

理系大学生のための  
太陽研究最前線体験ツアー  
2022年3月15日

# 宇宙天気と宇宙気候 太陽活動を予測する

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太陽宇宙環境物理学(SST)研究室

草野完也



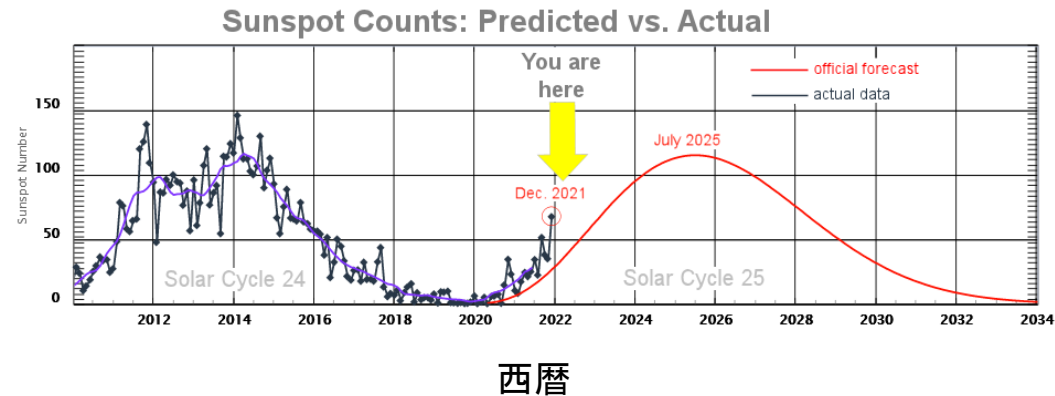
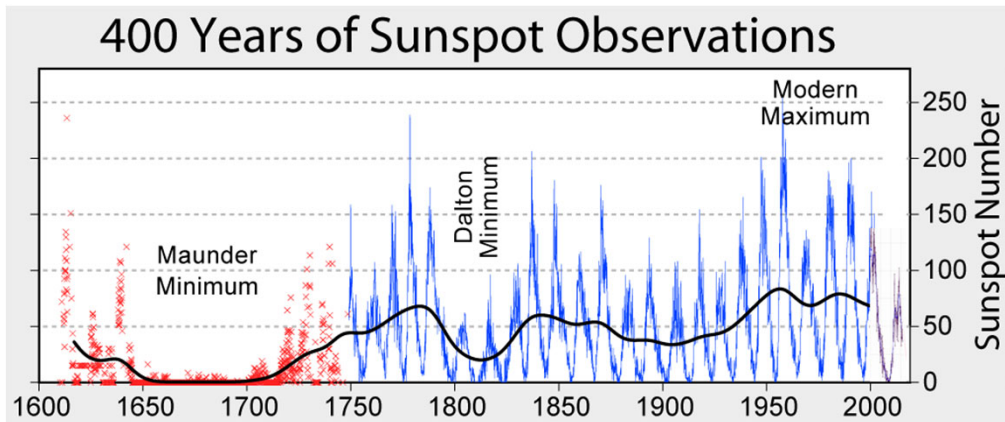
# 宇宙天気と宇宙気候

## ■ 宇宙天気 (Space Weather)

- 短期的な太陽活動(特に、フレア及びコロナ質量放出)に伴って発生する地球と地球周辺宇宙空間の環境変動:オーロラ嵐、磁気嵐、プロトンイベントなど

## ■ 宇宙気候 (Space Climate)

- 長期的な太陽活動の変化(黒点周期変動)に伴って発生する地球と地球周辺宇宙空間の環境変動:気候変動、大気成分変化、大気散逸など



<https://spaceweatherarchive.com/2022/01/09/solar-cycle-25-update/>

# 太陽面爆発

## 太陽系最大級の爆発現象～ $10^{25}$ J

### ■ 太陽フレア

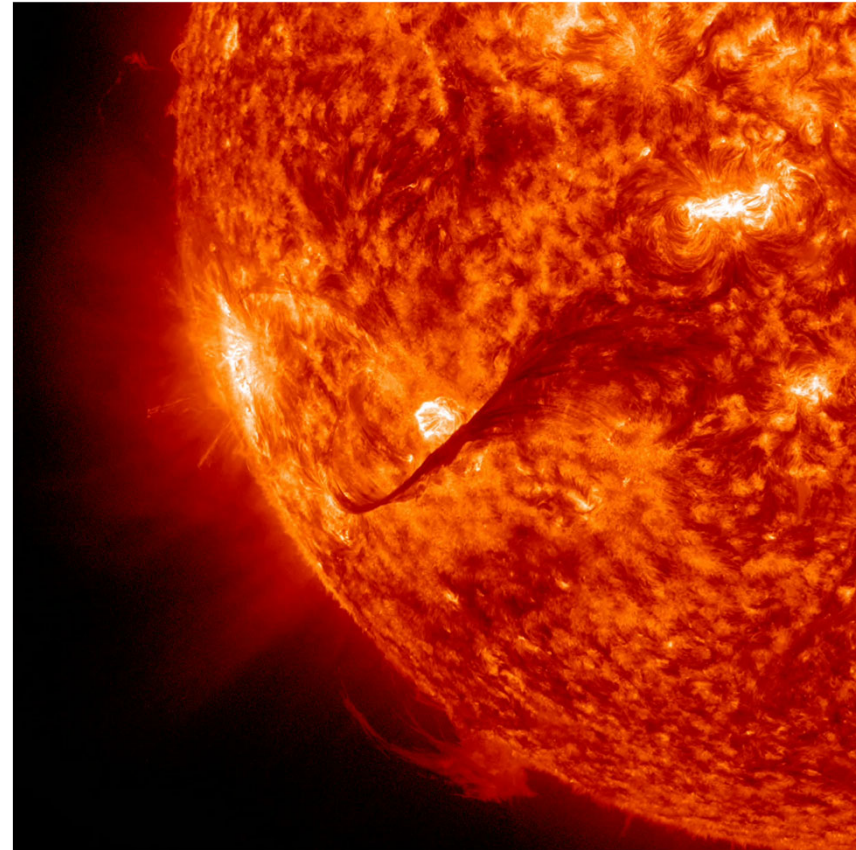
- 突発的で強力な電磁波放射(電波～ $\gamma$ 線)
- 高エネルギー粒子

### ■ フィラメント噴出

- フィラメント(プロミネンス)の突発的噴出

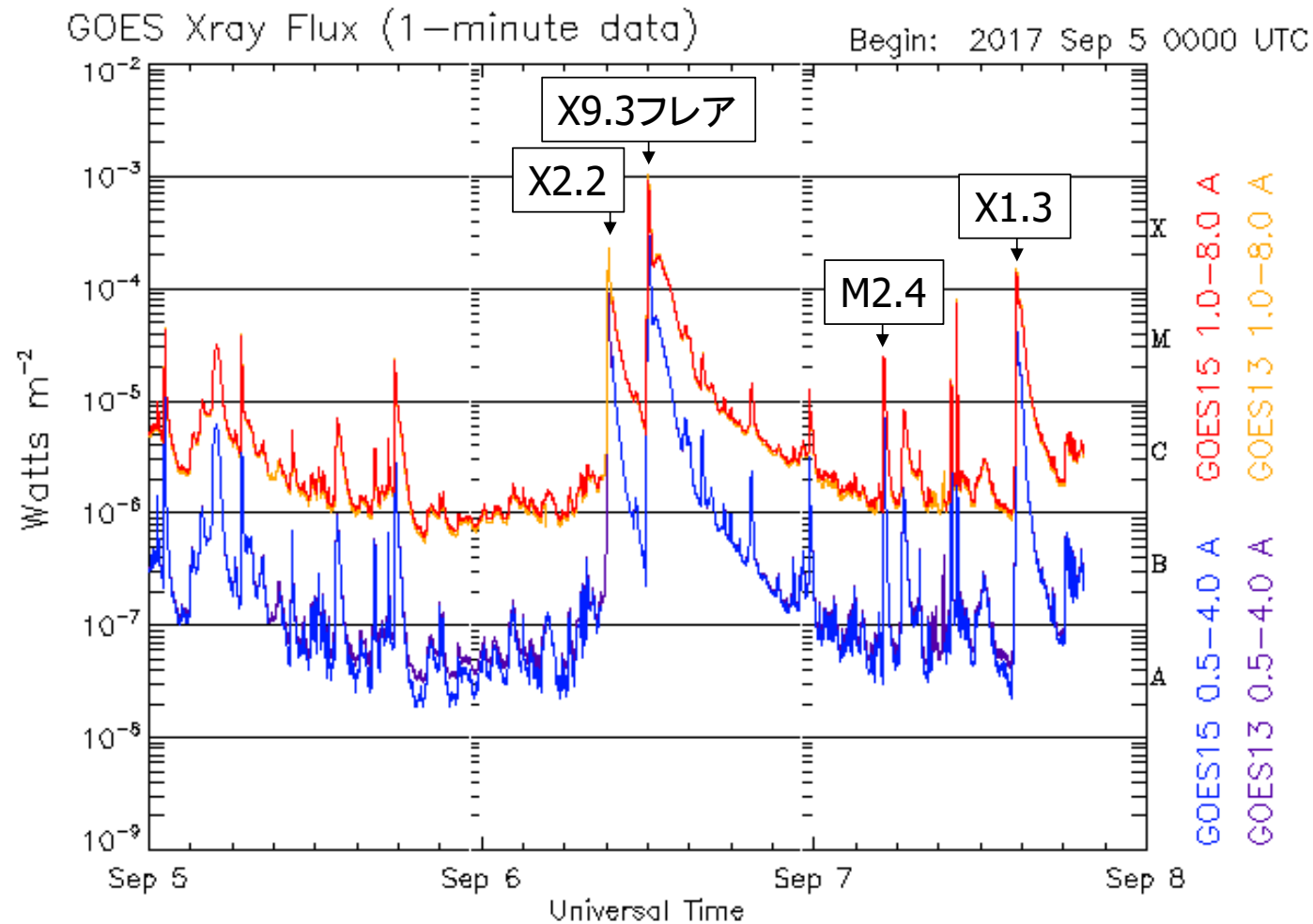
### ■ コロナ質量放出:CME

- コロナプラズマの突発的放出



SDO衛星が観測したフィラメント噴出とフレアリボン

# GOES衛星が観測したX線フラックス

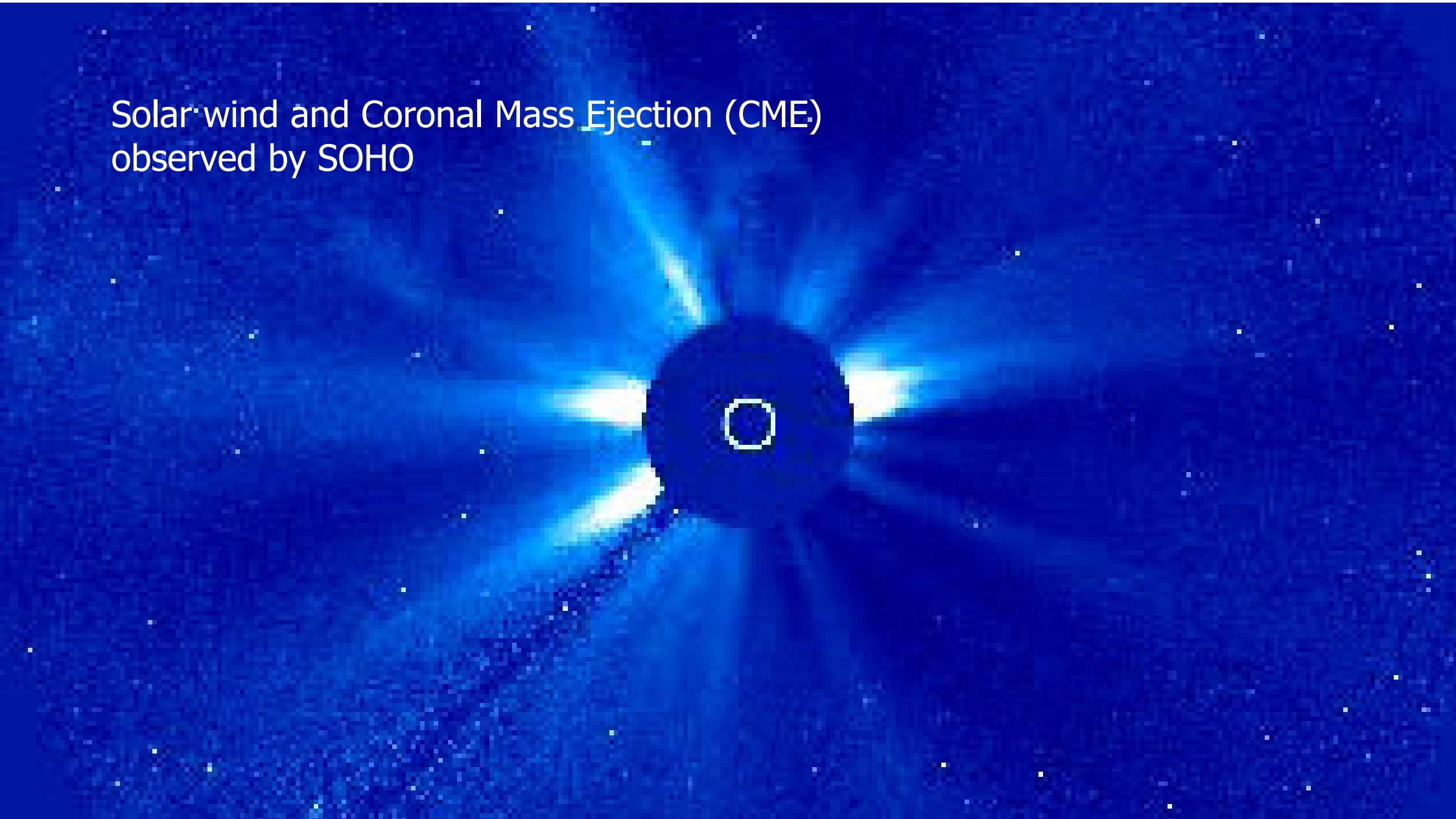


Updated 2017 Sep 7 19:28:12 UTC

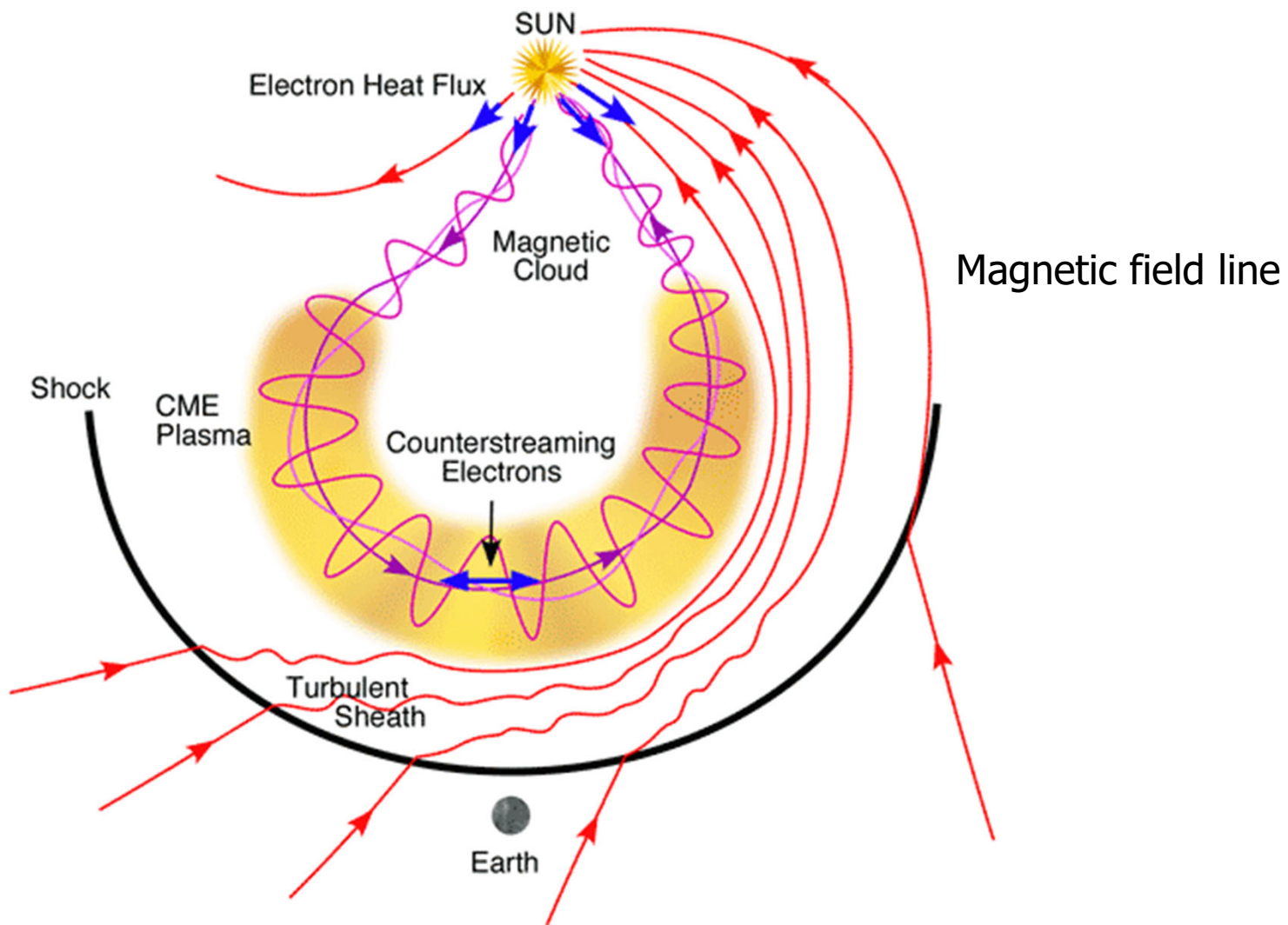
NOAA/SWPC Boulder, CO USA



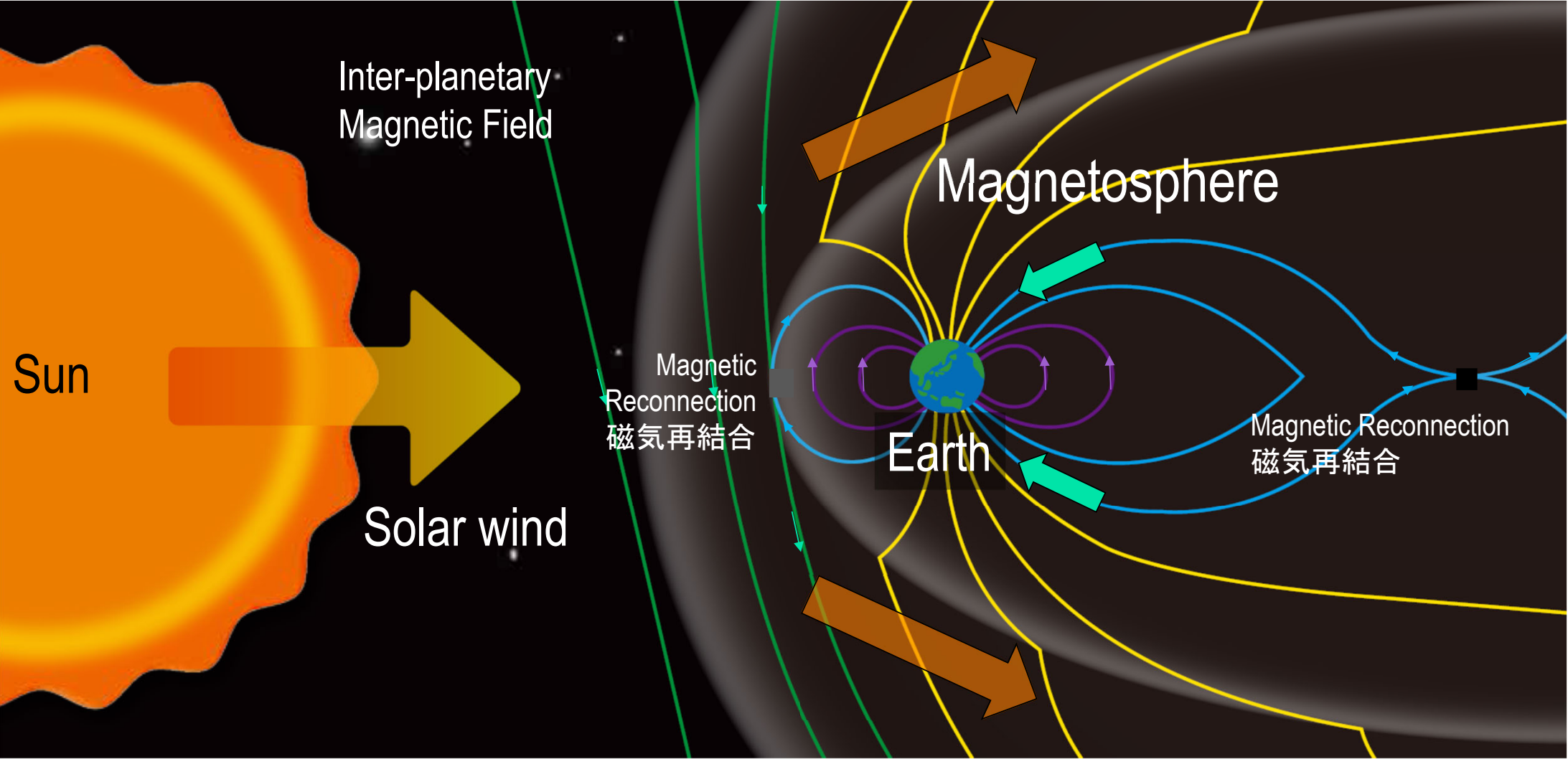
Solar wind and Coronal Mass Ejection (CME)  
observed by SOHO



# Interplanetary Coronal Mass Ejection (ICME)



# Solar Wind-Magnetosphere Interaction

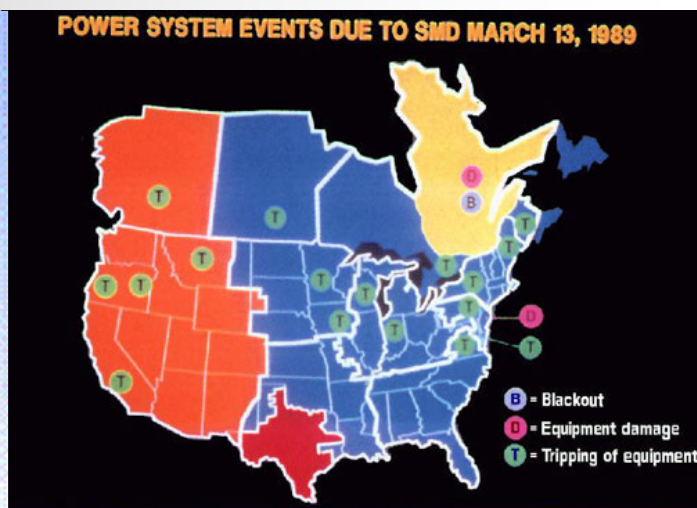
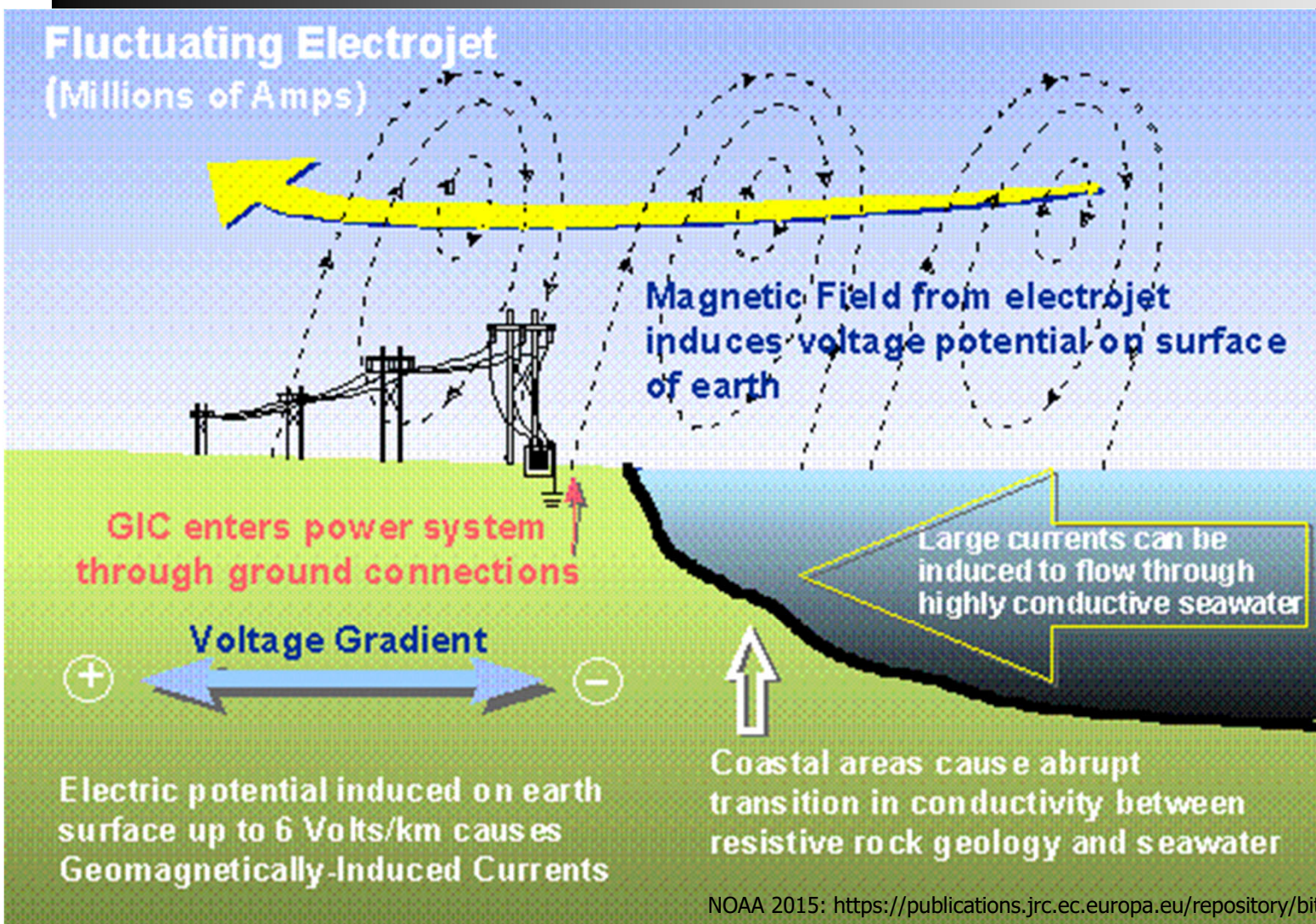




[http://en.wikipedia.org/wiki/File:Polarlicht\\_2.jpg](http://en.wikipedia.org/wiki/File:Polarlicht_2.jpg)



# Geomagnetically Induced Currents (GICs)



PJM Public Service Step Up Transformer  
Severe internal damage caused by the space storm of 13 March, 1989

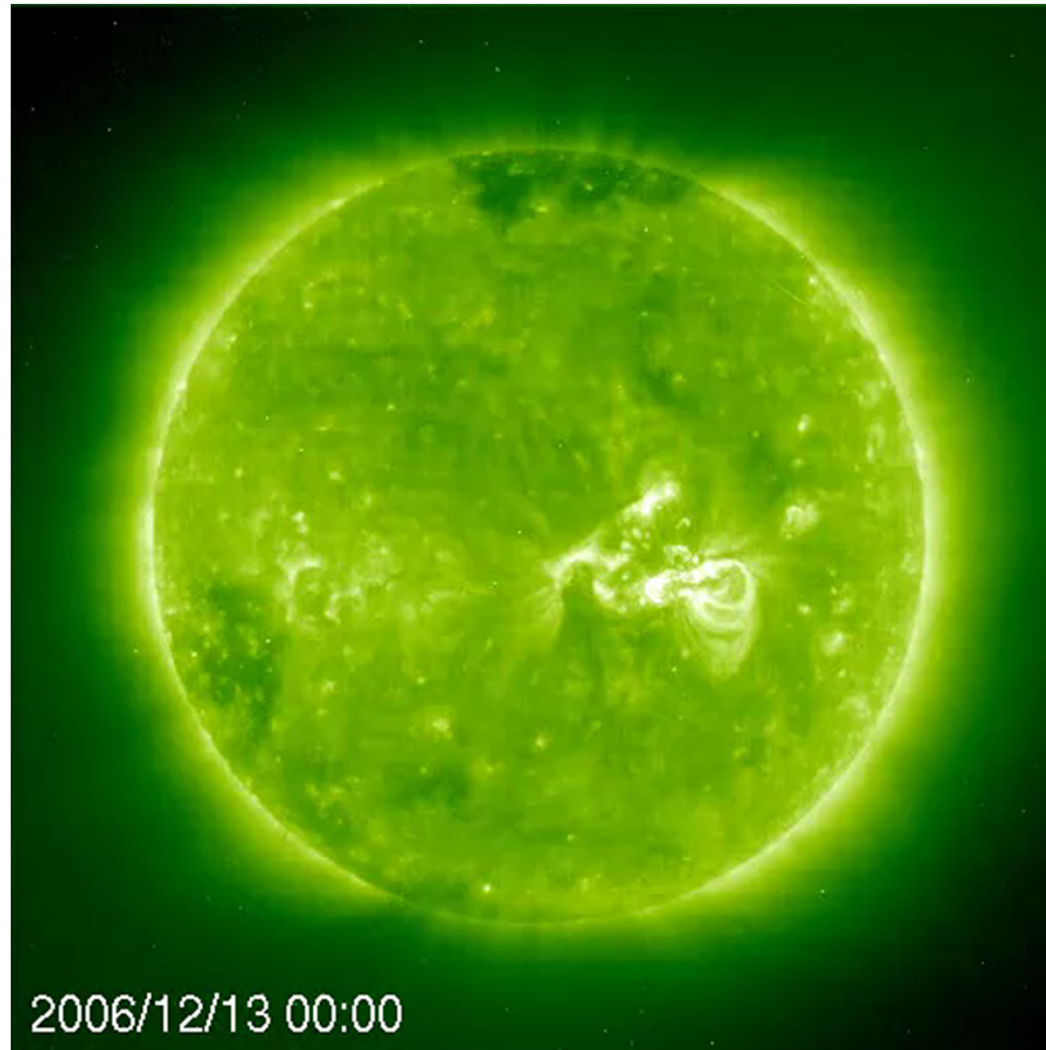


NOAA 2015: [https://publications.jrc.ec.europa.eu/repository/bitstream/JRC98593/eur27571en\\_sw%26pg\\_scandinavia.pdf](https://publications.jrc.ec.europa.eu/repository/bitstream/JRC98593/eur27571en_sw%26pg_scandinavia.pdf)

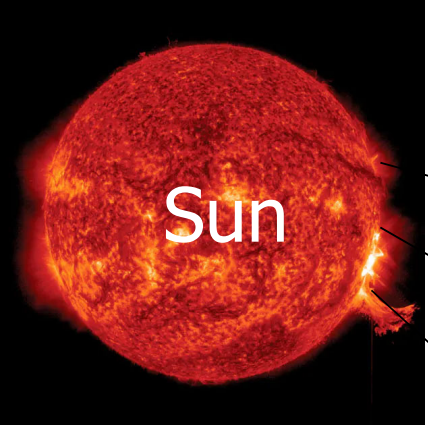


# Solar Particle Events (SPE)

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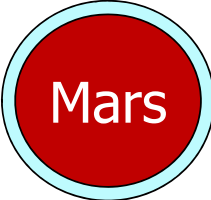
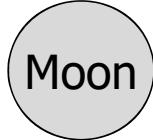


# Space Radiation Health Risk



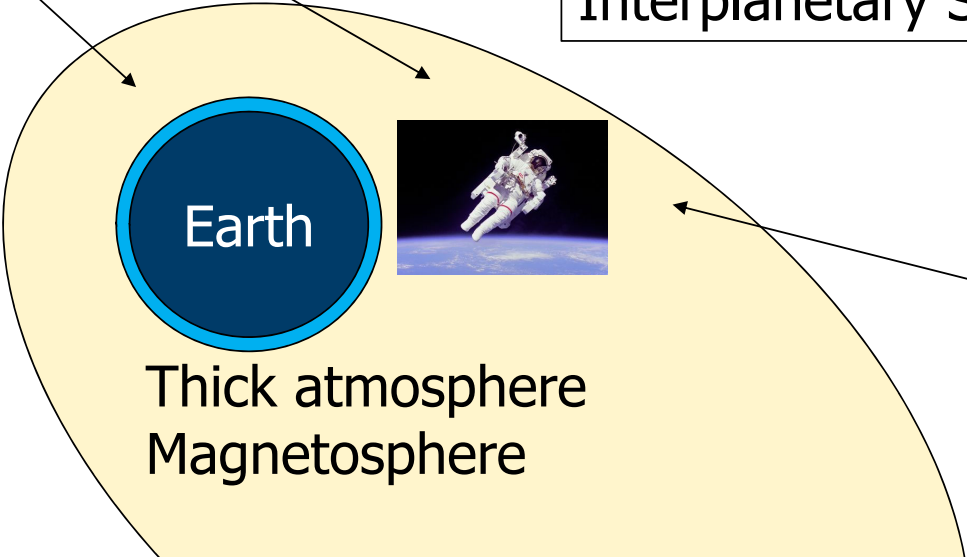
Solar Energetic Particle (SEP)  
 $\sim 100\text{MeV}$  ( $10^8\text{eV}$ )

No atmosphere  
No magnetosphere



Thin atmosphere  
No magnetosphere

Interplanetary Space

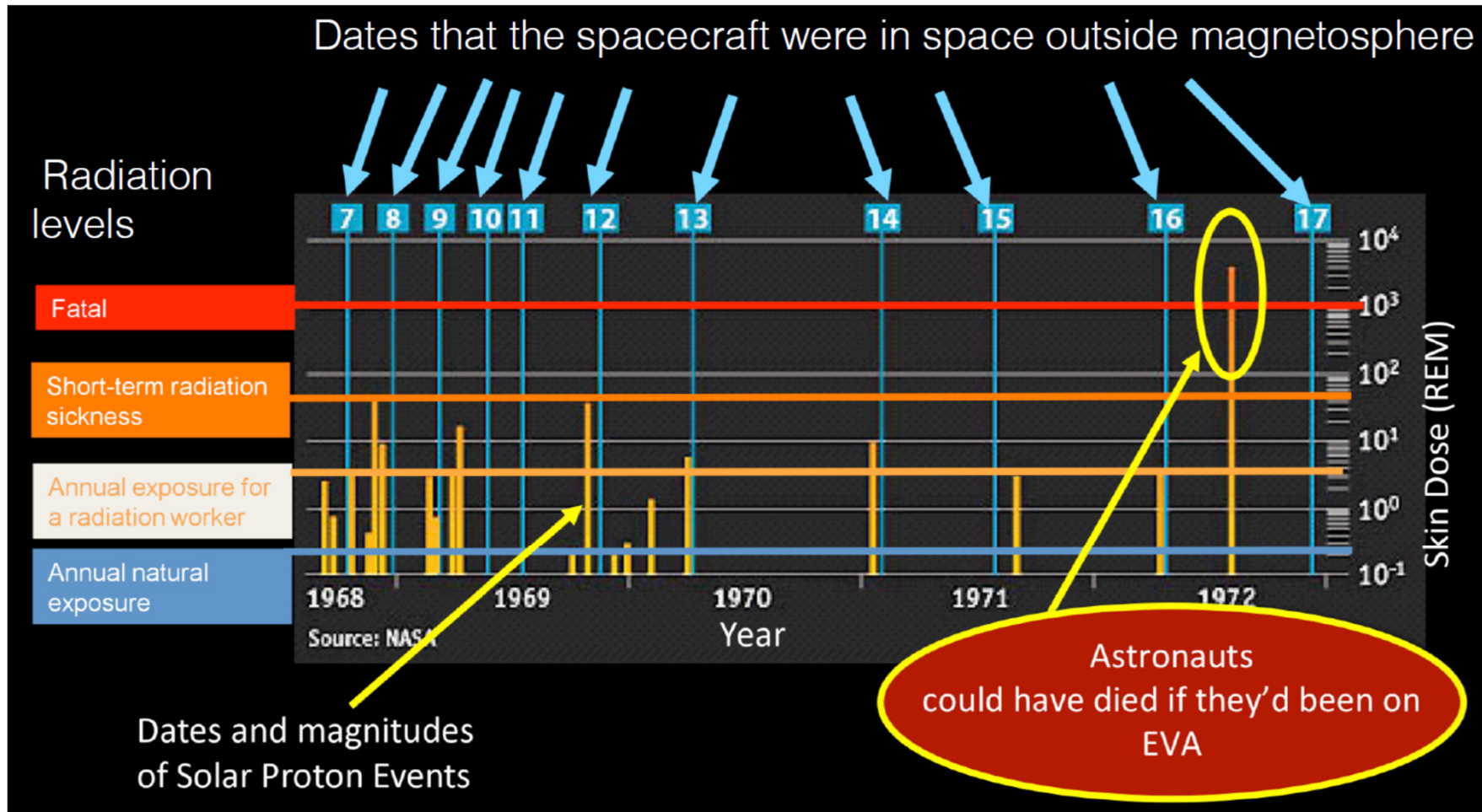


Thick atmosphere  
Magnetosphere

Galactic Cosmic Ray (GCR)  
 $> \text{GeV}$  ( $10^9\text{eV}$ )

Heliopause

# Solar Particle Events during Apollo Missions



Courtesy of Miho Janvier (Institut d'Astrophysique Spatiale, France)

# 太陽

## フレア

高エネルギー粒子

地球到達時間  
30分～2日

X線放射 8分

CME

太陽風擾乱

2～3日

宇宙放射線

熱圏擾乱

衛星障害

通信障害

被ばく影響

電離圏擾乱

地球

電力障害

オーロラ活動

地磁気擾乱

磁気圏

# 宇宙天気現象の発生と障害



# Project for Solar-Terrestrial Environment Prediction

## PSTEP: 新学術領域「太陽地球圏環境予測」



Supported by MEXT, Japan (2015-2019)



### 【Science Research】

To answer fundamental questions of solar-terrestrial environment

physics-based model

**prediction**  
**evaluation**

### 【Operational Forecast】

To build the base of next-generation space weather forecast system

Prediction of Solar Flares

Prediction of CME

Prediction of Solar Cycle

GIC Forecast



Satellite Charging



Radiation Belts Dynamics

Ionospheric Plasma Bubble

Influence on Climate

Dose control



Radio comm.





# 太陽フレア予測の課題 (Issues)

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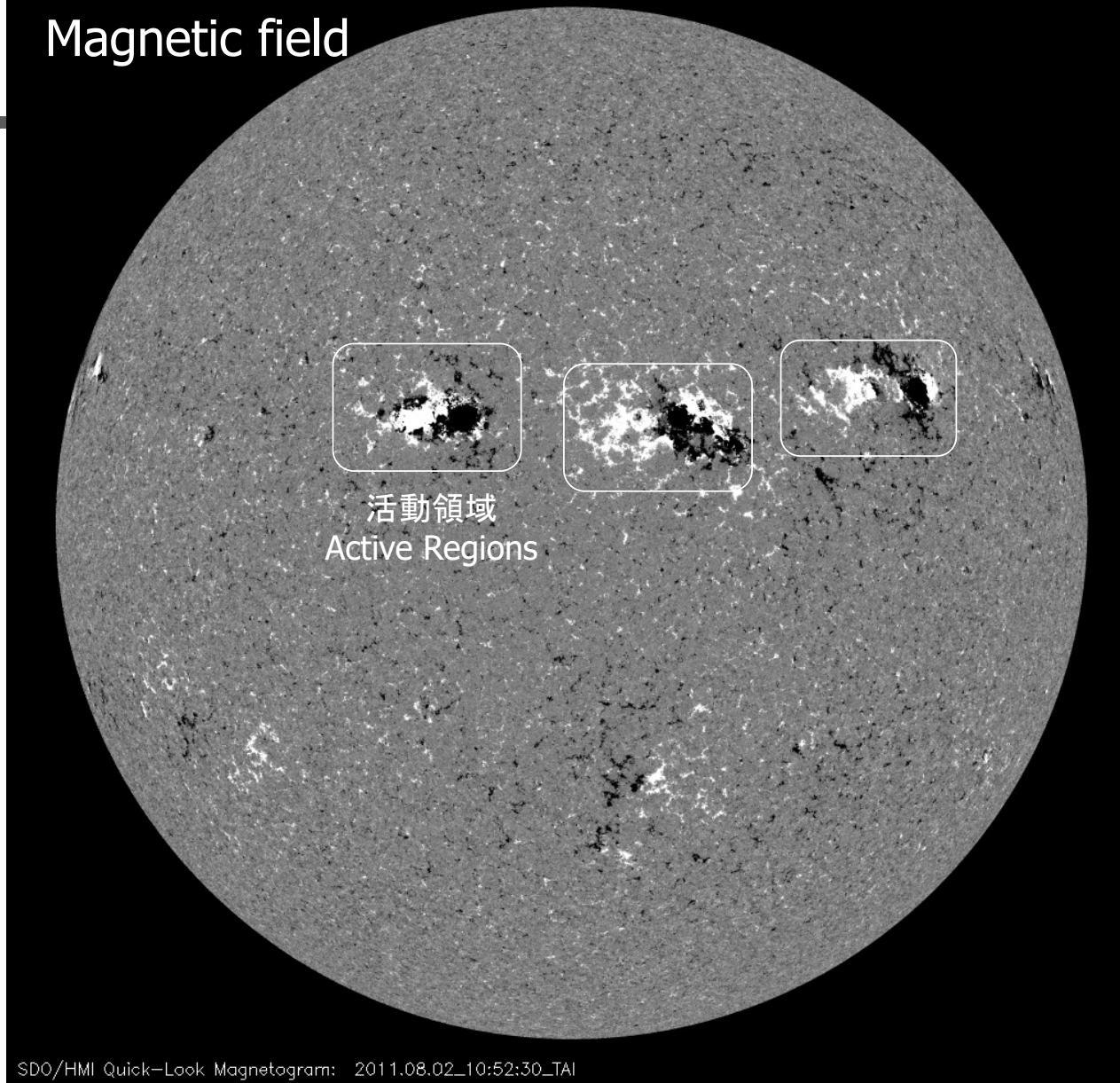
- 巨大フレアを如何にして予測するか？

How can we predict solar flares?

- いつ、どこで、どれほどの太陽フレアがどのように発生するのか？

When, where, and how do solar flares occur?

## Magnetic field



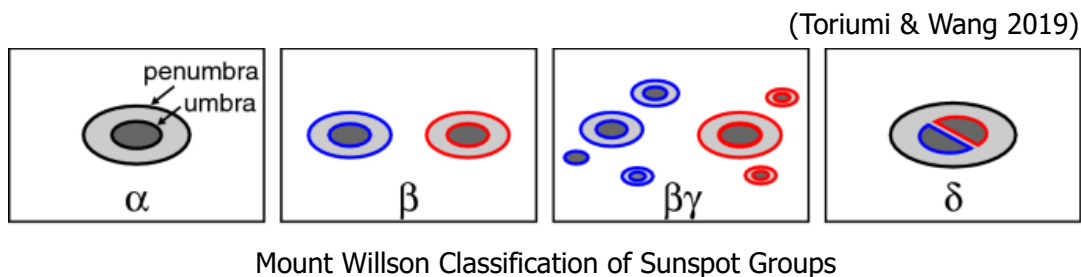
Observed by SDO  
Aug. 2, 2011

# これまでの太陽フレア予測の現状

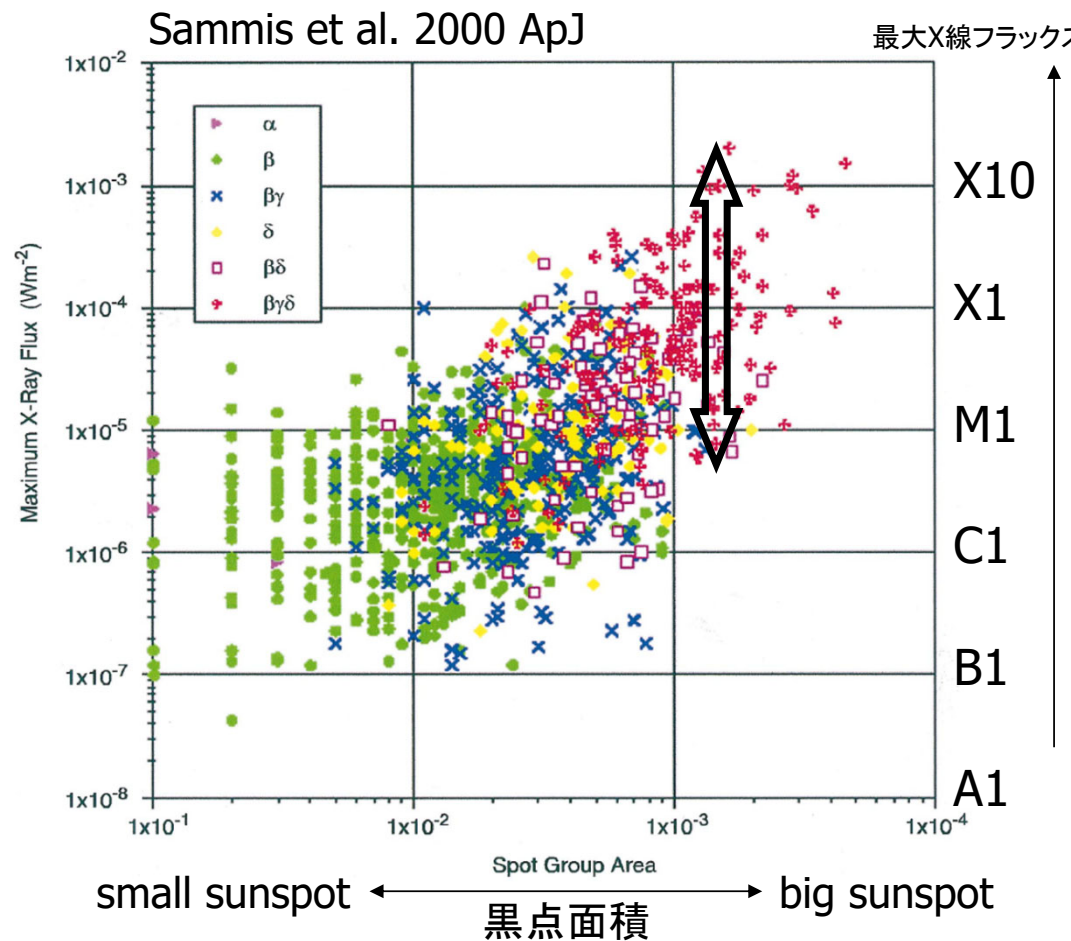
現在運用されているフレア発生予測は過去のデータから見出した黒点や活動領域の諸量とフレア活動の相関関係に基づく経験予測を用いている。

経験的にフレア発生・規模と相関がある量

- 磁場構造の複雑さ
- 黒点面積、全磁束量

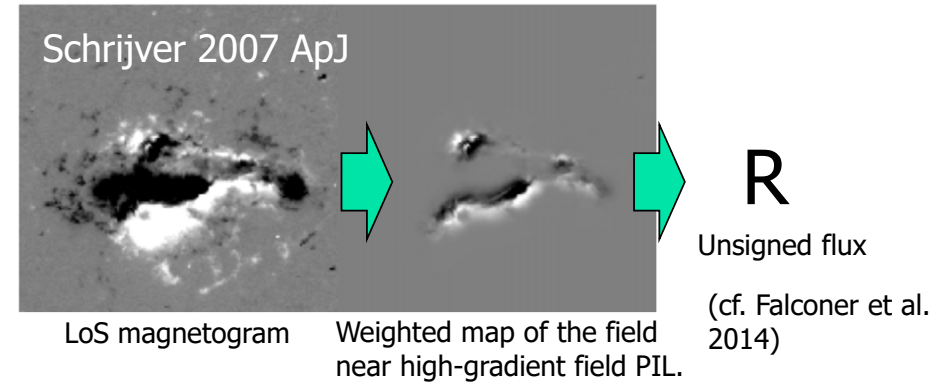


The dependence of large flare occurrence on the magnetic structure of sunspots



# これまでの太陽フレア予測の現状

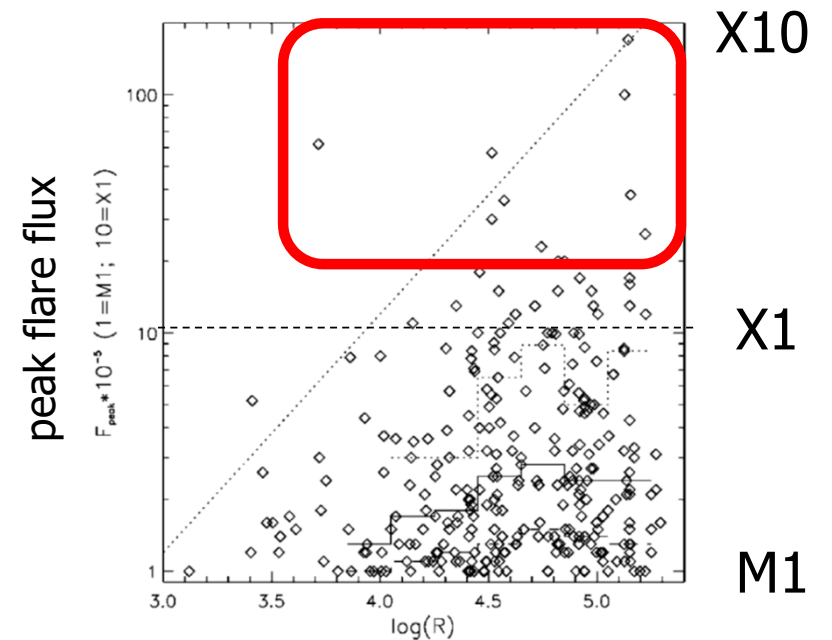
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経験的にフレア発生・規模と相関がある量

- 磁場構造の複雑さ
- 黒点面積、全磁束量

CLASS	PROBABILITY					
	log R ≈ <3.0 (%)	log R ≈ 3.0 (%)	log R ≈ 3.5 (%)	log R ≈ 4.0 (%)	log R ≈ 4.5 (%)	log R ≈ 5.0 (%)
>M1 .....	...	2	5	12	50	~80
>M3 .....	...	~0	<1	3	20	35
>X1 .....	...	0	~0	~1	10	20
>X3 .....	...	0	0	~0	1	1-2
Maximum .....	<C9	<M1	<M4	<X1	<X4	<X10

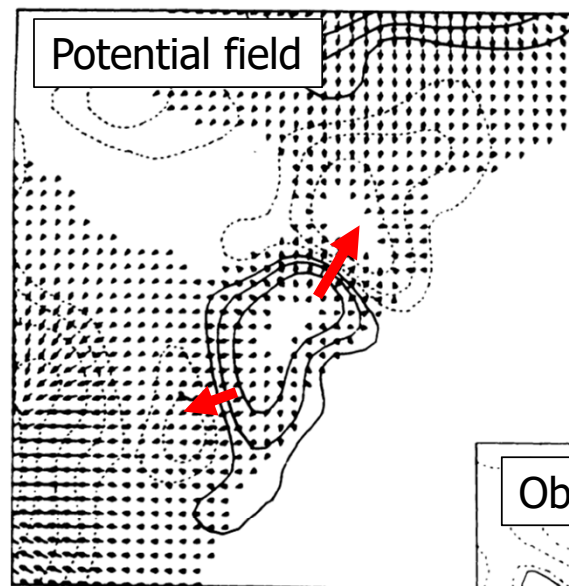


# これまでの太陽フレア予測の現状

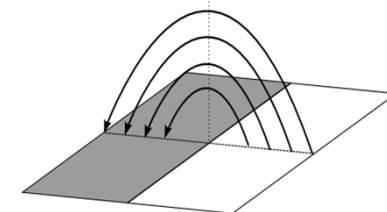
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経験的にフレア発生・規模と相関がある量

- 磁場構造の複雑さ
- 黒点面積、全磁束量
- 磁場のねじれ



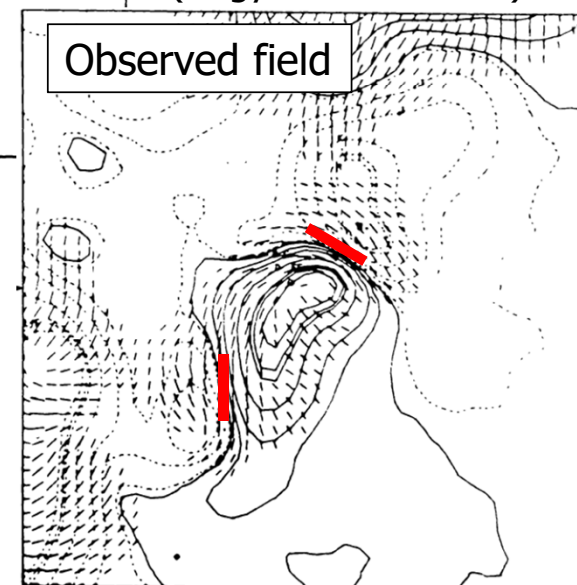
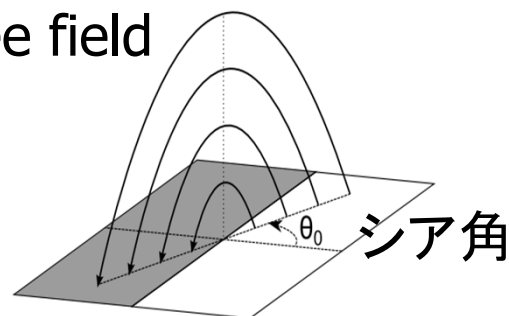
$$B = -\nabla\phi$$
$$\nabla \times B = 0$$



(Hagyard et al. 1984)

$$\nabla \times B = \alpha B$$

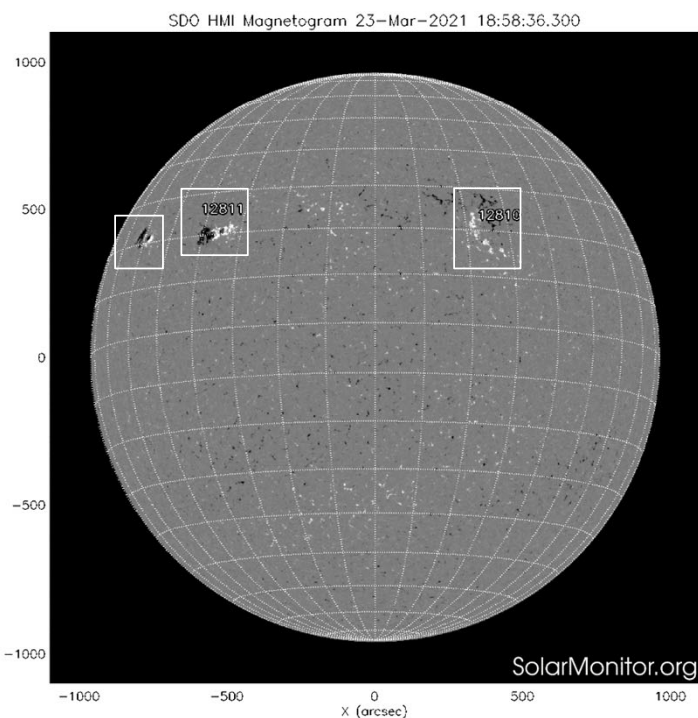
force-free field





**Table 1**  
SHARP Active Region Parameter Formulae

Keyword	Description	Formula	F-Score	Selection
TOTUSJH	Total unsigned current helicity	$H_{c\text{total}} \propto \sum  B_z \cdot J_z $	3560	Included
TOTBSQ	Total magnitude of Lorentz force	$F \propto \sum B^2$	3051	Included
TOTPOT	Total photospheric magnetic free energy density	$\rho_{\text{tot}} \propto \sum (\mathbf{B}^{\text{Obs}} - \mathbf{B}^{\text{Pot}})^2 dA$	2996	Included
TOTUSJZ	Total unsigned vertical current	$J_{z\text{total}} = \sum  J_z  dA$	2733	Included
ABSNJZH	Absolute value of the net current helicity	$H_{c\text{abs}} \propto  \sum B_z \cdot J_z $	2618	Included
SAVNCPP	Sum of the modulus of the net current per polarity	$J_{z\text{sum}} \propto \left  \sum J_z^+ dA \right  + \left  \sum J_z^- dA \right $	2448	Included
USFLUX	Total unsigned flux	$\Phi = \sum  B_z  dA$	2437	Included
AREA_ACR	Area of strong field pixels in the active region	Area = $\sum$ Pixels	2047	Included
TOTFZ	Sum of z-component of Lorentz force	$F_z \propto \sum (B_x^2 + B_y^2 - B_z^2) dA$	1371	Included
MEANPOT	Mean photospheric magnetic free energy	$\bar{\rho} \propto \frac{1}{N} \sum (\mathbf{B}^{\text{Obs}} - \mathbf{B}^{\text{Pot}})^2$	1064	Included
R_VALUE	Sum of flux near polarity inversion line	$\Phi = \sum  B_{\text{LoS}}  dA$ within $R$ mask	1057	Included
EPSZ	Sum of z-component of normalized Lorentz force	$\delta F_z \propto \frac{\sum (B_x^2 + B_y^2 - B_z^2)}{\sum B^2}$	864.1	Included
SHRGT45	Fraction of Area with shear > 45°	Area with shear > 45° / total area	740.8	Included
MEANSHR	Mean shear angle	$\bar{\Gamma} = \frac{1}{N} \sum \arccos \left( \frac{\mathbf{B}^{\text{Obs}} \cdot \mathbf{B}^{\text{Pot}}}{ \mathbf{B}^{\text{Obs}}   \mathbf{B}^{\text{Pot}} } \right)$	727.9	Discarded
MEANGAM	Mean angle of field from radial	$\bar{\gamma} = \frac{1}{N} \sum \arctan \left( \frac{B_h}{B_z} \right)$	573.3	Discarded
MEANGBT	Mean gradient of total field	$ \nabla B_{\text{tot}}  = \frac{1}{N} \sum \sqrt{\left( \frac{\partial B}{\partial x} \right)^2 + \left( \frac{\partial B}{\partial y} \right)^2}$	192.3	Discarded
MEANGBZ	Mean gradient of vertical field	$ \nabla B_z  = \frac{1}{N} \sum \sqrt{\left( \frac{\partial B_z}{\partial x} \right)^2 + \left( \frac{\partial B_z}{\partial y} \right)^2}$	88.40	Discarded
MEANGBH	Mean gradient of horizontal field	$ \nabla B_h  = \frac{1}{N} \sum \sqrt{\left( \frac{\partial B_h}{\partial x} \right)^2 + \left( \frac{\partial B_h}{\partial y} \right)^2}$	79.40	Discarded
MEANJZH	Mean current helicity ( $B_z$ contribution)	$\bar{H}_c \propto \frac{1}{N} \sum B_z \cdot J_z$	46.73	Discarded
TOTFY	Sum of y-component of Lorentz force	$F_y \propto \sum B_y B_z dA$	28.92	Discarded
MEANJZD	Mean vertical current density	$\bar{J}_z \propto \frac{1}{N} \sum \left( \frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y} \right)$	17.44	Discarded
MEANALP	Mean characteristic twist parameter, $\alpha$	$\alpha_{\text{total}} \propto \frac{\sum J_z \cdot B_z}{\sum B_z^2}$	10.41	Discarded
TOTFX	Sum of x-component of Lorentz force	$F_x \propto -\sum B_x B_z dA$	6.147	Discarded
EPSY	Sum of y-component of normalized Lorentz force	$\delta F_y \propto \frac{-\sum B_y B_z}{\sum B^2}$	0.647	Discarded
EPSX	Sum of x-component of normalized Lorentz force	$\delta F_x \propto \frac{\sum B_x B_z}{\sum B^2}$	0.366	Discarded



# これまでの太陽フレア予測の現状

Contingency Table for X-class Flare  
Prediction of NOAA/SWPC for Cycle 23

Forecast	Observation positive	Observation negative	
positive	50 (TP)	67 (FP)	$\frac{TP}{TP+FP}$ ~0.43
negative	52 (FN)	31315 (TN)	

Precision (精度)

Crown 2012 Space Weather

$\frac{TP}{TP+FN}$   
~0.49

Recall (再現性)

# 太陽フレア予測の課題 (Issues)

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- 巨大フレアを如何にして予測するか？

How can we predict solar flares?

- いつ、どこで、どれほどの太陽フレアがどのように発生するのか？

When, where, and how do solar flares occur?

# 太陽フレア予測の課題 (Issues)

---

## ■ 巨大フレアを如何にして予測するか？

How can we predict solar flares?

- いつ、どこで、どれほどの太陽フレアがどのように発生するのか？

When, where, and how do solar flares occur?

- 太陽フレアの発生を何が決定づけるのか？

What determines the onset of solar flares?

- そもそも、なぜ太陽フレアは(突発的かつ爆発的に)発生するのか？

Why do solar flares occur (suddenly and explosively)?

# 経験予測と物理予測

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## 経験予測 Empirical Prediction

過去の観測データより黒点や活動領域の諸量とフレア発生の相関関係を求め、フレア発生を決定づける(であろう)パラメタを経験的に見出すことで予測を実現する。

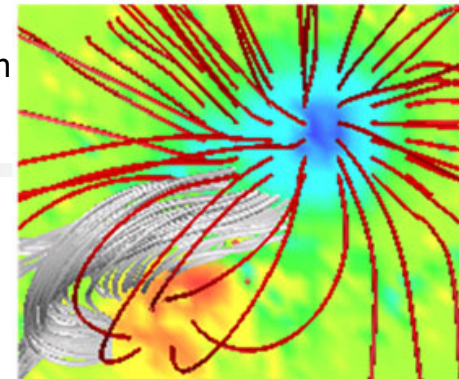
## 物理予測 Physics-Based Prediction

理論的にフレア発生とその性質を決定づける(であろう)物理過程を明らかにし、その理論に基づいて予測パラメタを導出し、予測を実現する。



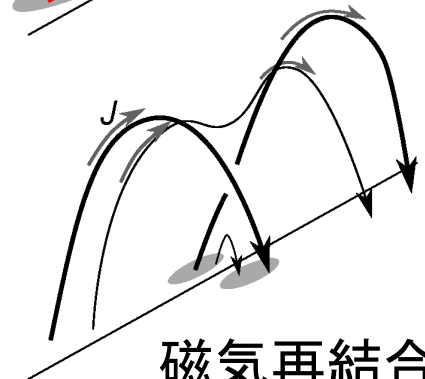
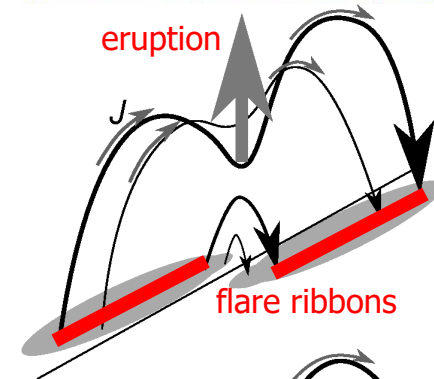
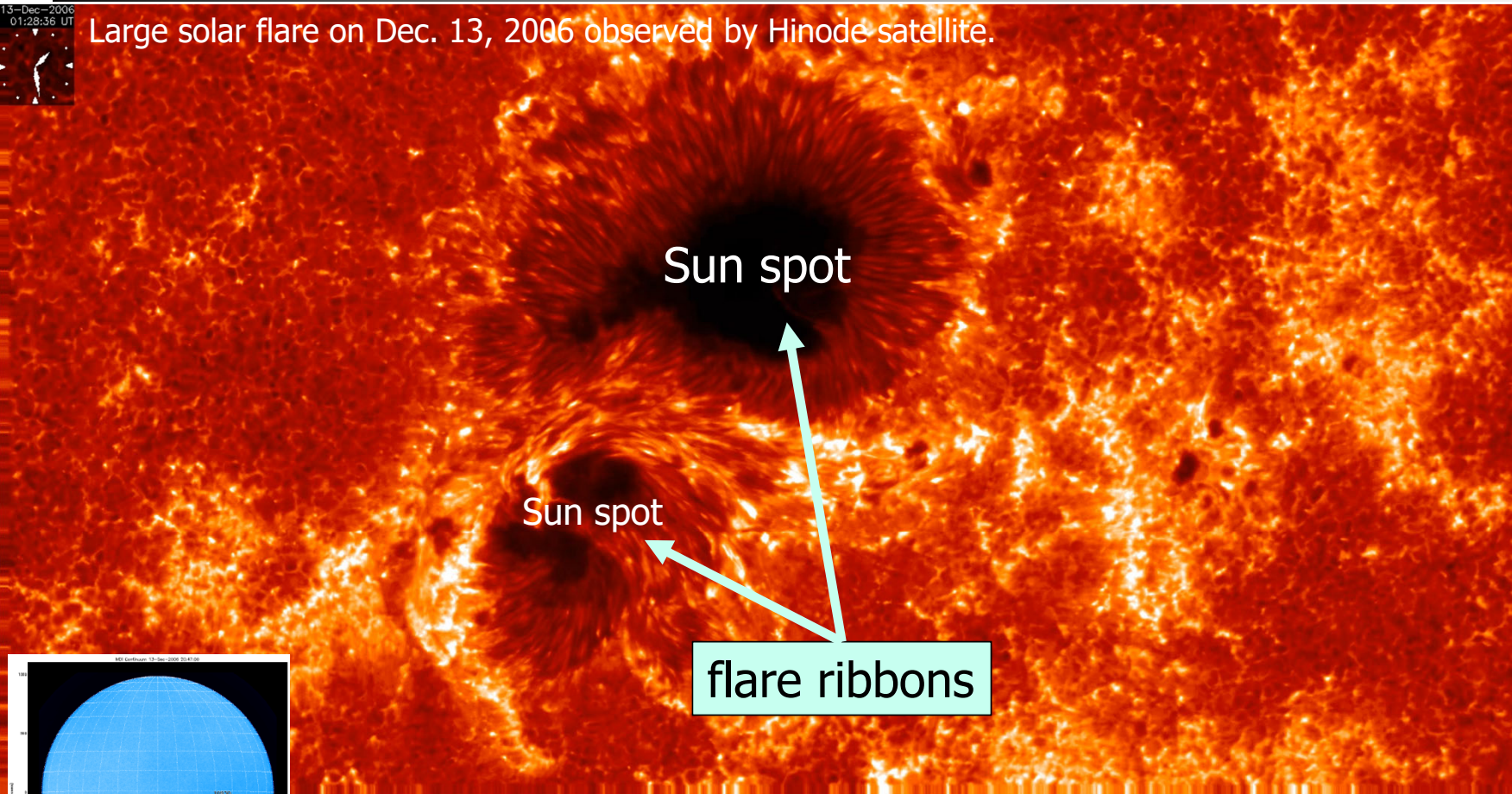
# 黒点と太陽フレア

Magnetic field lines in the active region

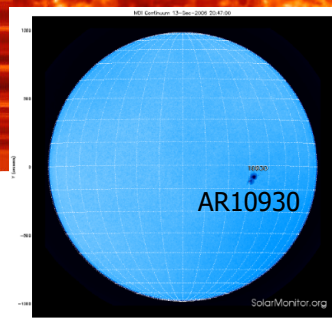


13-Dec-2006  
01:28:36 UT

Large solar flare on Dec. 13, 2006 observed by Hinode satellite.

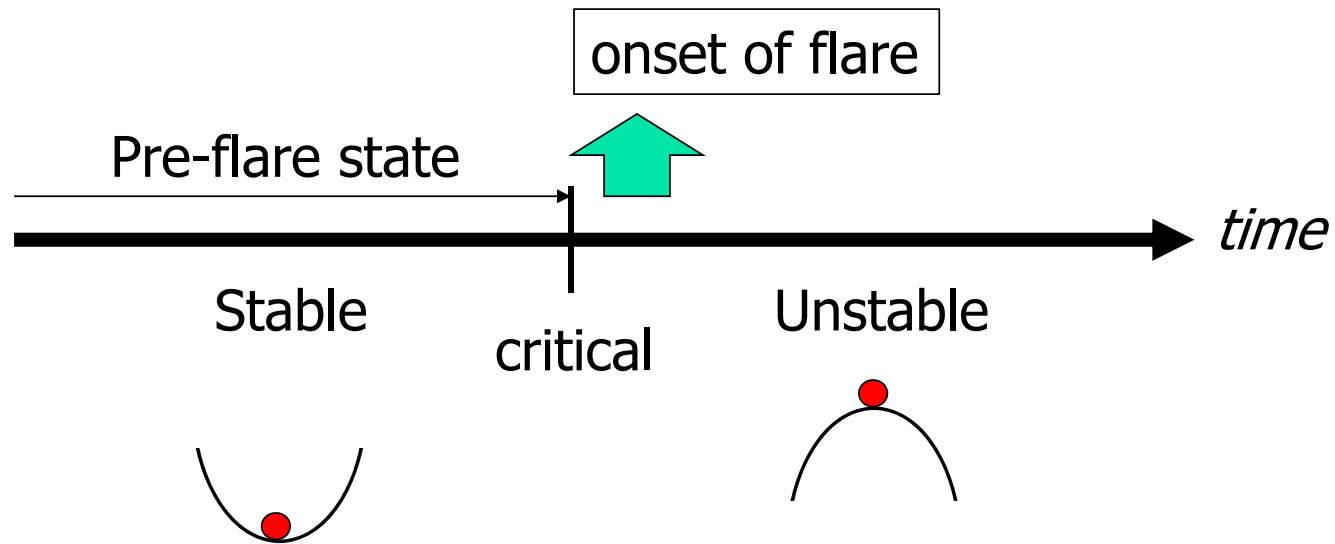


磁気再結合  
magnetic reconnection



Solar flares are large explosion driven by magnetic energy in solar active regions around sunspots and emit strong electromagnetic radiation and high-energy particles.

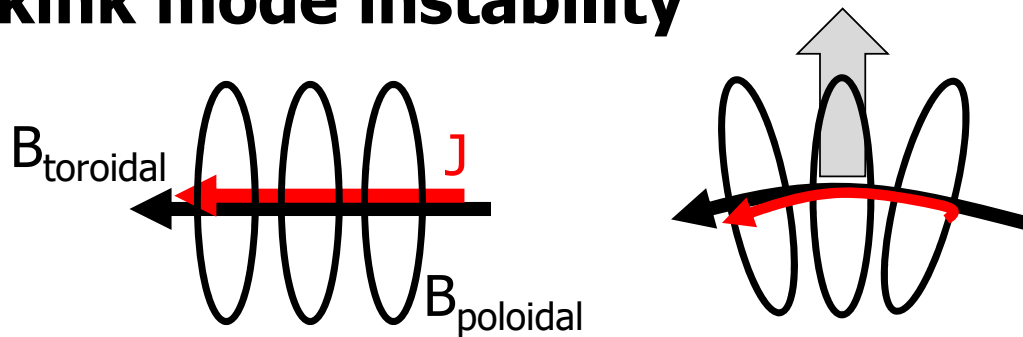
# 不安定性仮説



What kind of instability is responsible for the onset of flare?

# キンク不安定性とトーラス不安定性

## kink mode instability



Twist number

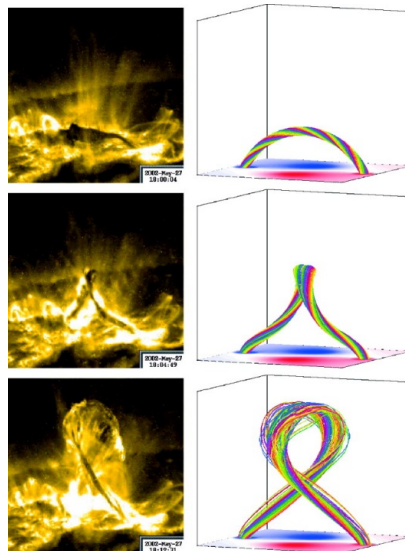
$$T_w = \frac{d\Phi_{poloidal}}{d\Phi_{toroidal}} > O(1)$$

Kruskal+1954

Hood & Priest 1979, 1981

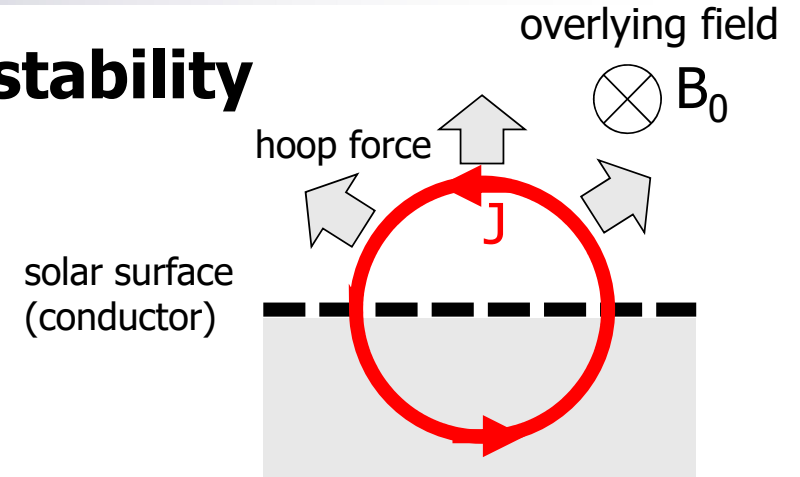
Török & Kliem 2005

Török, Kliem & Titov 2004



Török & Kliem 2005

## torus instability



$$\text{Decay index } n = -\frac{R}{B_0} \frac{dB_0}{dR} > O(1)$$

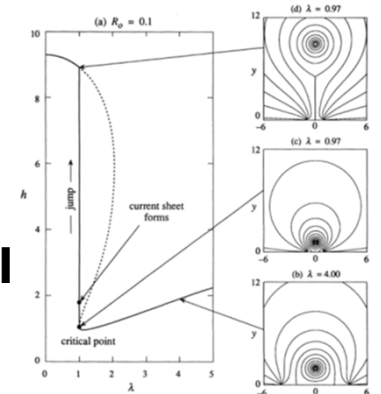
Shafranov 1966

Kliem & Török 2006

Demoulin & Aulanier 2010

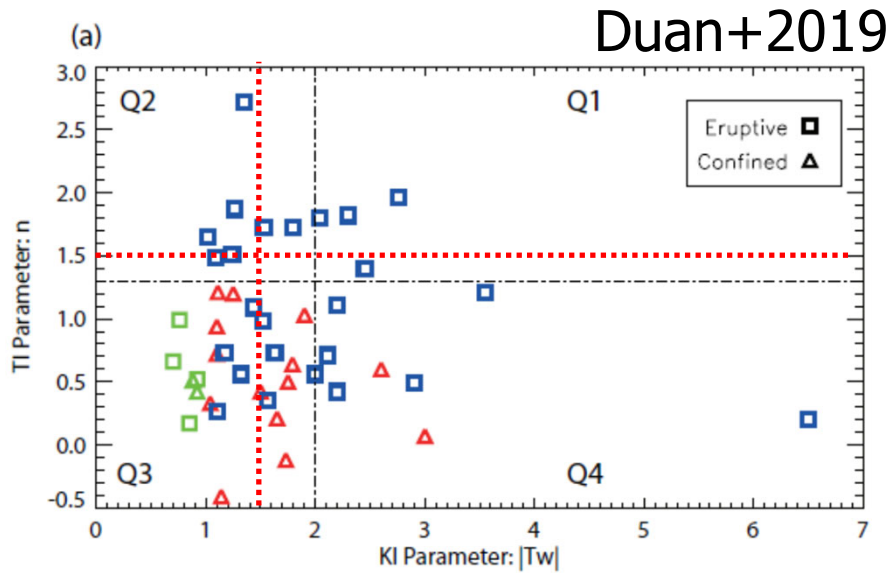
**Loss of Equilibrium Model**

Forbes & Priest 1995



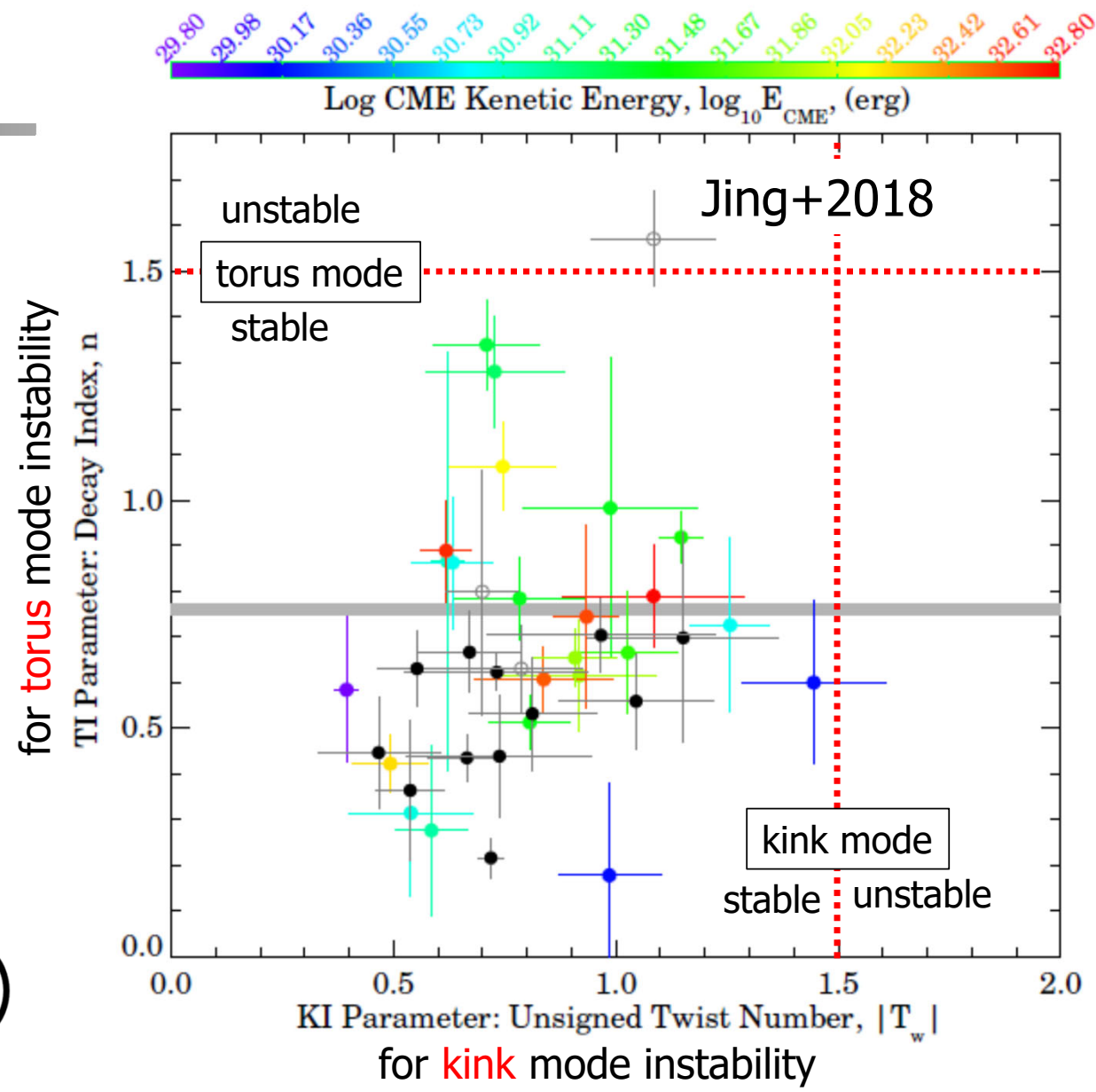
Forbes & Priest 1995

# 不稳定性解析



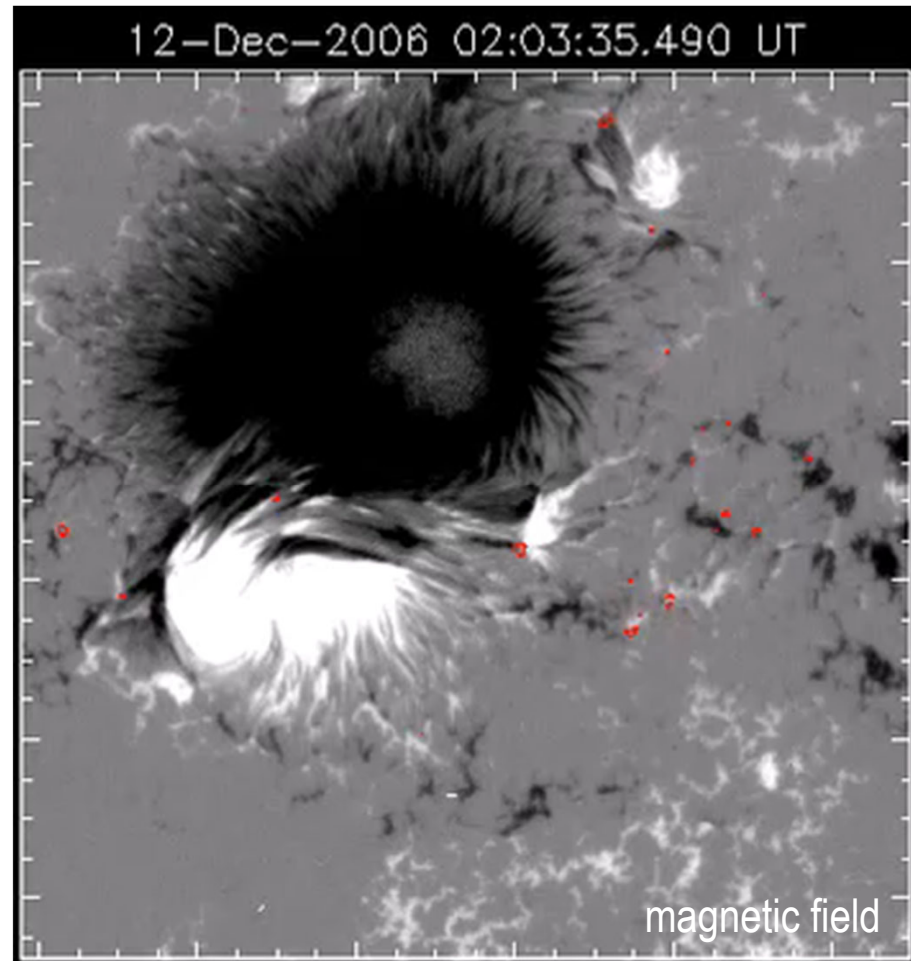
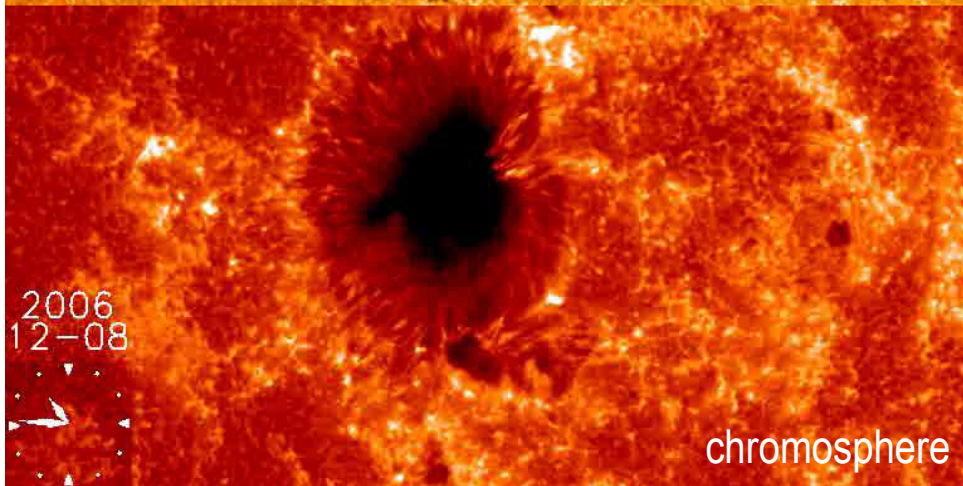
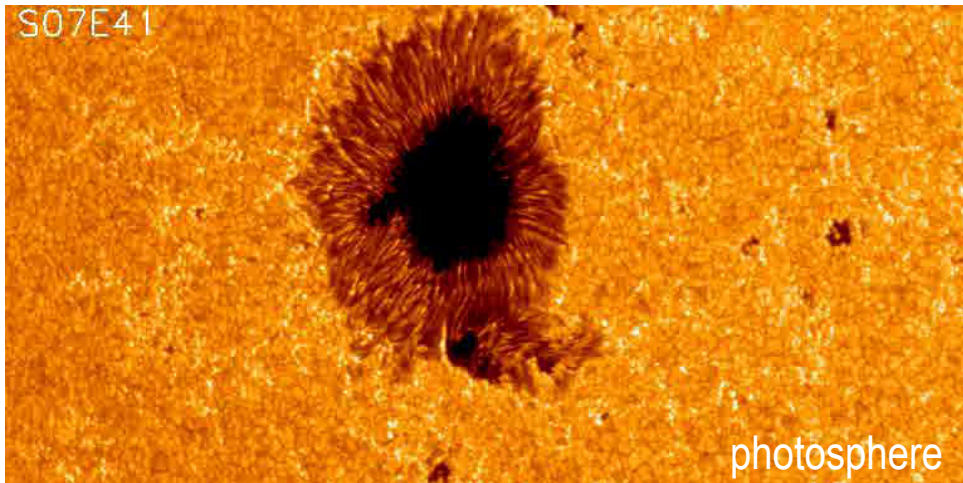
There is no clear correlation between the critical condition of kink and torus instabilities and the onset of large flares.

Something was missed. 😞





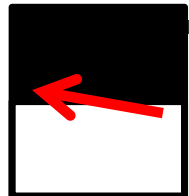
# What is the precursor of solar flare?



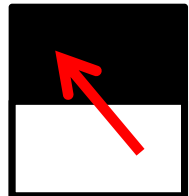
Hinode observation

# Numerical Simulation of Flare Trigger Process

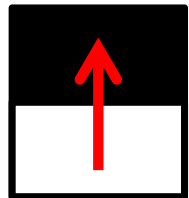
K. Kusano et al., MAGNETIC FIELD STRUCTURES TRIGGERING SOLAR FLARES AND CORONAL MASS EJECTIONS, ApJ, 760:31, 2012 November 20.



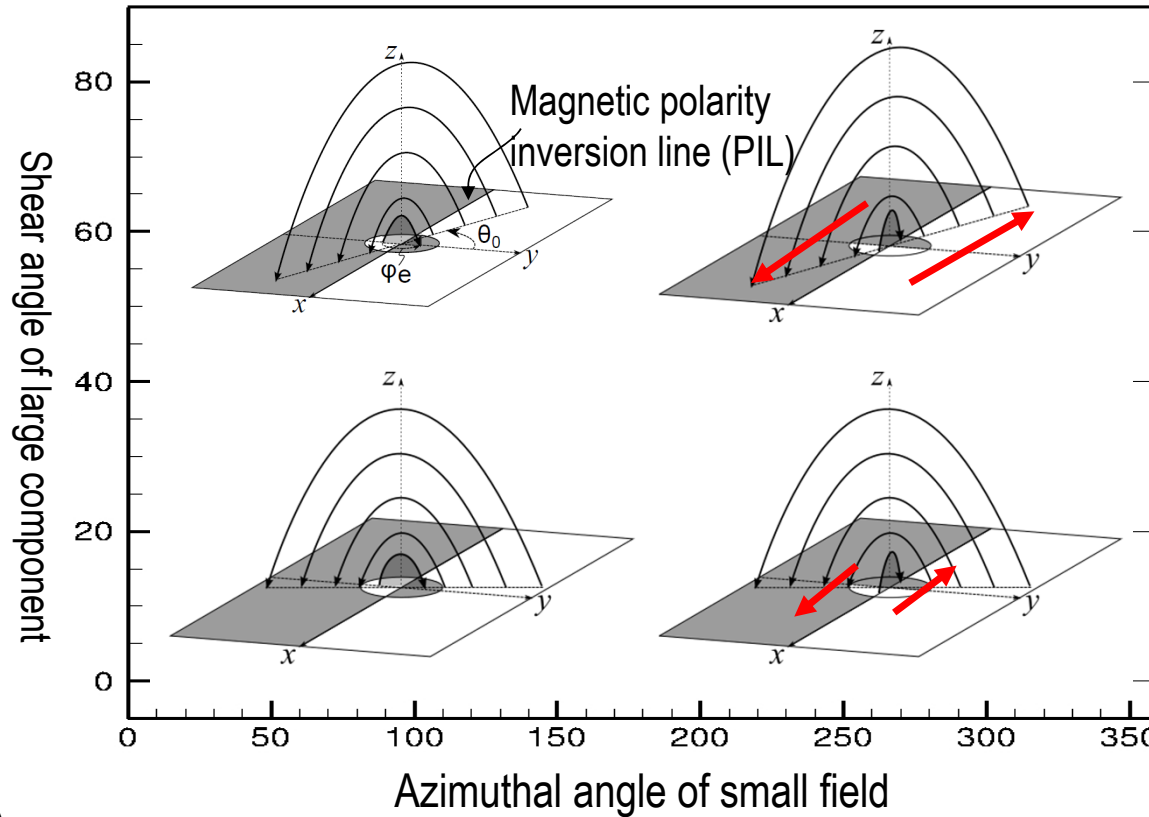
Strong shear



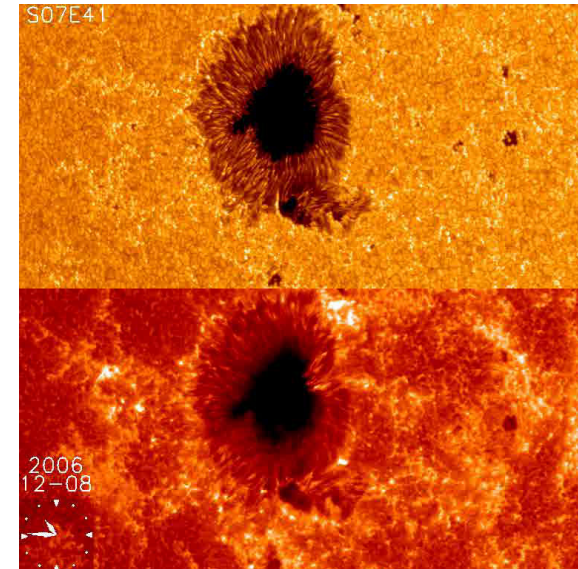
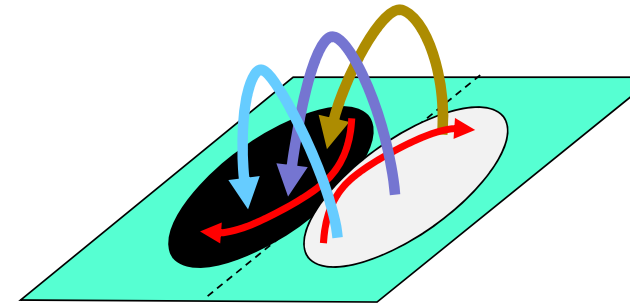
Weak shear



shear free  
(potential field)

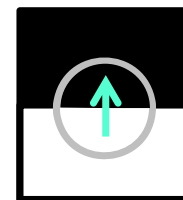
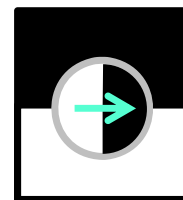
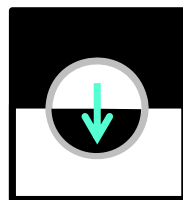
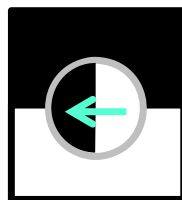
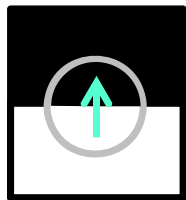


large  
(magnetic free energy)  
Magnetic Twist  
small



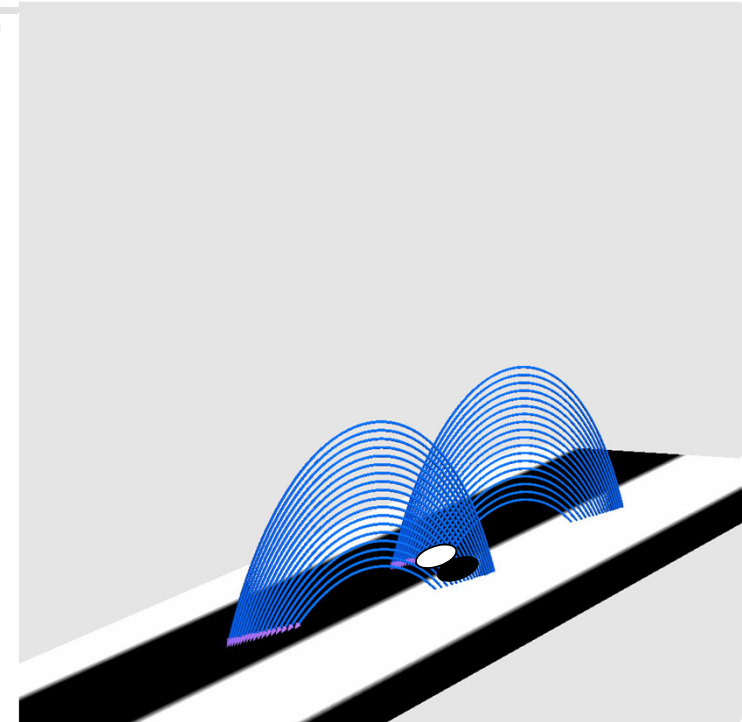
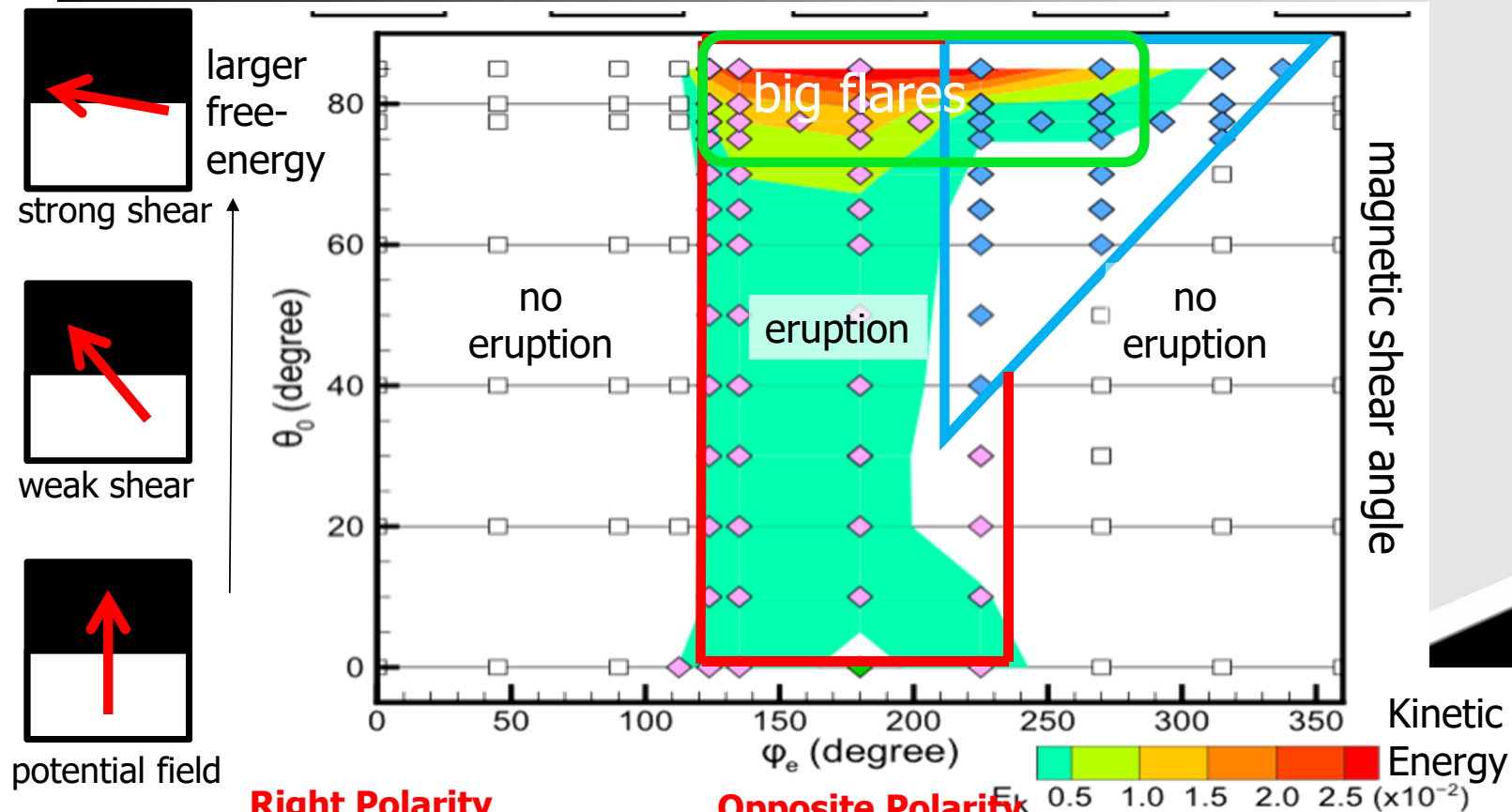
Twisting sunspot and Flare  
(Hinode observation, 2006 Dec)

Right Pol (RP) Normal Shear (NS) Opposite Pol (OP) Rev Shear (RS) Right Pol (RP)



# Results of Ensemble Simulation

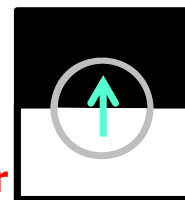
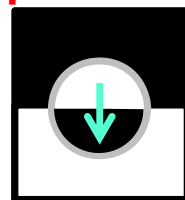
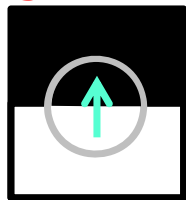
Kusano et al. 2012



MHD simulation result  
 $\Theta_0=77^\circ.5$ ,  $\phi_e=180^\circ$

**Right Polarity**

**Opposite Polarity**

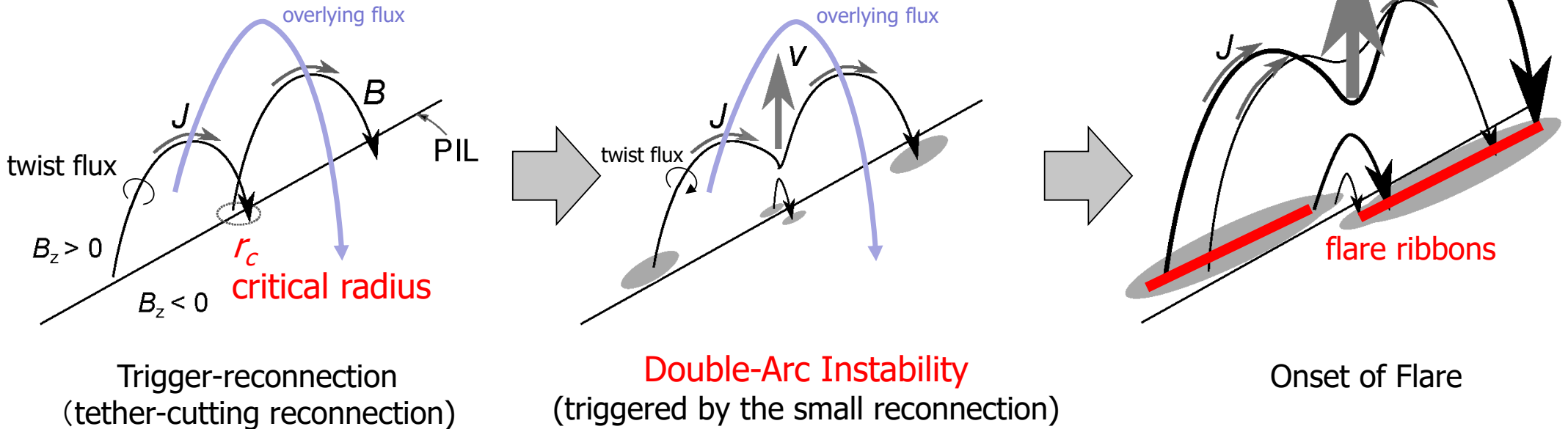


**Normal Shear**

**Reversed Shear**

# New Scenario for Solar Flare Onset

- Triggered Instability Model (Ishiguro and Kusano 2017 ApJ)



Trigger-reconnection  
(tether-cutting reconnection)  
Moore+(2001)

**Double-Arc Instability**  
(triggered by the small reconnection)

Onset of Flare

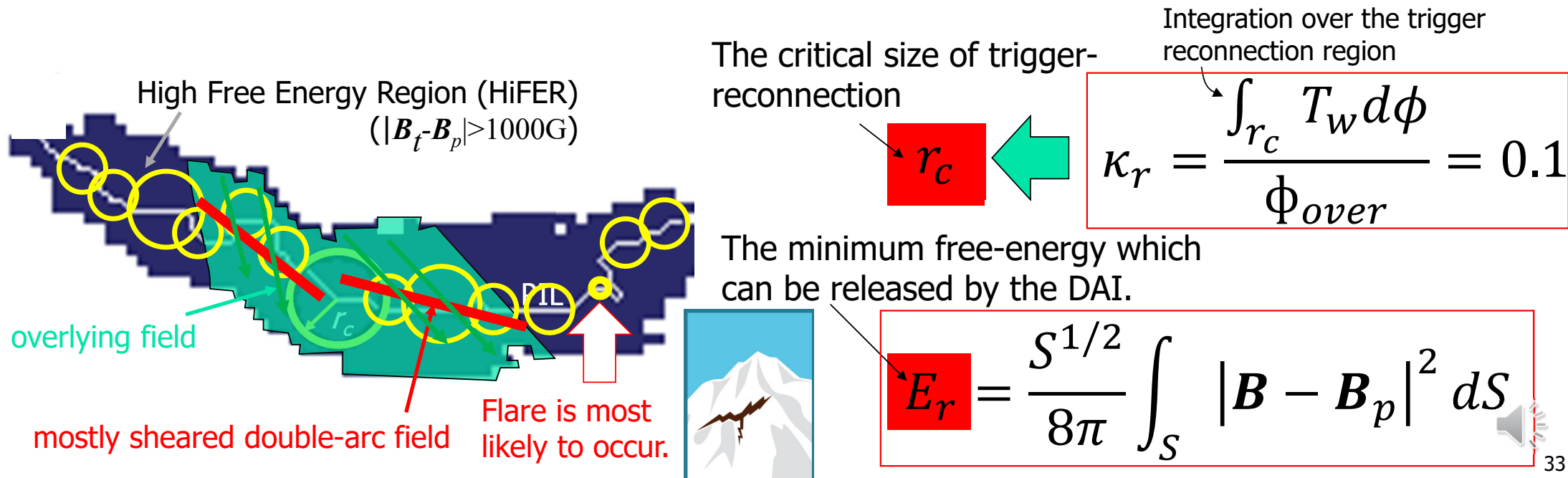
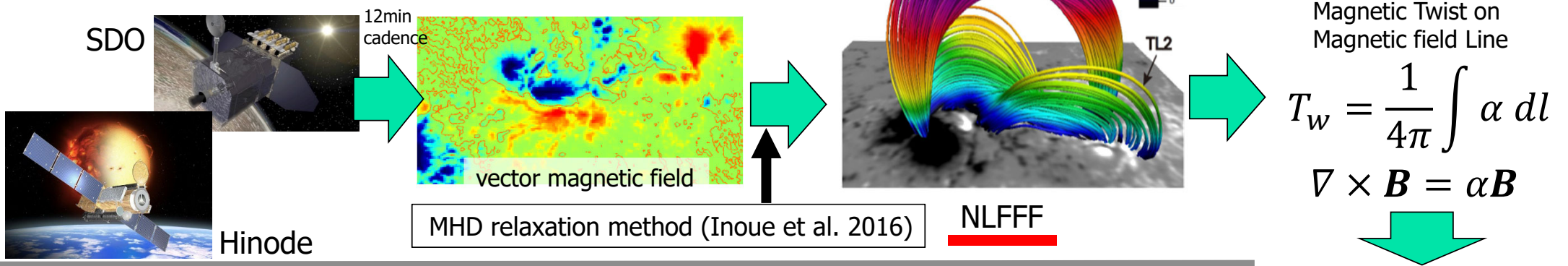
The critical condition of D-A instability

$$\kappa = \frac{\int_{r_c} T_w d\phi}{\Phi_{over}} > 0.1$$

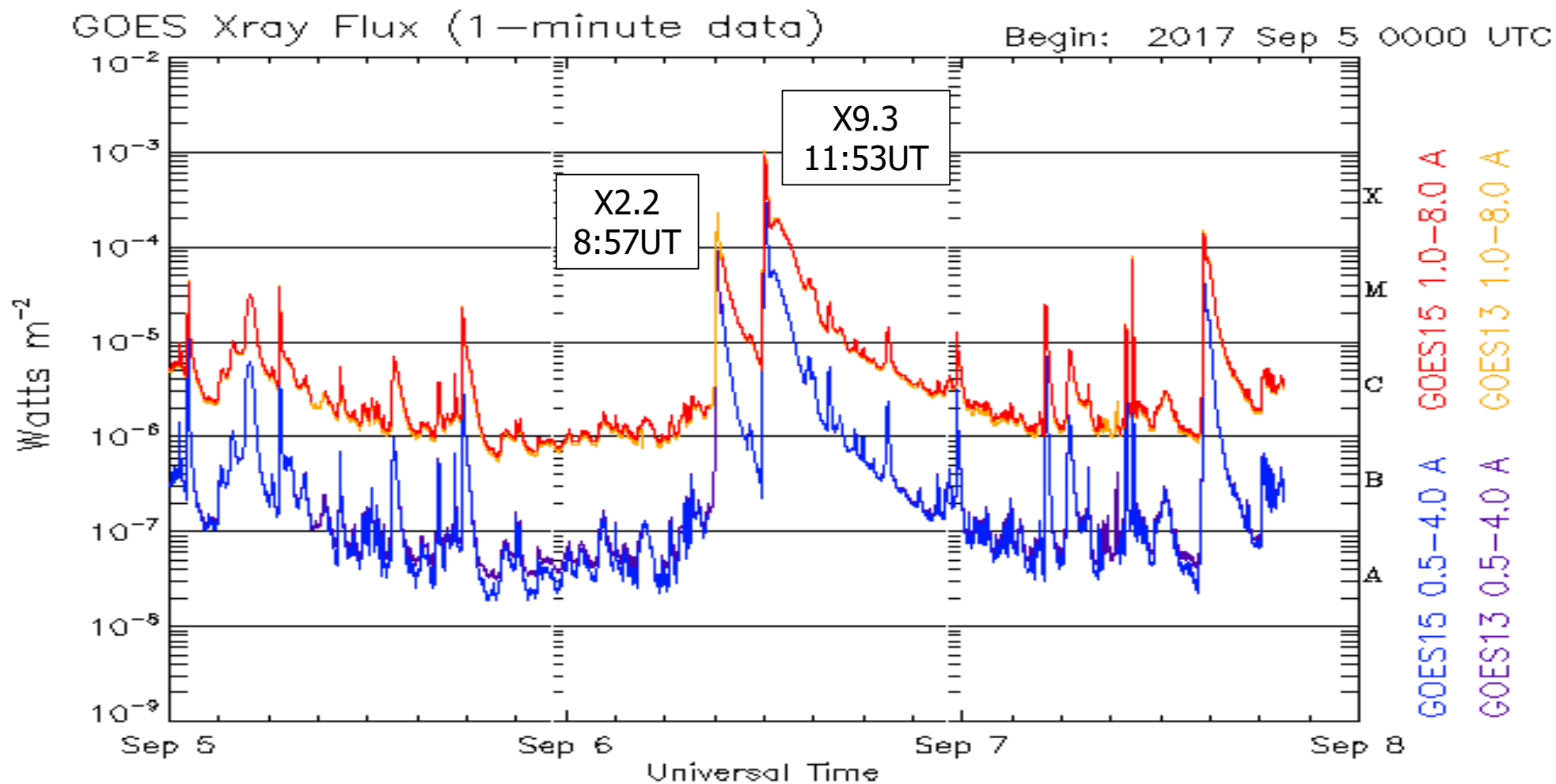
Labels in the diagram:  
 - magnetic twist (points to the integrand  $T_w$ )  
 - twist flux (points to the integration variable  $d\phi$ )  
 - overlying magnetic flux (points to the denominator  $\Phi_{over}$ )



# Prediction scheme ( $\kappa$ -scheme)



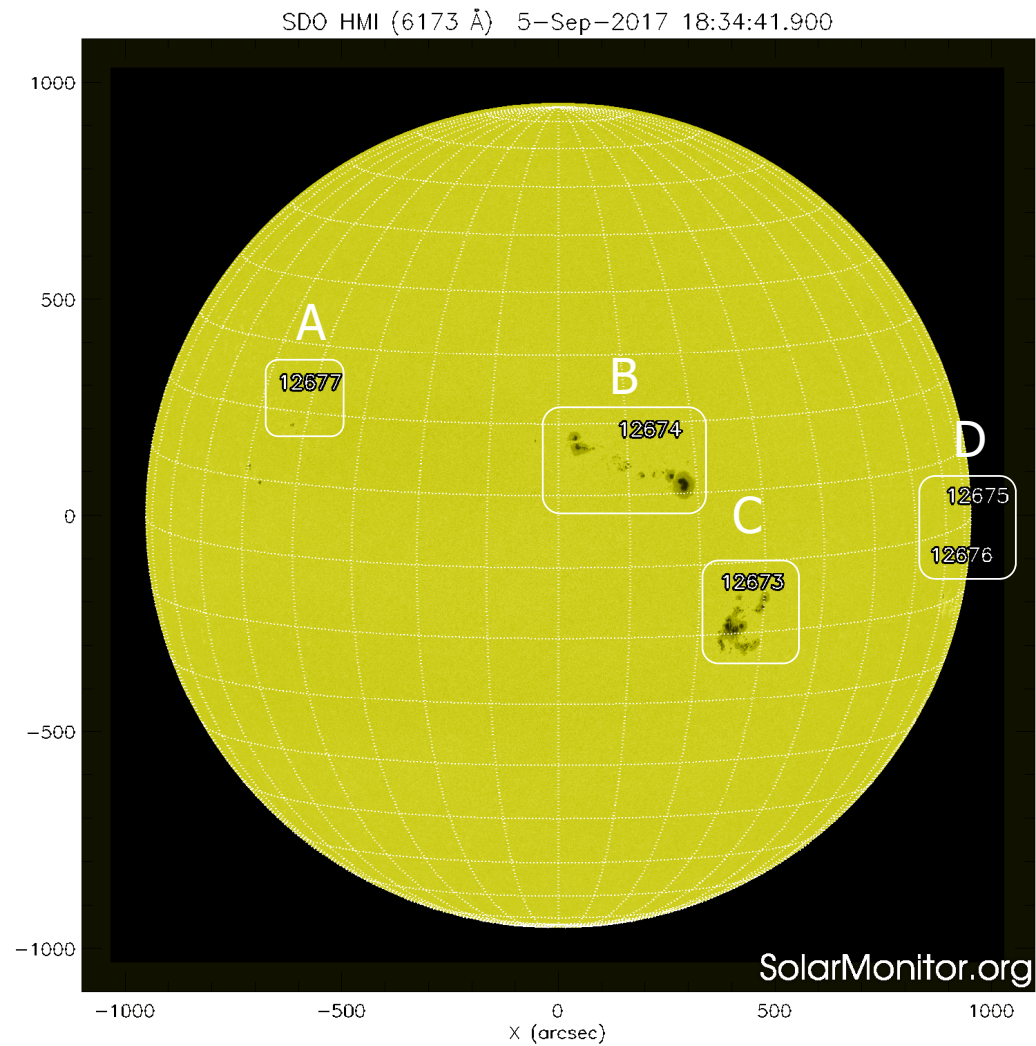
# X-class Flares on Sep. 6, 2017 (largest in cycle 24)



Updated 2017 Sep 7 19:28:12 UTC

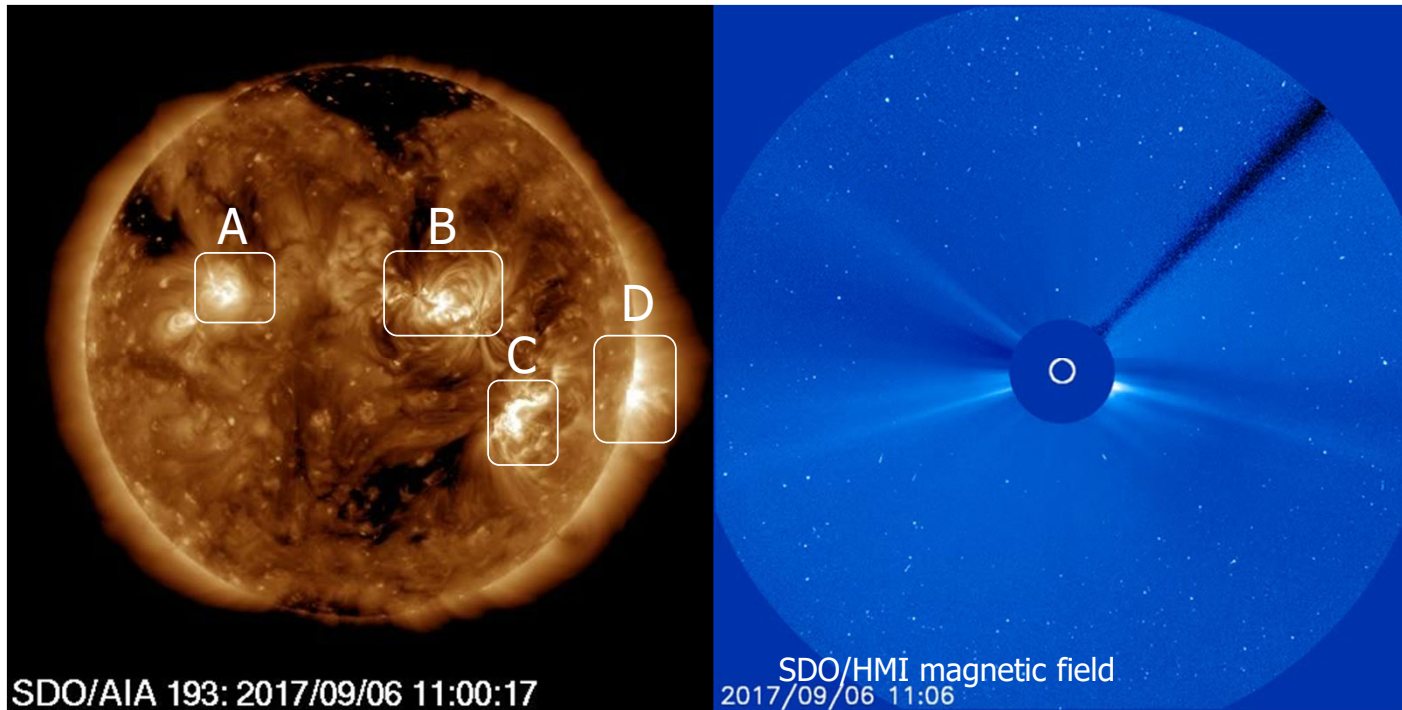
NOAA/SWPC Boulder, CO USA 34

# Which sunspot produced the giant flare?



# X9.3 flare on Sep 6, 2017

- The largest flare in the solar cycle 24 on the active region 12673.





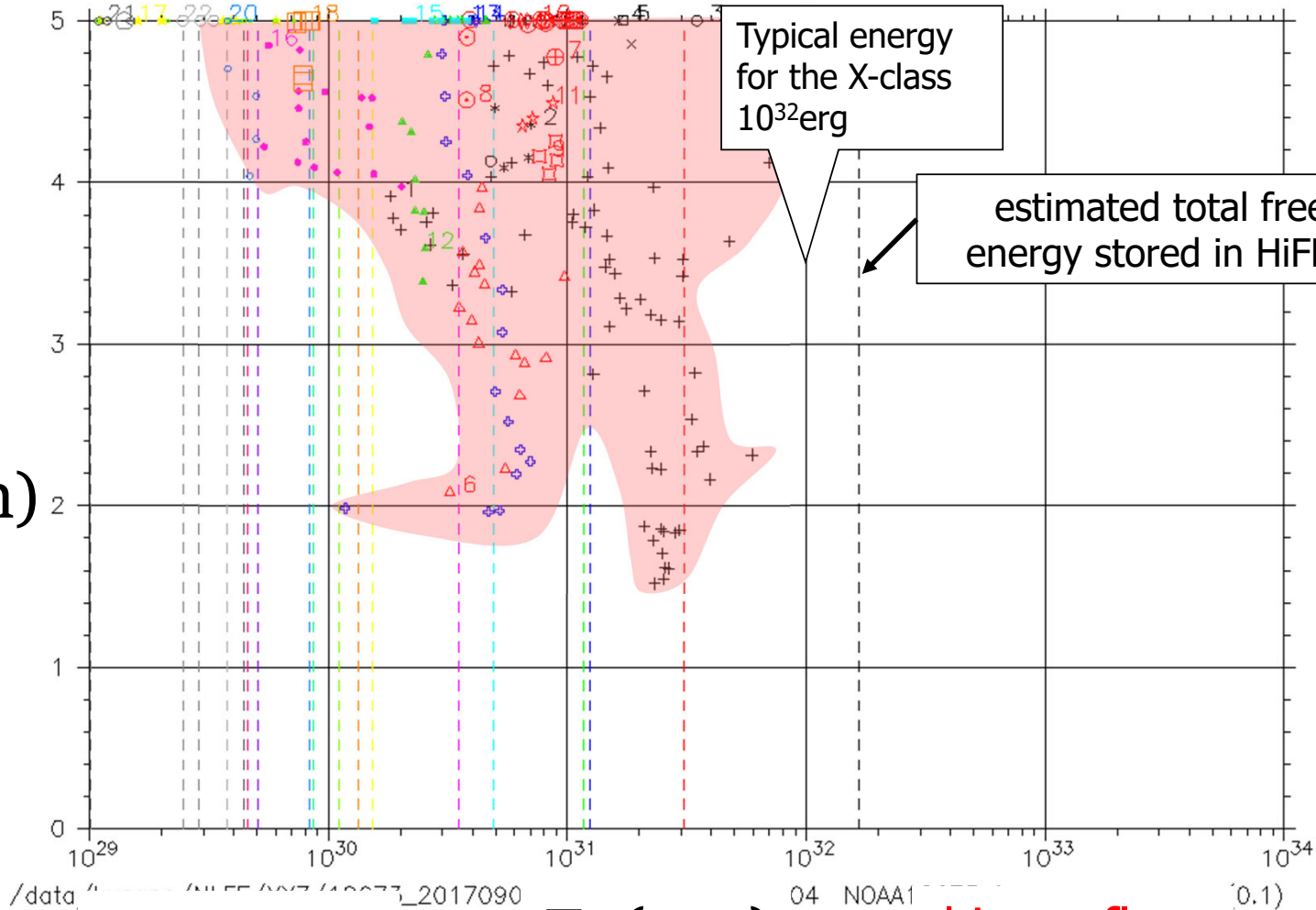
# 5:36 UT on Sep. 4 (two days prior to the flare)

more stable



less stable

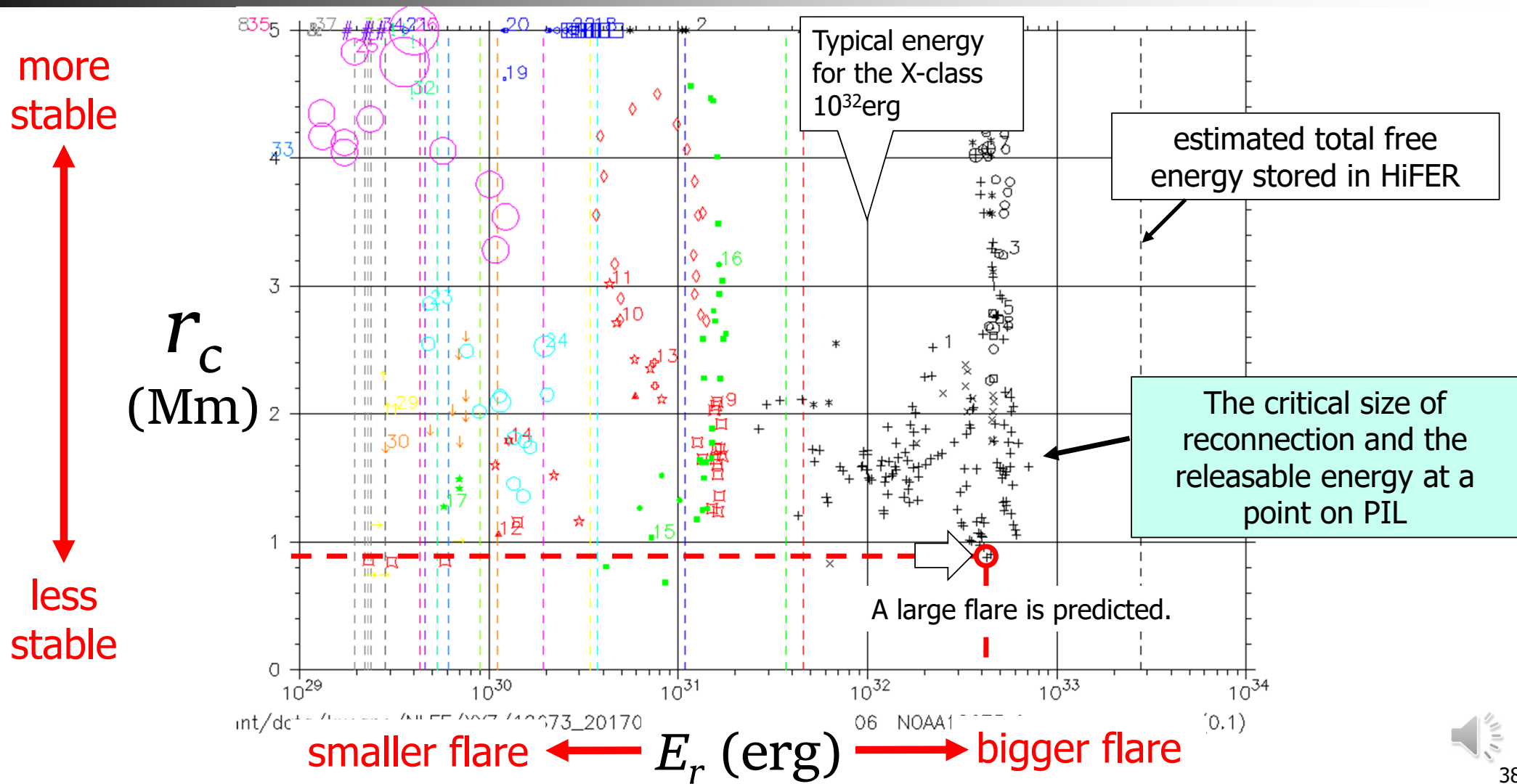
$r_c$   
(Mm)



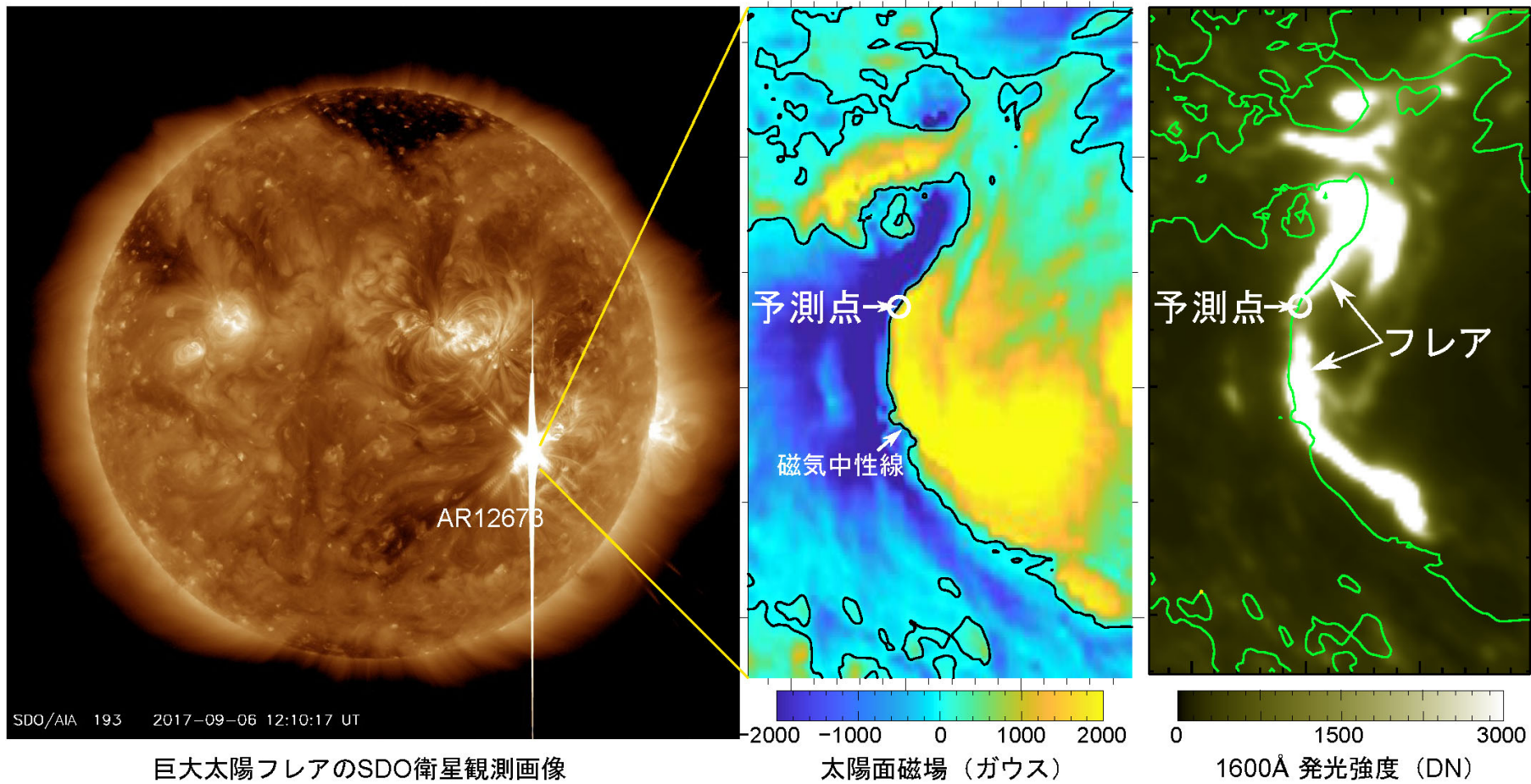
smaller flare ←  $E_r$  (erg) → bigger flare



# 11:48 UT on Sep. 6 (12 min prior to the X9.3 flare)



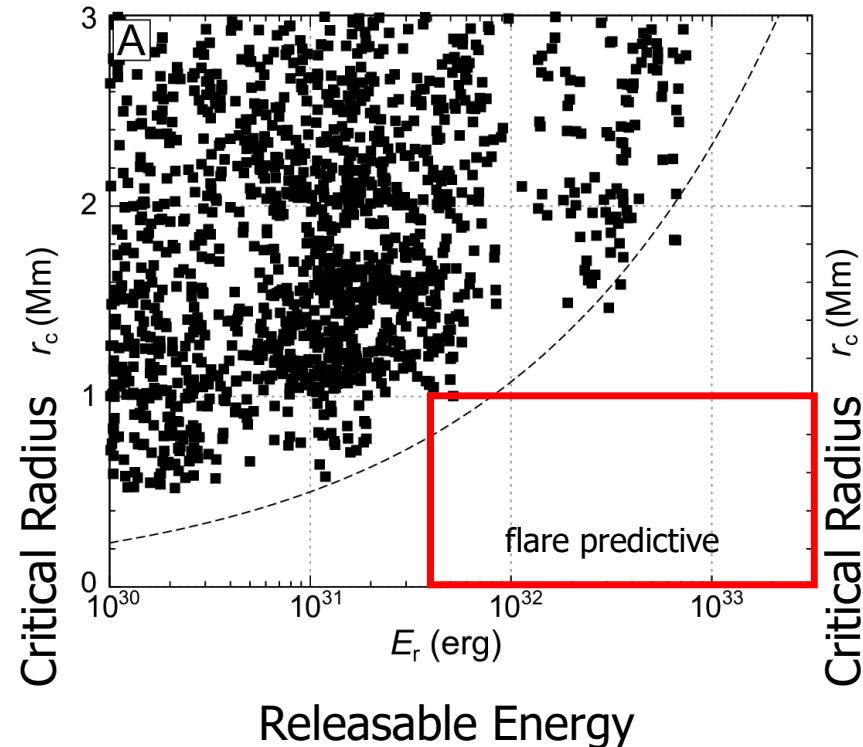
# $\kappa$ -schemeの予測結果



# $\kappa$ -schemeの統計的検証

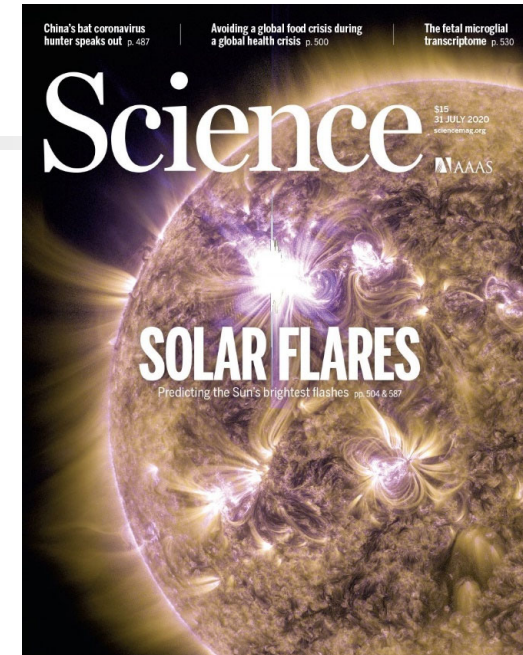
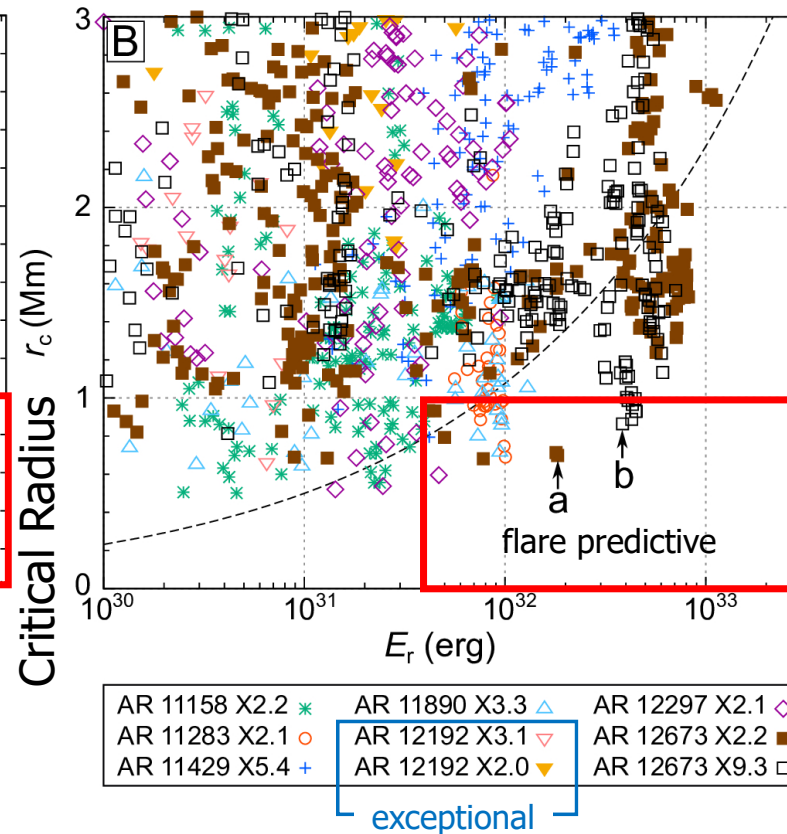
## Group 1: Non-flaring regions

- 198 largest sunspot regions in solar cycle 24
- No large flare > X2 occurred for 20 h after the observation
- Data when the region was on the central meridian.



## Group 2: Flaring regions

- The seven active regions that produced all flares of class X2 or larger within solar latitudes  $\pm 50^\circ$  during solar cycle 24.



Kusano et al. 2020, Science  
DOI: 10.1126/science.aaz2511

Six out of the seven flaring regions (the only exception being AR 12192) satisfied the condition

$$r_c < 1 \text{ Mm and } E_r > 4 \times 10^{31} \text{ erg}$$

before their flares.



# まとめ summary

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- 巨大太陽フレアは現代社会における潜在的な脅威であり、その予測は科学課題であると共に社会課題でもある。これまでの太陽フレア予測は形態学的に分類された黒点(活動領域磁場)とフレア活動の相関関係に基づく経験予測に基づいており、予測能力には限界があった。
- 近年、太陽表面磁場の精密観測に基づく新たな予測スキームが開発されつつある。我々は電磁流体力学不安定性理論に基づく新しいフレア予測スキーム( $\kappa$ -scheme)を世界で初めて開発した。 $\kappa$ -schemeは少数の例外を除いて、発生直前の巨大フレア(X2クラス以上)を発生位置まで正確に予測できる。
- 名古屋大学宇宙地球環境研究所(ISEE)では、太陽フレアのみならず、CMEの発生と伝搬の予測、磁気嵐の予測、未来の太陽黒点周期活動の予測など様々な太陽活動と宇宙天気擾乱の予測研究を進めています。