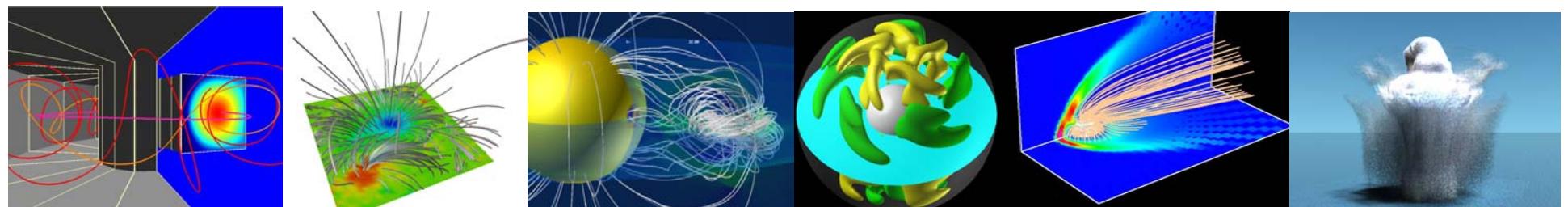




# 太陽フレアの予測可能性について

草野完也

名古屋大学太陽地球環境研究所



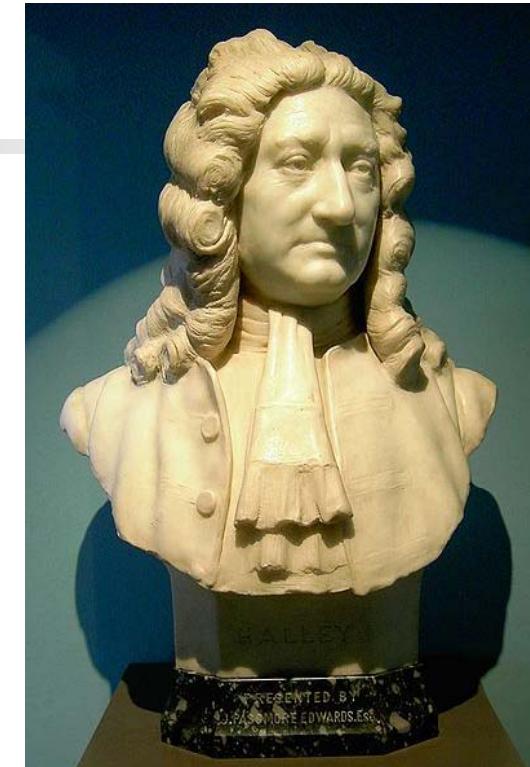
# 予測と近代科学

## ■ ハレー彗星



Wikipediaより

- 1682年に出現した彗星の観測データとニュートン力学から、この彗星が76年の周期を持つ楕円軌道を持つと結論(プリンキピア出版は1687年)
- 過去の記録から、1531年、1607年に出現した彗星が同一のものと推測
- 次回の回帰が1758年であると予測。
- 1758年12月25日、予測通り彗星が出現。

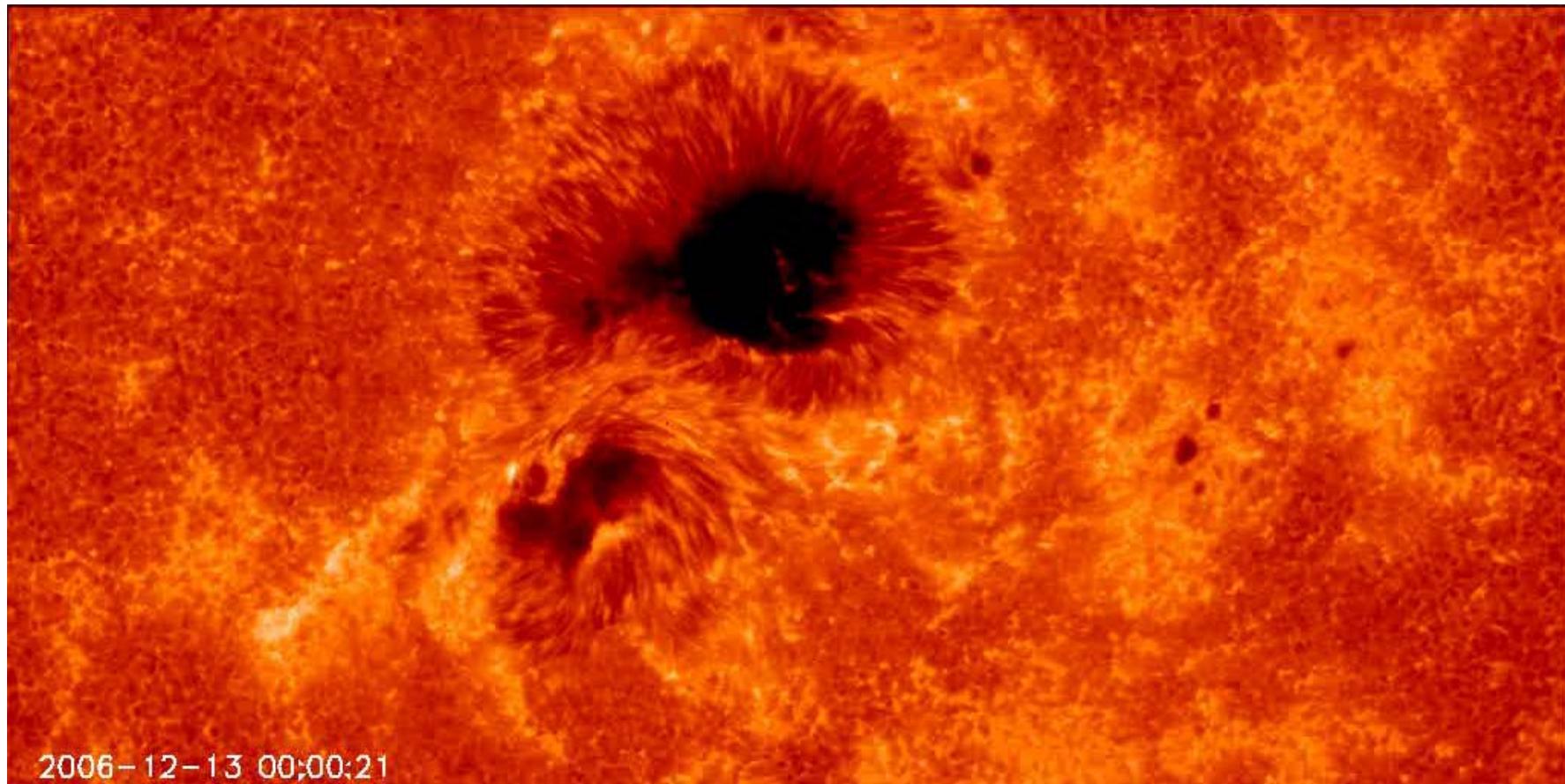


エド蒙ド・ハレー(1656年10月29日 - 1742年1月14日)

# Solar Flares

---

突発的なコロナ磁気エネルギーの解放現象  
その発生を予測できるか？



2006-12-13 00:00:21

# Skill Score of X-flare prediction

1day	2day	3day	year (events)
-0.068	-0.096	-0.141	2011 (8)
0.112	-0.147	-0.171	2006 (4)
0.242	0.147	0.127	2005 (13)
0.052	-0.001	-0.044	2004 (9)
0.200	0.093	0.076	2003 (17)
-0.037	-0.050	-0.033	2002 (12)
-0.061	-0.034	-0.006	2001 (18)



Space Weather Prediction Center

[http://www.swpc.noaa.gov/forecast\\_verification/](http://www.swpc.noaa.gov/forecast_verification/)

$$SS = \frac{n_{ff} - (n_q - n_{qq})}{n_f}$$

# McIntosh classification

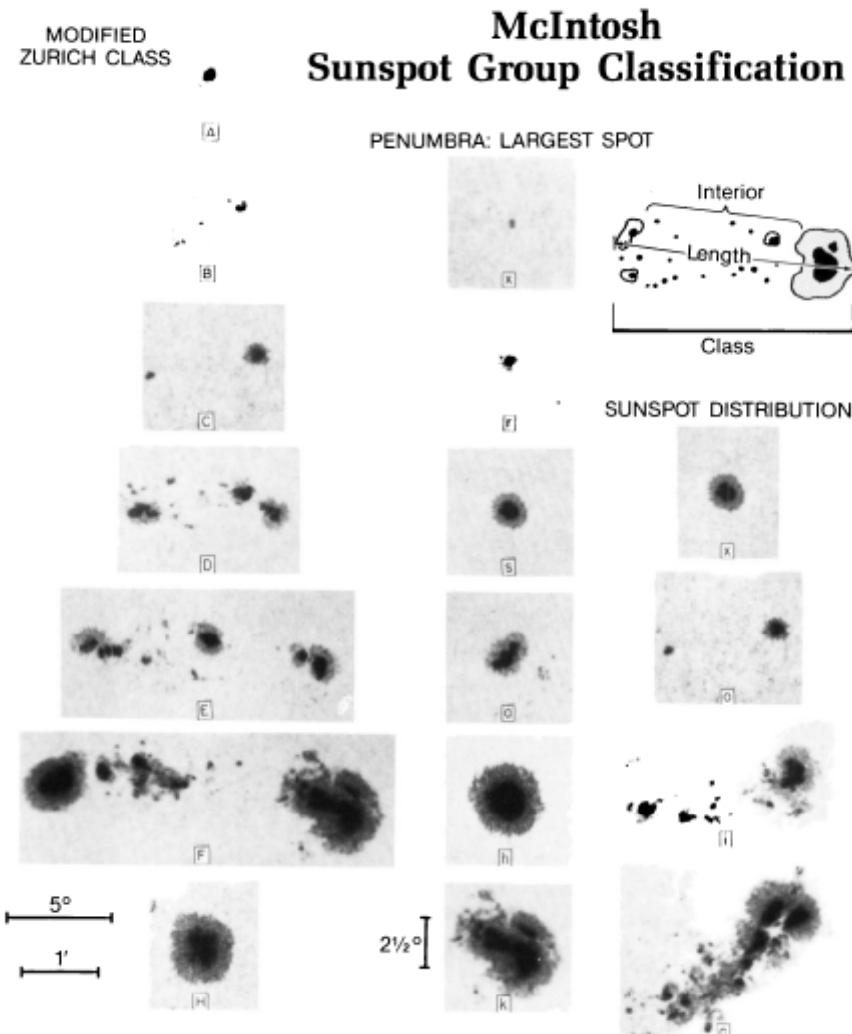


Fig. 1. The 3-component McIntosh classification, with examples of each category.

McIntosh 1990

# Flare Prob. for each McIntosh class

- Gallacher, Moon, Wang 2002 Sol. Phys.

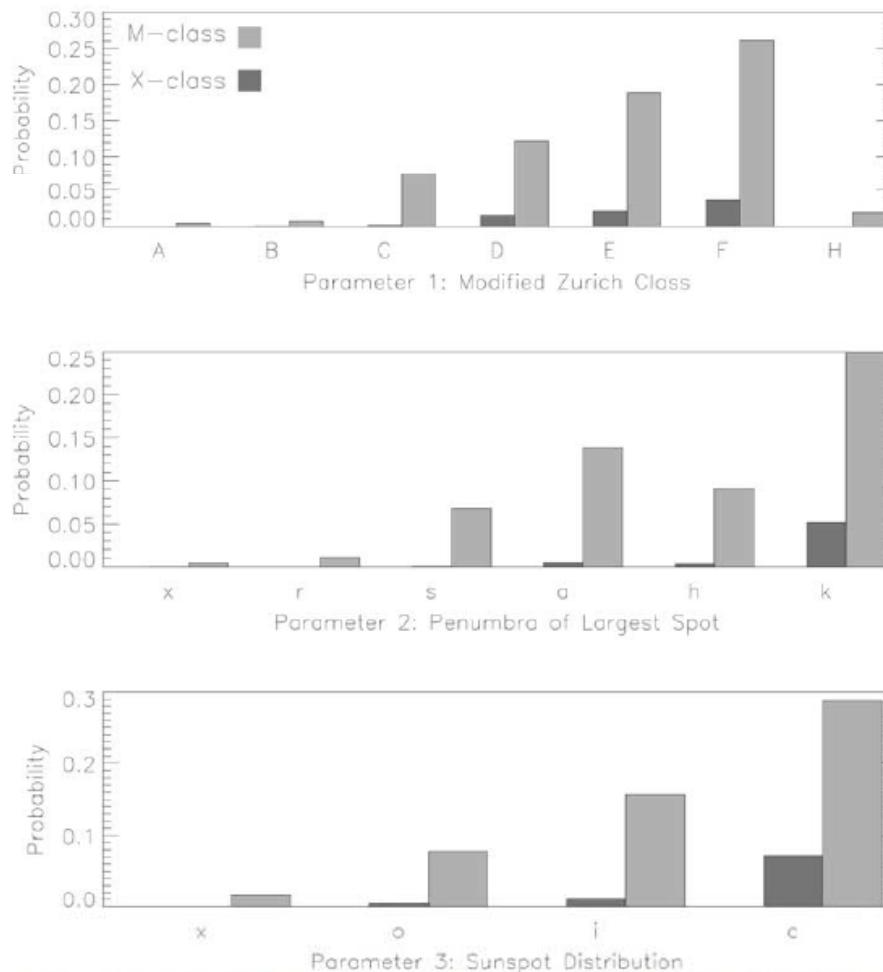
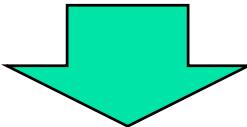
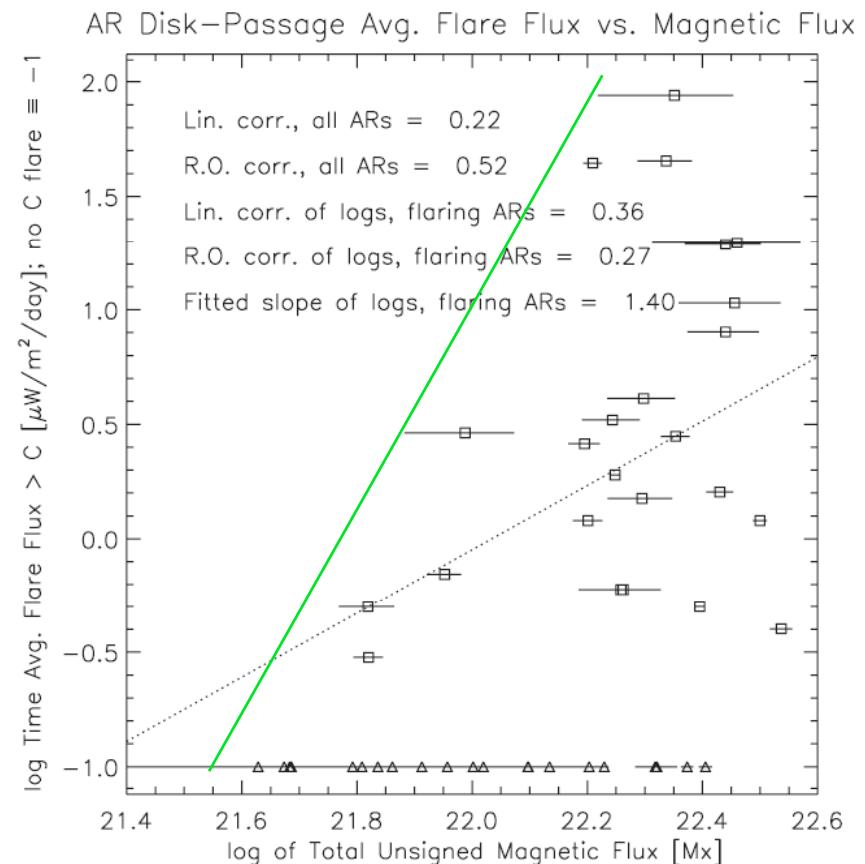


Figure 4. Derived 24-hour active-region flare probabilities for each of the three McIntosh classification parameters using Poisson statistics.

# Welsch et al. 2009 ApJ

- 全磁束量とフレアの規模の関係
- 大フレアは大黒点で起きる。しかし、
- 大黒点が必ずしも大フレアを起こすとは限らない。  

- では何が、巨大フレア発生の条件か？



# フレア発生条件として磁場構造

---

- strong magnetic shear (Hagyard, et al. 1984)
- reversed magnetic shear (Kusano et al. 2004)
- sigmoidal structure (Rust & Kumar 1996; Canfield et al. 1999)
- flux cancellation (van Ballegooijen & Martens 1989)
- converging foot point motion (Inhester et al. 1992)
- the sharp gradient of magnetic field (Schrijver 2007)
- emerging magnetic fluxes (Heyvaerts, Priest & Rust 1977; Moore & Roumeliotis 1992; Feynman & Martin 1995; Chen & Shibata 2000)
- multipolar topologies (Antiochos et al. 1999)
- flux rope (Forbes & Priest 1995; Torok & Kliem 2005)
- narrow magnetic lanes between major sunspots (Zirin & Wang 1993)
- topological complexity (Schmieder et al. 1994)
- intermittency and multifractality (Abramenko & Yurchyshyn 2010)
- double loop structure (Hanaoka 1997)

# 本研究の目的

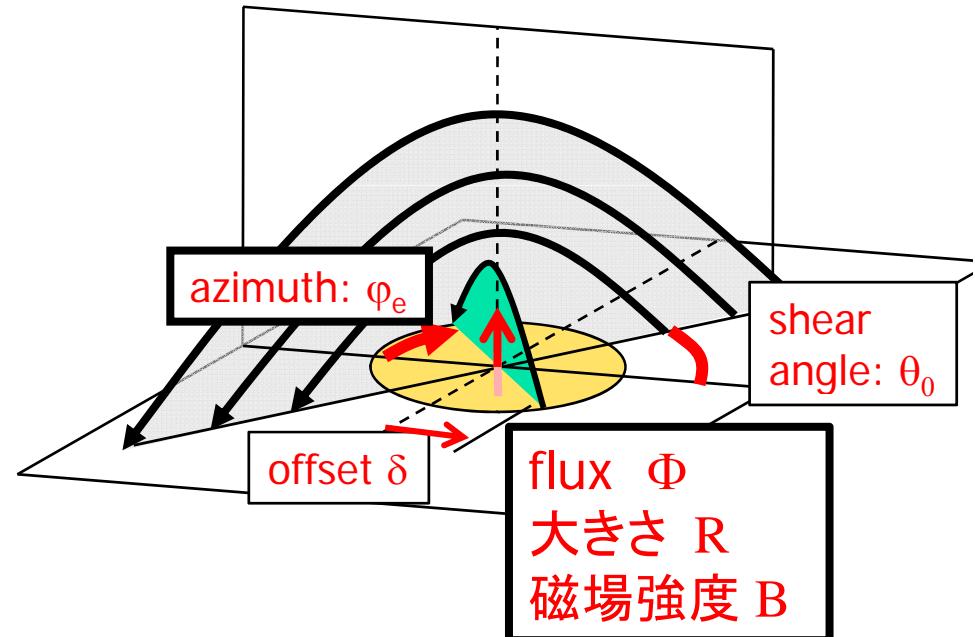
- 目的:

トリガ磁場構造(特に、OP型)が満たすべき臨界条件を非線形シミュレーションと安定性解析より明確にする。

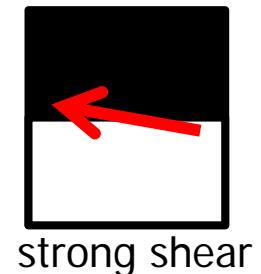
- シミュレーションモデル:

- 3D MHD (zero-beta model)
- 256x1024x512 grids (finite difference scheme)
- 初期条件:LFFF、境界条件:磁束入射
- output: 800 GB/run

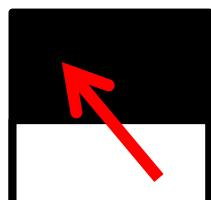
Simulation Model



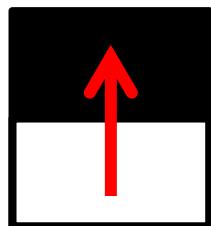
# Parameter Space: $\theta_0$ vs. $\varphi_e$



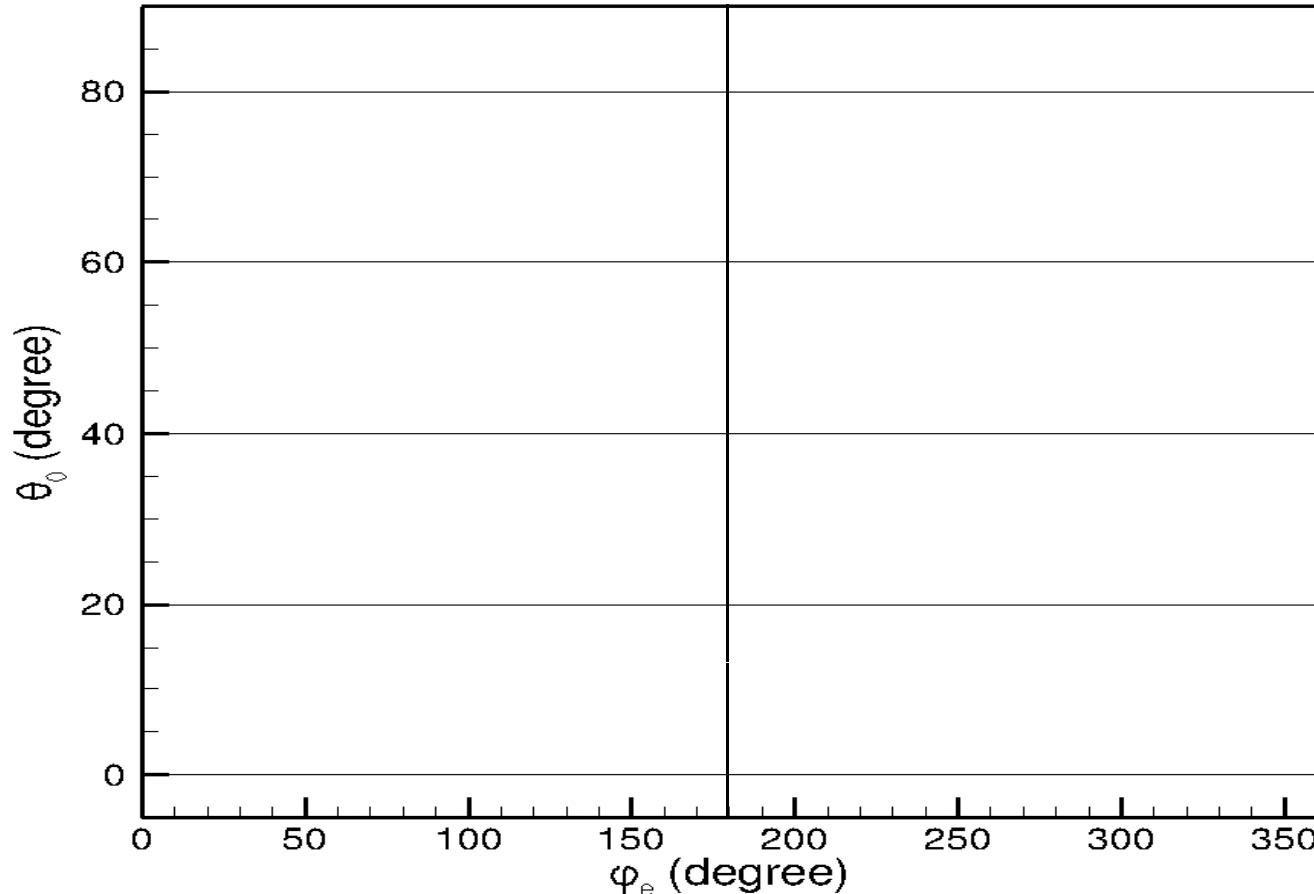
strong shear



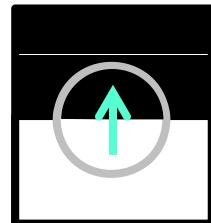
weak shear



potential field



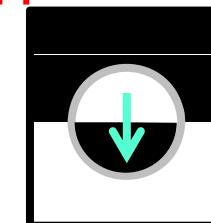
Right Polarity



Opposite Polarity

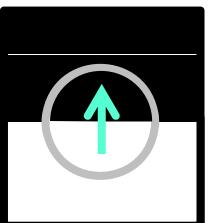


Normal Shear

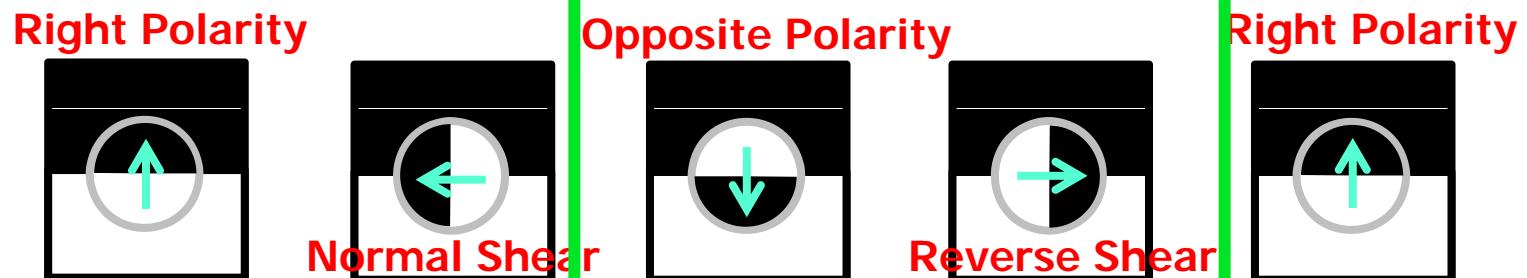
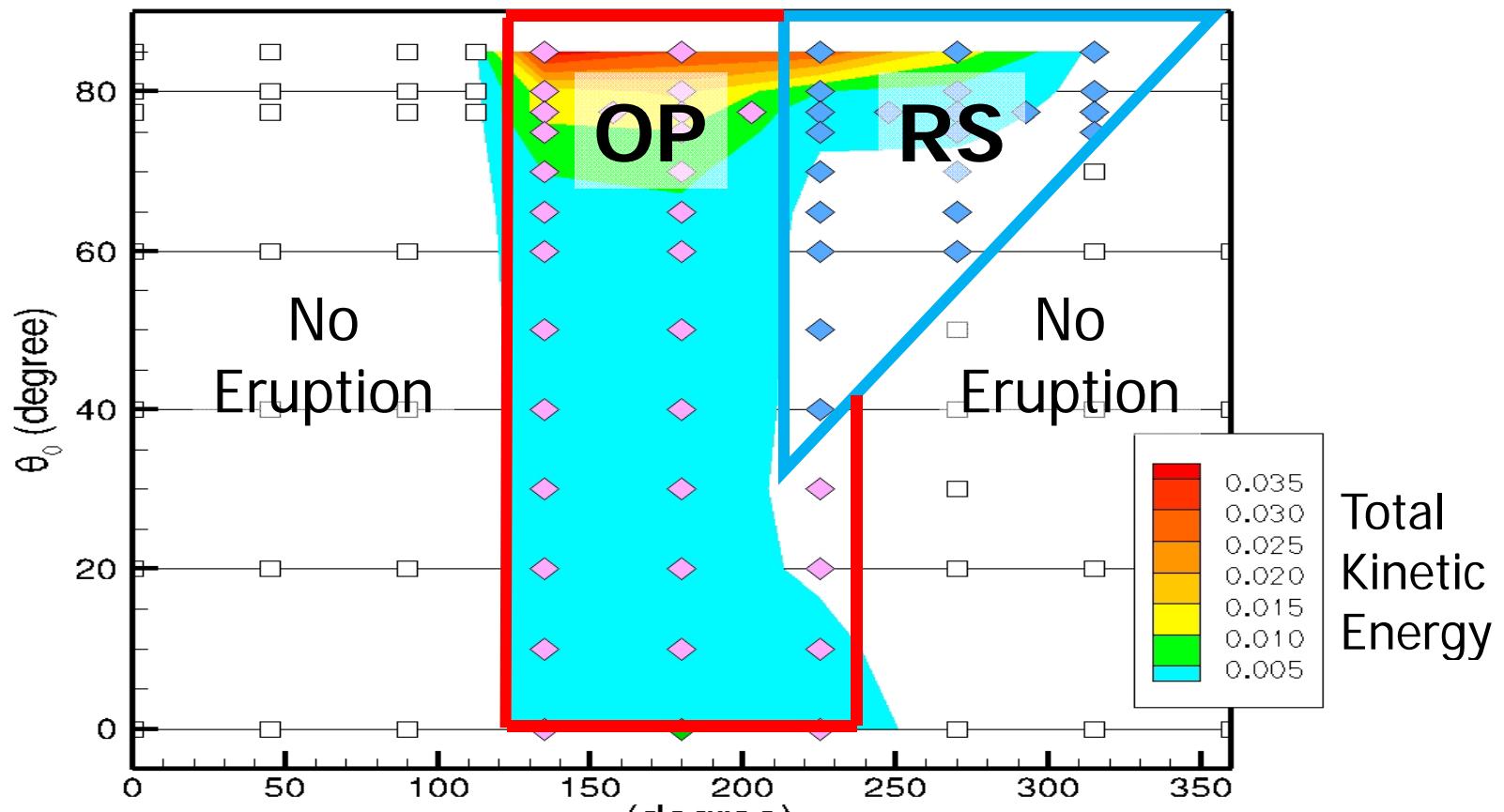
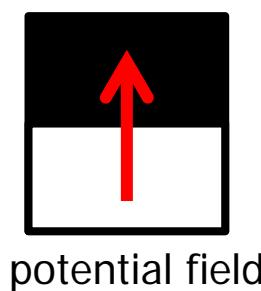
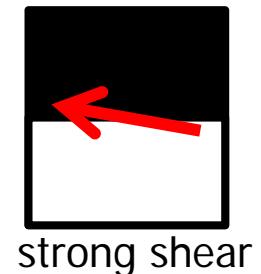


Reversed Shear

Right Polarity

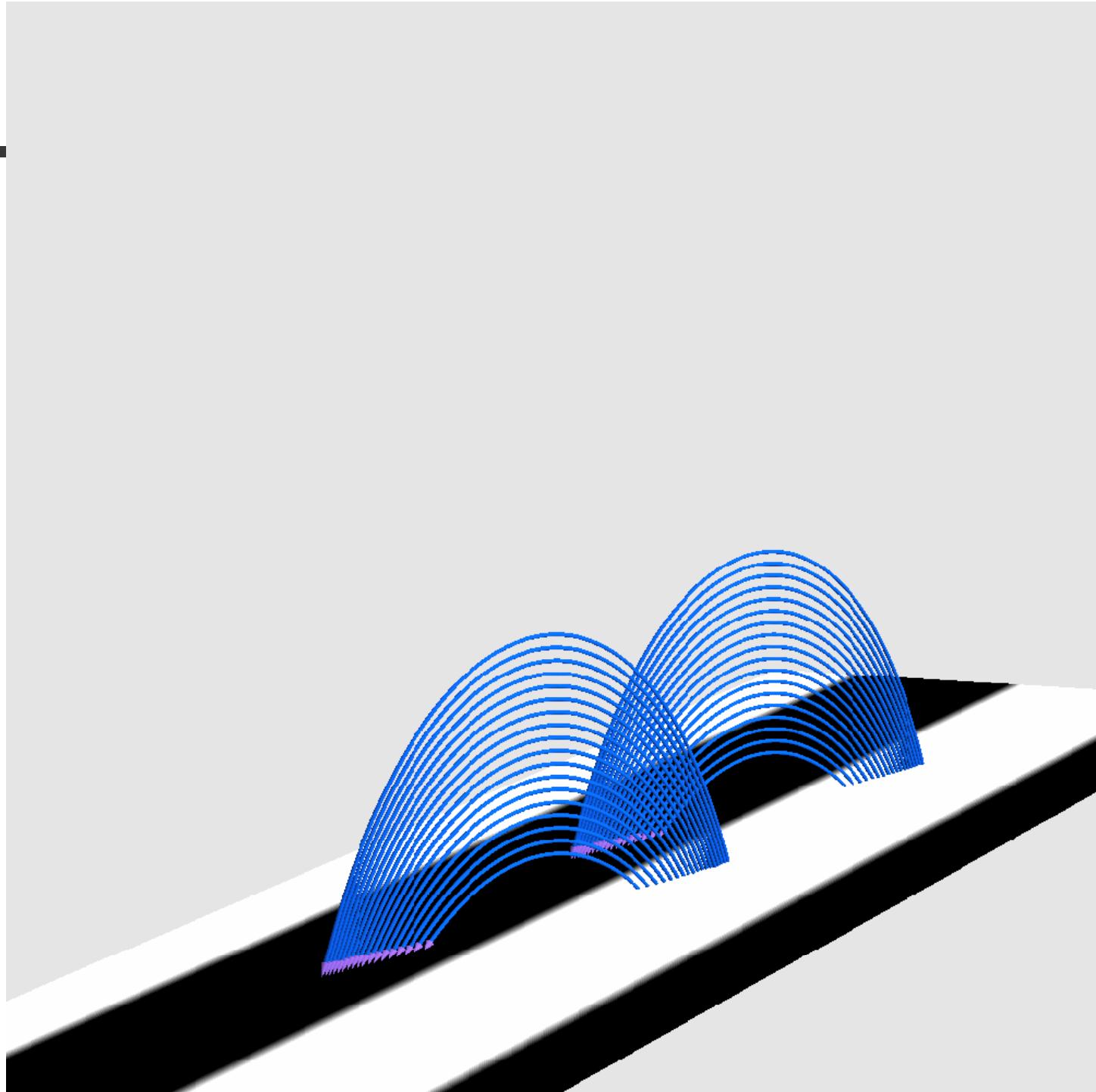


# Simulation Results



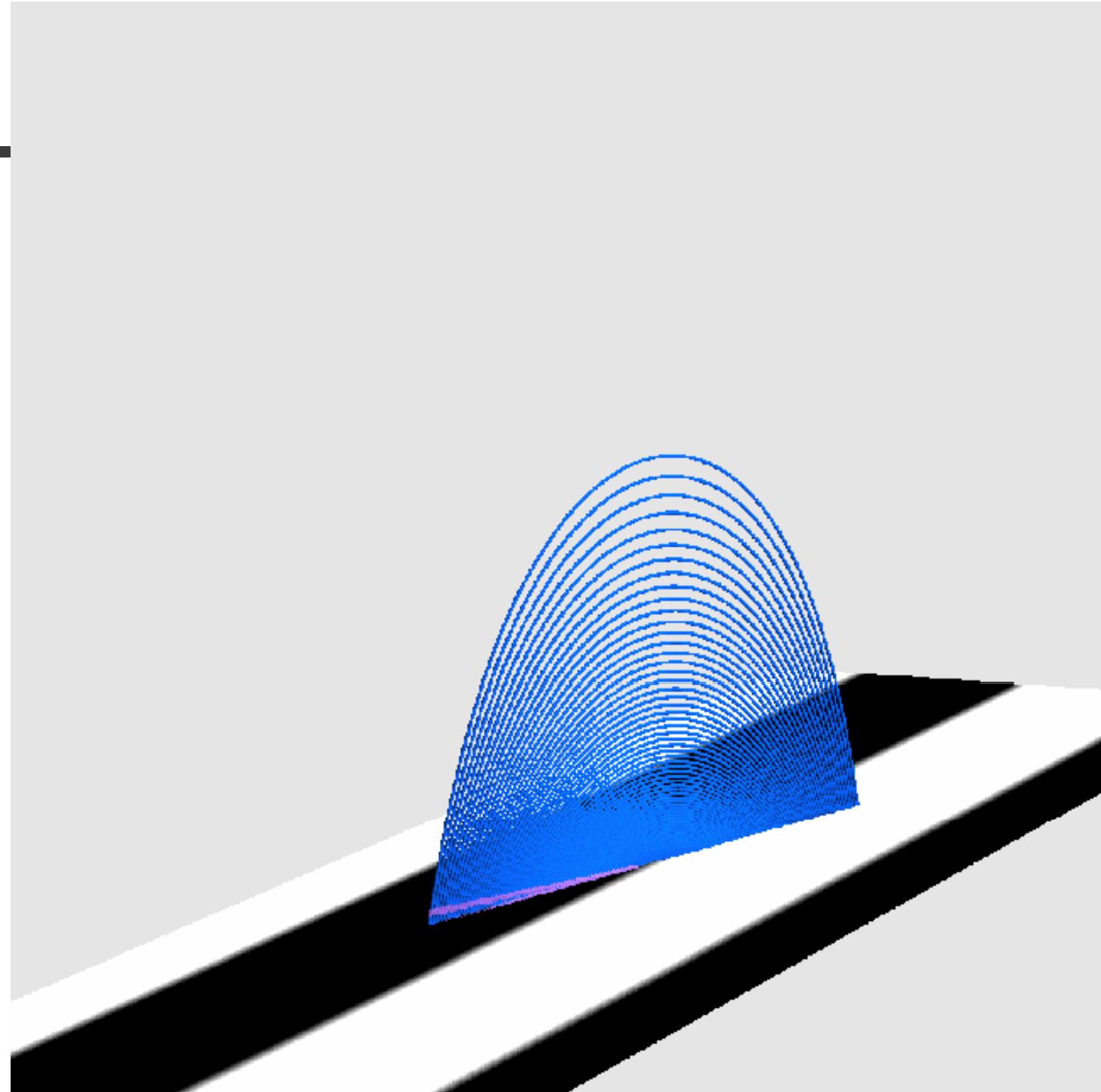
OP

---



RS

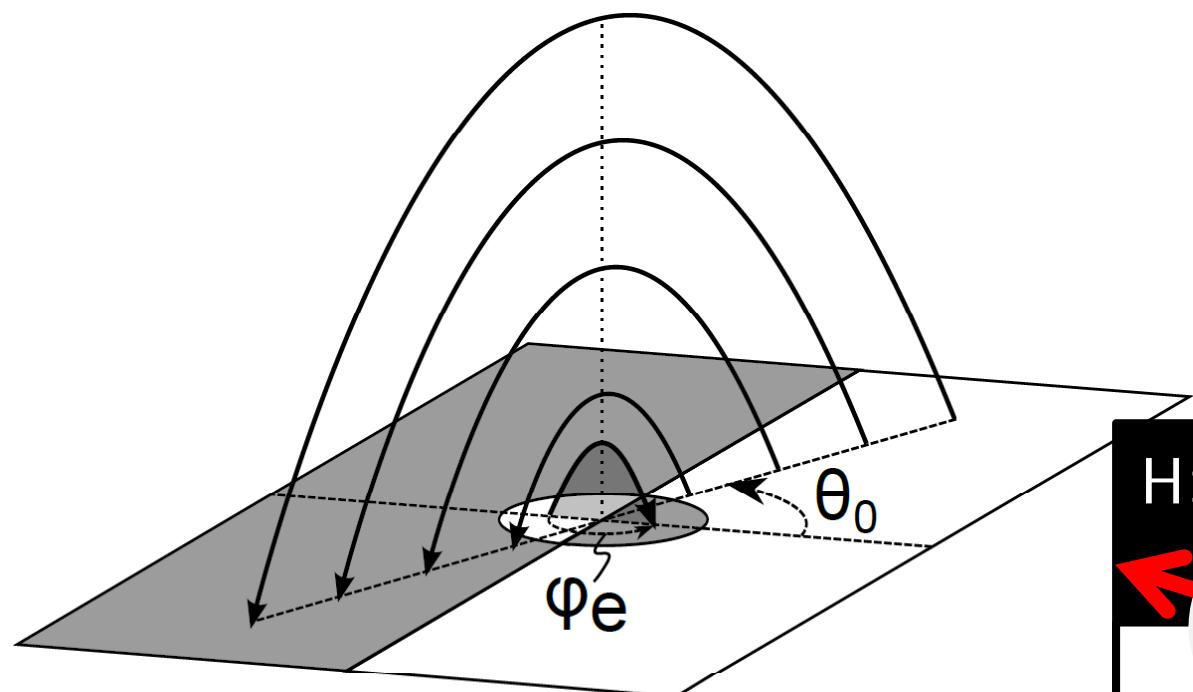
---



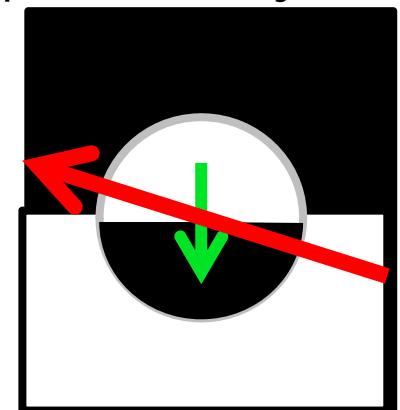
# 2つの条件

- Kusano et al. 2012 ApJ (in press)

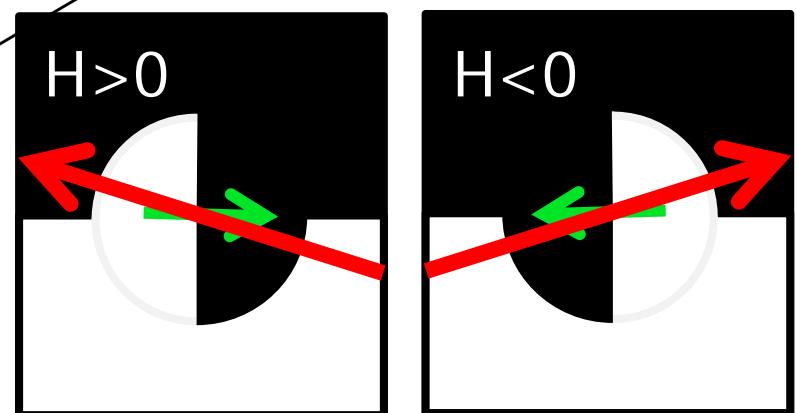
- ①強いシア磁場    ②2種類の磁場擾乱

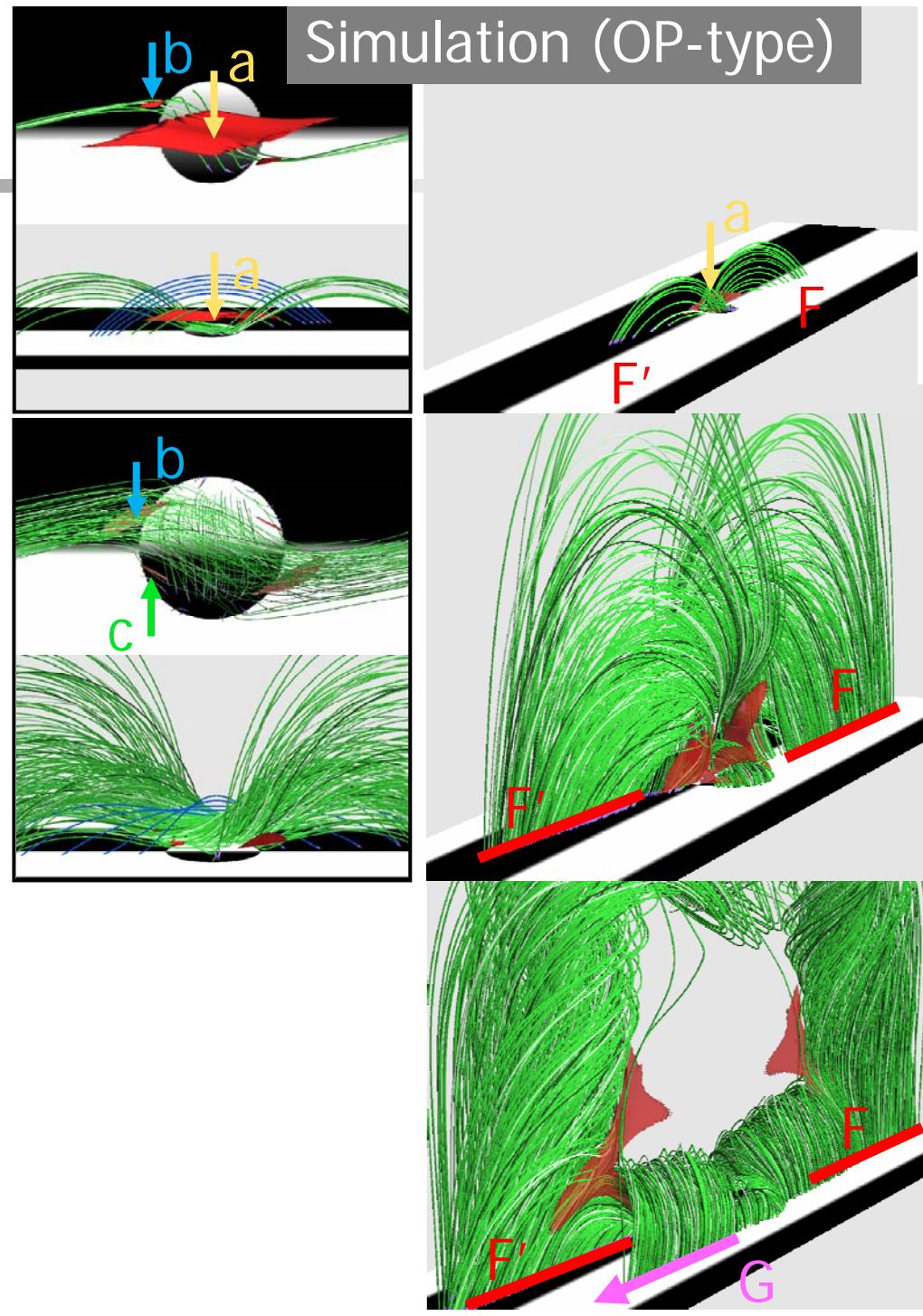
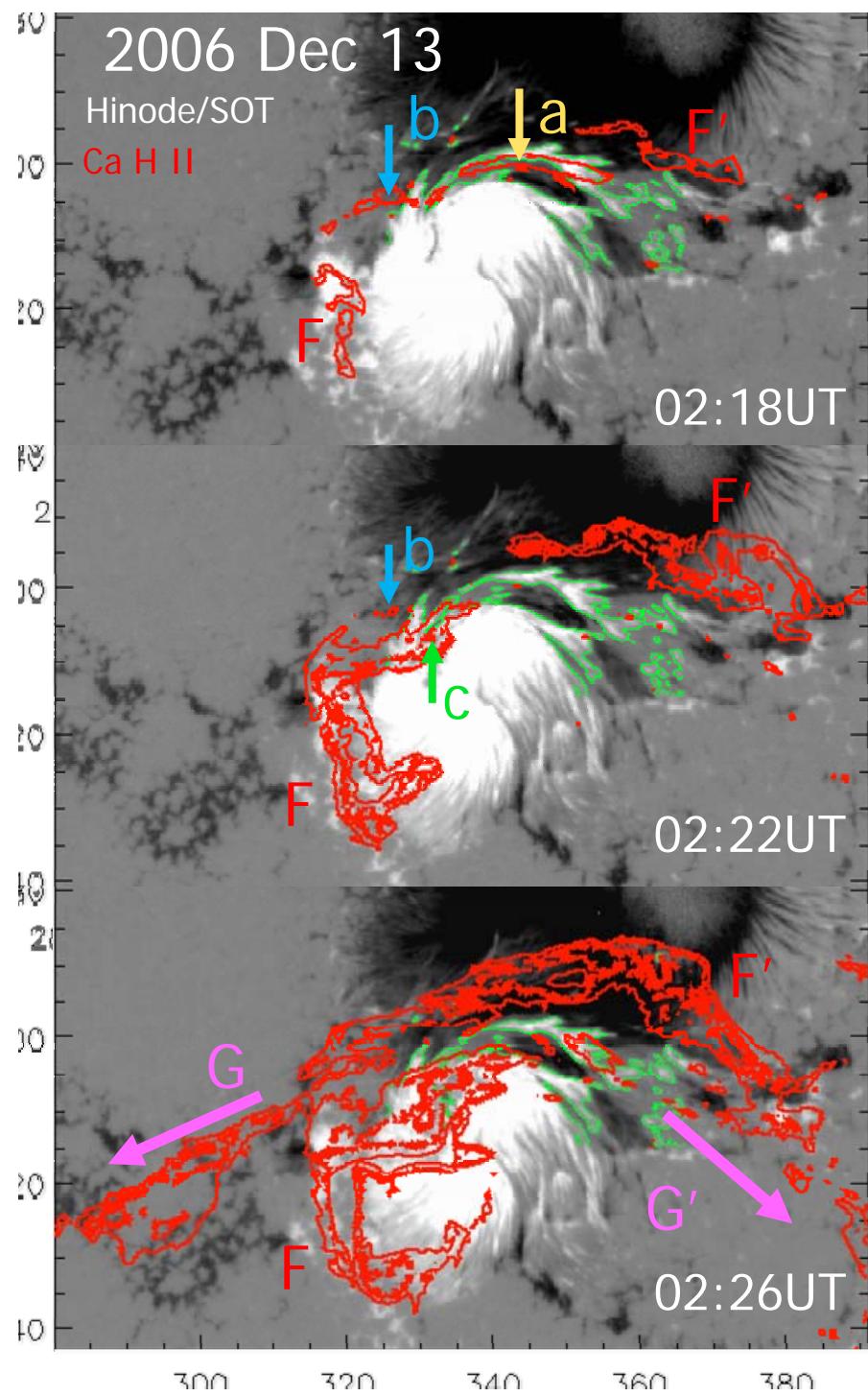


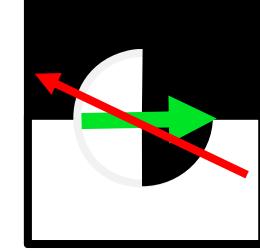
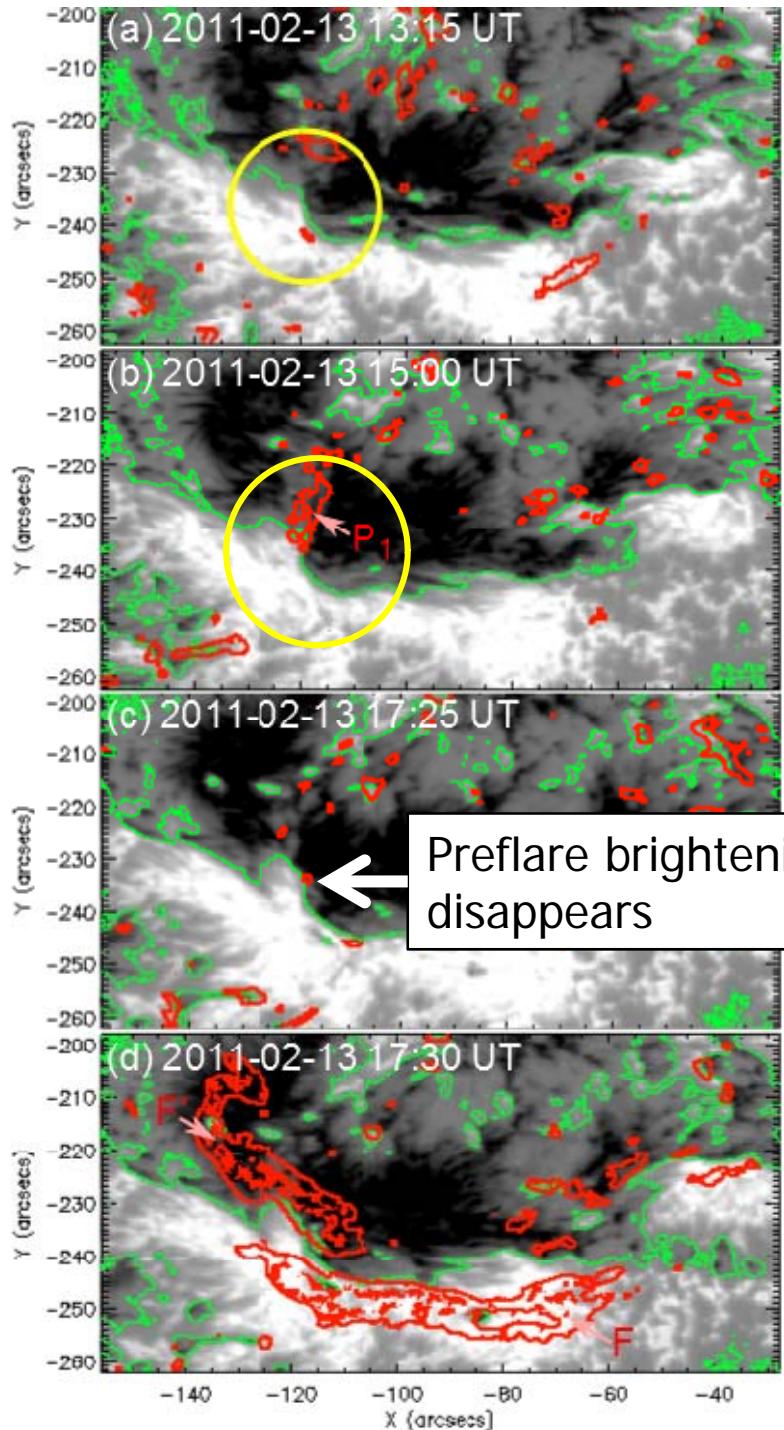
Opposite Polarity (OP)



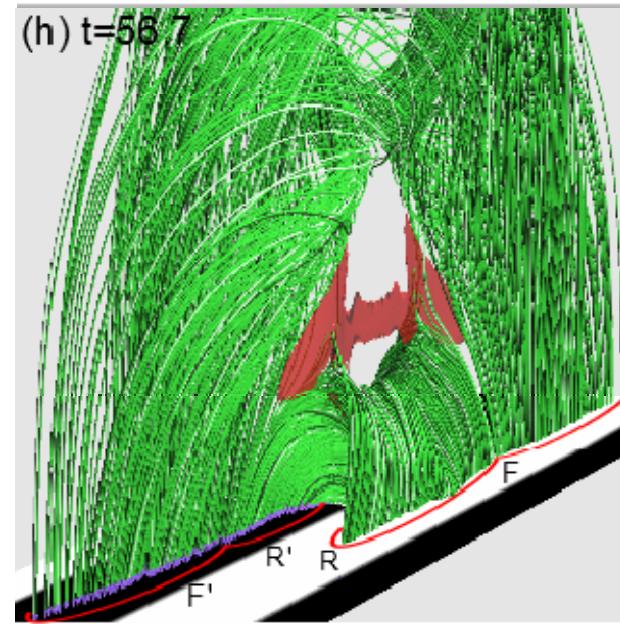
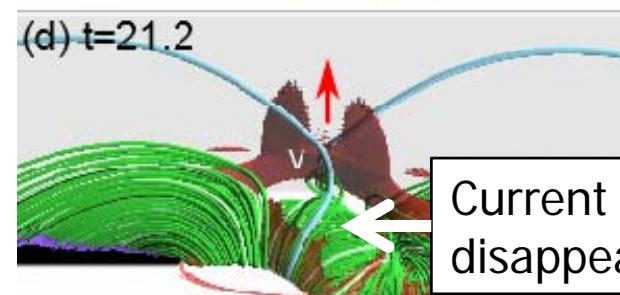
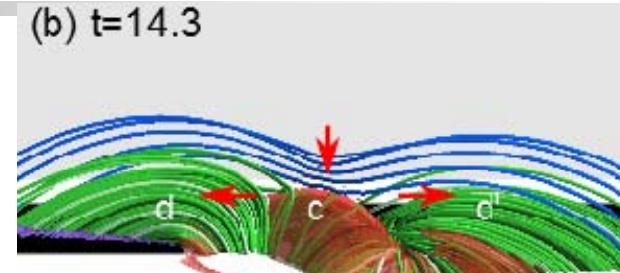
Reversed Shear (RS)



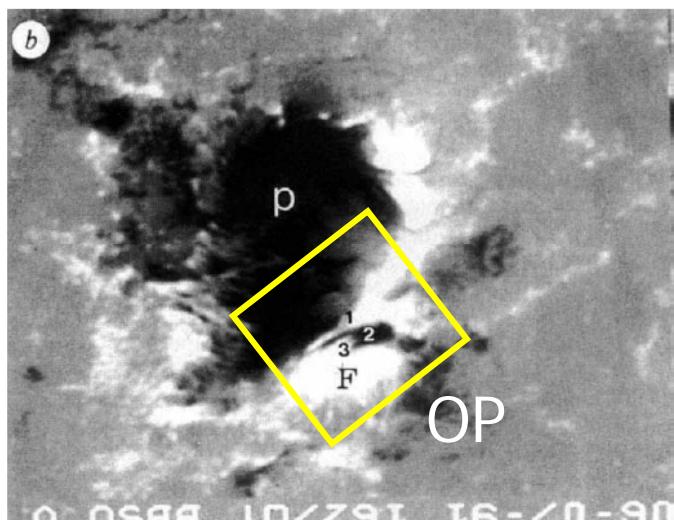
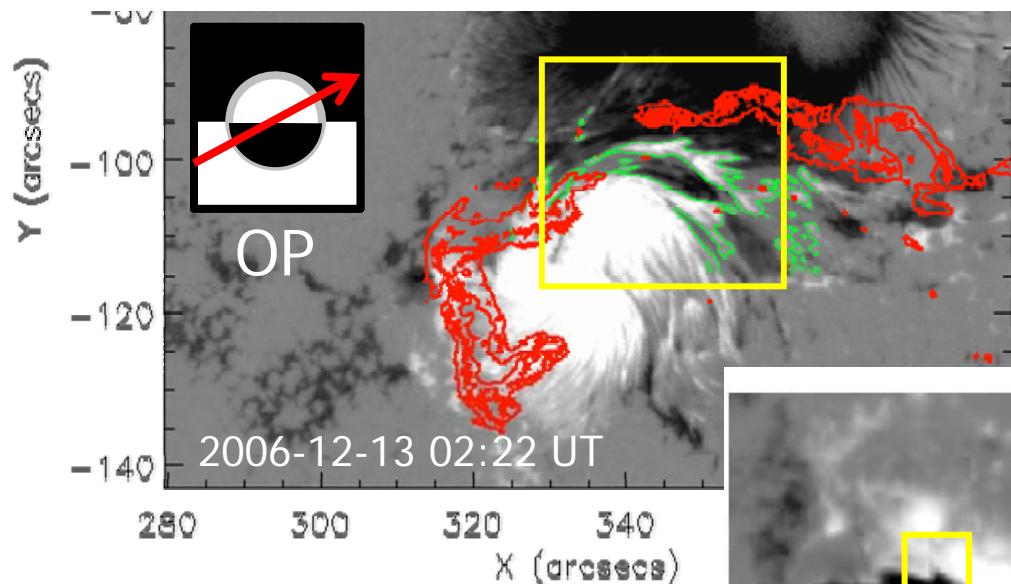




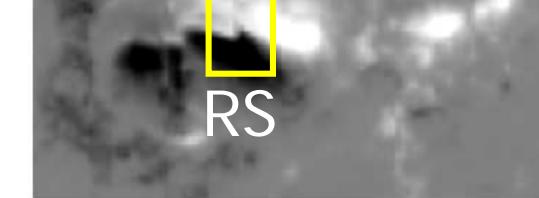
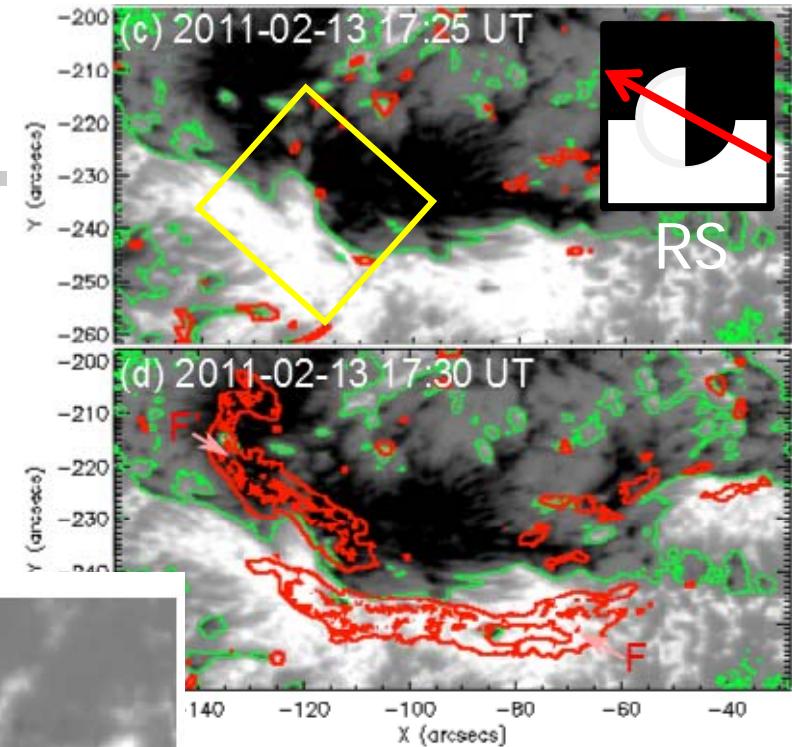
## Simulation (RS-type)



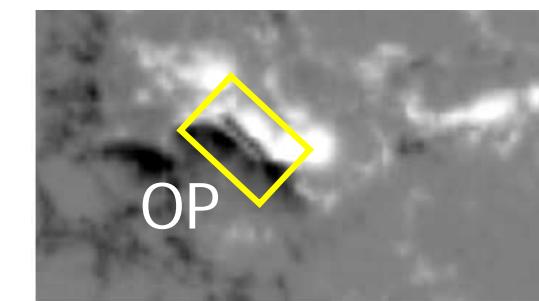
# 様々な観測的証拠



Zirin and Wang 1993

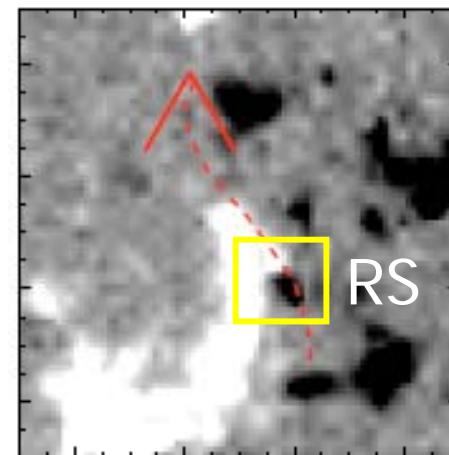


(k) 00-Jun-06 12:51:30



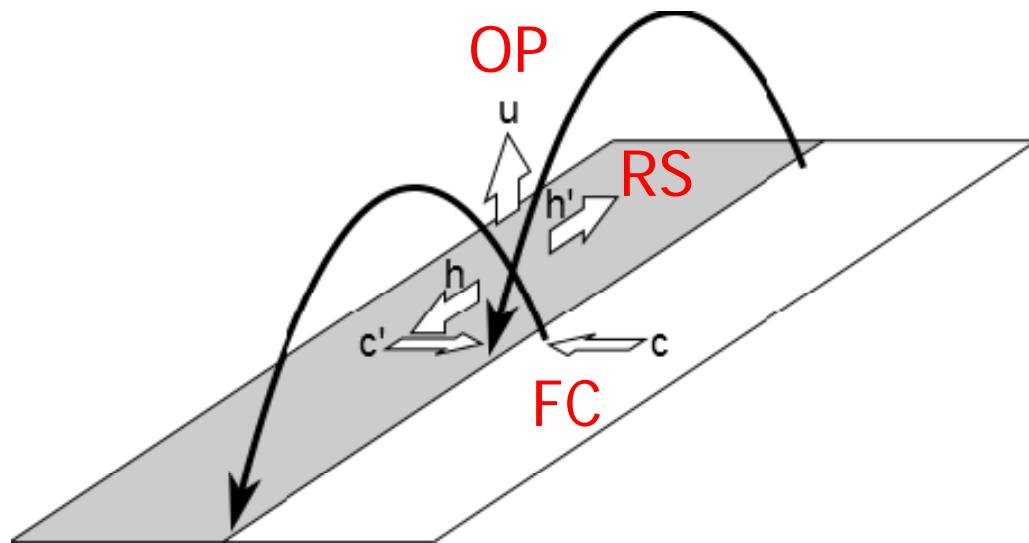
(q) 00-Jun-07 14:24:36

Kurokawa, Wang & Ishii 2002



Green, Kliem & Wallace 2011

# Comparison with Experiments



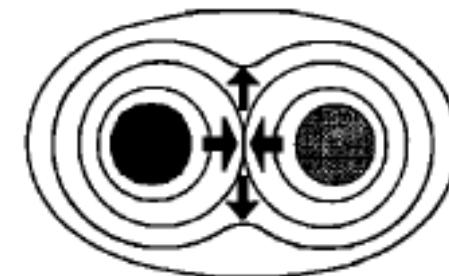
“pull” mode

1. OP-type horizontal flow ( $h-h'$ )
2. RS-type vertical flow ( $u$ )

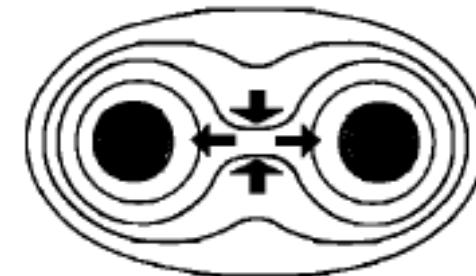
“push” mode

3. FC-type Convergent flow ( $c-c'$ )

Reconnection Experiments  
(Yamada 1999)



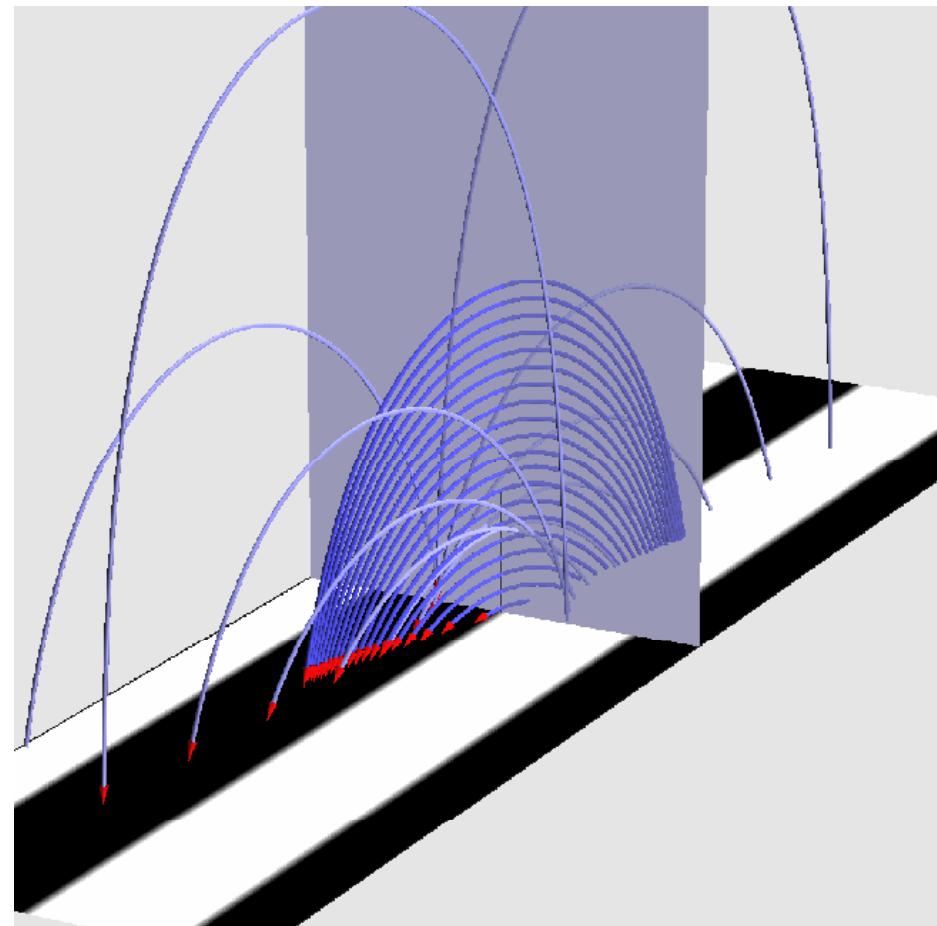
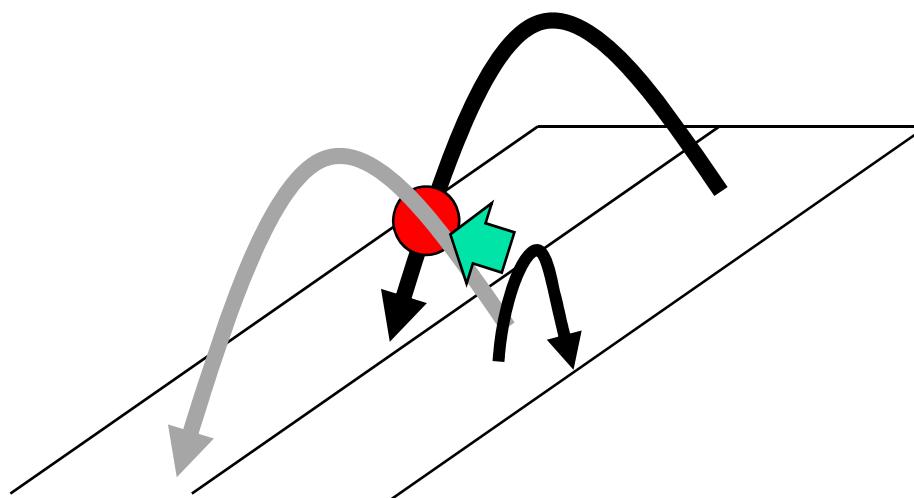
“push” mode



“pull” mode

# Emerging Flux of OP off PIL

- “Push” mode

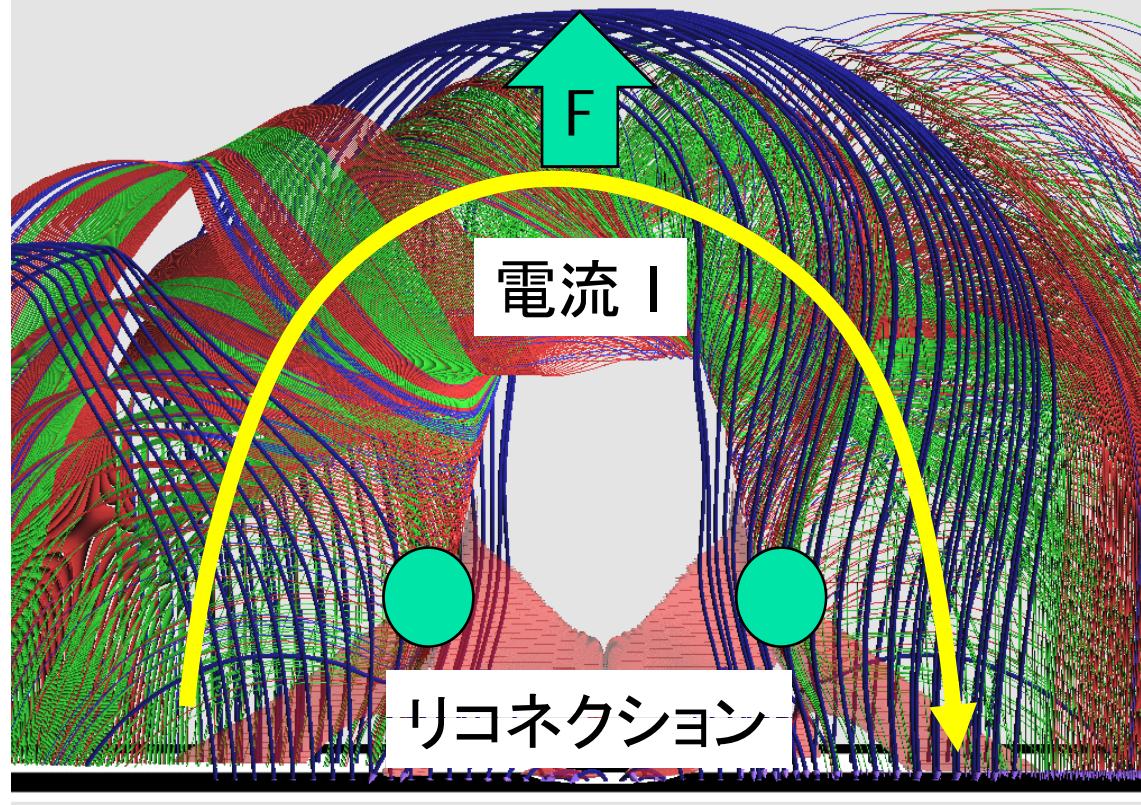


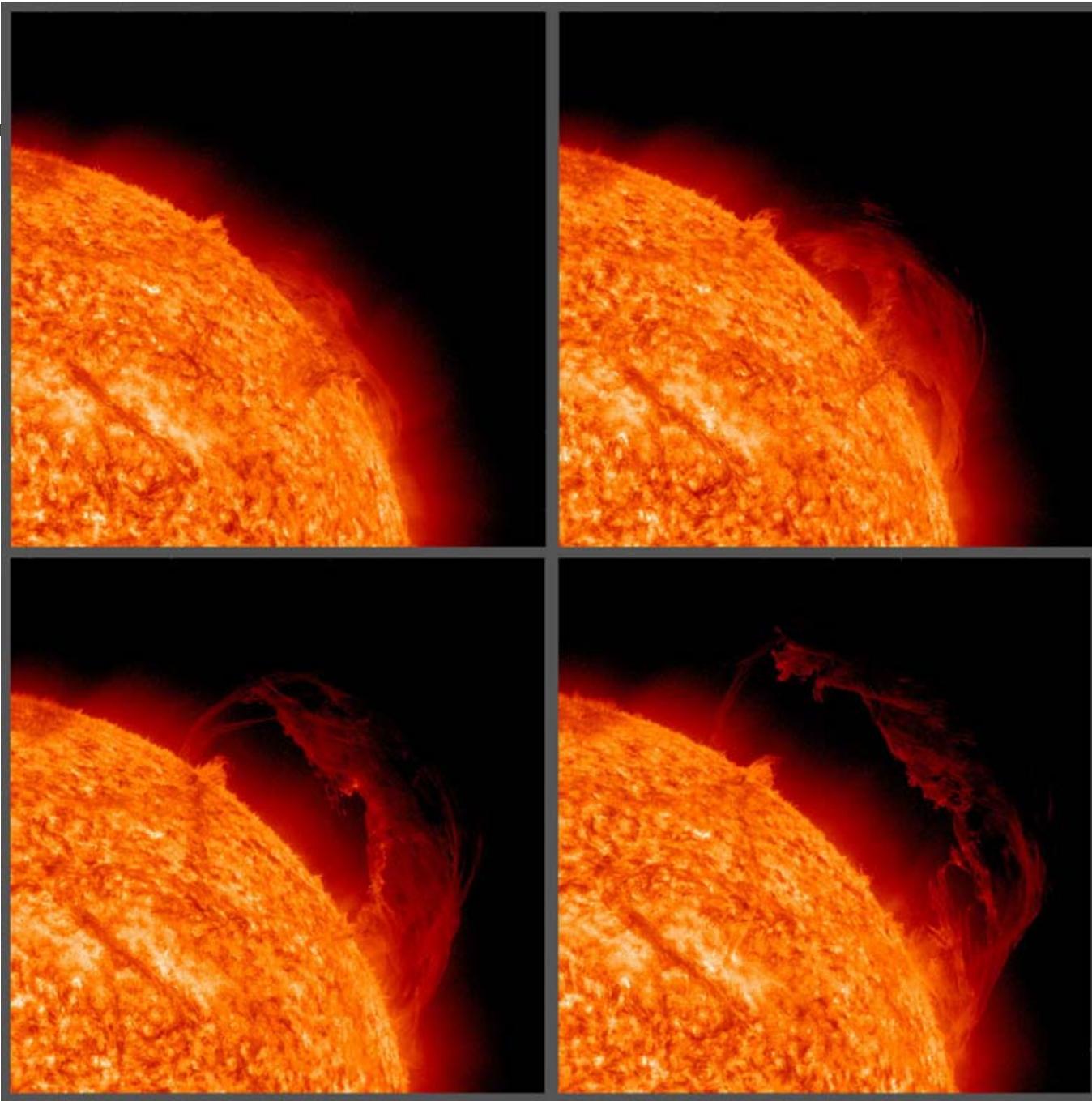
# Eruption & Reconnection (OP)

Tether cutting model  
Moore & Roumeliotis  
1992

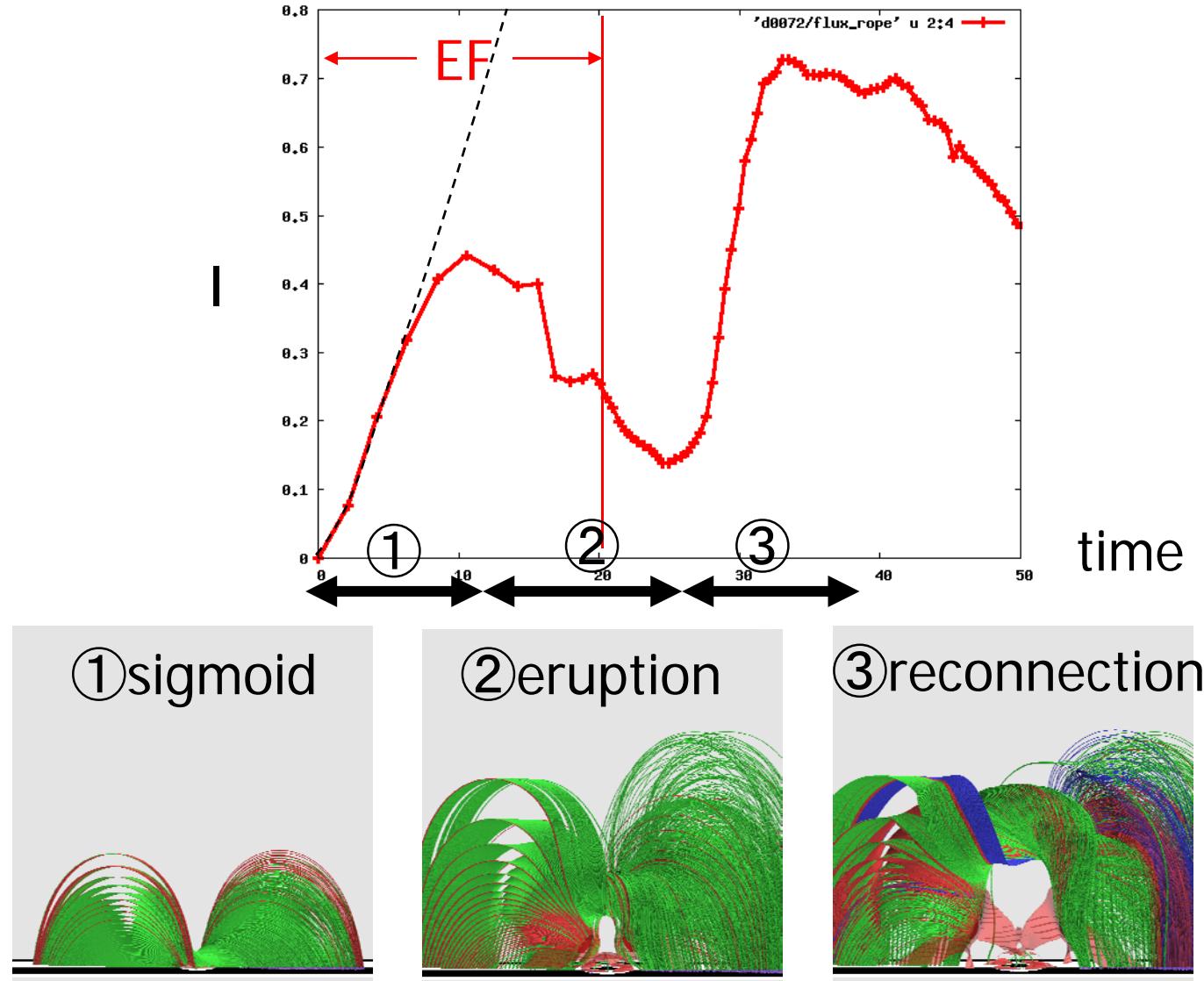
$$F = r_c I^2 - B_p I$$

Loss of equilibrium  
Forbes & Priest 1995  
Torus Instability  
Kliem & Torok 2006



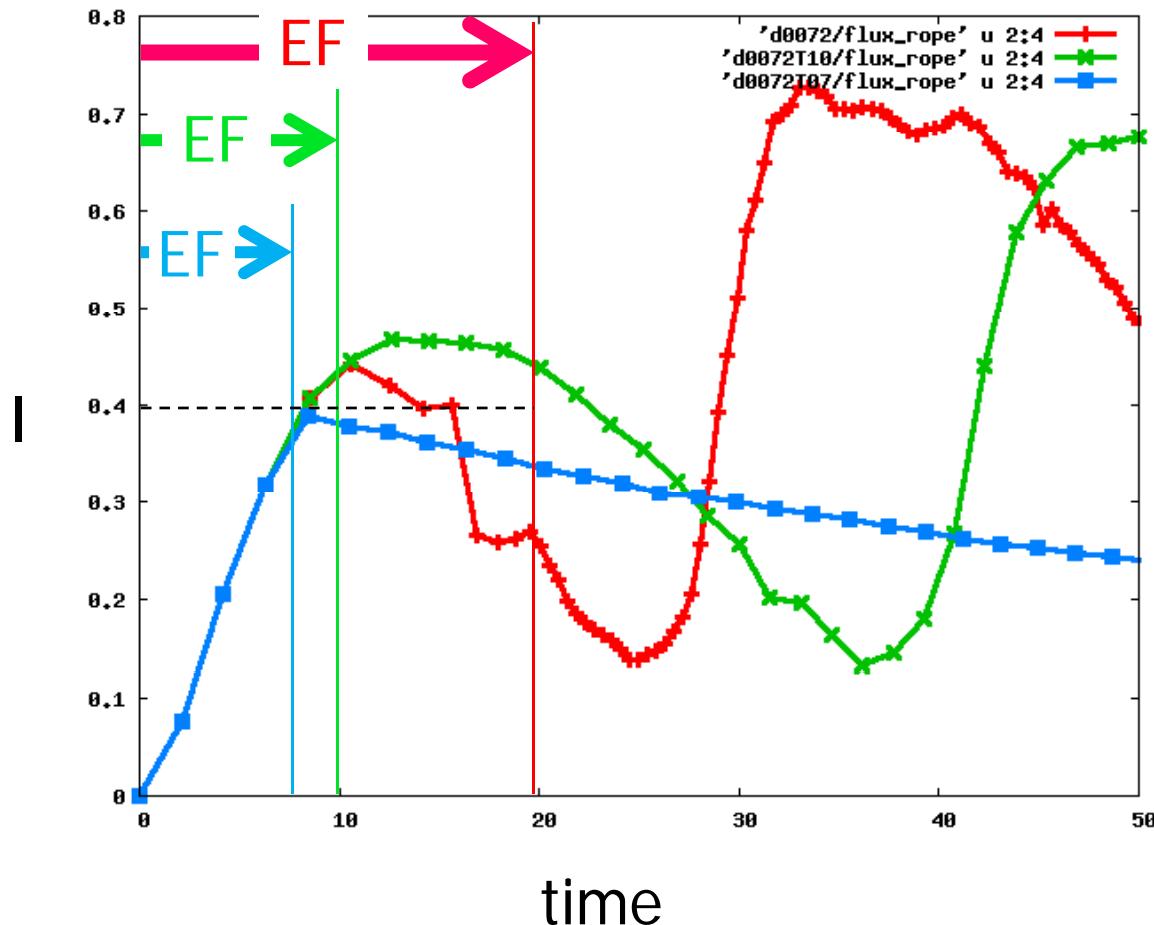


# Flux Rope 電流の変化



# 安定性の臨界条件

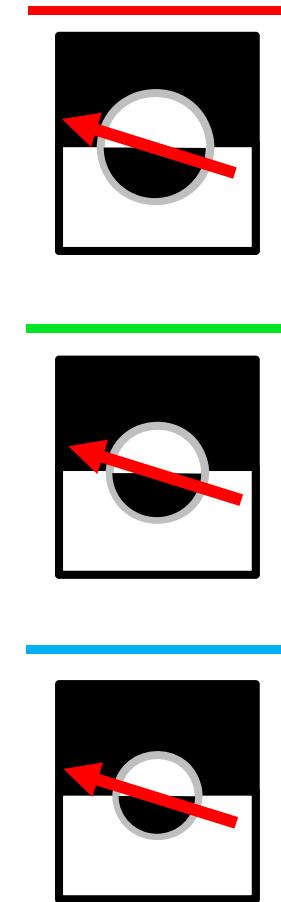
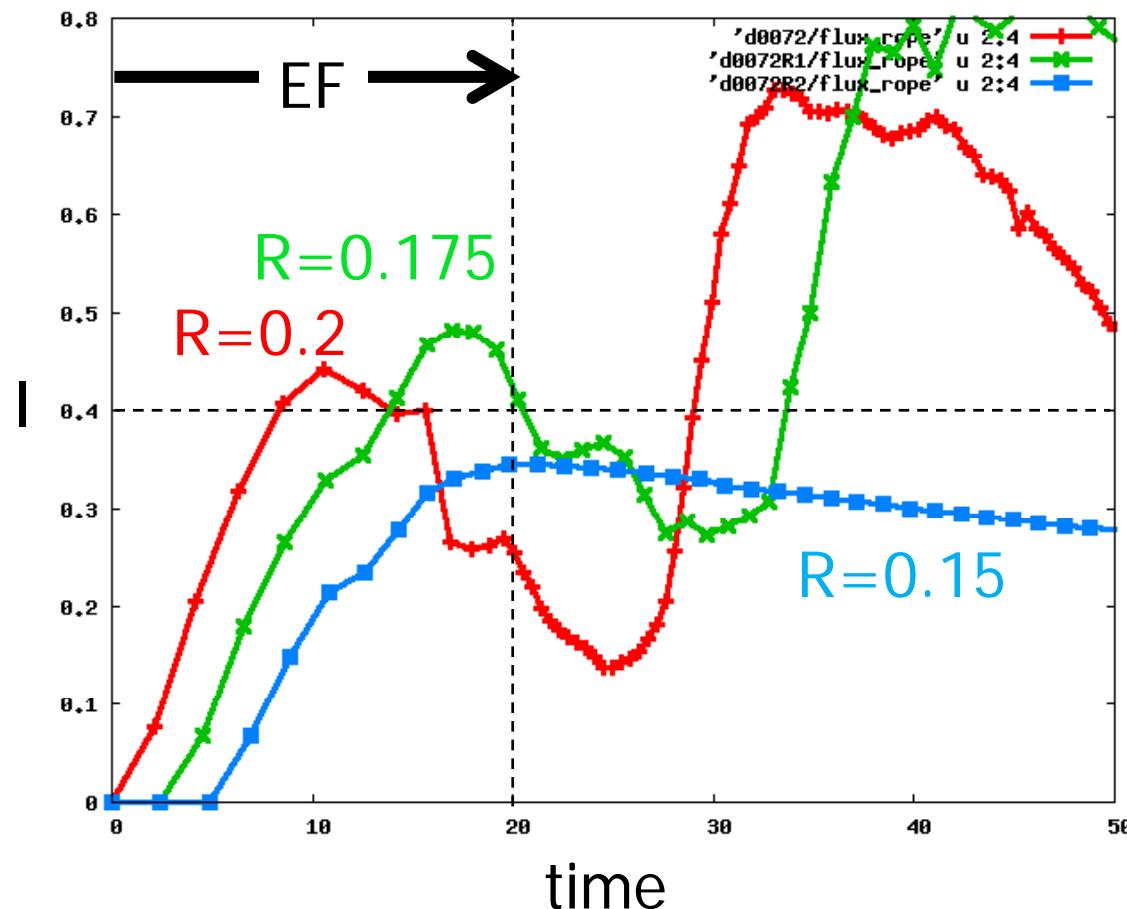
EFの継続時間をパラメタとした3つの場合の  
シミュレーション結果



擾乱磁場が未臨界の場合

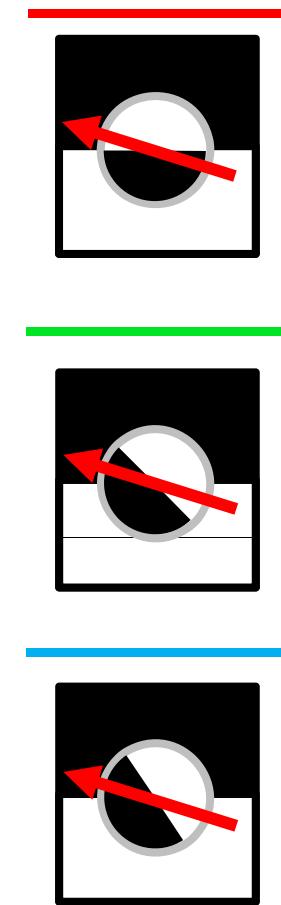
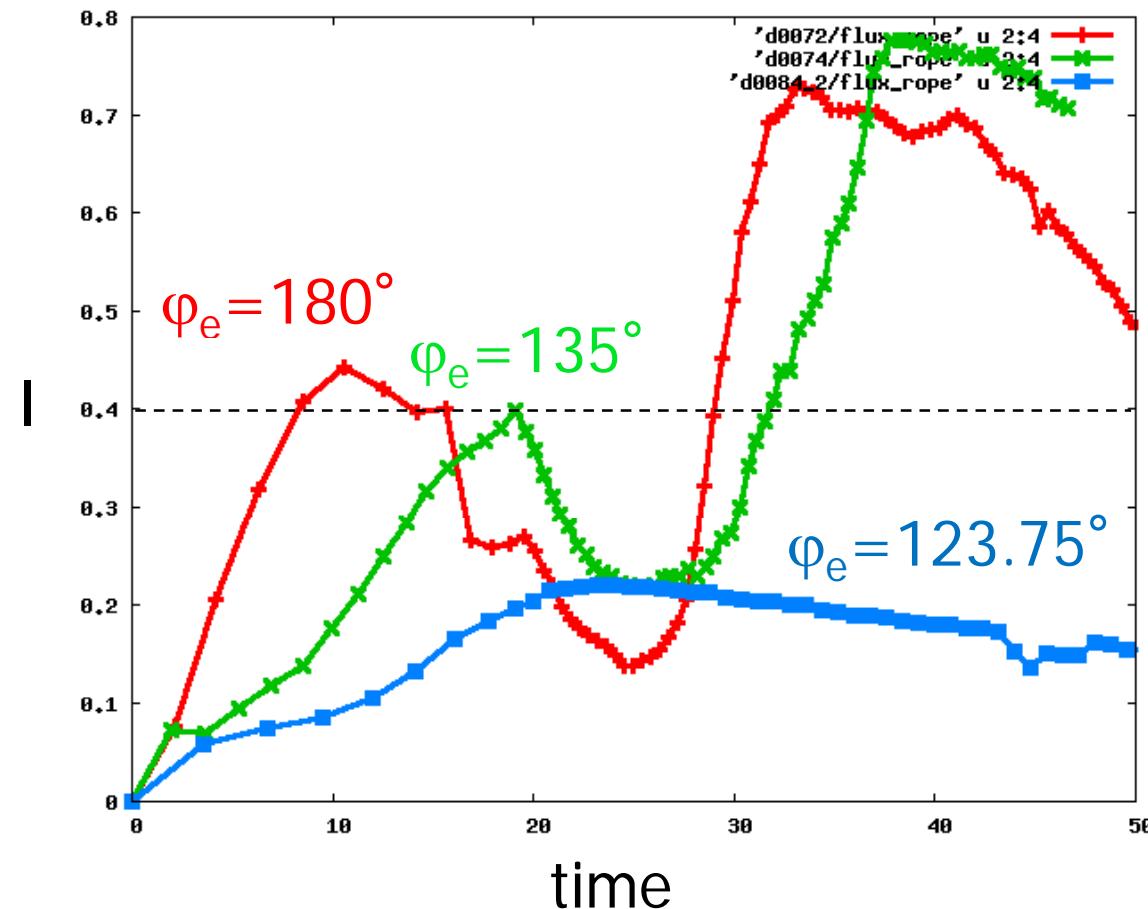
# 安定性の臨界条件

- EFの半径Rをパラメタとした場合



# 安定性の臨界条件

- EFの方方位角をパラメタとした場合



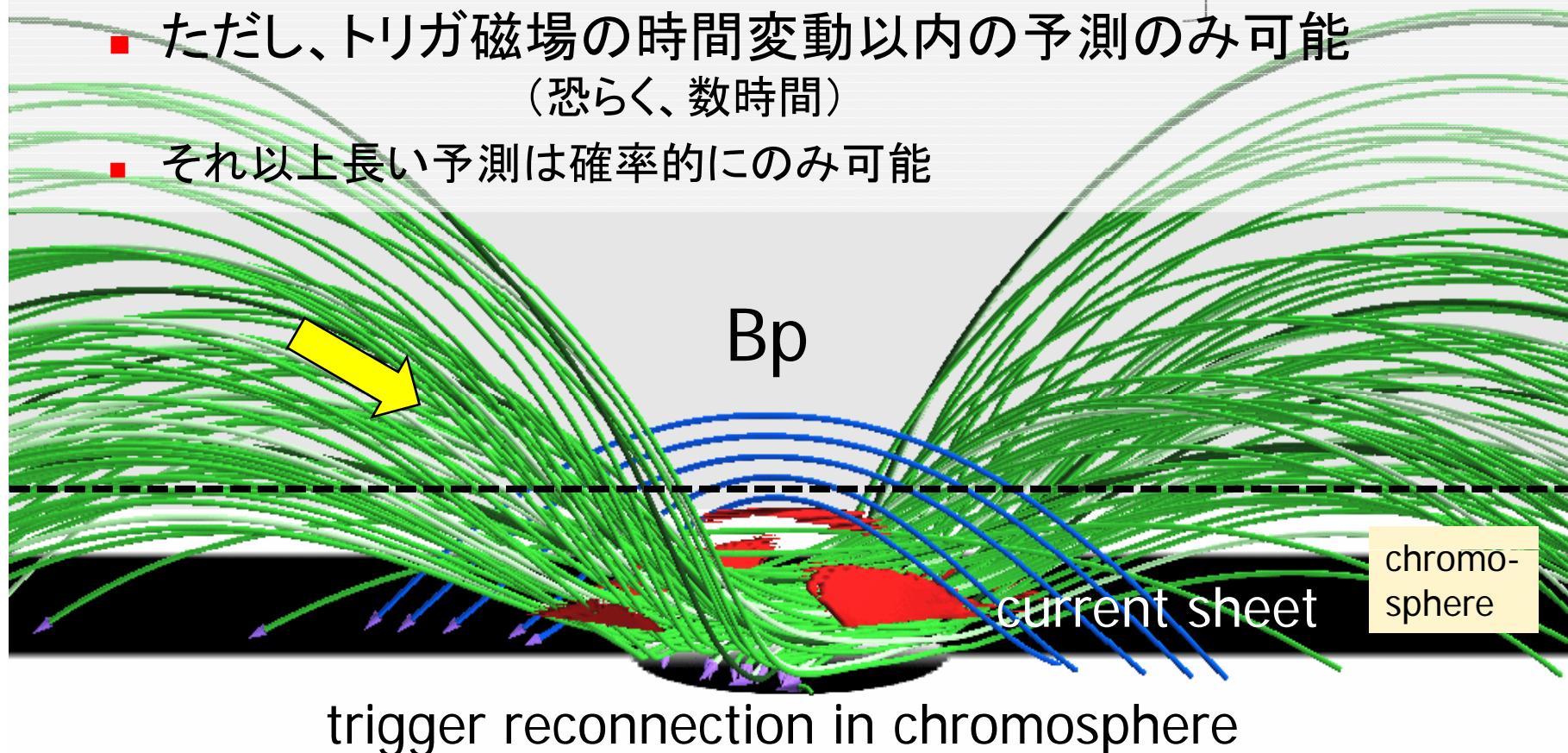
# まとめ

---

- Opposite Polarity (OP)とReversed Shear (RS)はフレアを誘発しやすい磁場構造(トリガ磁場)である。
- OP磁束はシア磁場からtwisted flux rope (TFR)を作る。TFRの電流が臨界値を超えるとトーラスモード不安定性(非平衡性)が現れ、eruptionを引き起こす(トリガの原因)。
- Eruptionの結果、overlaying fluxはリコネクションを通して、flux ropeに取り込まれ、これをさらに成長させる(爆発的成長の原因)。

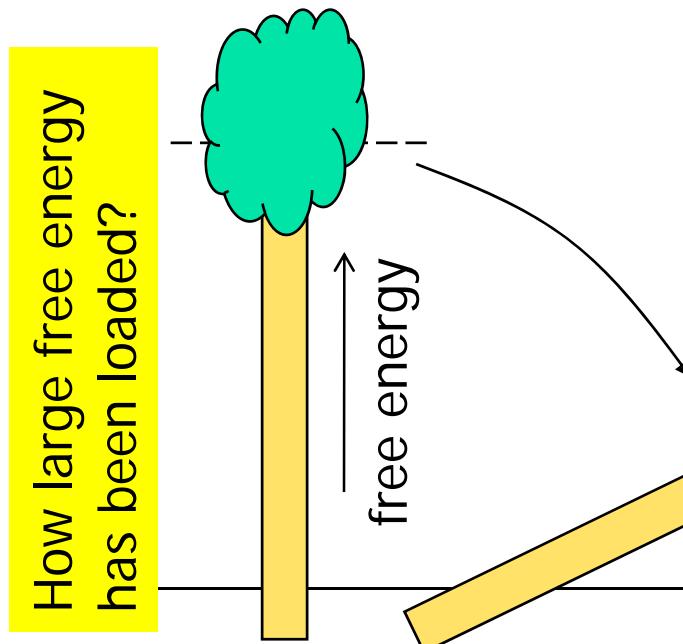
# Magnetic structure just prior to flare

- シア磁場の観測→臨界電流値
- 光球面磁場→flux ropeの電流値を計算
  - ただし、トリガ磁場の時間変動以内の予測のみ可能  
(恐らく、数時間)
  - それ以上長い予測は確率的にのみ可能

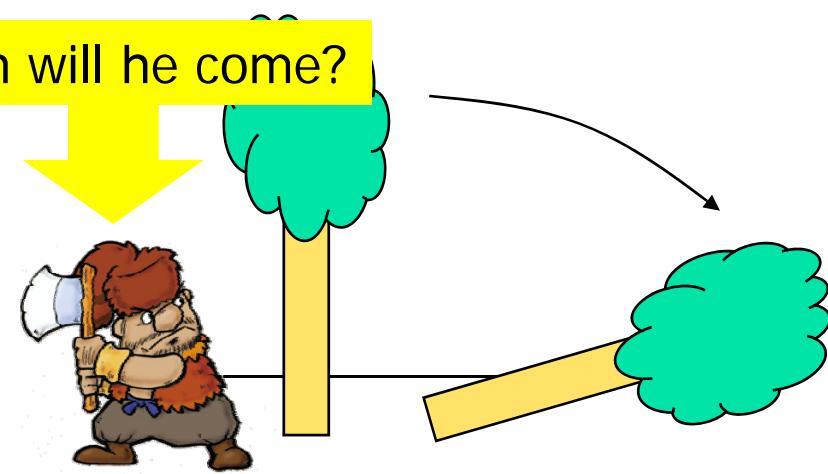


# The Onset of Storage-and-Release

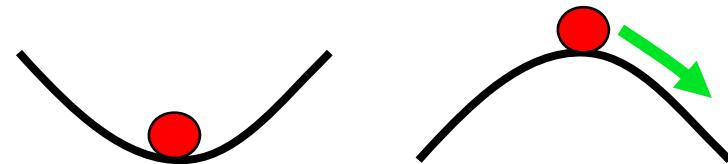
Critical Phenomena



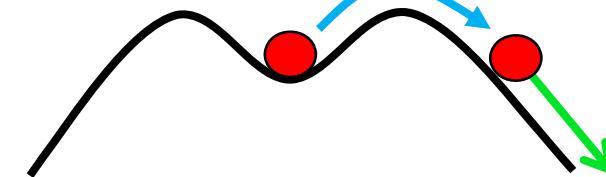
Triggered Phenomena



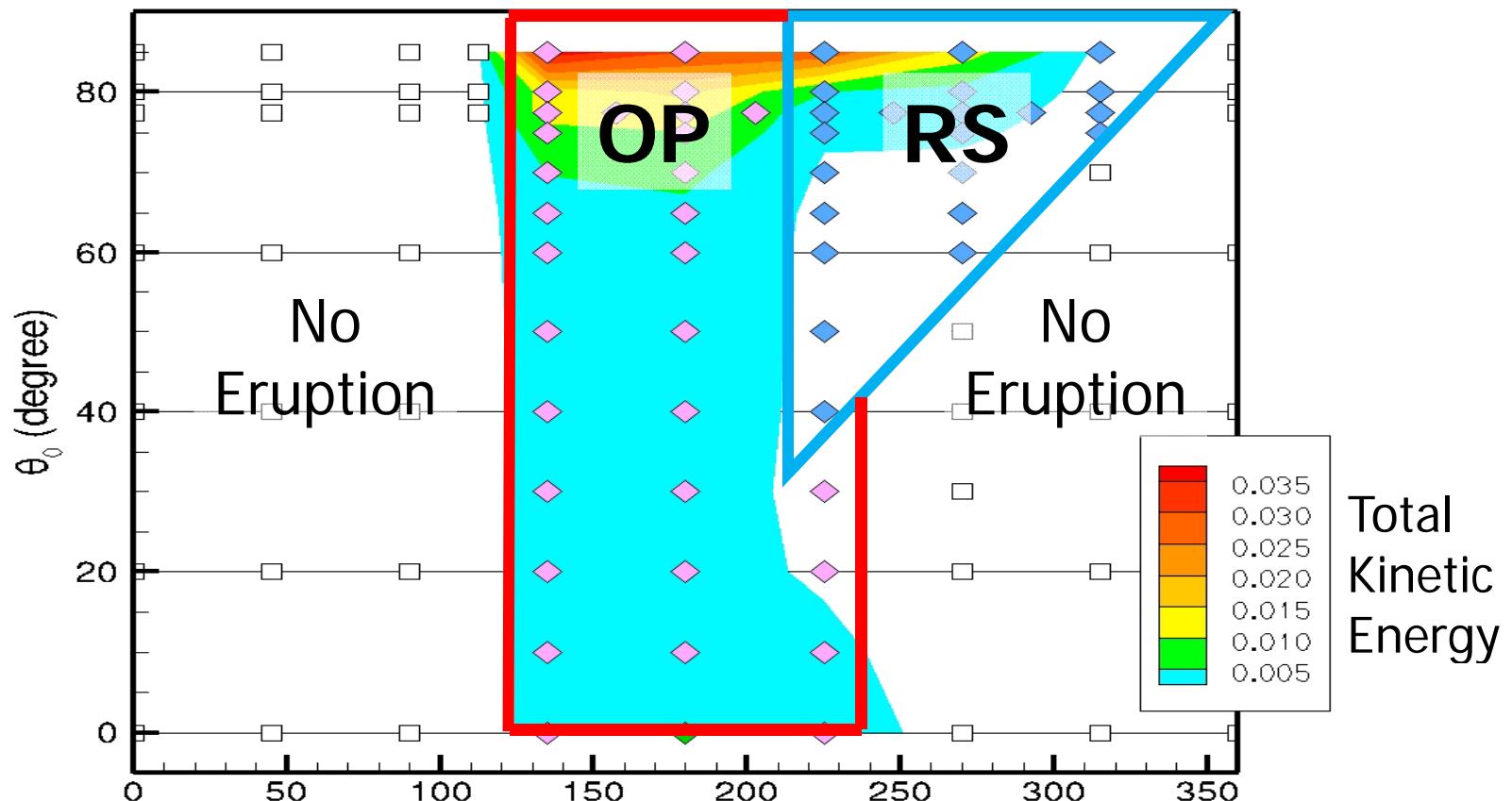
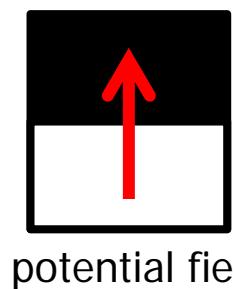
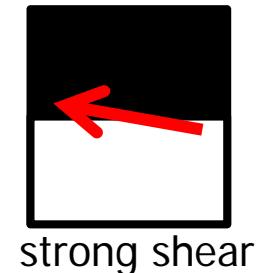
Linear instability



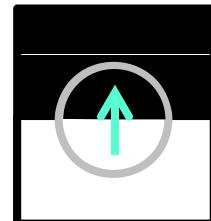
Nonlinear instability



# Flare Phase Diagram



Right Polarity



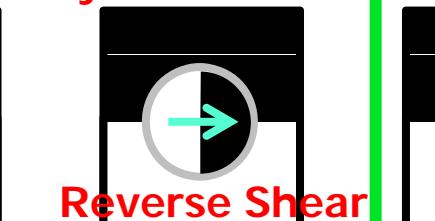
Normal Shear

Opposite Polarity



Normal Shear

Right Polarity

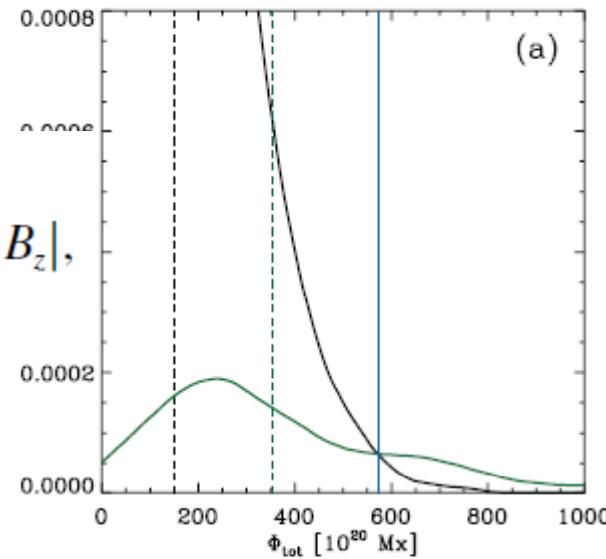


Reverse Shear

# 磁場パラメタとフレアの関係

(M&X class within 1d)

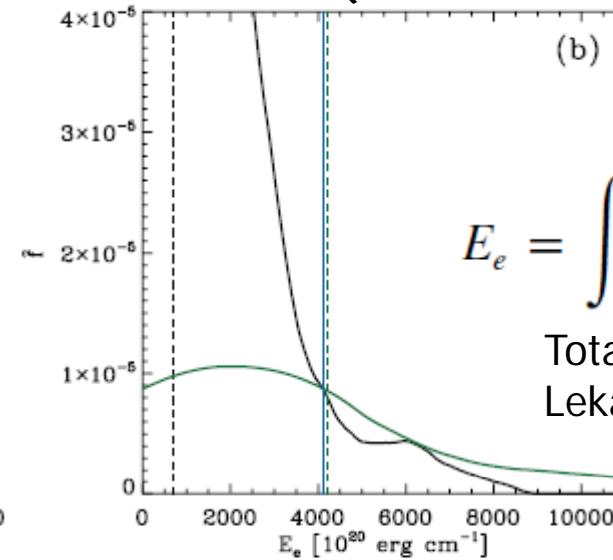
$$\Phi_{\text{tot}} = \int d^2x |B_z|,$$



(a)

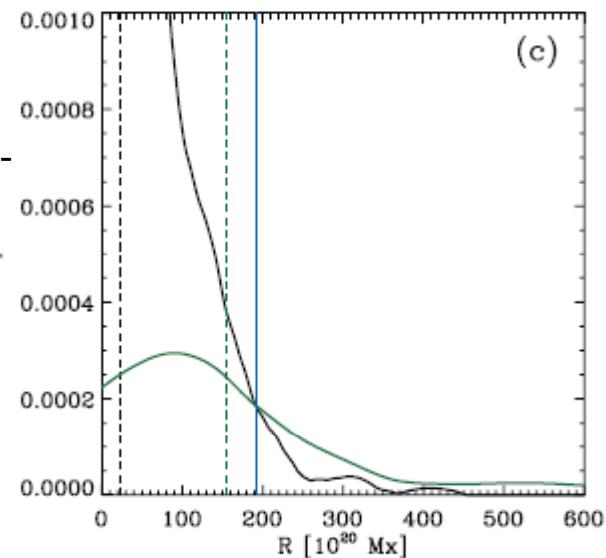
$$E_e = \int d^2x (\mathbf{B} - \mathbf{B}_p)^2,$$

Total excess energy  
Leka & Barnes 2003



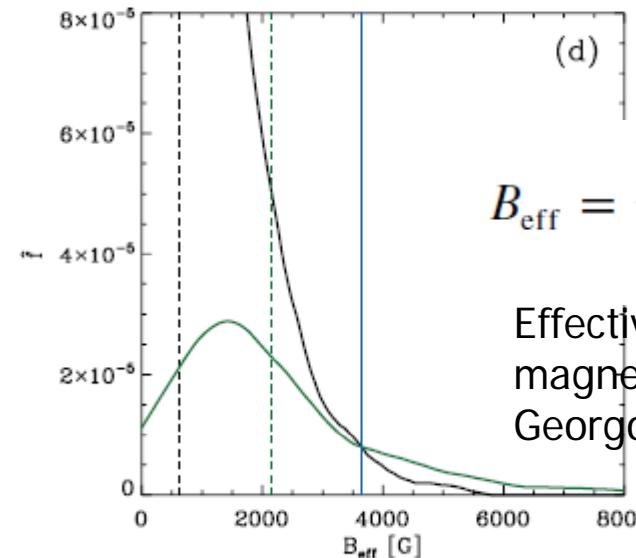
(b)

R: unsigned flux  
over the high-  
gradient polarity-  
separation lines  
Schrijver 2007



(c)

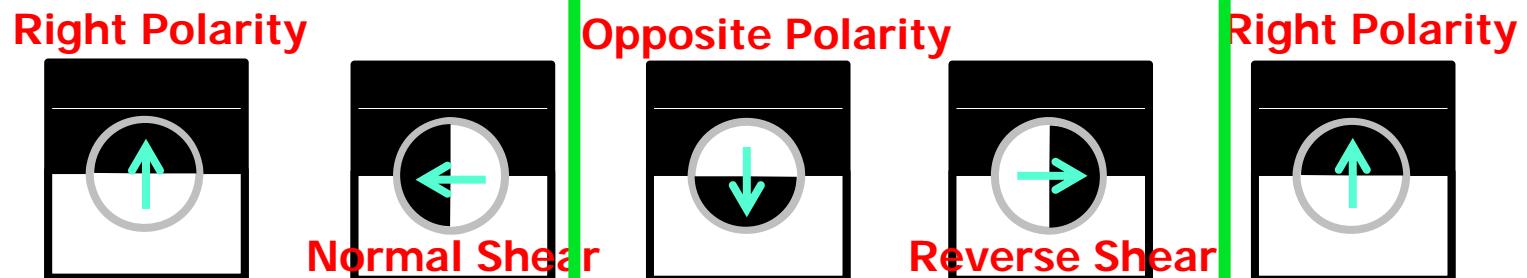
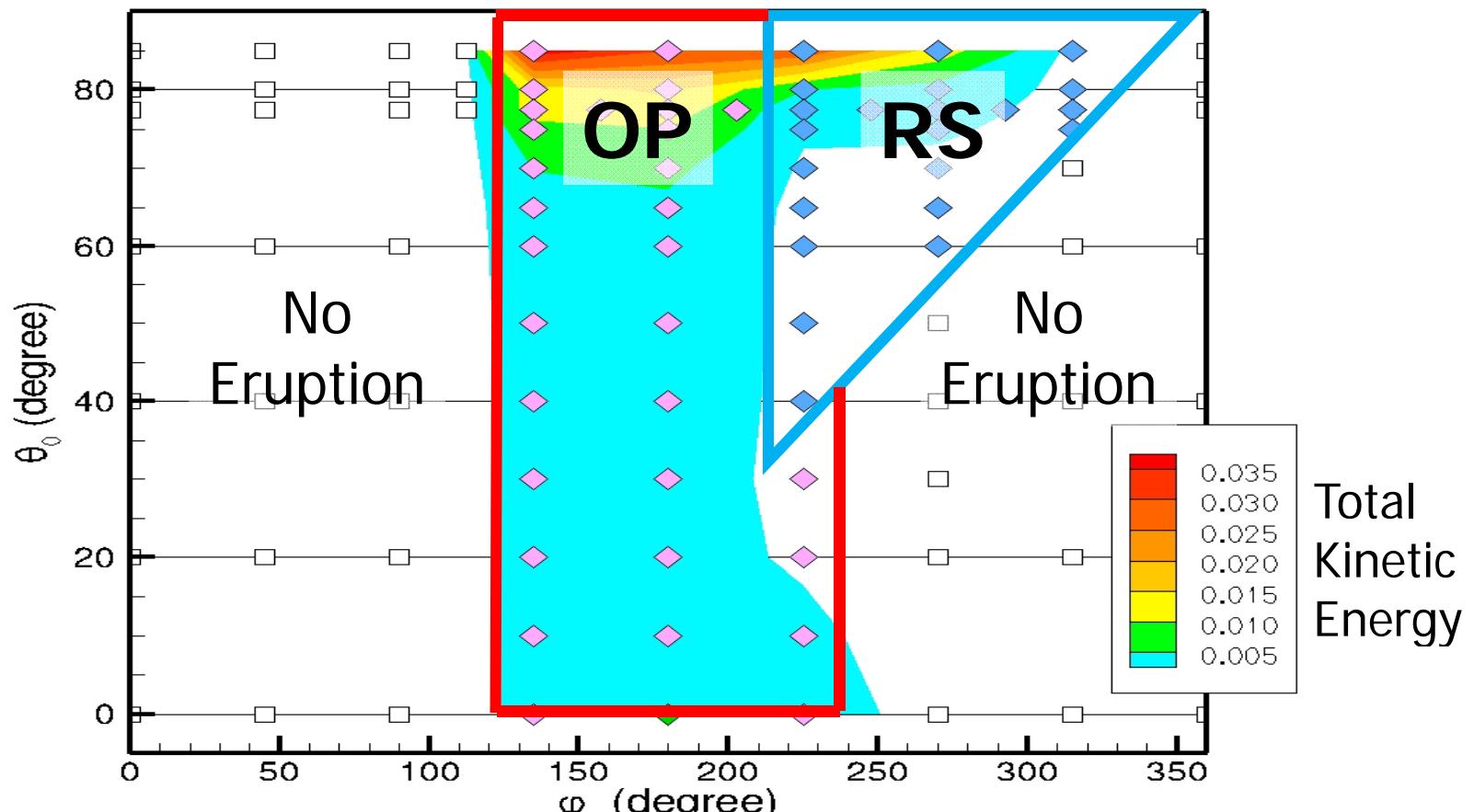
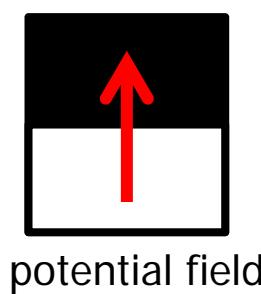
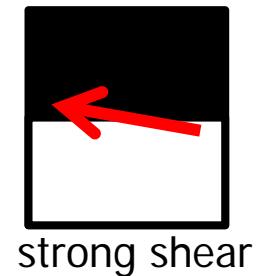
Barnes and Leka 2008



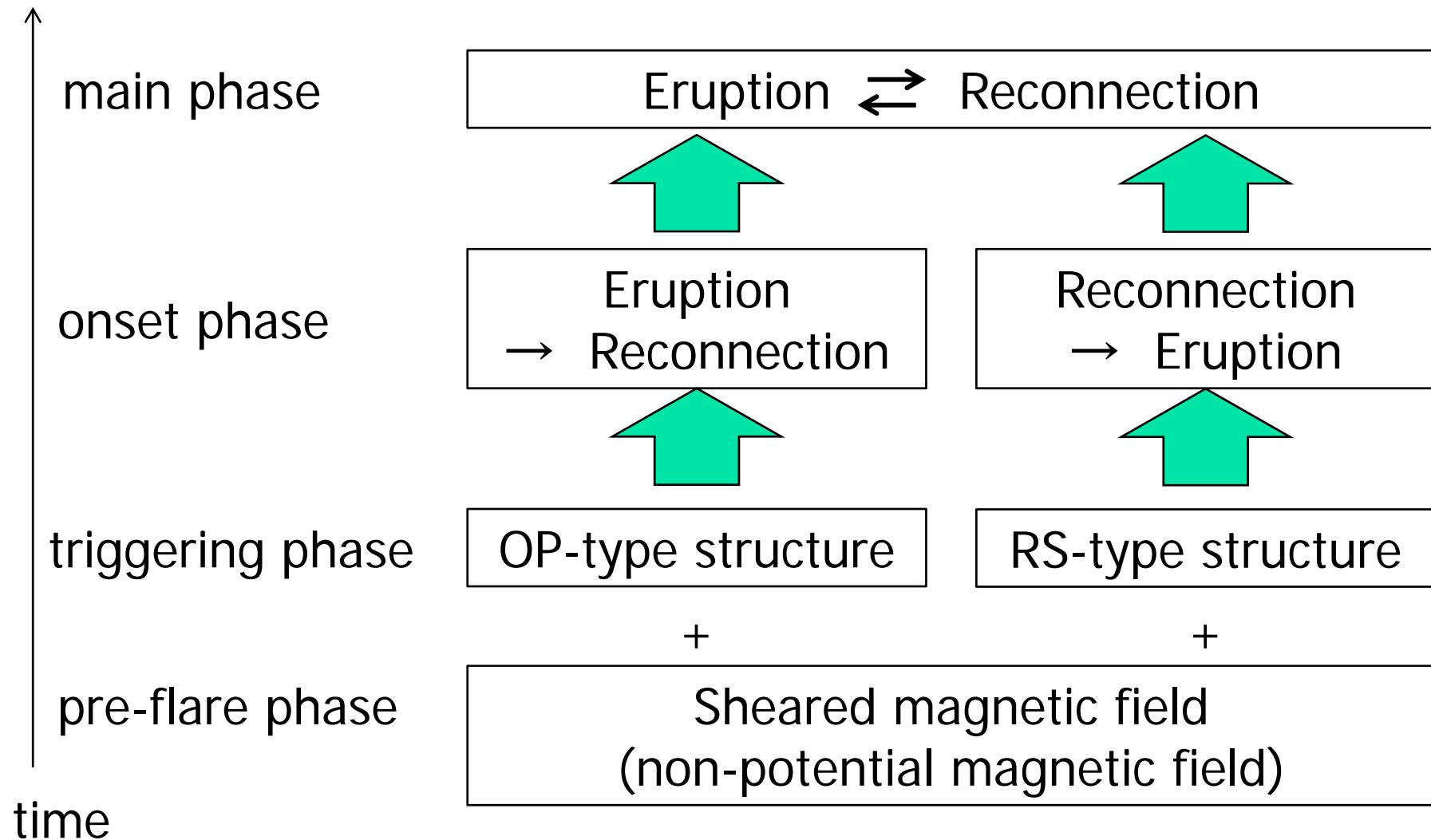
$$B_{\text{eff}} = \frac{1}{2} \sum_{i \neq j} \frac{\psi_{ij}}{|\mathbf{x}_i - \mathbf{x}_j|^2},$$

Effective connected  
magnetic field  
Georgoulis & Rust 2007

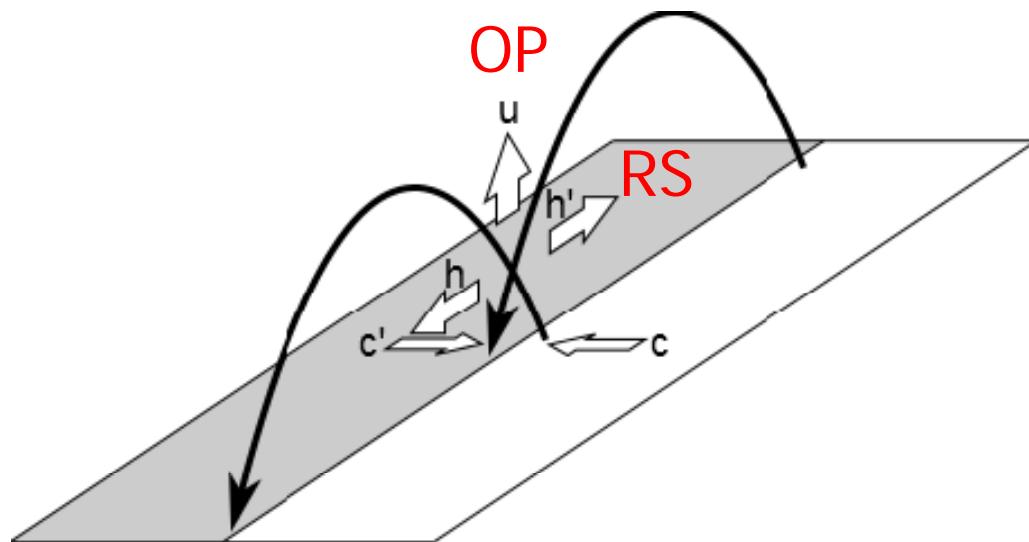
# Simulation Results



# Two Scenarios for Triggering Flare



# Comparison with Experiments



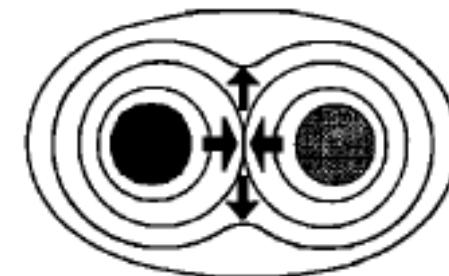
“pull” mode

1. OP-type horizontal flow ( $h-h'$ )
2. RS-type vertical flow ( $u$ )

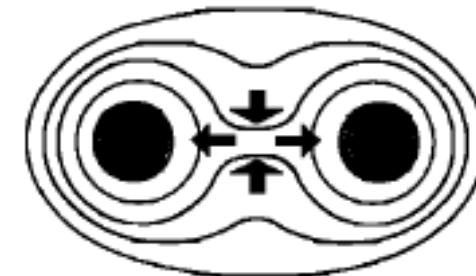
“push” mode

3. Convergent flow ( $c-c'$ )

Reconnection Experiments  
(Yamada 1999)



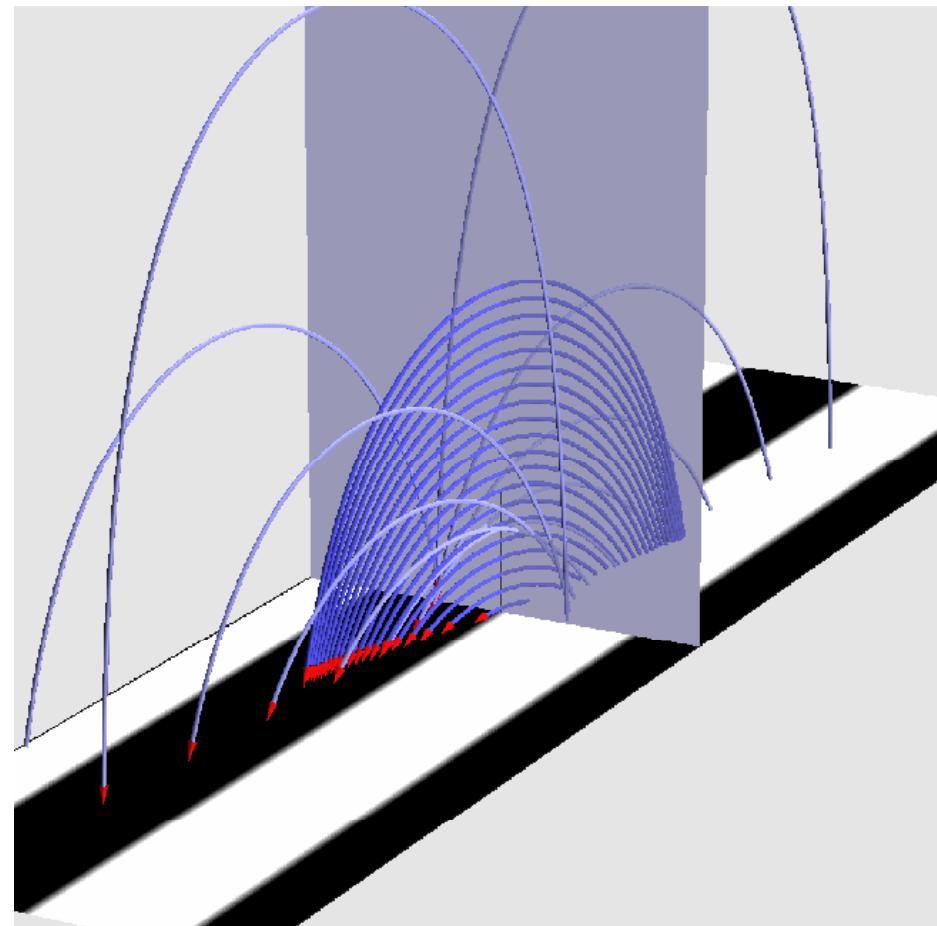
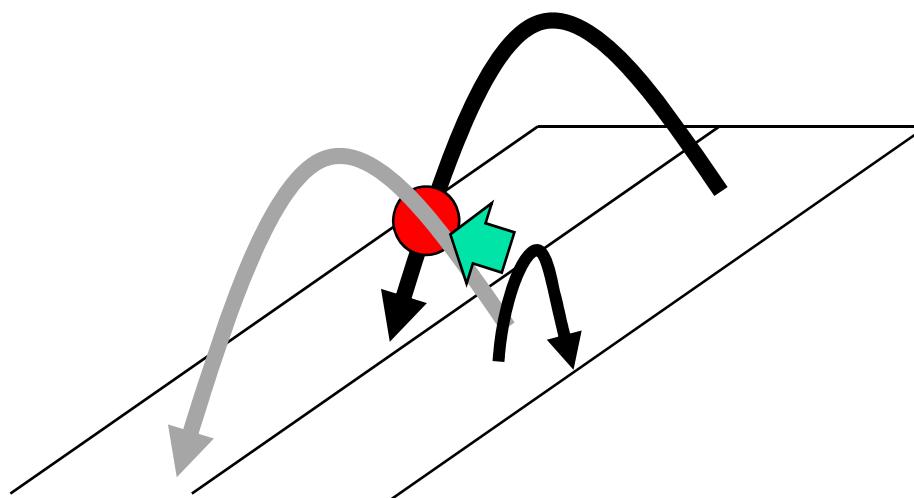
“push” mode



“pull” mode

# Emerging Flux of OP off PIL

- “Push” mode





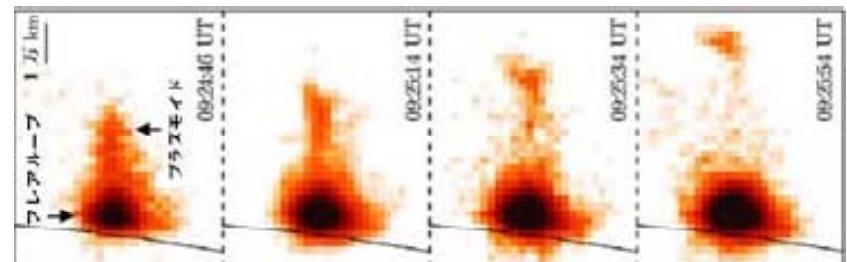
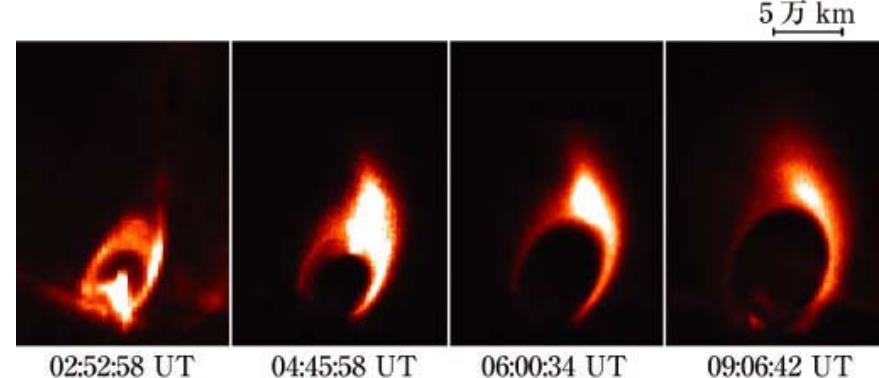
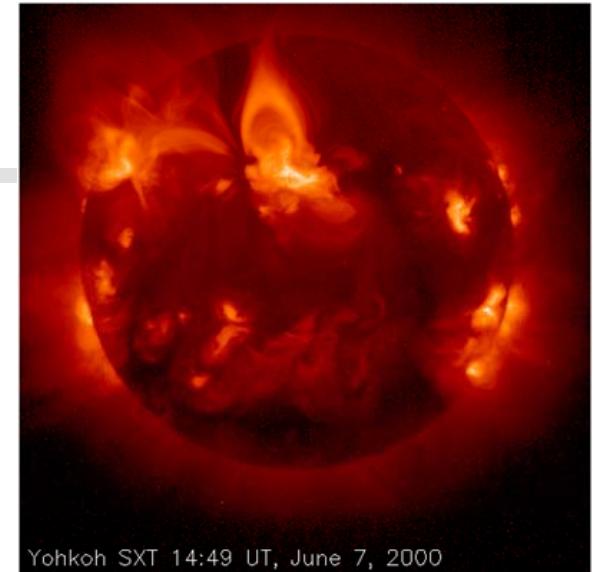
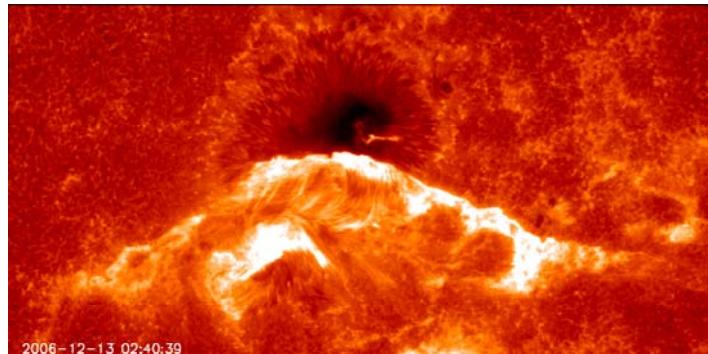
# Properties of Flares

near sunspots

cusp loop

two-ribbon

plasmoid ejection



# Papers for Flare Prediction

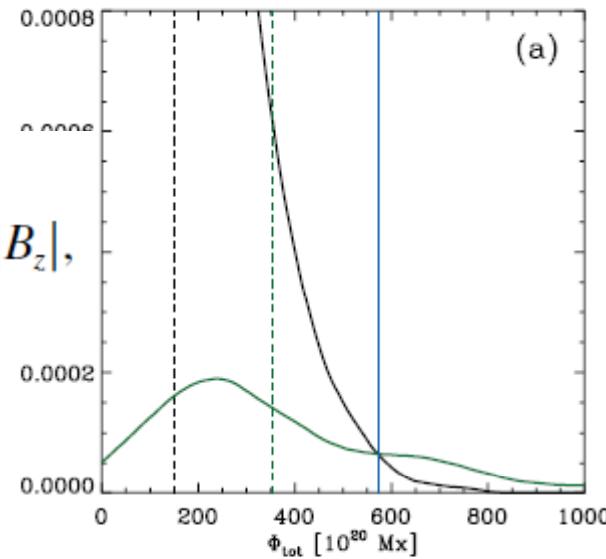
---

- Poisson statistics (Gallagher et al. 2002, Bloomfield1 et al 2012)
- Bayesian statistics (Wheatland 2005)
- wavelet predictors (Yu et al. 2010a)
- Bayesian networks (Yu et al. 2010b)
- vector machines (Li et al. 2007)
- discriminant analysis (Barnes et al. 2007)
- ordinal logistic regression (Song et al. 2009; Yuan et al. 2010)
- neural networks (Colak & Qahwaji 2009; Yu et al. 2009; Ahmed et al. 2012)
- predictor teams (Huang et al. 2010)
- superposed epoch analysis (Mason & Hoeksema 2010)
- empirical projections (Falconer et al. 2011).

# 磁場パラメタとフレアの関係

(M&X class within 1d)

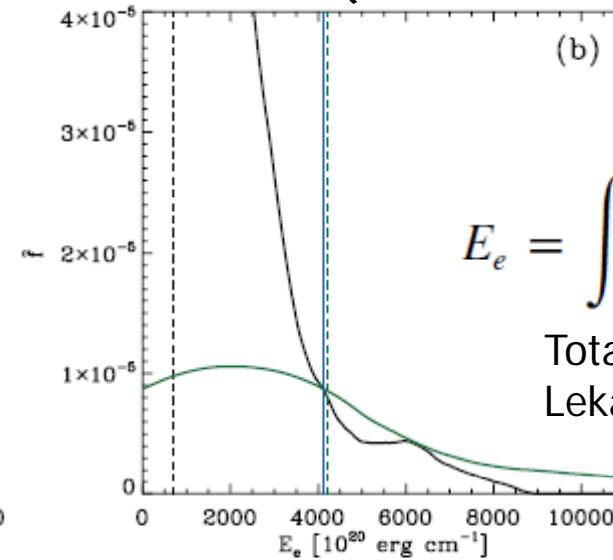
$$\Phi_{\text{tot}} = \int d^2x |B_z|,$$



(a)

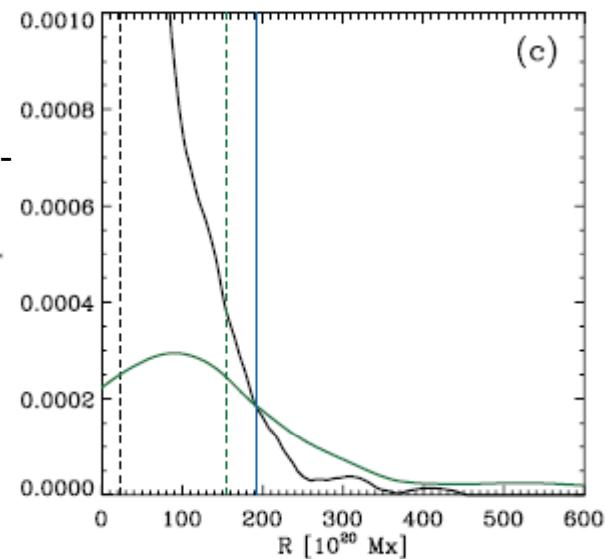
$$E_e = \int d^2x (\mathbf{B} - \mathbf{B}_p)^2,$$

Total excess energy  
Leka & Barnes 2003



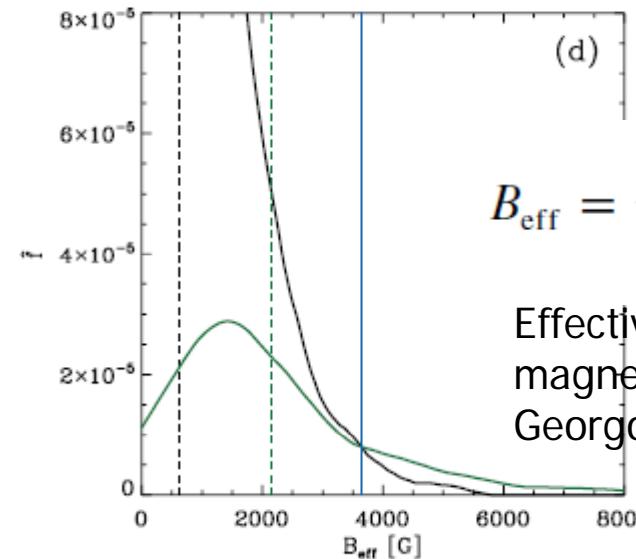
(b)

R: unsigned flux  
over the high-  
gradient polarity-  
separation lines  
Schrijver 2007



(c)

Barnes and Leka 2008



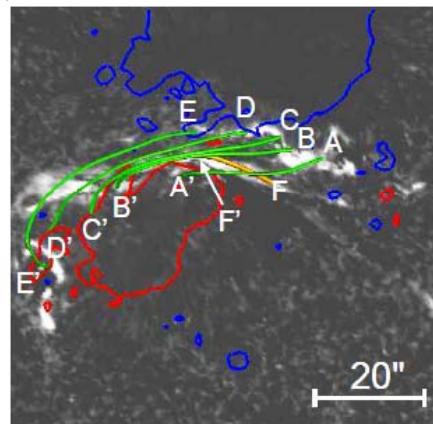
$$B_{\text{eff}} = \frac{1}{2} \sum_{i \neq j} \frac{\psi_{ij}}{|\mathbf{x}_i - \mathbf{x}_j|^2},$$

Effective connected  
magnetic field  
Georgoulis & Rust 2007

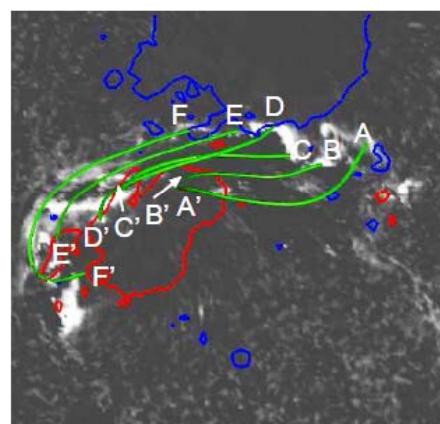
# Magnetic Twist in terms of NLFFF

Inoue, Kusano et al. ApJ 2011

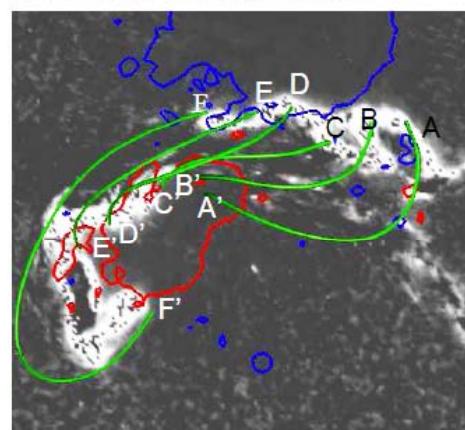
(a) 02:18 UT on Dec.13



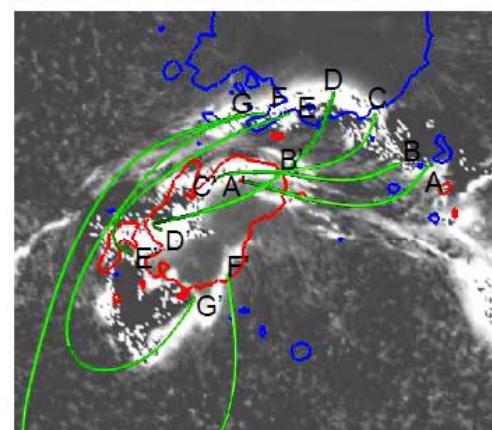
(b) 02:20 UT on Dec.13



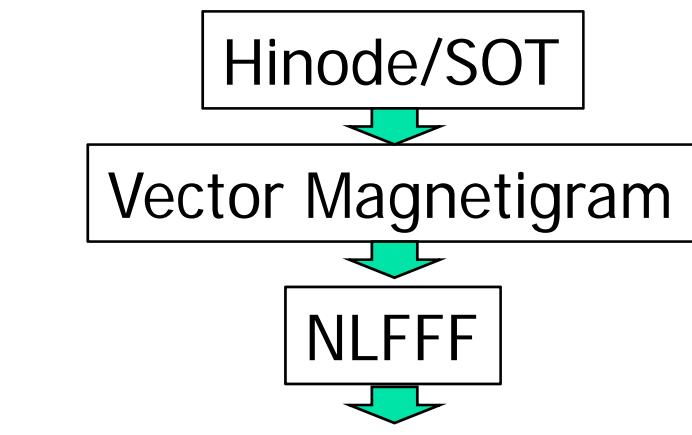
(c) 02:22 UT on Dec.13



(d) 02:24 UT on Dec.13

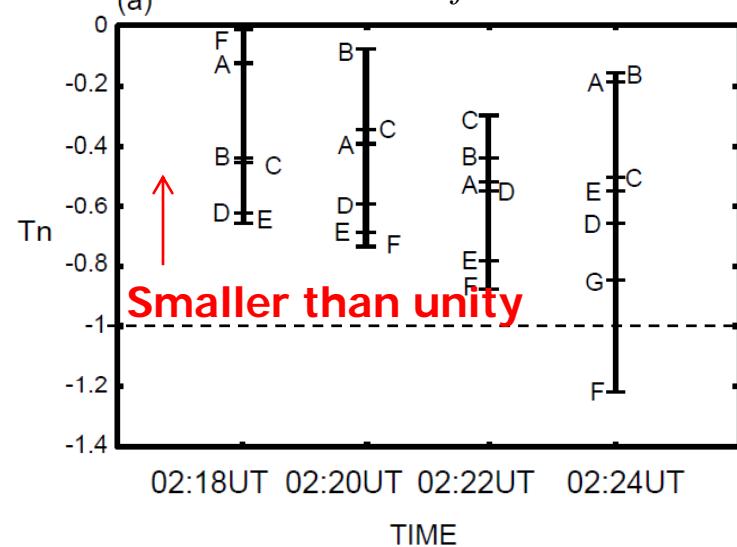


Magnetic field at 20:30UT on Dec.12, 2006  
Flare onset at 02:12UT on Dec.13, 2006

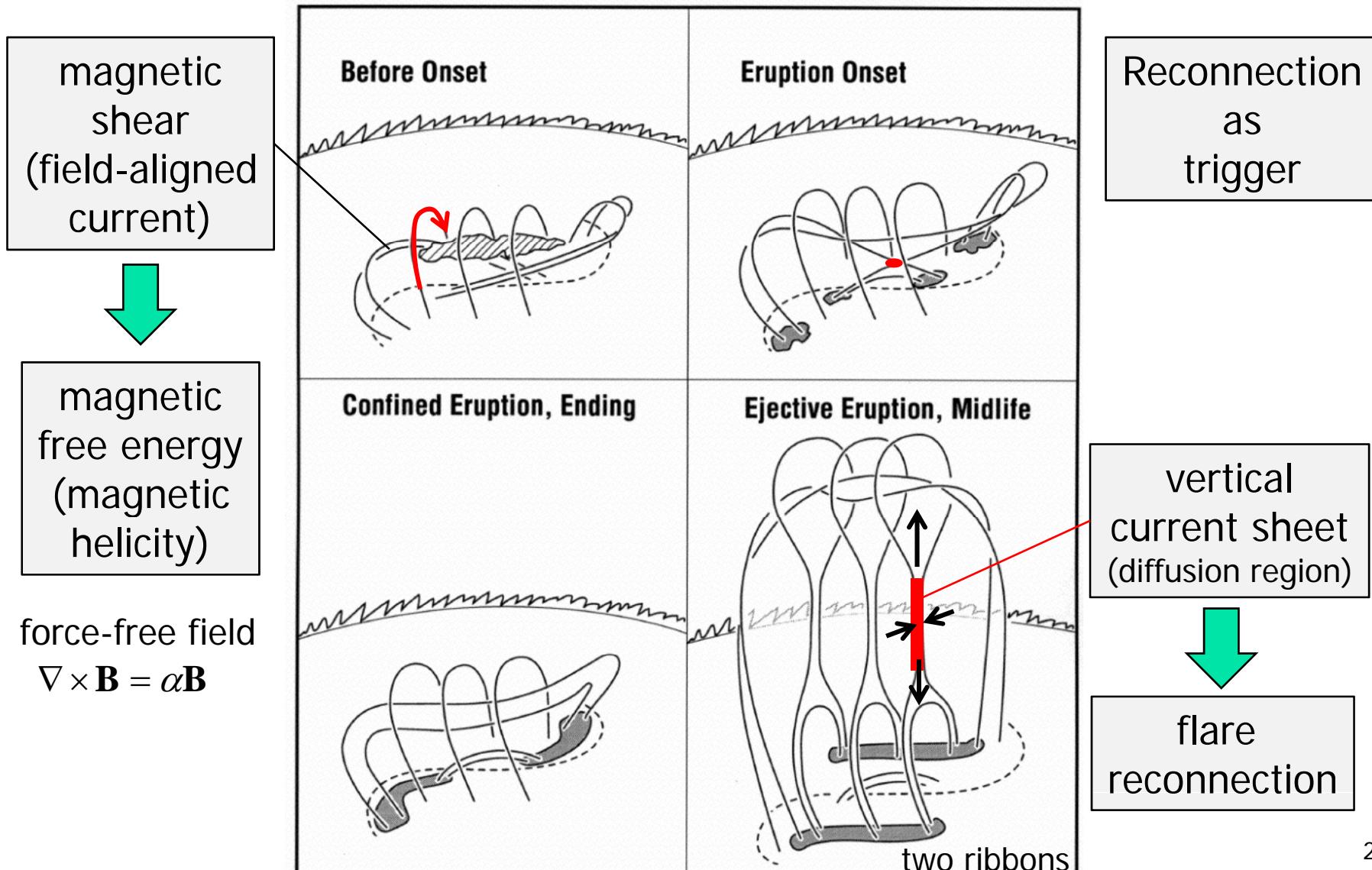


Magnetic Twist

$$T_n = (4\pi)^{-1} \int_{\text{field line}} \alpha \cdot dl$$

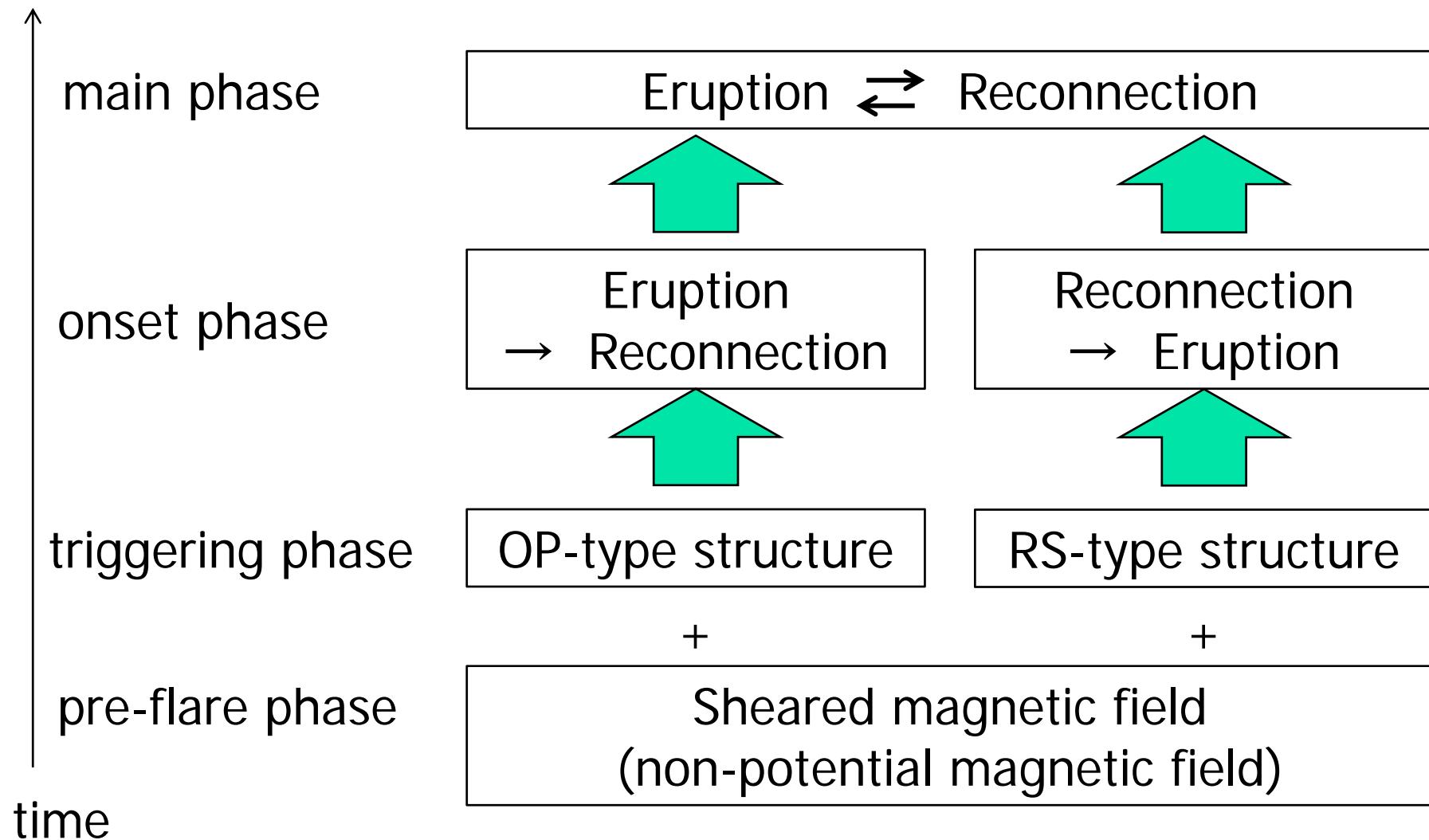


# Tether Cutting Scenario



Moor et al. 2001

# Two Scenarios for Triggering Flare



# The Onset of Storage-and-Release

---

