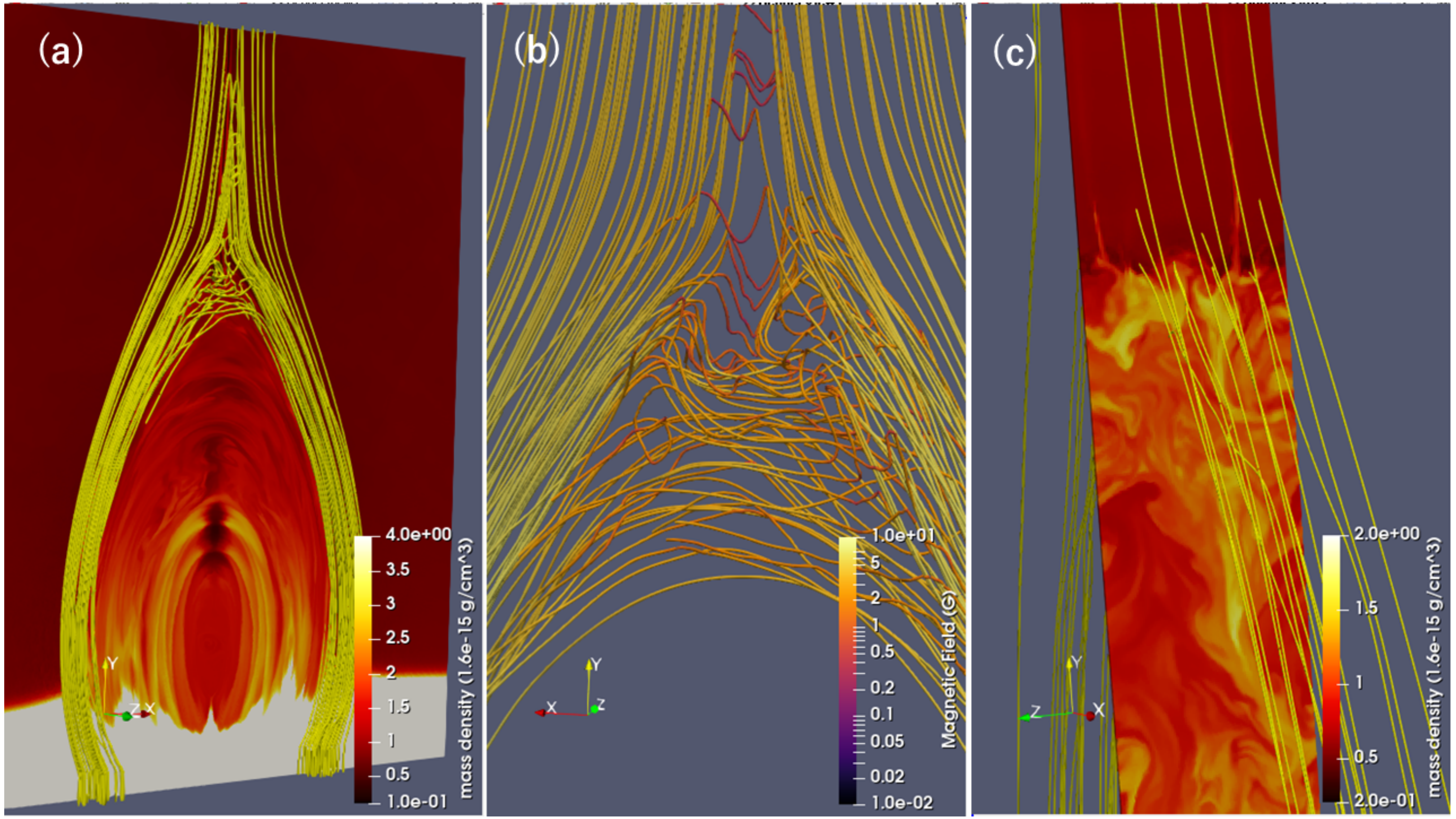
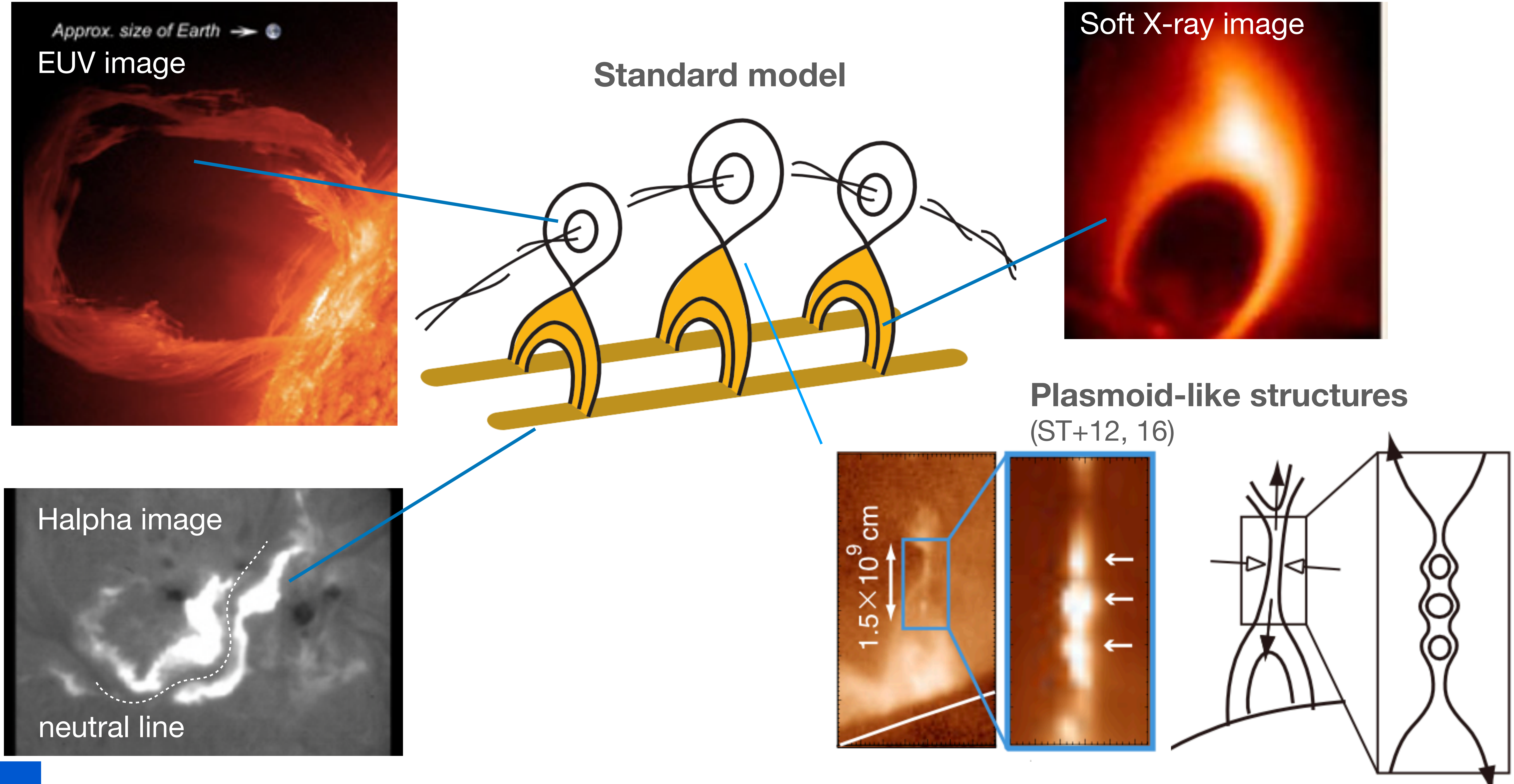
Numerical modeling of flare loop-top regions

Shinsuke Takasao (Osaka Univ.)

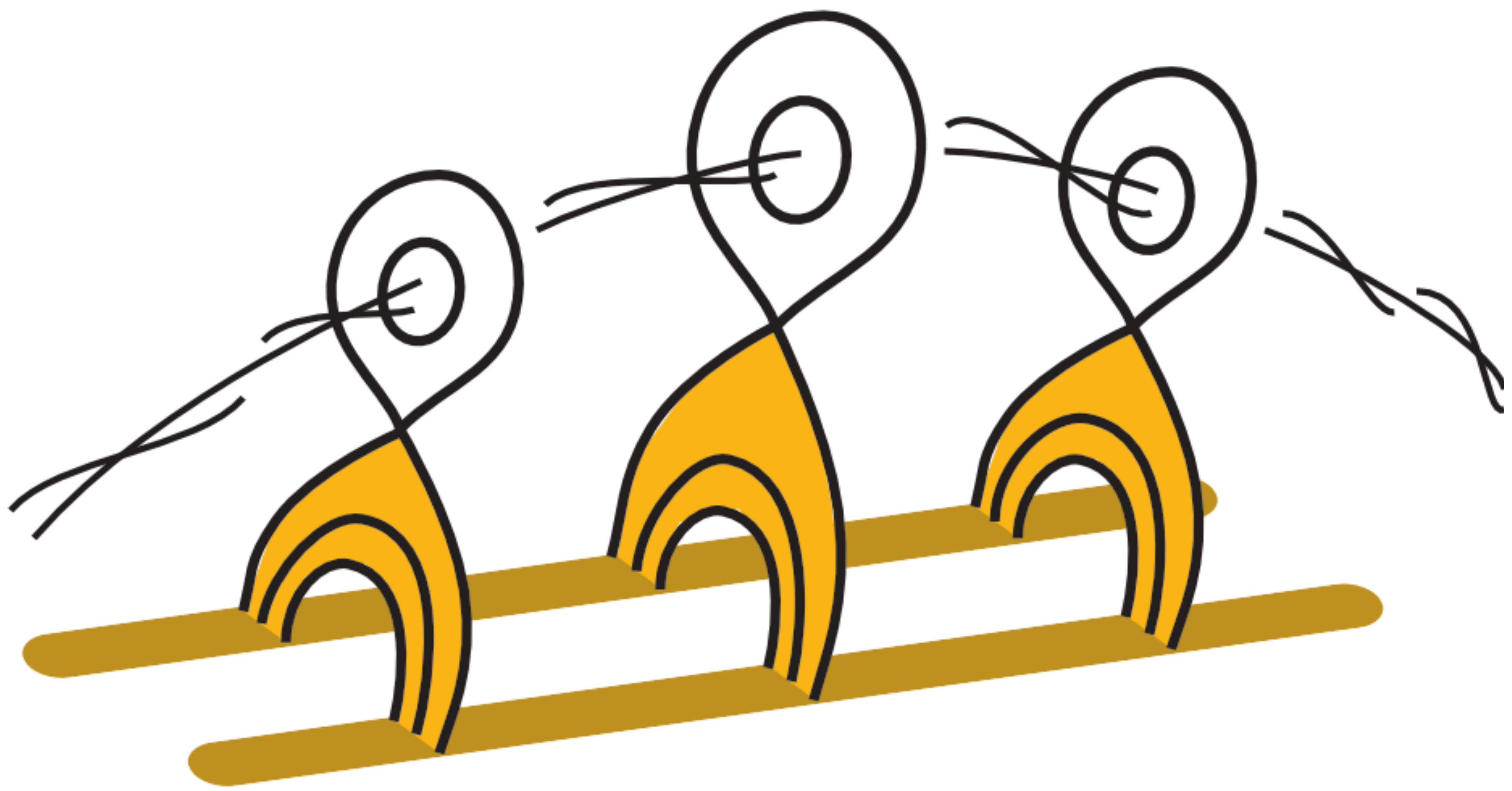
With thanks to
Kengo Shibata (Osaka Univ.)



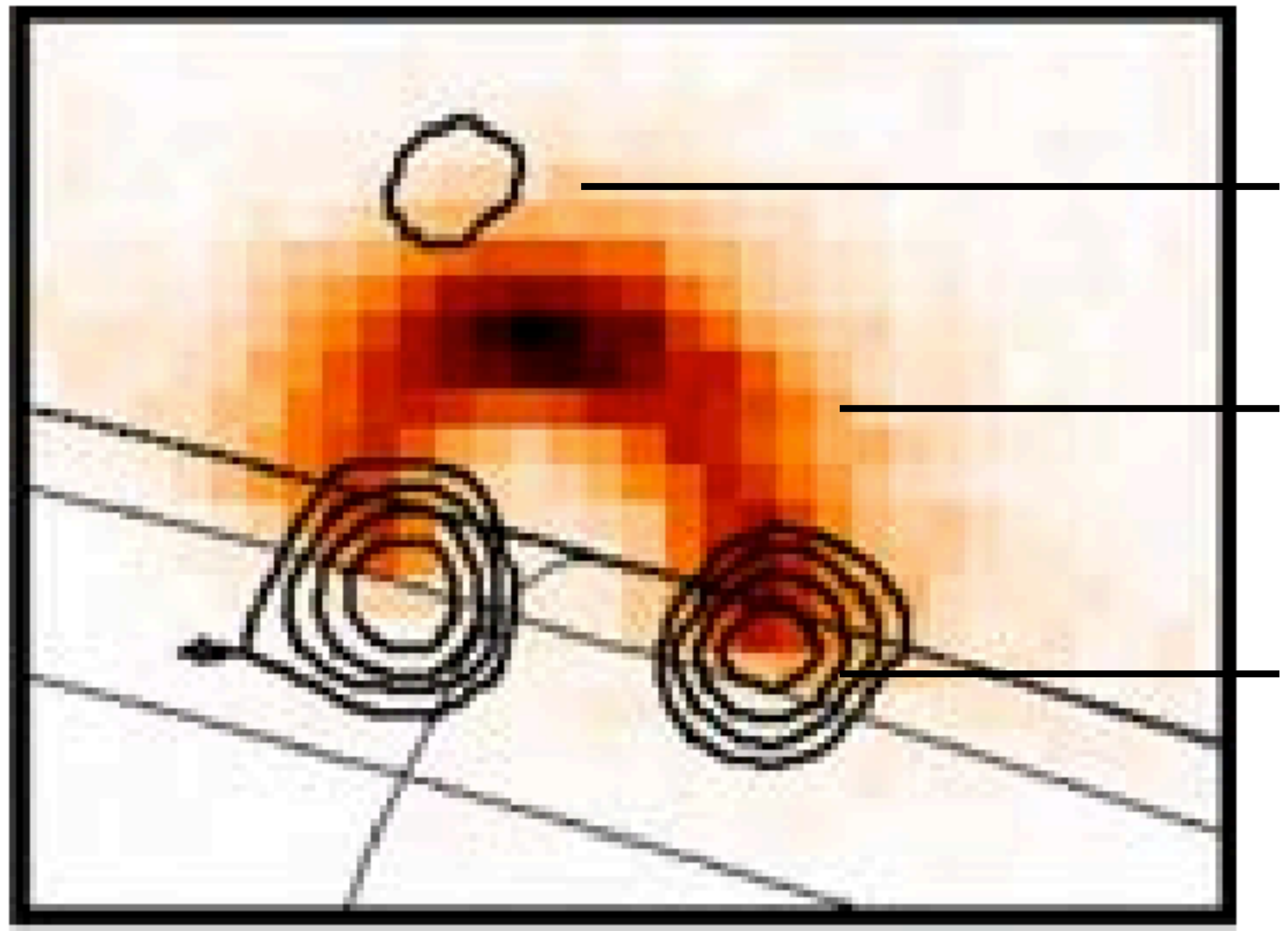
Solar flares



Solar flares: thermal and nonthermal emissions in X-rays



Contours: hard X-ray at 33-53 keV



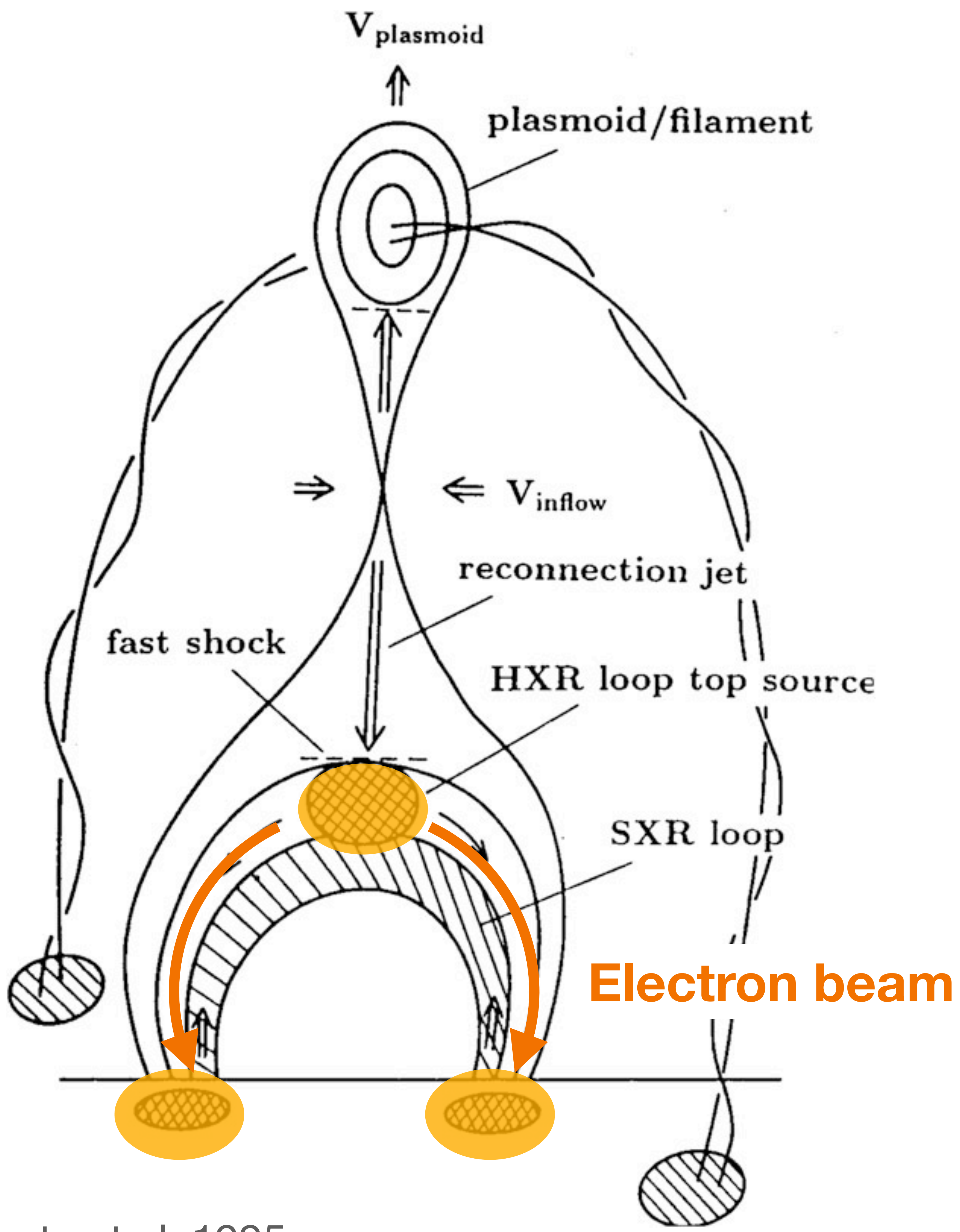
Nonthermal (or superhot)
Above-the-loop-top source
(very faint)

Thermal soft X-ray flare loop
(~10^7 K)

Nonthermal
Foot-point sources

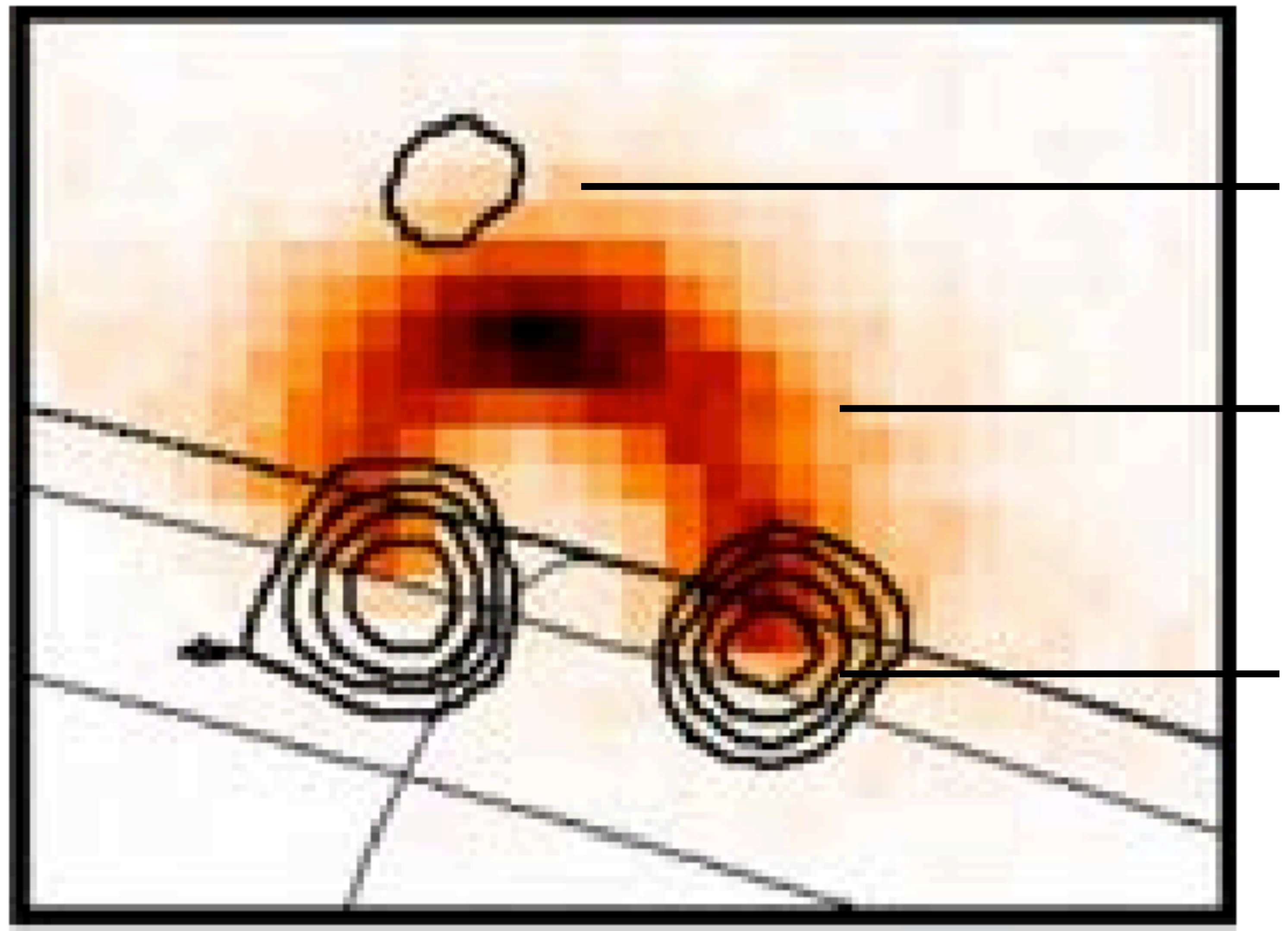
Masuda et al. 1994
(figure from Krucker et al. 2006)

Solar flares: thermal and nonthermal emissions in X-rays



Shibata et al. 1995

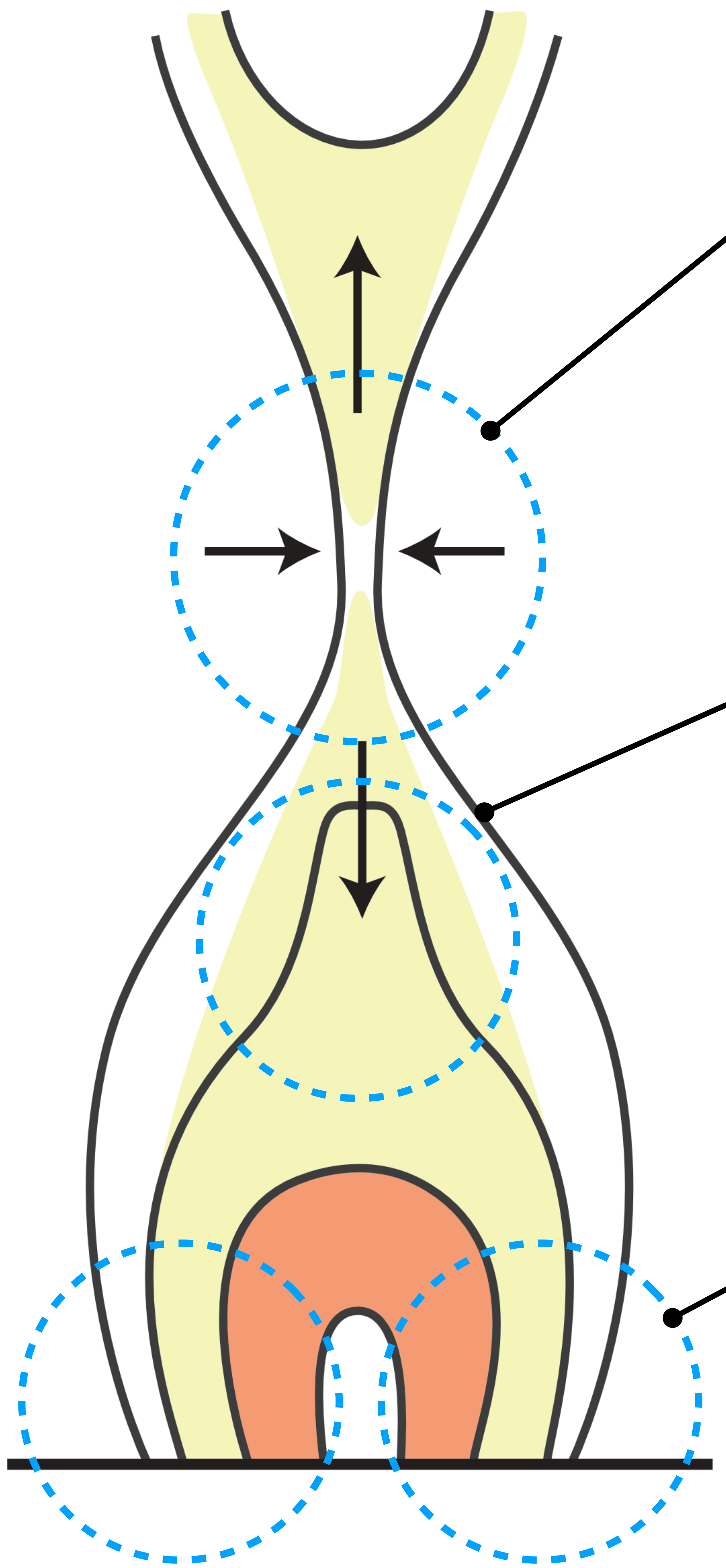
Contours: hard X-ray at 33-53 keV



Masuda et al. 1994
(figure from Krucker et al. 2006)

Coronal nonthermal X-ray sources are much fainter
than thermal loops and foot-point sources,
which makes observational studies of coronal sources difficult.

Acceleration regions



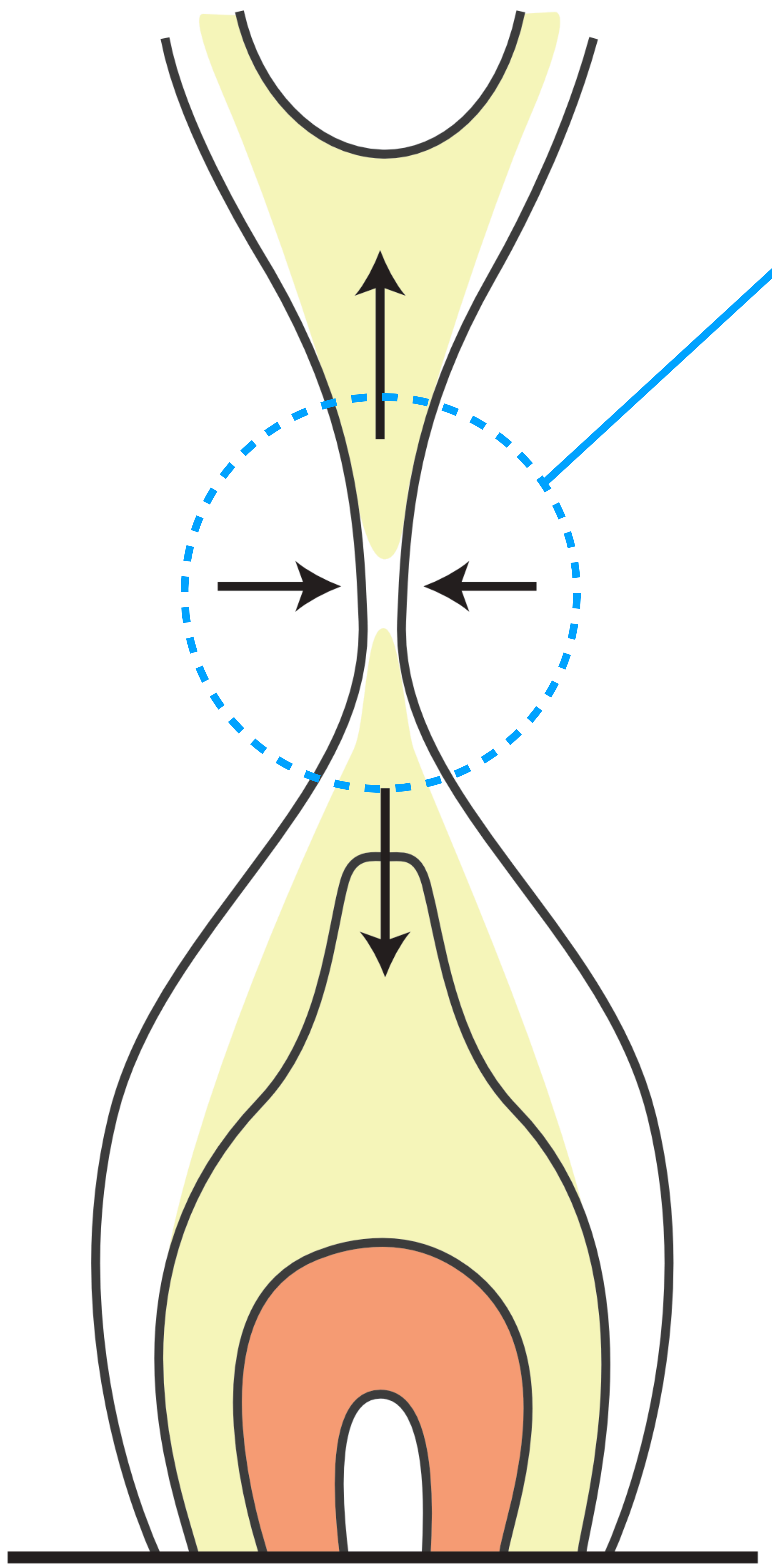
1. Reconnection region

2. (Above-the) loop-top region, ALT region

Main topic of this talk:
MHD scale structure of the ALT region.
This talk does not cover details of kinetic scale processes.

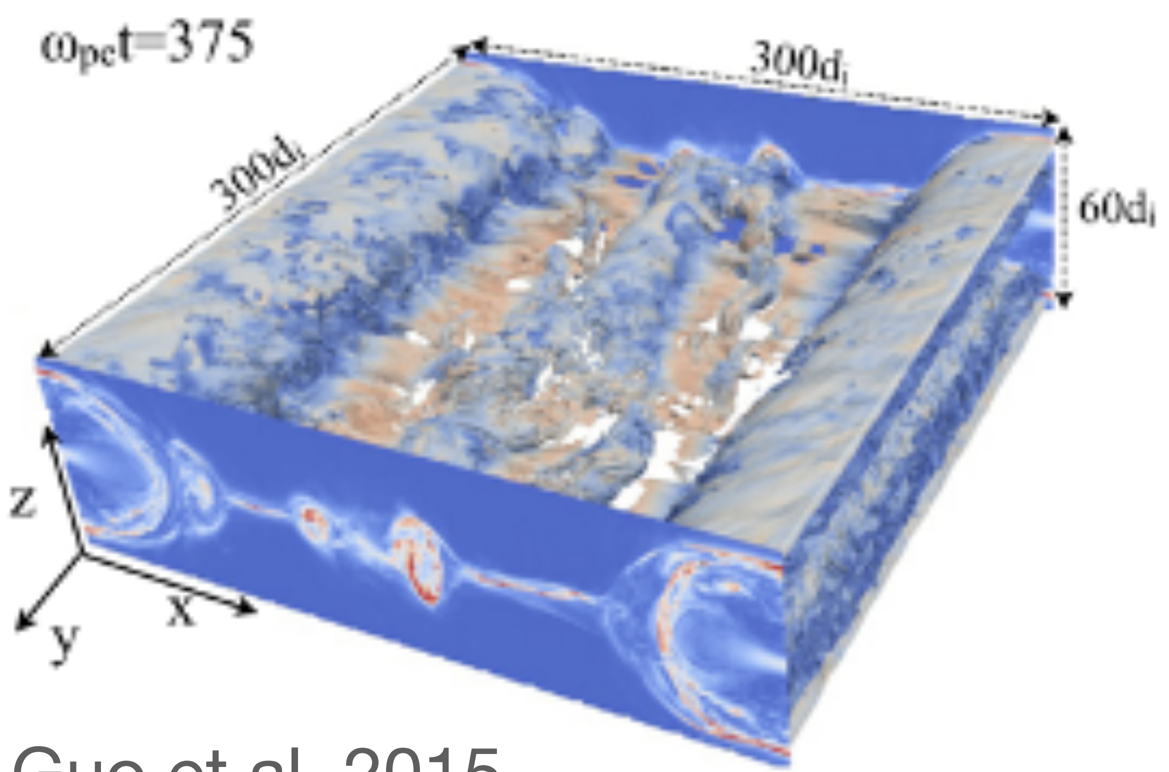
3. Foot-point regions

Acceleration regions

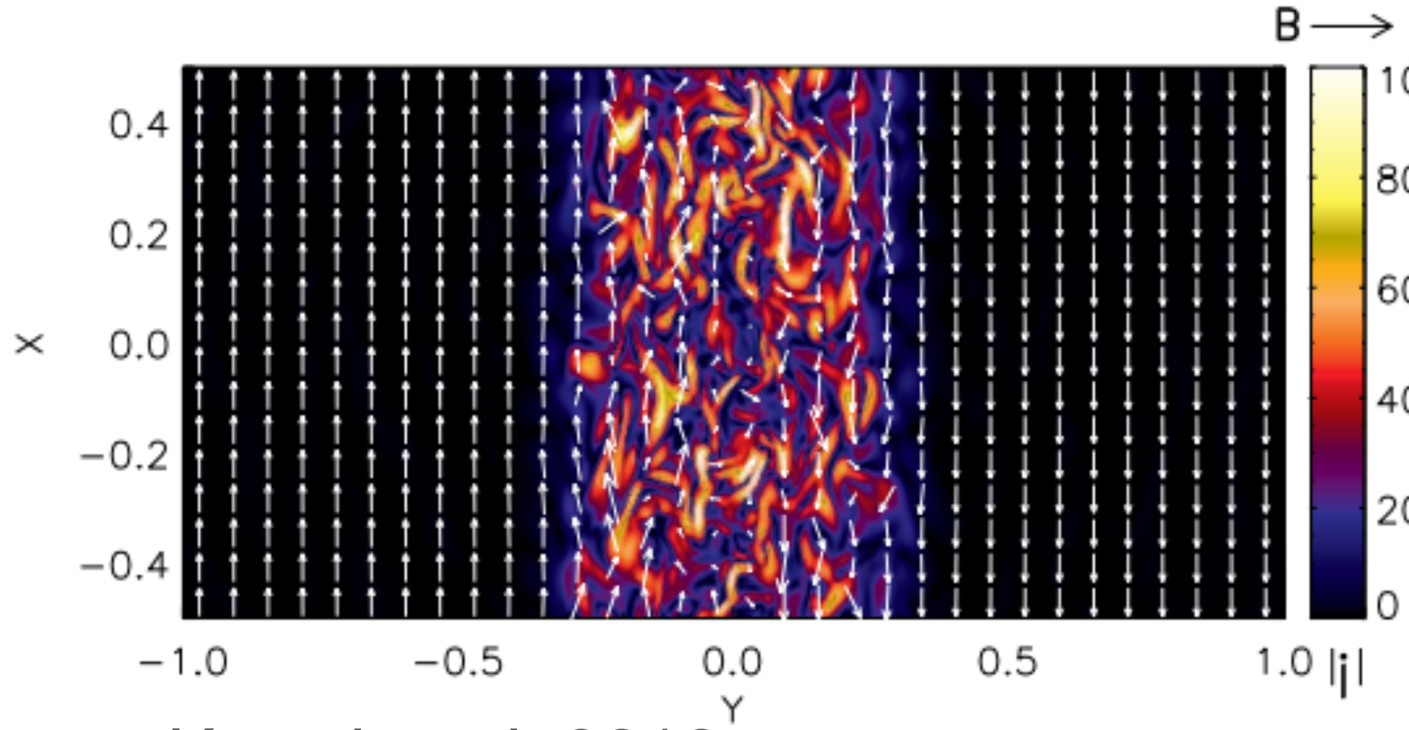


1. Reconnection region

Acceleration in turbulent reconnection regions

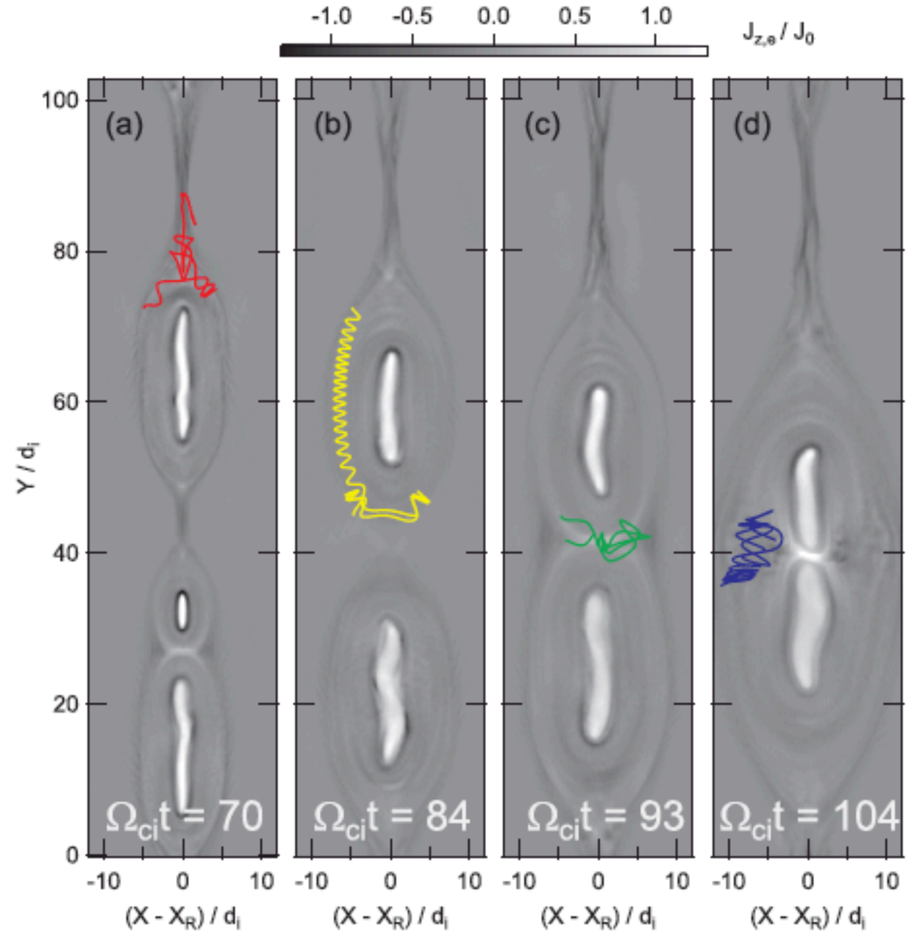


Guo et al. 2015

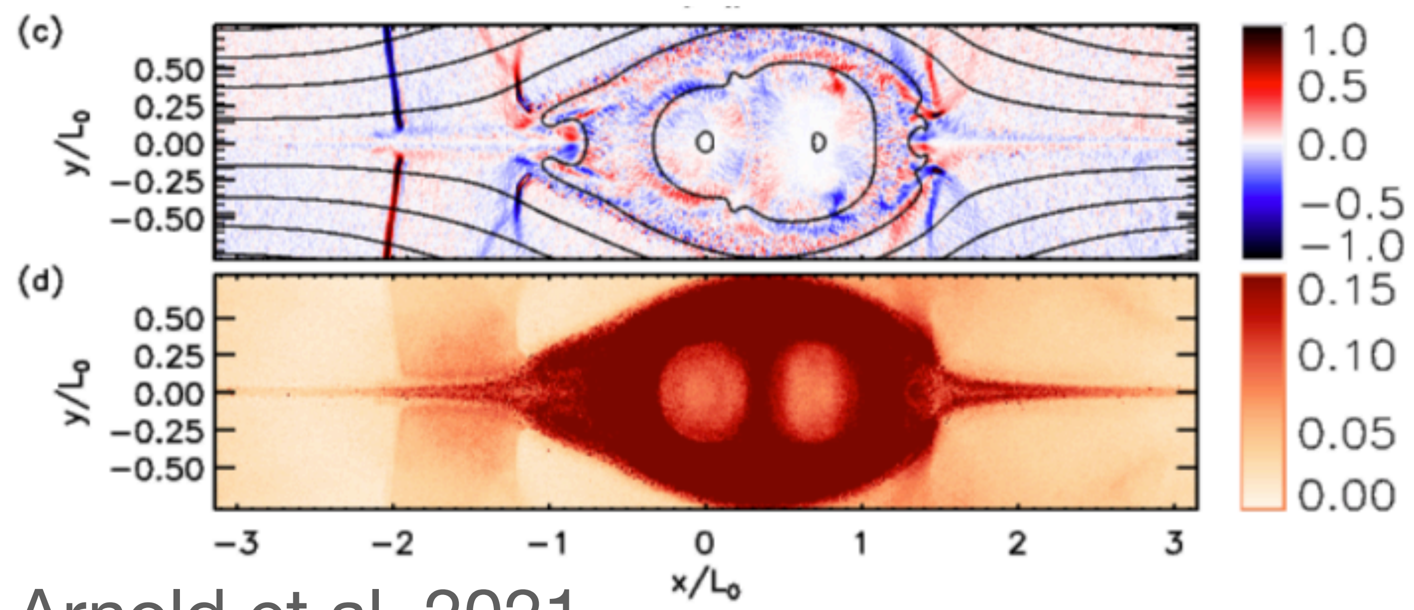


Kowal et al. 2012

Acceleration in/around plasmoids



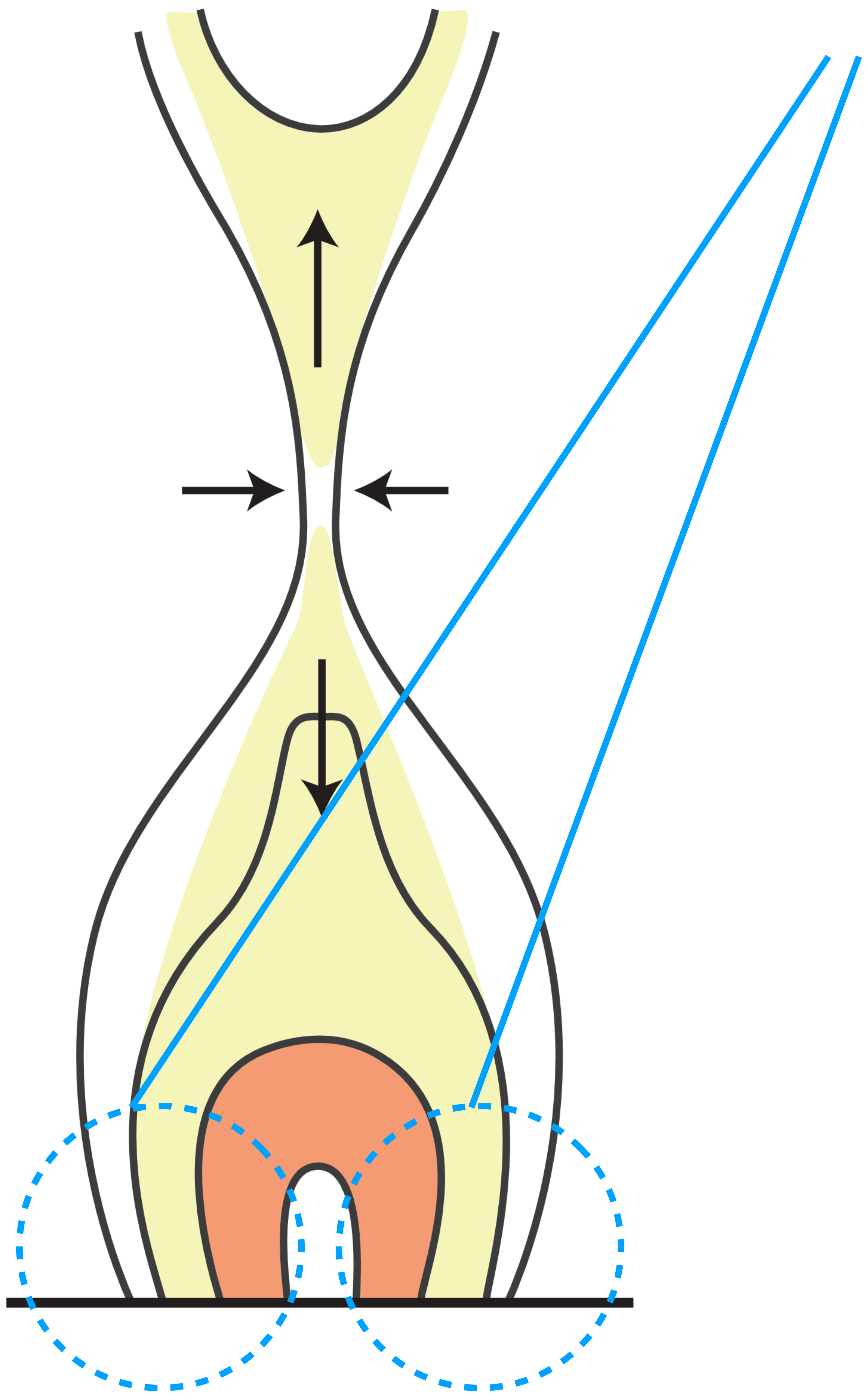
Oka et al. 2010



Arnold et al. 2021

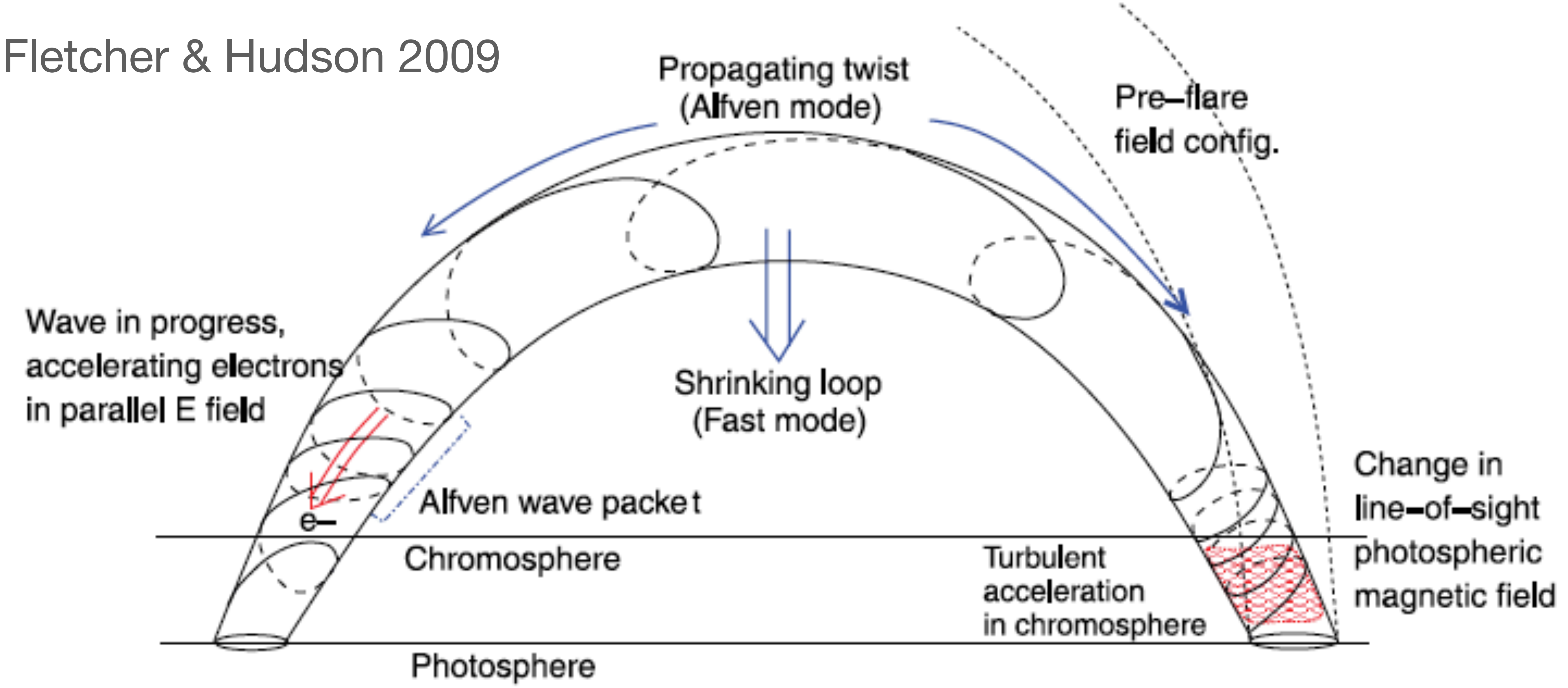
and many other studies. See also
Lazarian & Vishniac 1999, Shibata & Tanuma 2001,
Drake et al. 2006, Shibayama et al. 2015,
S. Wang, Yokoyama, Isobe 2015,
Kowal et al. 2017, Hoshino 2017

Acceleration regions



3. Foot-point regions

Fletcher & Hudson 2009



See also Fletcher & Hudson 2007, Reep et al. 2018

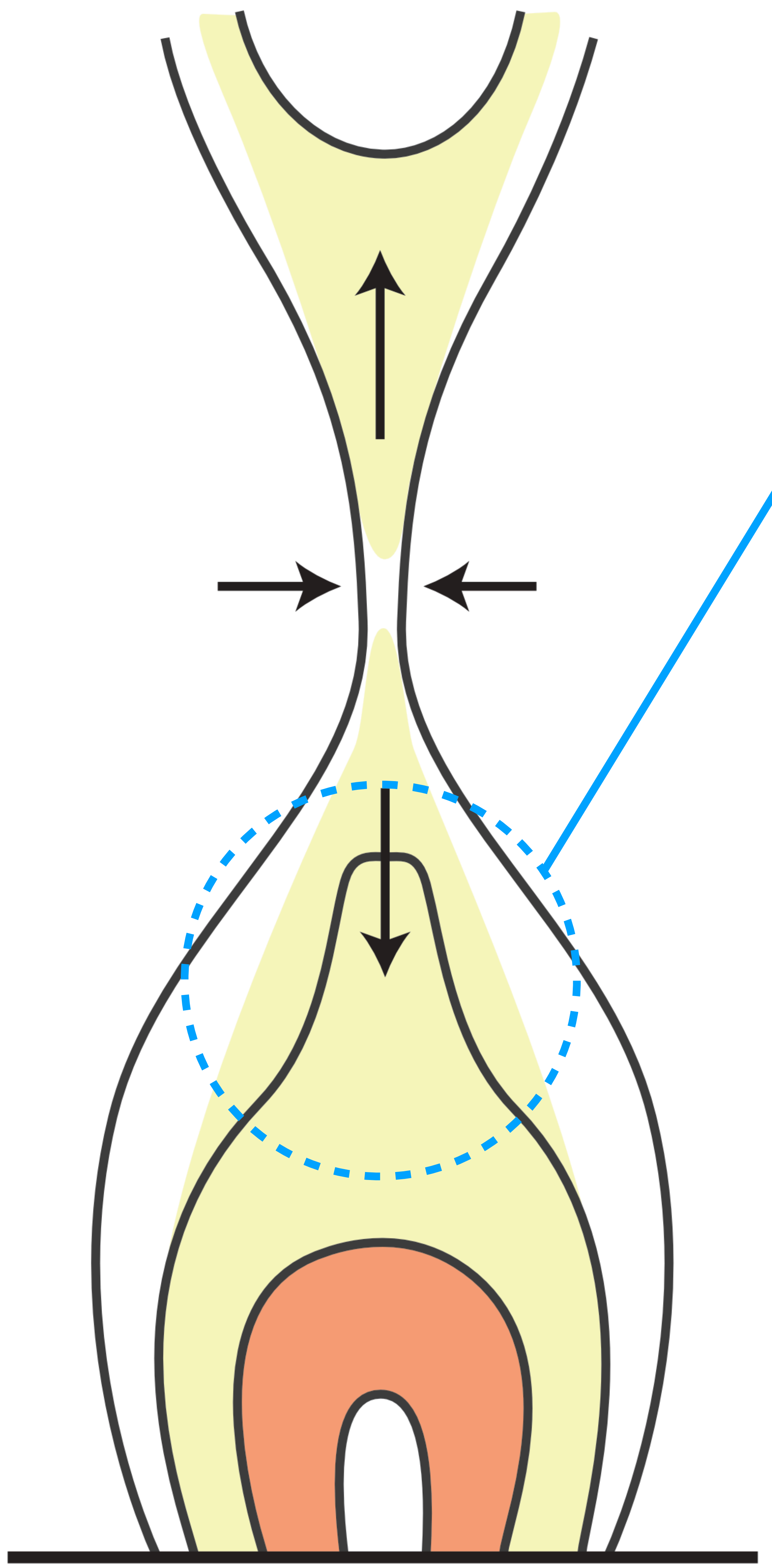
Reconnection

—> release of twist/shear in magnetic fields

—> Large amplitude Alfvén waves

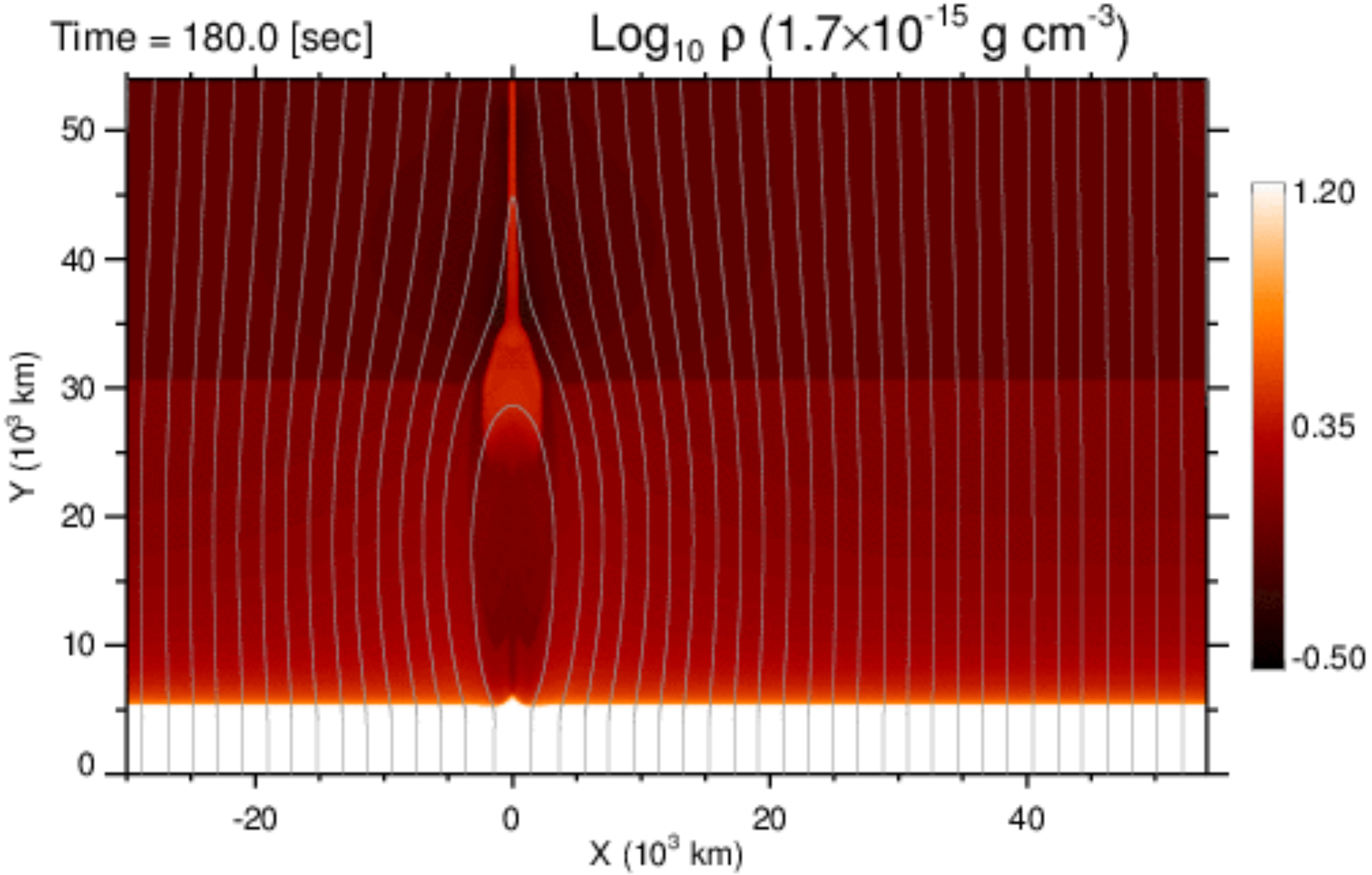
—> Electron acceleration at foot-points

Acceleration regions



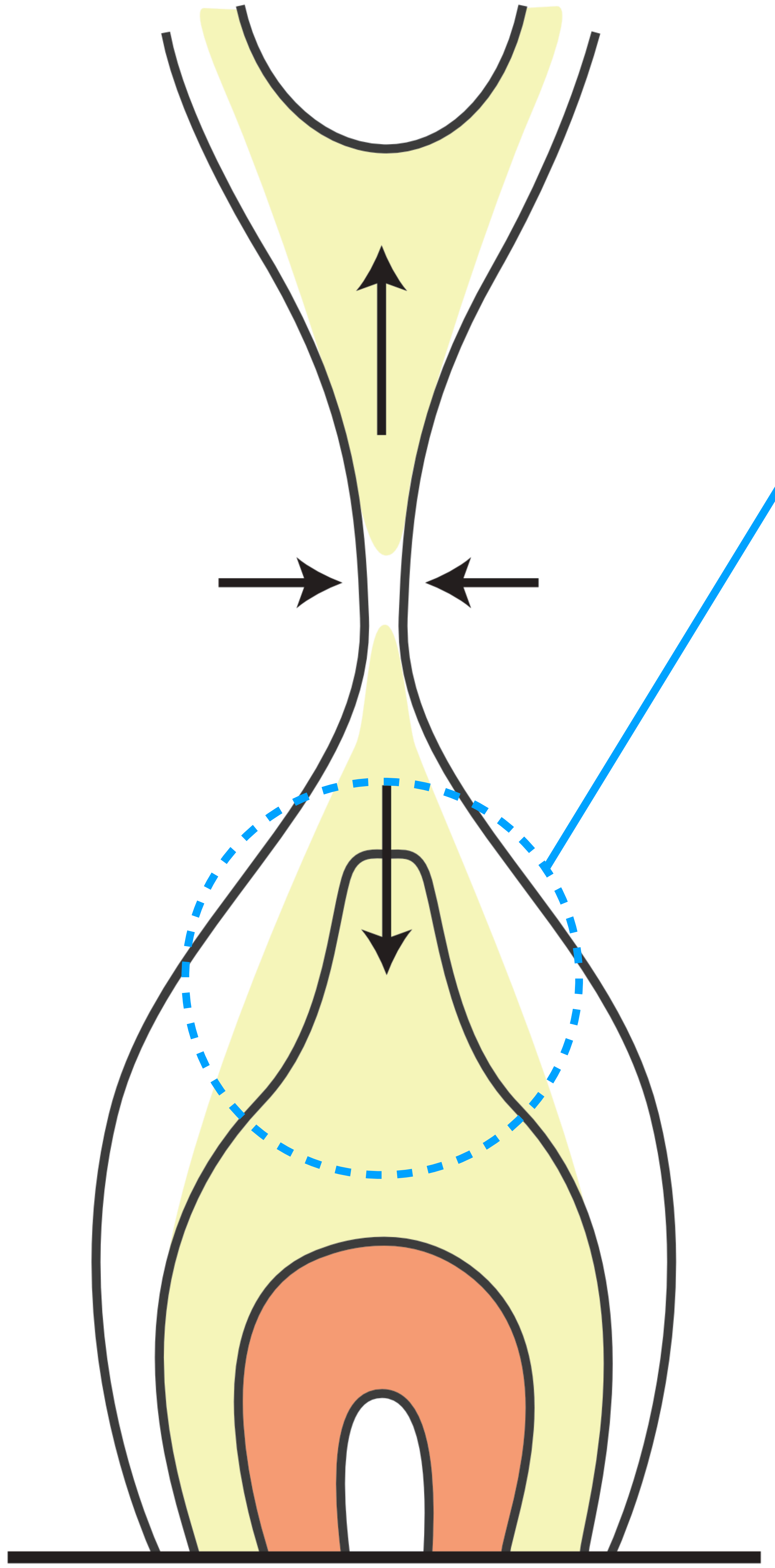
2. (Above-the) loop-top region, ALT region

ST & Shibata 16



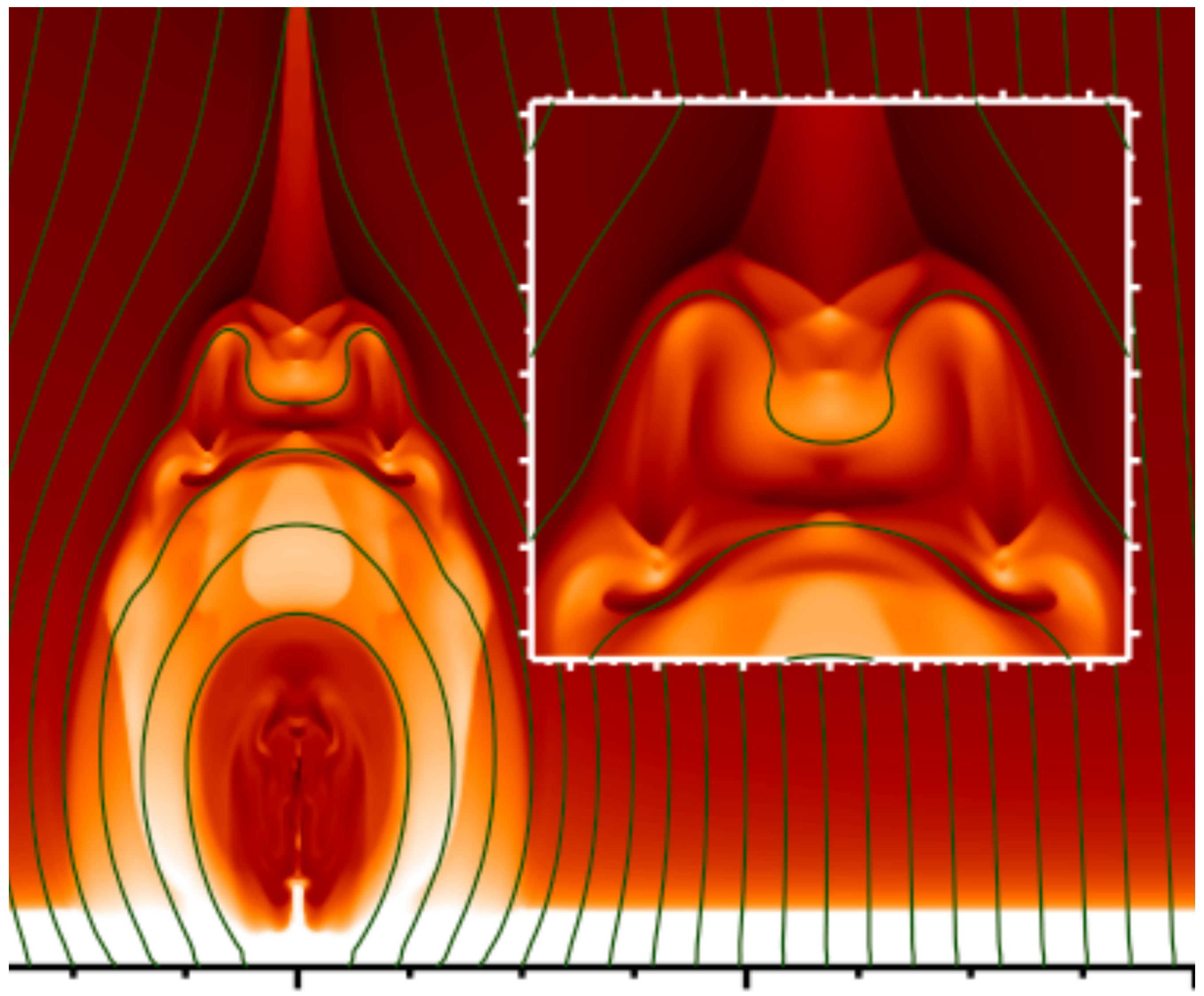
ALT region: where reconnection jet stops.
Important site for energy conversion in solar flares

Acceleration regions



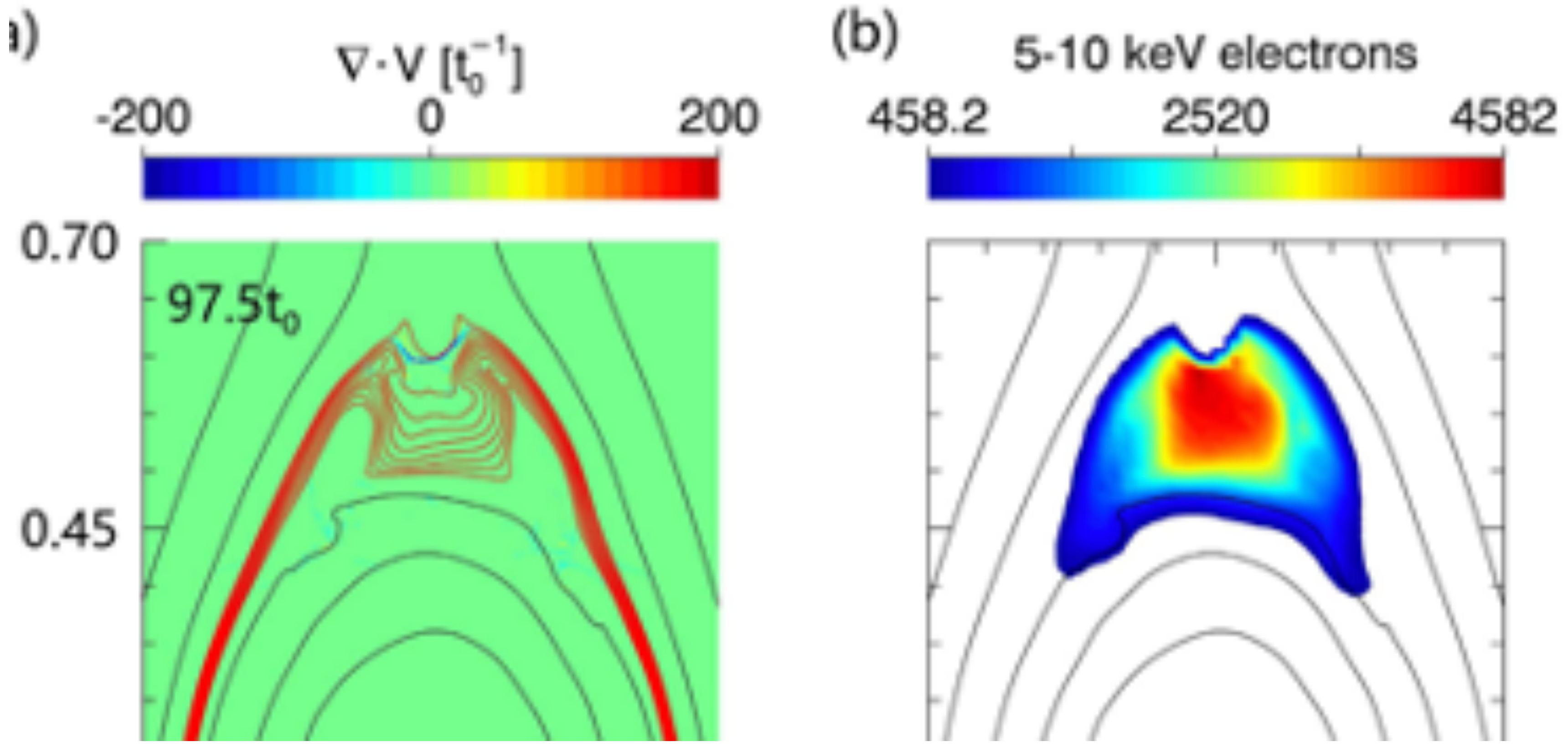
2. (Above-the) loop-top region, ALT region

Multiple termination shocks,
Complicated flow/field structures



ST+15, ST & Shibata 16

MHD + kinetic modeling (Kong et al. 2019)

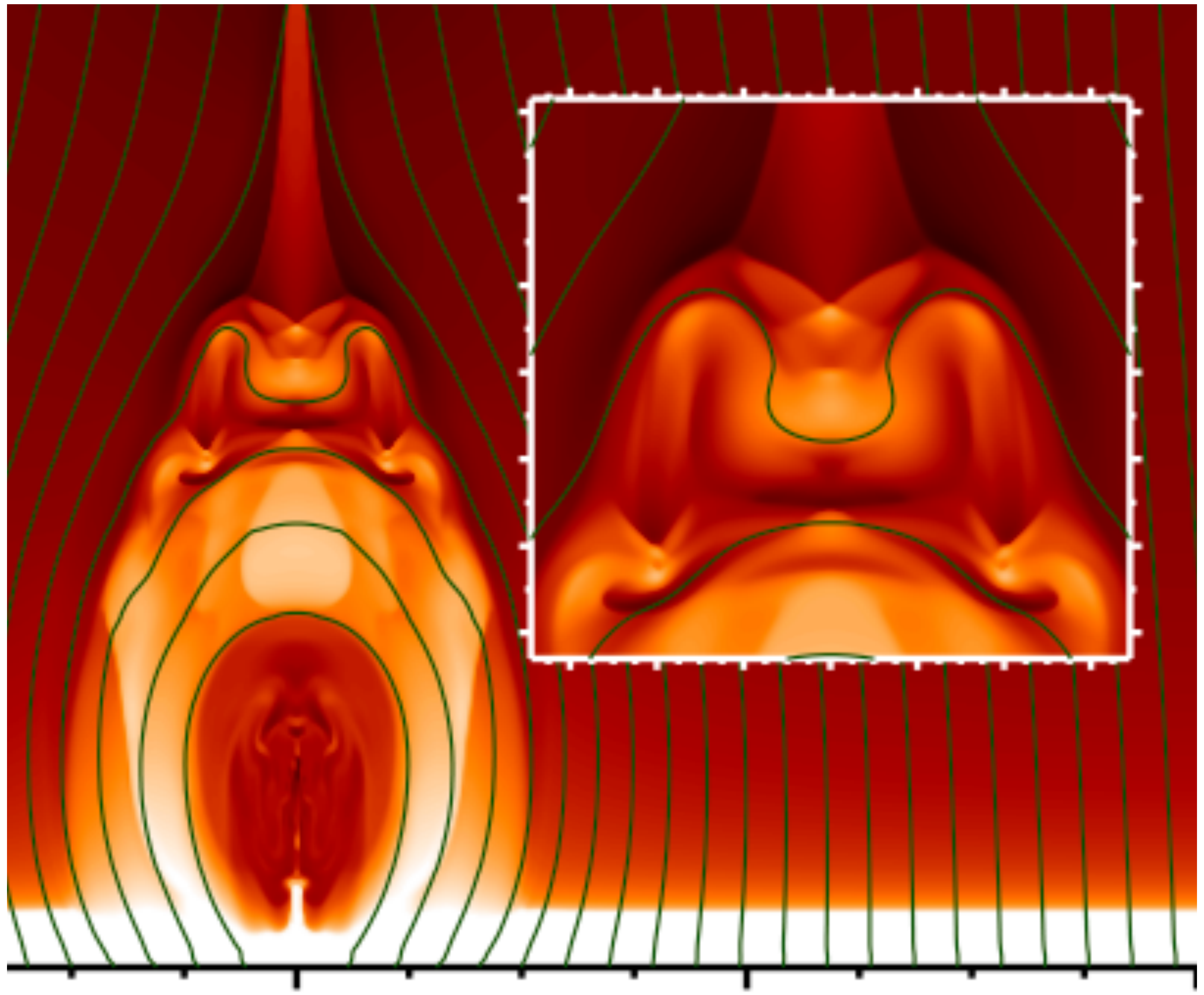


Termination shock
+ strong **turbulent diffusion for electrons**
=> Diffusive Shock Acceleration **(DSA)**

(See also Tsuneta & Naito 1998)

Above-the-loop-top region

The ALT region plays essential roles in energy partitioning and electron acceleration.



ST+15, ST & Shibata 16

But the ALT region would be very small and observationally difficult to find its location and resolve the structure:

flare size L, current sheet width w

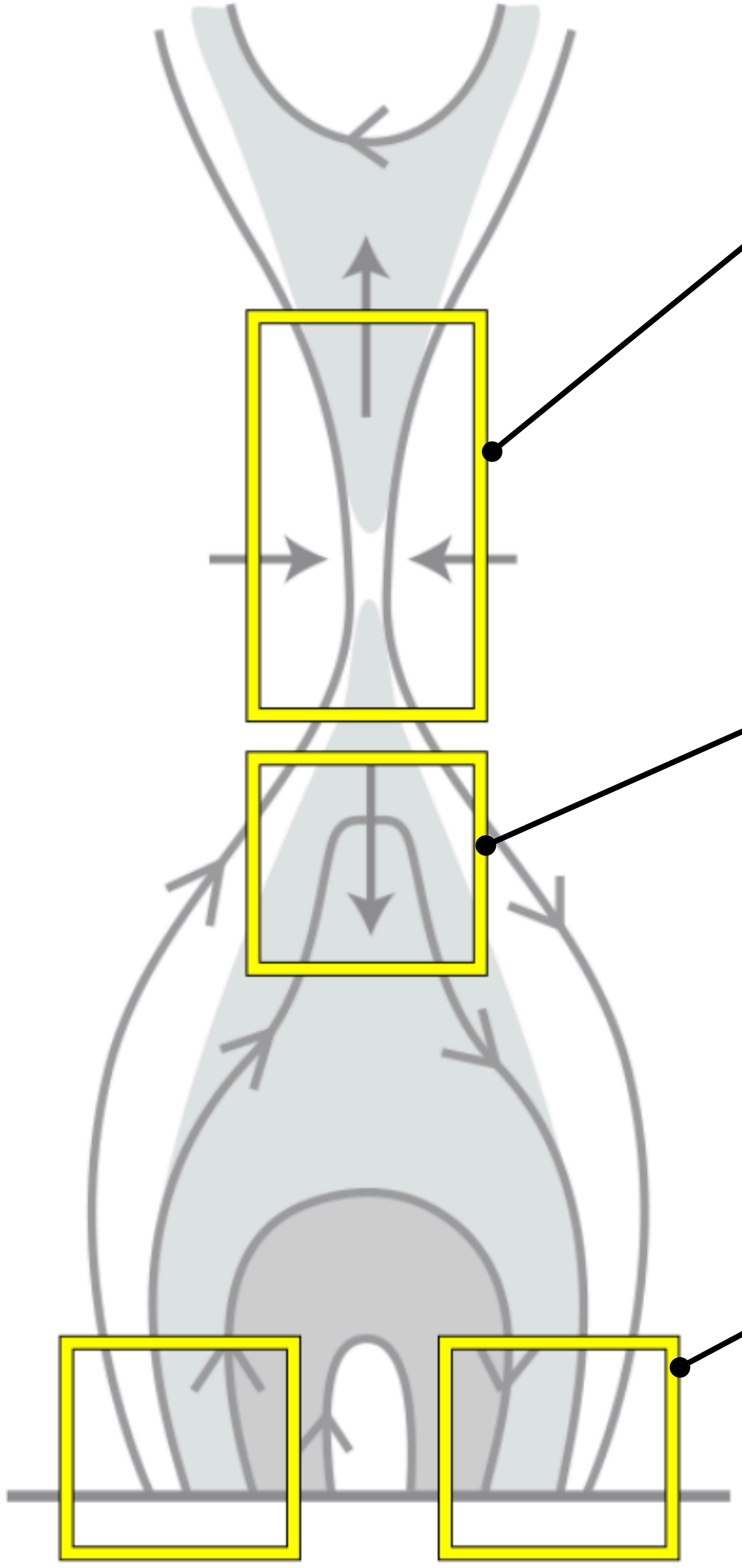
$$\longrightarrow \frac{w}{L} \sim \text{Normalized reconnection rate}$$

~ **0.01-0.1**

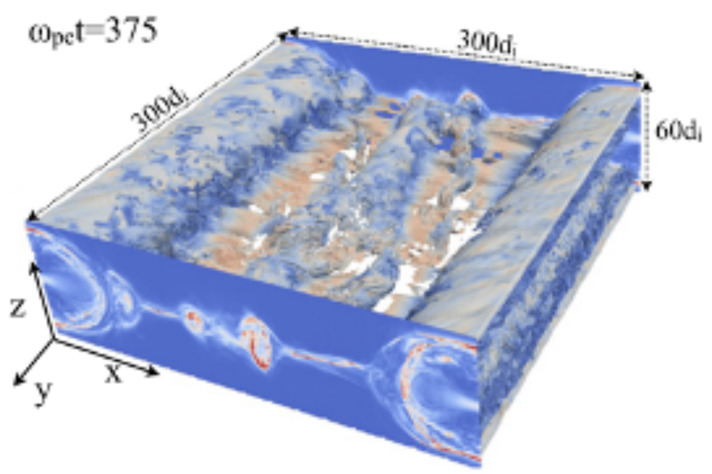
(e.g. observational estimates by Isobe et al. 2005, Narukage & Shibata 06)

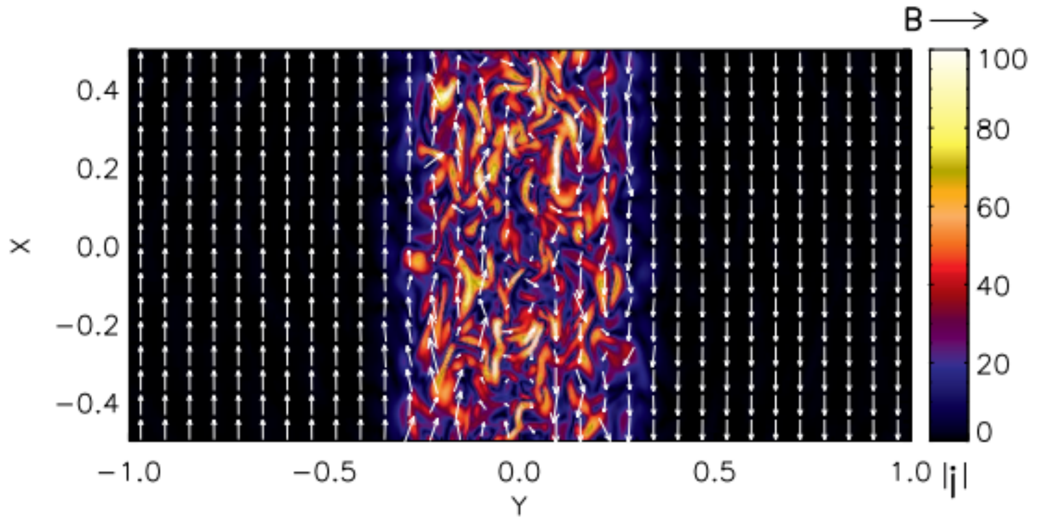
Flare structure is generally complicated.
How can we find the ALT region observationally?

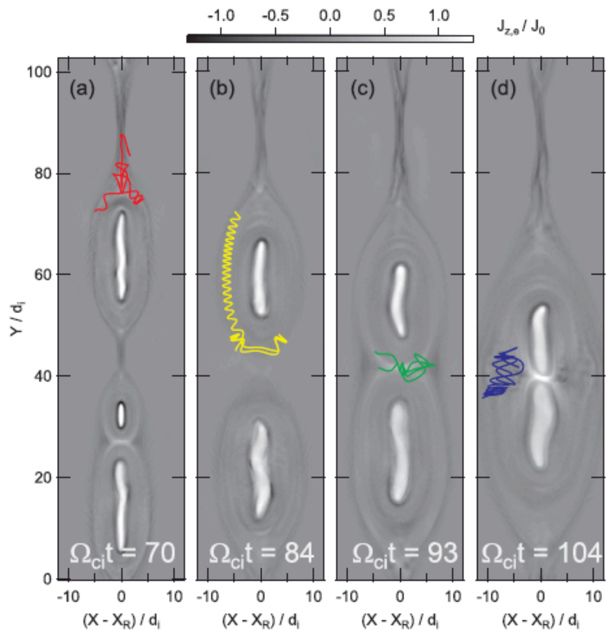
Acceleration regions

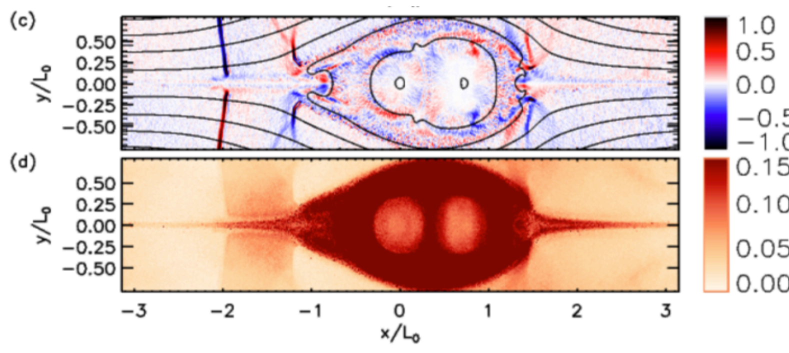


1. Reconnection region

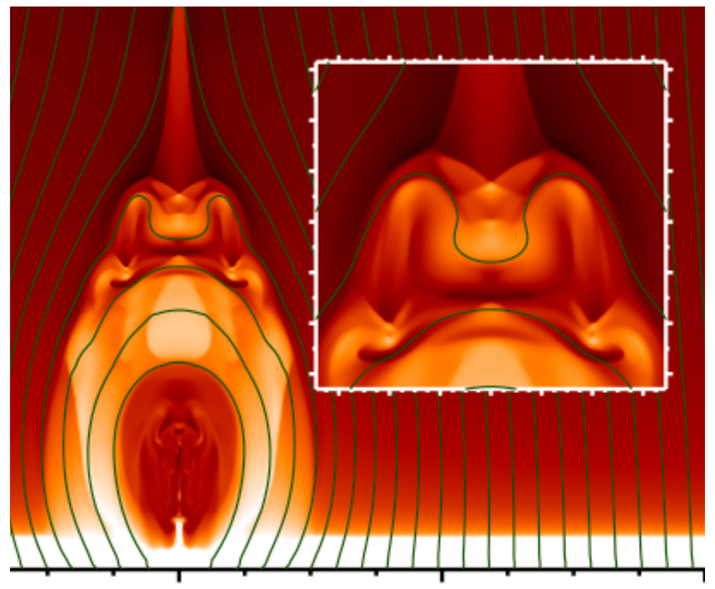


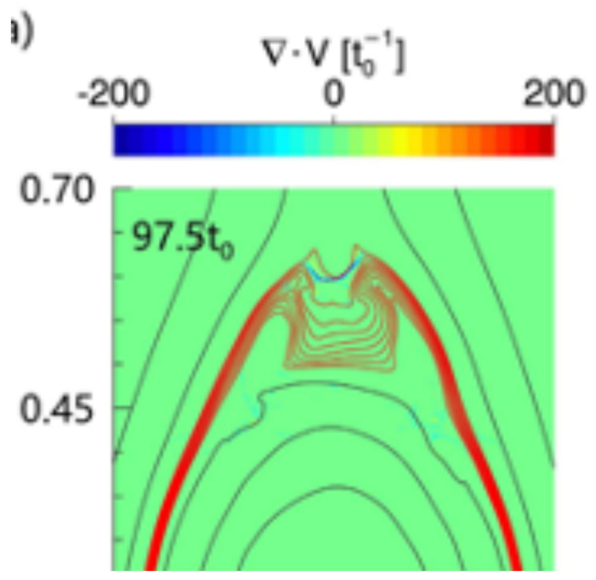


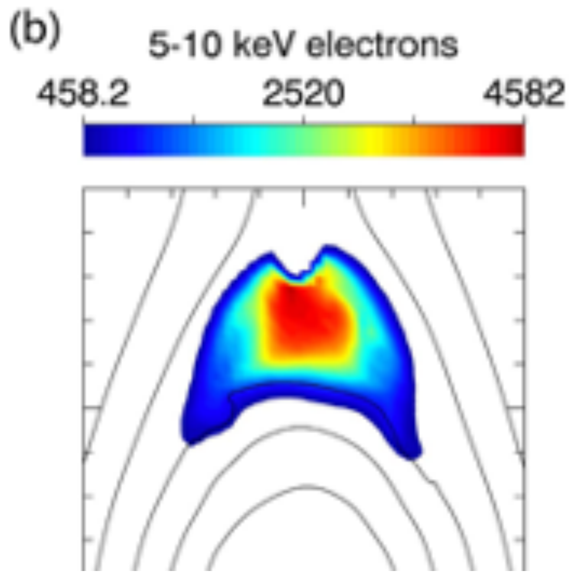




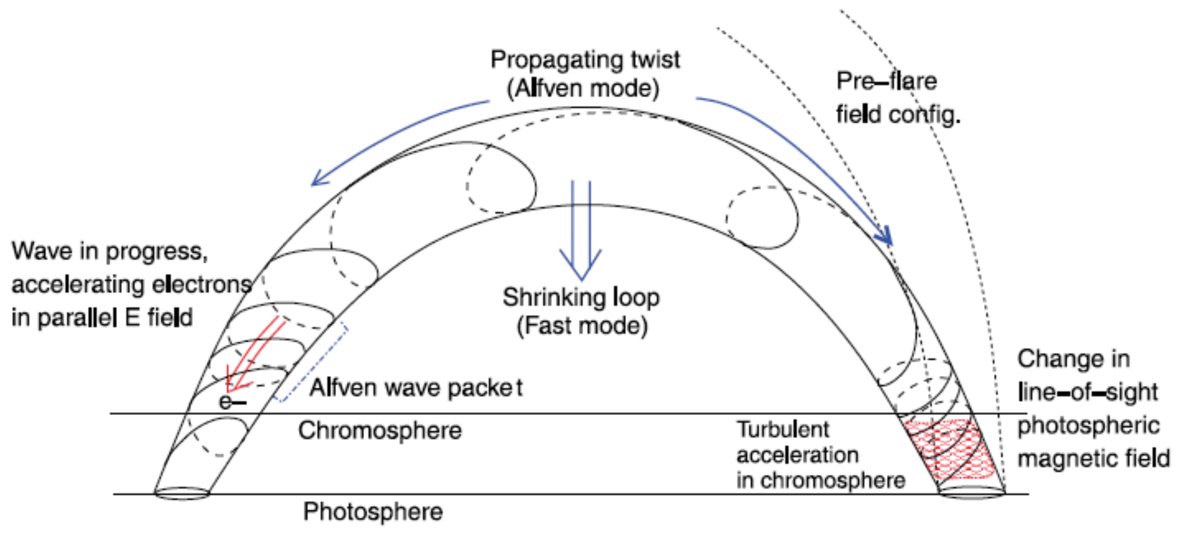
2. (Above-the) loop-top region





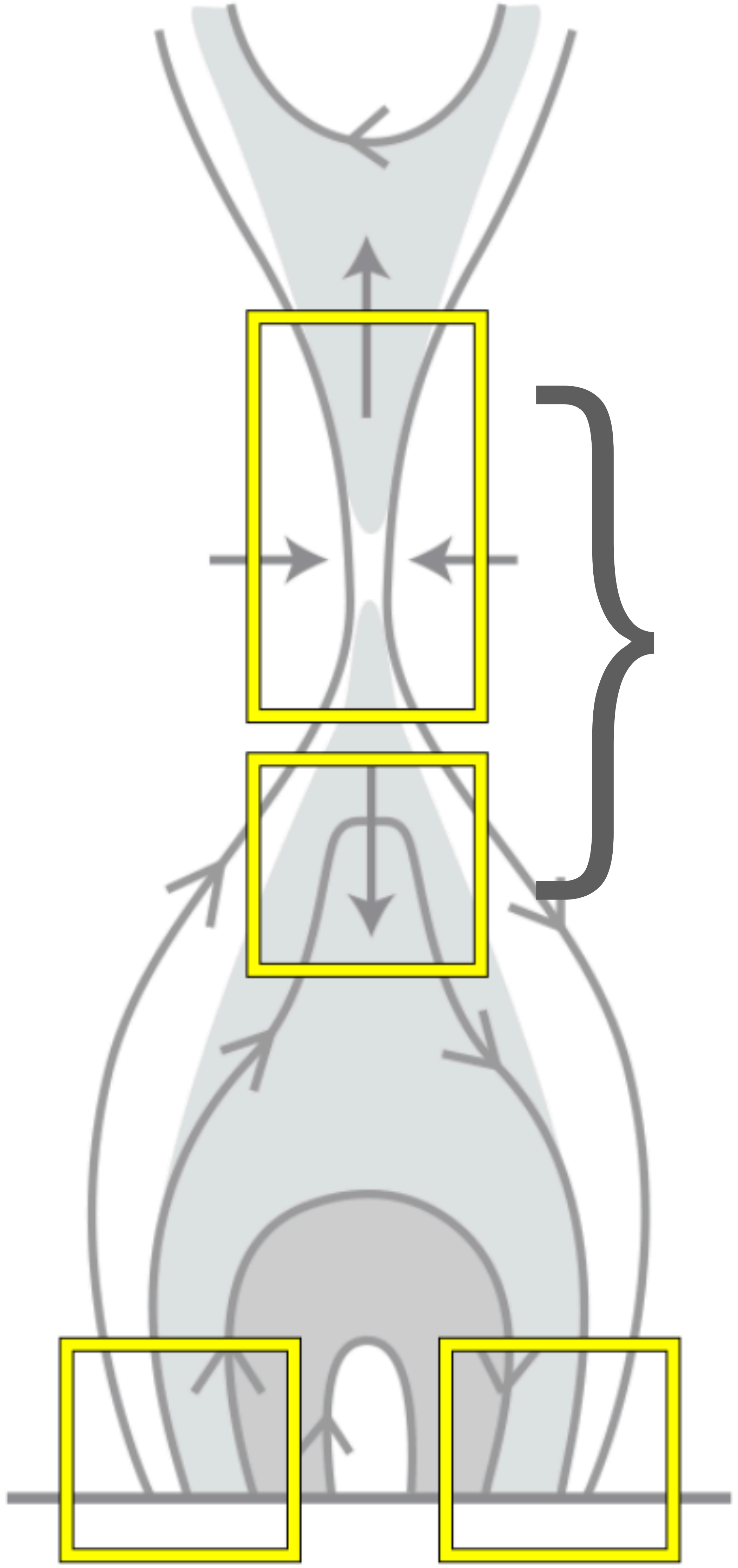


3. Foot-point regions



Many processes proposed!!

Comprehensive observations are difficult



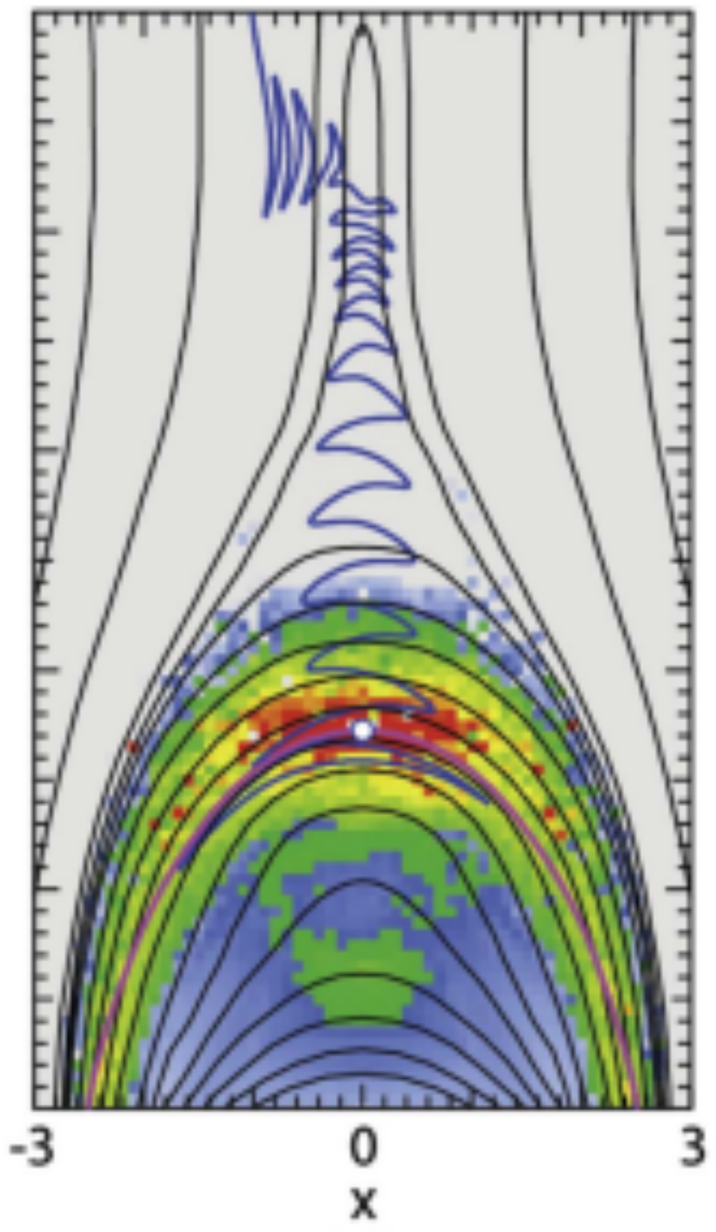
Coronal parts:
Very difficult to observe because of their low emissivities. Comprehensive observations are challenging.

Considerable efforts are being made by
the SolFER, PhoENiX, Solar-C_EUVST, *MUSE* teams etc.

In addition, we do not have an established model that describes the detailed MHD scale structure, particularly around the ALT region.

Impacts of MHD scale processes on particle acceleration & trap

- **Magnetic field structure affects**
  - Magnetic reconnection physics
    (e.g. roles of **the guide field**; Arnold et al. 21)
  - Efficiency of particle trap via magnetic mirror
    (e.g. Somov & Kosugi 97, Birn et al. 17)



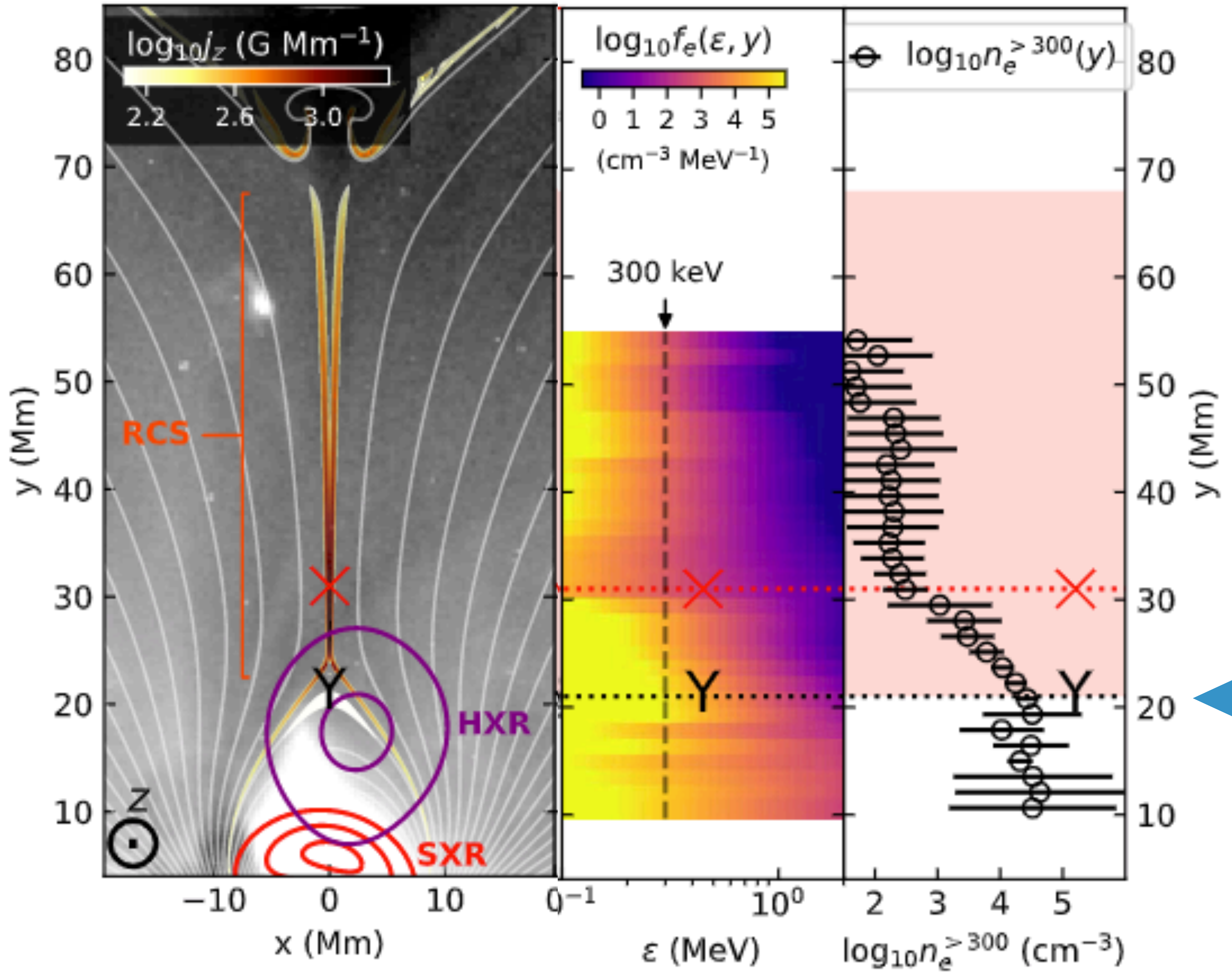
An example of magnetic mirror trap

Birn et al. 17

- **Thermal and (turbulent) flow structures affect**
  - Preheating the plasma before particle acceleration
  - How and where shocks form
    - Diffusive shock acceleration (e.g. Kong et al. 19)
    - Producing the temperature anisotropy
      (generation of whistler waves —> stochastic acceleration; e.g. Riquelme et al. 22)

Observations of the above-the-loop-top (ALT) region

Bin Chen et al. 2020 (see also Sijie Yu et al. 2020)



EUV (SDO/AIA),
Hard X-ray (RHESSI),
Radio (EOVSA)

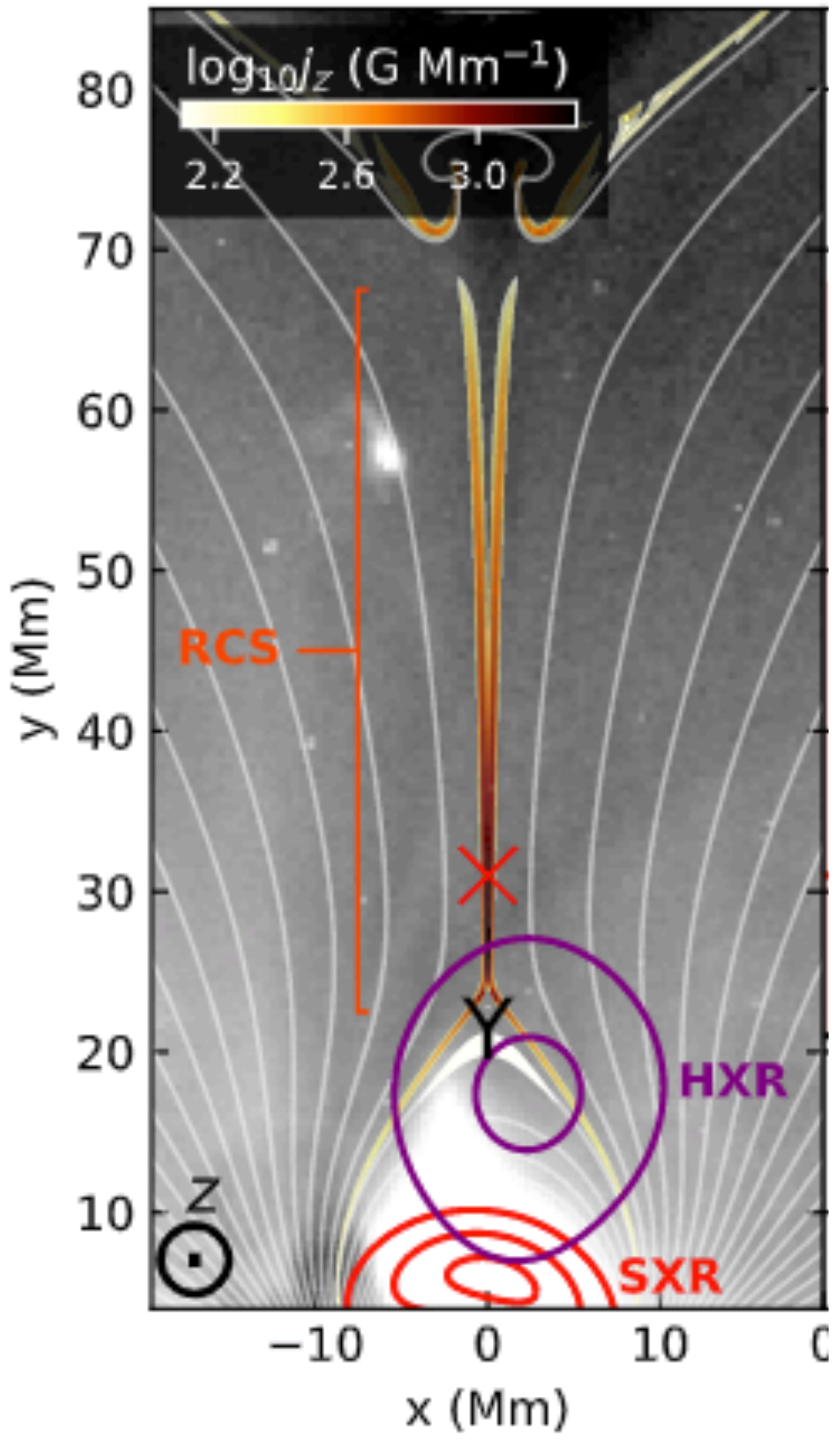
Concentration of energetic electrons around the ALT region

See also Krucker et al. 2010, W. Liu et al. 2013

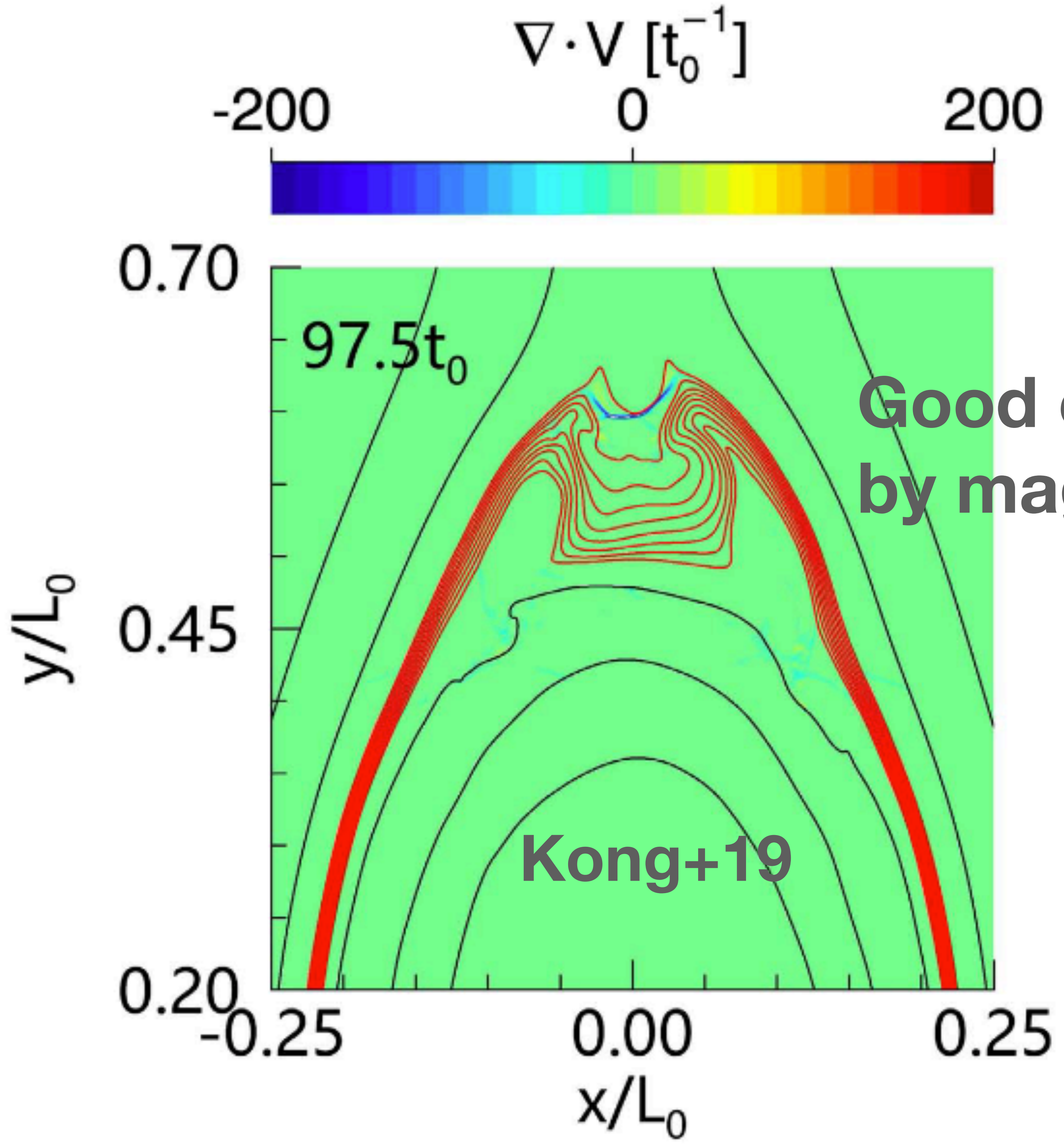
The ALT region is likely the primary site for accelerating and/or confining nonthermal electrons.

Confinement of nonthermal electrons in ALT regions

Bin Chen et al. 2020

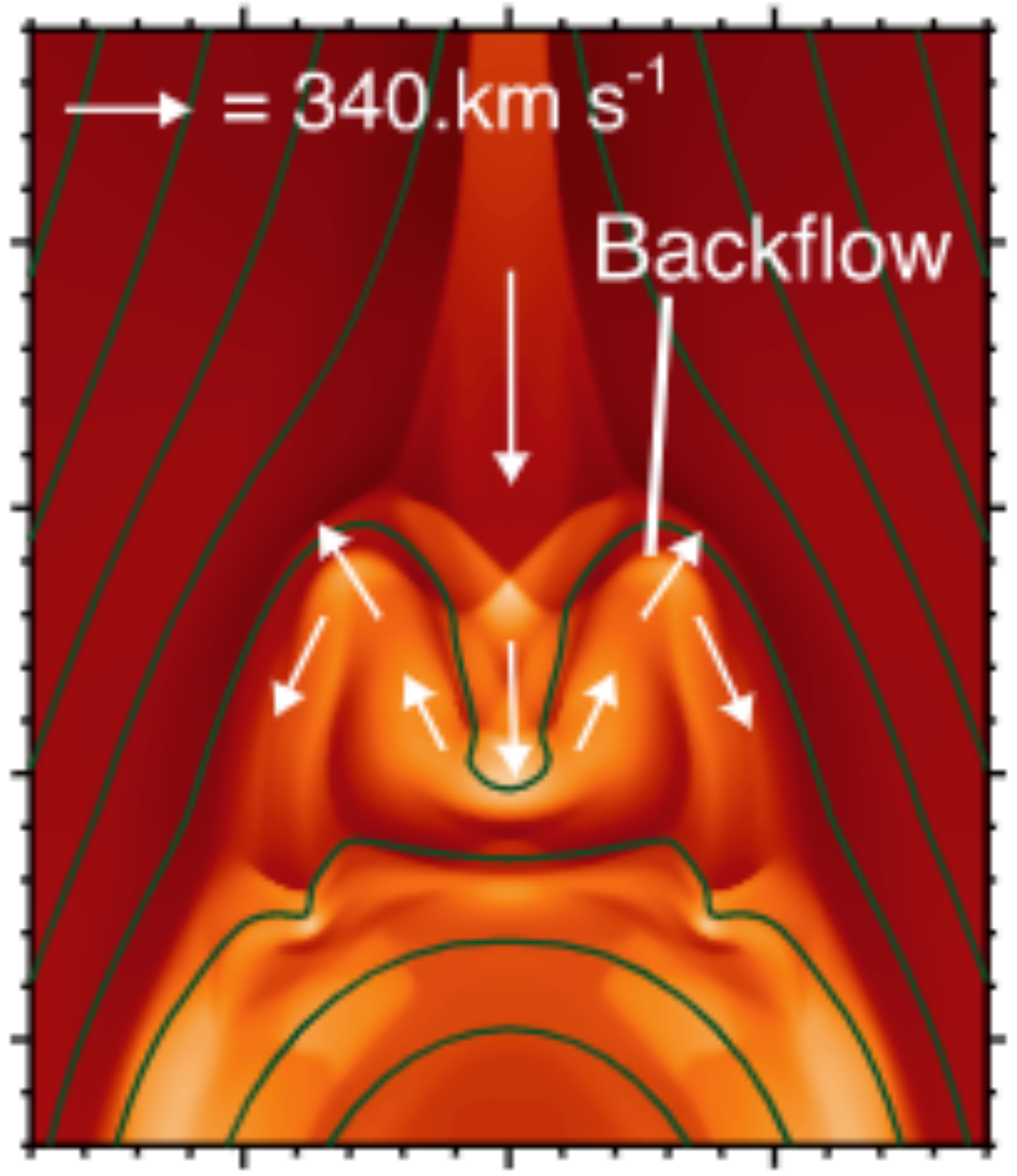


See also Krucker et al. 2010,
W. Liu et al. 2013



Good confinement by magnetic mirror

Density

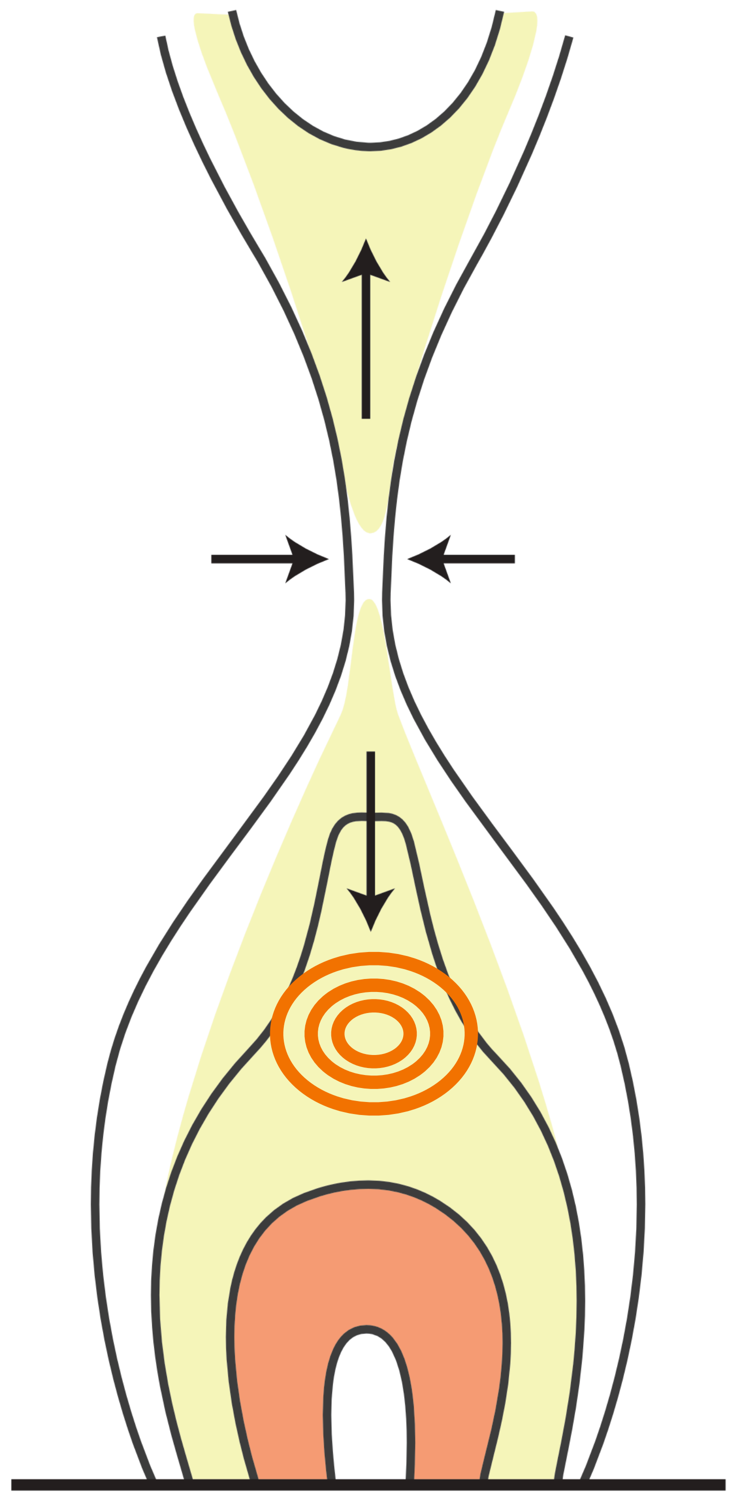


ST+15, ST & Shibata 16

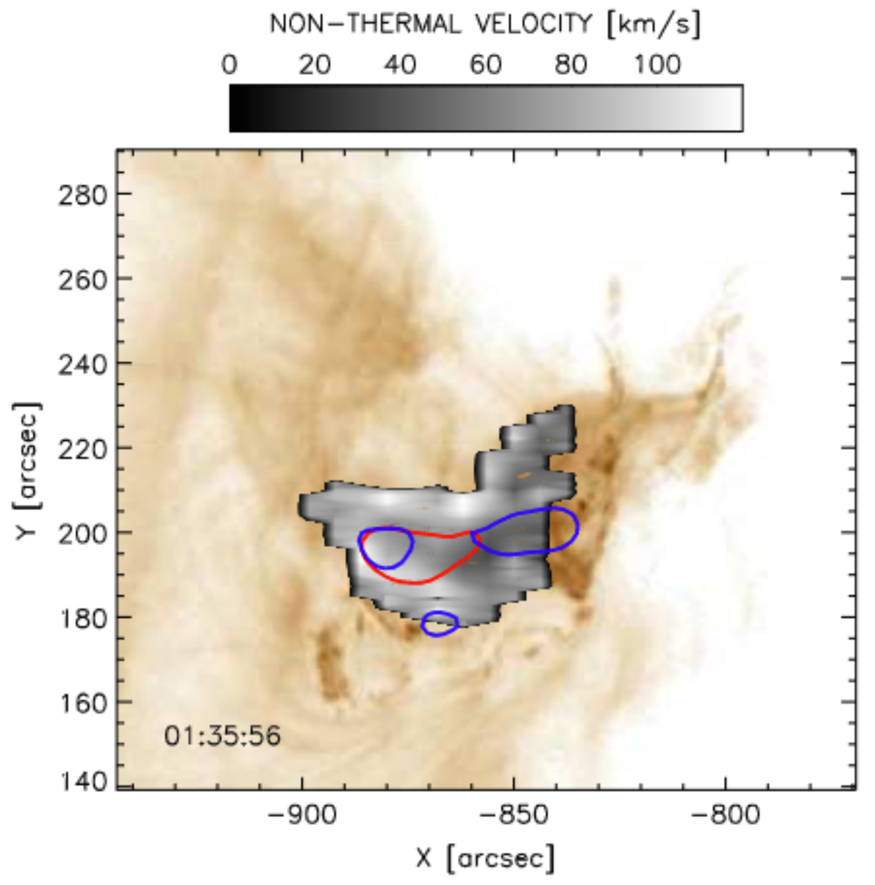
Narrow jet naturally produce a local magnetic bottle

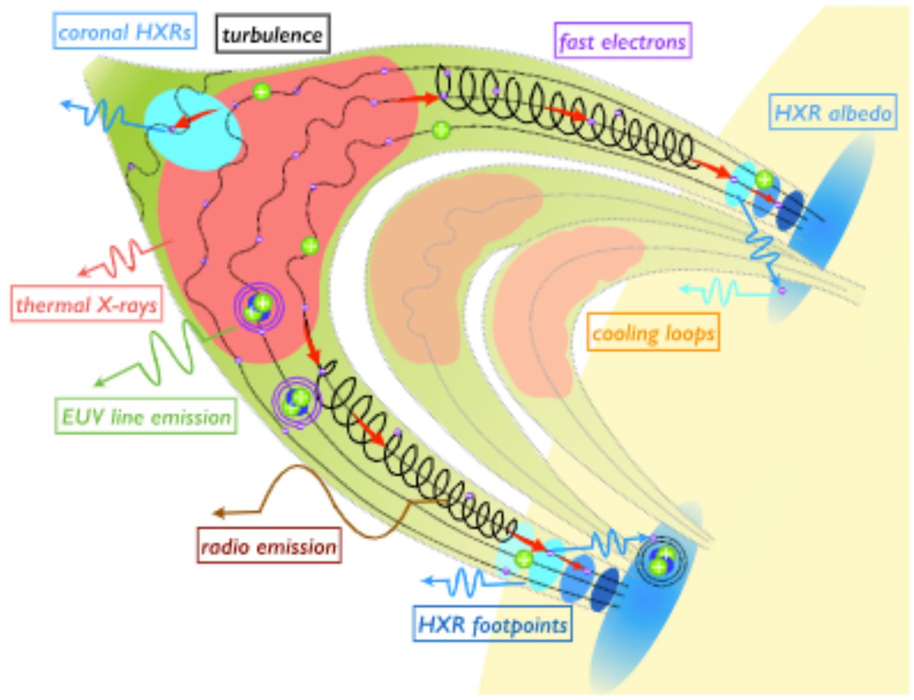
MHD scale flow structure in small ALT region determines magnetic field geometry and will affect the confinement of nonthermal electrons.

Turbulence around ALT regions: observations

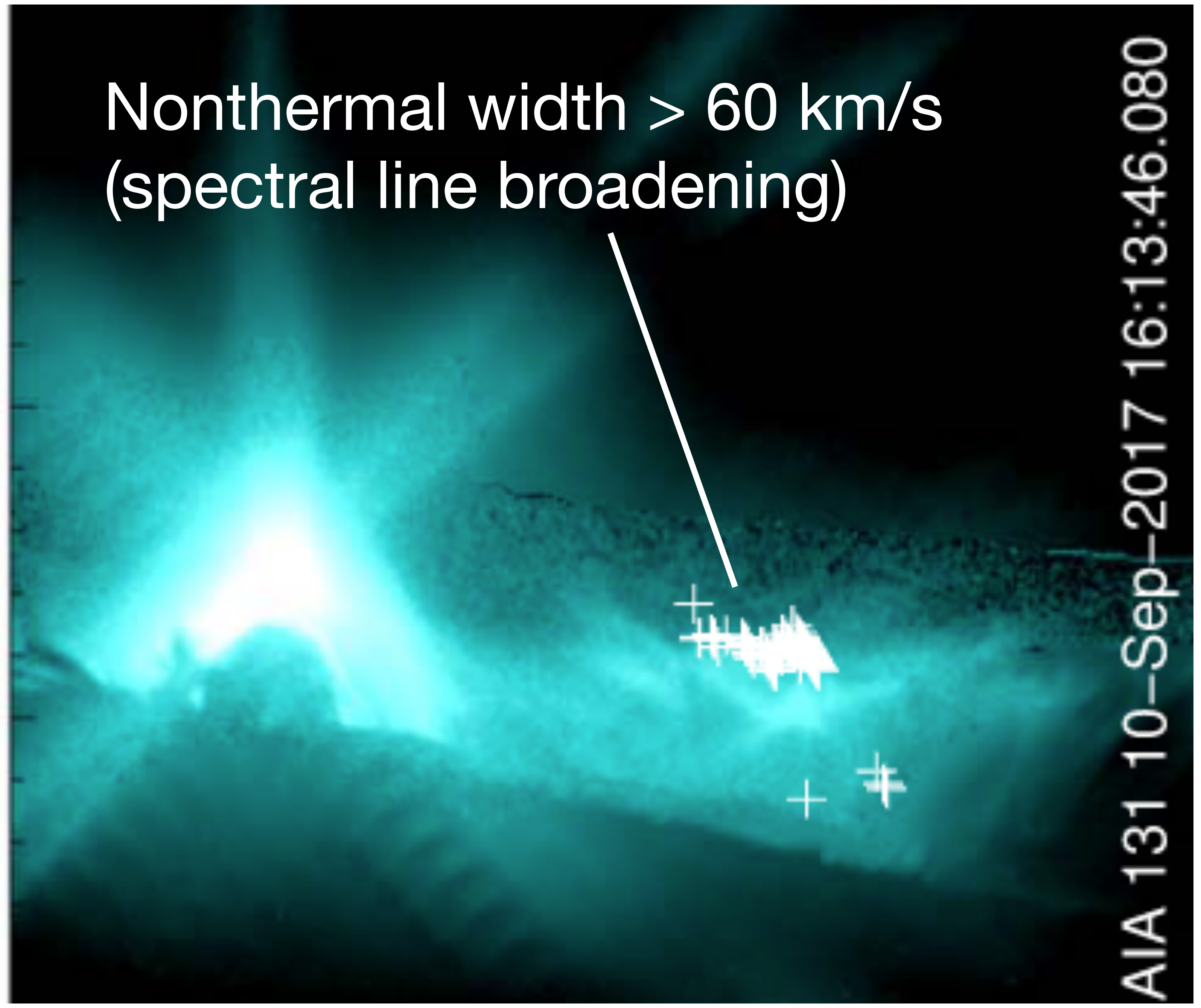


Nonthermal velocity (signature of turbulence)





Kontar et al. 2017



Reeves et al. 2020

Kinetic energy of **turbulent motions** may be sufficient for energizing electrons (Kontar et al. 2017): Turbulence will be energetically important.

ALT regions will be turbulent. But

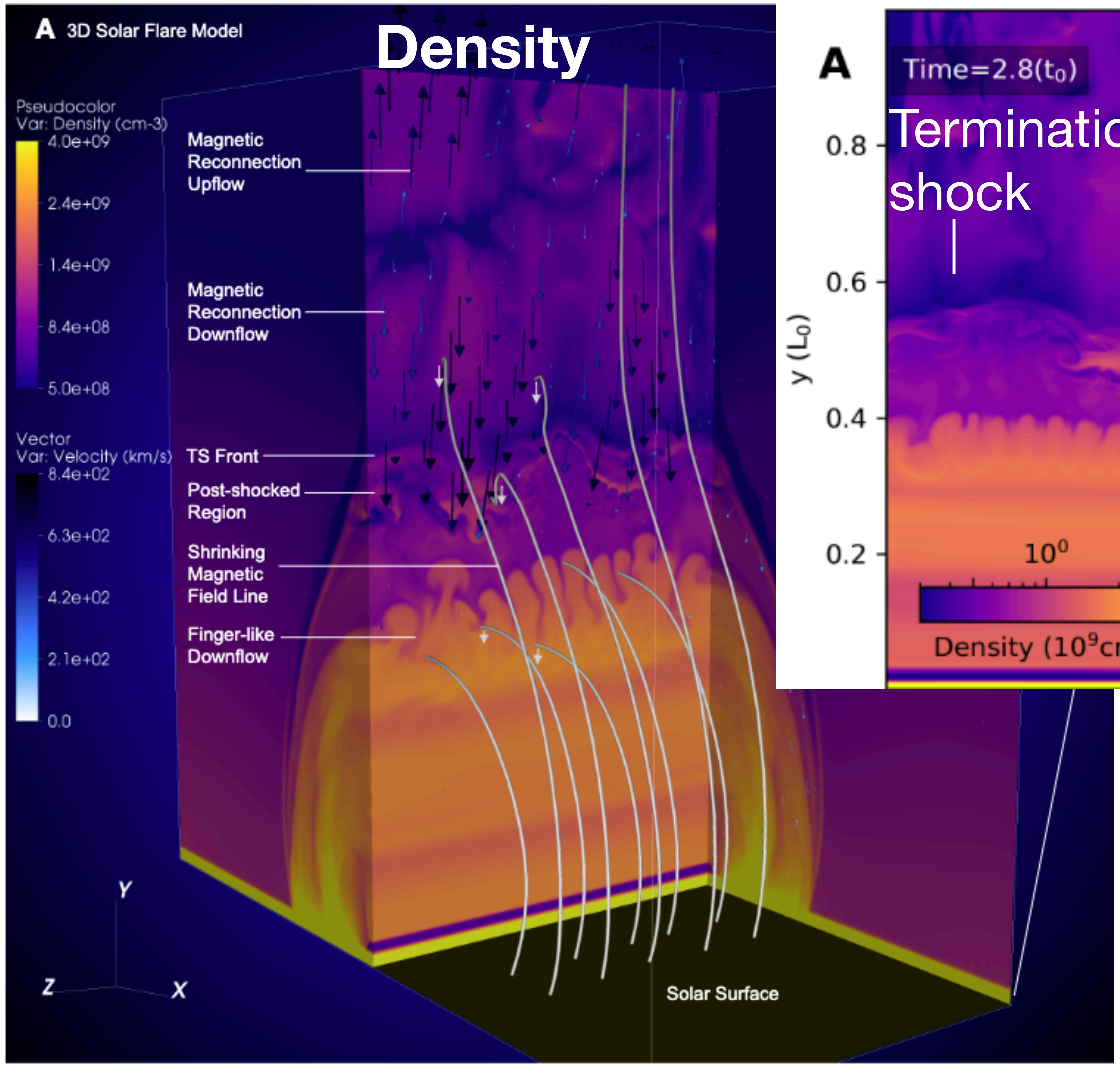
- **origin of turbulence? (Turbulent reconnection or other instabilities?)**
- **the strength and spatial distribution of turbulence?**

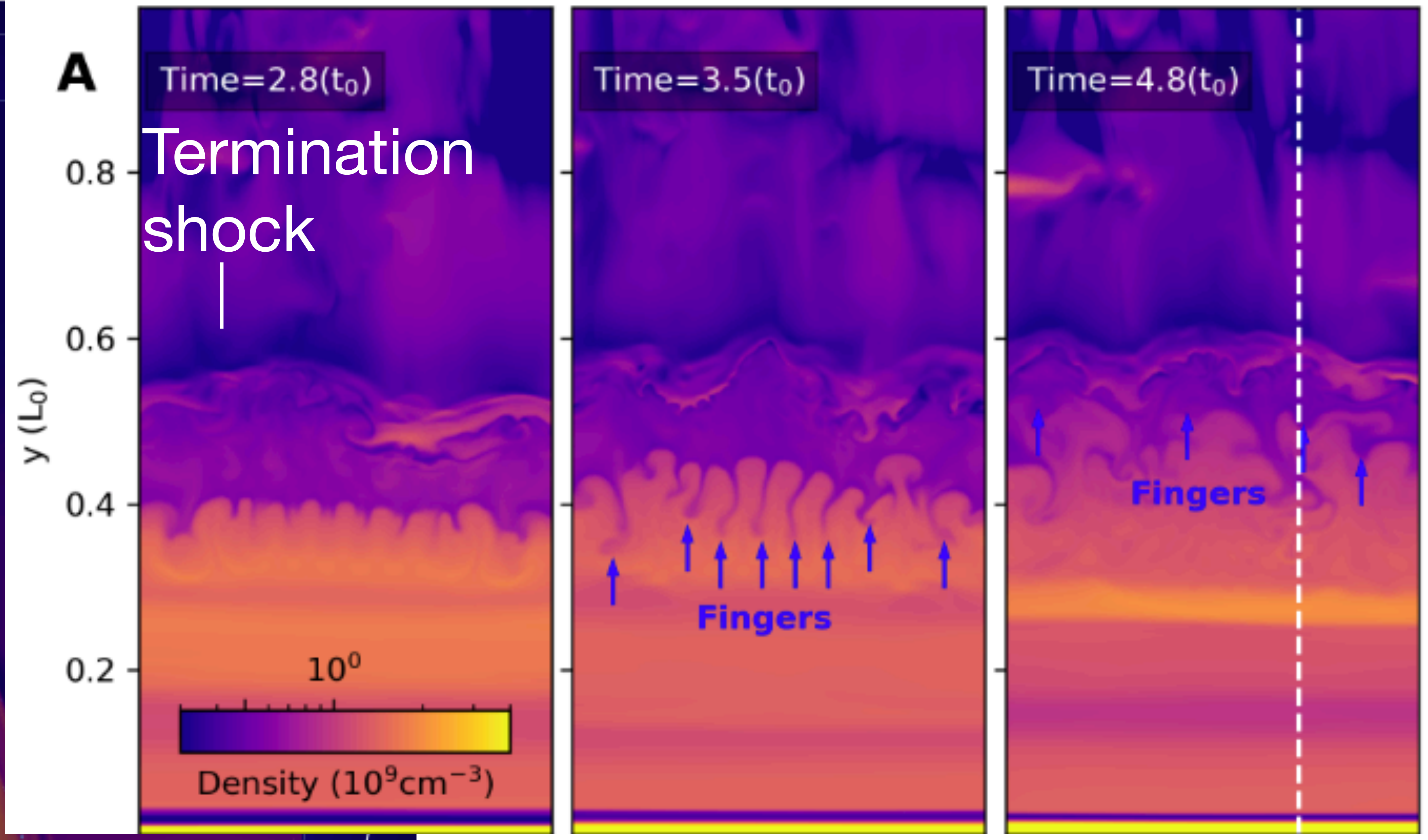
Supra-arcade downflows (SADs)

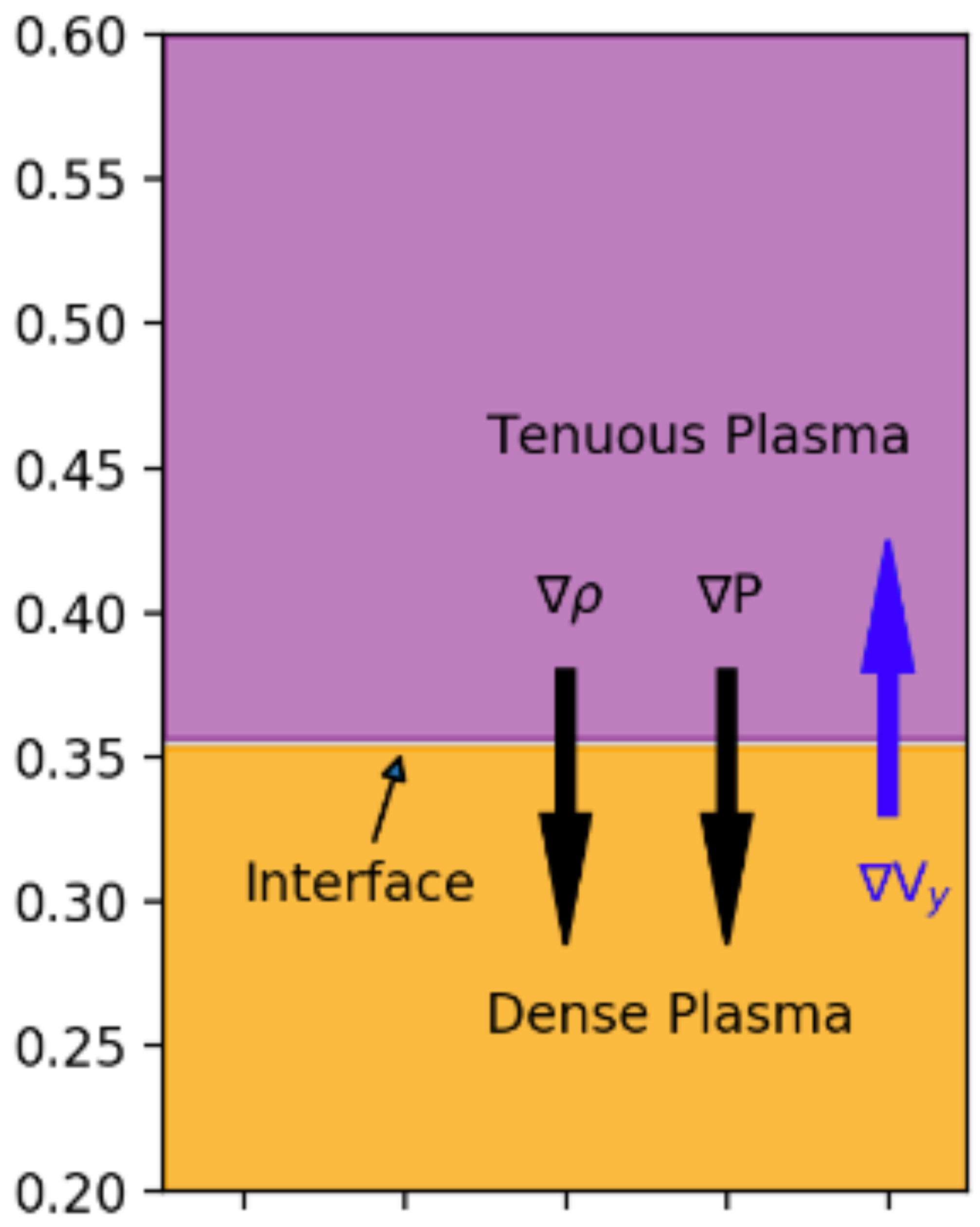
SADs:

- **descending, dark, finger-like plasma voids** (McKenzie & Hudson 99, Asai et al. 04, Savage & McKenzie 2011, …)
- **less dense** than the surrounding (e.g. Hanneman & Reeves 14)
- **move at a much lower speed than the typical Alfven speed**; v ~ 100 km/s (e.g. Savage & McKenzie 2011)
- **The relation to the turbulence** around the loop top has been discussed (e.g. McKenzie 2013)

Turbulence around ALT regions: simulations







Turbulent flows appear around the layer with a sharp density gradient
(See also Guo et al. 2014 ApJL)

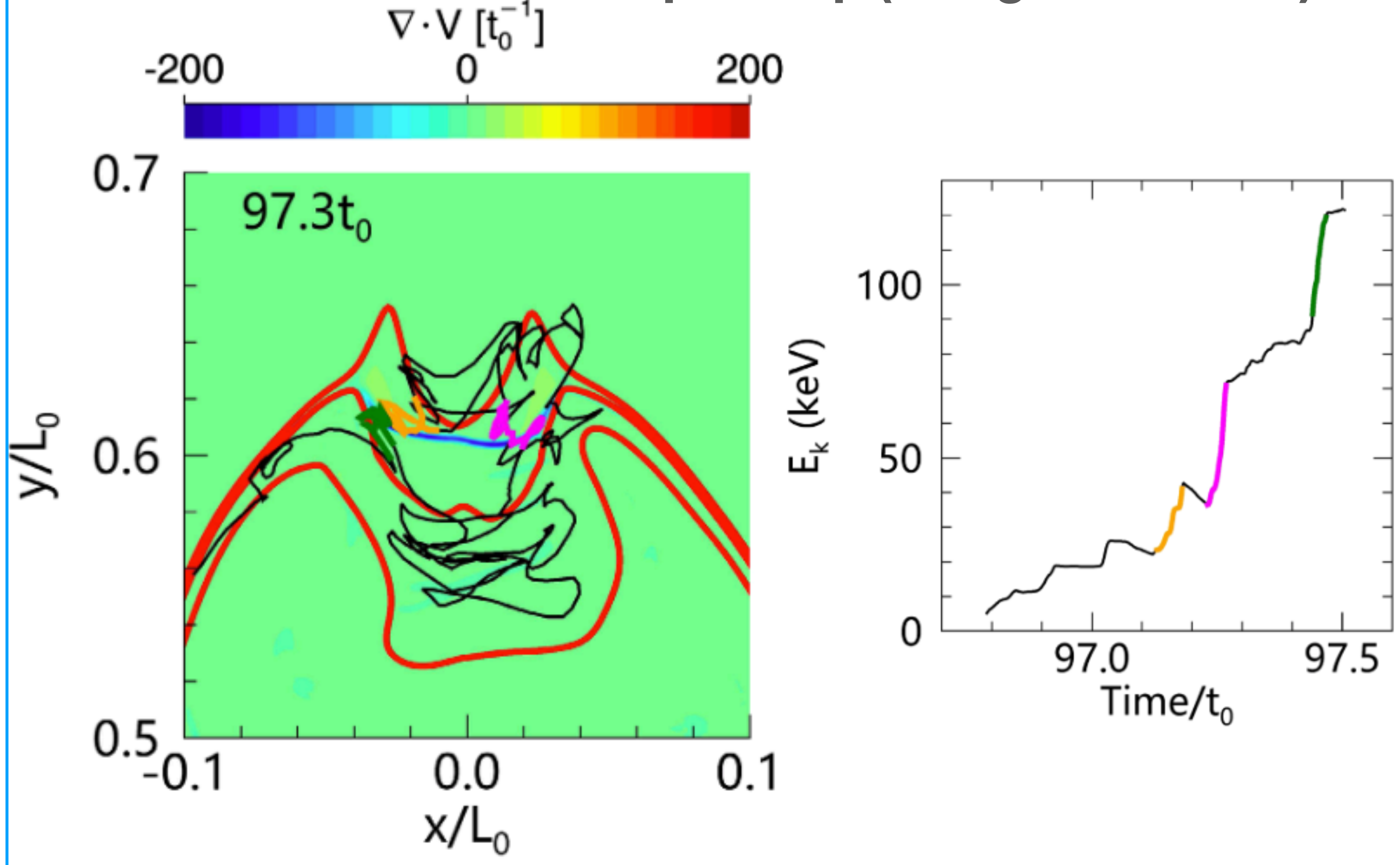
Shen et al. 2021 Nat.Astro. infer that the turbulence is caused by a mixture of **the Rayleigh-Taylor instability** and **the Richtmyer-Meshkov instability**.

Local generation of turbulence in the ALT region

Importance of turbulence in ALT regions

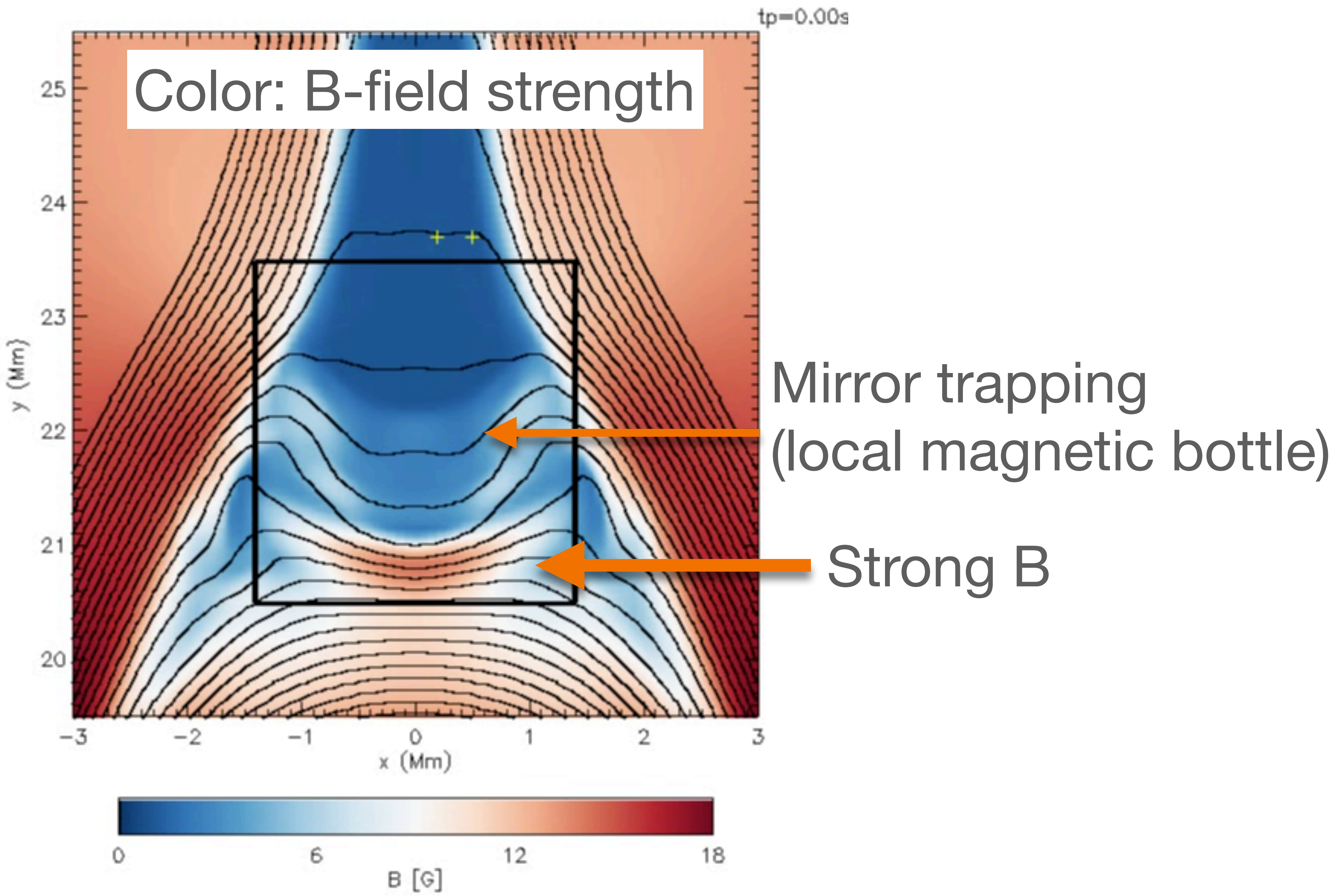
Strength and distribution of turbulence change the story.

MHD + Parker's transport eq. (Kong et al. 2019)



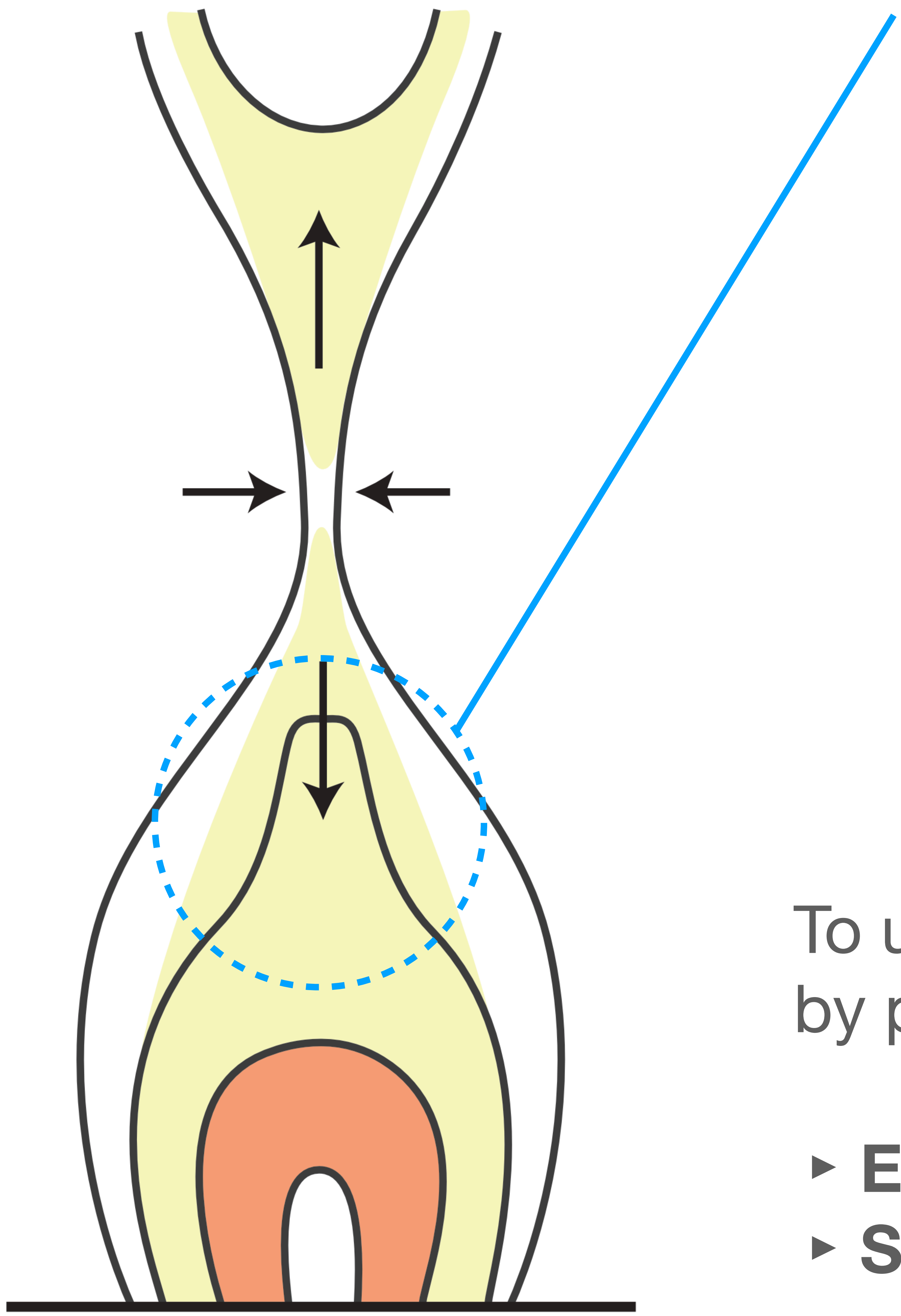
Termination shock
+ strong **turbulent diffusion** for electrons
=> Diffusive Shock Acceleration (**DSA**)

MHD + Guiding Center Approx. (by K. Kaneko)

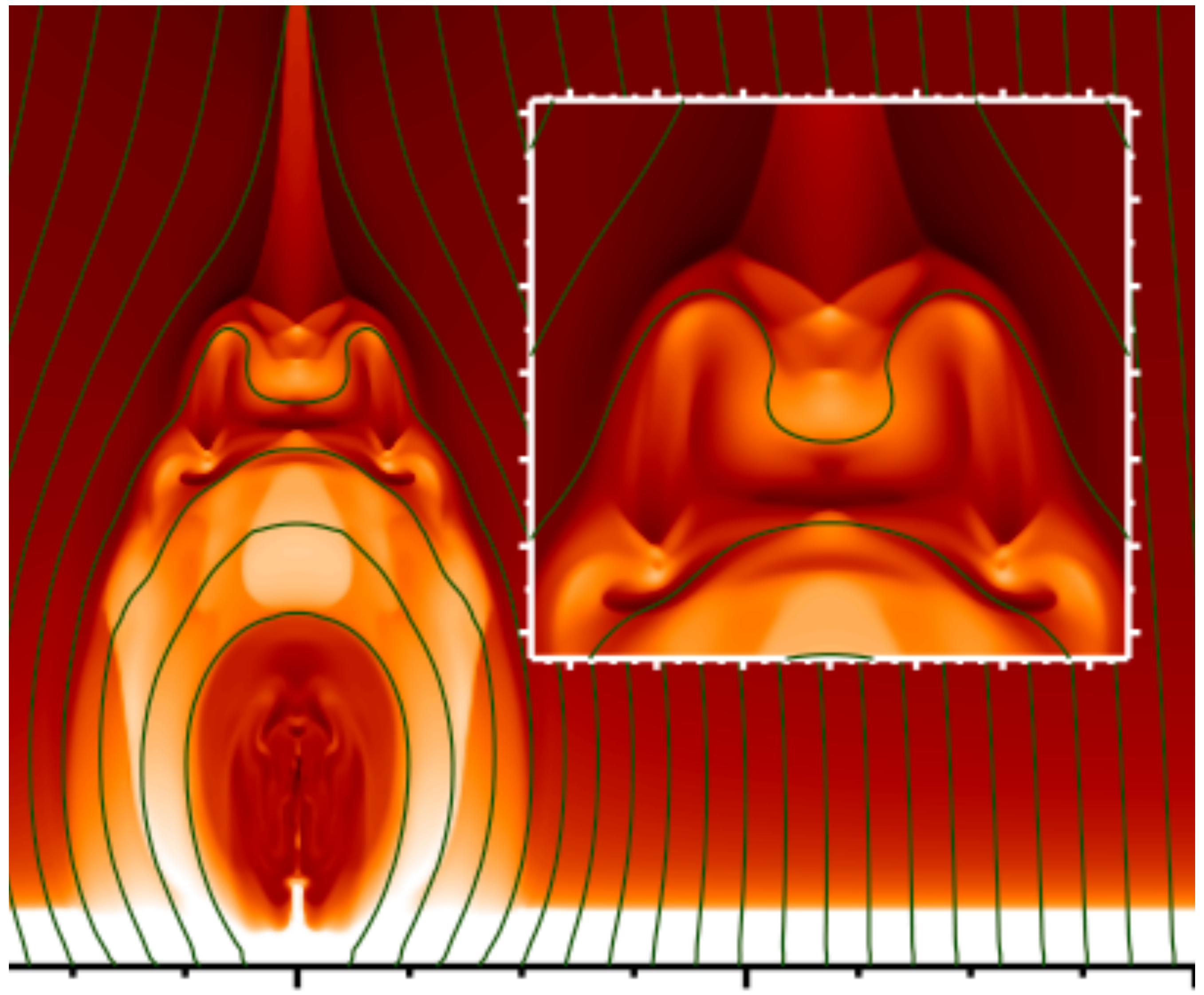


No turbulence
=> **Betatron acceleration**
behind the termination shock

Aim of our study



2. (Above-the) loop-top region, ALT region



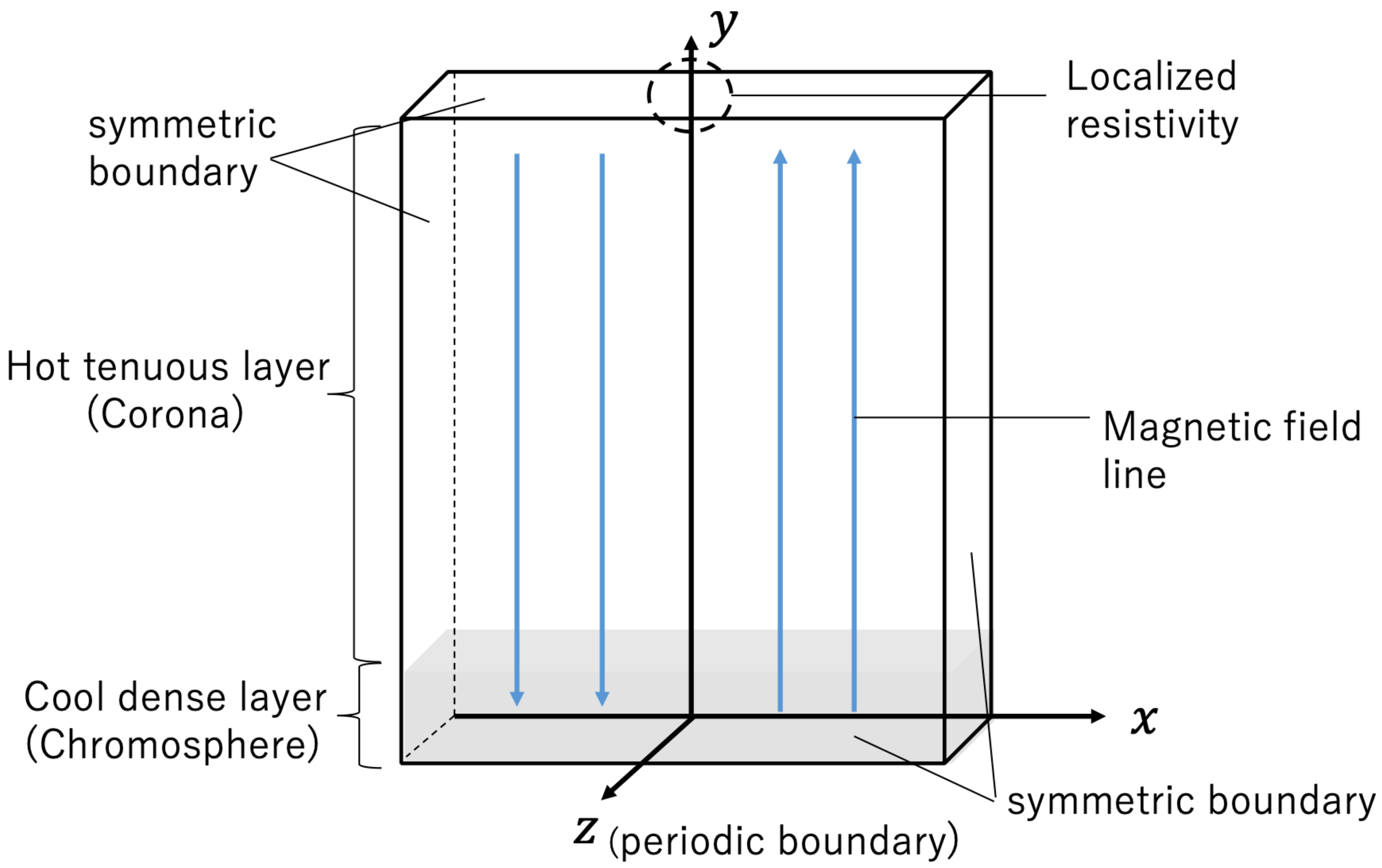
ST+15, ST & Shibata 16

To update the picture of the ALT region based on 2D MHD models by performing 3D MHD simulations.

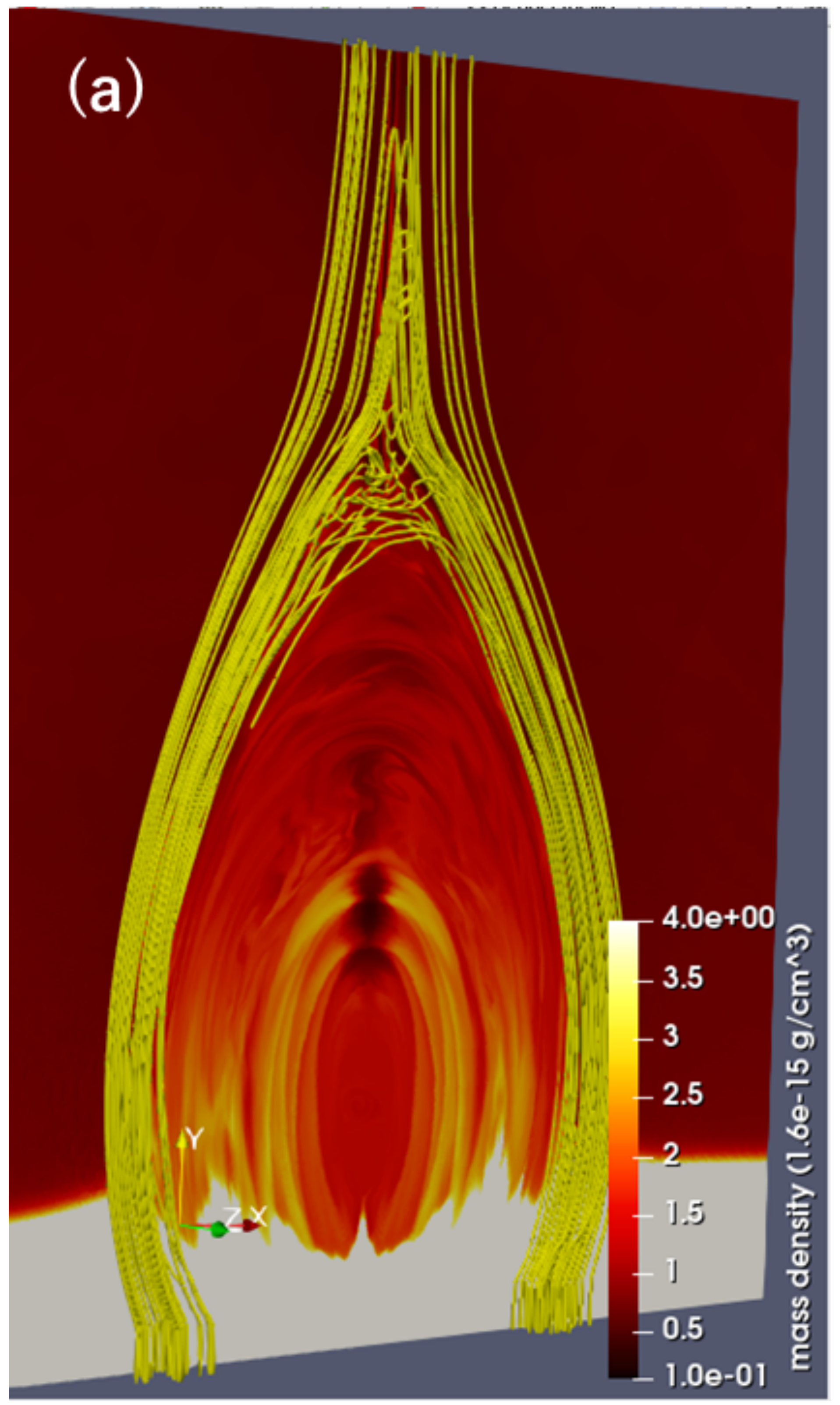
- **Excitation mechanisms of turbulence?**
- **Spatial distribution of turbulence?**

Numerical setting

Shibata, ST et al. in prep.



Resulting flare loop

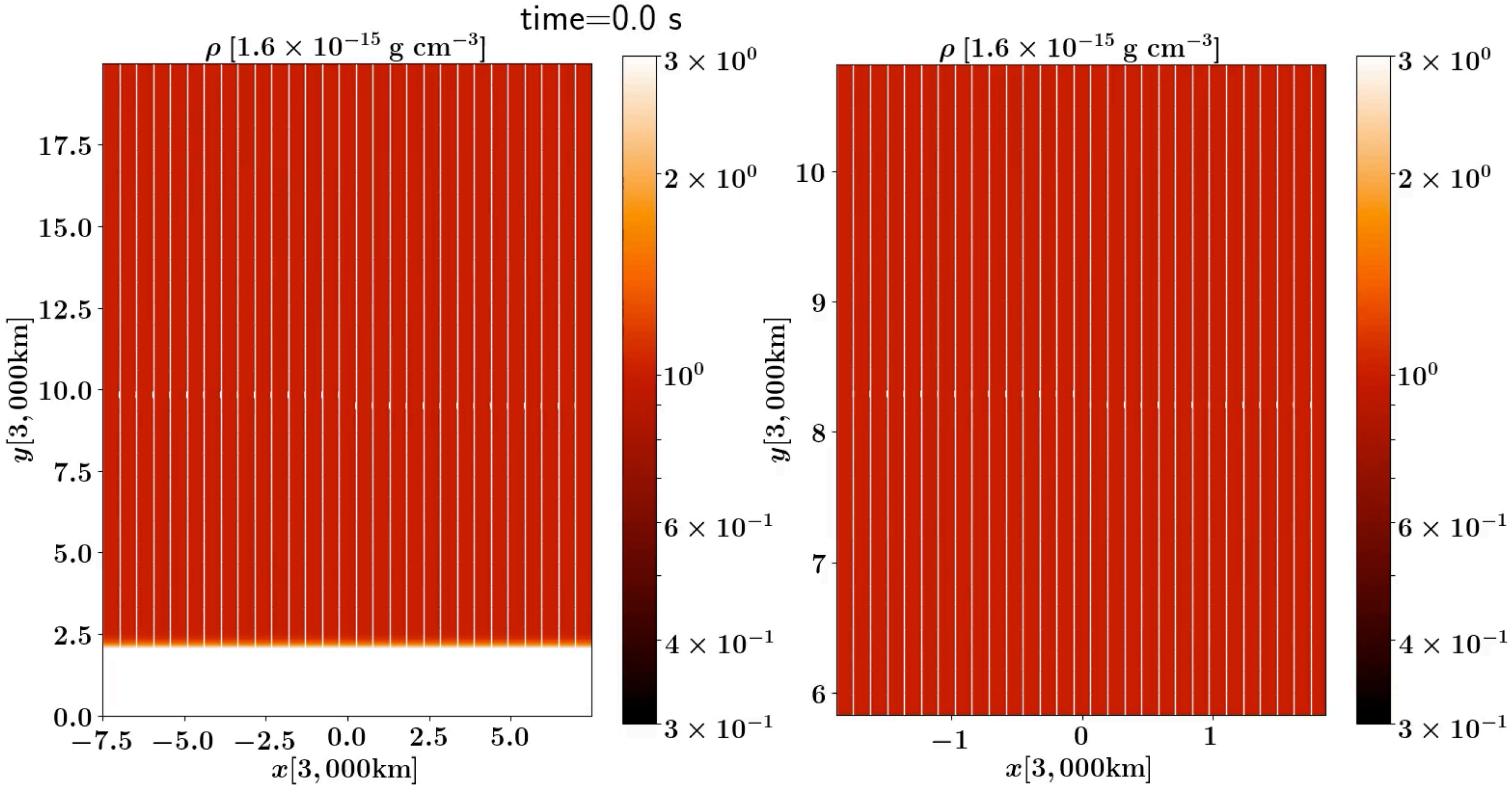


Lx x Ly x Lz = 45 Mm x 60 Mm x 4.5 Mm
Nx x Ny x Nz = 900 x 1200 x 90
Plasma beta = 0.13
Resistive MHD equations (here, we introduce a 3D model without heat conduction)
Code : Athena++ (Stone et al. 21), 3rd order accuracy in space and time.

General evolution

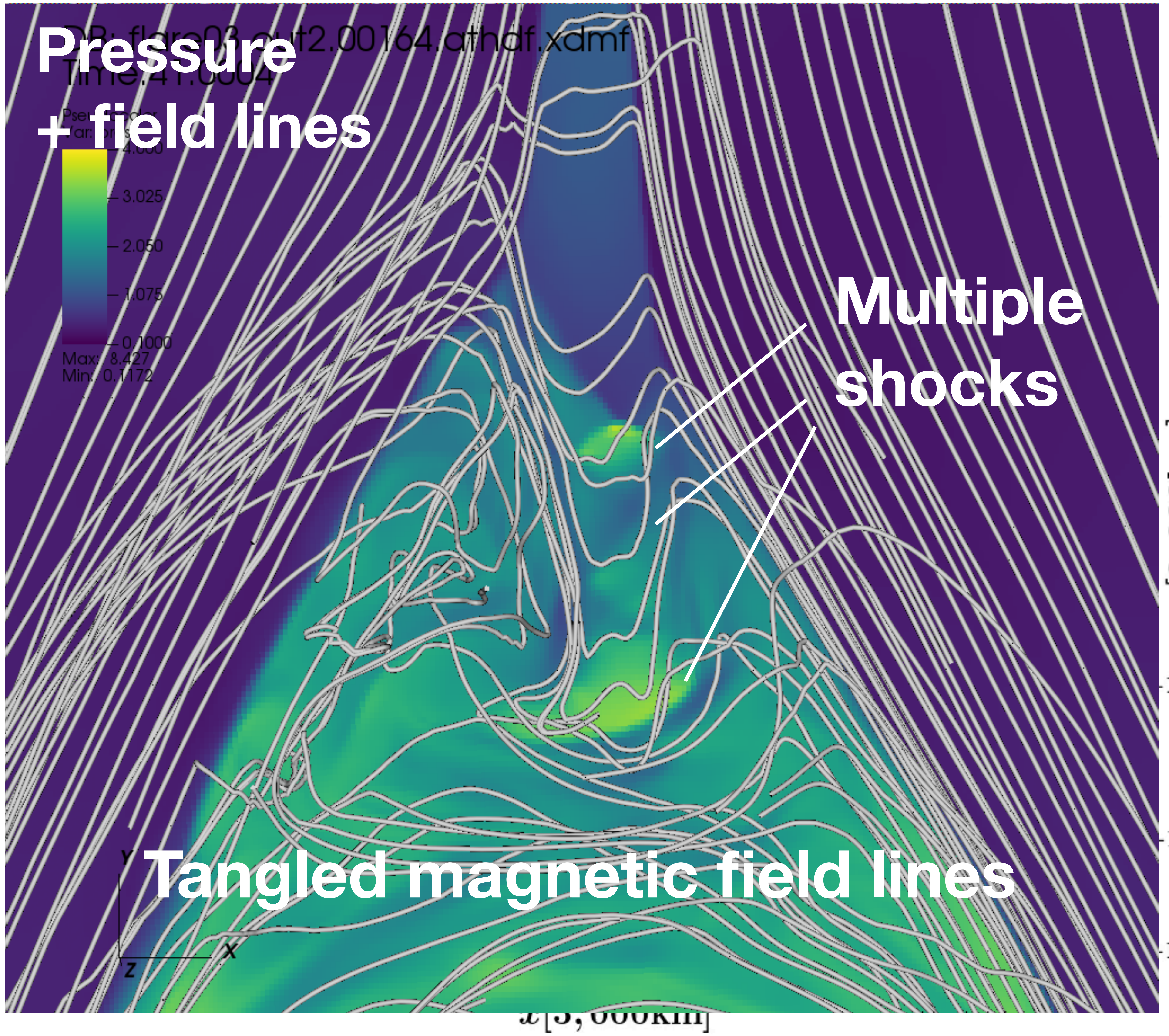
Shibata, ST et al. in prep.

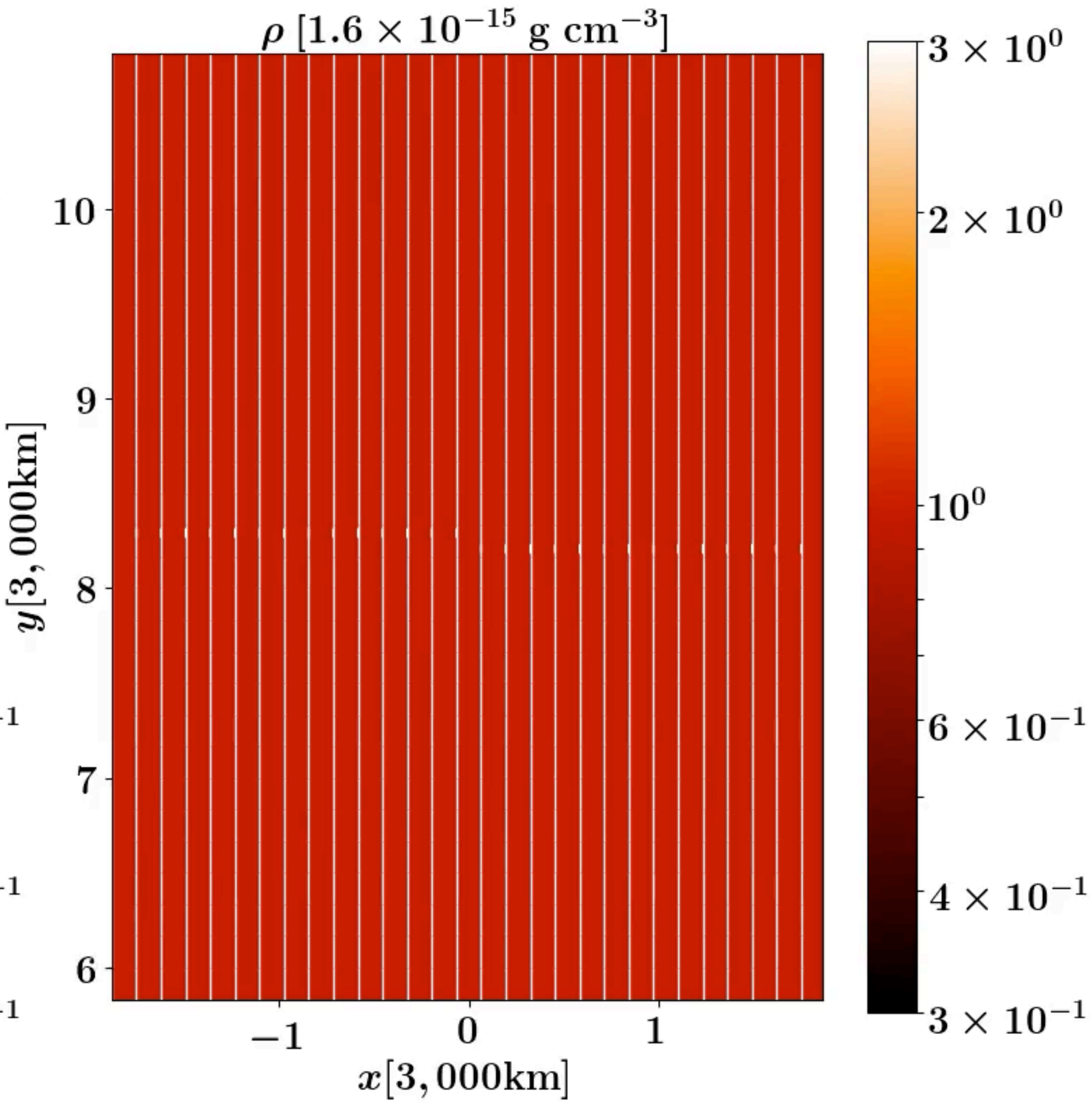
Solar flare with a single reconnection point



General evolution: multiple shocks and turbulence

Solar flare with a single reconnection point



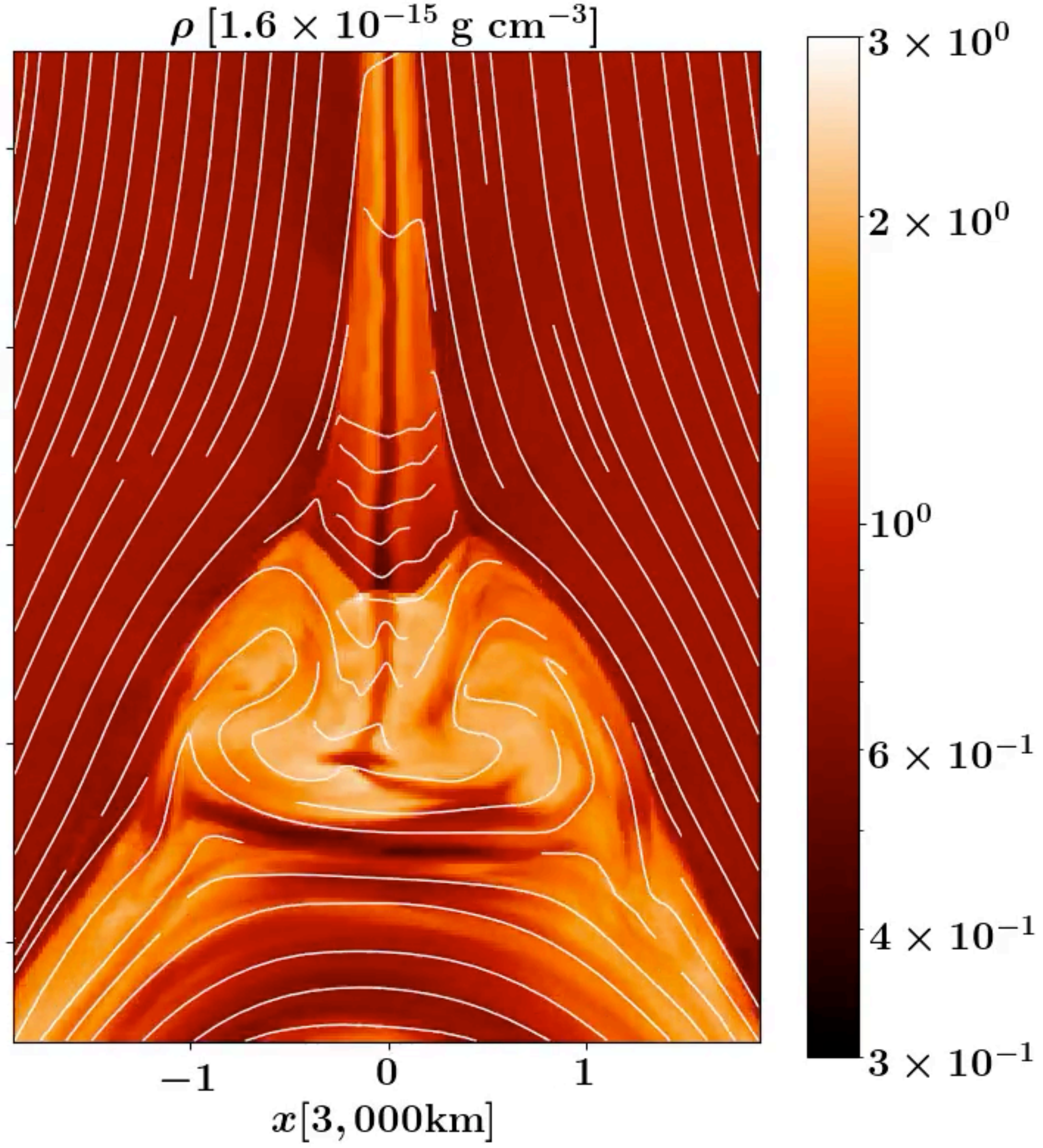


General evolution: development of turbulence

Plasma β

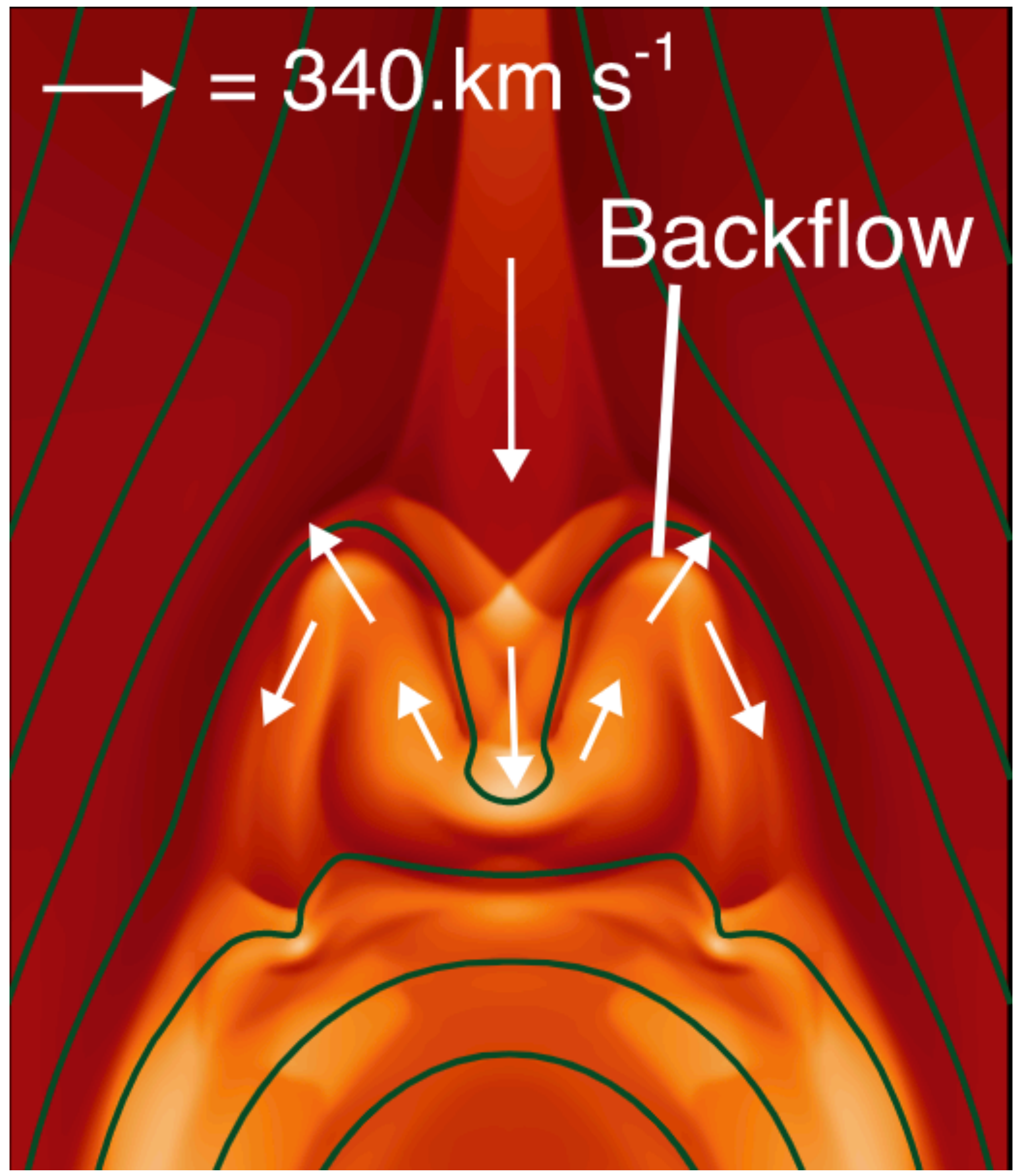
The ALT region is filled with turbulent flows.

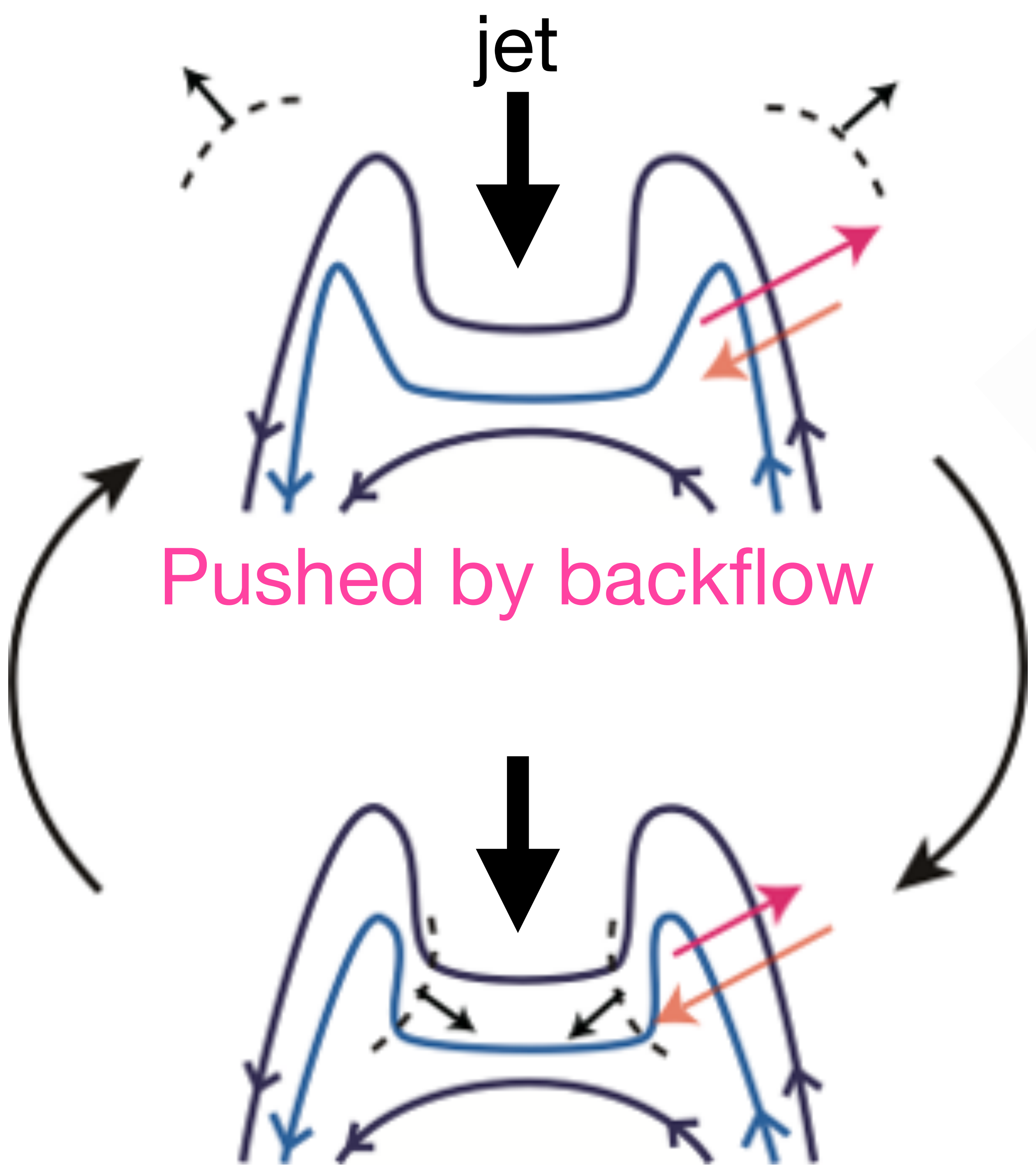
General evolution: ALT oscillation



ALT oscillation (found by ST & Shibata 2016)

Symmetric 2D model





Pushed back by magnetic pressure

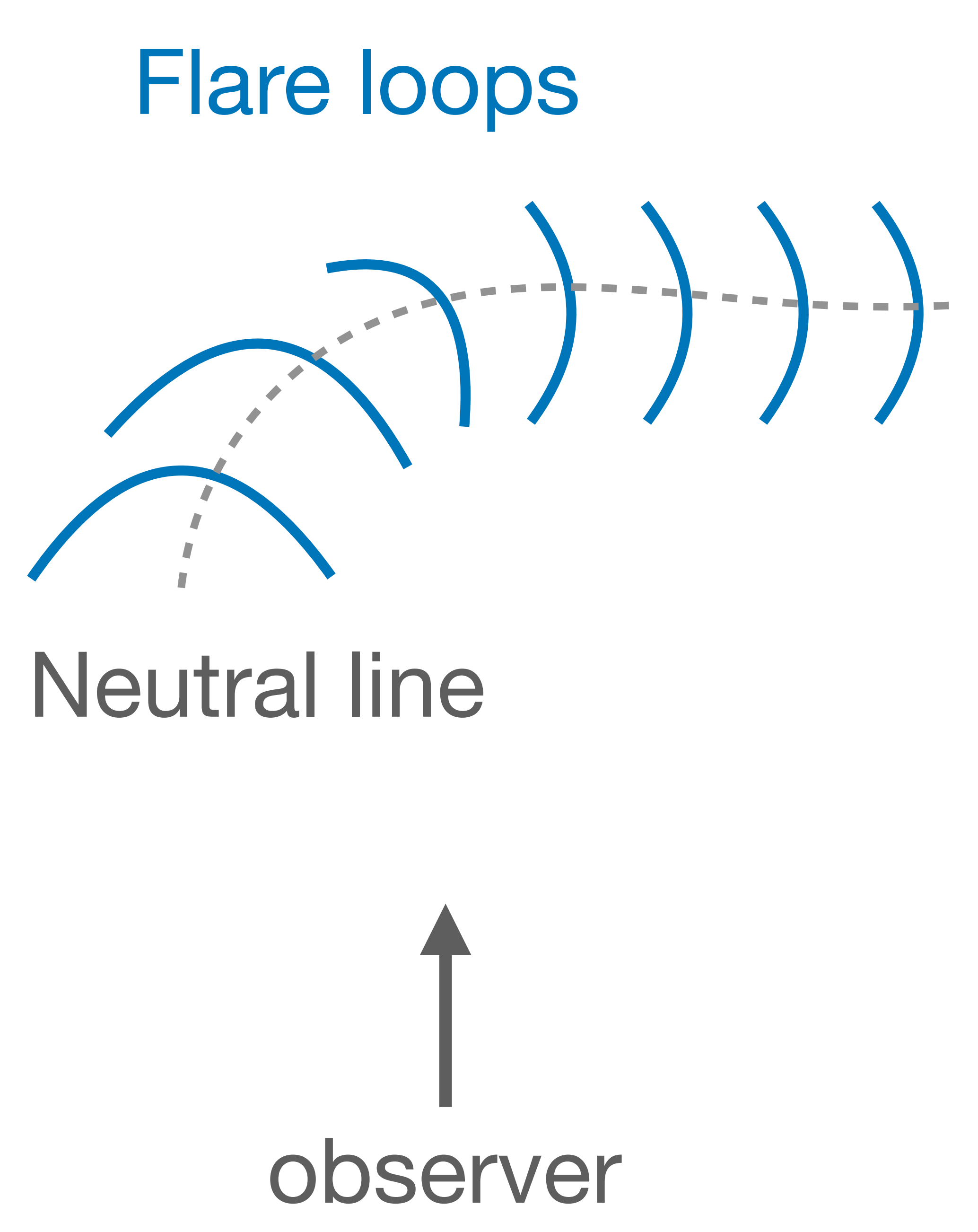
Magnetic tuning fork

ALT oscillation = an oscillation forced by the backflow

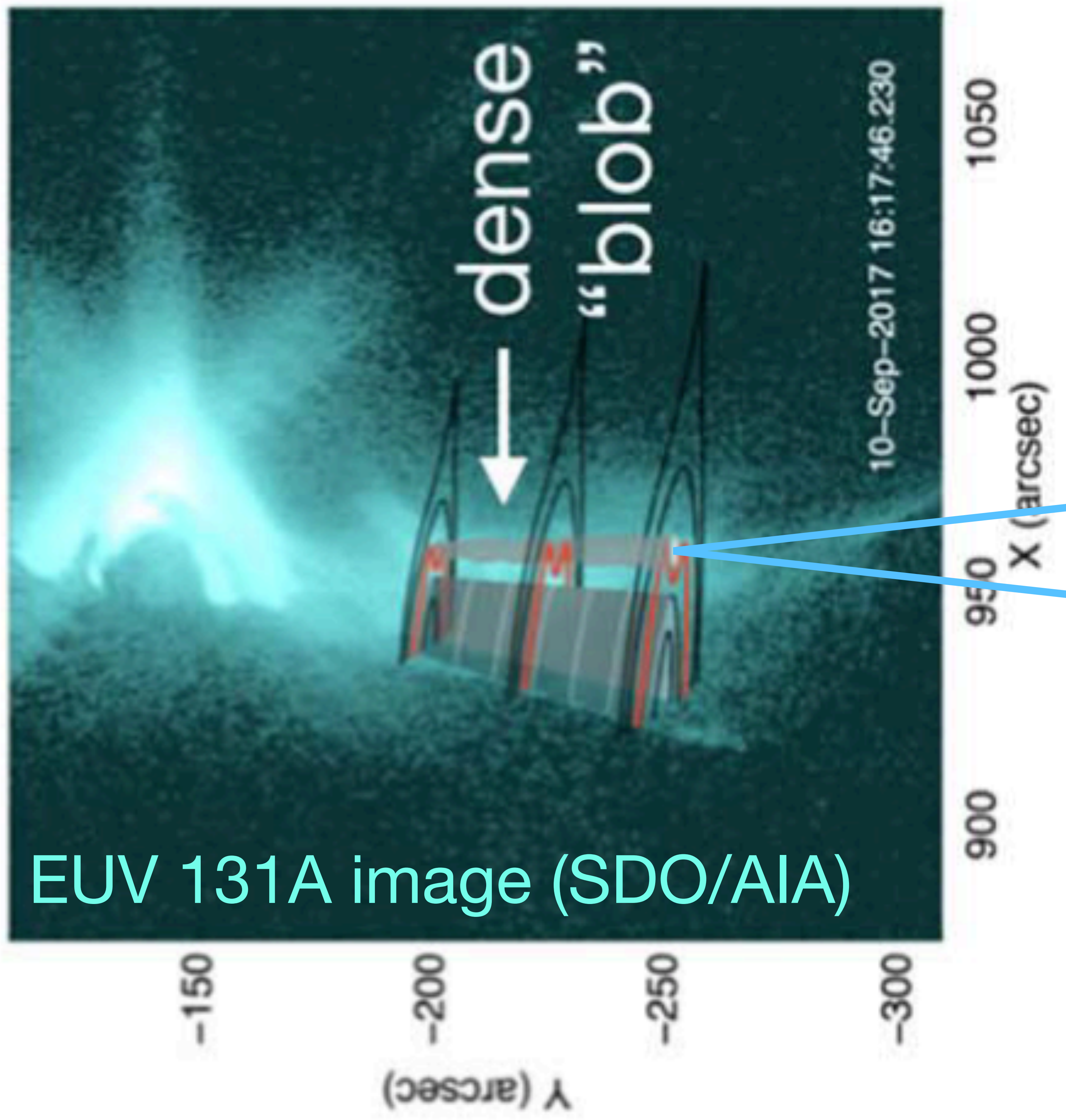
Our 3D model shows that asymmetric ALT oscillation can occur in 3D and even in the presence of turbulence.

Observation of ALT oscillation

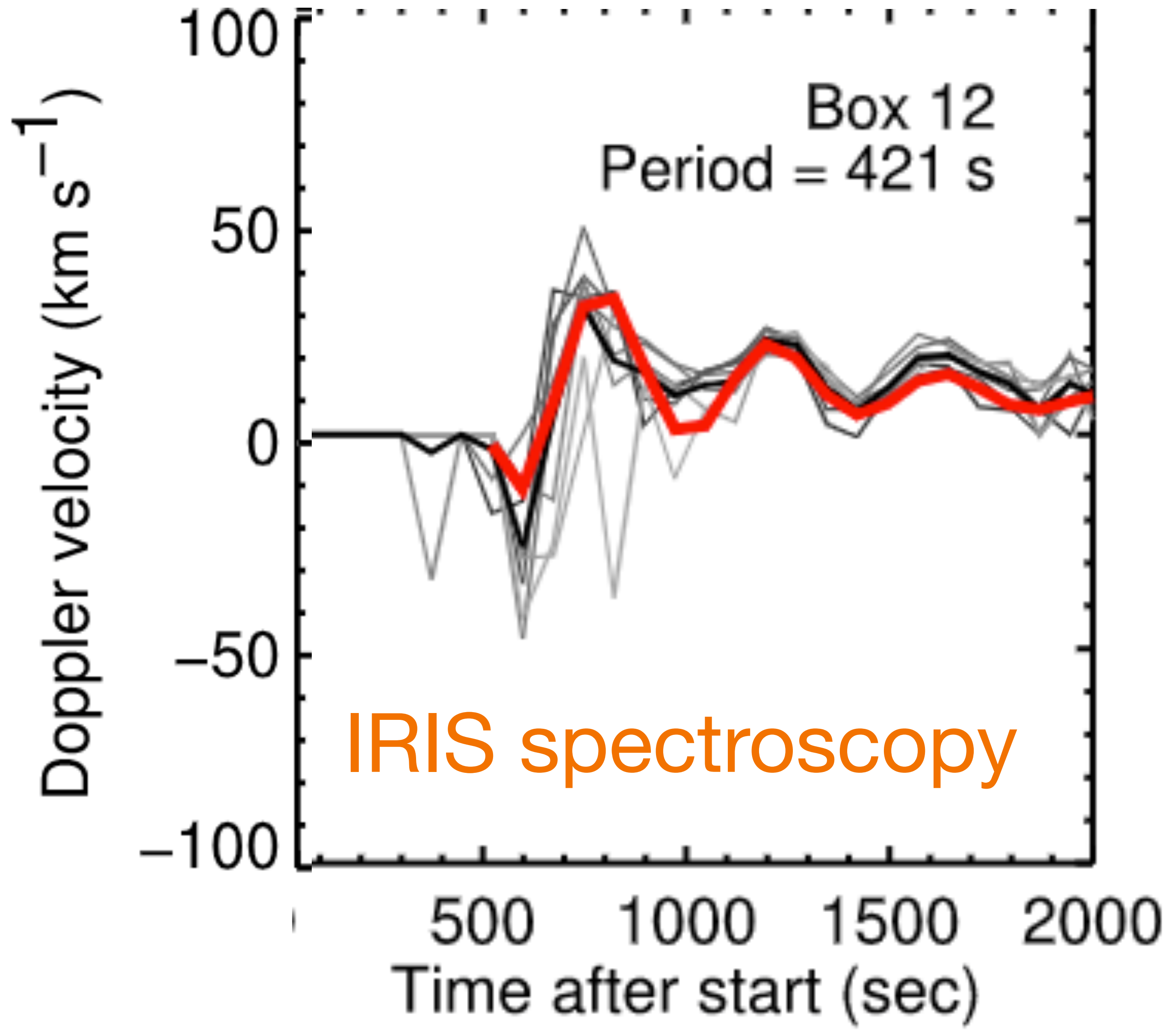
Expected top-down view



Reeves et al. 2020

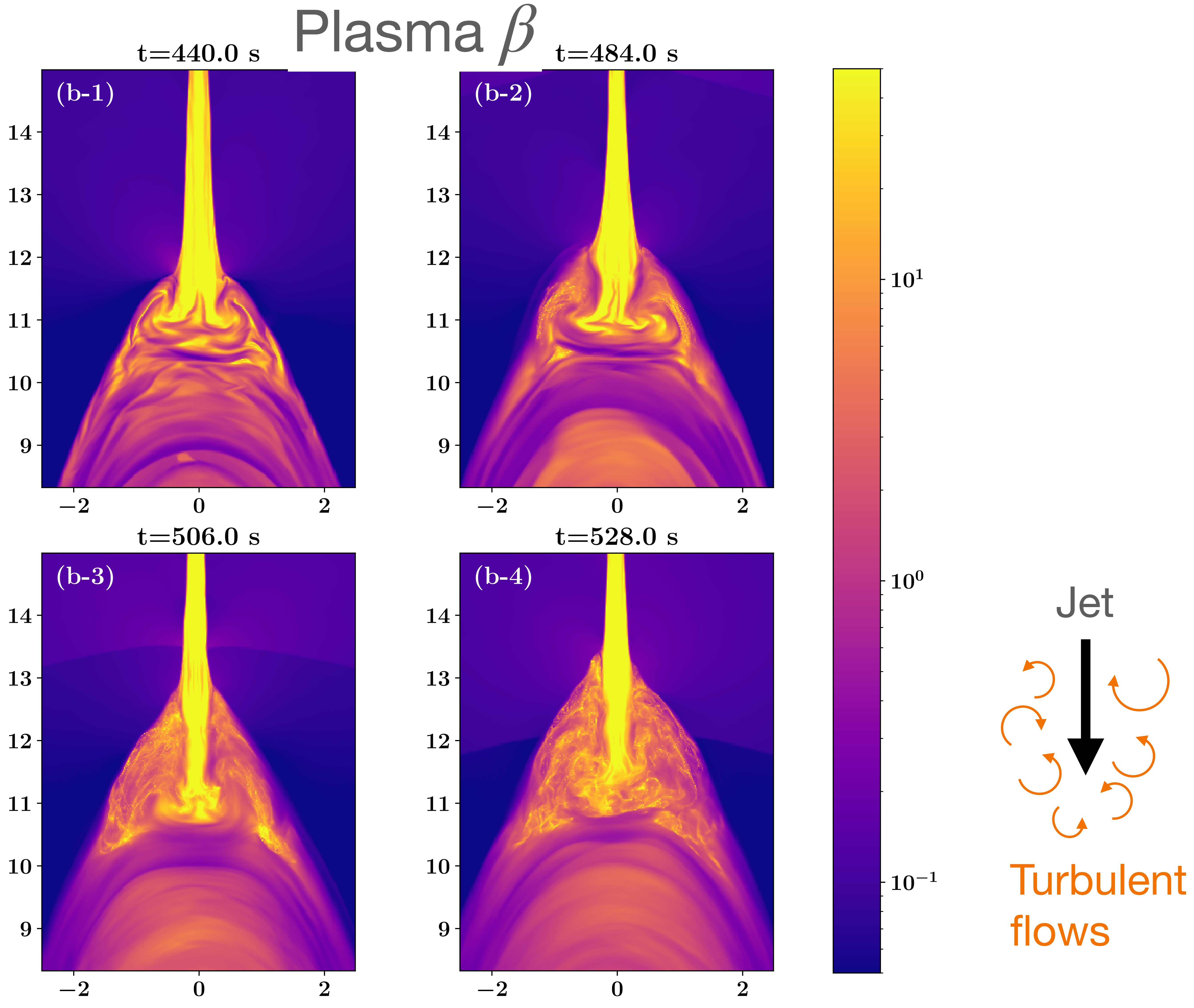


ALT oscillation observed in the Doppler velocity!!



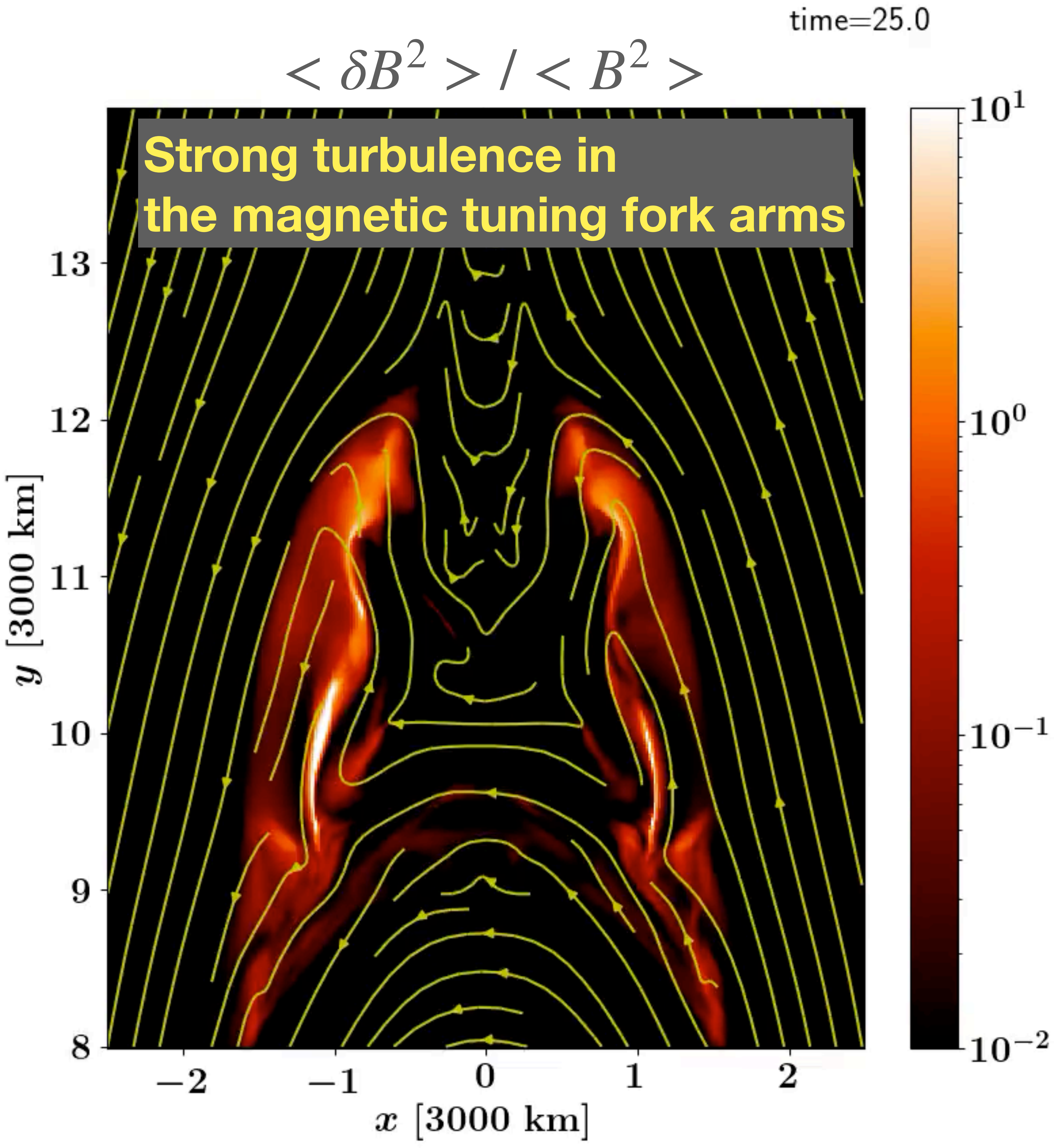
Symmetric ALT oscillation will not be able to produce that signal.
So, the ALT oscillation should be asymmetric, as the 3D model indicates.

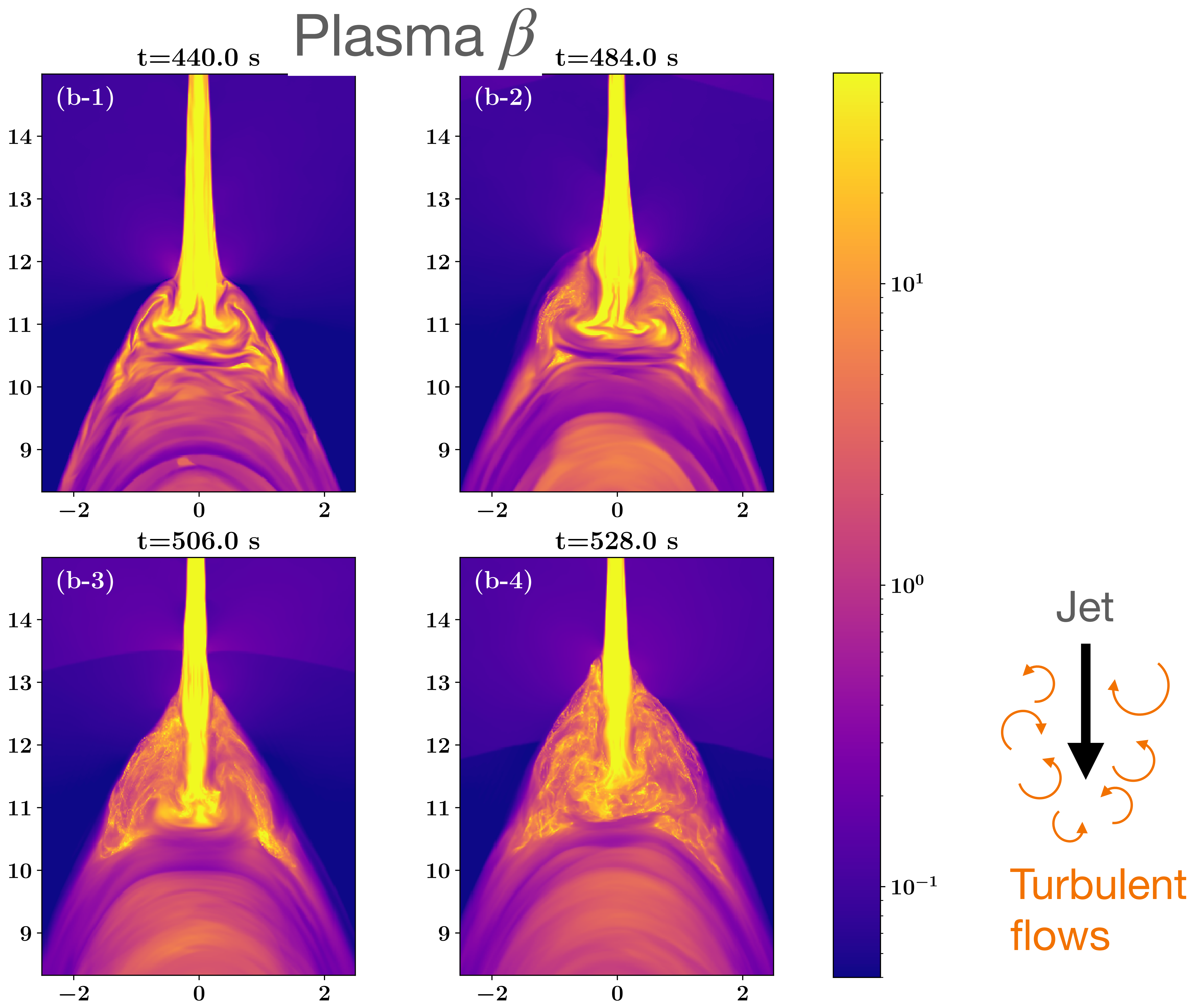
Spatial distribution of turbulence



Turbulent flows surround the lower end of the reconnection jet

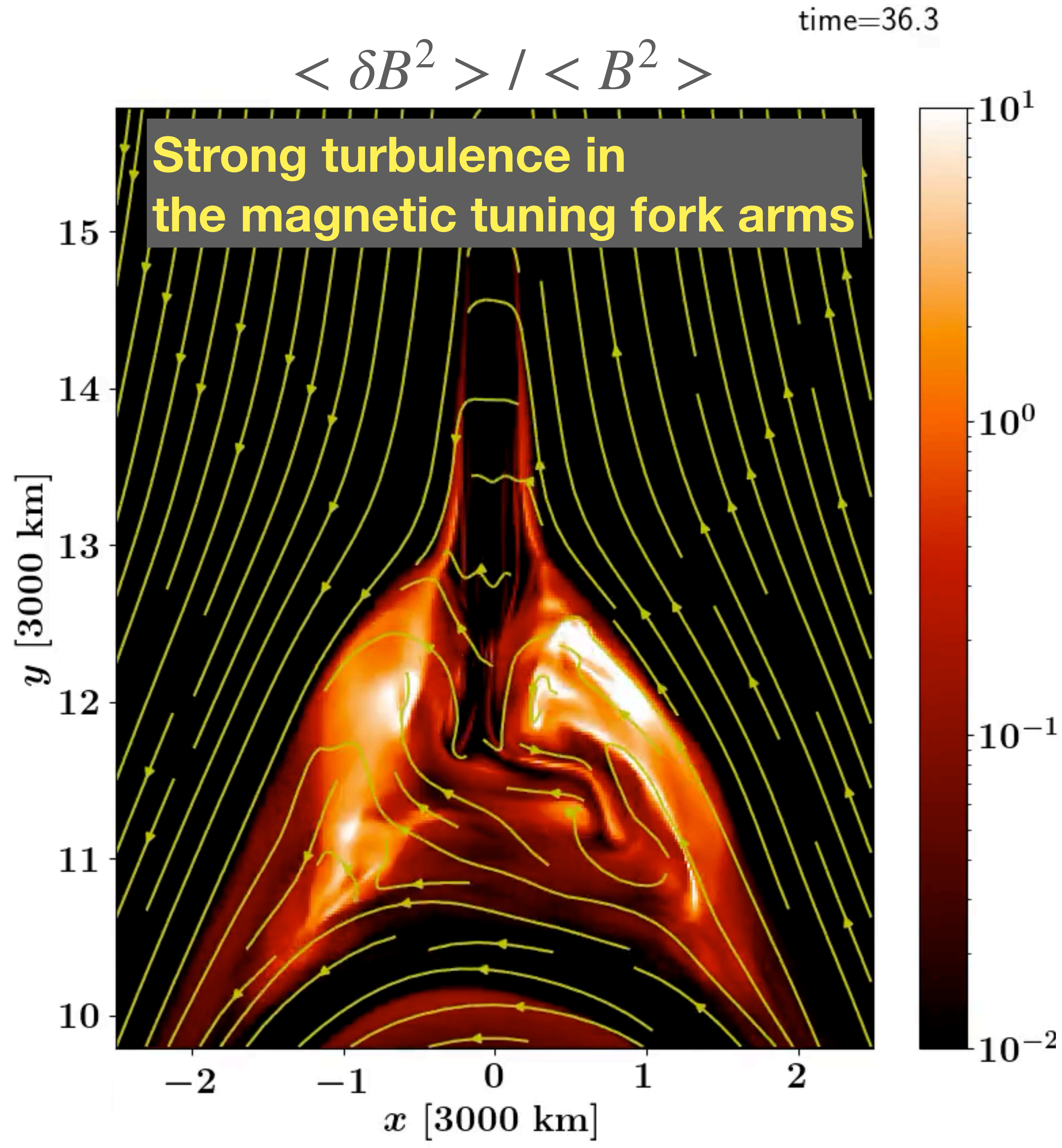
Spatial distribution of turbulence



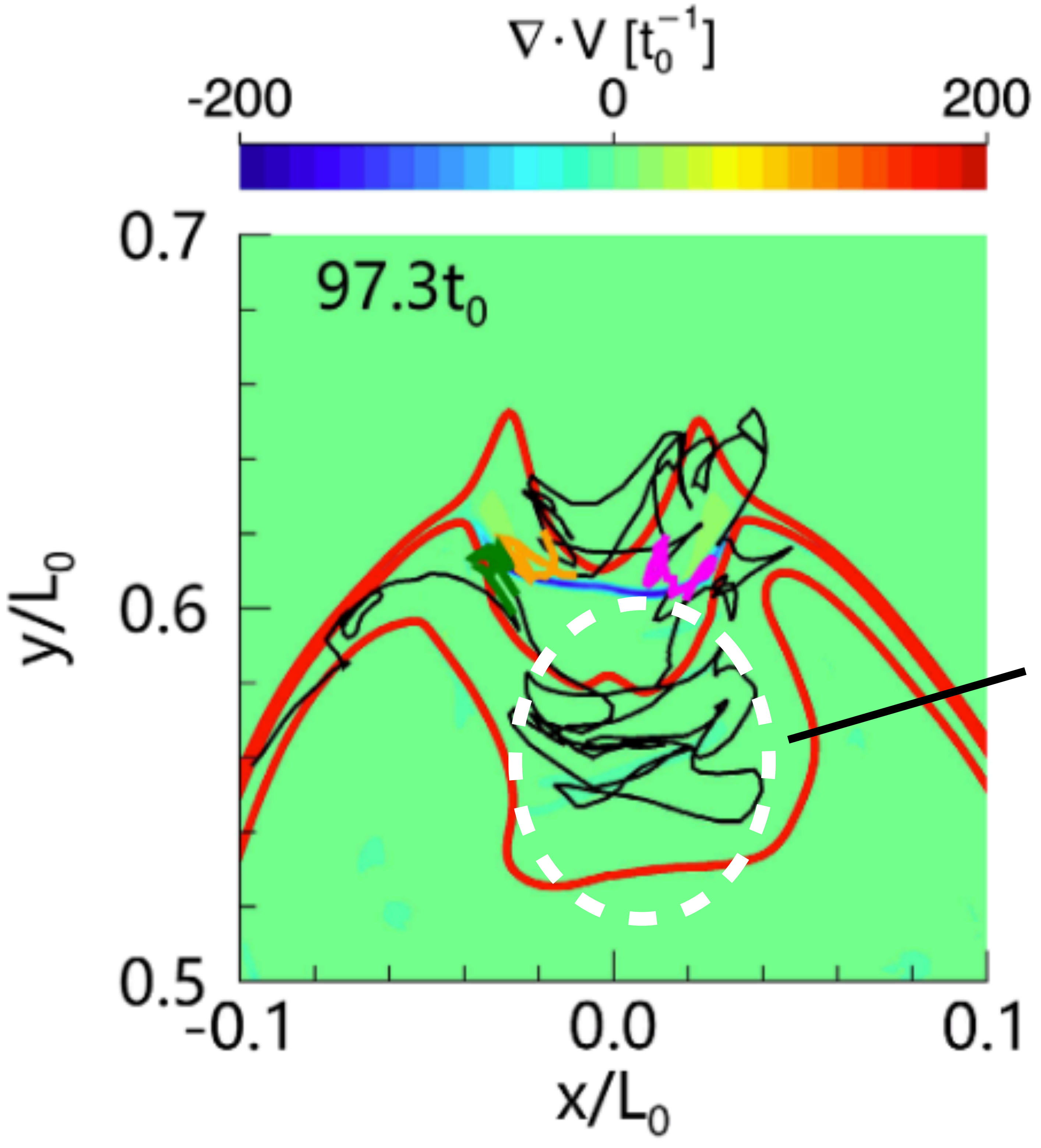


Turbulent flows surround the lower end of the reconnection jet

Spatial distribution of turbulence



Strength of turbulence is highly **inhomogeneous**.
Weak turbulence just behind the termination shock
(negative effect for DSA?).

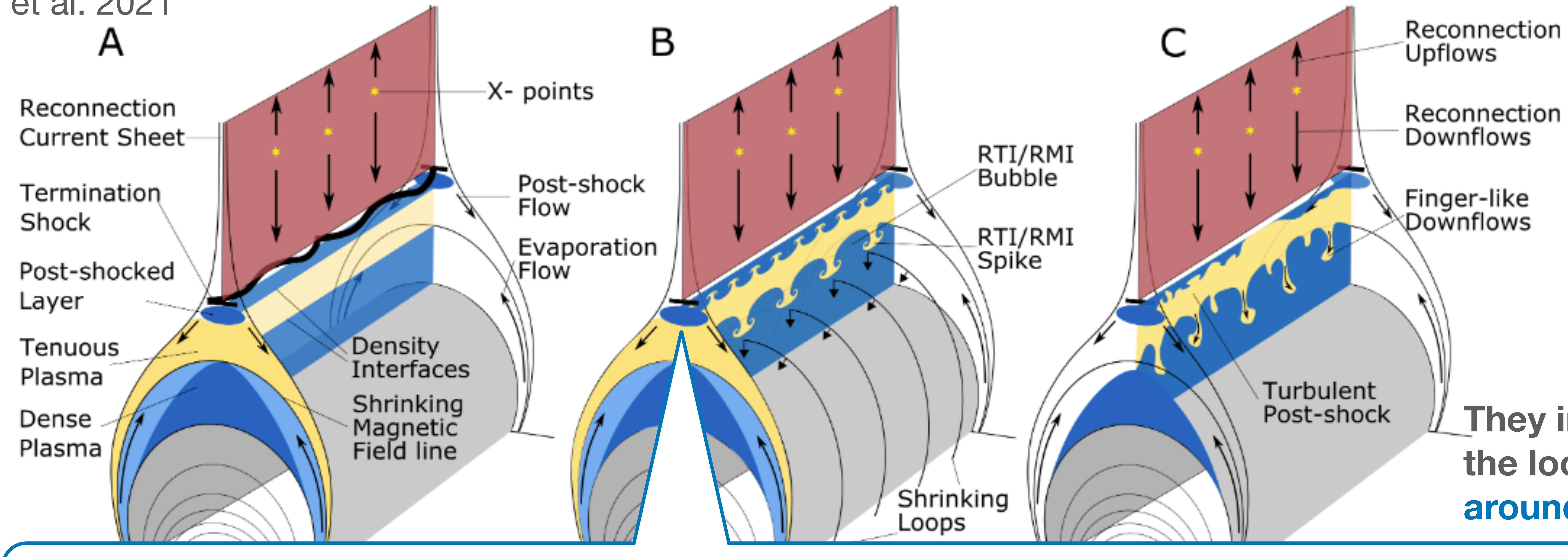


Kong et al. 19

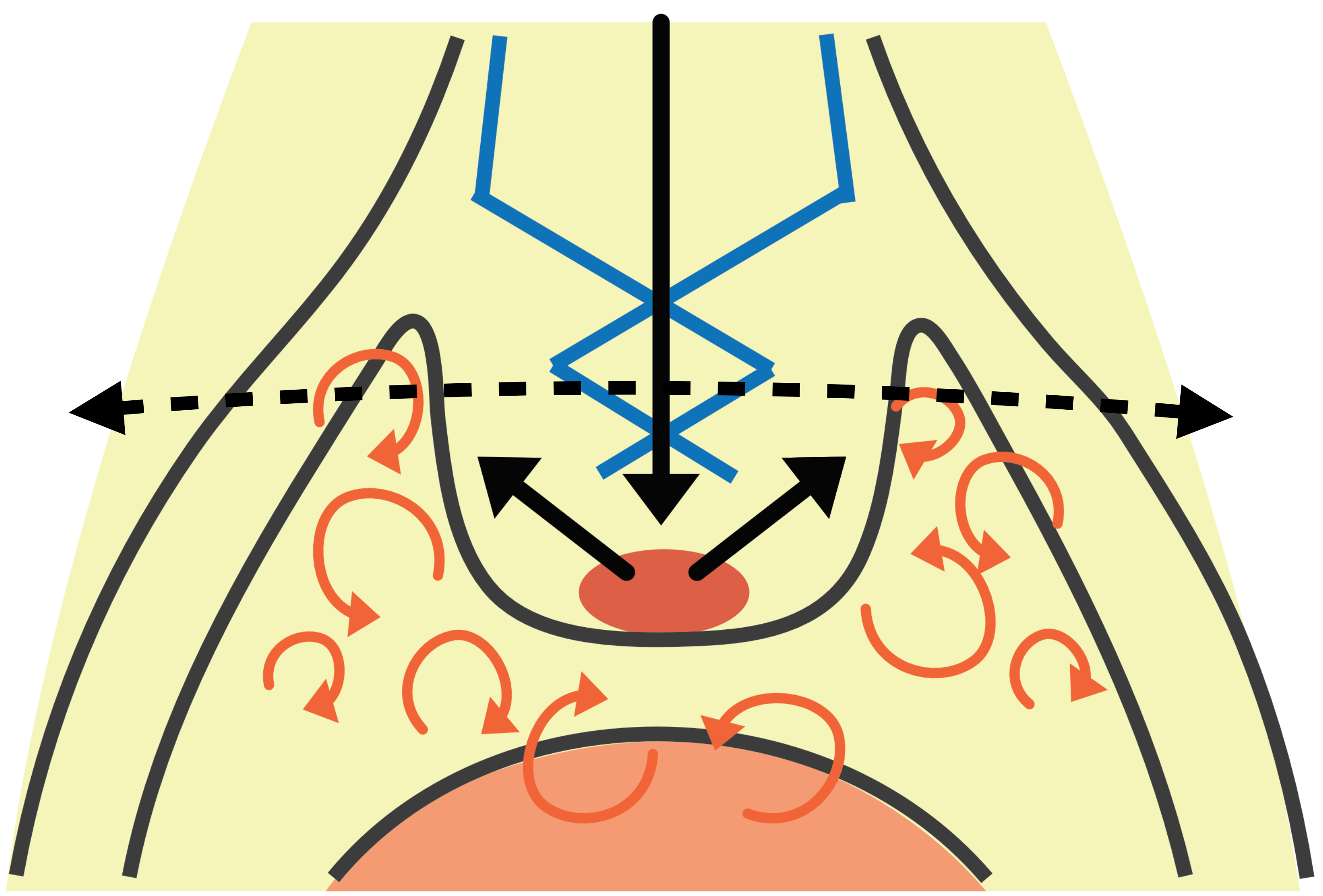
This region may not
be as turbulent
as assumed in the model.
We need more considerations.

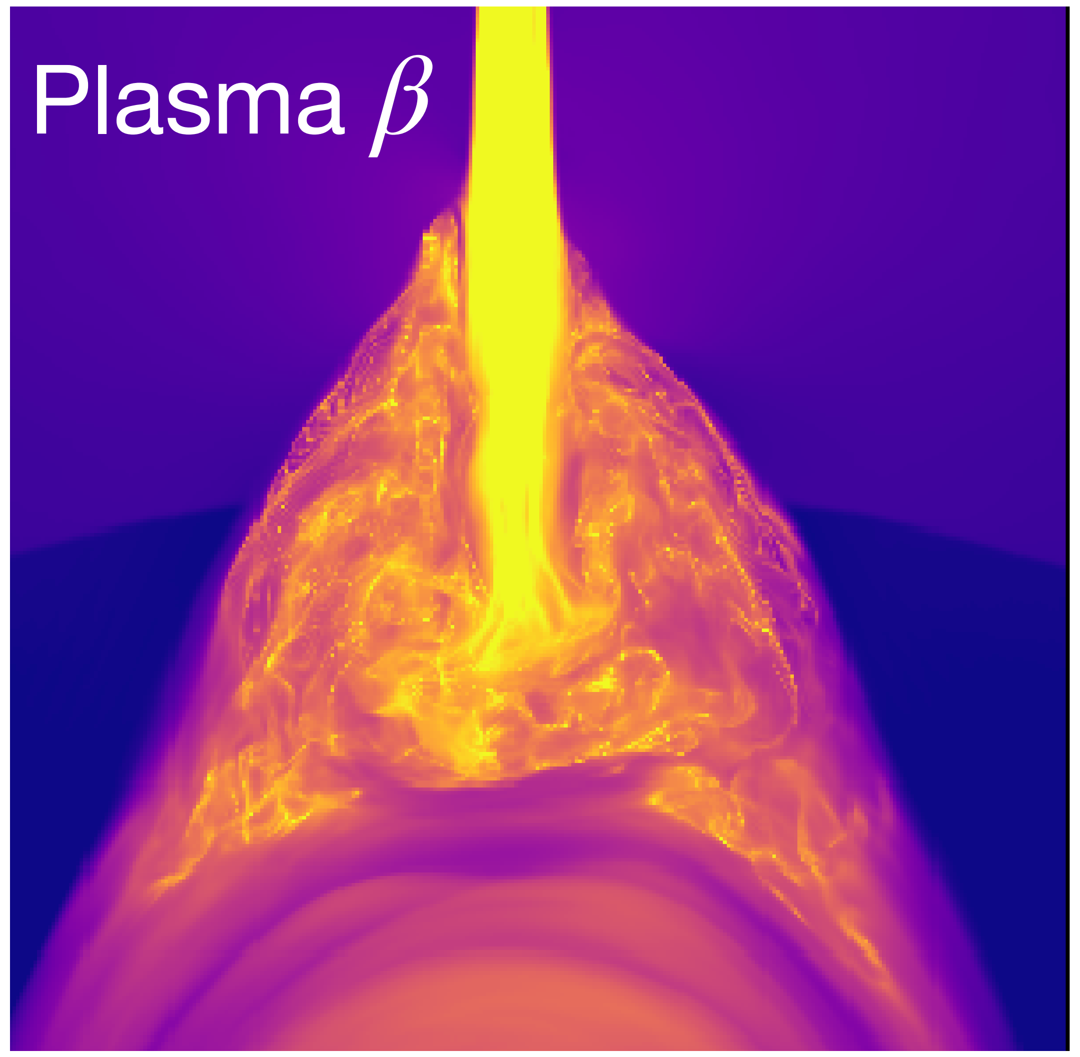
A short summary of the ALT structure

Shen et al. 2021



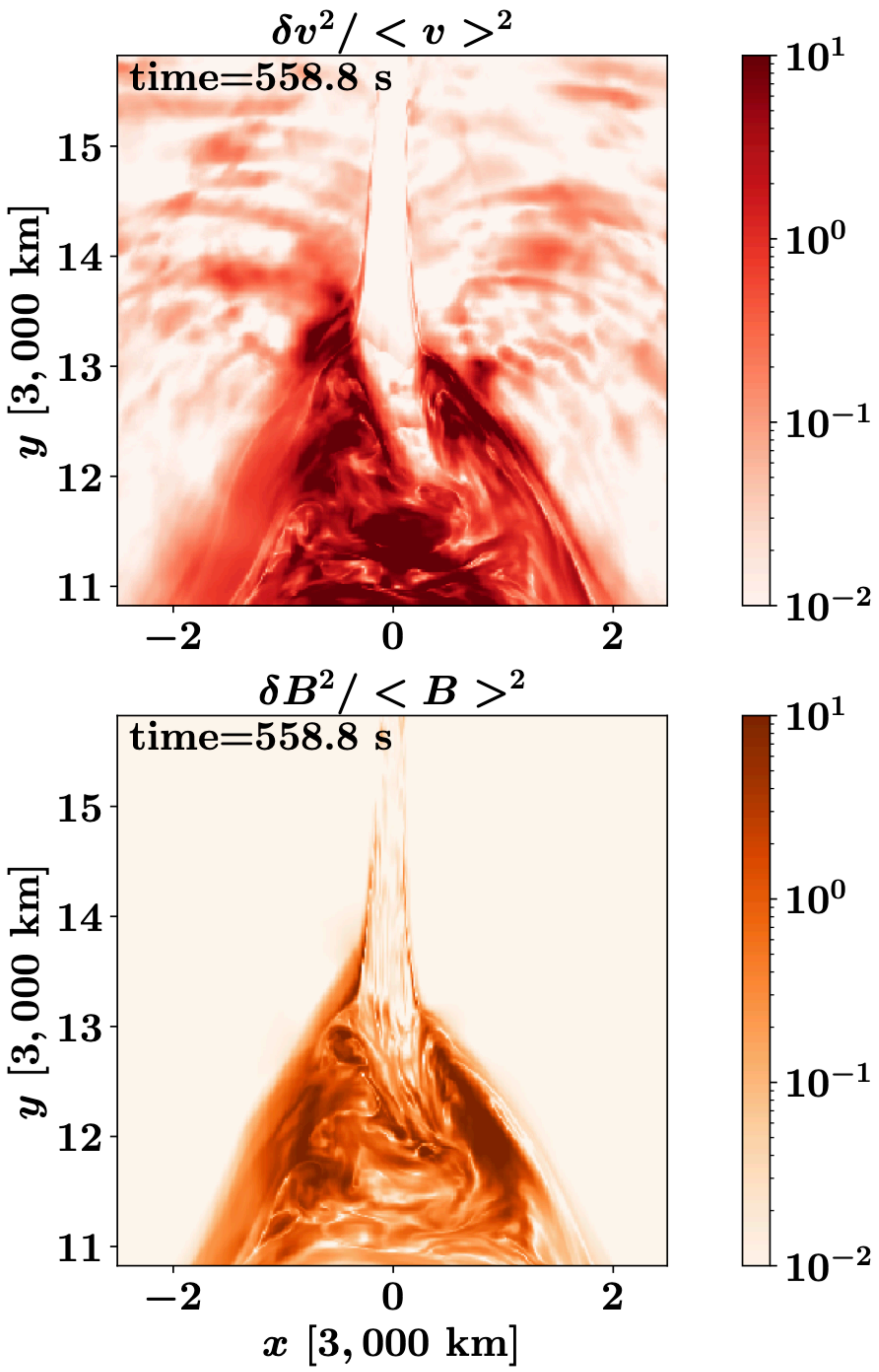
They investigated the local generation of turbulence around the lower end of the jet





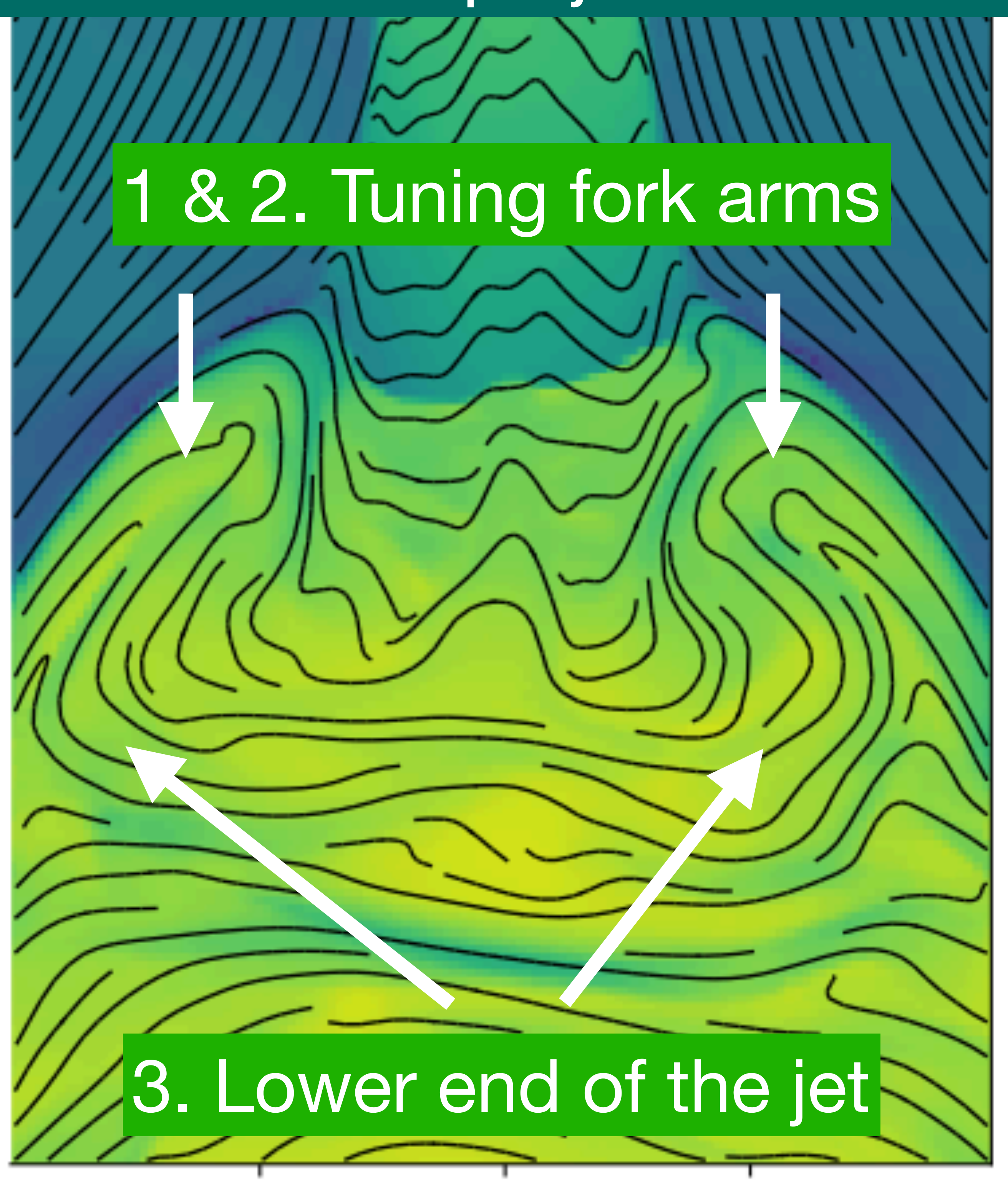
- Multiple termination shocks
- **Local generation of turbulence** (the lower end of the jet and **two arms of the magnetic tuning fork**)
- ALT oscillation

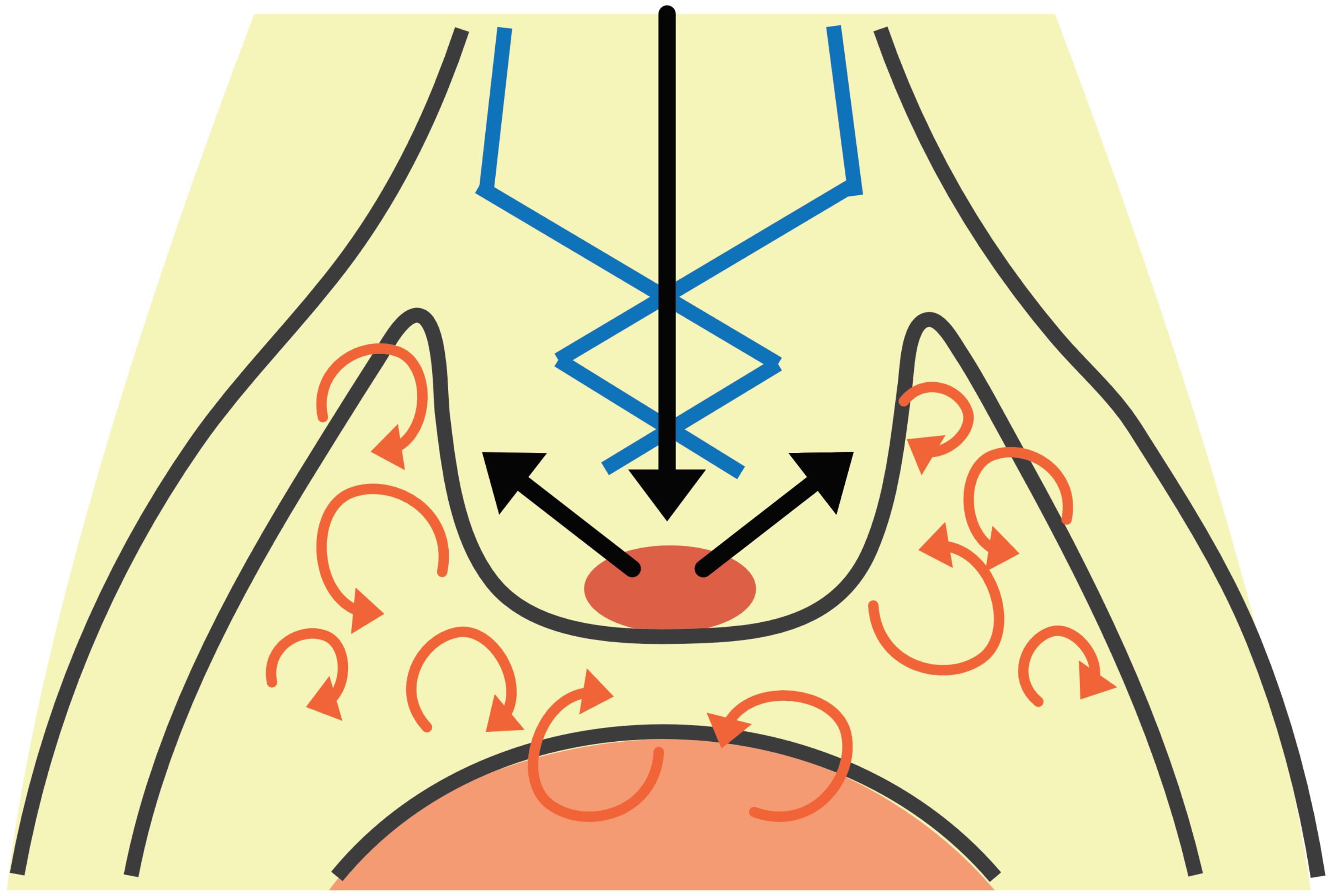
Origin of turbulence?



Strong turbulence in
the magnetic tuning fork arms.

Gas pressure with projected B-field lines

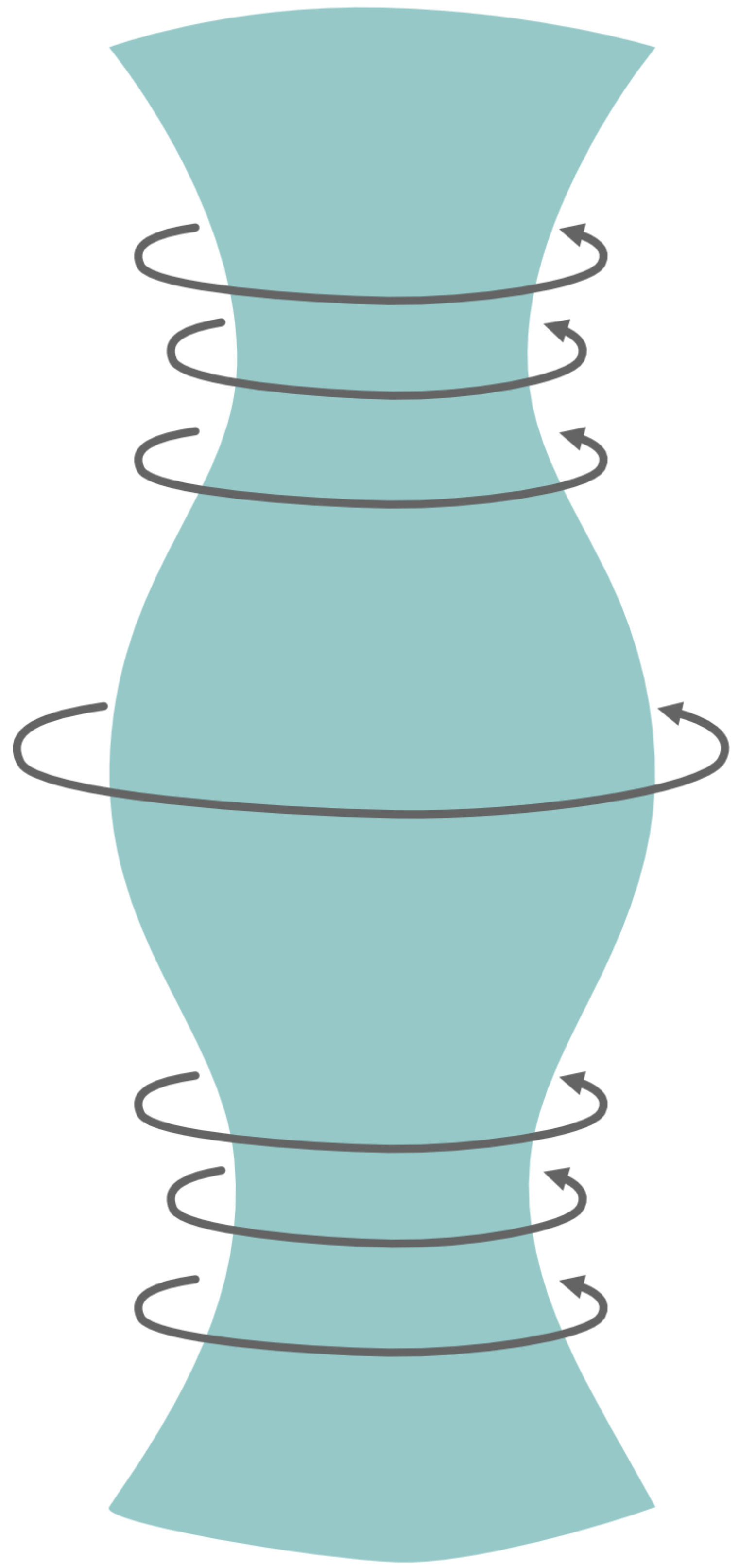




High pressure gas is confined
by a curved magnetic field ("bad curvature")

Three (or four) bad curvature regions
—> the pressure-driven instability may grow

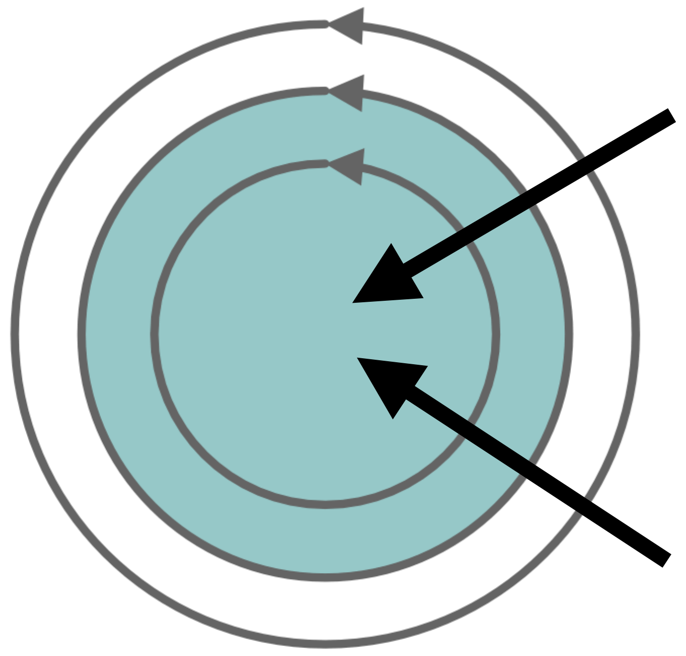
The pressure-driven instability



Assume a cylindrical plasma confined by a purely toroidal field.

1. Set a MHD equilibrium plasma ($-\nabla p + \boldsymbol{J} \times \boldsymbol{B} = \boldsymbol{0}$)
2. Shrink magnetic loops
3. B increases
4. Inward magnetic tension force increases
5. Nothing can overcome the inward force
6. Instability:
   uniform in the azimuth direction: the sausage/interchange mode
   nonuniform : **the ballooning mode**

High pressure gas confined by a curved magnetic field can become unstable.



∇p

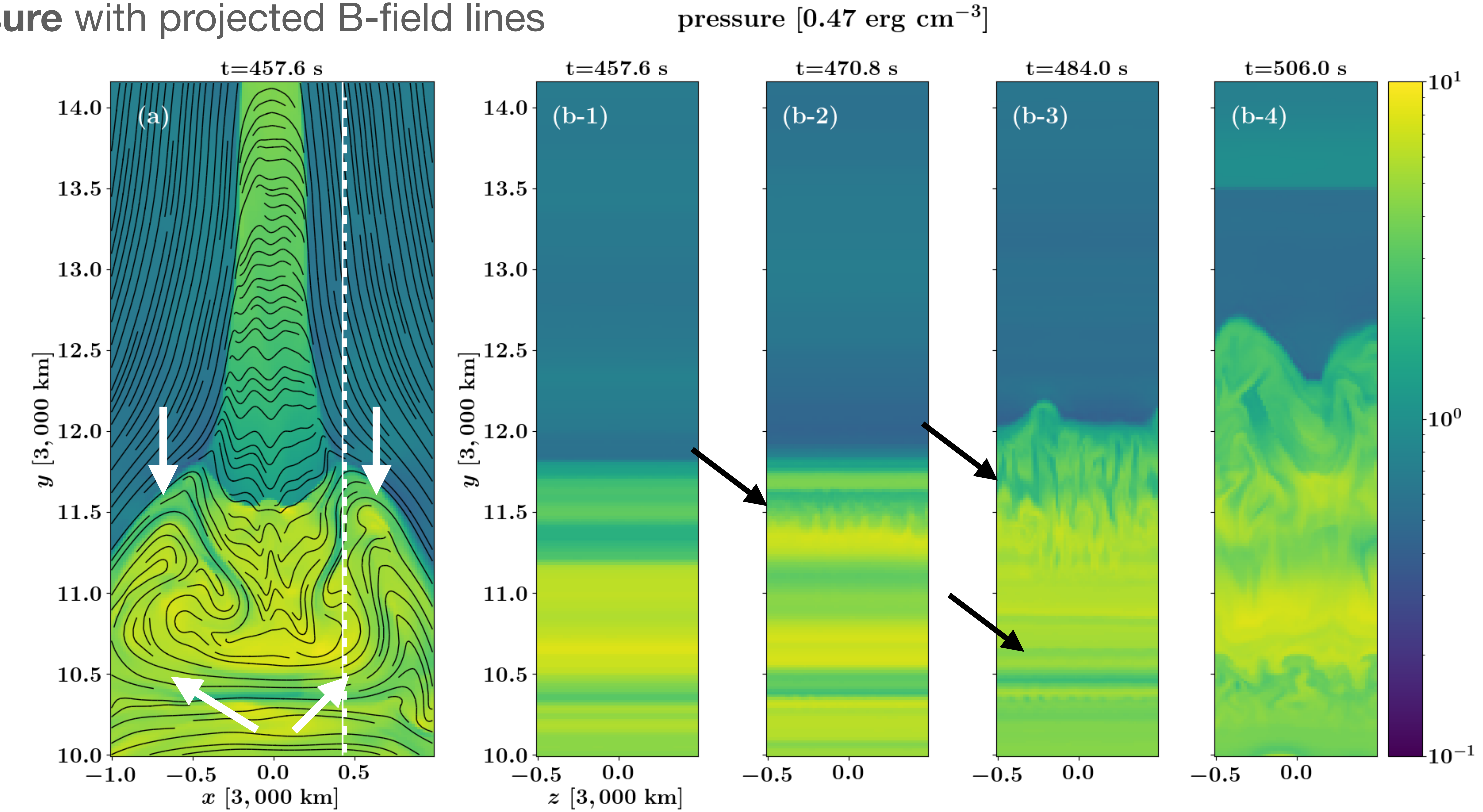
$\boldsymbol{\kappa} = (\boldsymbol{b} \cdot \nabla)\boldsymbol{b}$, curvature

In other words,
plasma with "bad curvature" regions ($\boldsymbol{\kappa} \cdot \nabla p > 0$) can become unstable.

Many similarities to the Rayleigh-Taylor type instability.

Development of the instability

Gas pressure with projected B-field lines

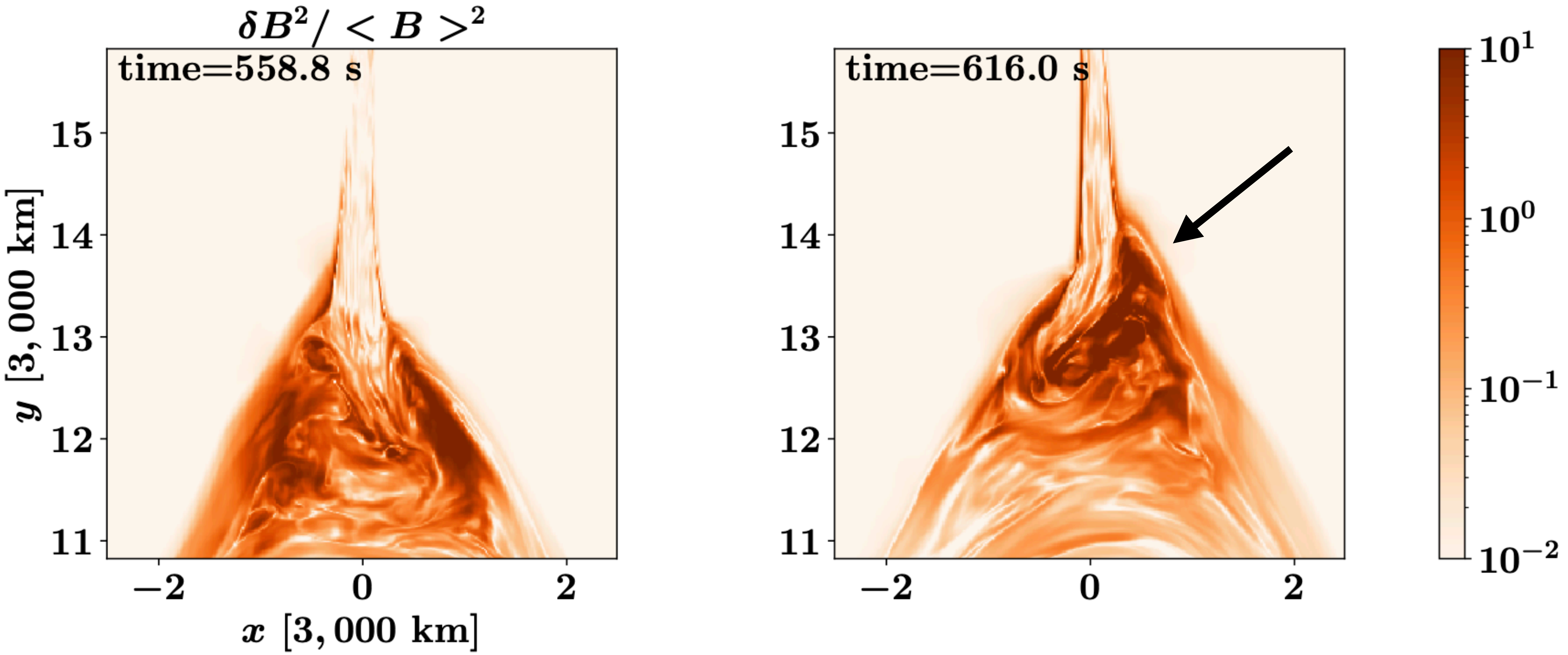


Three (or four) bad curvature regions:

- Two arms of the magnetic tuning fork
- The lower end of the reconnection jet

- **Finger-like structures (Ballooning modes) appear around all the three regions.**
- **The instability grows faster in the arms.**

Turbulence in the magnetic tuning fork arms



The growth rate

$$\gamma \sim \sqrt{\frac{|\nabla p|}{\rho R_c}} \sim \frac{c_{s,\mathrm{ALT}}}{R_c}$$

$$= 0.3\ \mathrm{s}^{-1} \left(\frac{c_{s,\mathrm{ALT}}}{300\ \mathrm{km\ s}^{-1}} \right) \left(\frac{R_c}{10^3\ \mathrm{km}} \right)^{-1}$$

where Rc is the radius of curvature.

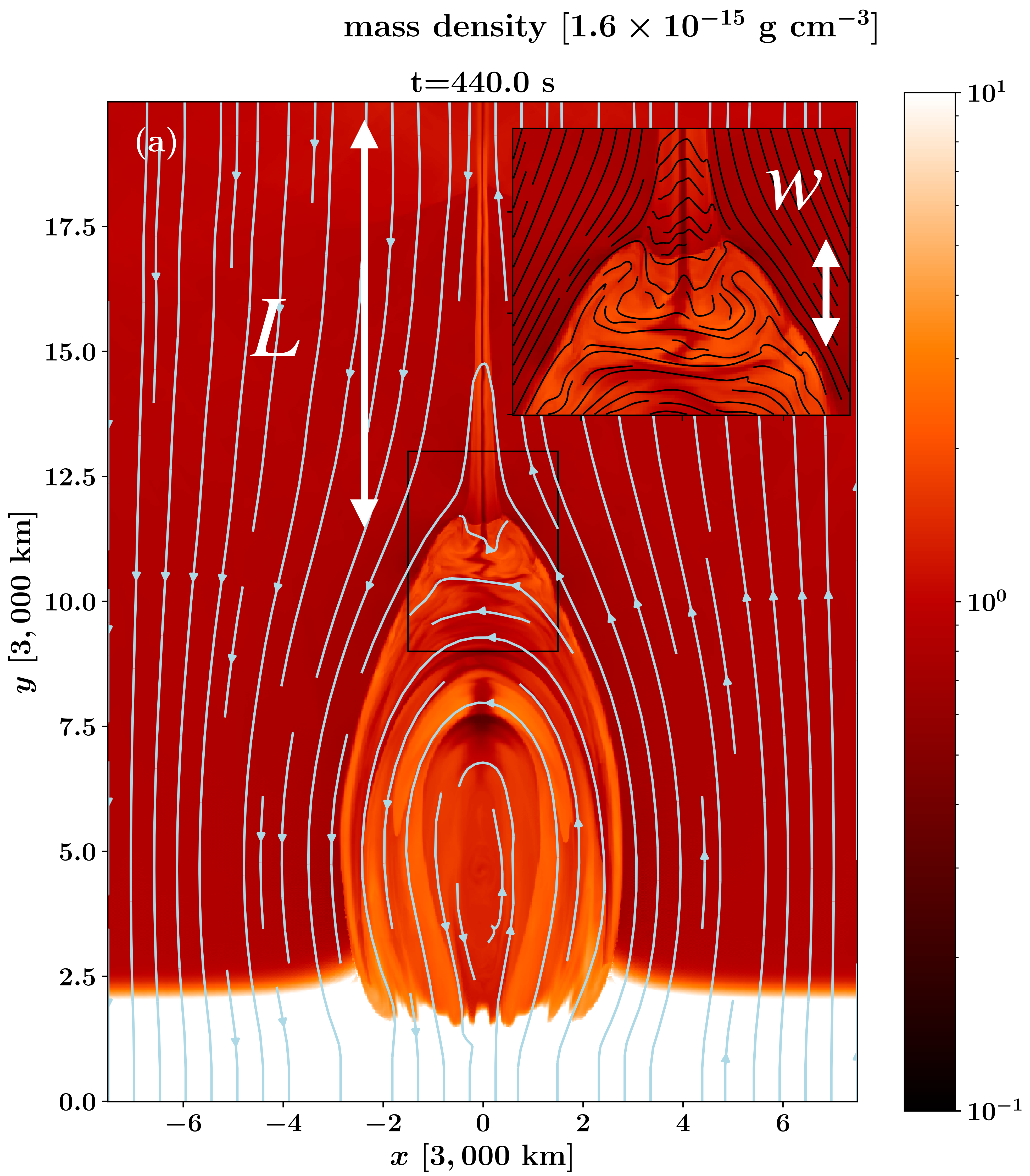
Asymmetric ALT oscillation

—> Increases the pressure gradient in one arm

—> Enhances the growth rate

—> **Promotes the turbulence generation**

Timescales



$t_{\rm bal} = \gamma^{-1} \sim R_c / c_{\rm s,ALT}$: growth timescale

$t_{\rm A,in} = L / v_{\rm A,in}$: Alfven timescale for the system

~reconnection rate   Mach number of the jet

$$\frac{t_{\rm bal}}{t_A} \sim 0.01 \left(\frac{R_c/L}{0.01}\right) \left(\frac{v_{\rm A,in}/c_{\rm s,ALT}}{1}\right)$$

Turbulence can grow instantaneously in flares.

Let's take one step further.

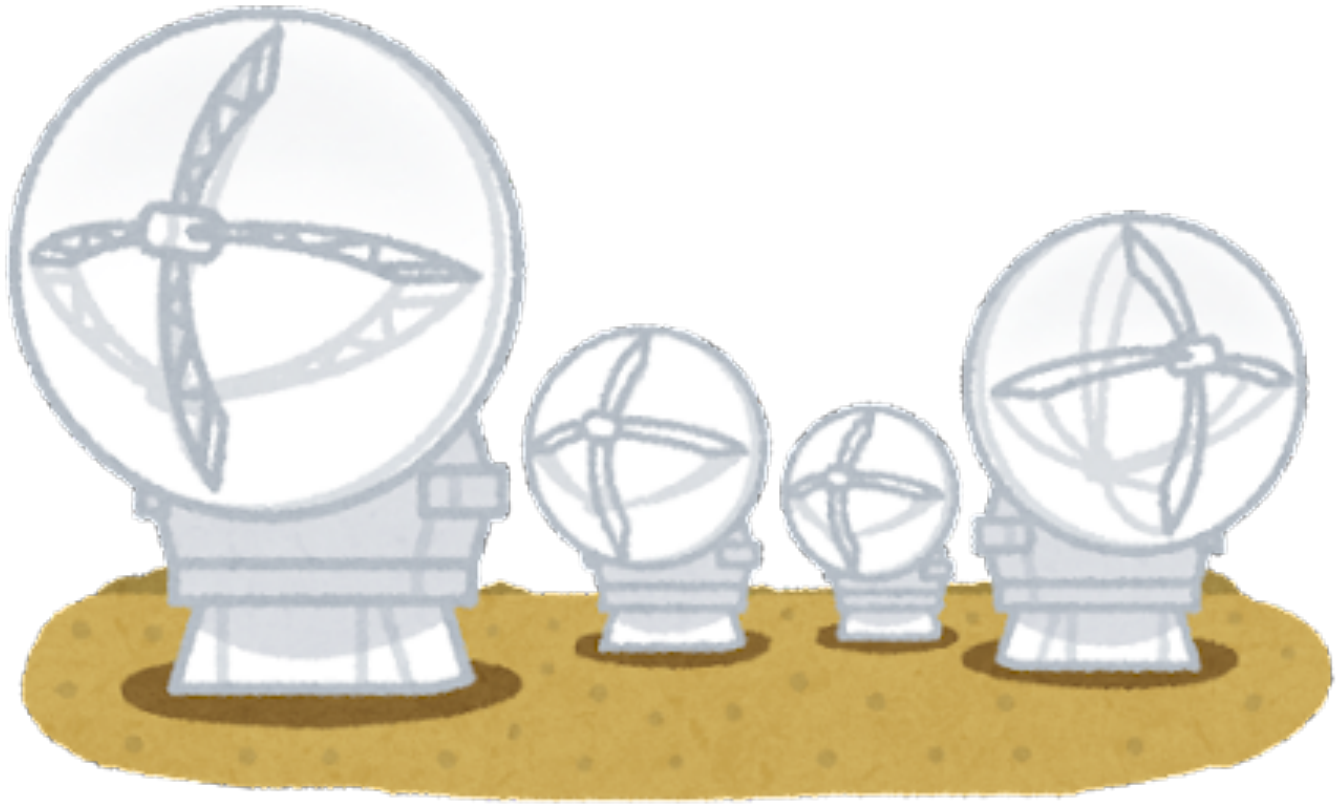
Scaling relation for the model with heat conduction:

Assuming that $R_c \sim w$ and using scaling relation for the Mach number derived in ST & Shibata 16,

$$\frac{t_{\rm bal}}{t_A} \propto \beta_{\rm in}^{2/7} L^{1/7}$$

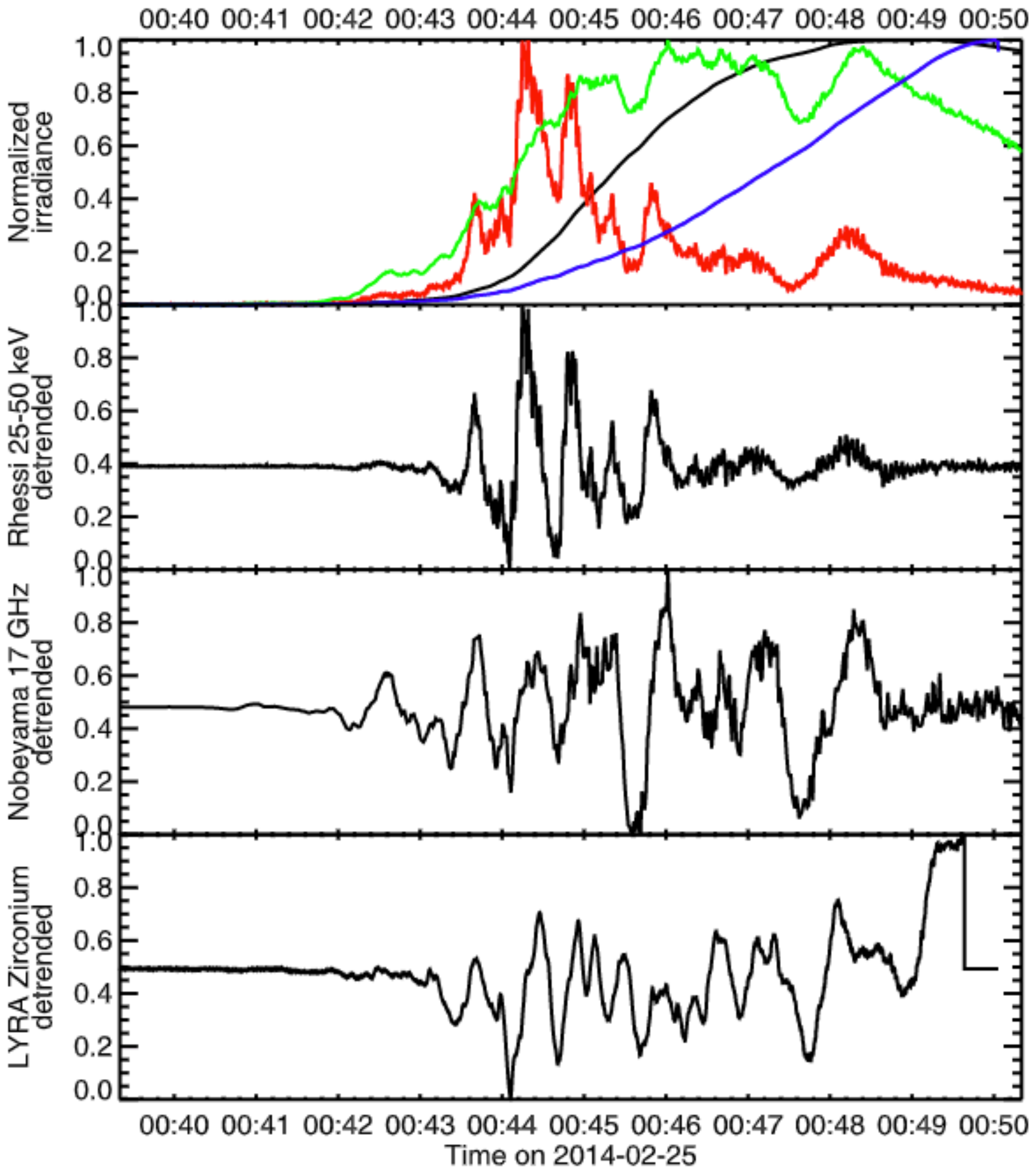
Turbulence will grow more quickly in flares with stronger fields (low beta plasma).

Implications for observations



Oscillations in flares

Quasi-periodic pulsations (QPPs)

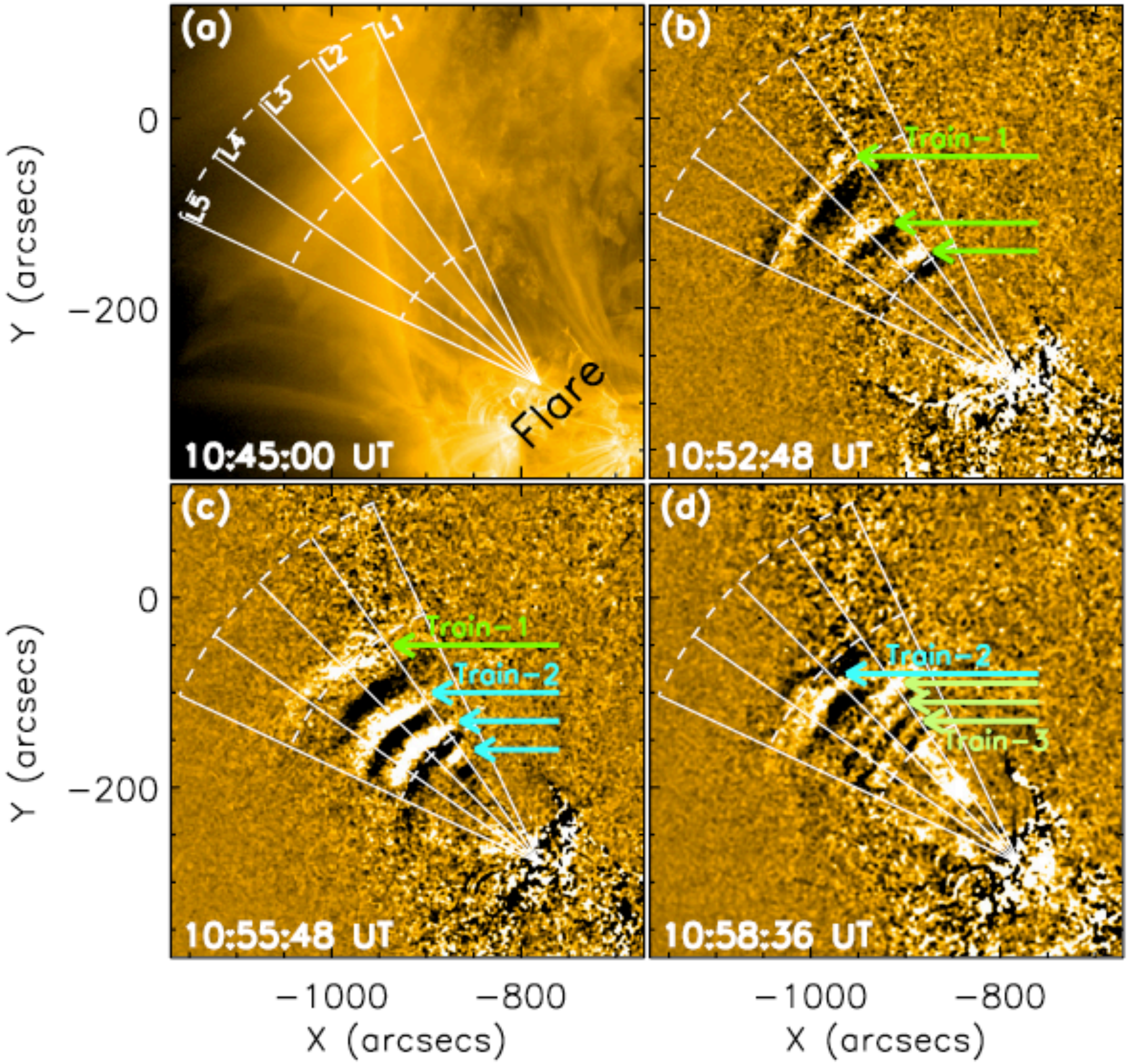


McLaughlin+18

Most prominent in nonthermal emissions

Common origin in some events?

Quasi-periodic propagating fast MHD waves (QPFs)

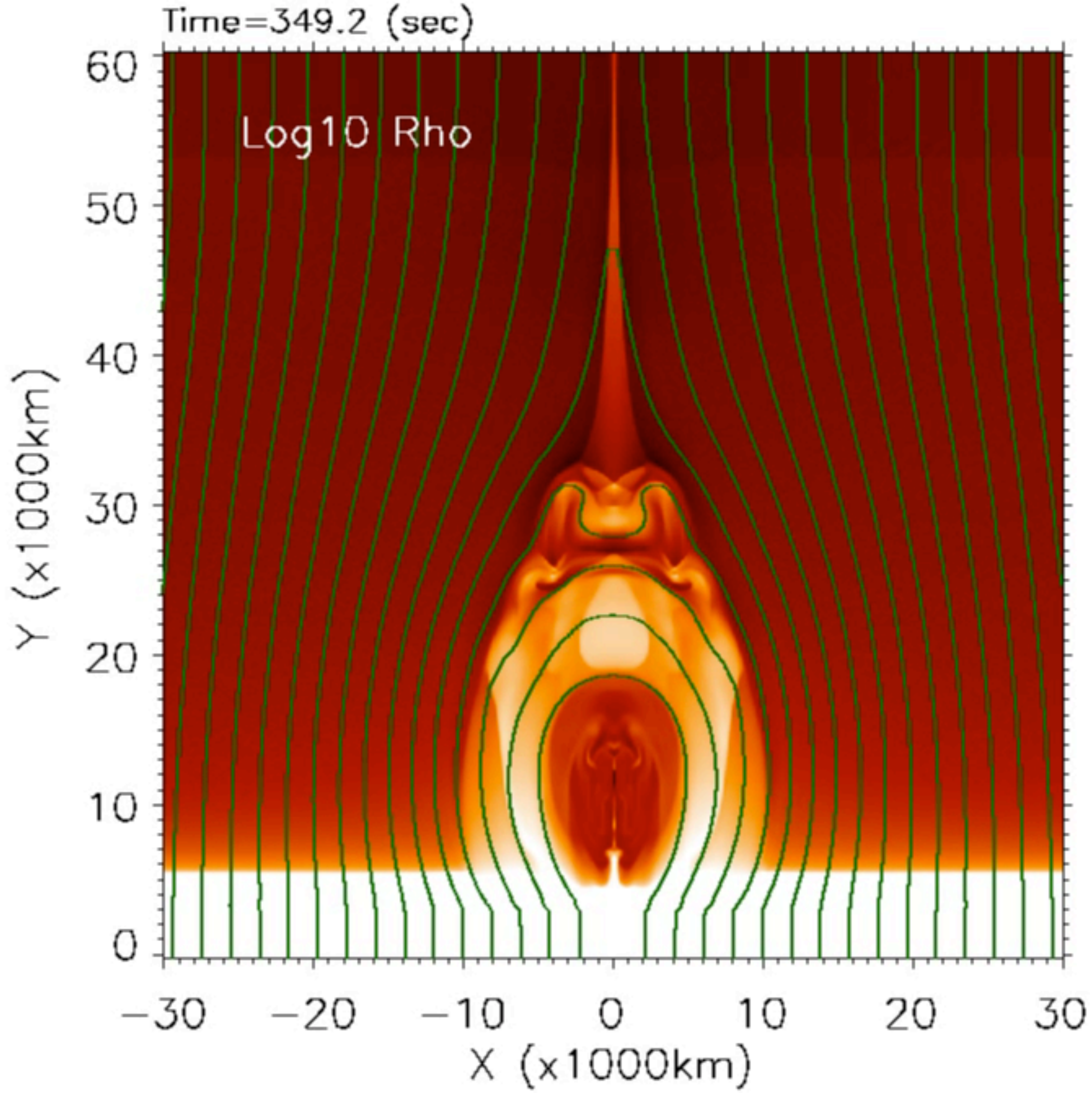


Yuan+13 A&A

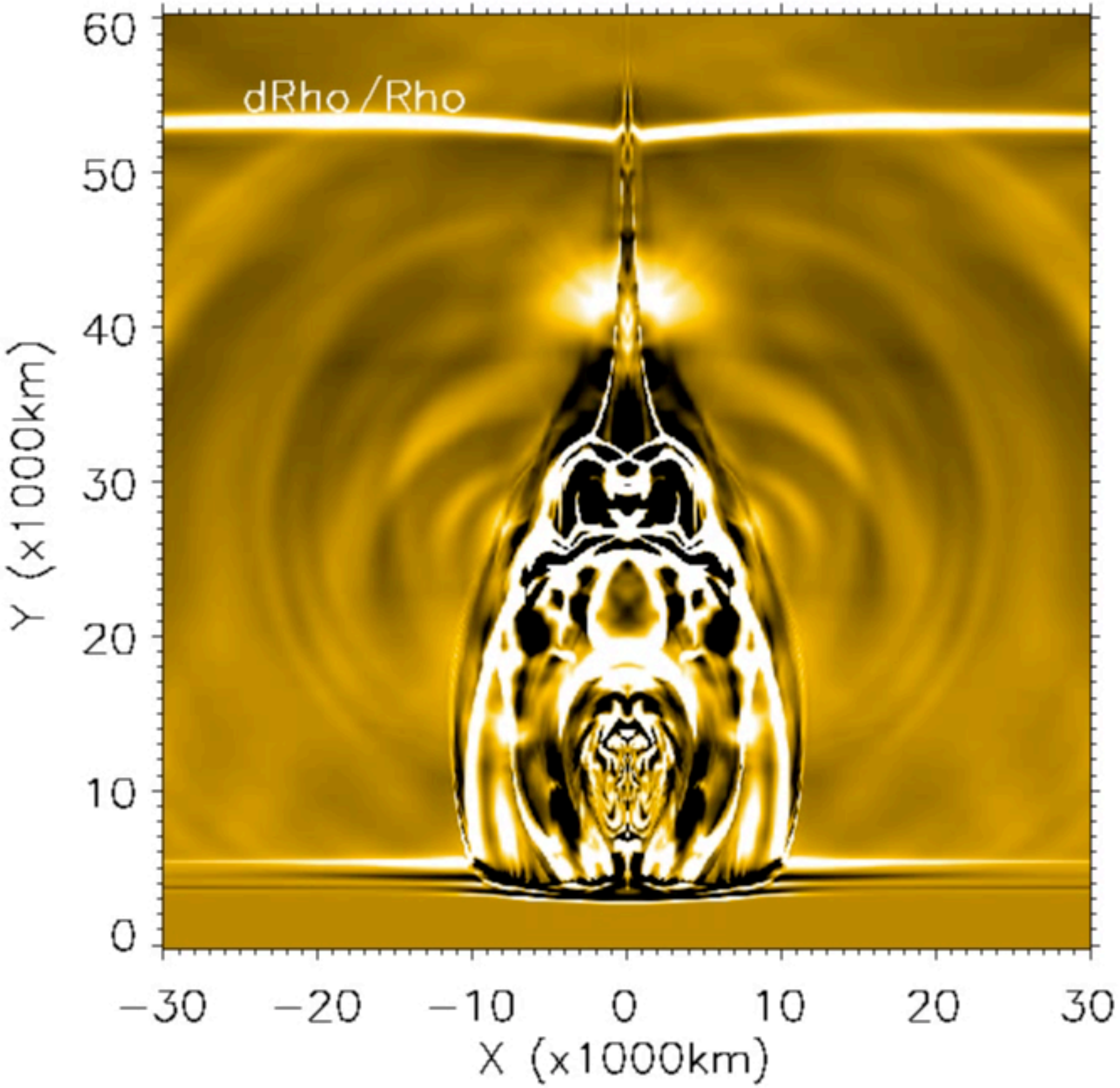
Formation of wave trains is correlated in time with radio bursts in some events (see also Miao et al. 21)

ALT oscillation can produce QPFs (propagating waves)

See ST & Shibata 16



Running diff. $[\rho(\boldsymbol{x},t)-\rho(\boldsymbol{x},t-\Delta t)]/\rho(\boldsymbol{x},t)$

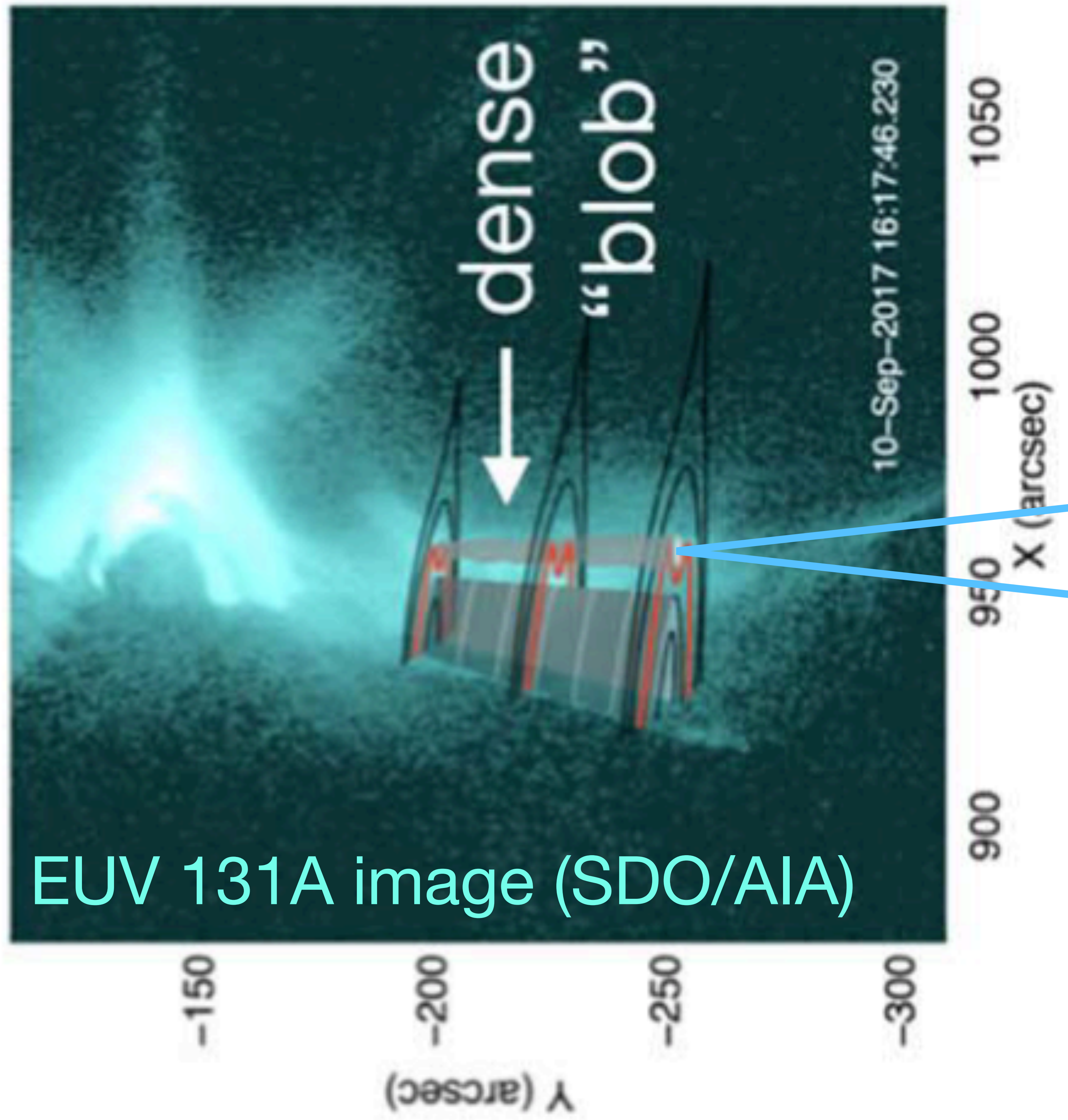


If the ALT region is an crucial site for electron acceleration/trap,
the ALT oscillation may account for both **QPP** & **QPF** in some flares.

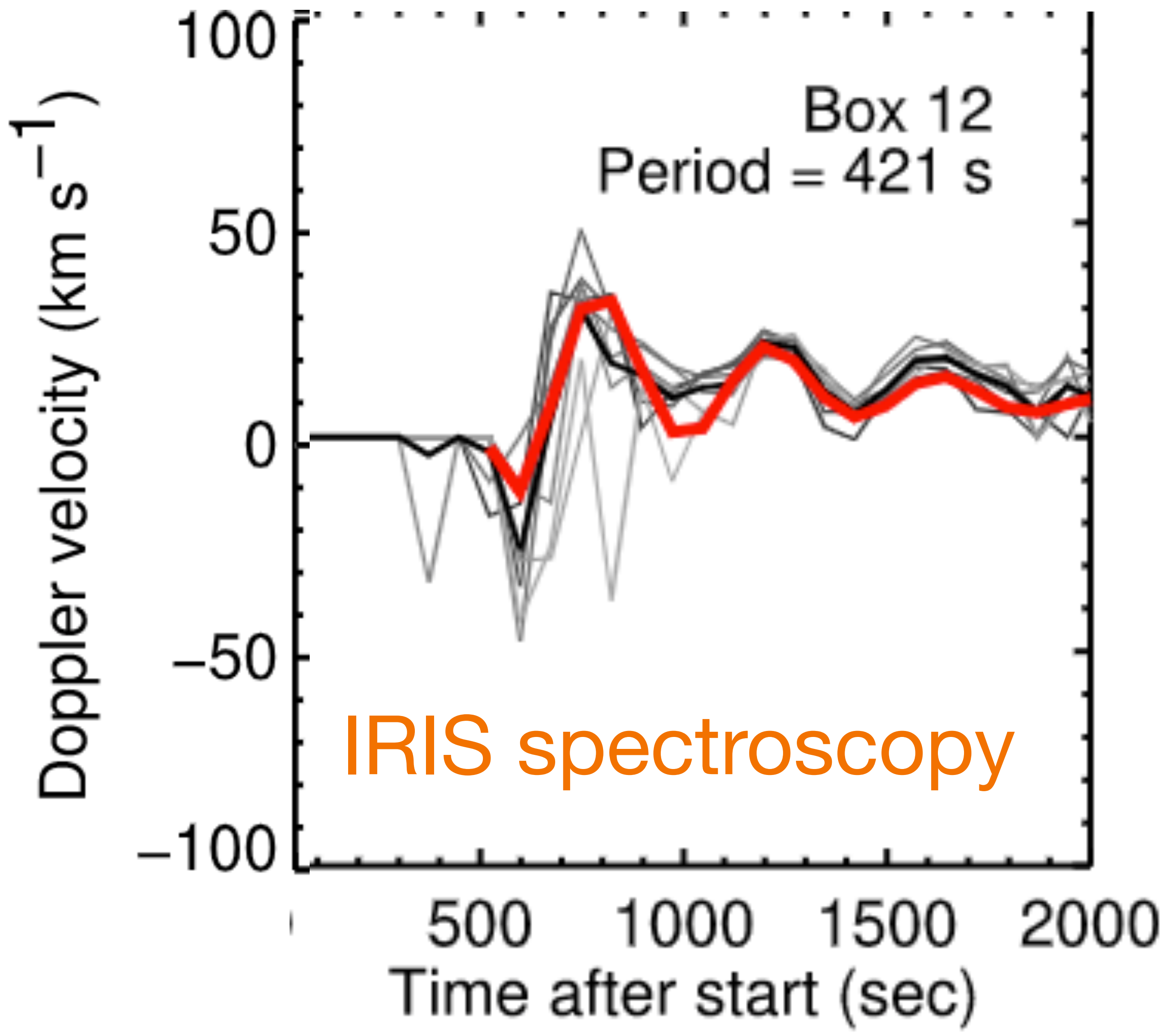
Oscillation in the ALT region

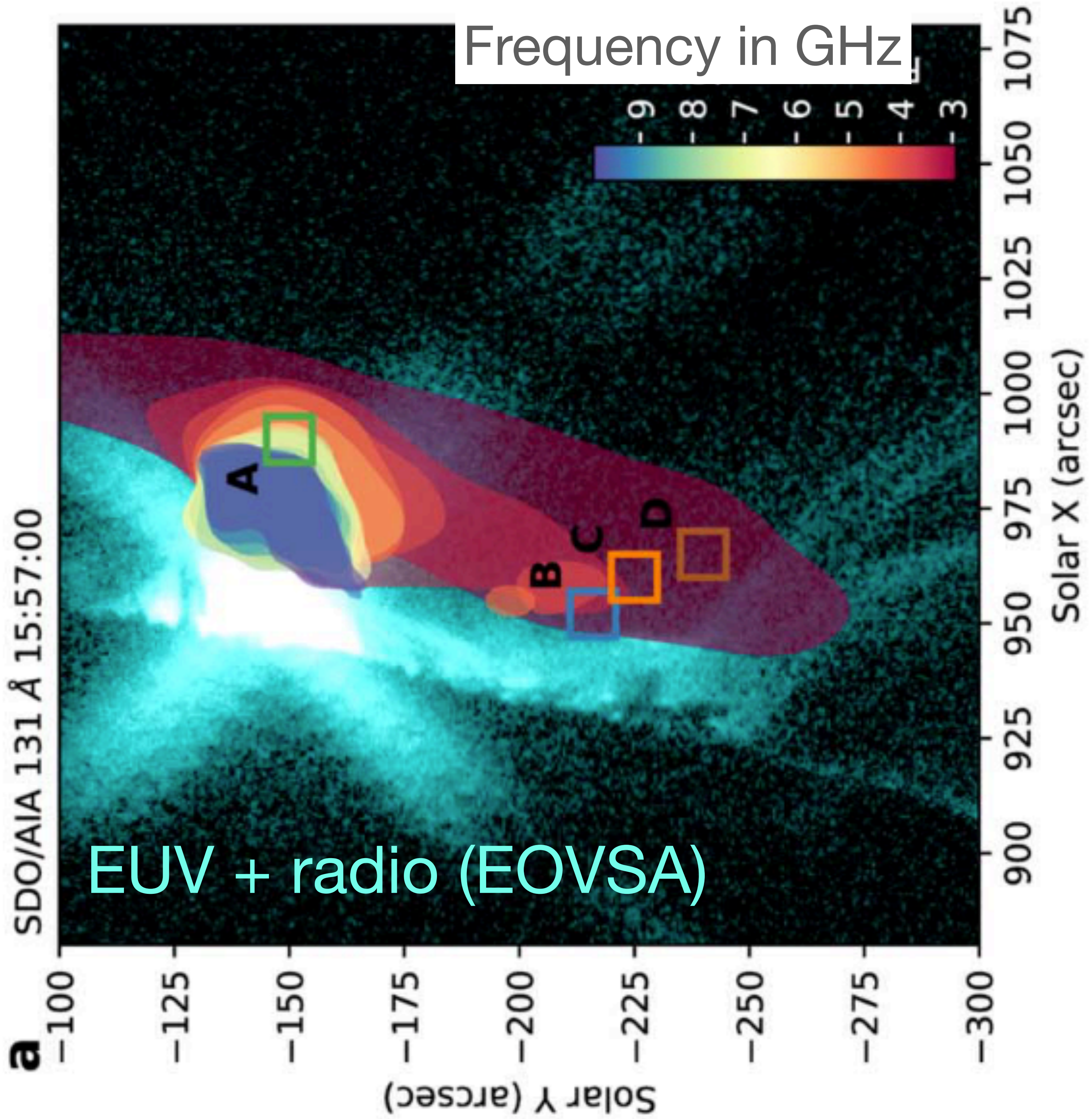
MHD models suggest that "Locally oscillating region = ALT region"

Reeves et al. 2020



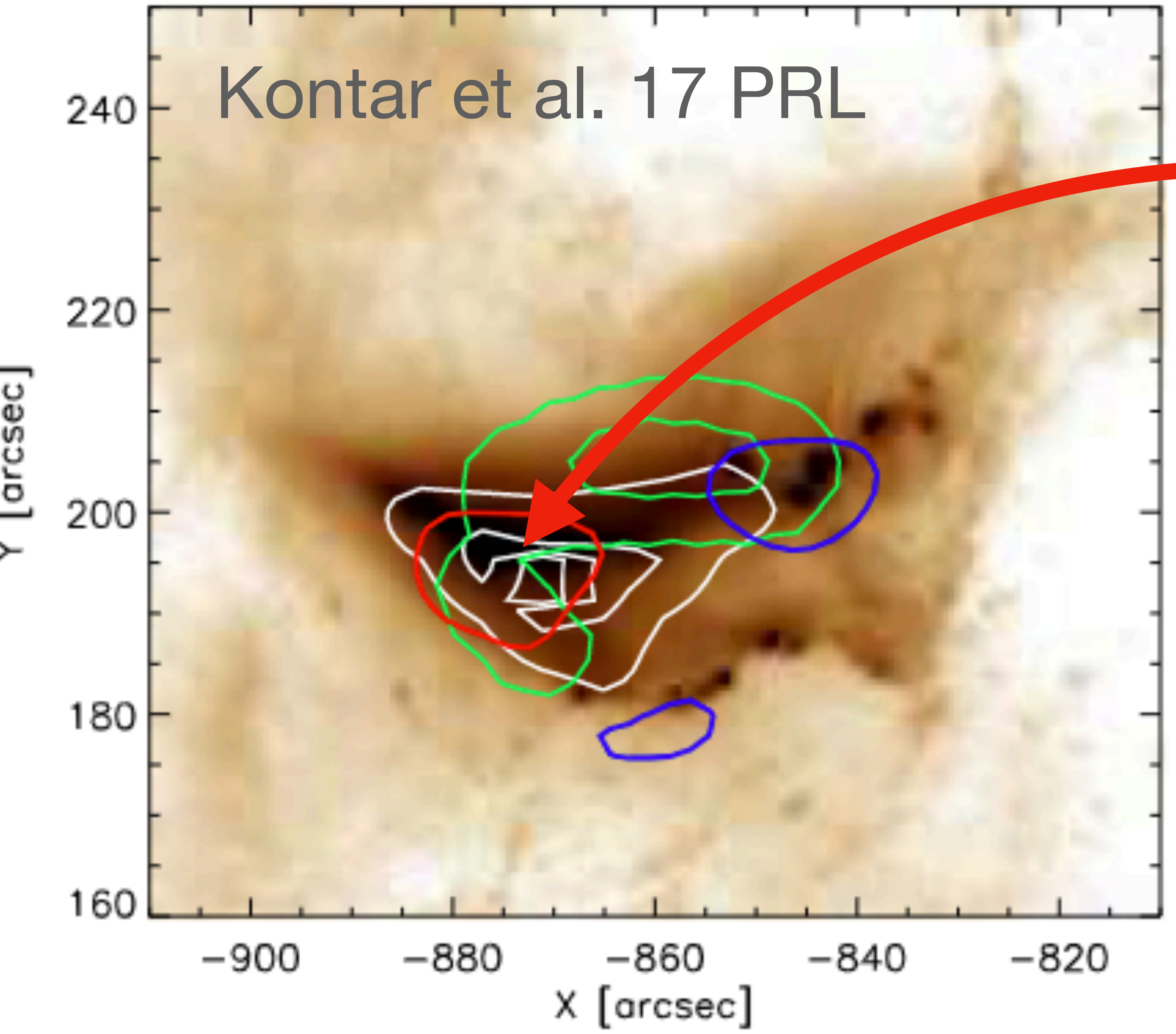
ALT oscillation observed in the Doppler velocity!!



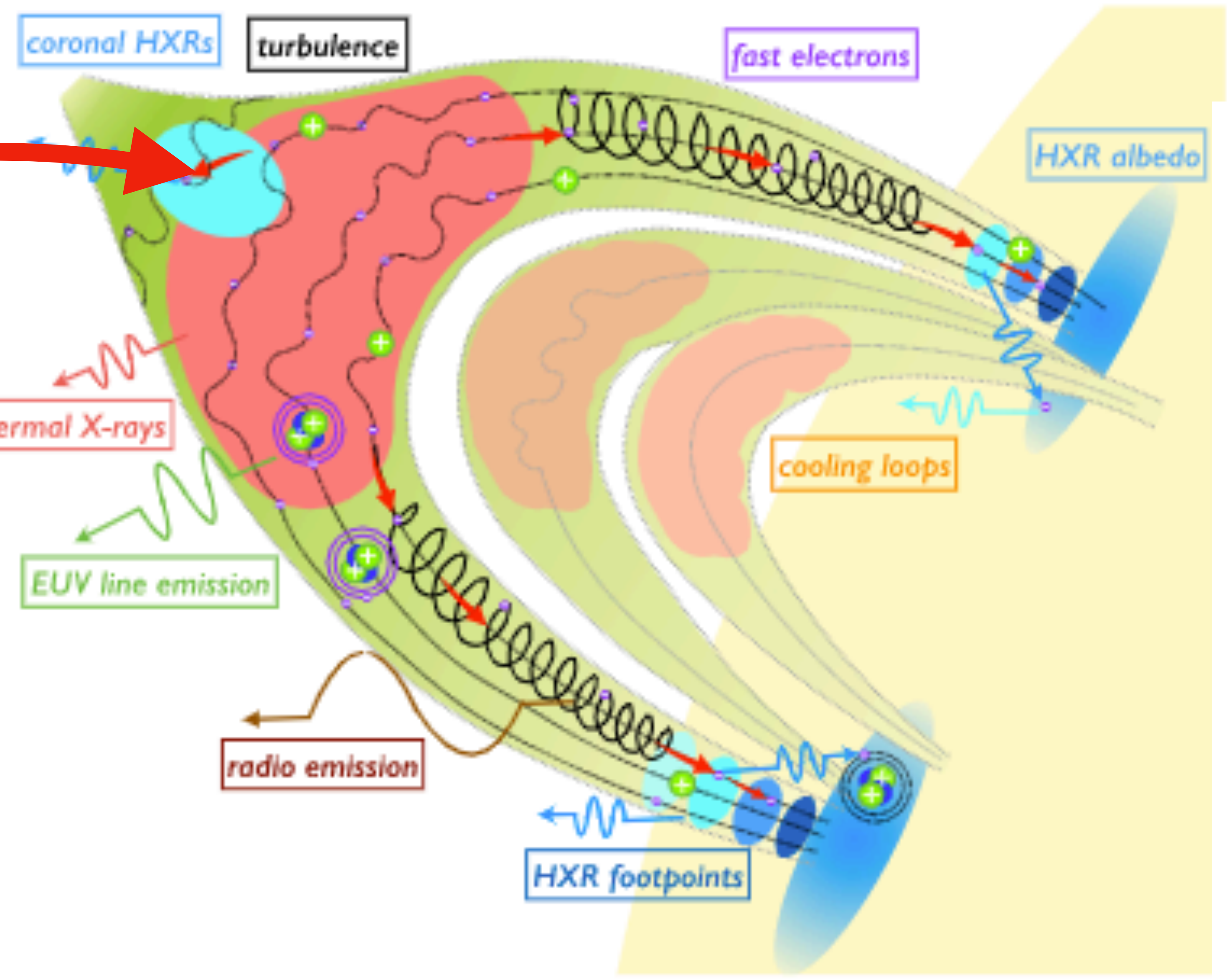


Oscillating Doppler shift will be a good indicator of locations of ALT regions!
Combinations between spectroscopic obs and X-ray & radio obs will uncover loop-top processes.

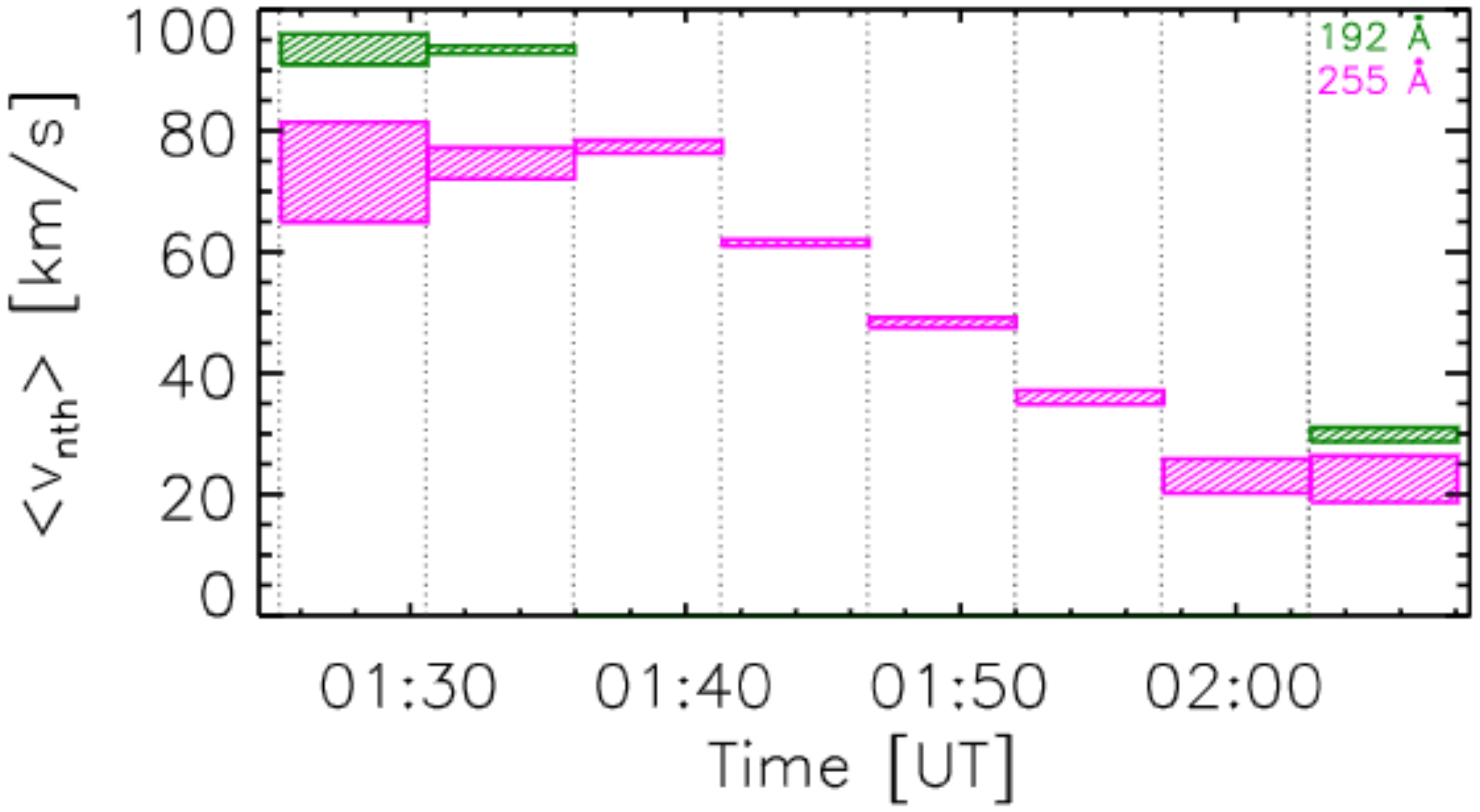
Decay of turbulent velocity



Red : RHESSI X-ray contour
at 50% of peak value for 6-16 keV



Nonthermal line broadening velocity at the loop-top

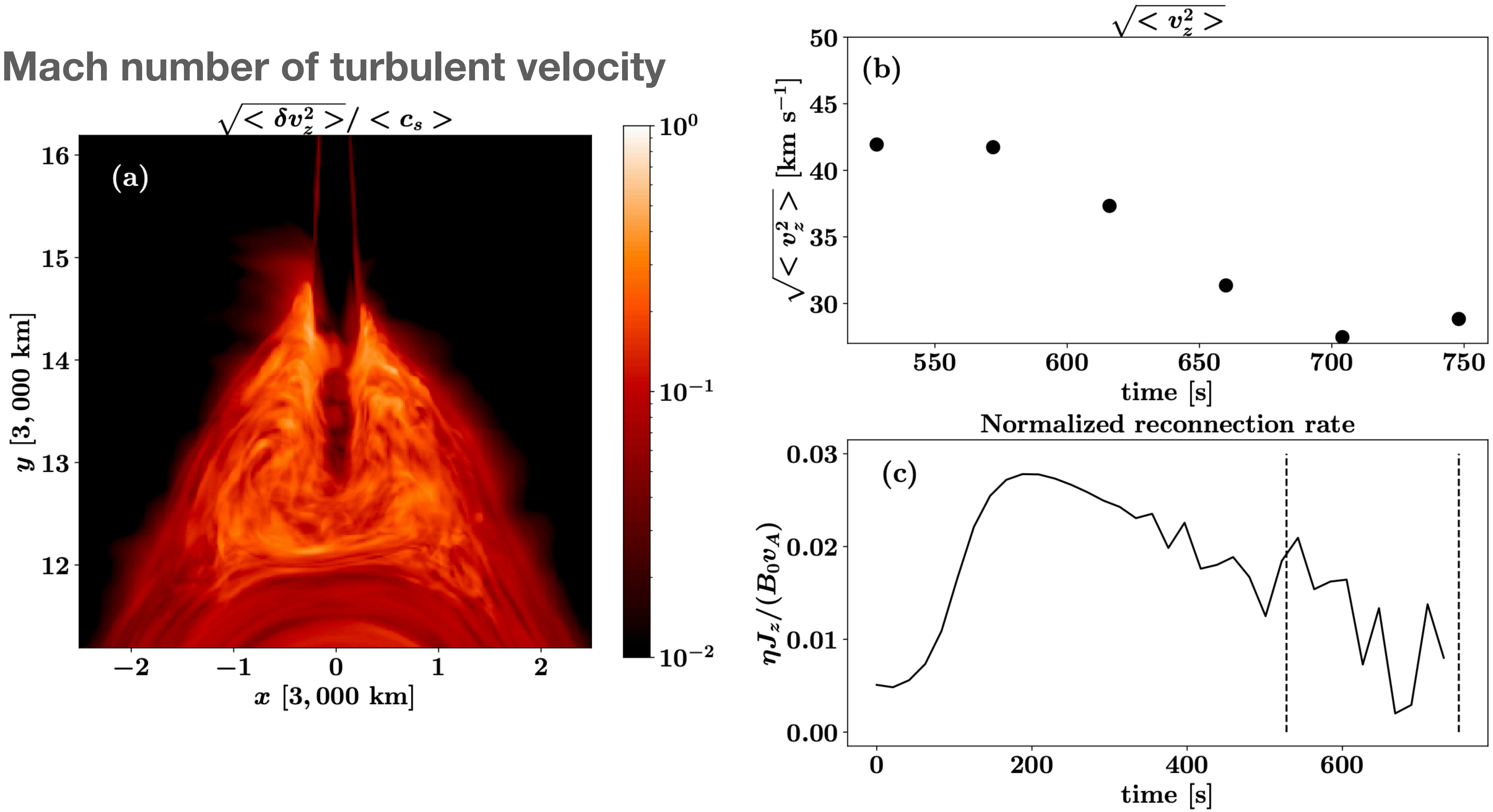


~100 km/s —> a few 10 km/s

What determines the decay timescale?

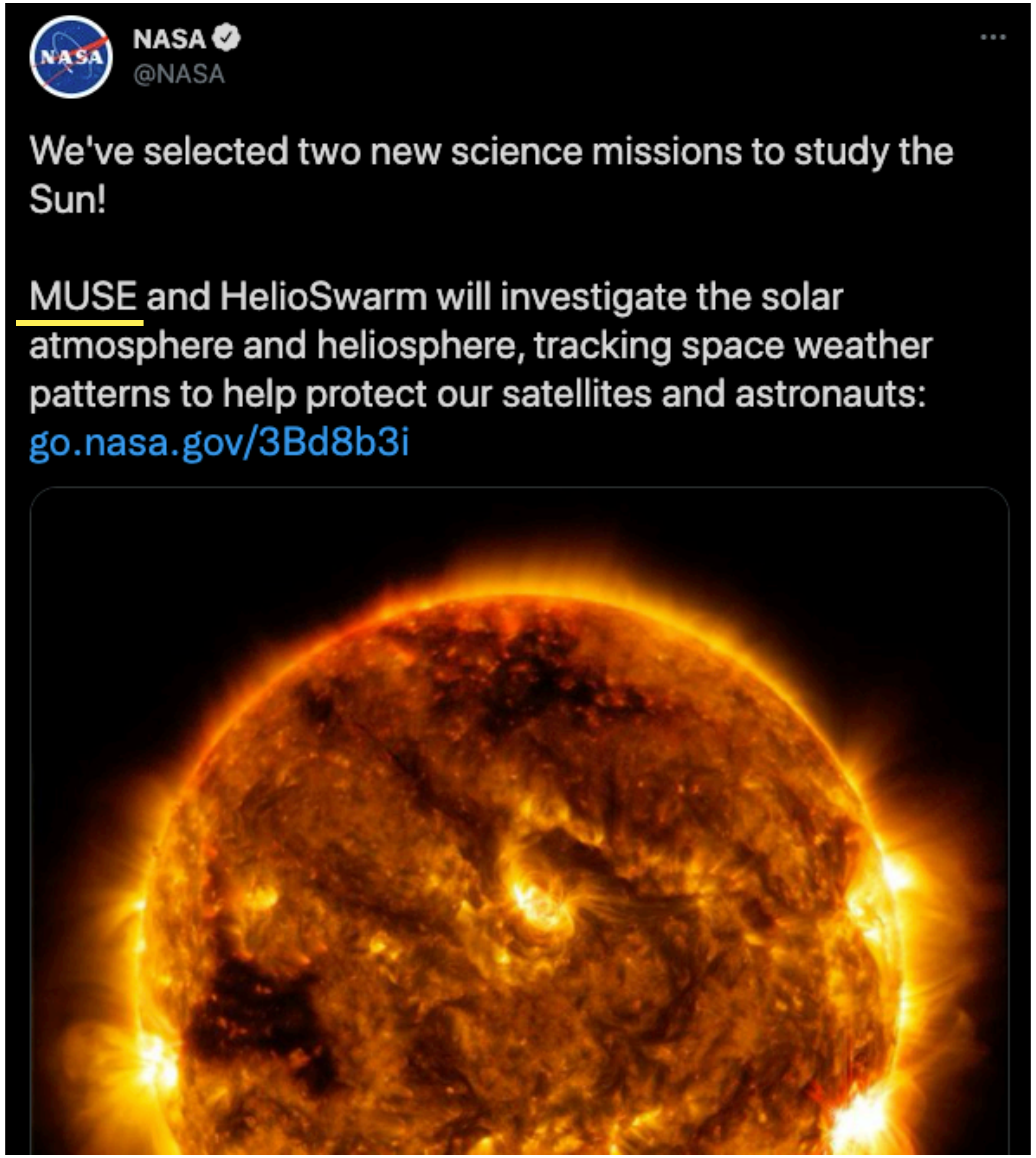
Decay of turbulent velocity

Mach number of turbulent velocity



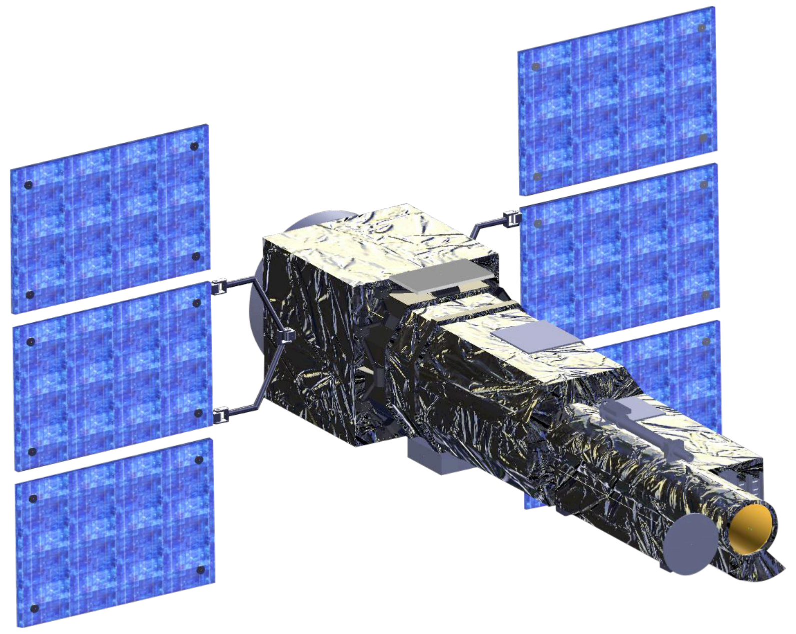
The turbulent velocity seems to decrease in response to the shrinkage and disappearance of the magnetic tuning fork arms. (preliminary)

Future observations



The Multi-slit Solar Explorer (***MUSE***):

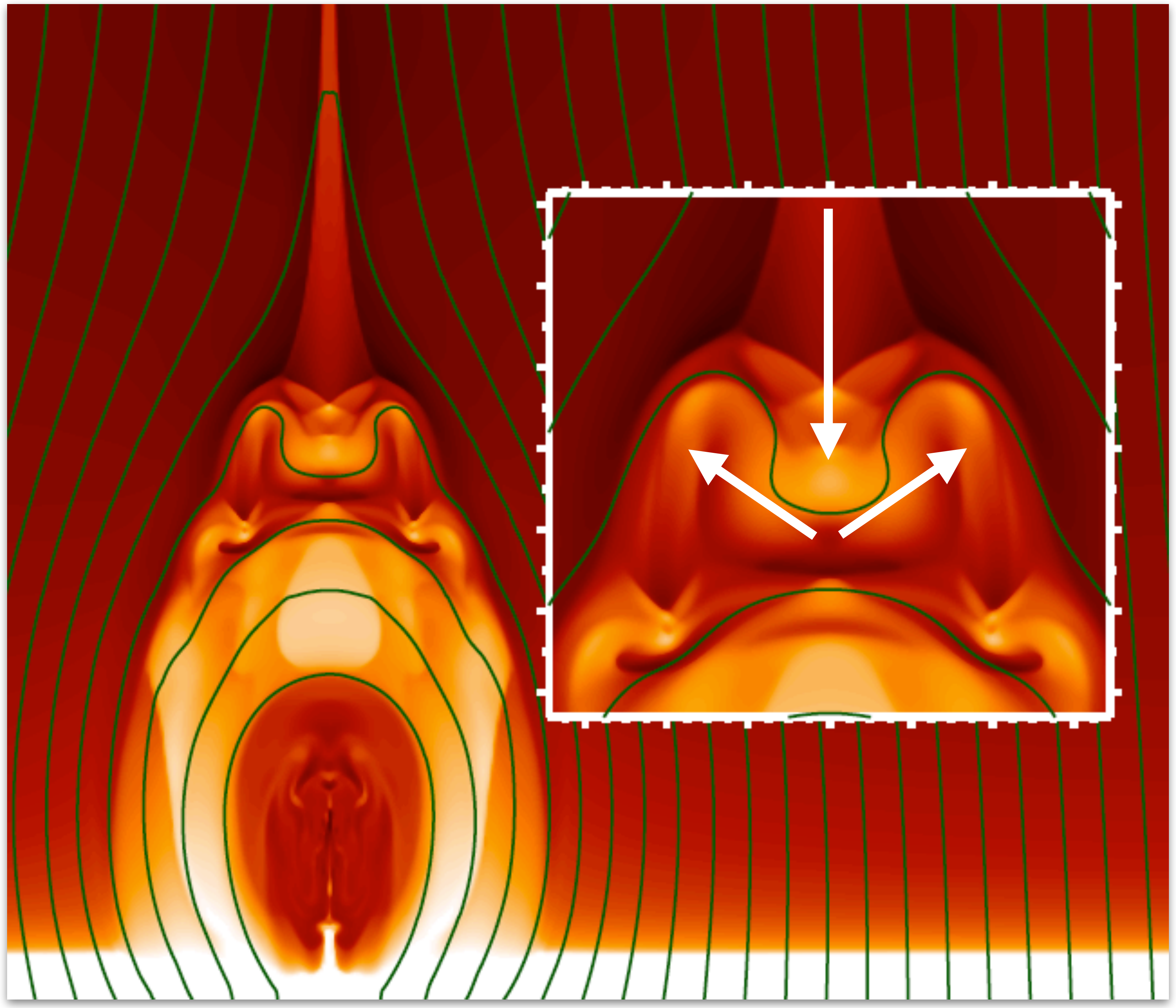
- Multi-slit EUV spectrograph
- Scheduled for launch in 2026
  (the timing will coincide with **Solar-C_EUVST**)



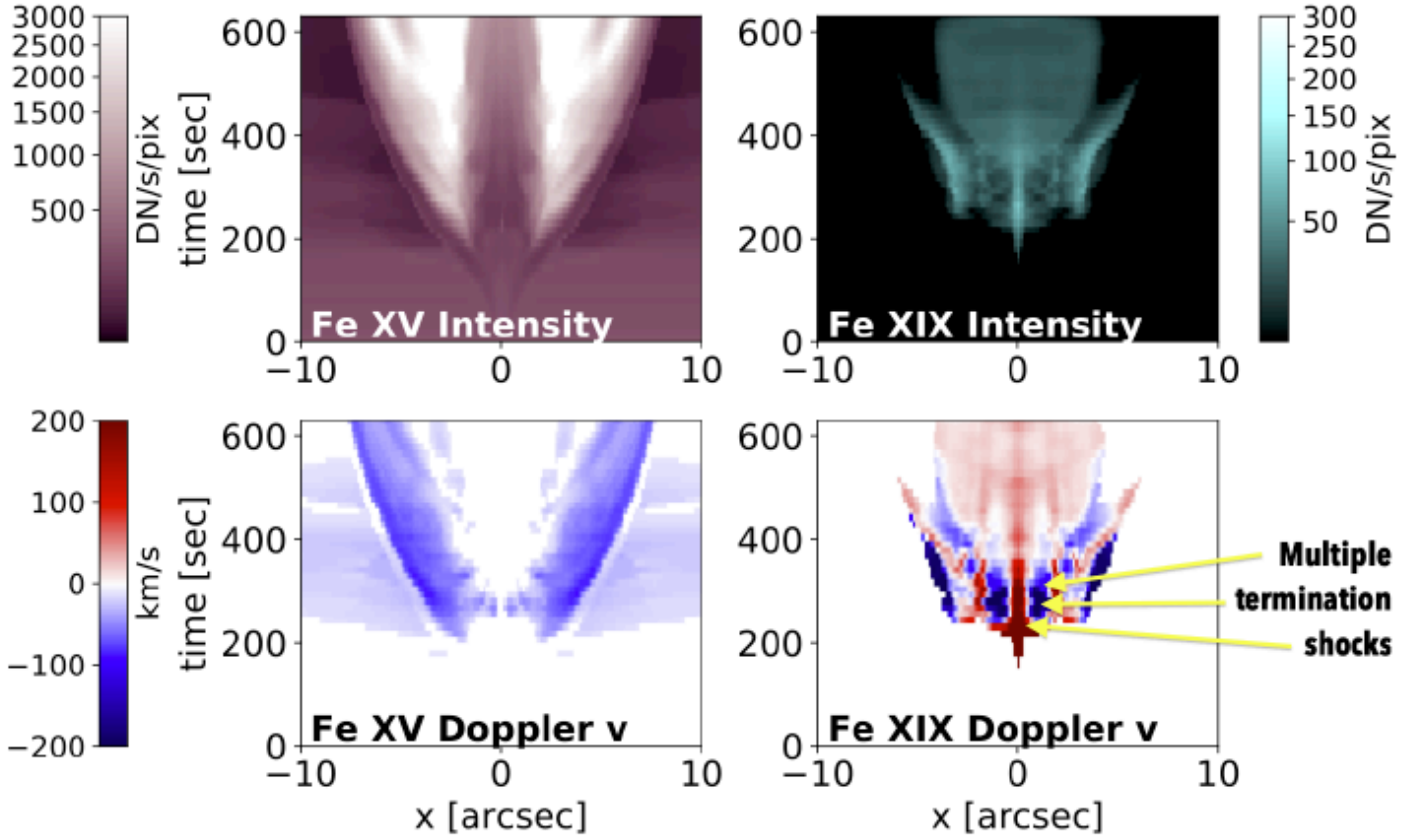
Synthesis of *MUSE* spectral observables

Cheung et al. (+ST) 2021, MUSE paper II

ST+15, ST & Shibata 16



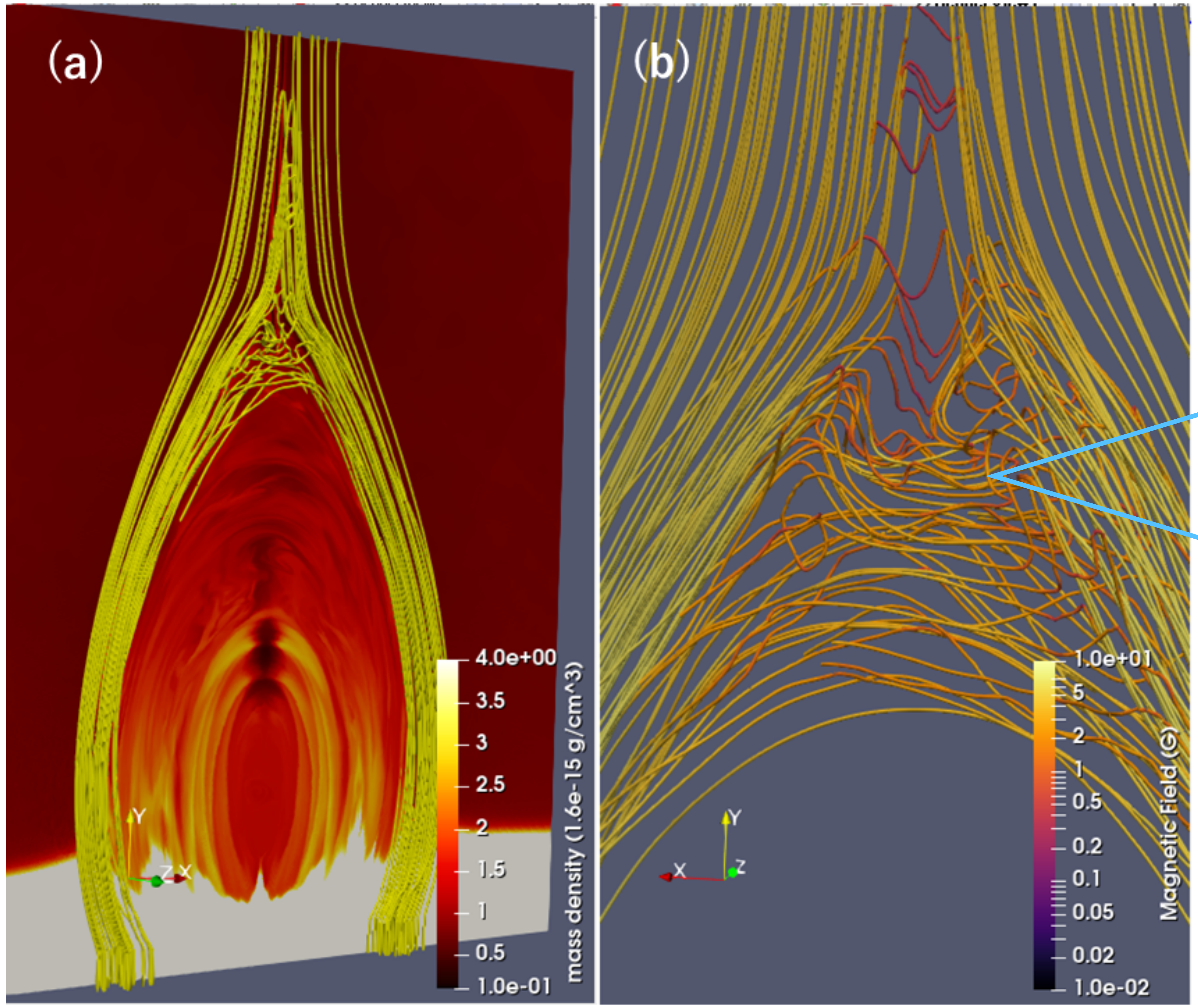
Spectral data taken from the top-down view

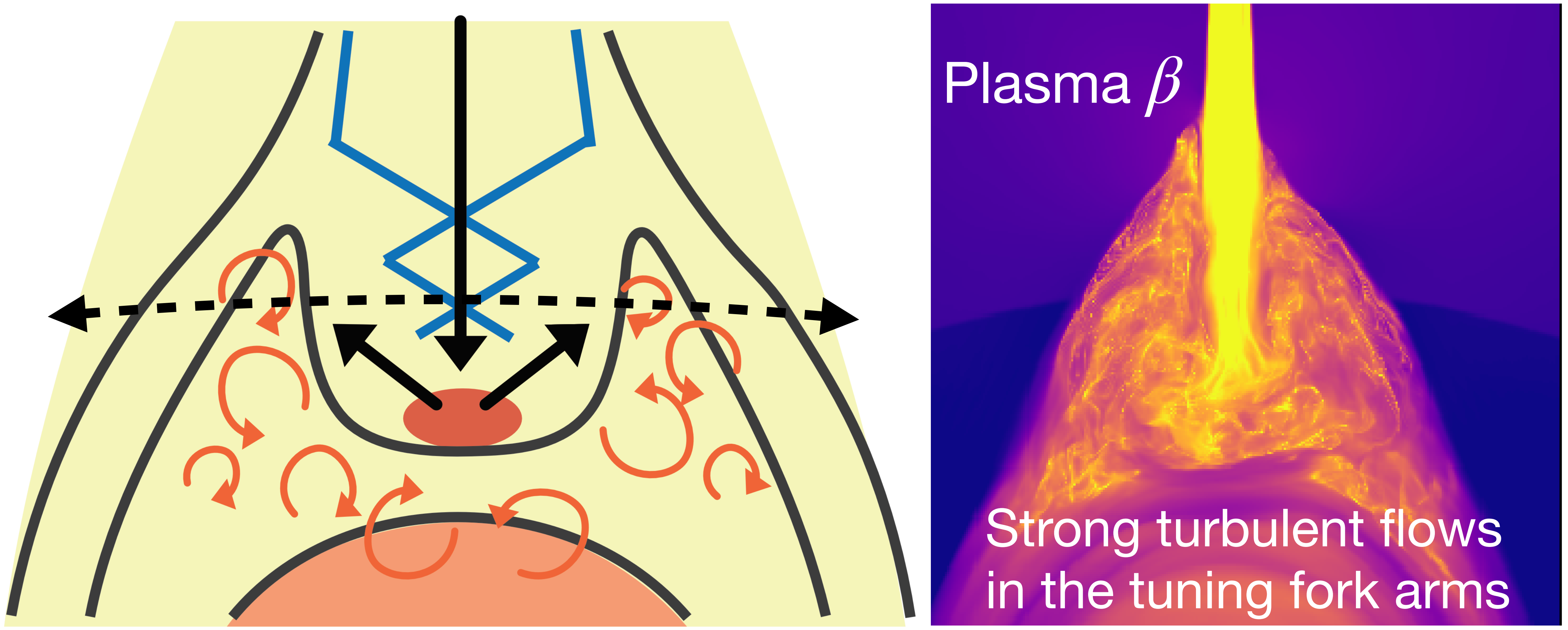


Backflows will be discern as a hot, blue-shifted flows

—> Smoking gun to prove the presence of backflows.

Summary





The ALT region shows

- Multiple termination shocks
- **Local generation of turbulence**
  (the lower end of the jet
  and **two arms of the magnetic tuning fork**)
- ALT oscillation

The backflow of the reconnection jet makes the magnetic tuning fork arms unstable to the pressure-driven instability, continuously producing turbulent flows.

Next steps: realistic modeling of the initial B-fields, developing models to connect kinetic-MHD scales etc.