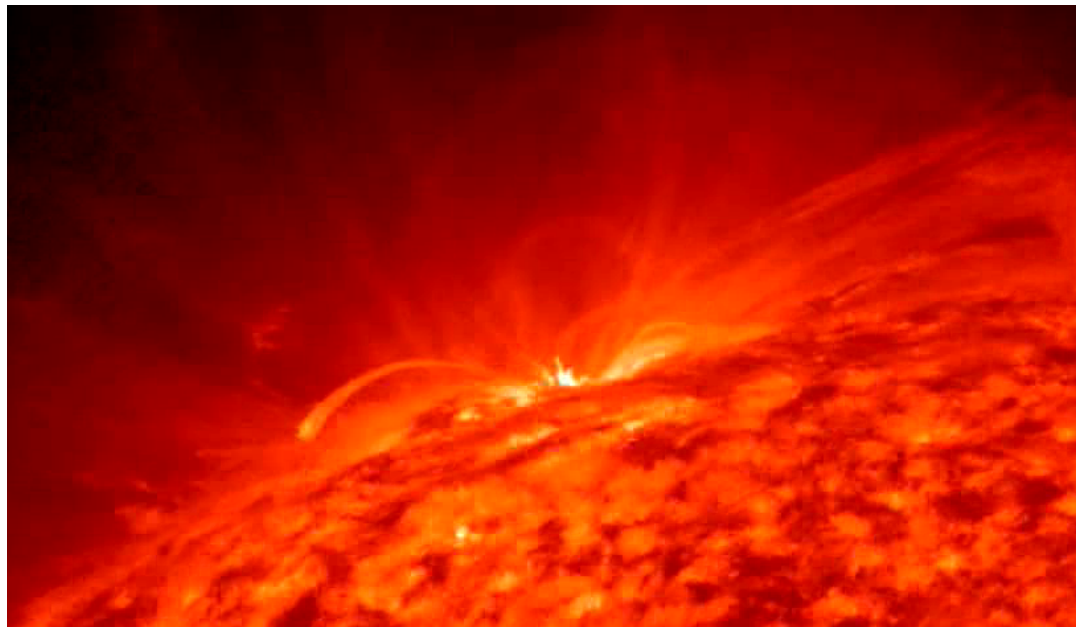


MHD Simulations of Quasi-Periodic Pulsations from Post Flare Loop Top

Shinsuke TAKASAO (Kyoto Univ.)

Collaborator: Kazunari SHIBATA (Kyoto Univ.)



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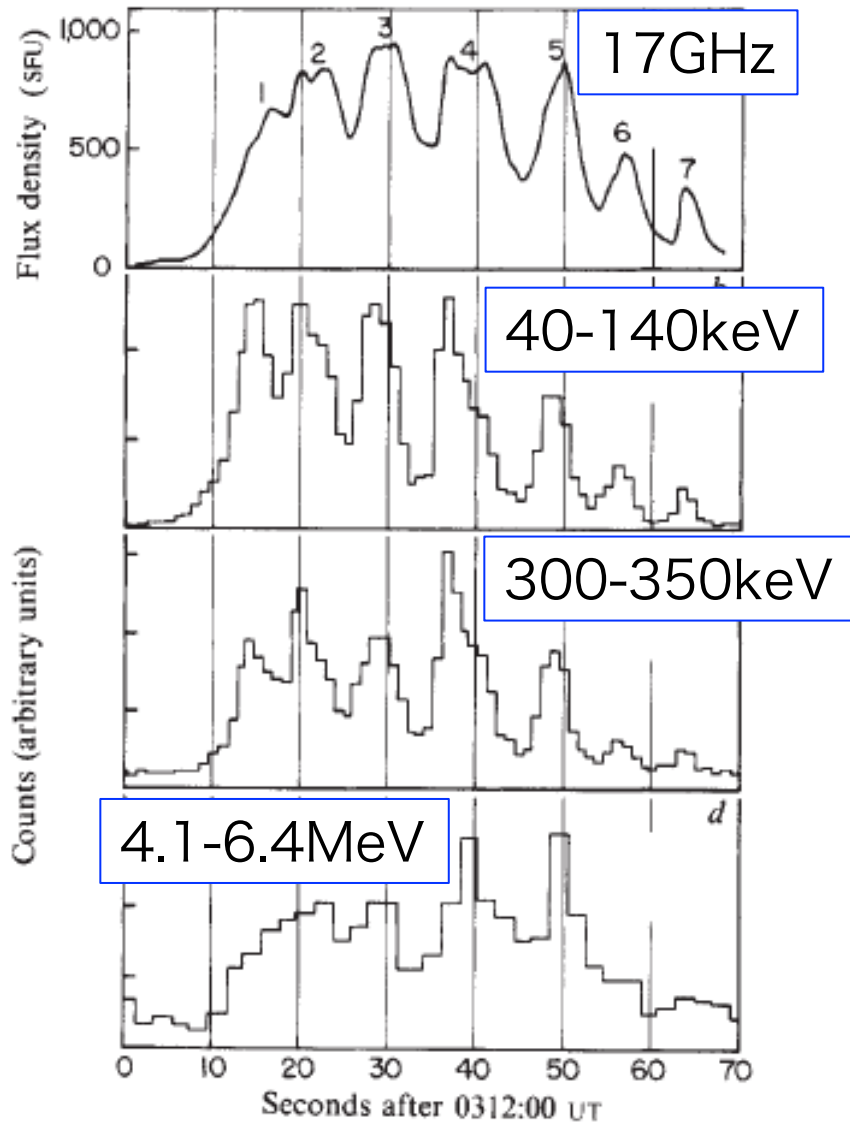
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Quasi-Periodic Pulsation (QPP) in Flare Emissions



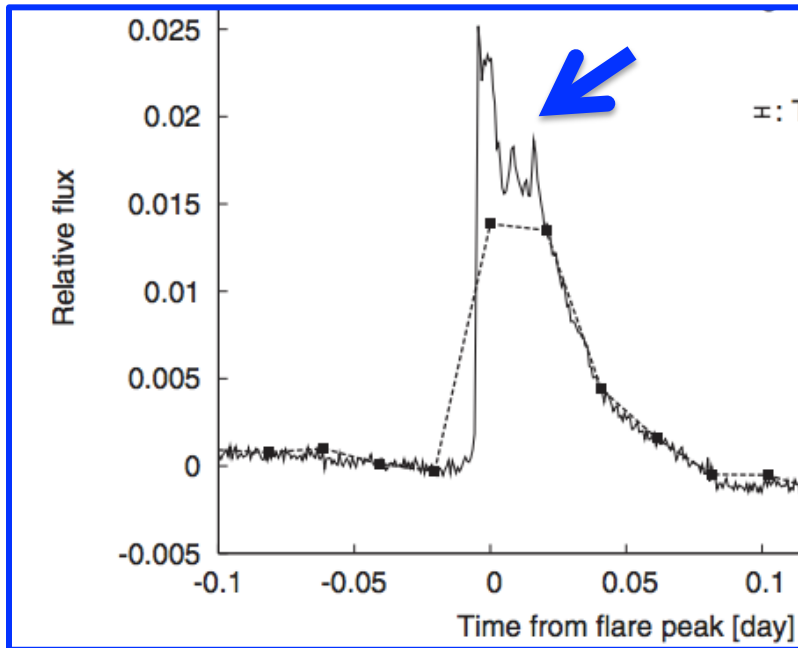
An example of QPP
in non-thermal emissions
(Nakajima et al. 1983, Nature)

- Period: ~1 sec to several min.
- As for QPPs with the period of >1 sec, **MHD processes may affect the particle acceleration or non-thermal emission processes.**

See also
Asai et al. 2001,
Nakariakov and Melnikov 2009,
Dolla et al. 2012

Quasi-Periodic Pulsations in White-light Emissions of Stellar Flares

Light-curve of a **superflare** observed by Kepler:
Superflares are stellar flares from solar-type stars with the energy of $\gg 10^{32}$ ergs



In many solar flares,
WL emissions and hard X-ray emissions behaves similarly
(non-thermal particles \Rightarrow WL)

Common physics (!?).
It may be possible to estimate physical quantities of stellar flares which are not visible.

Shibayama + 2013

see also

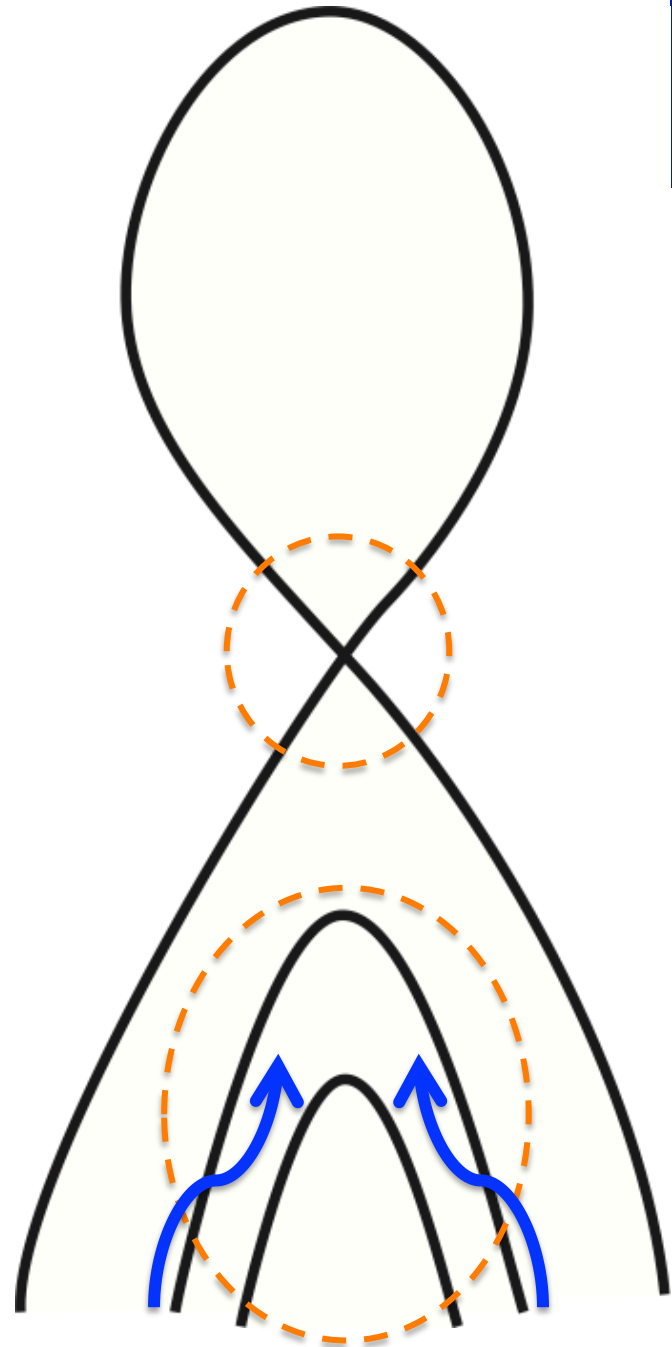
Maehara et al. 2012,
Mathioudakis+2003, Kowalski+2010,
Anfinogentov+2013

We can learn many things from the solar physics!!

Origin of Quasi-Periodic Pulsation?

Models can be divided into two groups:

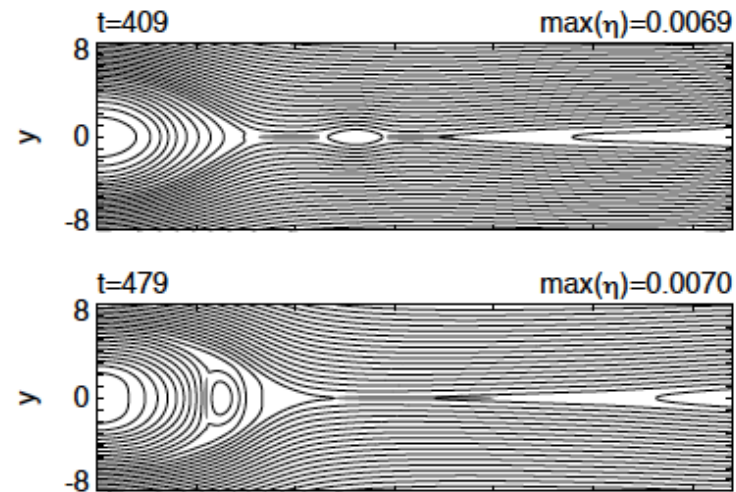
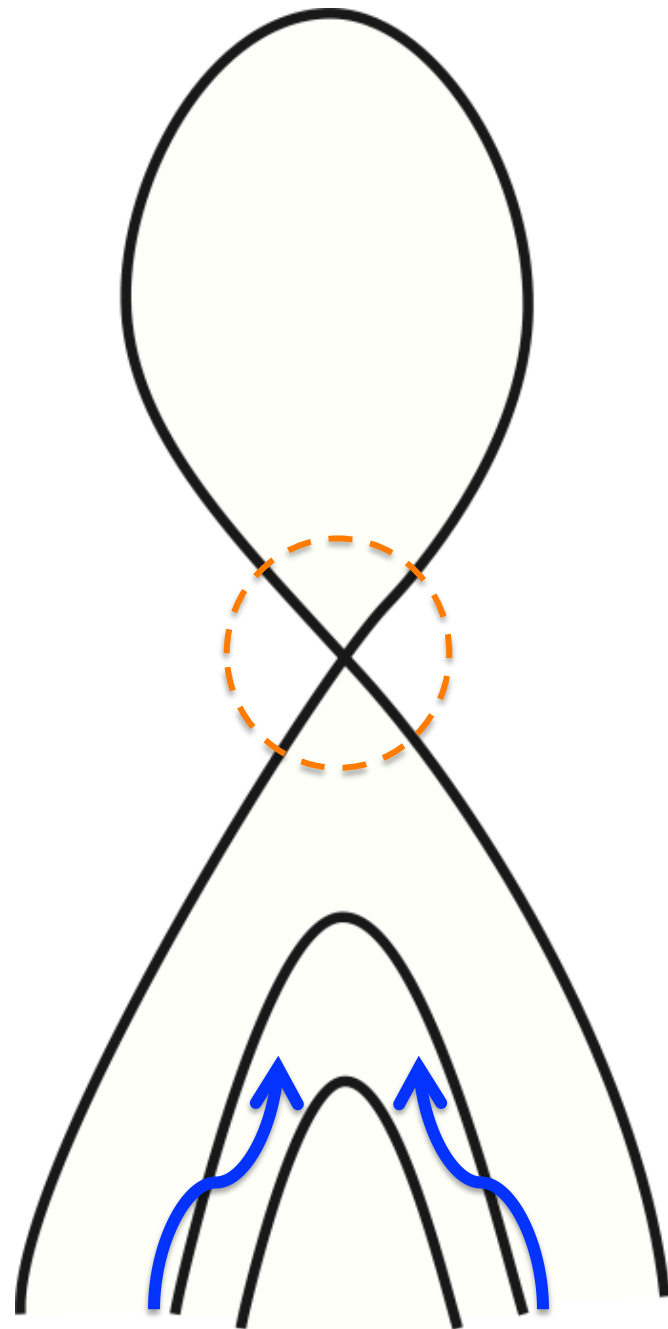
- Some kind of oscillation in reconnection regions
- MHD waves in post flare loops



Origin of Quasi-Periodic Pulsation?

Models can be divided into two groups:

- Some kind of oscillation in reconnection regions
- MHD waves in post flare loops



e.g. Recurrent plasmoid formation (Tajima+1987, Kliem+2000 and others)

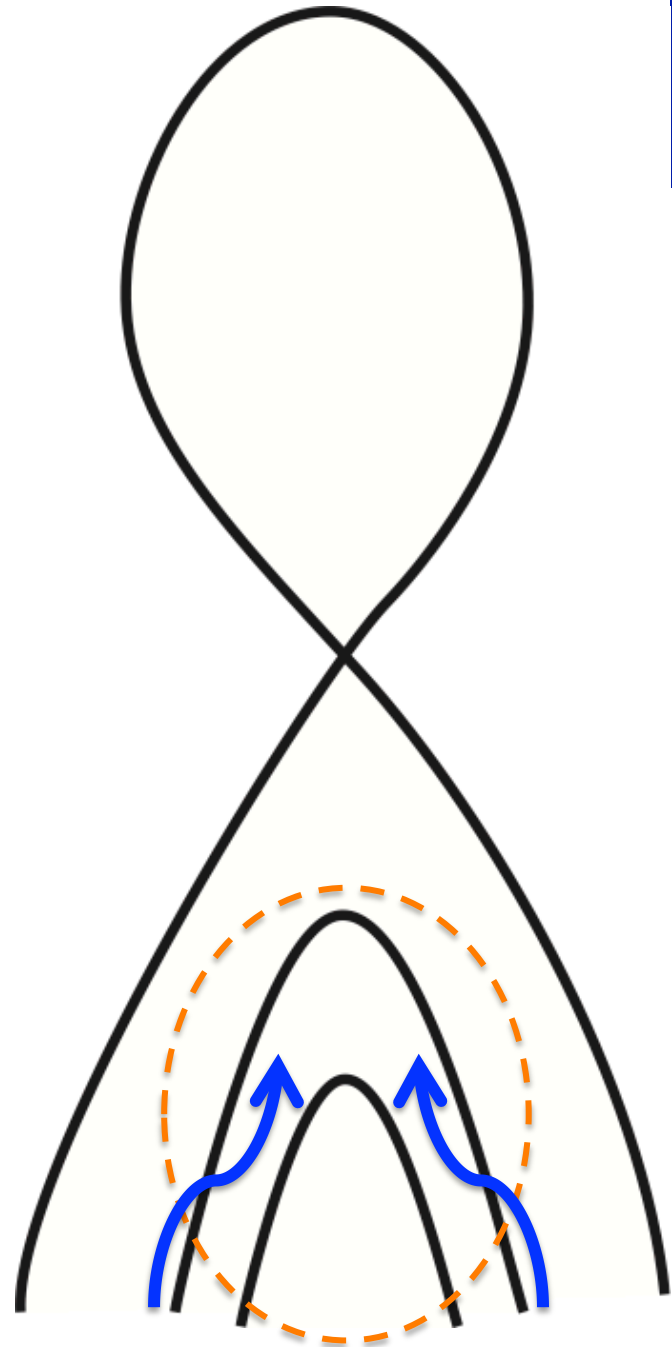
Origin of Quasi-Periodic Pulsation?

Models can be divided into two groups:

- Some kind of oscillation in reconnection regions
- **MHD waves in post flare loops**

Standing/propagating MHD waves
⇒ modify the conditions of
the particle acceleration site
at the loop top
(hard X-ray source) **But, how?**

Nakariakov & Melnikov 2009 (review paper)
Van Doorselaere+2011,
Fletcher and Hudson 2008 and many authors



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Cyon: 25–50 keV, 22, 80%

Liu et al. 2013

non-thermal
emission

05:23:12–05:26:32

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⇒ modify the conditions of the particle acceleration site at the loop top
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What kind of waves?
How they modify the loop top condition?



Cyon: 25–50 keV, 22, 80%

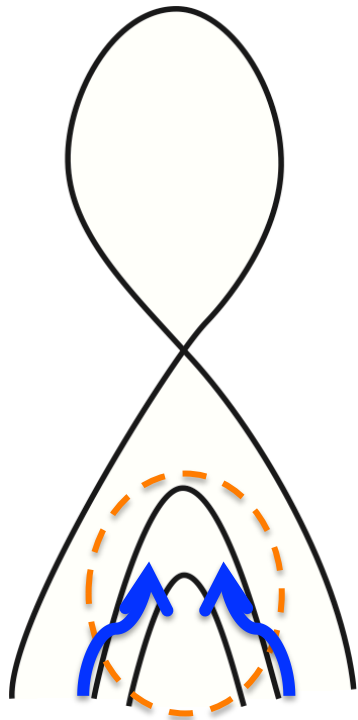
Liu et al. 2013

non-thermal emission

05:23:12–05:26:32

Motivation of This Study

Understand the link between MHD process and particle acceleration process on the basis of an MHD model

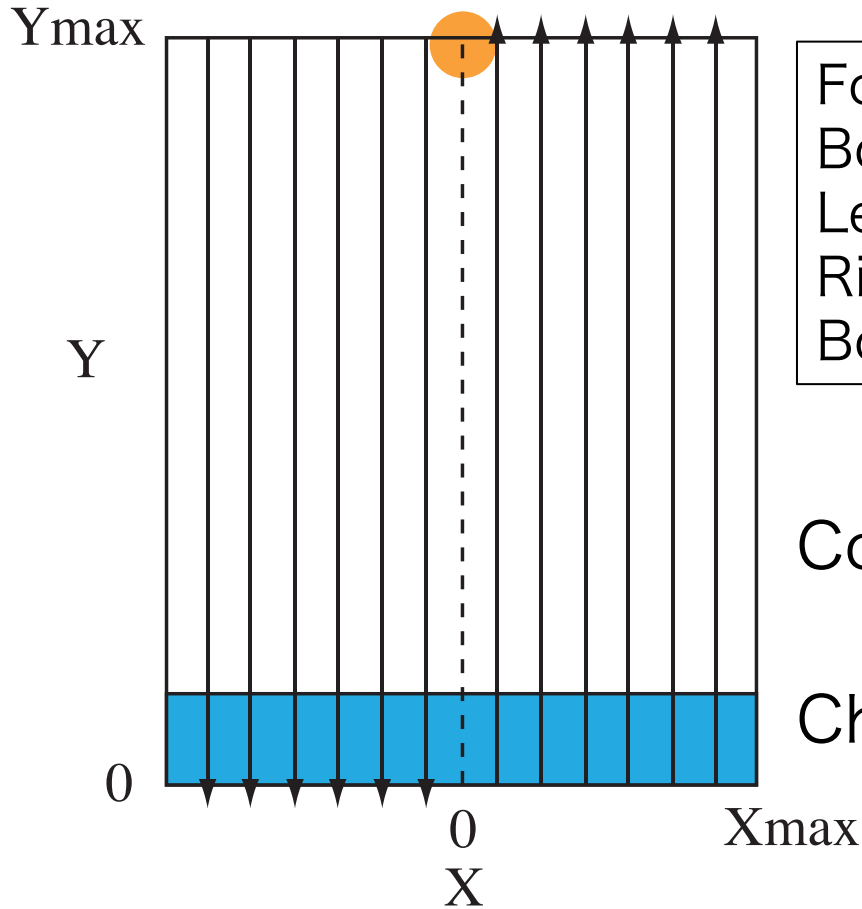


- Some kind of oscillation in reconnection regions
- MHD waves in post flare loops

This talk

Numerical Simulation of Reconnection Including Heat Conduction

Localized Resistivity



Force-free field used
Boundary cond:
Left ($x=0$): Rotationally symmetric
Right ($x=x_{\max}$): Mirror symmetric
Bottom and Top: symmetric

Corona (tenuous and hot)

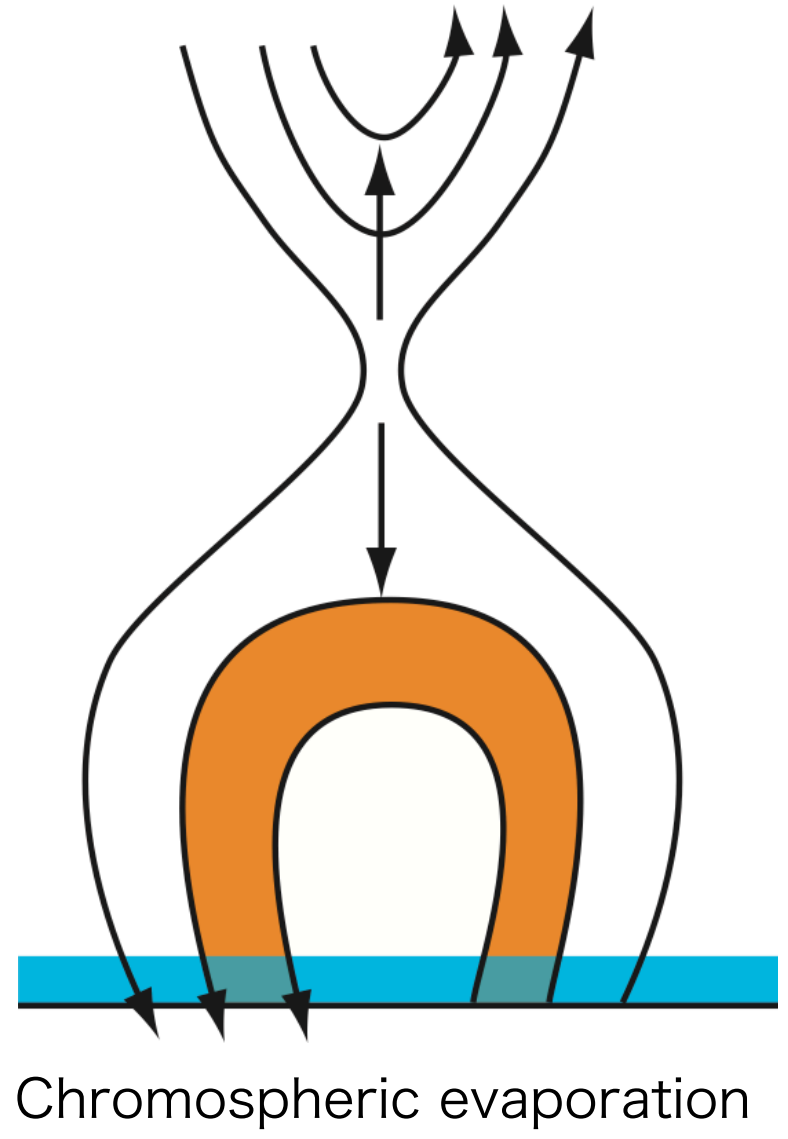
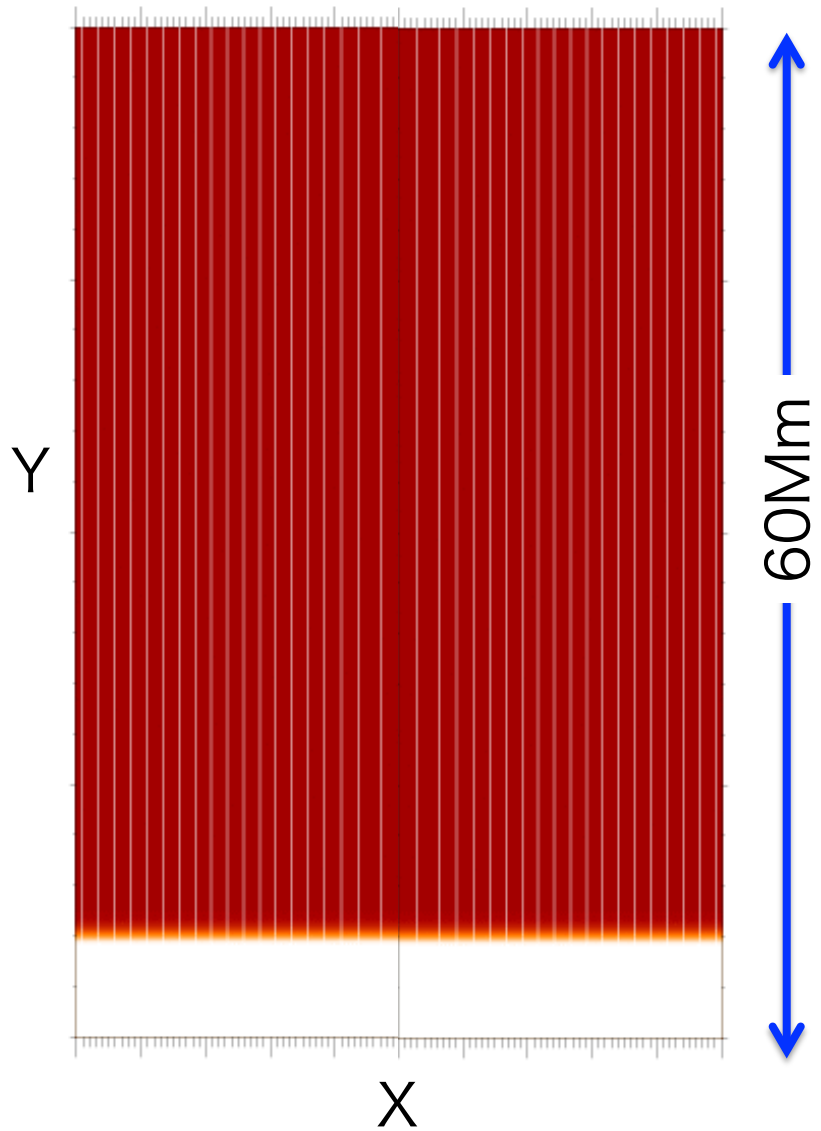
Chrom. (dense and cool)

Basic eqs:
MHD eqs with heat conduction
A fixed resistivity used
(i.e. no tearing/plasmoids)

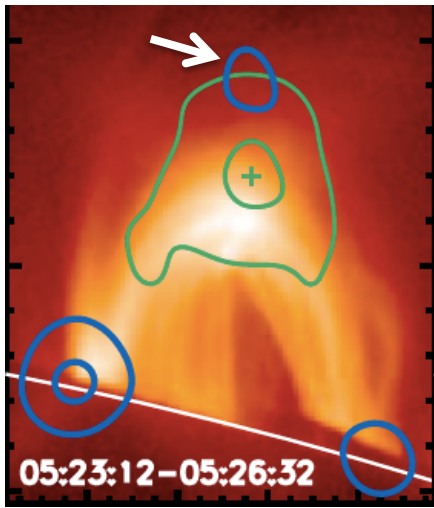
cf) Yokoyama & Shibata 2001

Global Evolution

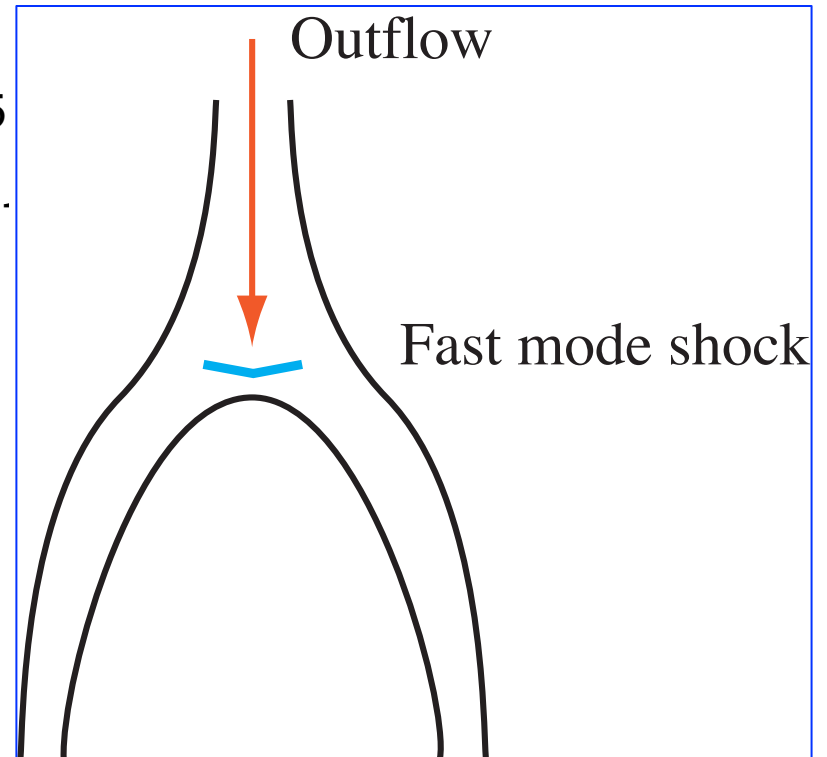
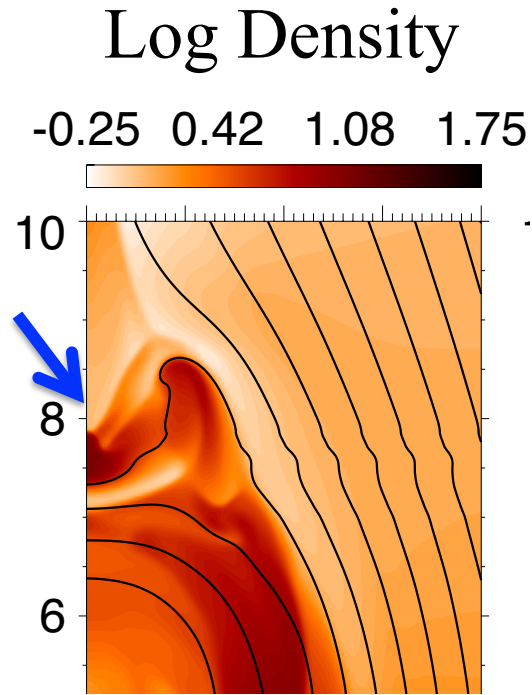
Log Density Time=0.00
-1.0 0.1 1.2



Quasi-Periodic Variation of Fast Shock Strength

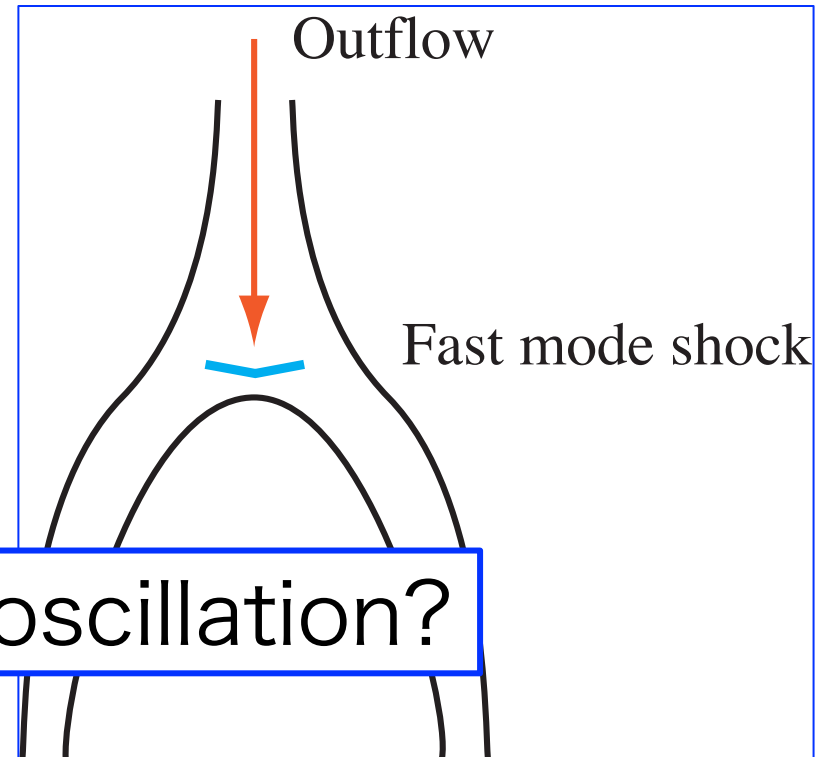
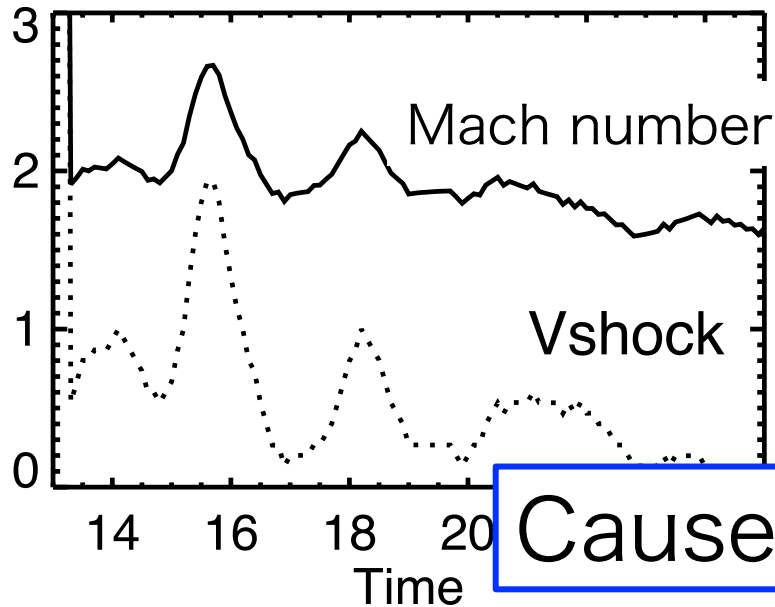


Liu et al. 2013



Shock above
the post flare loop
(good place for the particle
acceleration)

Quasi-Periodic Variation of Fast Shock Strength



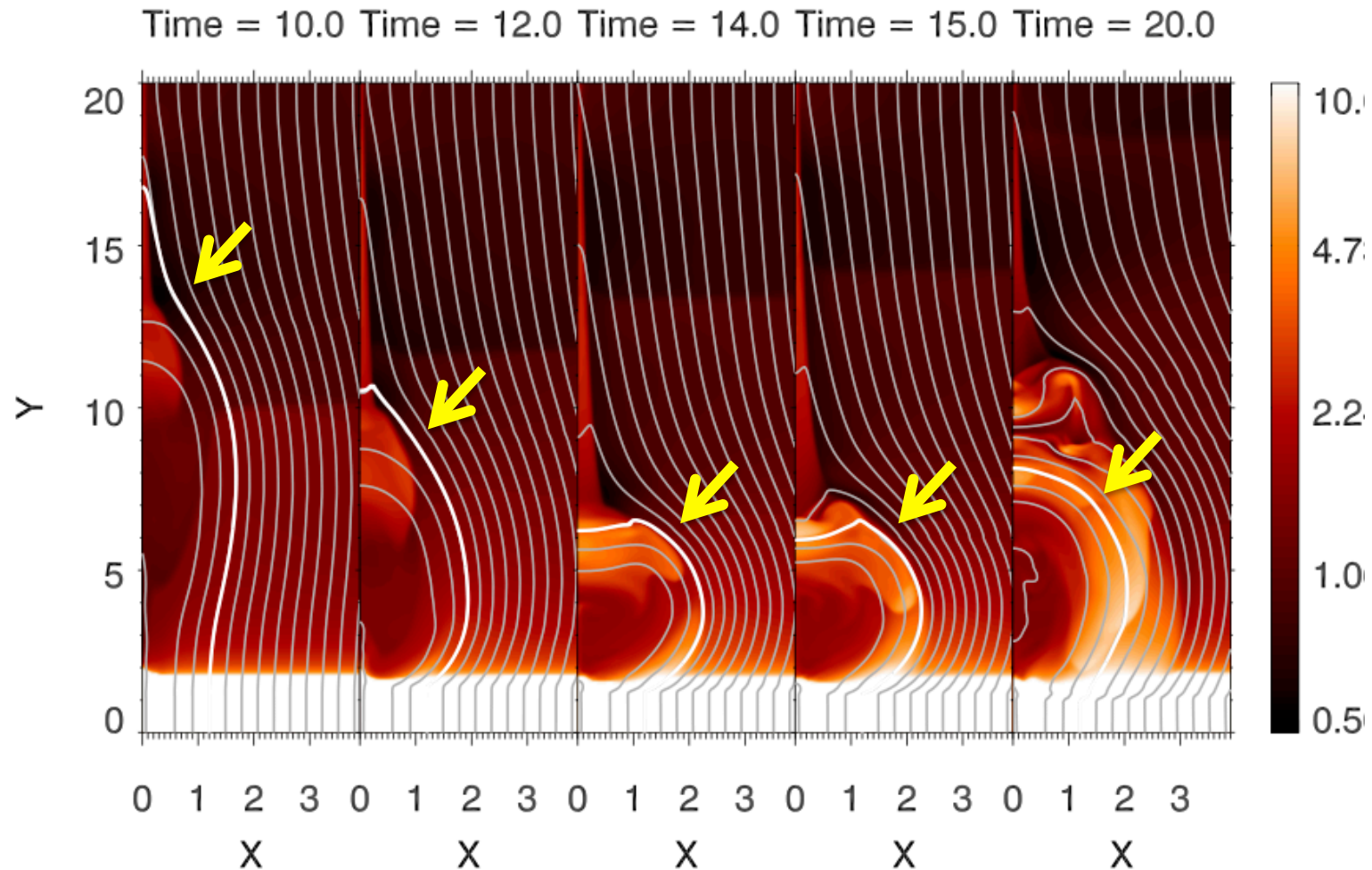
Cause of oscillation?

Period: ~2-3 unit time = 36-54 sec

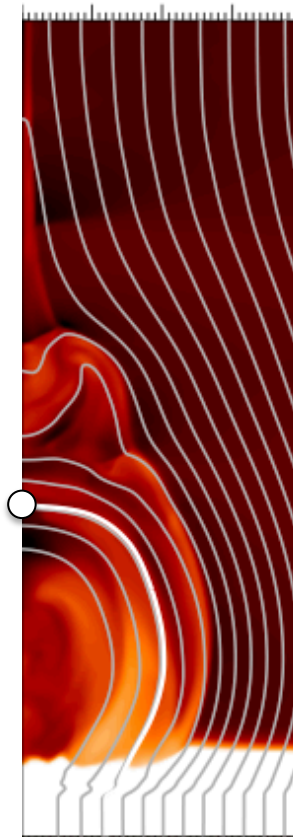
Quasi-periodic variation of the fast-mode shock strength
⇒ Possibly quasi-periodic variation of the generation rate of the high-energy particles

Waves Traveling Back and Forth in Post Flare Loops?

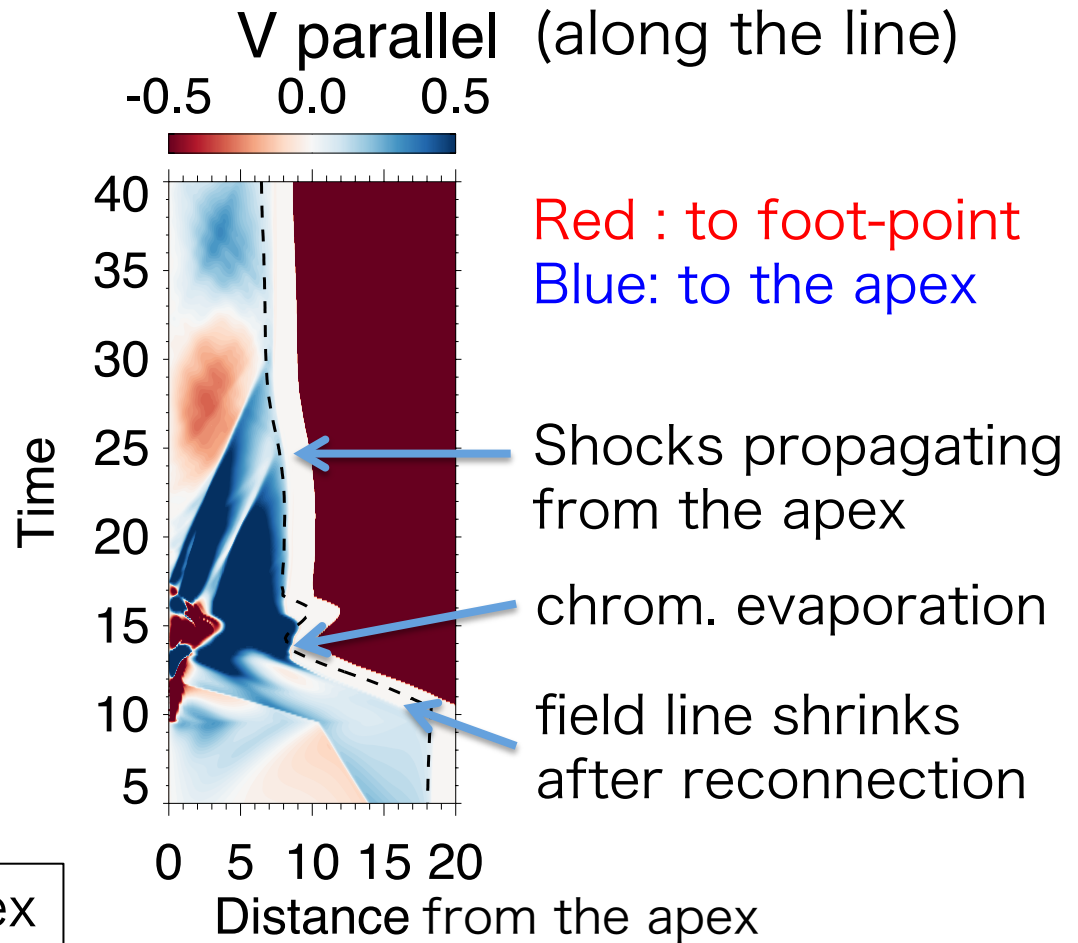
Track a specific field line, and measure the physical quantities on it.
Log Density



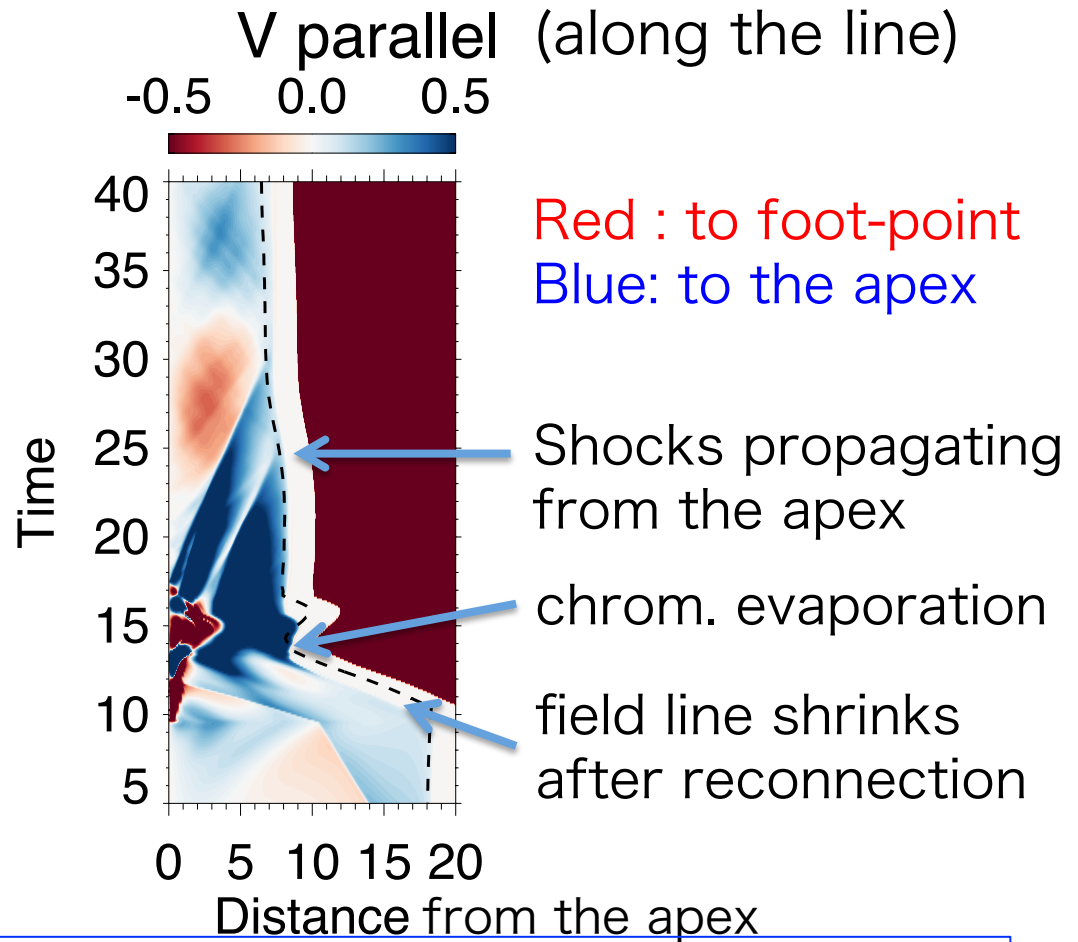
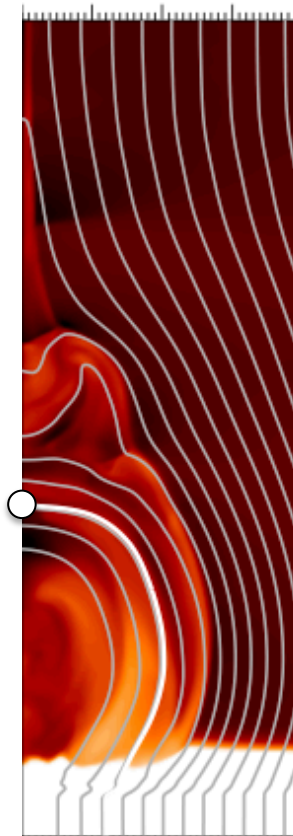
Waves Traveling Back and Forth in Post Flare Loops?



The distance from the apex is measured along the line



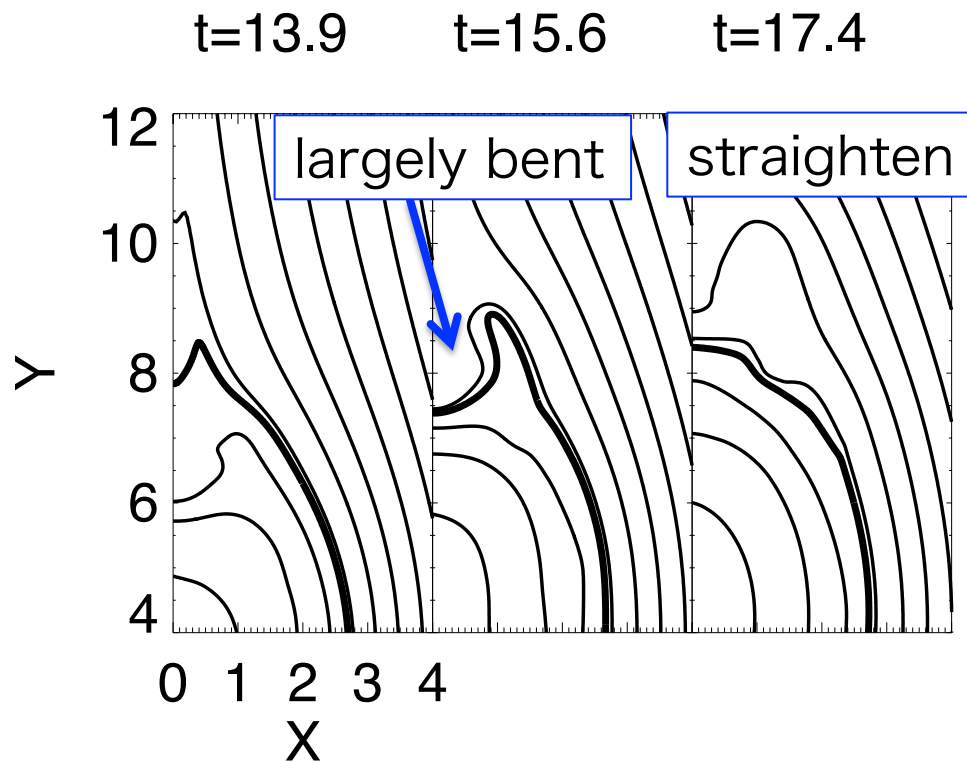
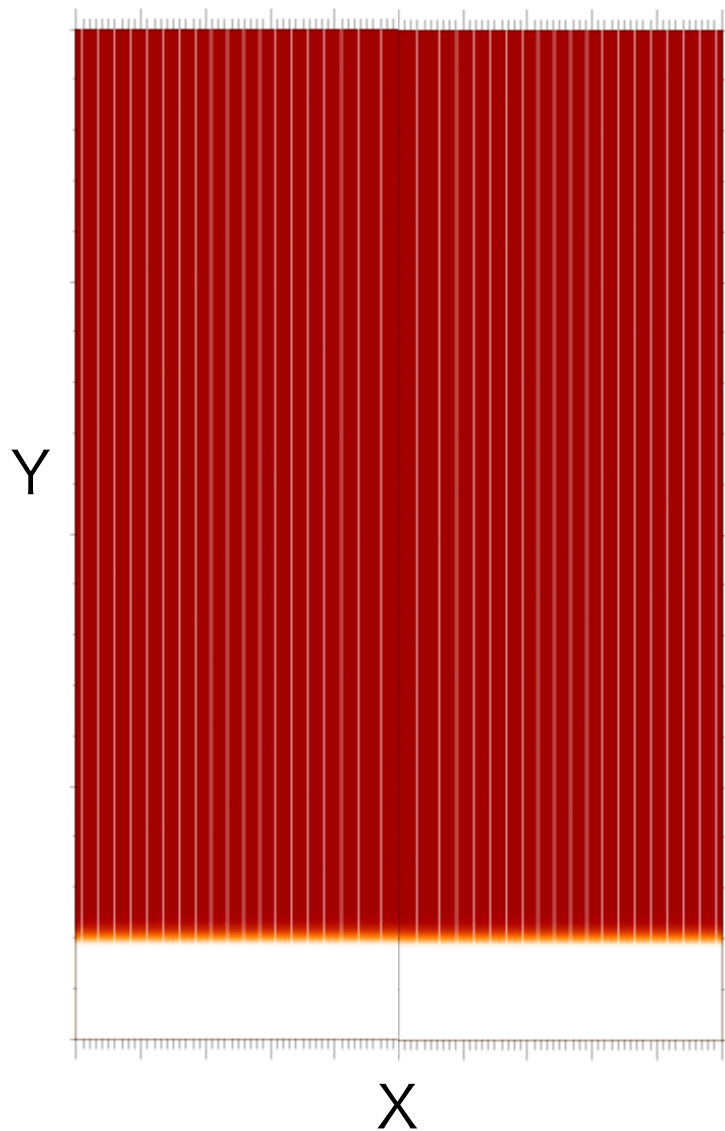
Waves Traveling Back and Forth in Post Flare Loops?



Longitudinal waves (slow-mode shocks) are quickly damped by the heat conduction (i.e. **no prominent waves traveling back and forth**)

Log Density Time=0.00
-1.0 0.1 1.2

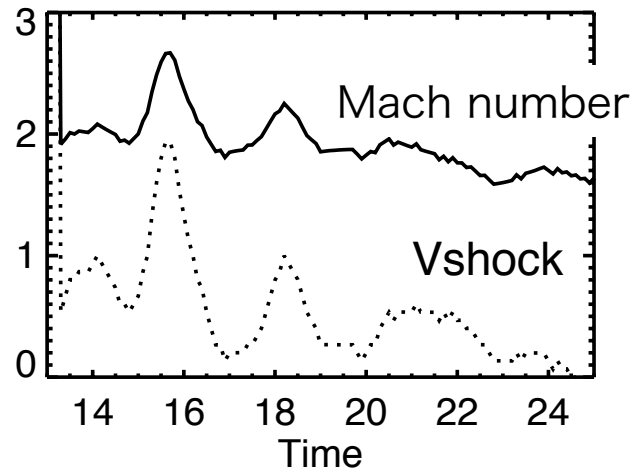
Oscillation at Loop Top



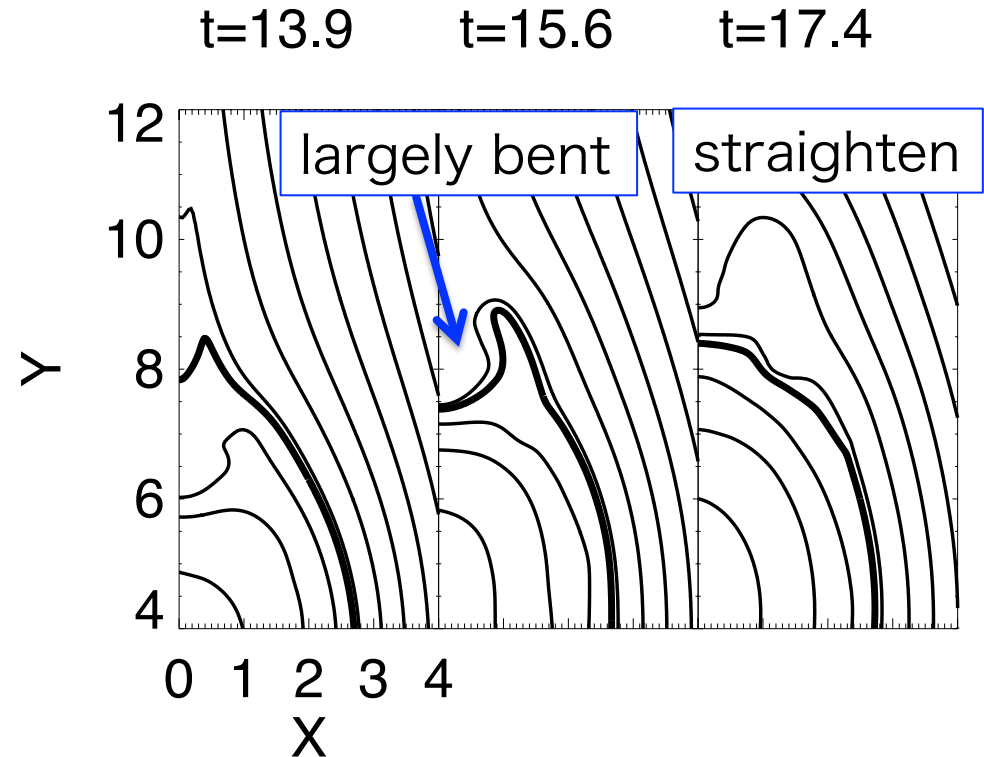
Transversal motion driven by the collimated outflow

Cause of Oscillation: Transversal motion driven by the collimated outflow

Evolution of shock strength



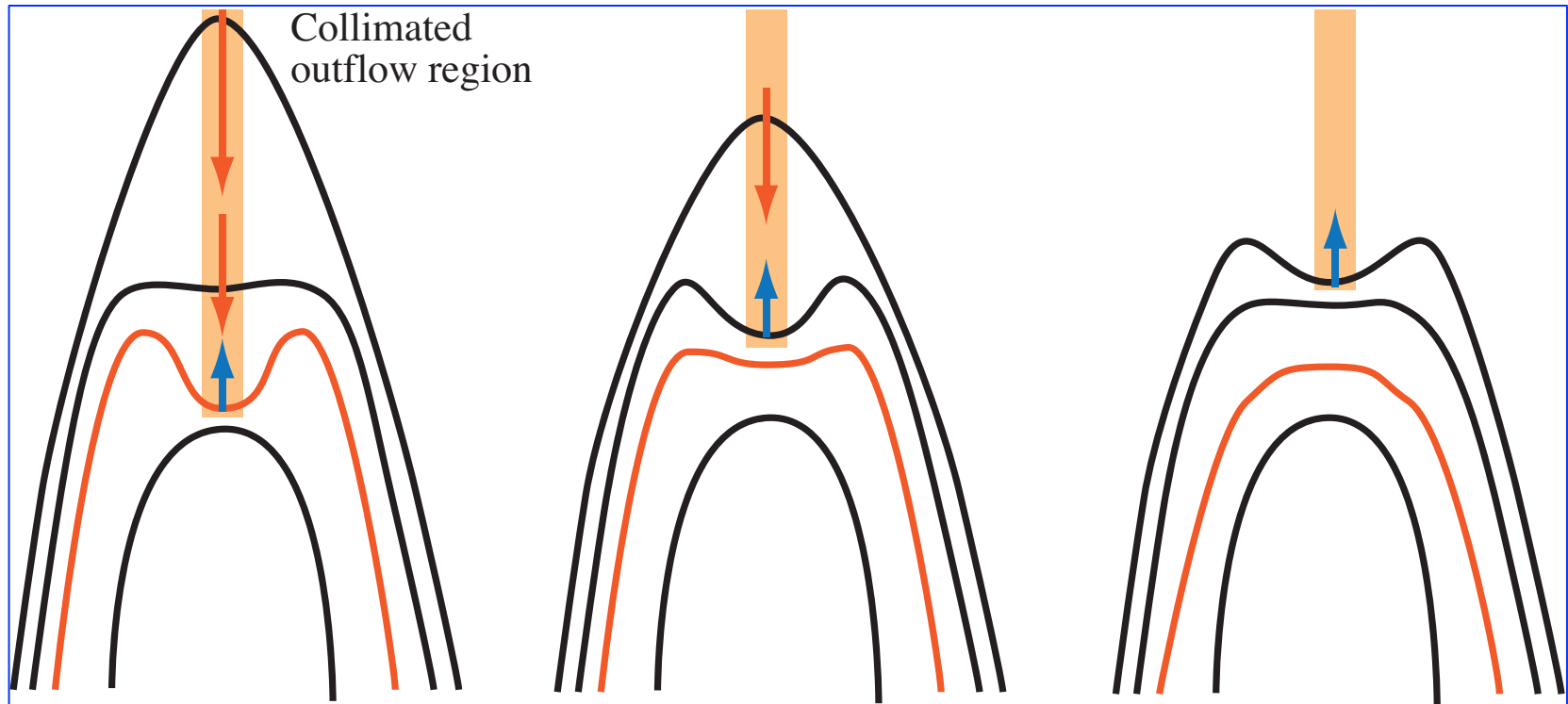
Period: $\Delta t \sim 2-3 = 36-54$ sec



A part of the field line near the apex shows a transversal motion. The typical time scale is 2-3.

⇒ Consistent with the period of the fast-mode shock strength variation

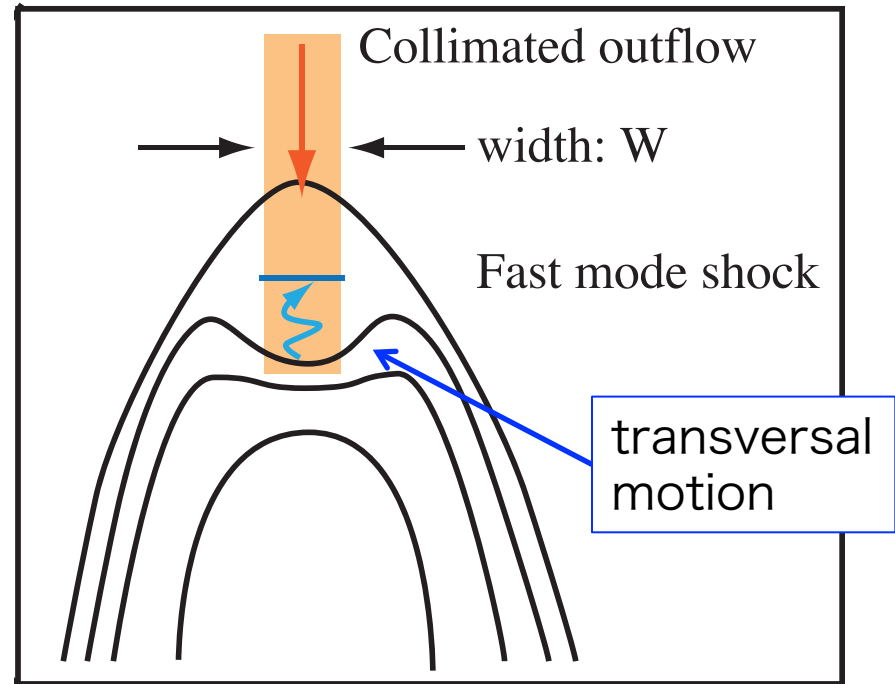
Cause of Oscillation: Transversal motion driven by the collimated outflow



Collimated outflow

- ⇒ The outflow bends the field lines at the apex
- ⇒ The field line straightens through **a transversal motion**
- ⇒ introducing a disturbance to the shock above the loop
- ⇒ quasi-periodic change in shock speed/Mach number

Cause of Oscillation: Transversal motion driven by the collimated outflow



Collimated outflow

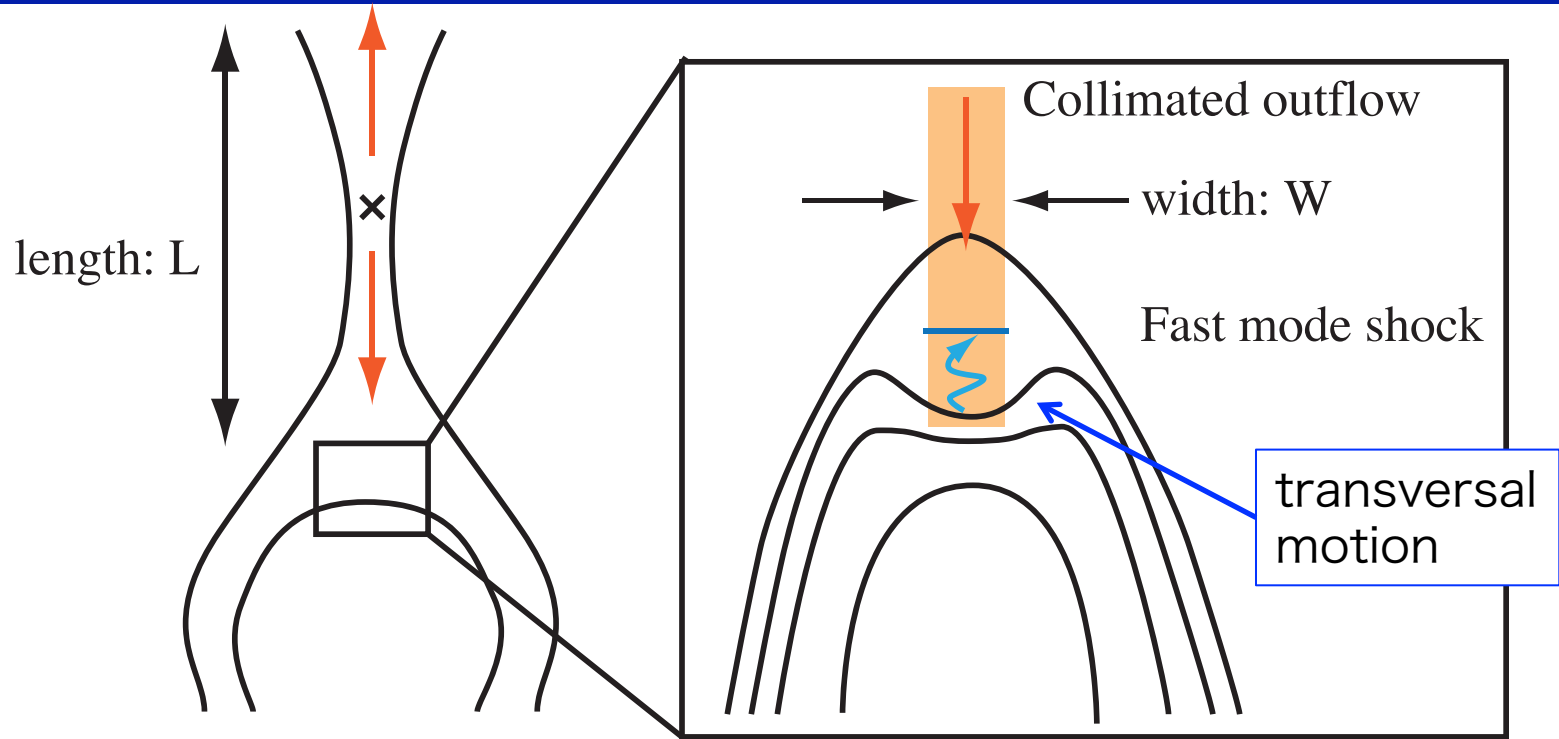
⇒ The outflow bends the field lines at the apex

⇒ The field line straightens through **a transversal motion**

⇒ **introducing a disturbance to the shock above the loop**

⇒ quasi-periodic change in shock speed/Mach number

Physical Interpretation based on Reconnection Theory



Period in the simulation: $\sim 2-3$ unit time = 36-54 sec

$$P \sim W / C_{f,top}$$

($W \sim 2 * Ma * L$ in the Petschek model)

$$\sim 2M_A L / \sqrt{V_{A,top}^2 + C_{s,top}^2} \sim 1.4 \left(\frac{M_A}{0.05} \right) \left(\frac{L}{20} \right) \left(\frac{V_{A,top}}{1} \right)^{-1} \sim 25 \text{ sec}$$

(taking $\beta \sim 1-3$) (similar!)

Summary

- We study possible mechanisms that can explain the quasi-periodic pulsations in flare emissions, on the basis of an MHD model. Particularly, **MHD wave scenarios are examined.**
- We found no waves propagating from end to end in our simulations (damping by heat cond.). But **a transversal oscillation at the apex is found. The transversal oscillation modifies the strength of the shock in which non-thermal particles are likely to be generated.**
- Using a reconnection theory, it is possible to express the oscillation period by MHD parameters.