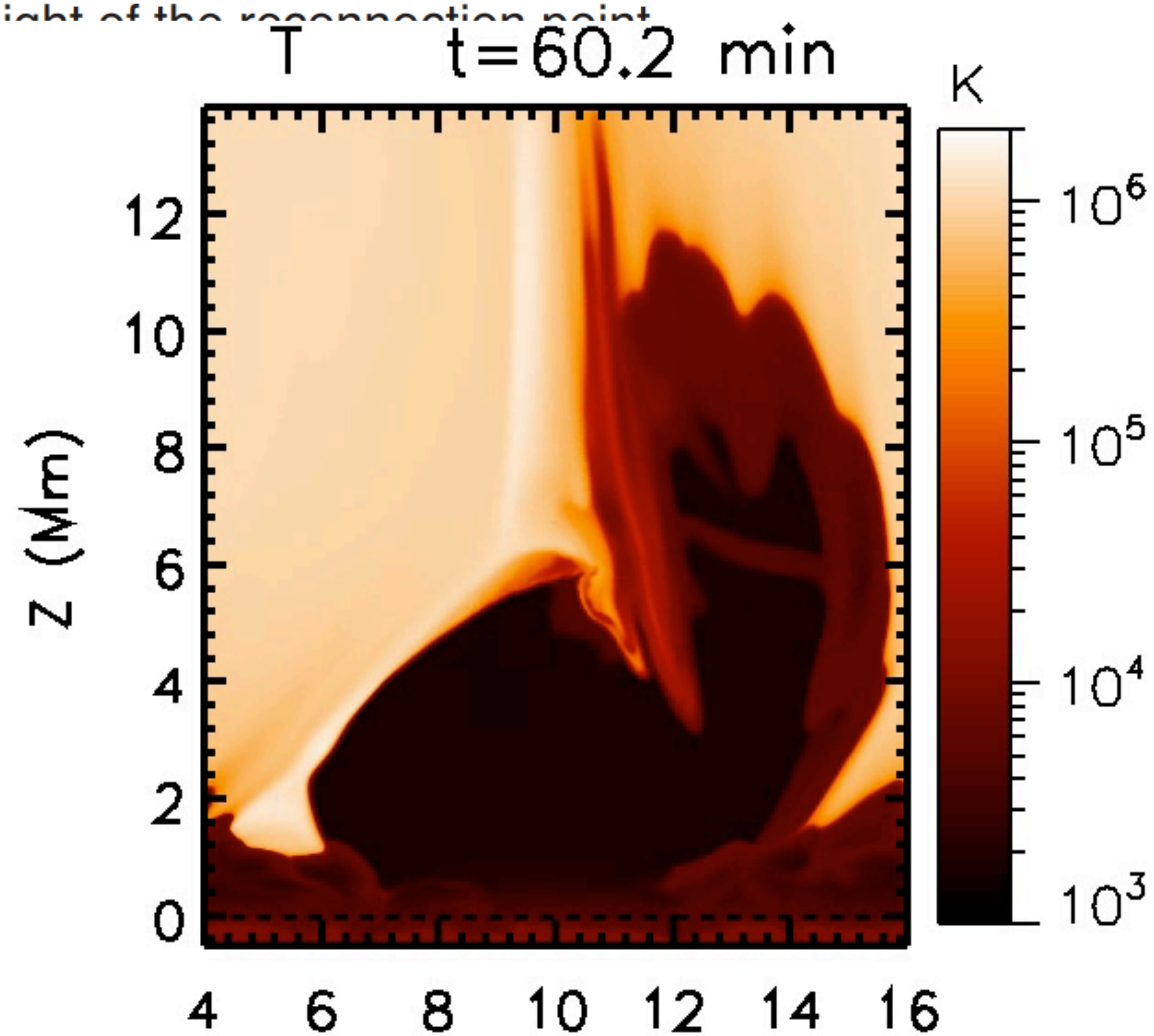
Jet formation



Takasao et al. (2013)

Guid-field reconnection model



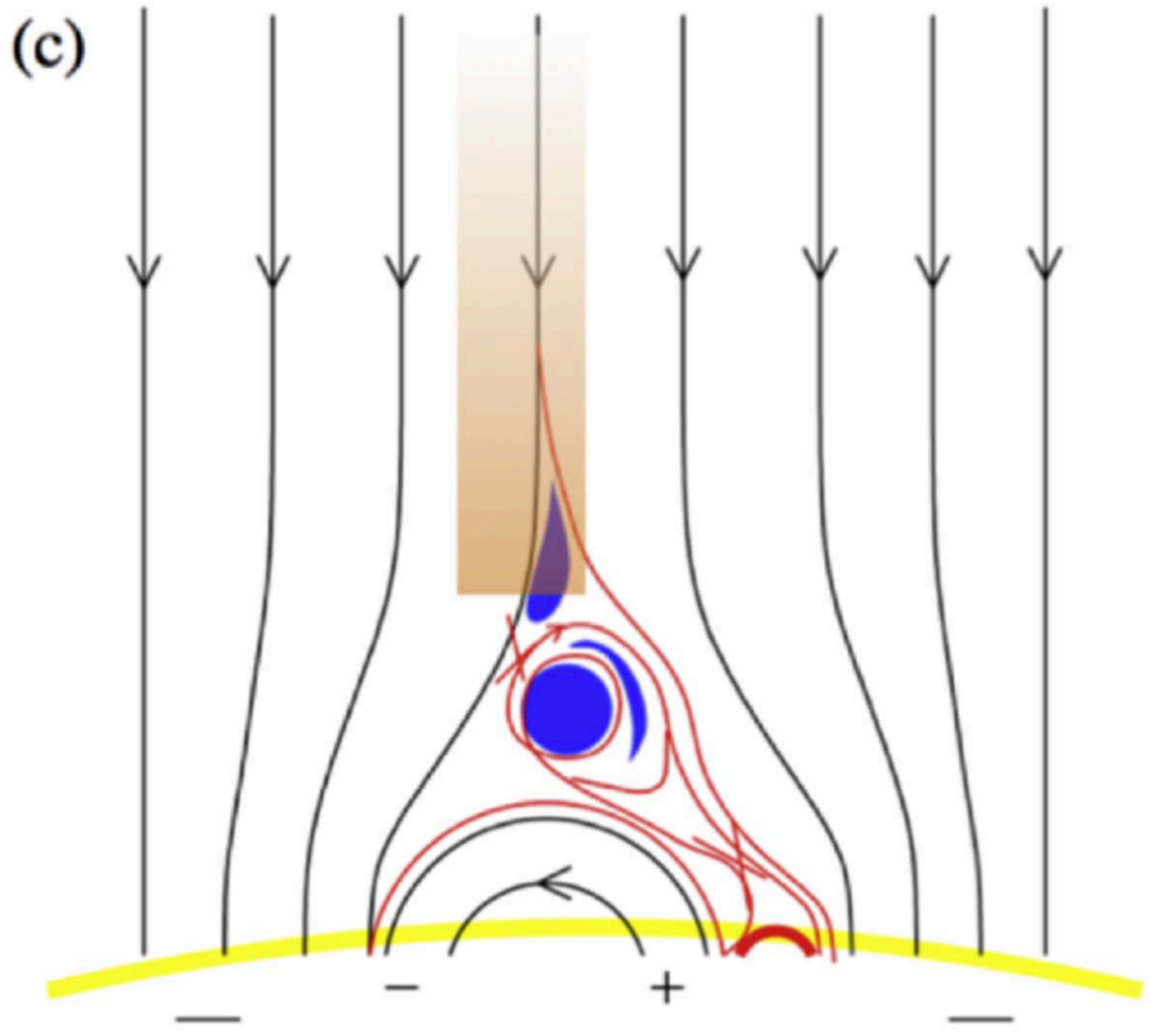


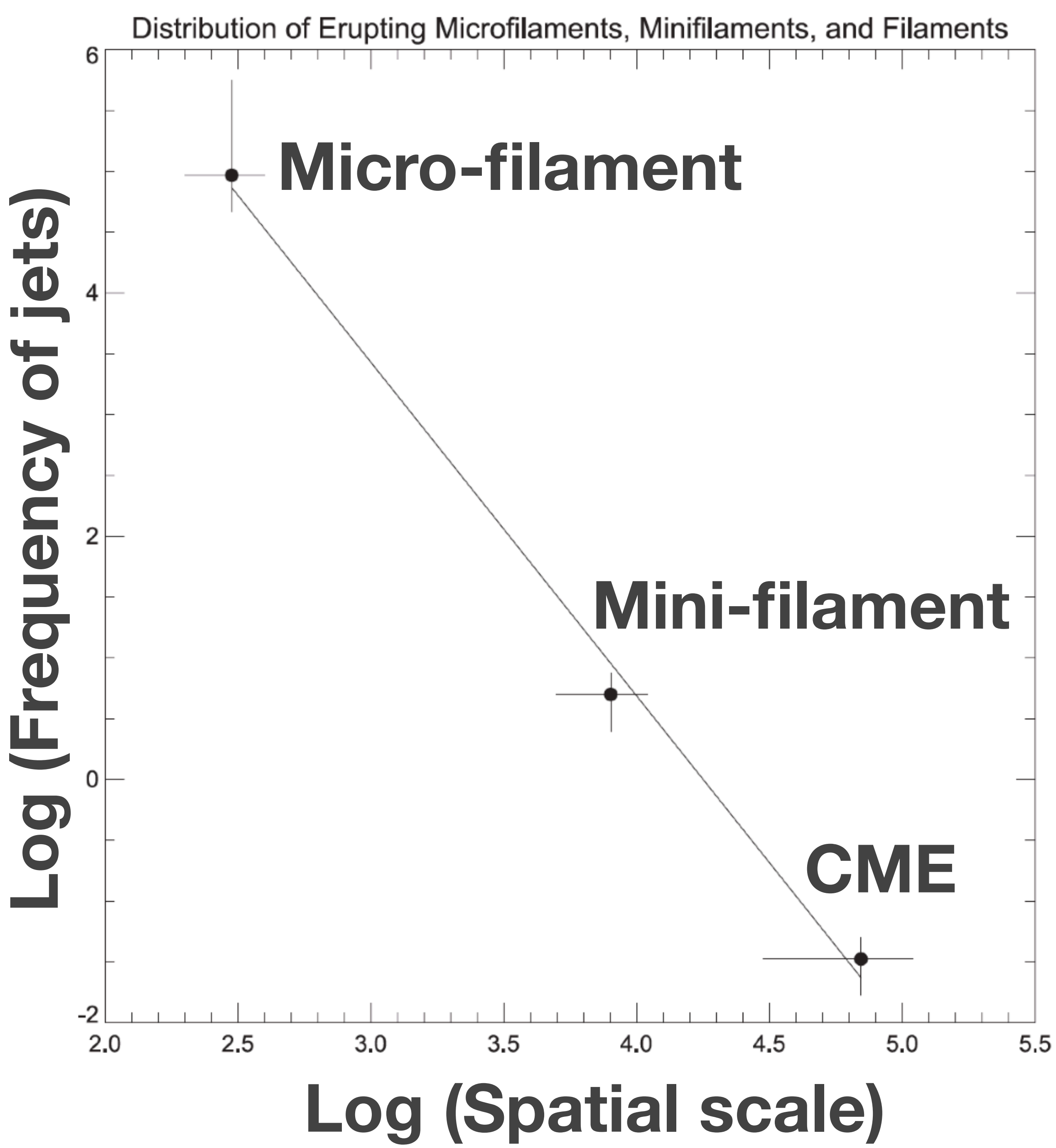
Nobrega-Siverio et al. (2016)

Jet formation

Takasao et al. (2013)

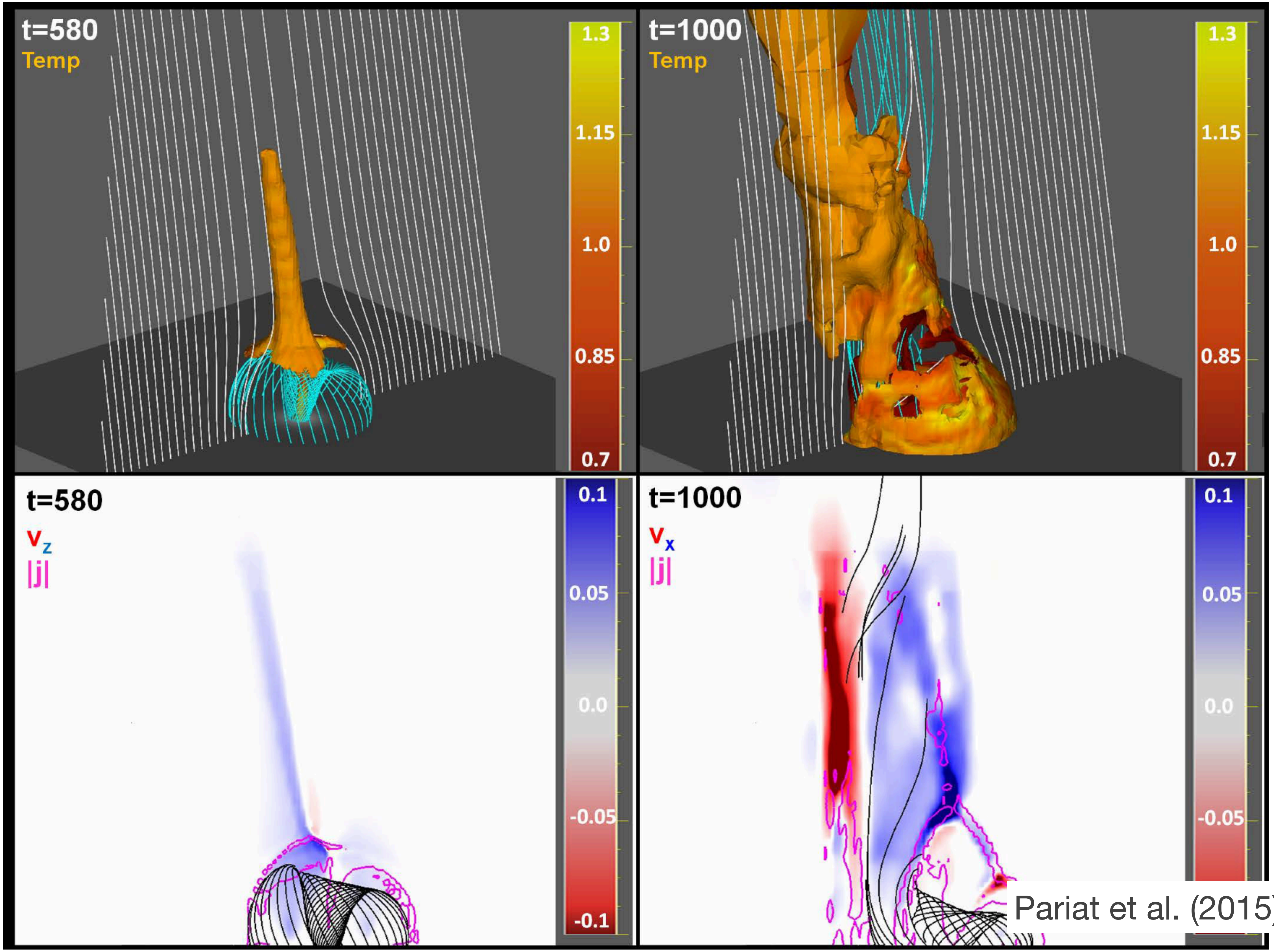
Micro-filament eruption model





Sterling et al. (2016)

Helical reconnection model



Pariat et al. (2015)

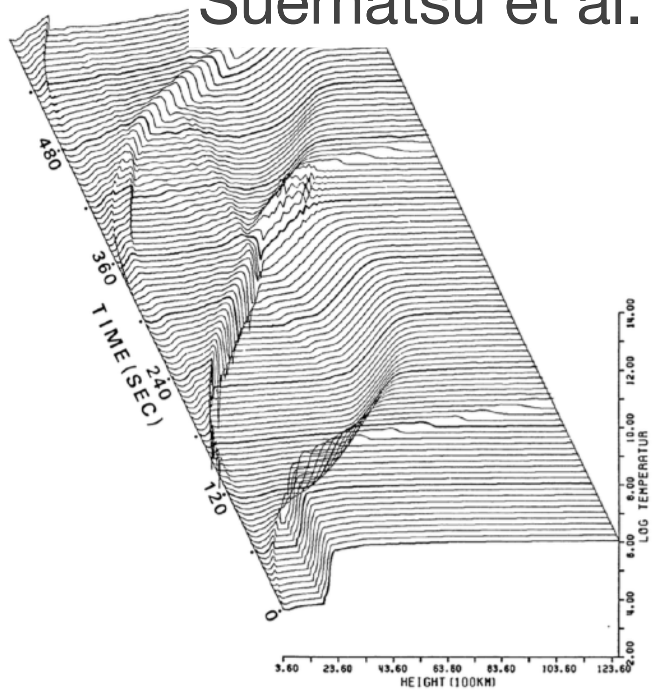
Magnetic reconnection model

- Energy source
  - Joule heating and/or reconnection outflow
- Expected signature
  - **Cancellation of magnetic polarity in the photosphere**
  - **Transient brightening in high temperature lines** (may be observed even in EUV or X-rays)
  - **Complex magnetic field structure** in photosphere and/or chromosphere, sometimes with flux emergence
  - Bi-directional outflow (in some cases)

Possible drivers of spicules

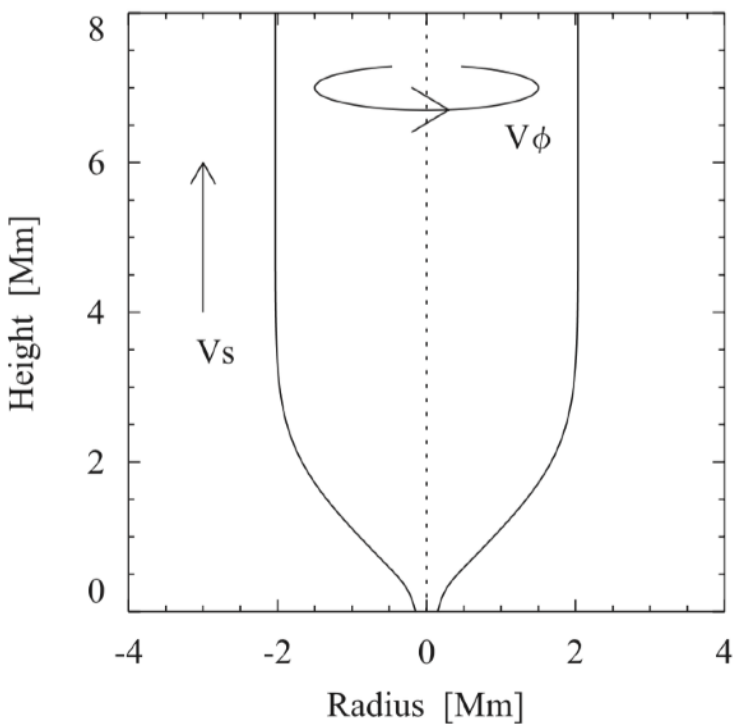
Acoustic wave

Suematsu et al. (1982)



Alfvén wave

Alfvén wave
-> Sound wave



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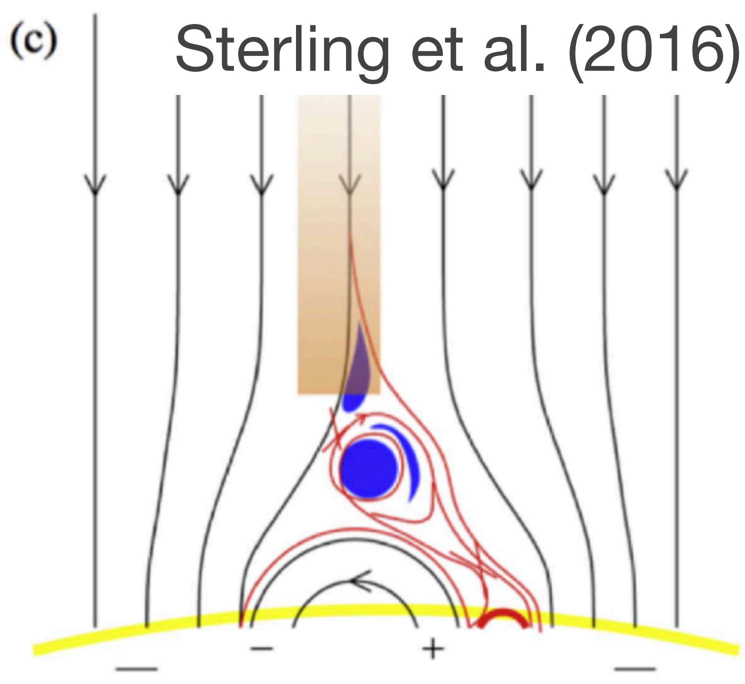
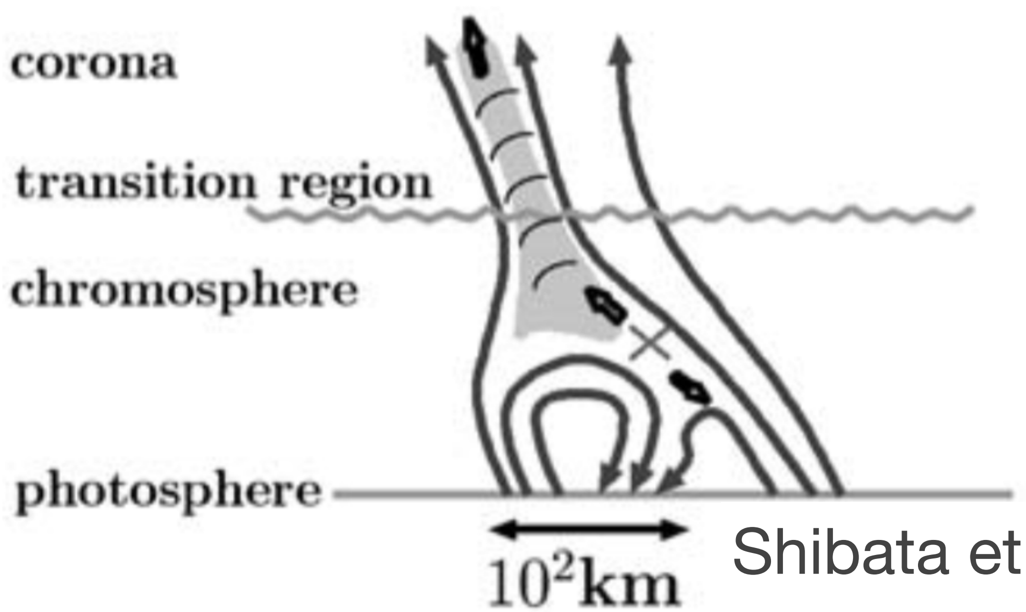
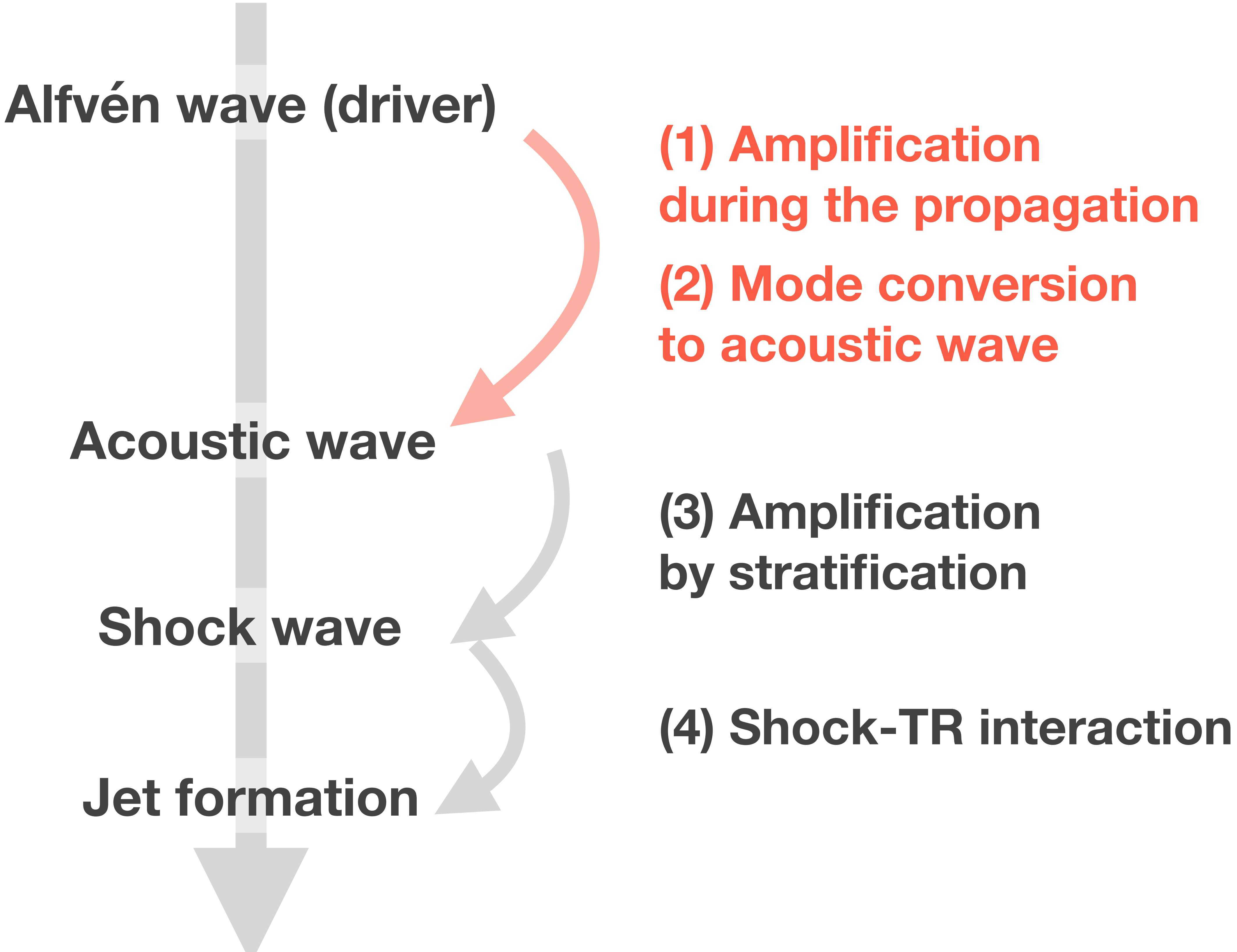




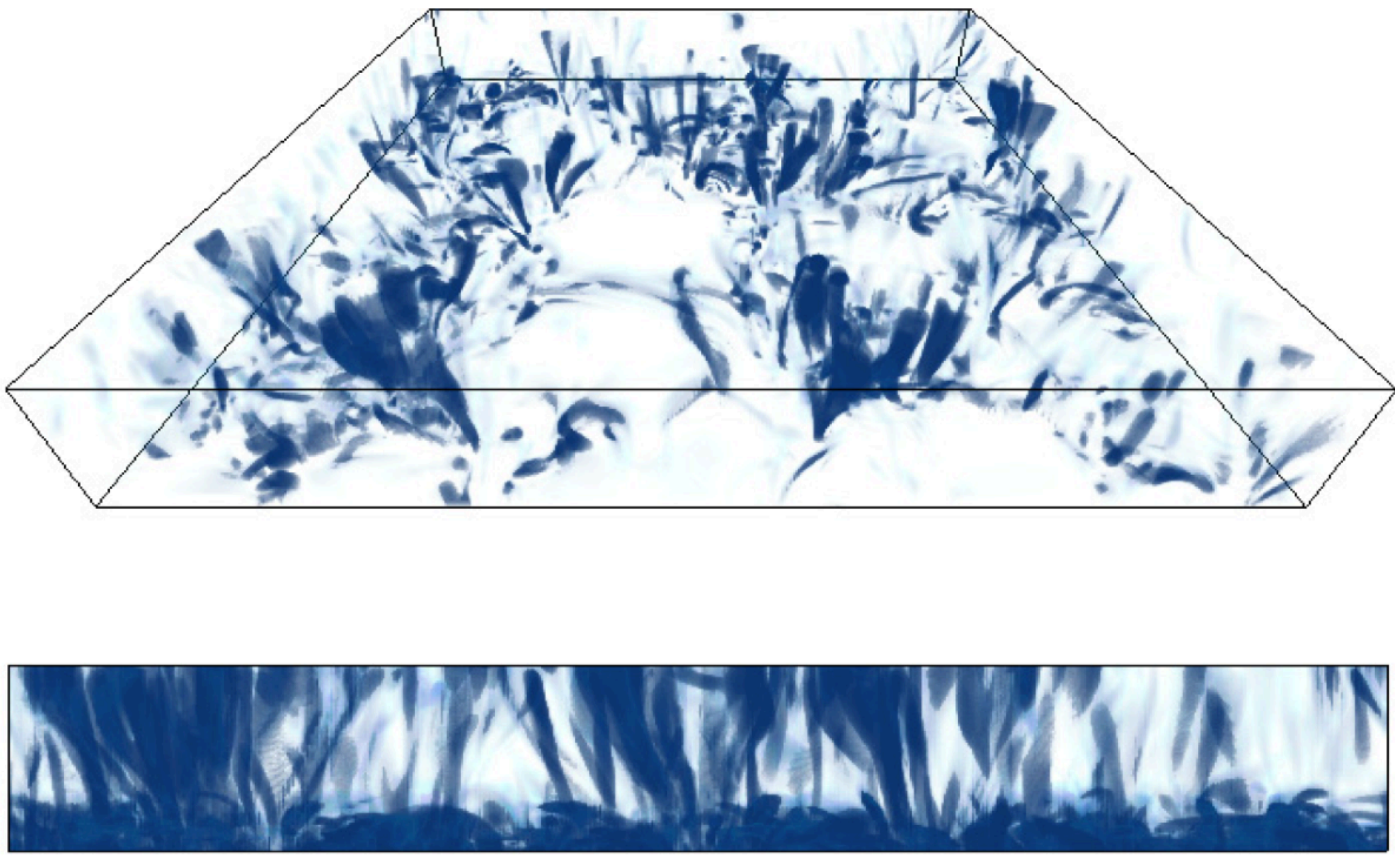
Shibata et al. (2007)

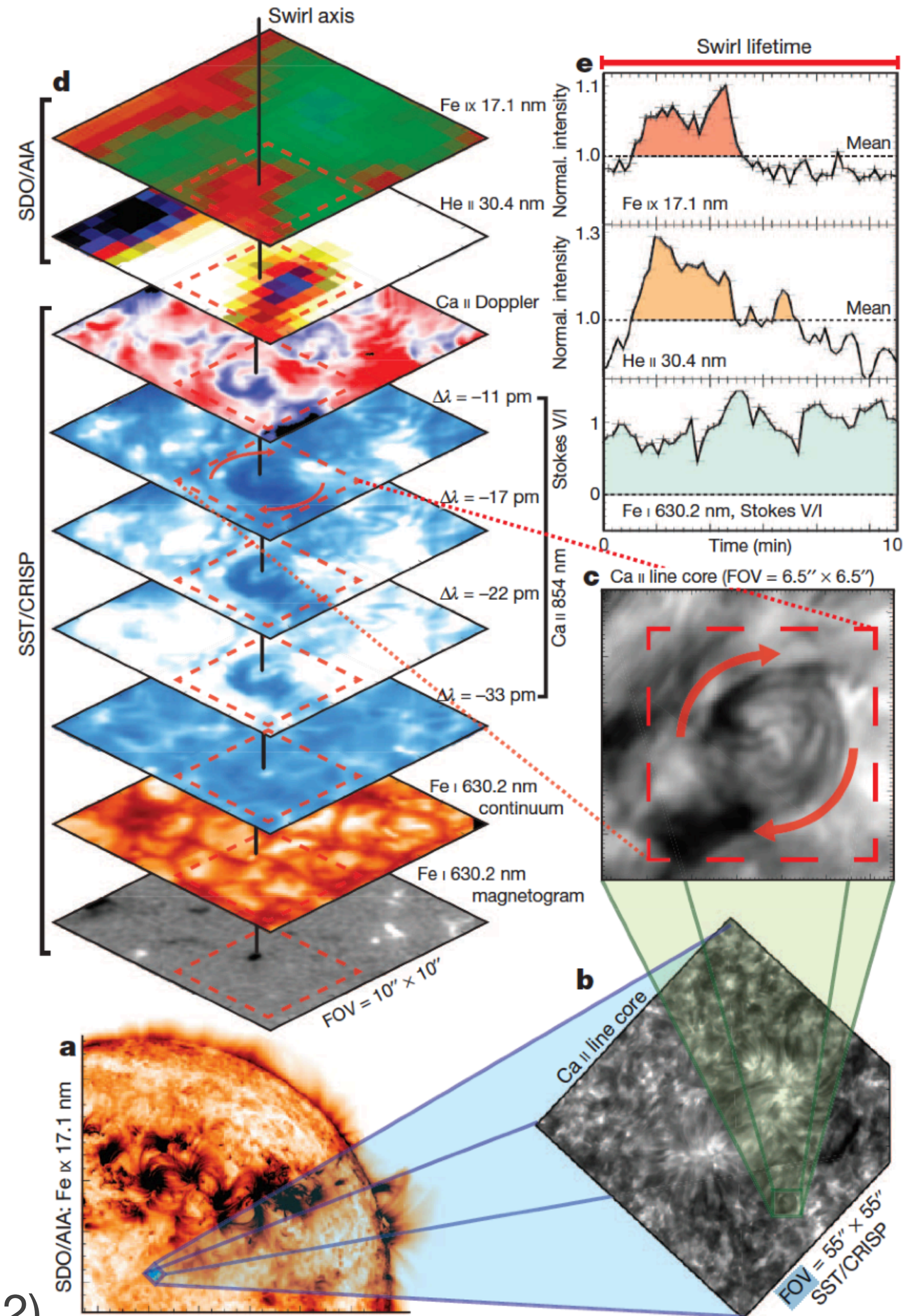
Mechanism of Alfvén wave driven jet



Vortex in the photosphere and chromosphere

Moll et al. (2012)



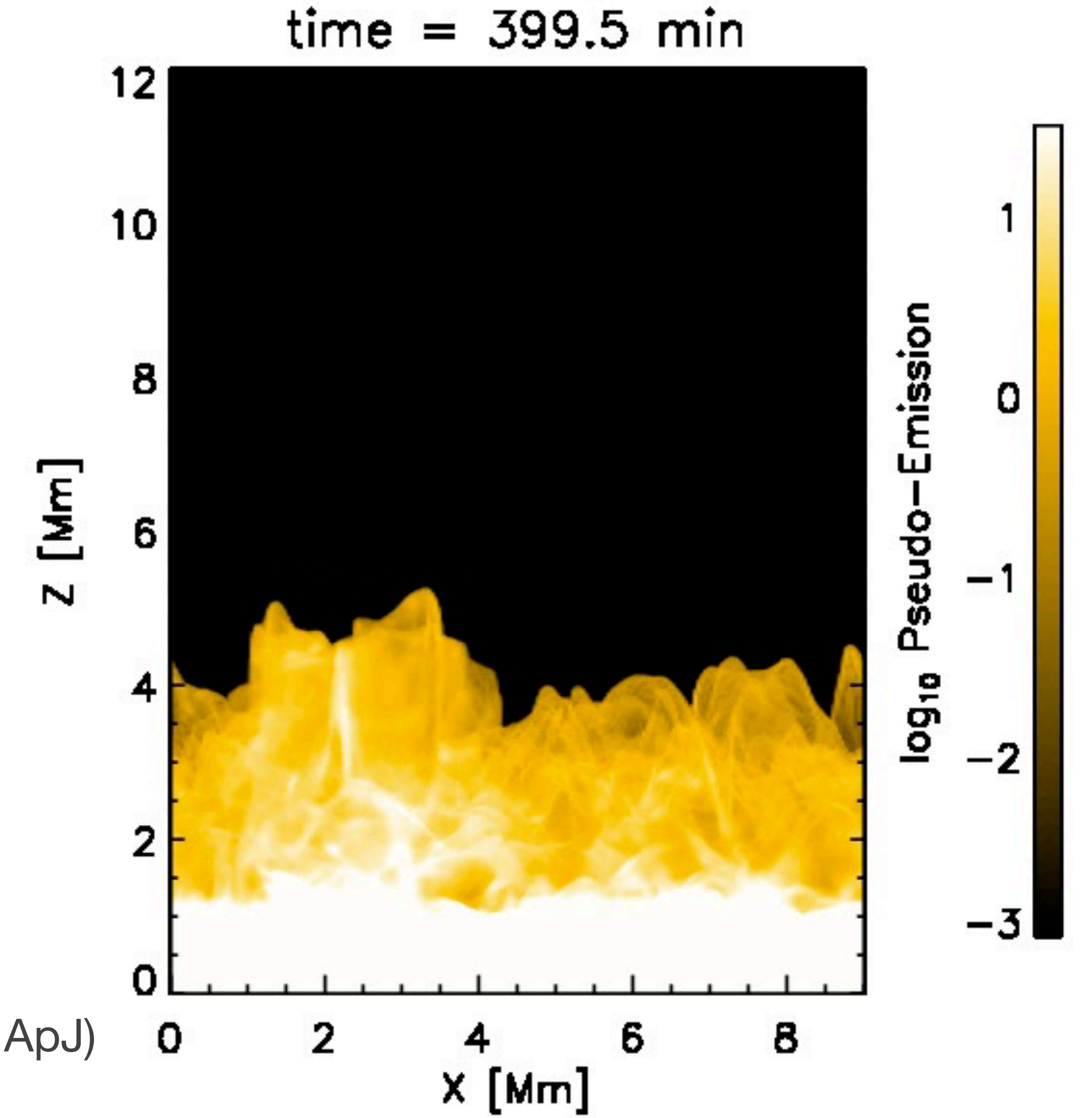


Wedemeyer et al. (2012)

Torsional wave model | 3D simulation

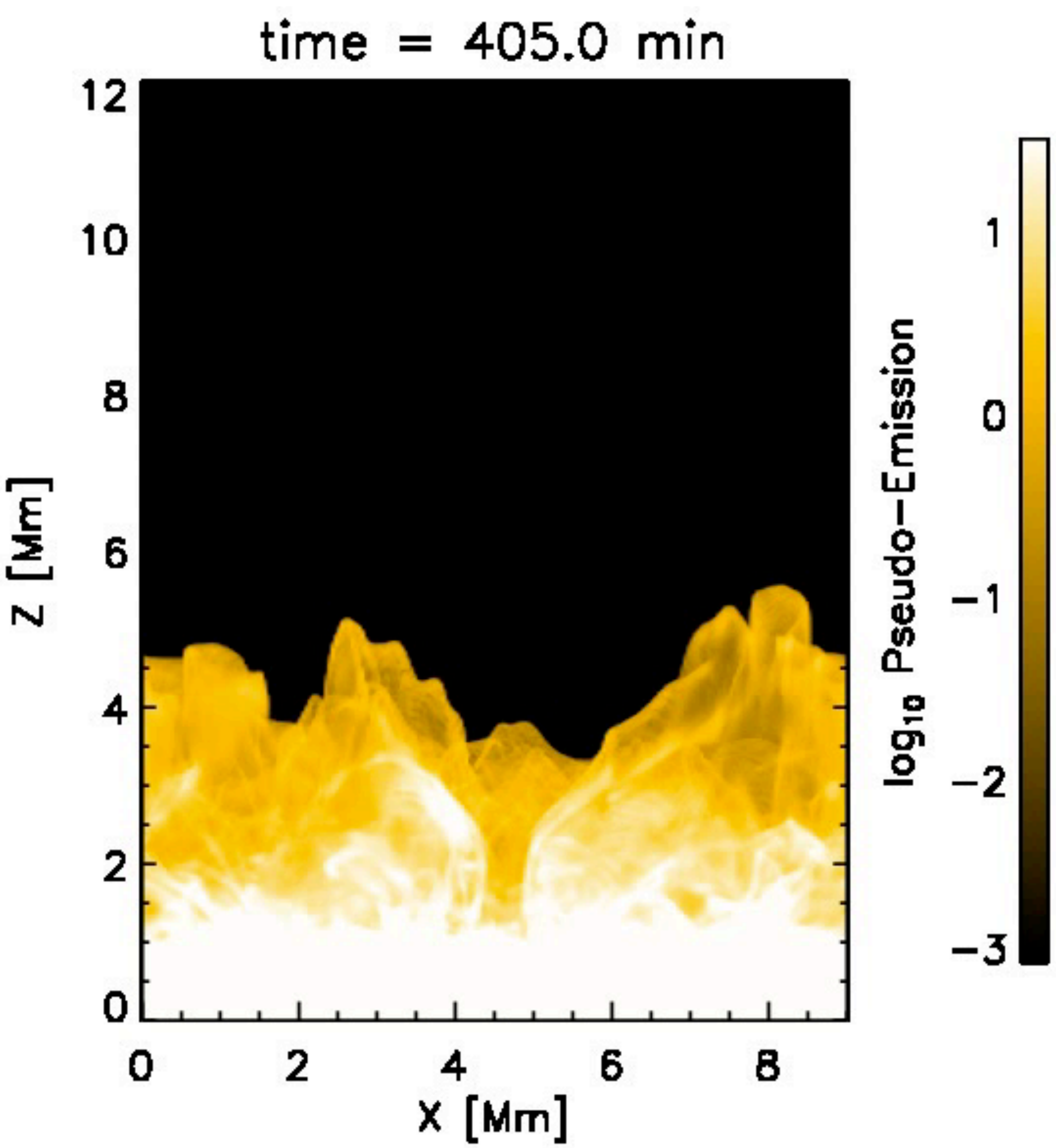
Right: optically thin emission with the Gaussian contribution function G(T) that mimics the chromospheric line emission (**~ 10 kK**).

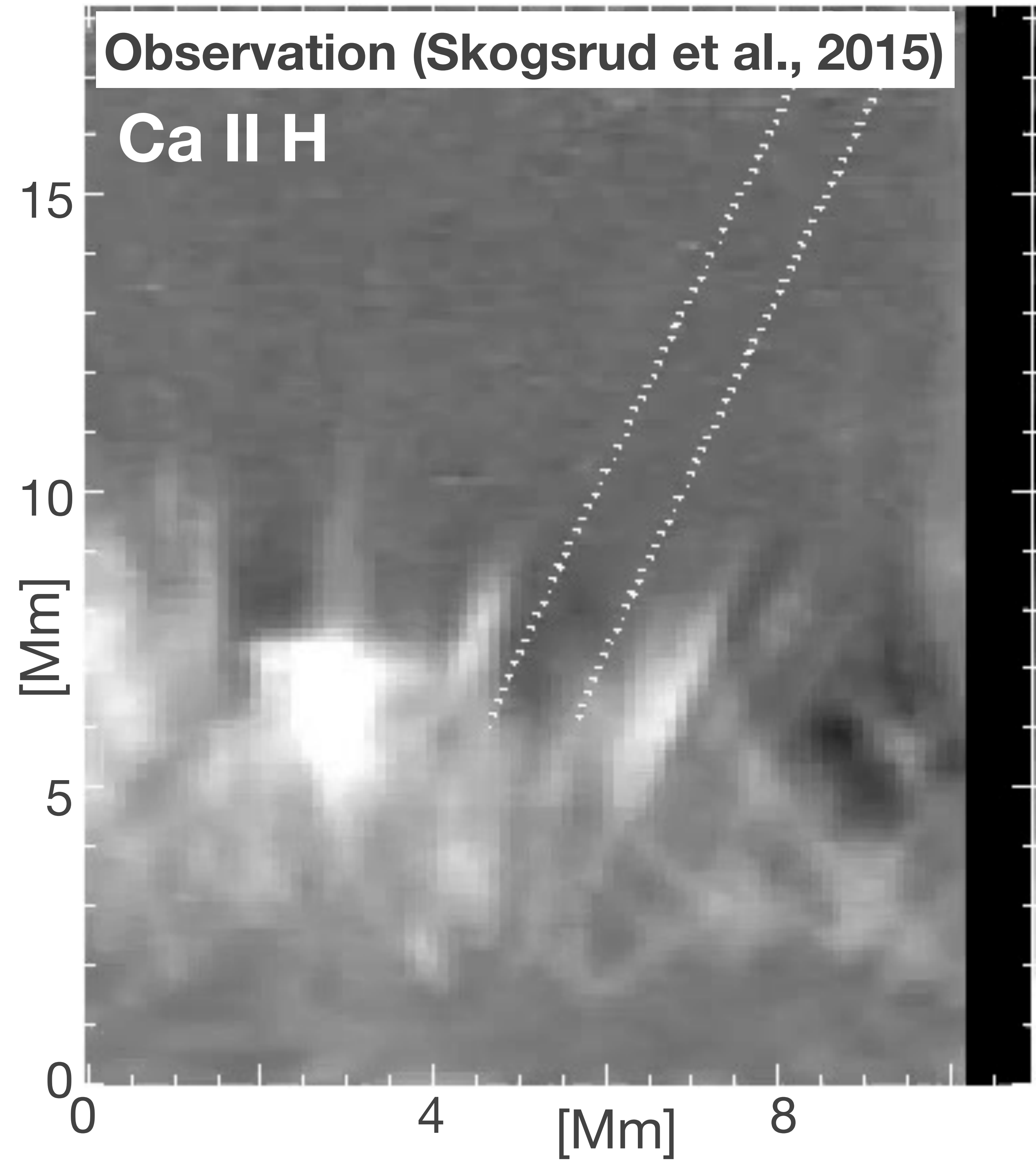
$$\epsilon = \int n_{\rm e} n_{\rm H} G(T) {\rm d}l$$



Iijima & Yokoyama (2017, ApJ)

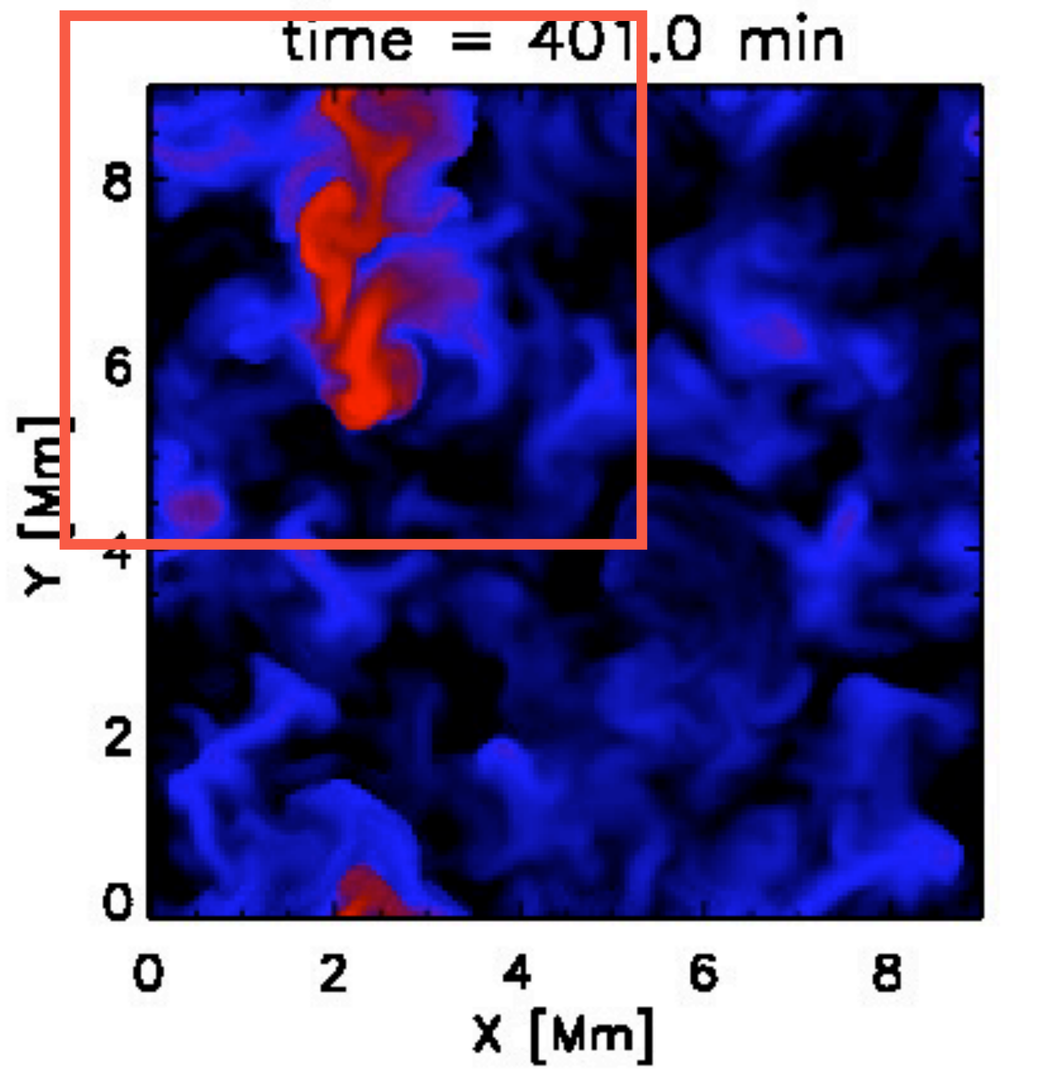
Multi-threaded nature of spicules

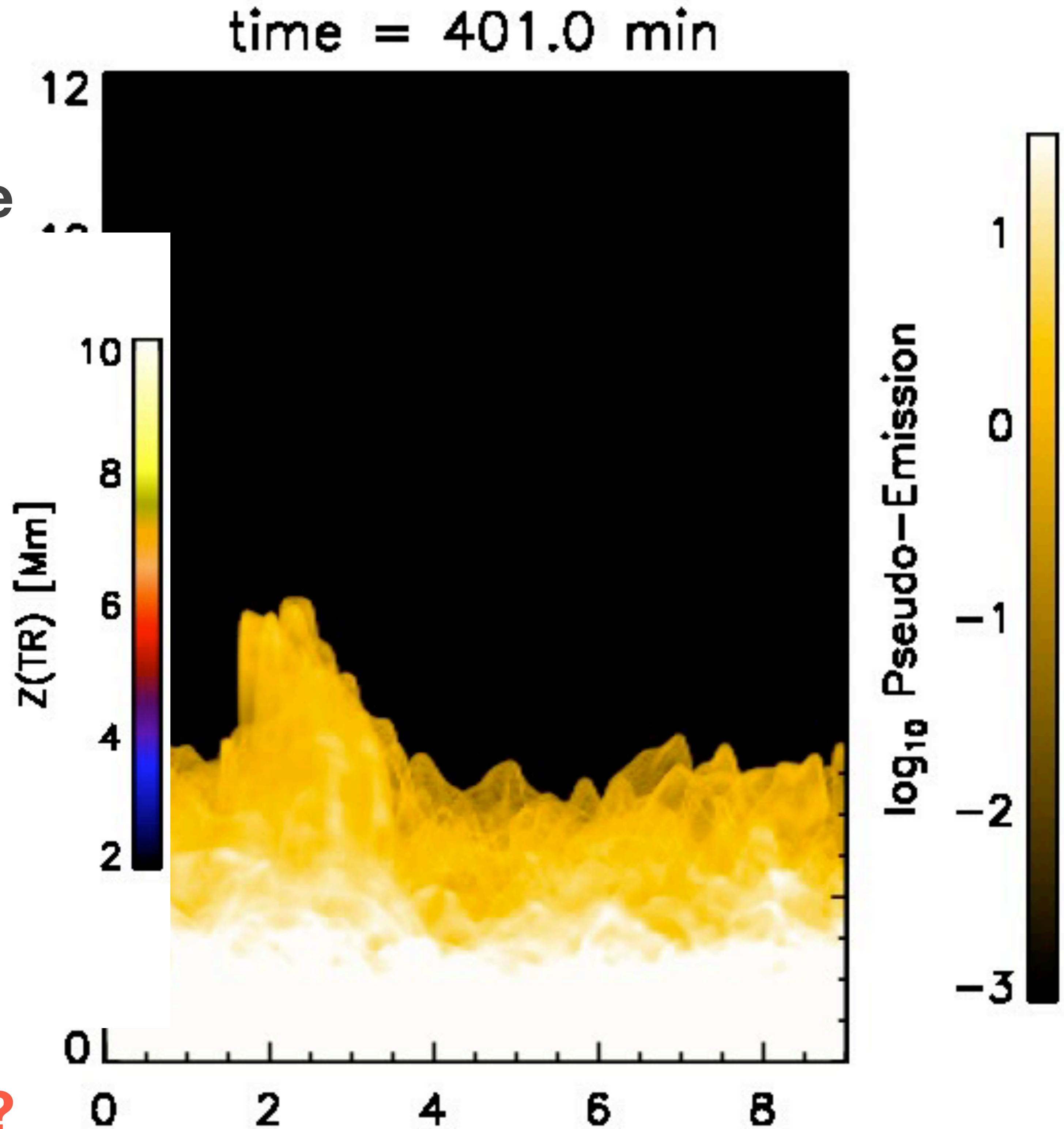




Torsional wave model | 3D simulation

Height of TR from above

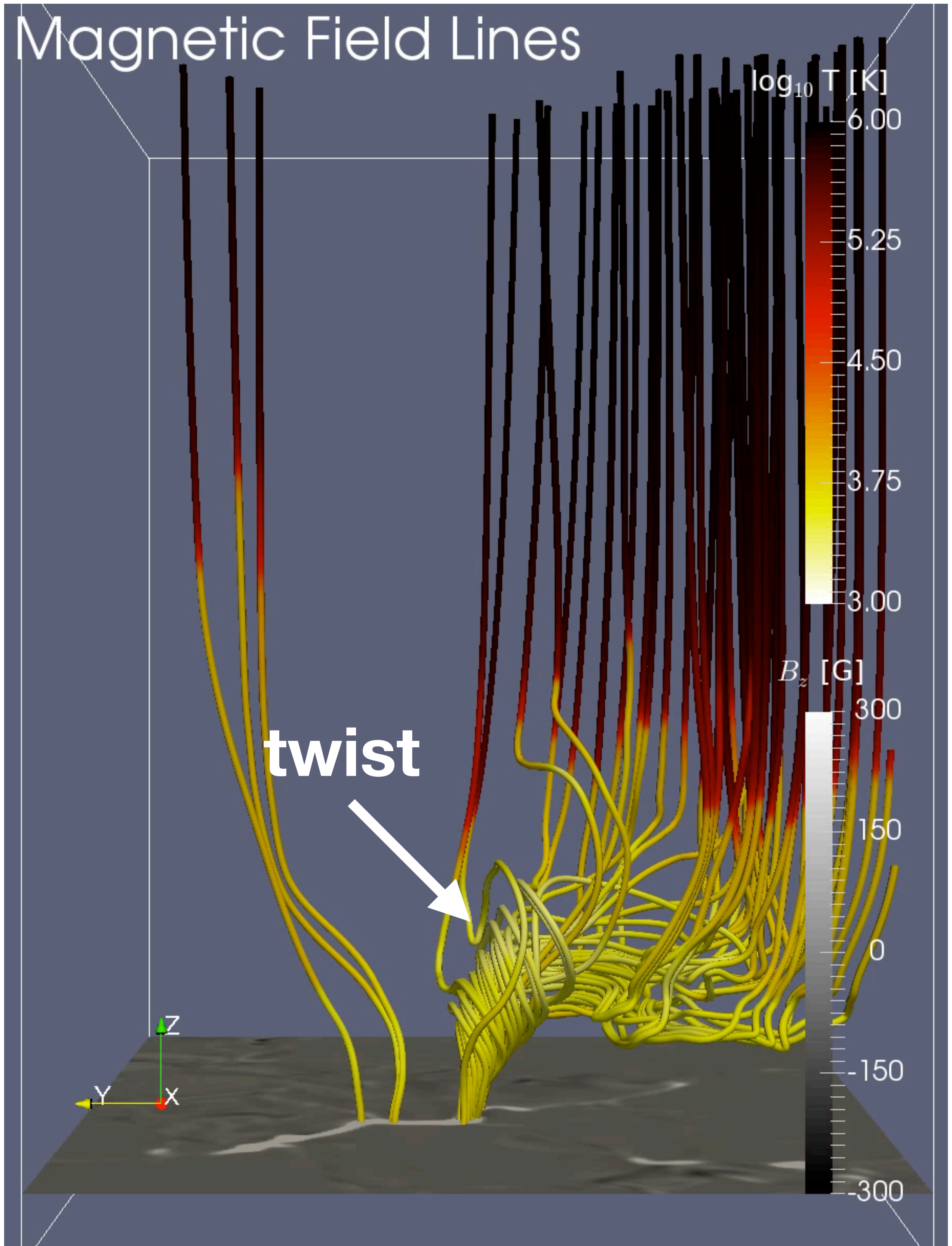




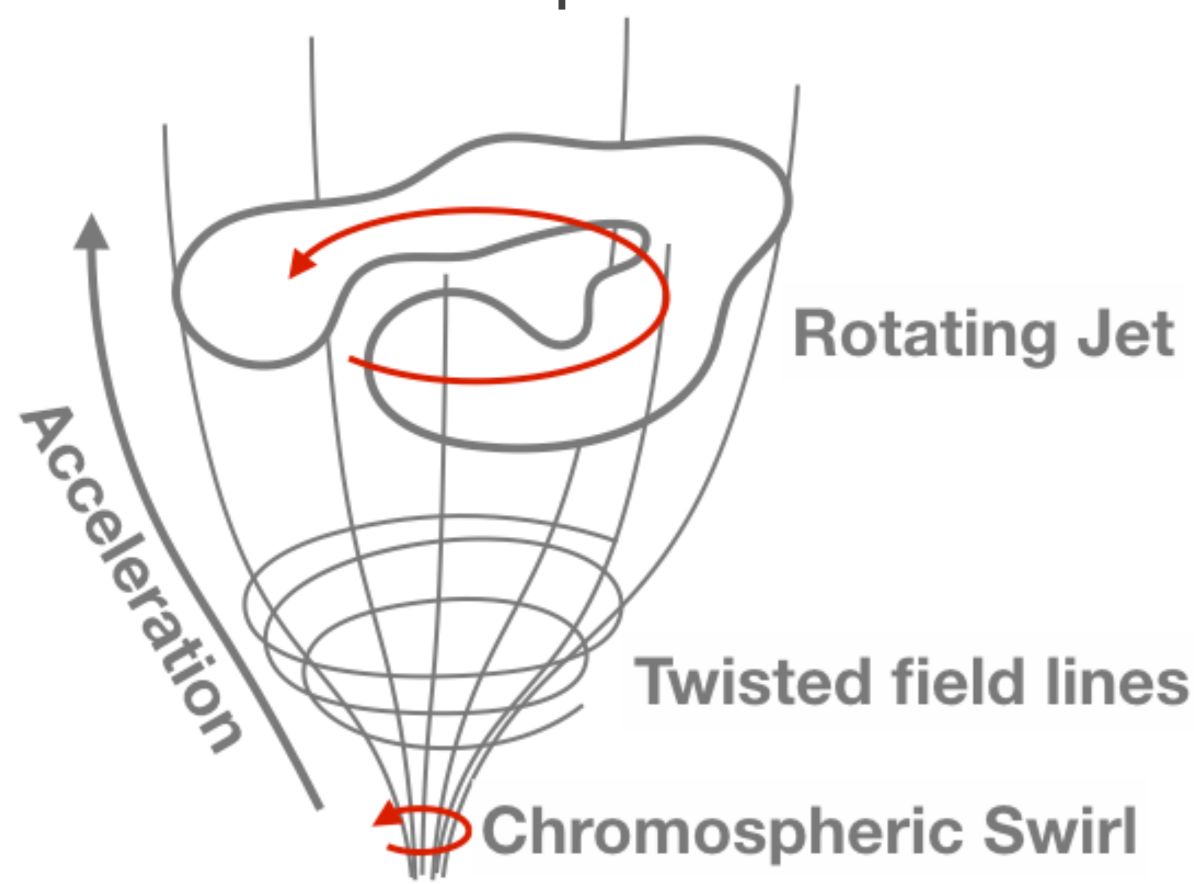
KH instability in spicule?

Iijima & Yokoyama (2017, ApJ)

Torsional wave model | 3D simulation



Torsional motion at the photosphere causes the twist in the chromosphere.
When twist becomes sufficiently strong, it releases the free energy and accelerate the plasma.



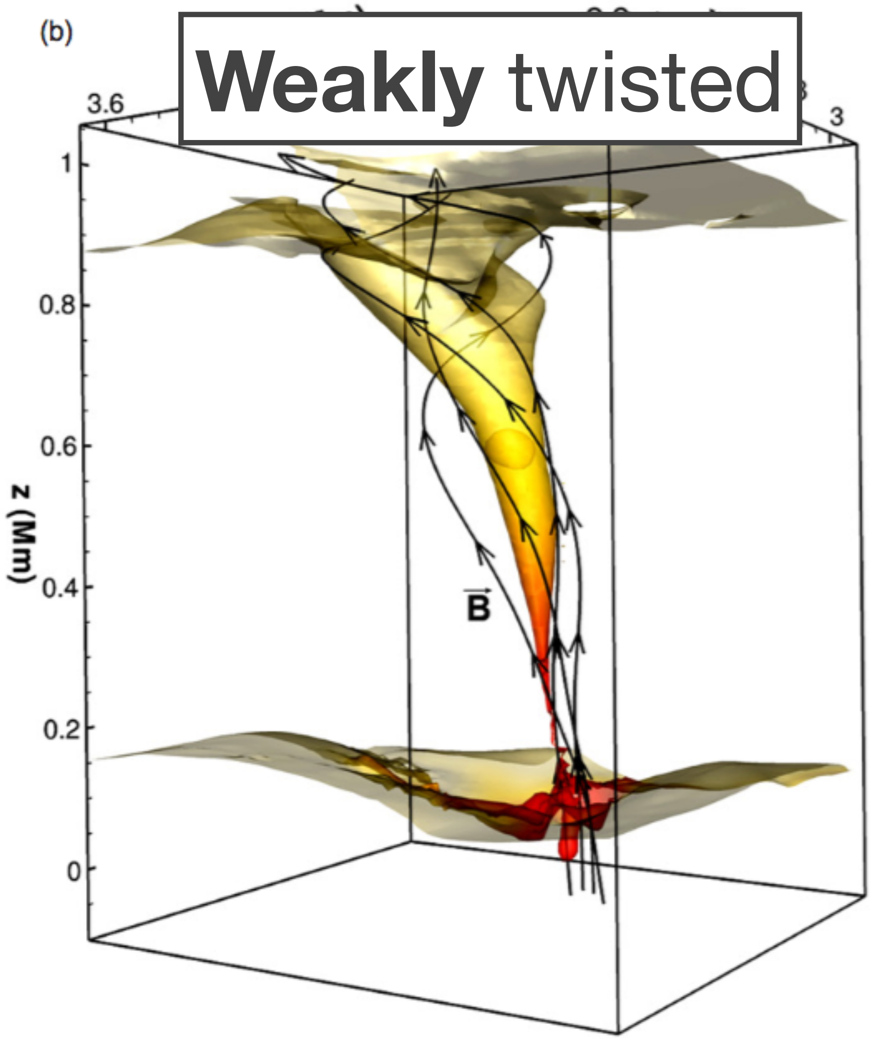
Iijima & Yokoyama (2017, ApJ)

Twist and magnetic flux imbalance

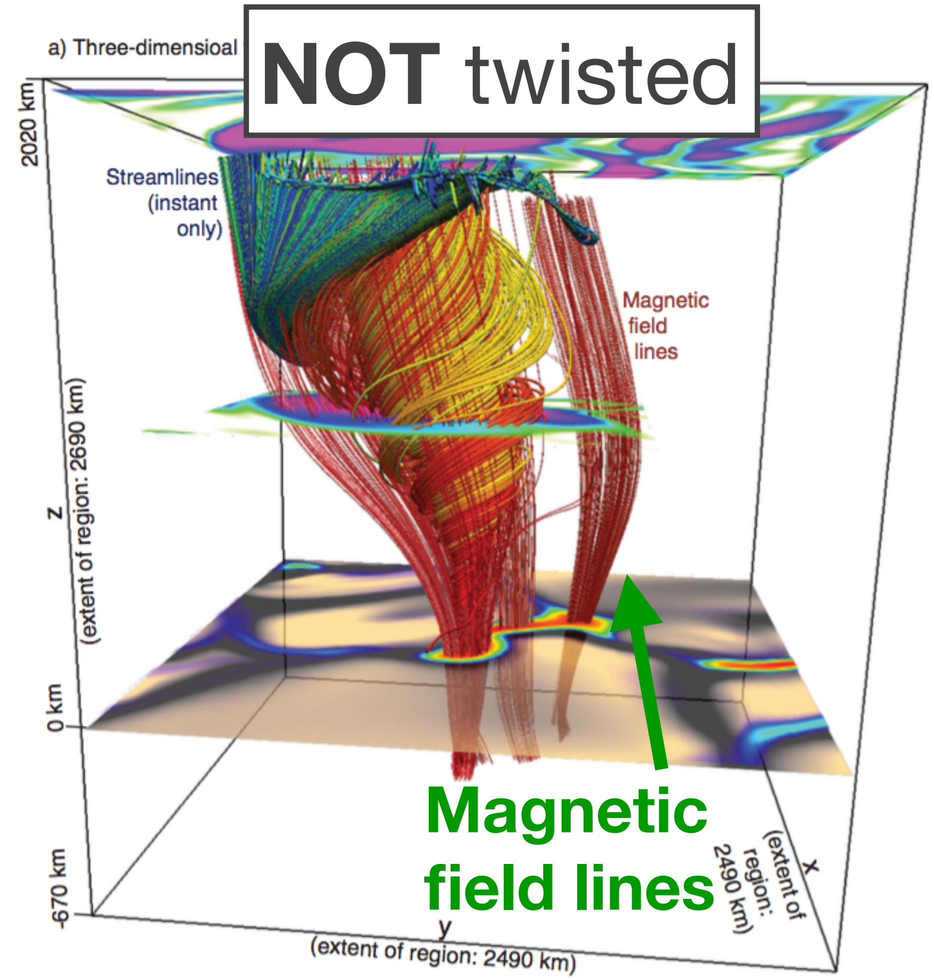
Flux imbalance

B_0 = 10 G | QS/CH | B_0 = 50 G | AR | B_0 = 200 G

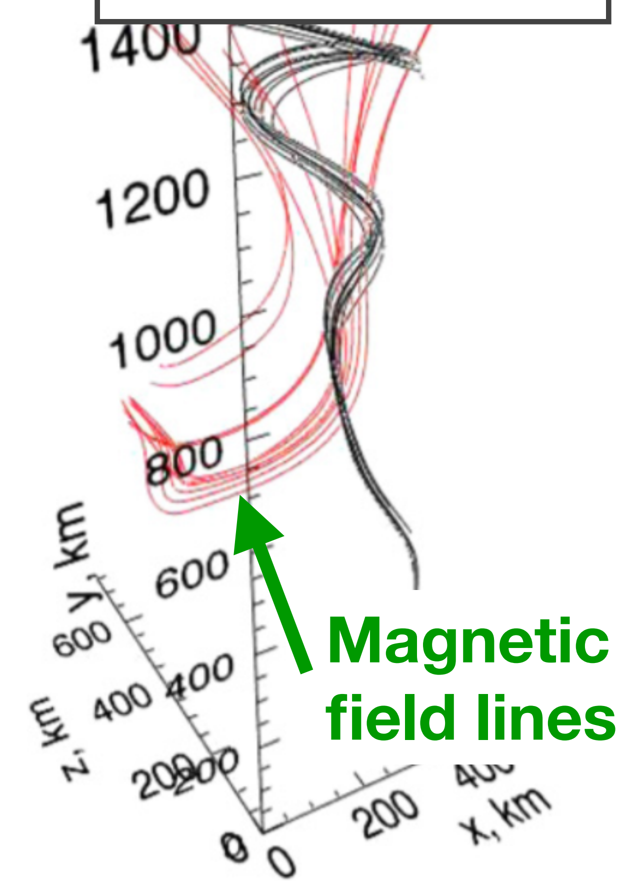
Weakly twisted | **NOT** twisted | **NOT** twisted



Kitiashvili et al. (2013)

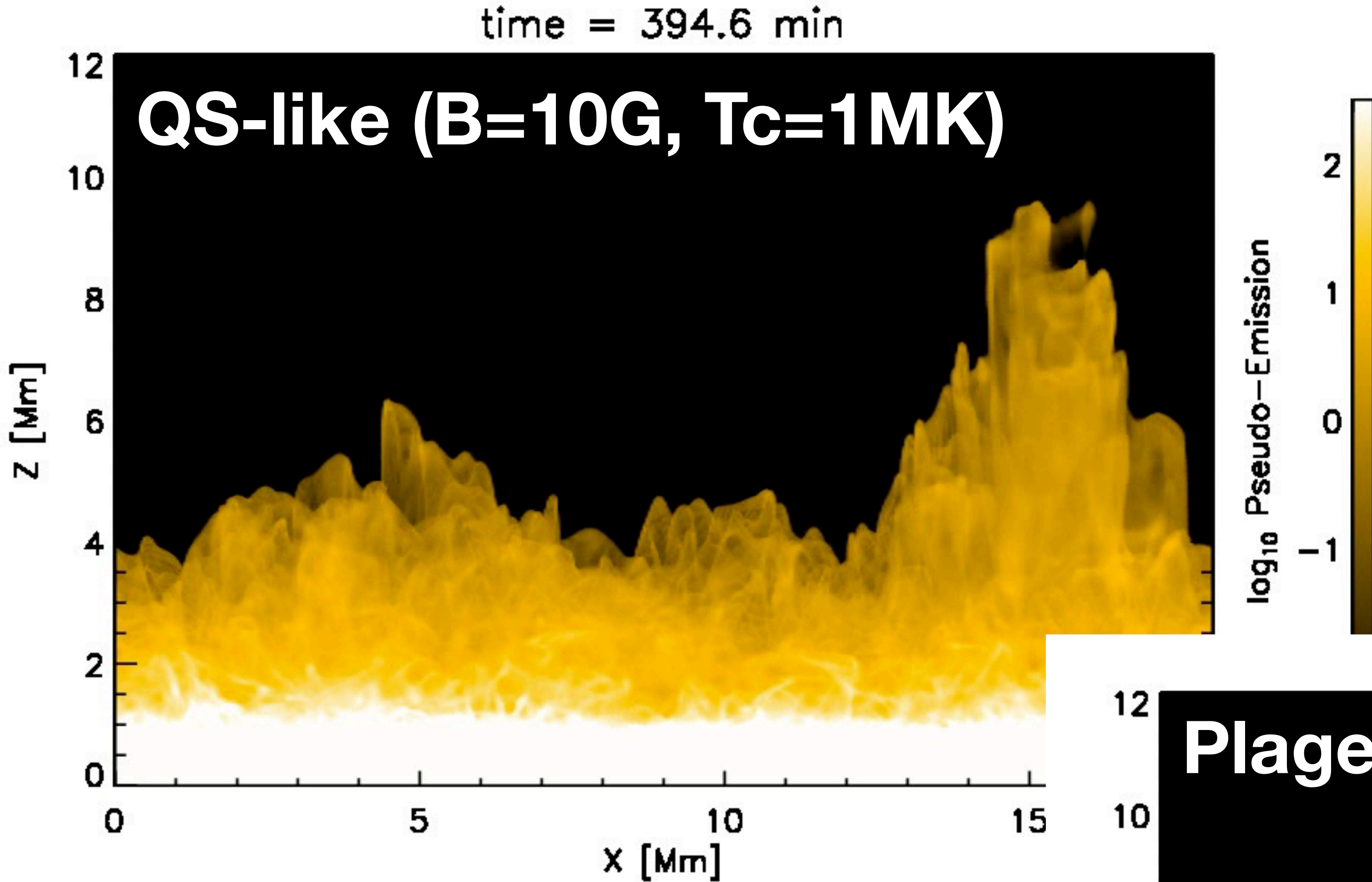


Wedemeyer & Steiner (2012/14)



Shelyag et al. (2013)

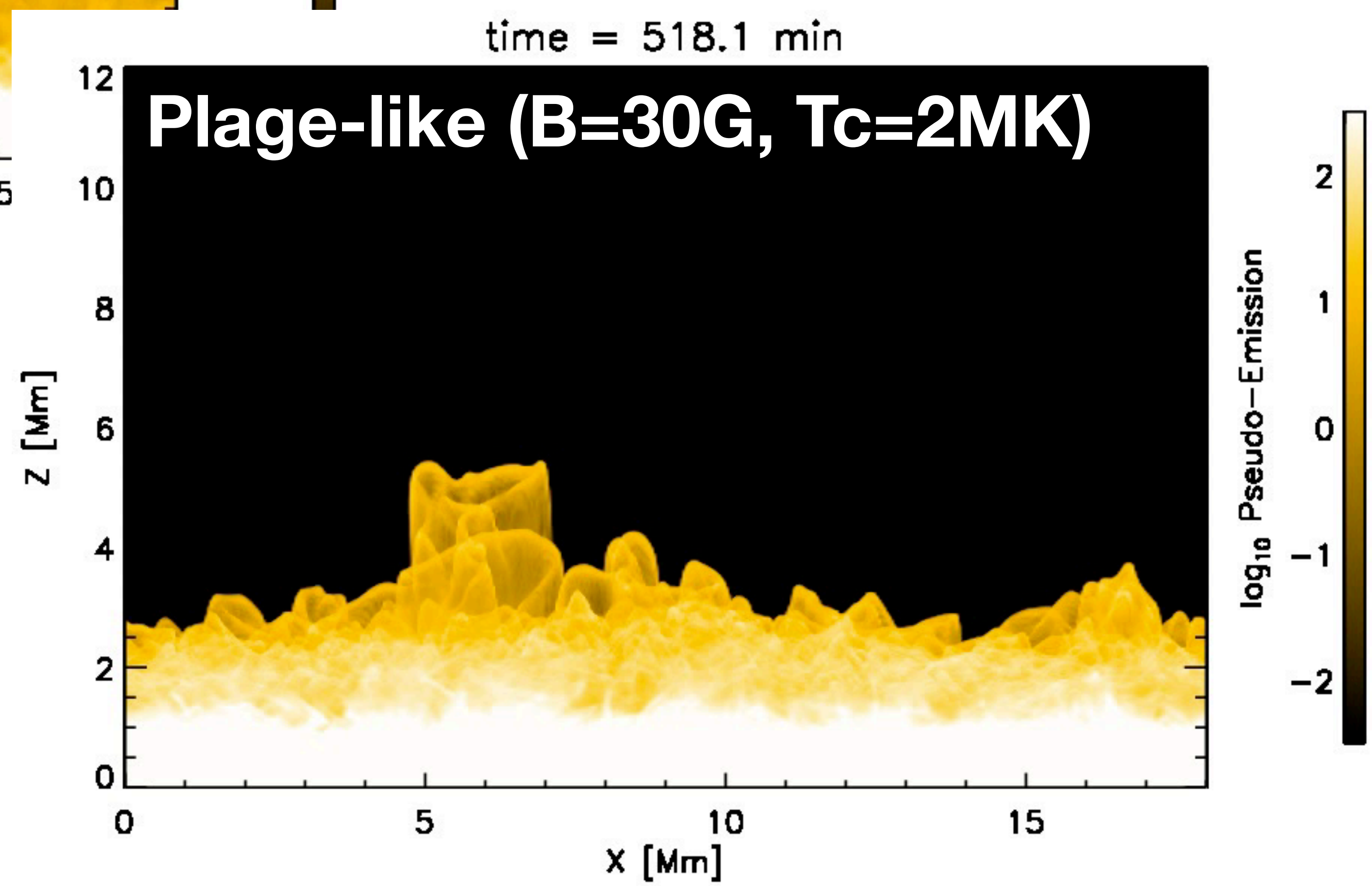
Regional dependence on flux imbalance



$$L_{\rm jet} \propto P_c^{-0.2} B_c^{-0.5}$$

Pc: Coronal gas pressure or TR density

Bc: Coronal field strength or Flux imbalance

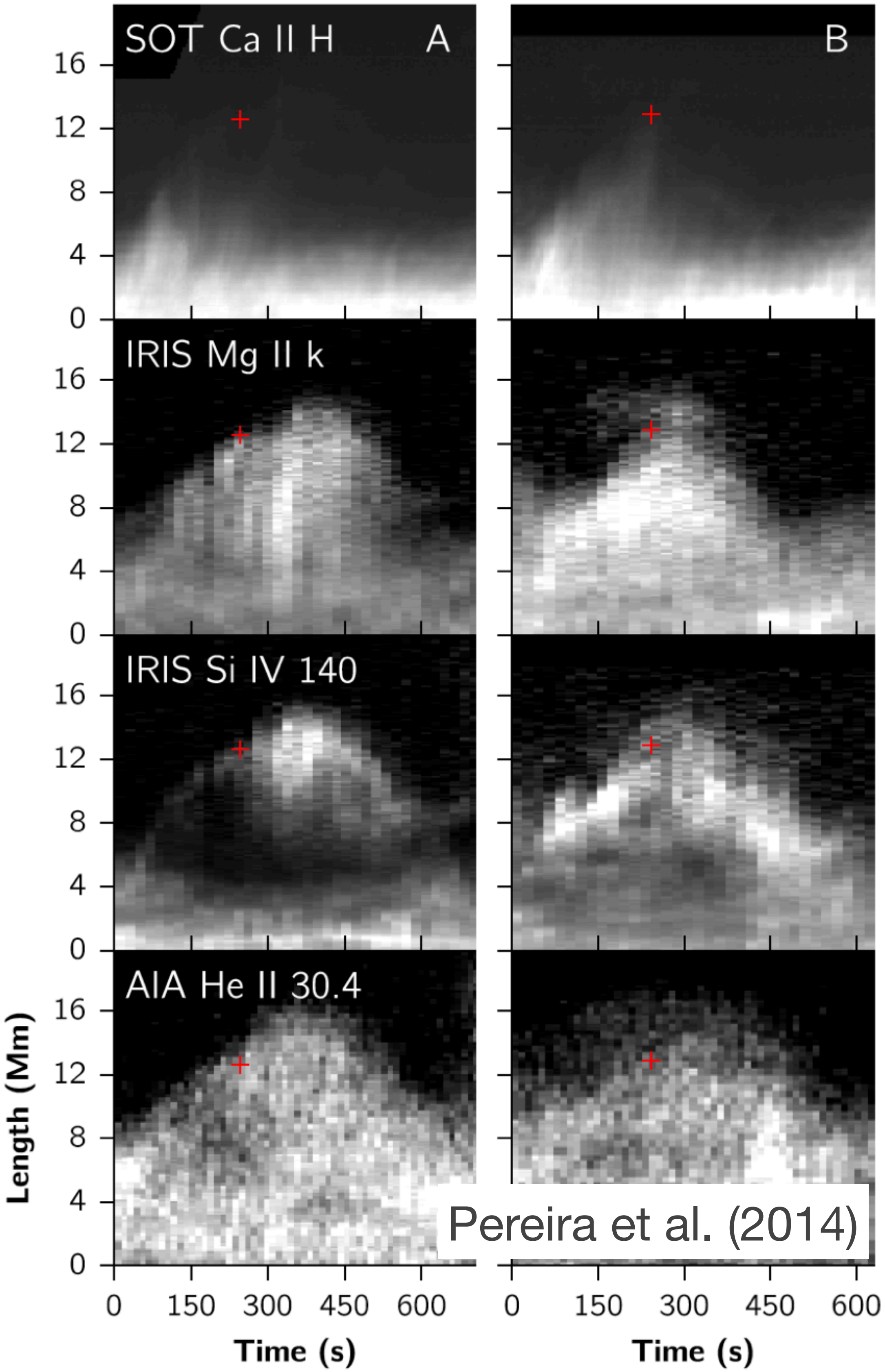


Iijima & Yokoyama (2018, in prep)

Alfvén wave model

- Energy source
  - Torsional Alfvén wave
- Expected signature
  - **Vortex in the photosphere and chromosphere**
  - **Twisted magnetic field in the chromosphere**
  - **Regional dependence on the flux imbalance**
  - No need of magnetic field cancellation

Spicule = Plasma? | Type II spicule



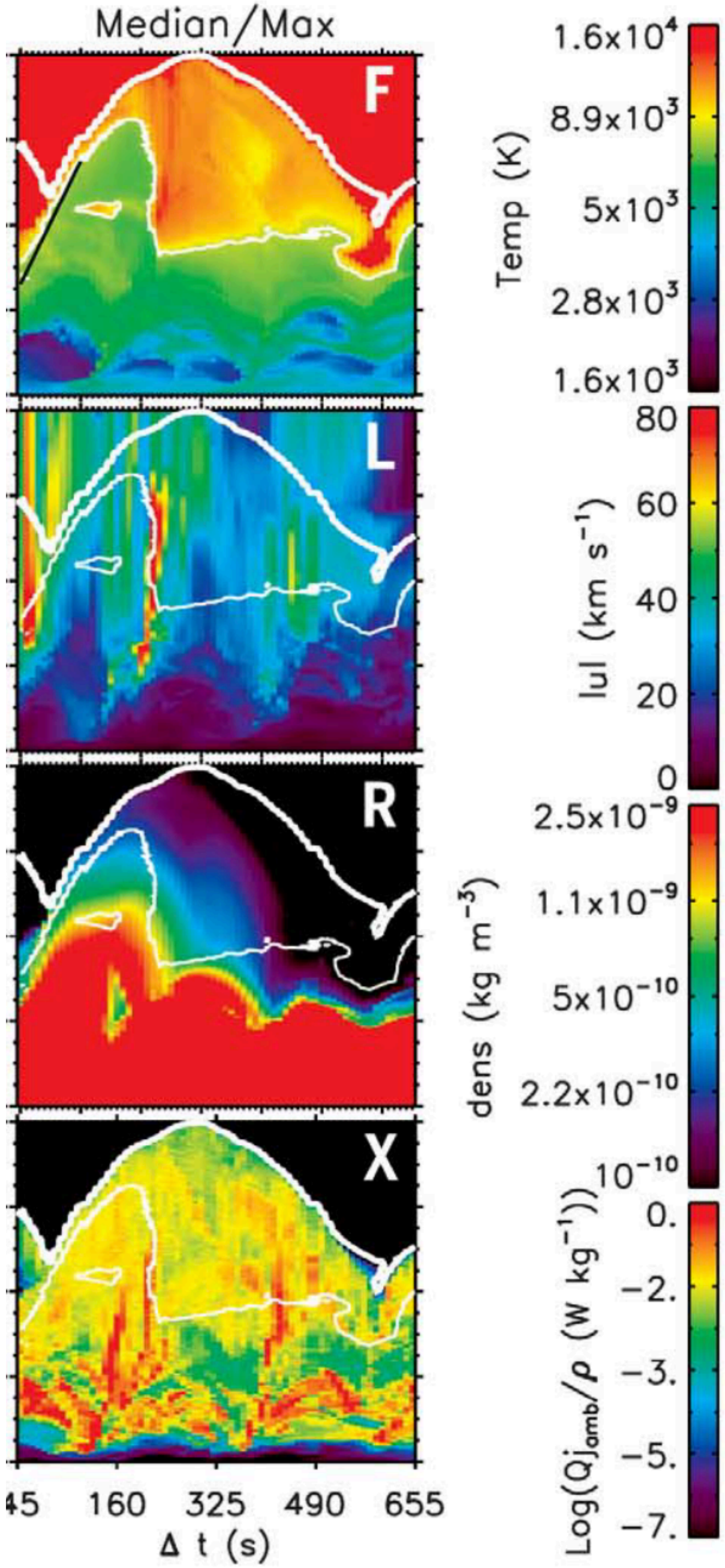
Pereira et al. (2014)

Fast apparent speed > 100 km/s

Linear trajectory (e.g., in SOT/Ca II H)

Heating during the evolution?

Heating during the evolution?



Temperature

Transverse Velocity

Apparent high-speed is produced by the propagating Alfvén wave? (De Pontieu et al., 2017)

Mass density

Heating by the (transverse) Alfvén wave with ambipolar diffusion?

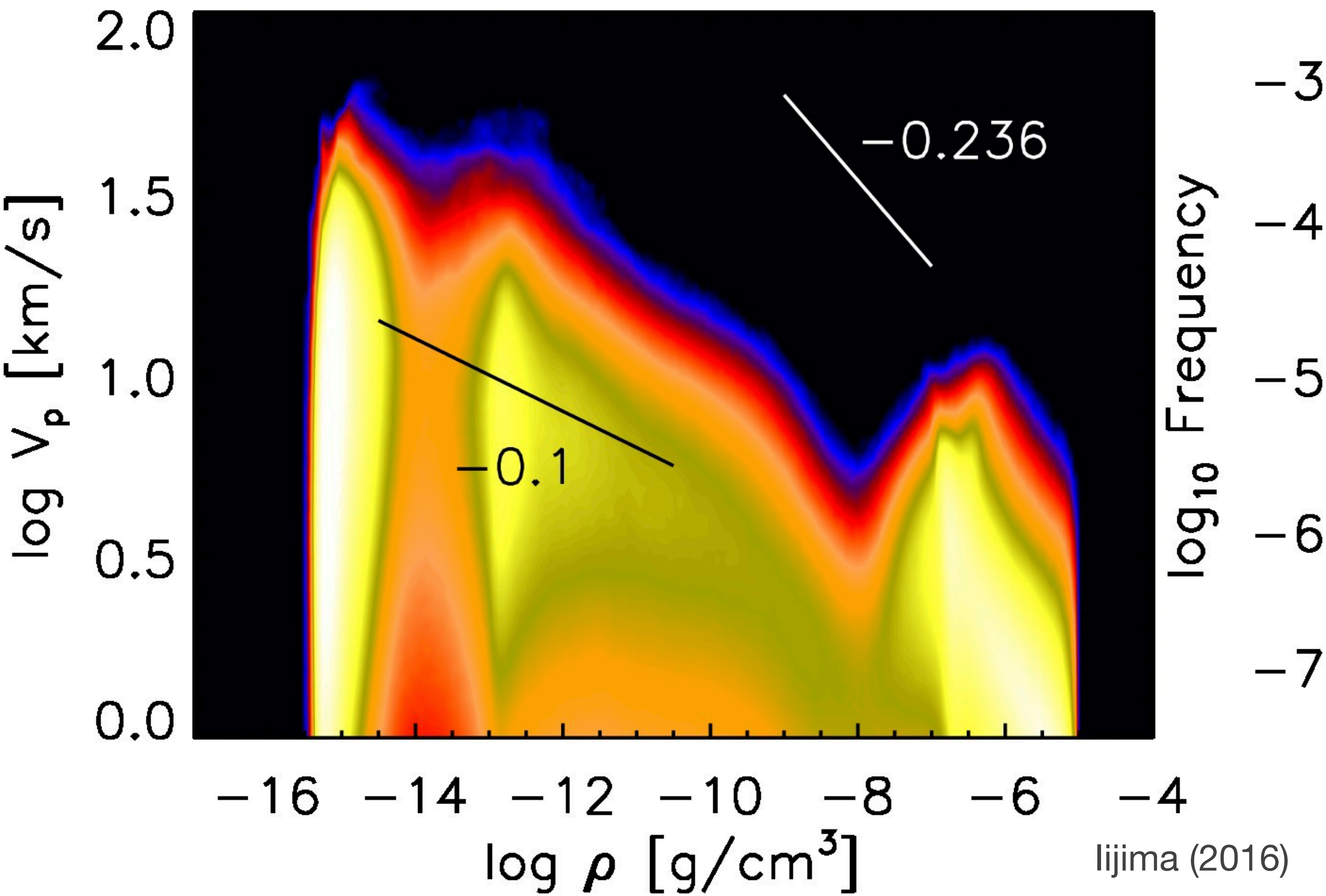
Joule heating

Martinez-Sykora et al. (2017)

How can we distinguish formation mechanisms?

- Sound wave model (most difficult?, requires highly quantitative analysis)
  - **Continuous and quantitative tracking of sound wave** from the photosphere to the TR.
- Reconnection model
  - **Cancellation** and **transient brightening** in high-T lines
- Alfvén wave model
  - **Vortex** and **twist in the chromosphere**
- In general
  - **Density diagnostics** in photosphere, chromosphere, and TR is very important to quantify the “amplitude” of the jet velocity under the amplification.
  - **Regional dependence** is also helpful to distinguish the formation process.

Importance of the density diagnostics



Iijima (2016)

Possible formation models of spicule

Energy source (driver)

- P-mode oscillation
- Collapsing granule
- Flux tube pumping

- Kink wave
- Alfvén wave

- Reconnection out flow
- Heating by reconnection
- Micro-filament eruption

Acoustic perturbation

Amplification by stratification

Shock wave

Shock-TR interaction

Jet formation

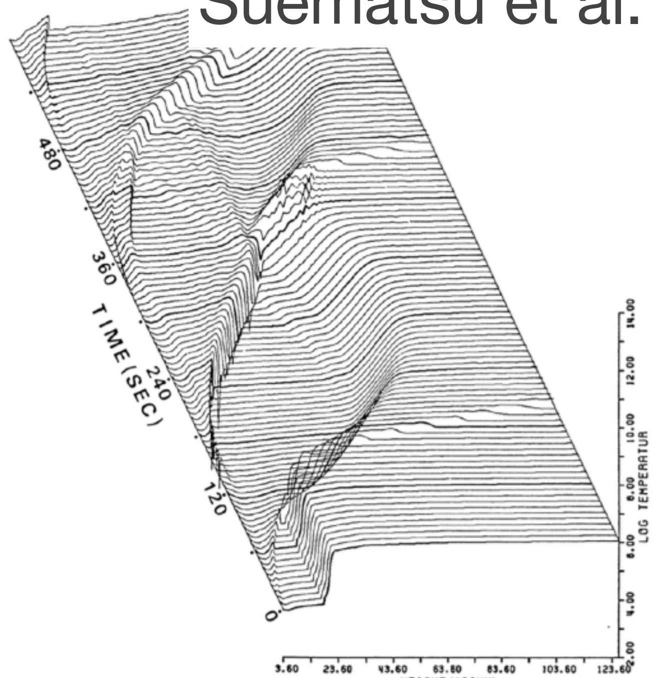
How we can distinguish formation mechanisms?

Flow chart

Possible drivers of spicules

Acoustic wave

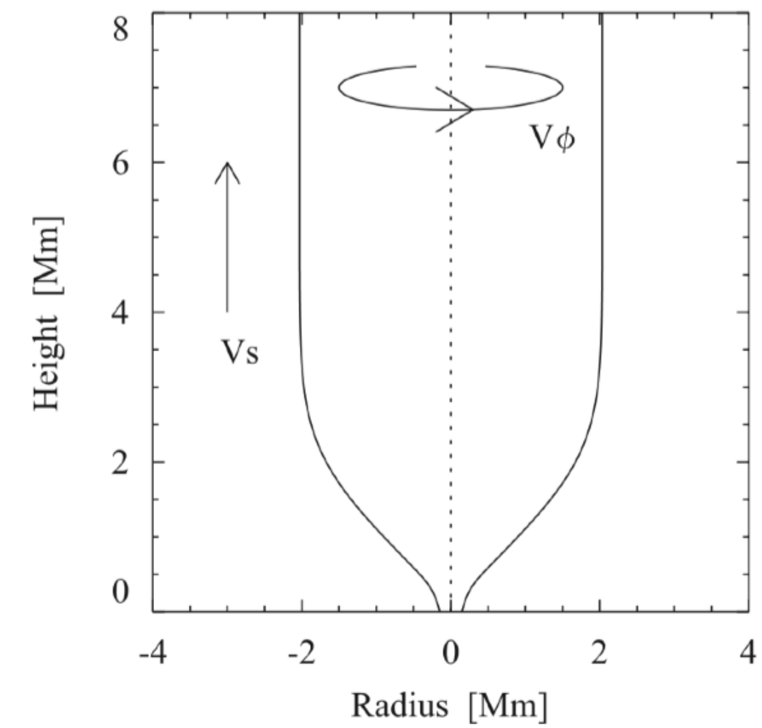
Suematsu et al. (1982)



Alfvén wave

Alfvén wave

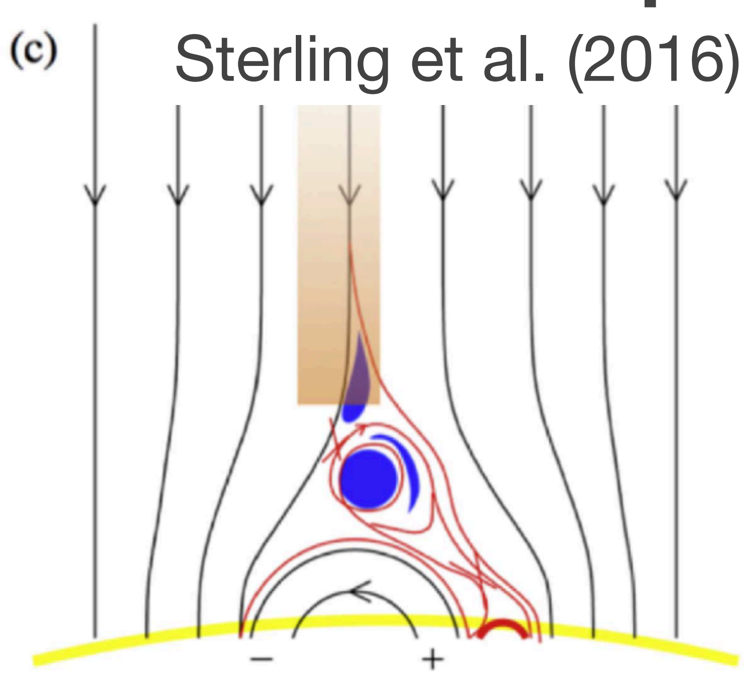
-> Sound wave



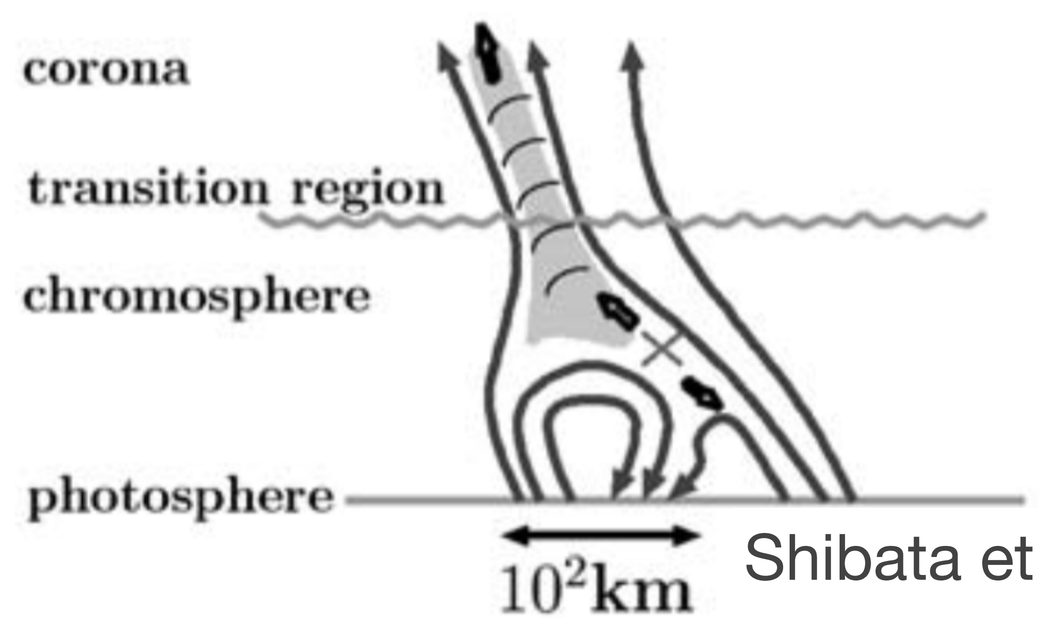
Matsumoto & Shibata (2010)

Micro-filament eruption

Sterling et al. (2016)



Guid-field reconnection

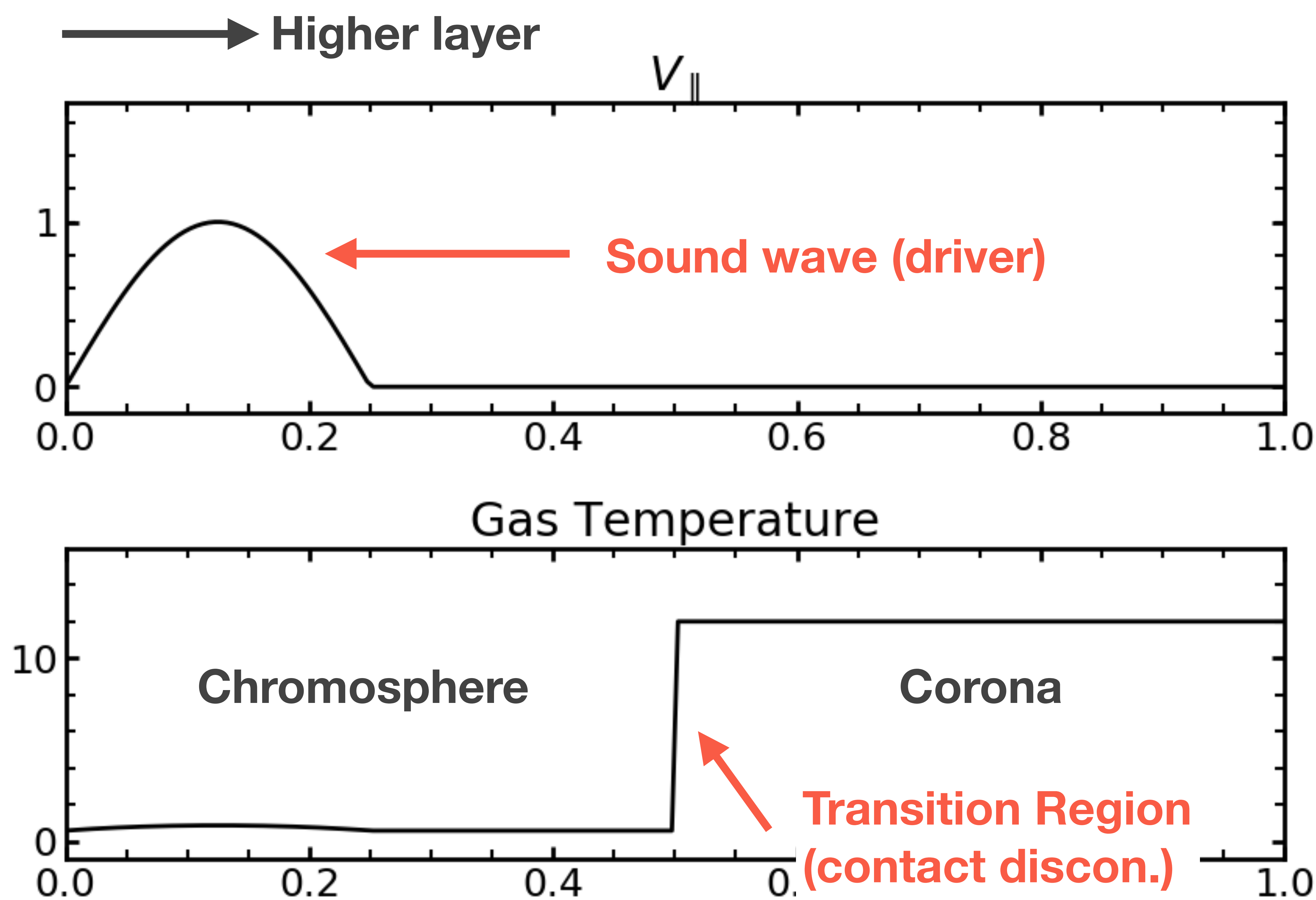


Shibata et al. (2007)

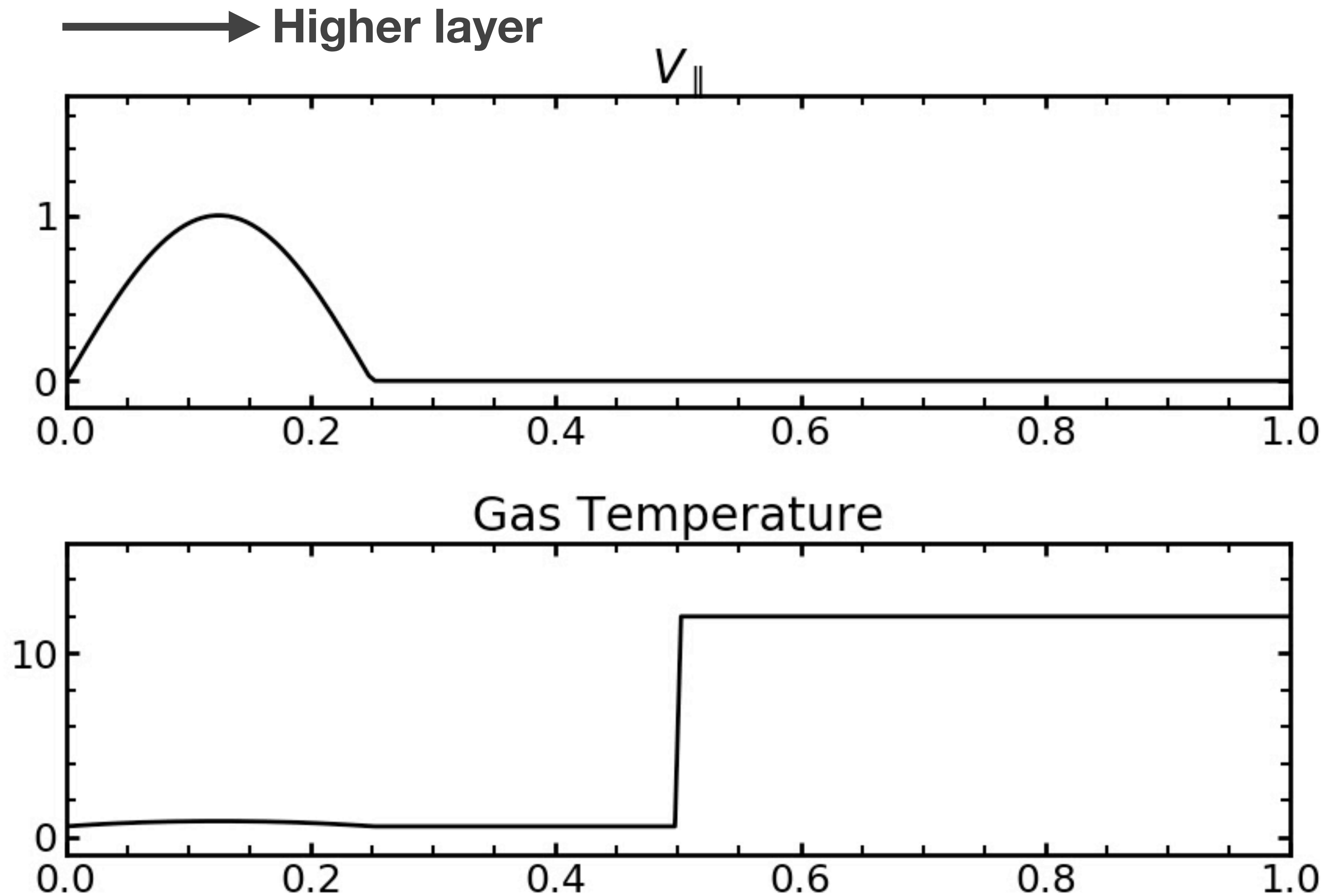
How we can distinguish formation mechanisms?

Regional dependence

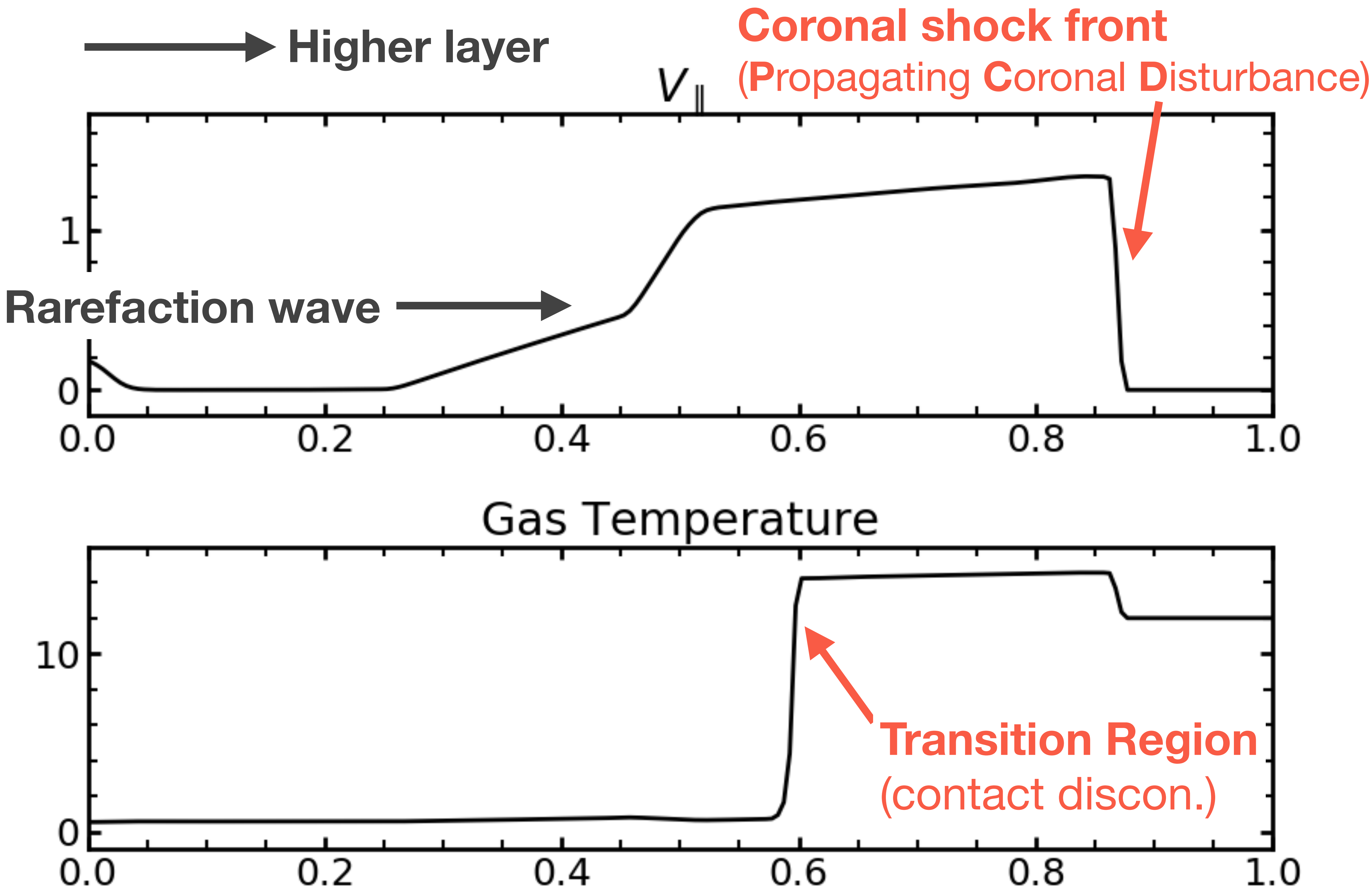
Shock-TR interaction (jet formation)



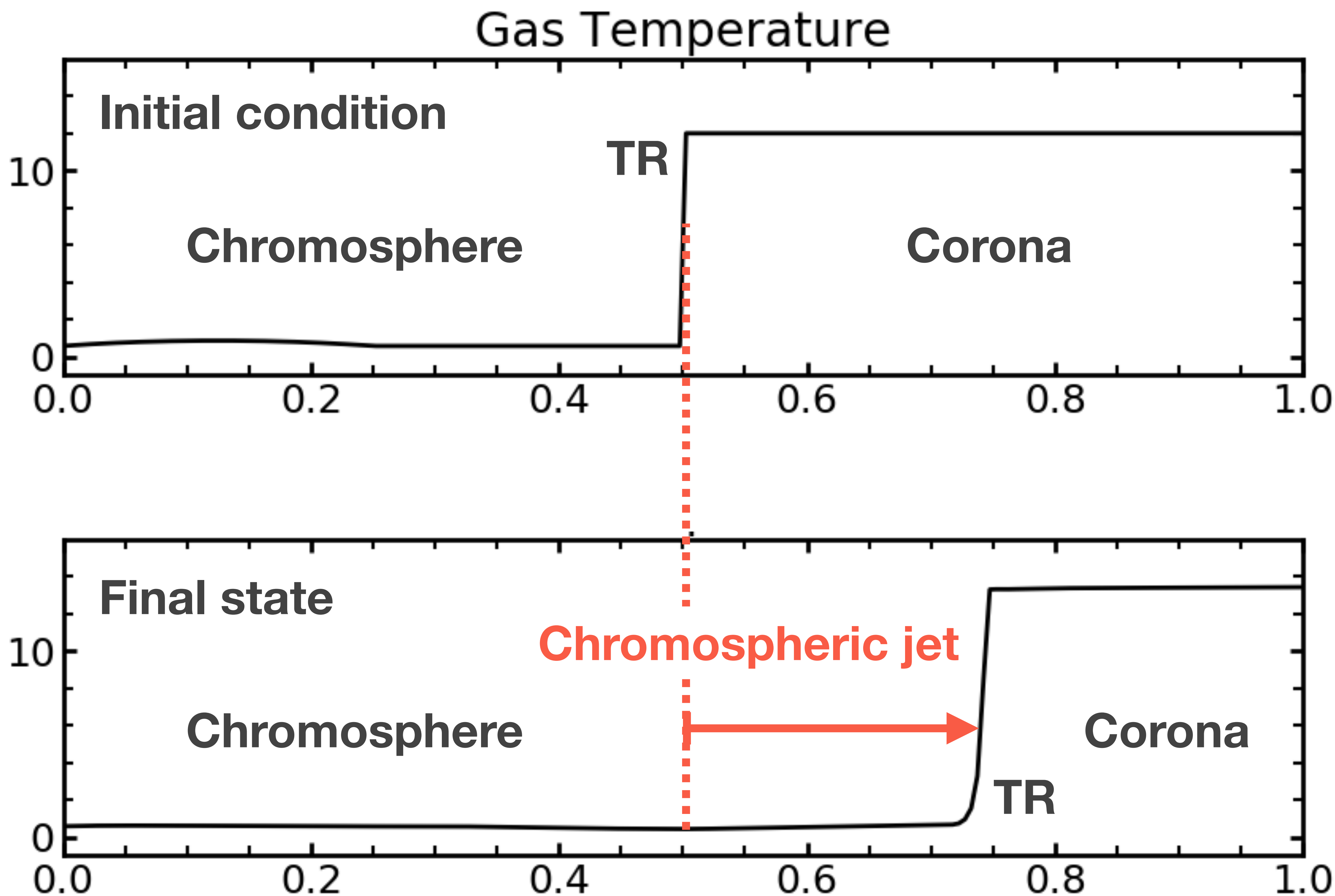
Shock-TR interaction (jet formation)



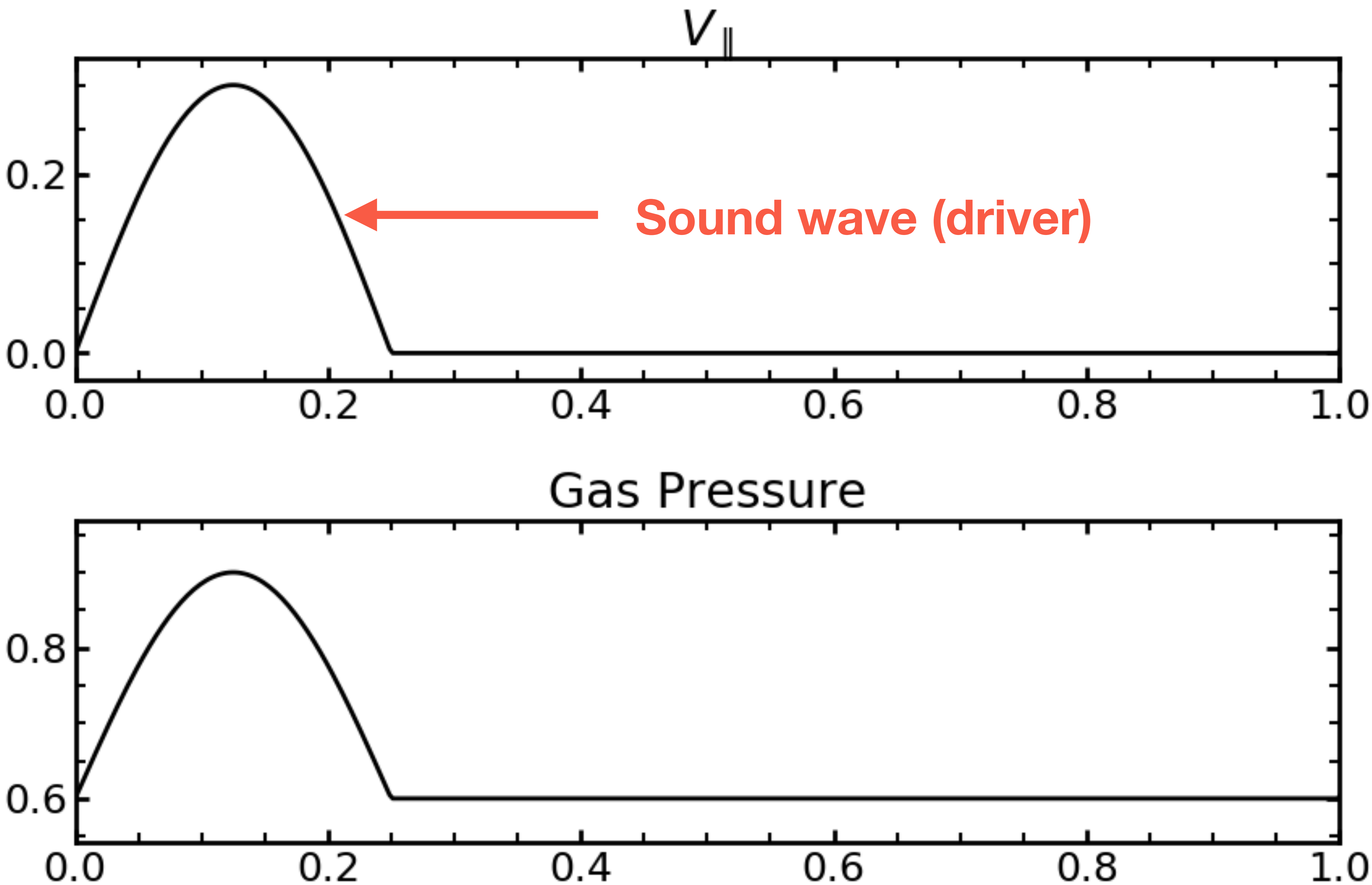
Shock-TR interaction (jet formation)



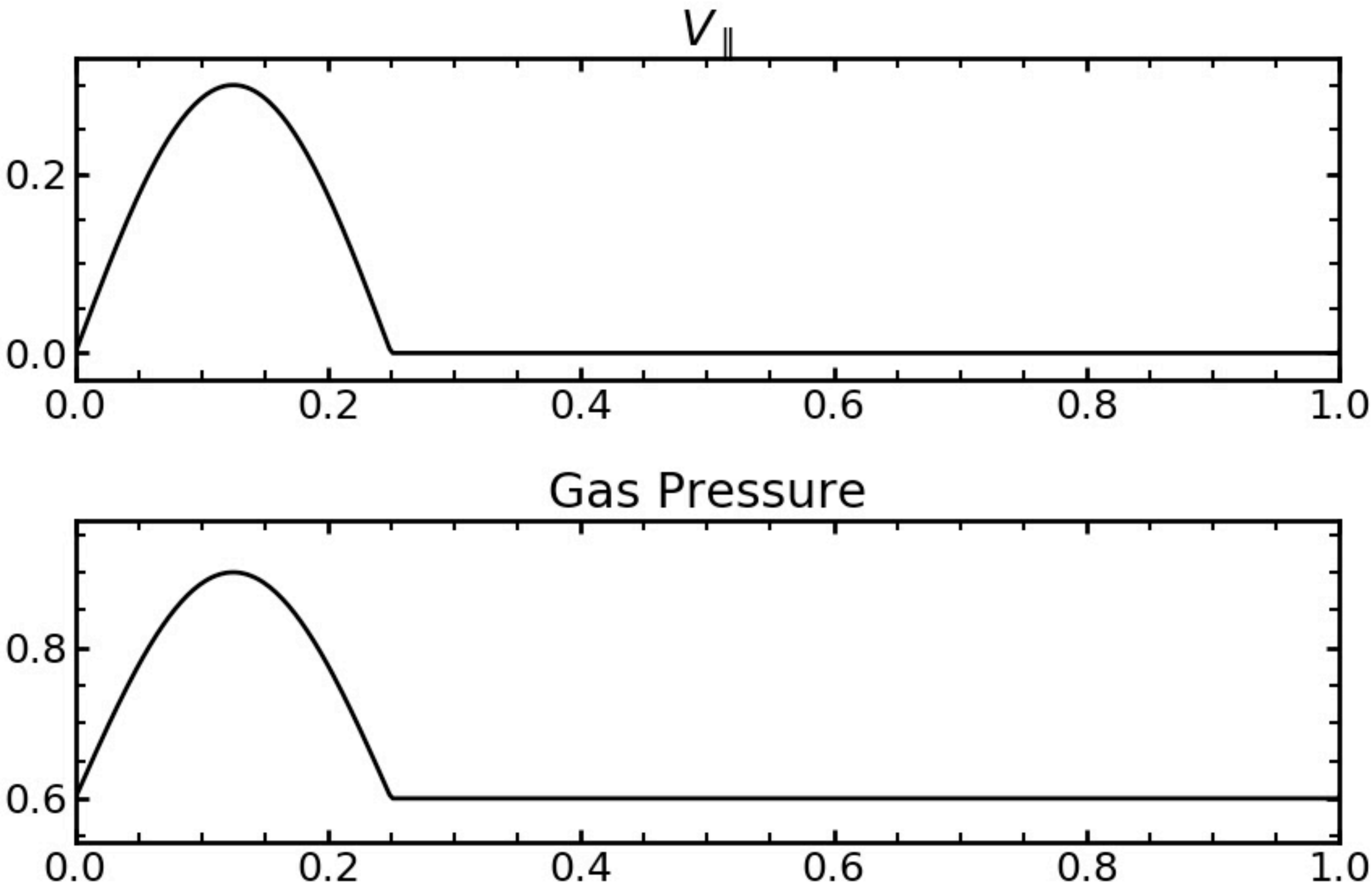
Shock-TR interaction (jet formation)



Formation of shock wave



Formation of shock wave



Formation of shock wave