# Simulation Study on the Self-Organization of Sigmoidal Structure and the Onset of Solar Flares

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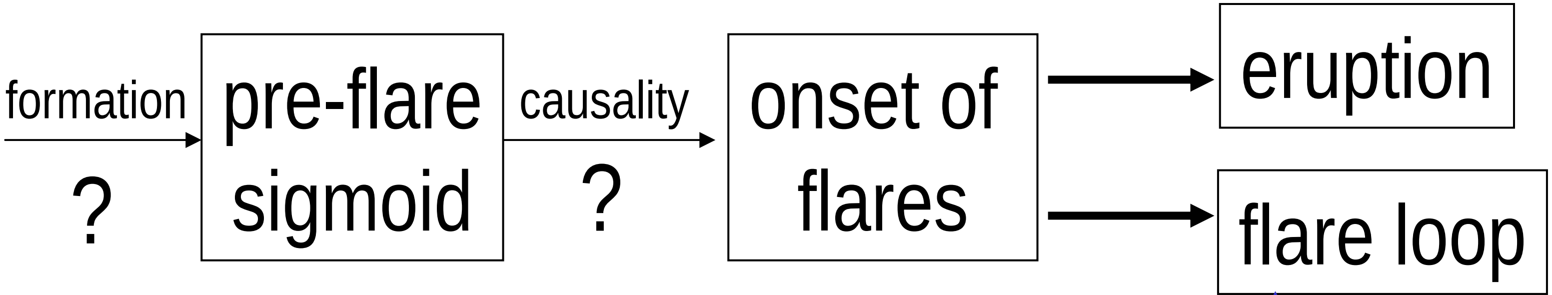
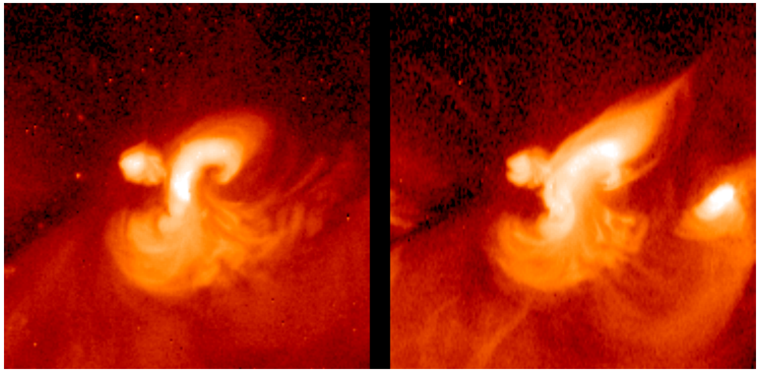
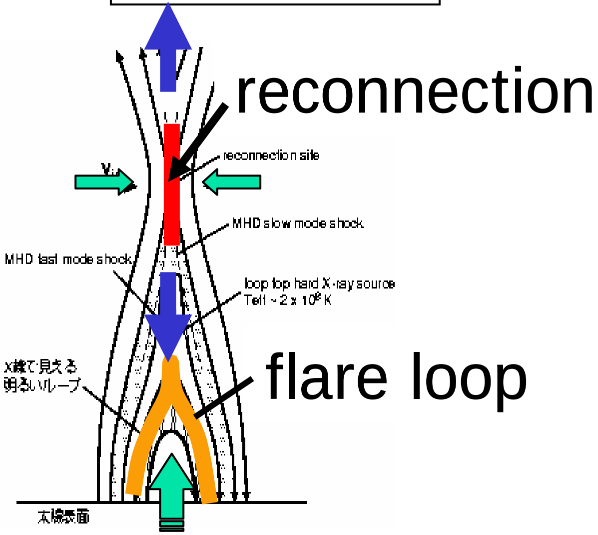
# Introduction







**<u>Questions</u>**

- the formation mechanism of sigmoids
- the causal relationship from sigmoids to the onset of flares.

→ 3D MHD Simulation

# Mechanism of sigmoid formation

- kink mode instability
  - proposed by Rust & Kumar 1996
  - simulations
    - Fan & Gibson 2004, Fan 2005
    - Kliem, Titov & Török 2004, Török & Kliem 2005

However, the several observations suggested that the field twist in sigmoids is insufficient for the kink instability. (Leamon et al. 2003, Yamamoto et al. 2005)

our model

- resistive tearing instability

(Kusano 2005 ApJ in press)

thin current sheet (reversed-shear layer)

→ self-organization → sigmoid formation

→ double reconnections → flare onset

# Helicity Injection Measurement

- Yamamoto et al. 2005 ApJ

(method developed by Kusano et al. 2002)

LCT + induction equation

$$\left[\frac{\partial \mathbf{B}}{\partial t}\right]_n = \left[\nabla \times (\mathbf{V}_t \times \mathbf{B}_n + \mathbf{V}_n \times \mathbf{B}_t)\right]_n$$

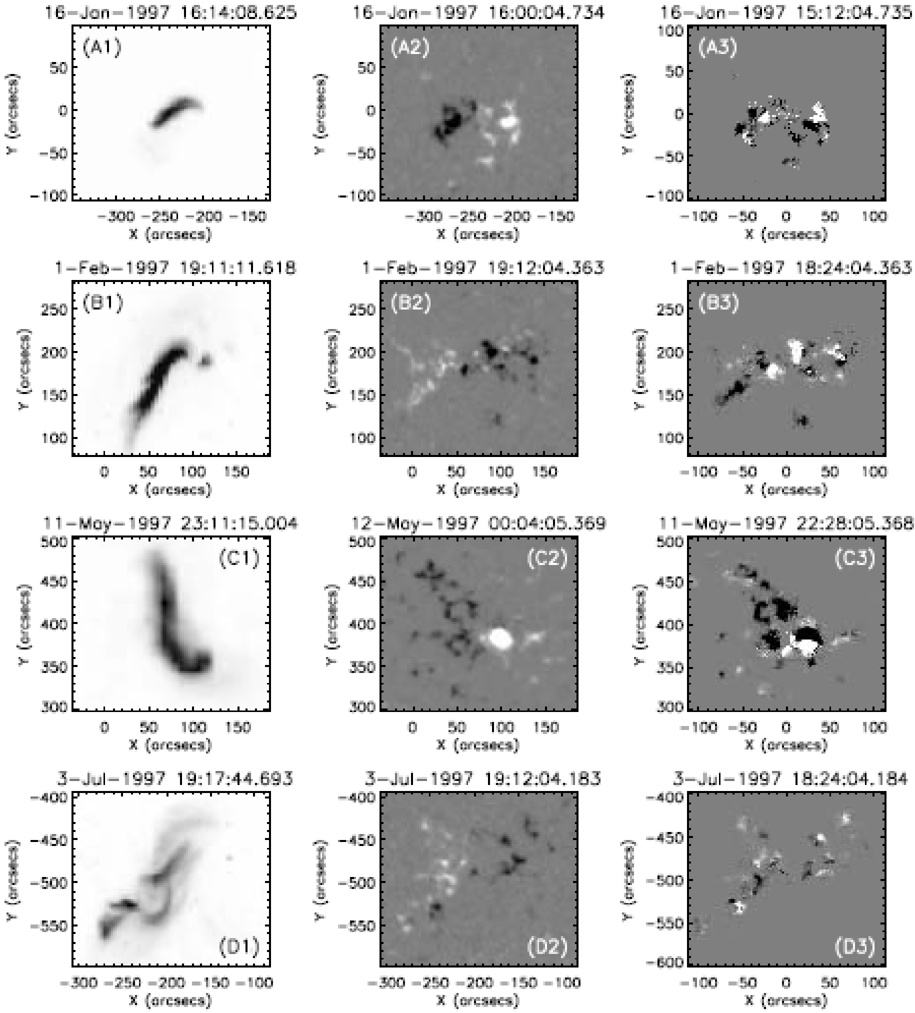
⇩

$$\dot{H} = \int \mathbf{E} \times \mathbf{A}_p \cdot d\mathbf{S}, \quad \mathbf{E} = \mathbf{V} \times \mathbf{B}$$

normalized twist rate $\Omega = \frac{\dot{H}}{\phi^2}$

$$(24h) \cdot \Omega \approx O(0.01) << 1$$

much less than one turn twist

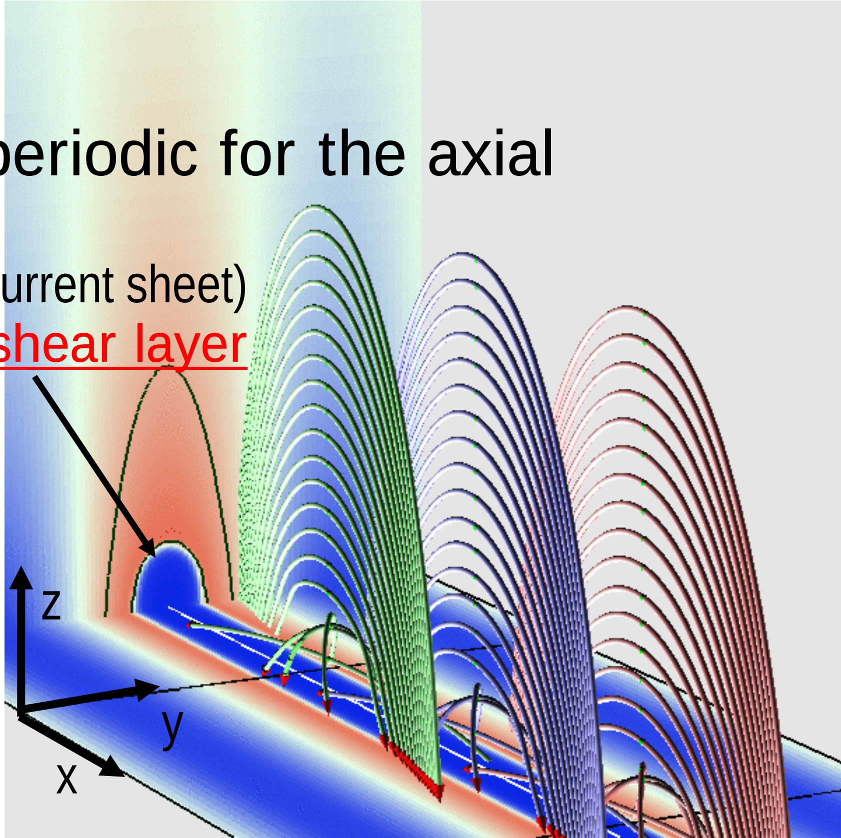


# Simulation Model (3D MHD)

- Basic equations $\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \cdot \nabla \mathbf{V} = \mathbf{J} \times \mathbf{B} + \nu \nabla^2 \mathbf{V}, \quad \frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{V} \times \mathbf{B} - \eta \mathbf{J})$
  - zero-$\beta$ version & finite $\beta$ version
- Finite difference: 512 X 512 X 1024 ($\Delta \sim 10^{-3}$)
  - parallelization in terms of MPI library (domain decomposition)
- Boundary Condition
  - line-tide on the bottom, periodic for the axial
- Initial state
  - force-free field with reversed-shear layer
- Anomalous resistivity

$$\eta = \begin{cases} \eta_0 & (J < J_0) \\ \eta_0 + \eta_1 \dfrac{J - J_0}{J_0} & (J > J_0) \end{cases}$$

$$\eta_0 = 10^{-5}, \quad \eta_1 = 5 \times 10^{-4}$$

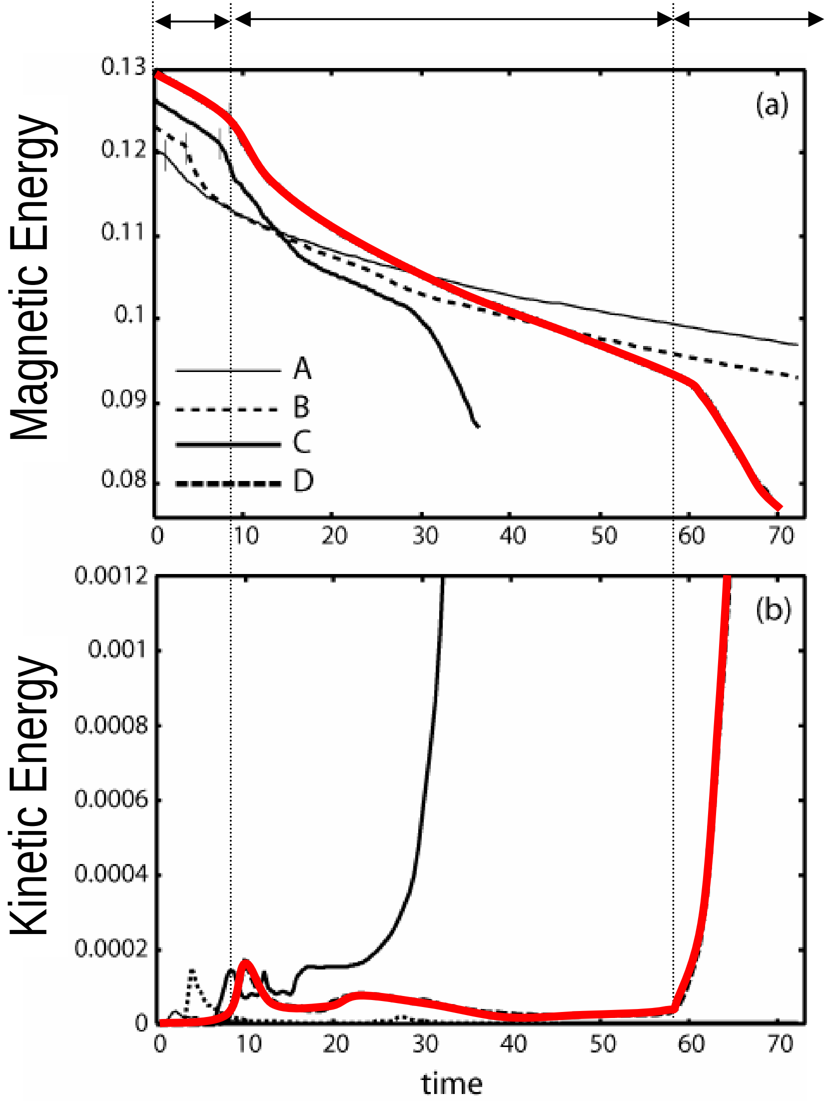

(current sheet)

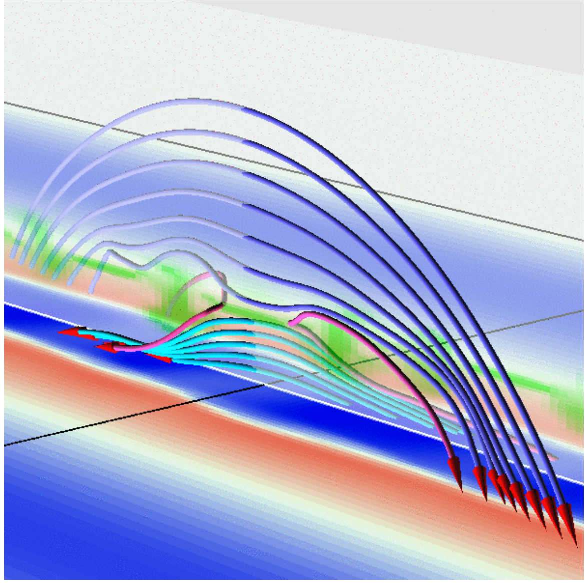
# Time Evolution of Energy

linear growth phase

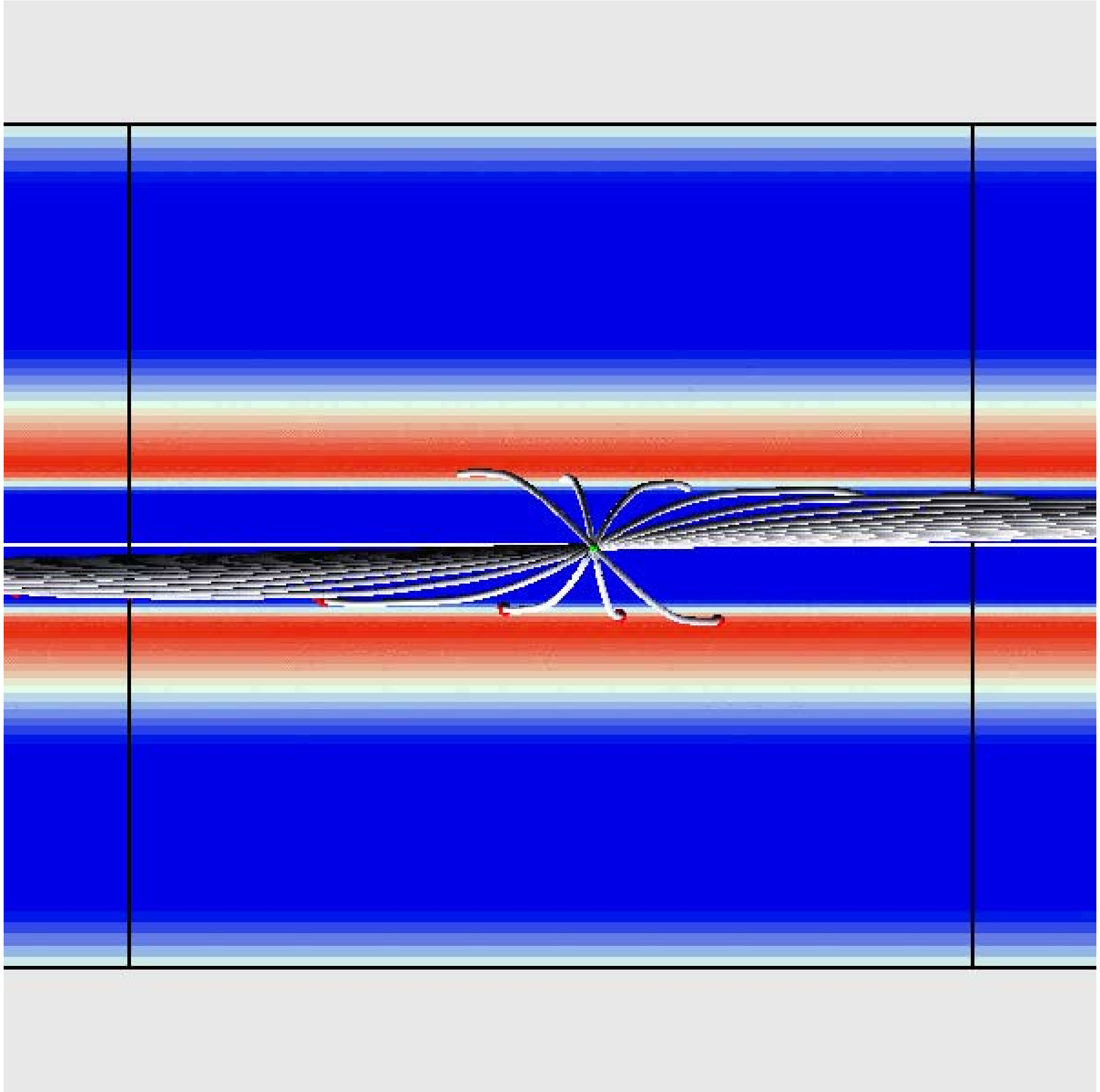
relaxation phase

eruption phase

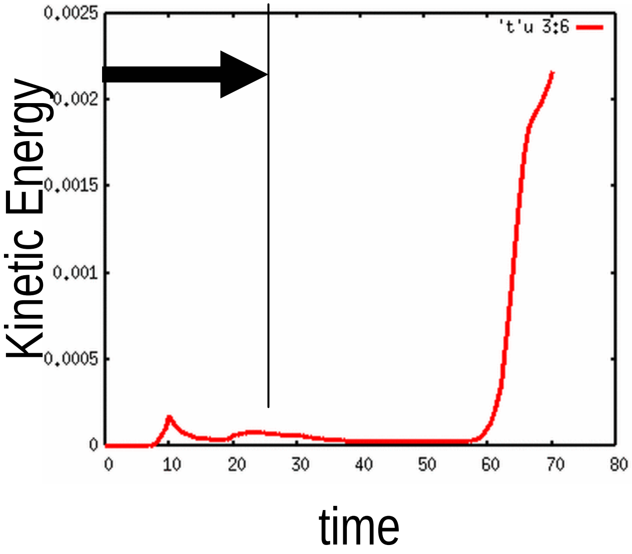




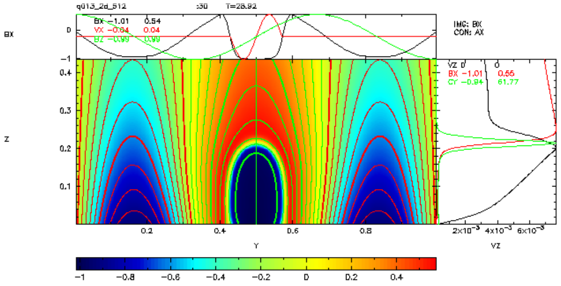
# Formation of Sigmoidal Structure



Case D



Strong Reversal



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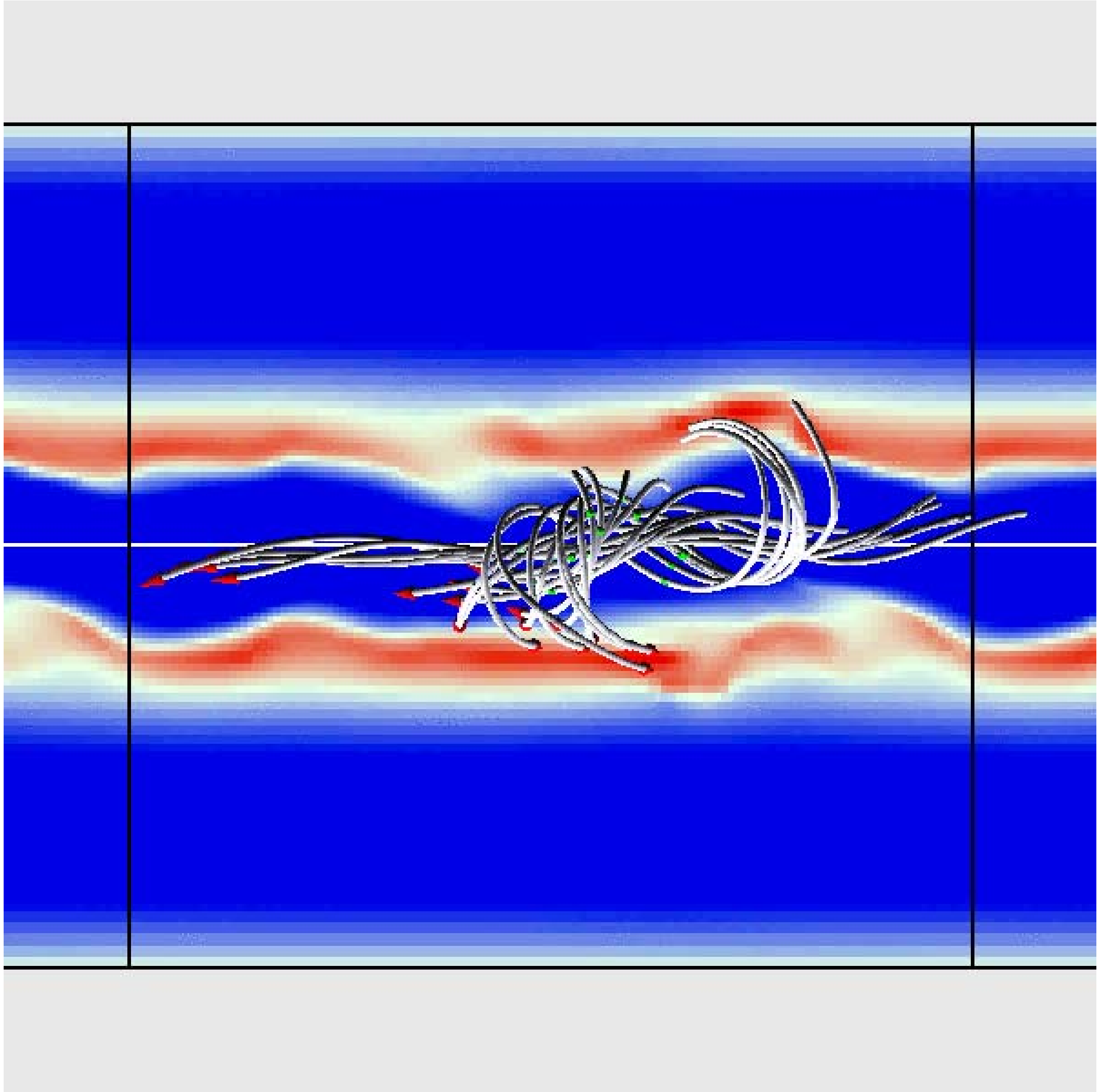
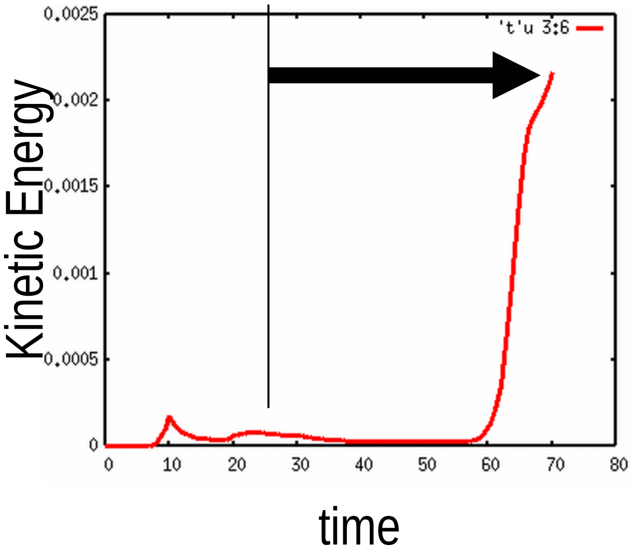
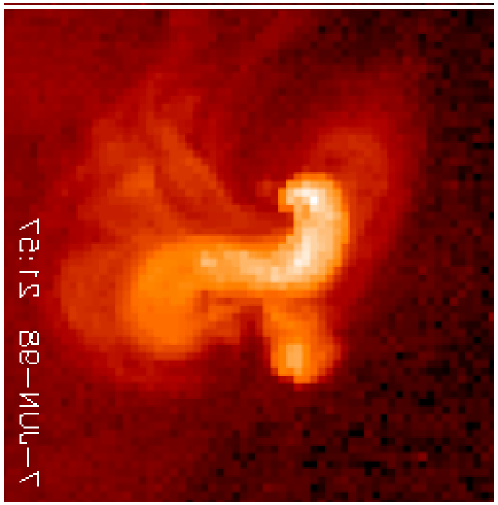


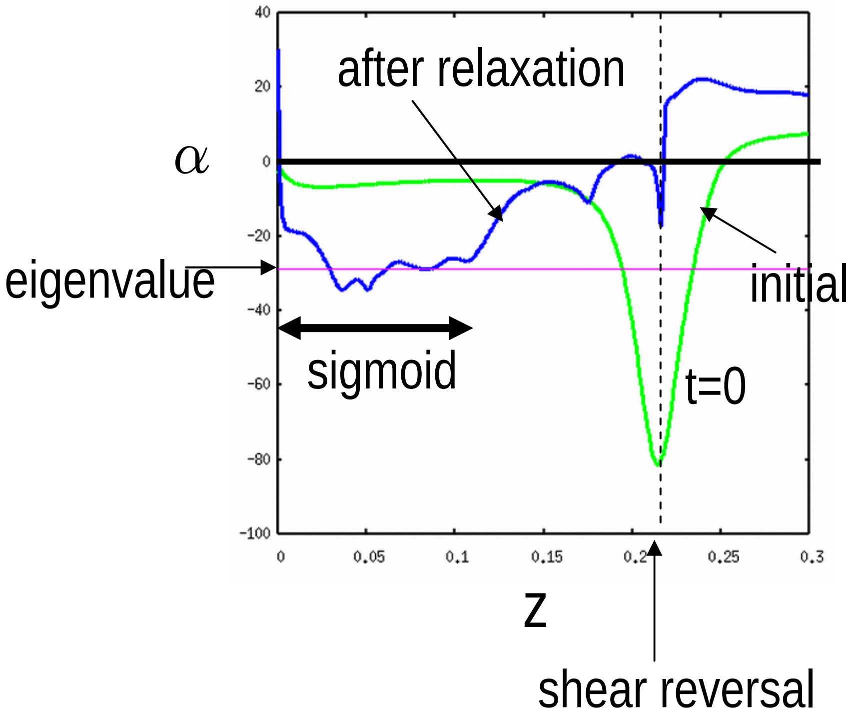


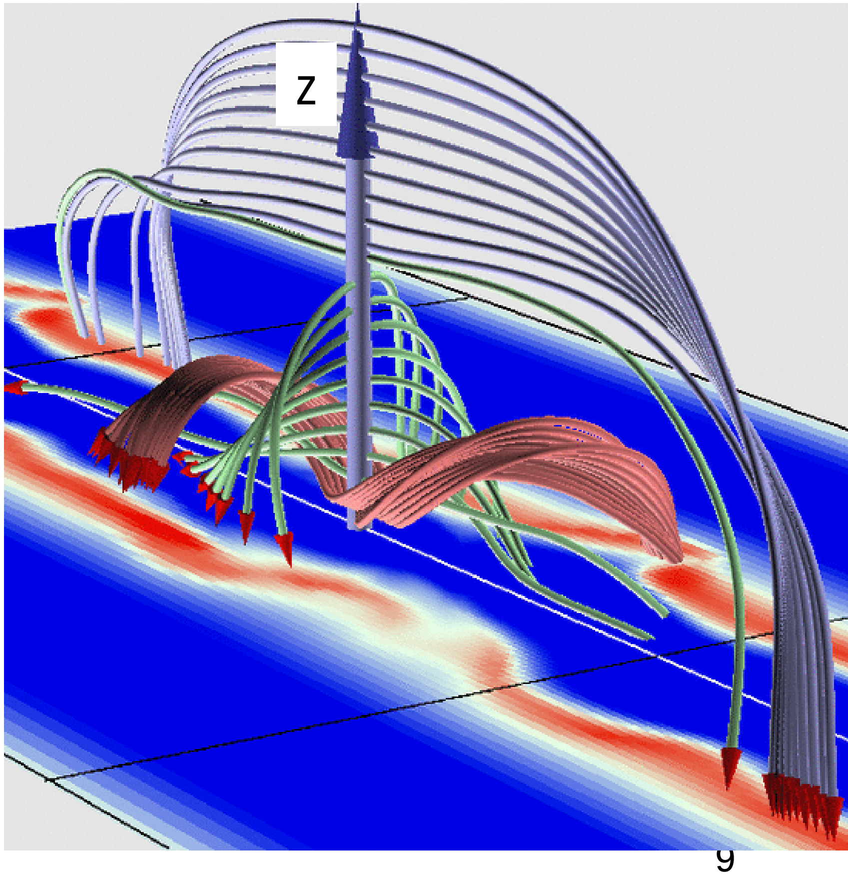


# distribution of α in sigmoid

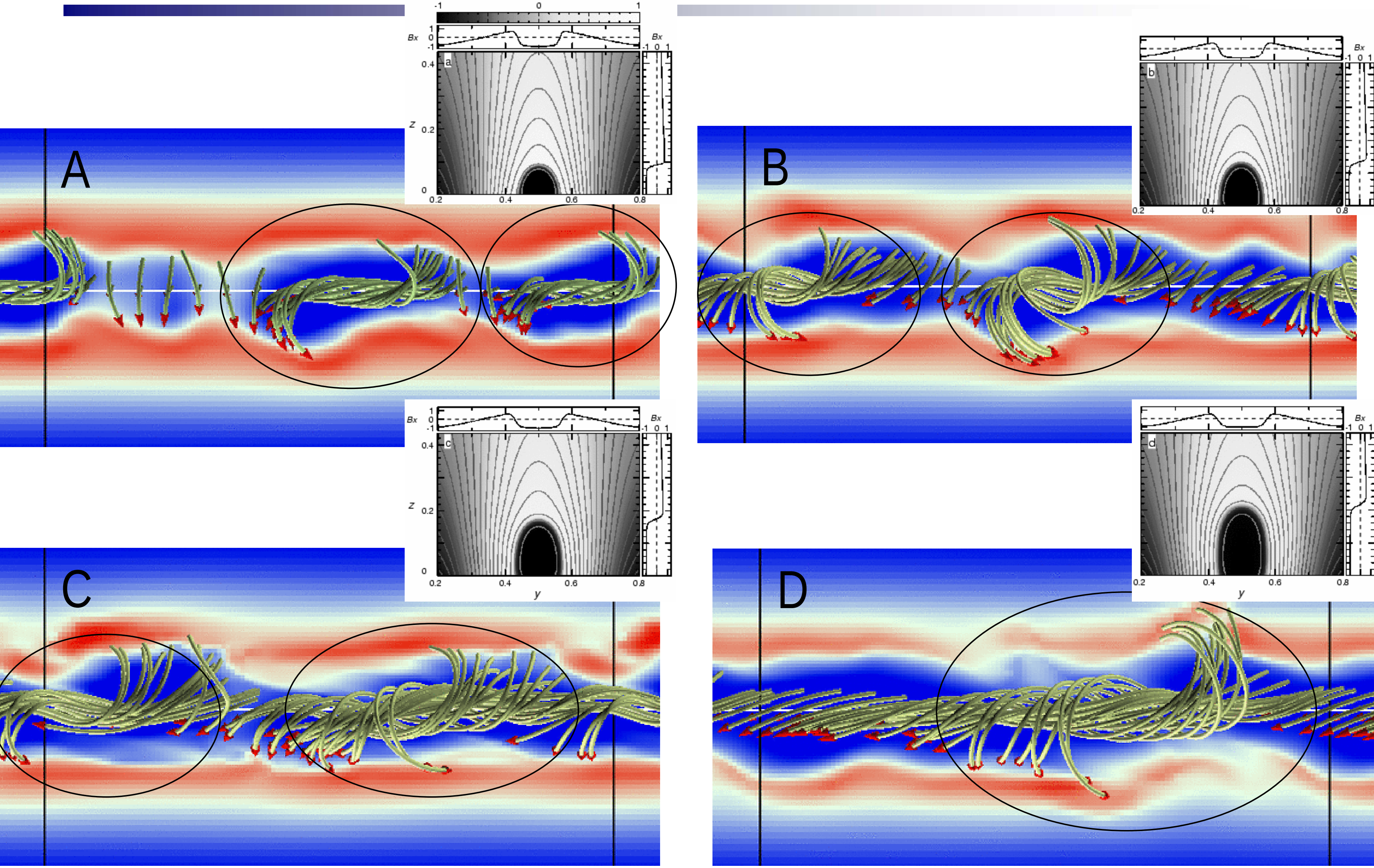
- α is flattened inside the sigmoid.
- α is limited by eigenvalue.

consistent with Taylor's relaxation theory





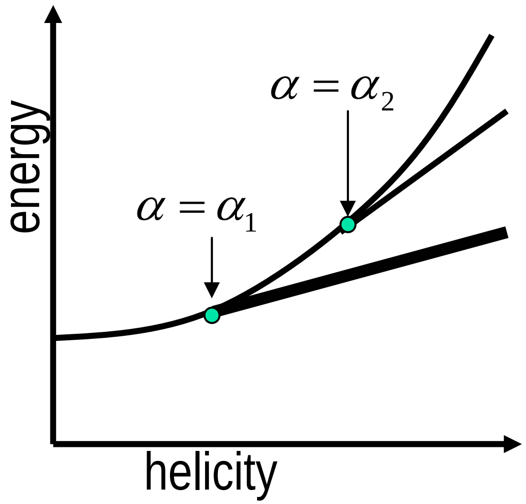
# dependency on the initial state

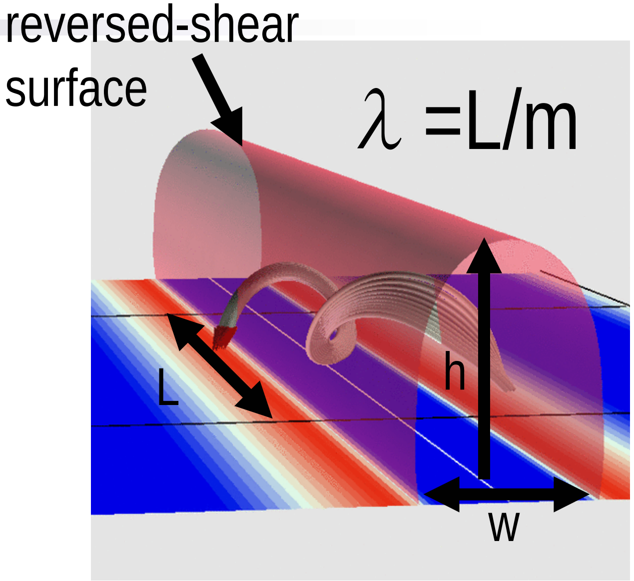


# Comparison with Taylor relaxation

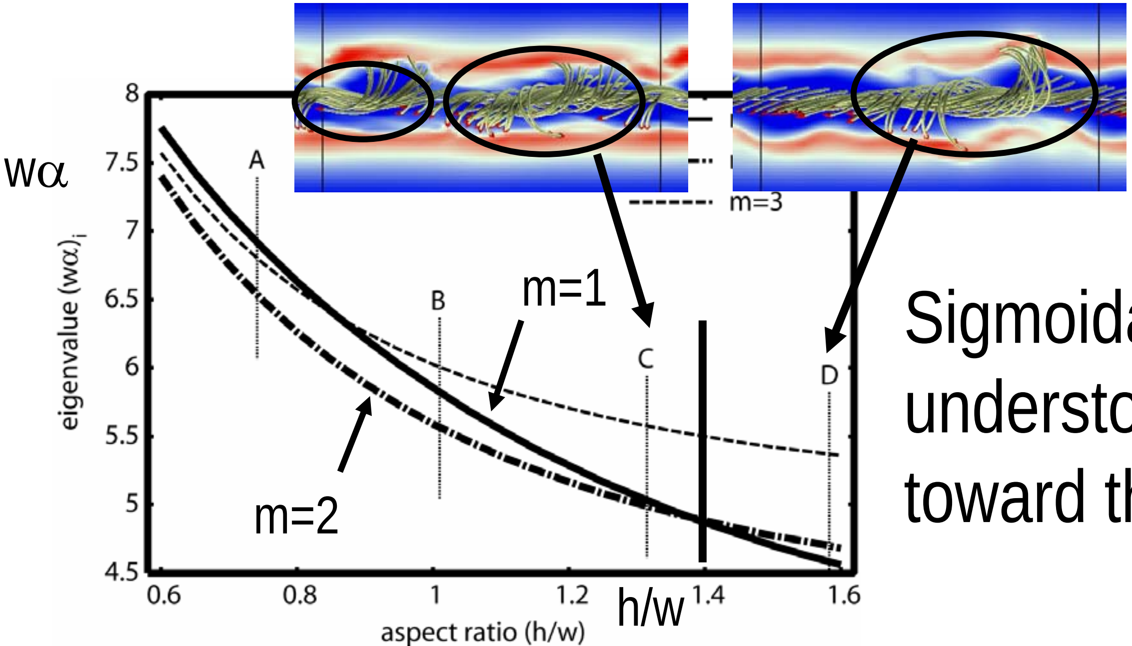
LFFF bifurcates into multiple solution, when $\alpha$ is larger than the eigen-value $\alpha_1$. (Taylor, 1986)

$$\nabla \times \mathbf{B} = \alpha_i \mathbf{B}$$



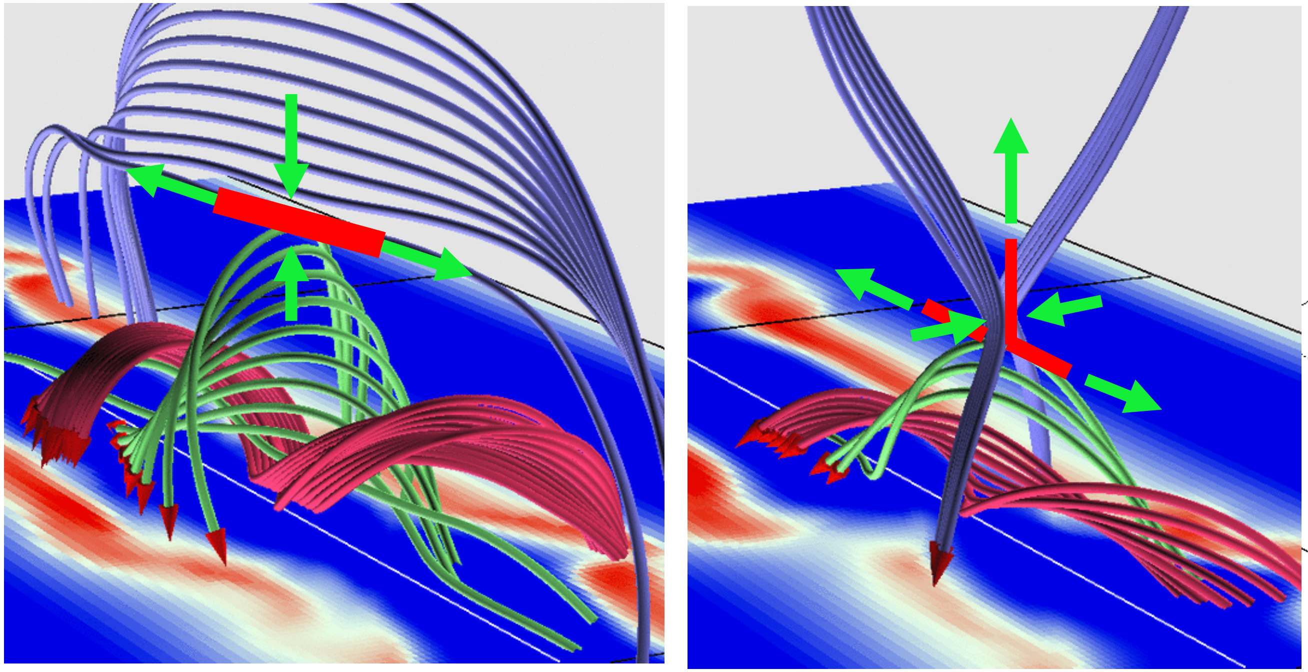


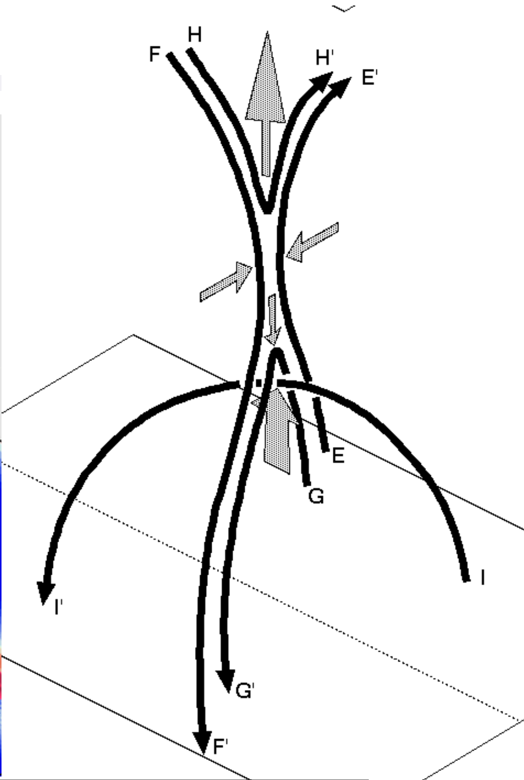
Sigmoidal wavelength is consistent with the Taylor's minimum energy principle.



Sigmoidal formation can be understood as the self-organization toward the Taylor type state.

# Sigmoid to Eruption

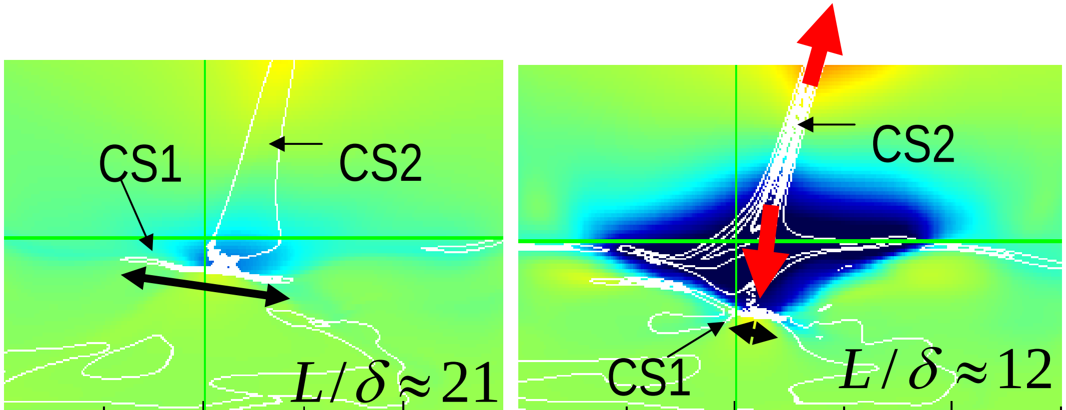




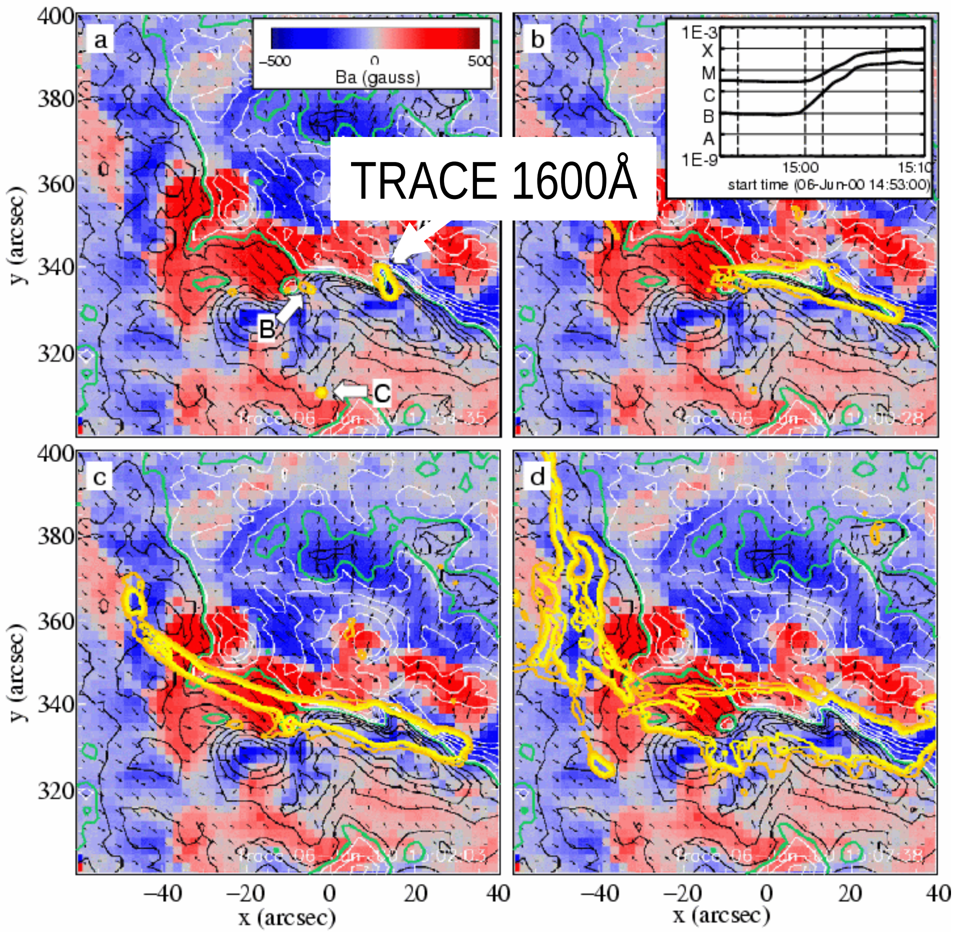
tearing mode reconnection → collapsing → double reconnection on T-shape current sheet

↓

explosive growth of energy liberation

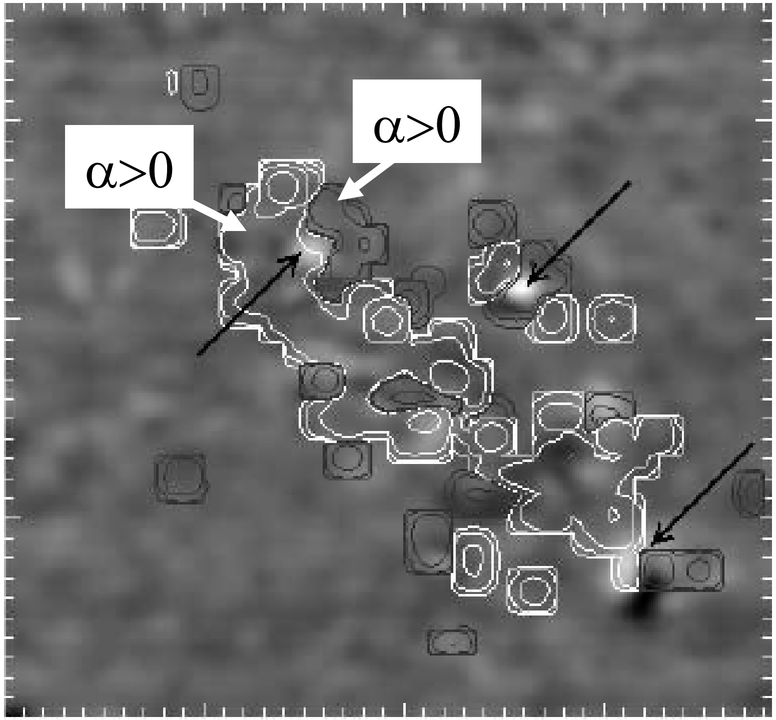


# flares from reversed-shear



TRACE 1600Å

Maeshiro et al. 2005



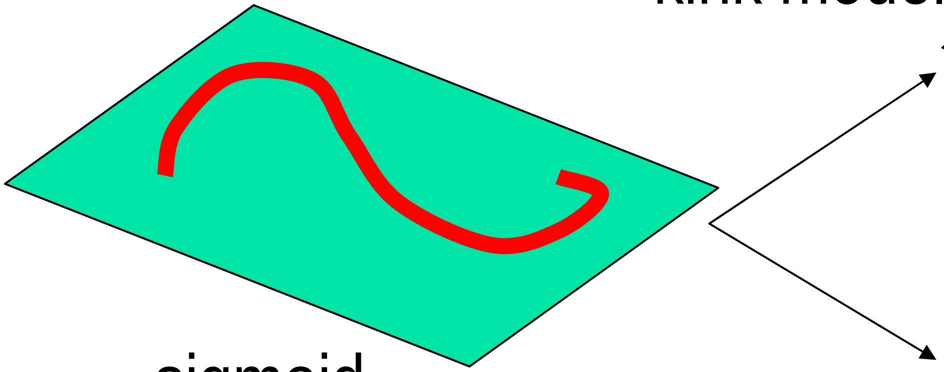
α>0

α>0

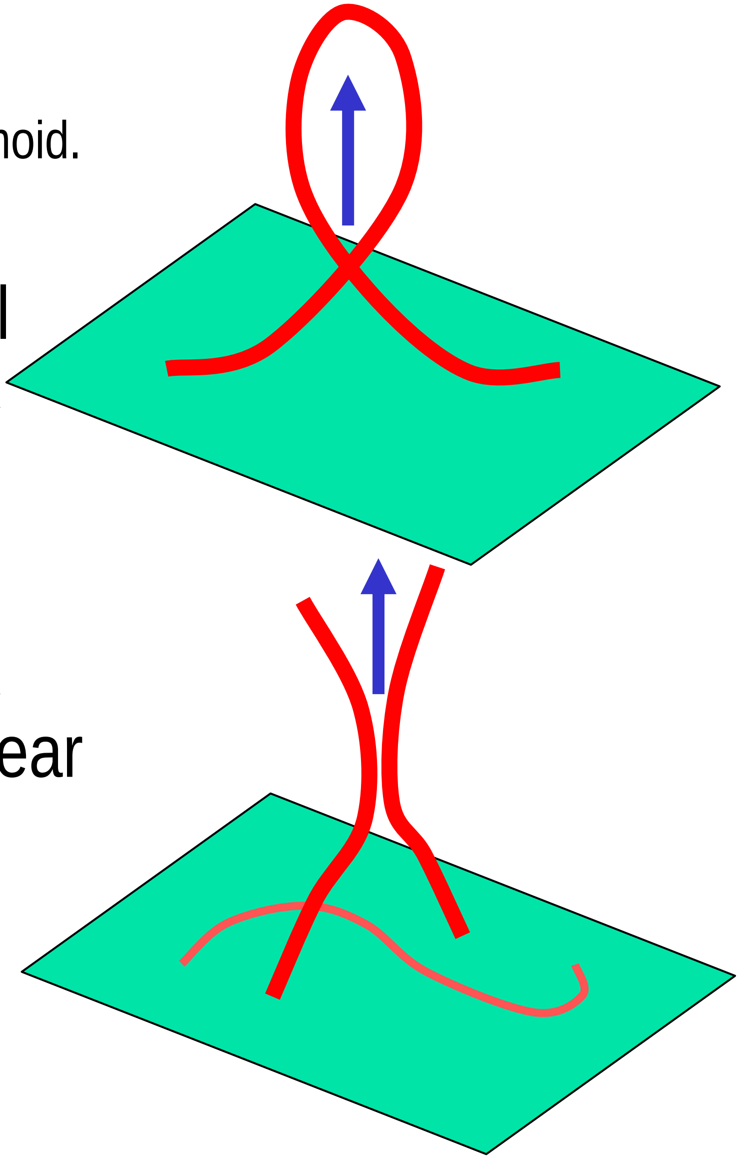
Hahn et al. 2005

# Kink Model vs. Reversed-Shear Model

The two models are geometrically different,
and the validity of them can be examined by
careful observation of continuous evolution of sigmoid.

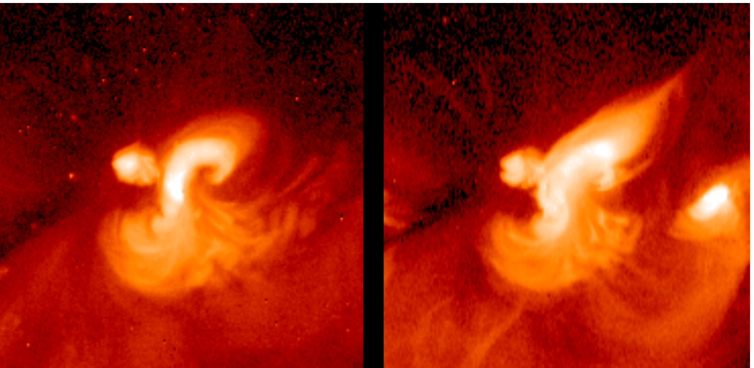


sigmoid



kink model

reversed-shear model



# Conclusions

- The resistive tearing mode instability on the reversed-shear layer may cause both the formation of sigmoids and the onset of eruption.
- The sigmoidal formation is consistent with the self-organization toward Taylor state.
- The transition from the quasi-steady sigmoid to the sudden onset of eruption can be explained by the arcade collapsing and the feed-back of double reconnections.
- Reversed-shear flare model.
    - Kusano et al. 2004 ApJ, Kusano 2005 ApJ (in press)