

MHD/プラズマ不安定性を軸とした 連携研究の可能性について

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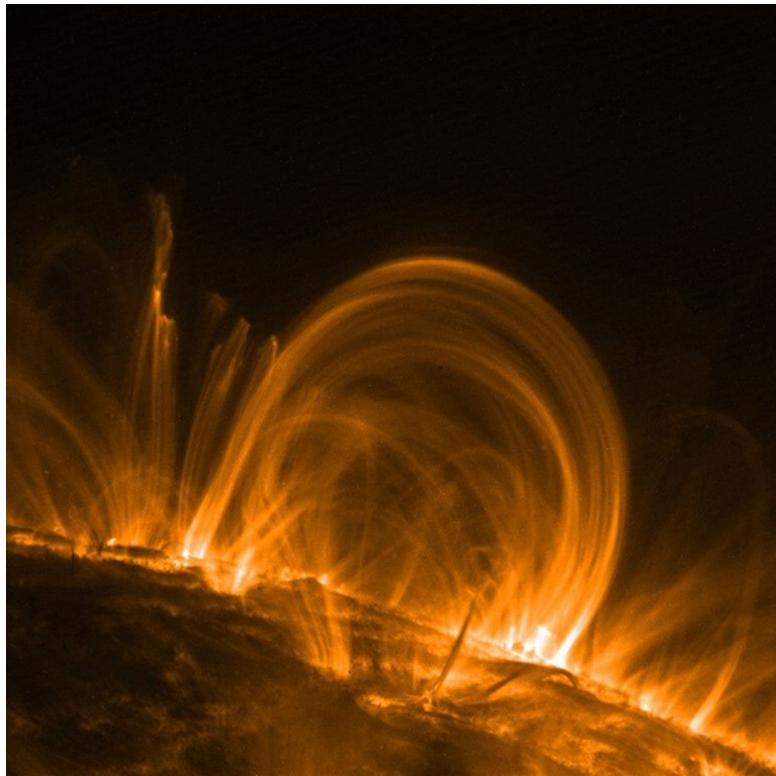
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Outlook

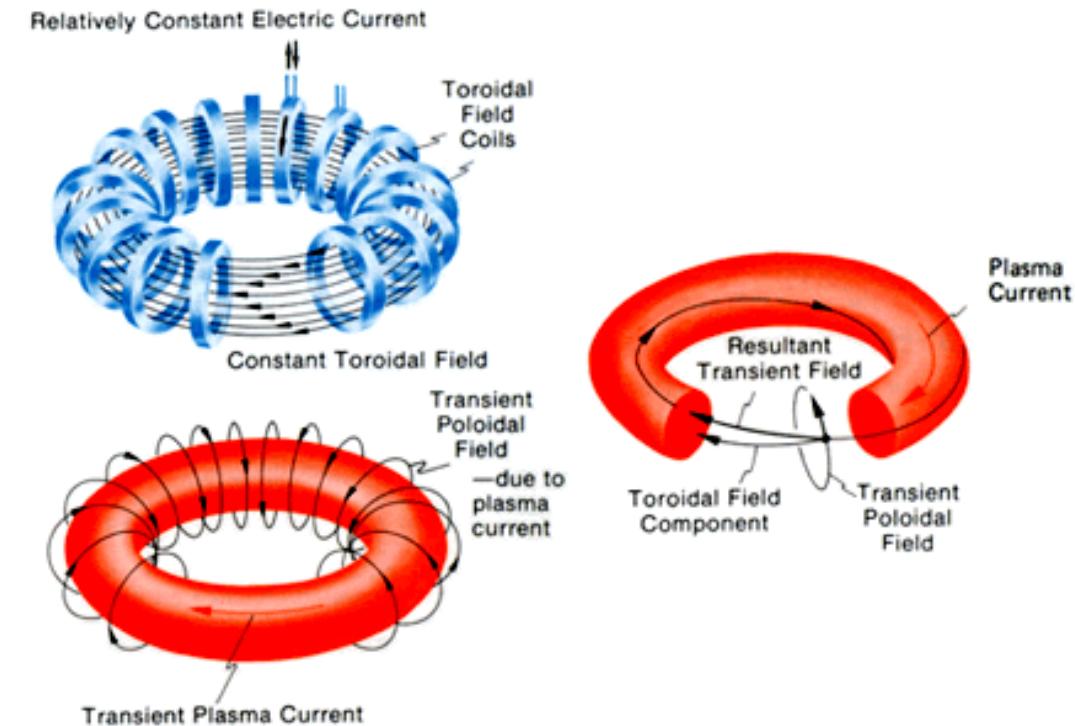
- 太陽コロナと核融合プラズマの共通性
 - low beta plasmas, MHD instabilities、粒子加速、加熱機構
 - 太陽面爆発(フレア)とトカマク・ディスラプション
 - 粒子加速、逃走電子加速
- 予測研究の重要性
 - 太陽フレアの物理予測
 - トカマク・ディスラプションの制御
- 共通した学術研究の可能性
 - データ駆動モデル、機械学習モデルの研究開発
 - MHDアルゴリズム開発(マルチスケール、粒子流体連結)
- まとめ

太陽コロナと核融合(トカマク)プラズマの類似性 (1)

太陽コロナ

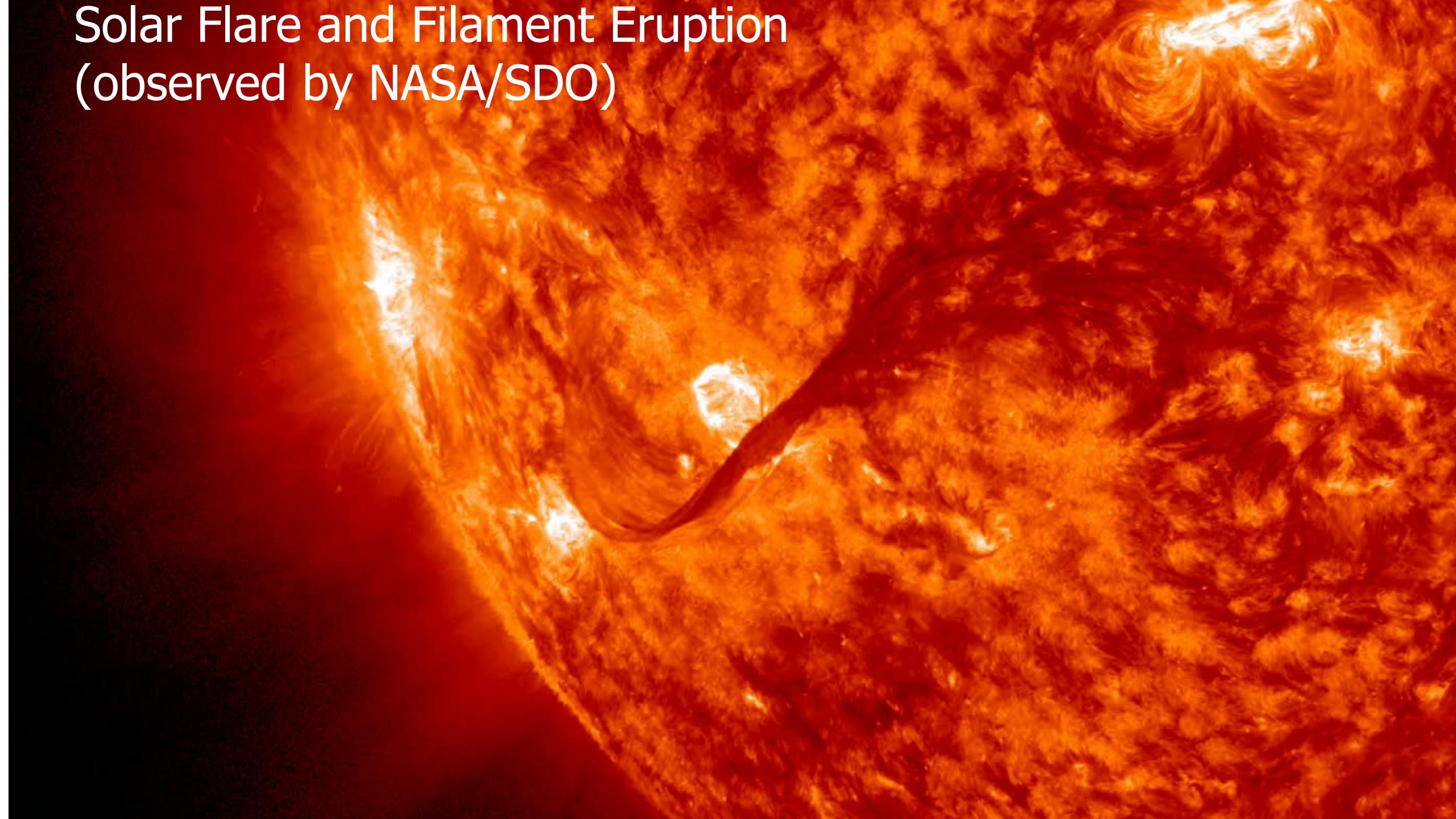


核融合(トカマク)プラズマ



低ベータ・プラズマ、ラーマー半径(電子、イオン) << システム長
磁気エネルギー優勢の高温プラズマ

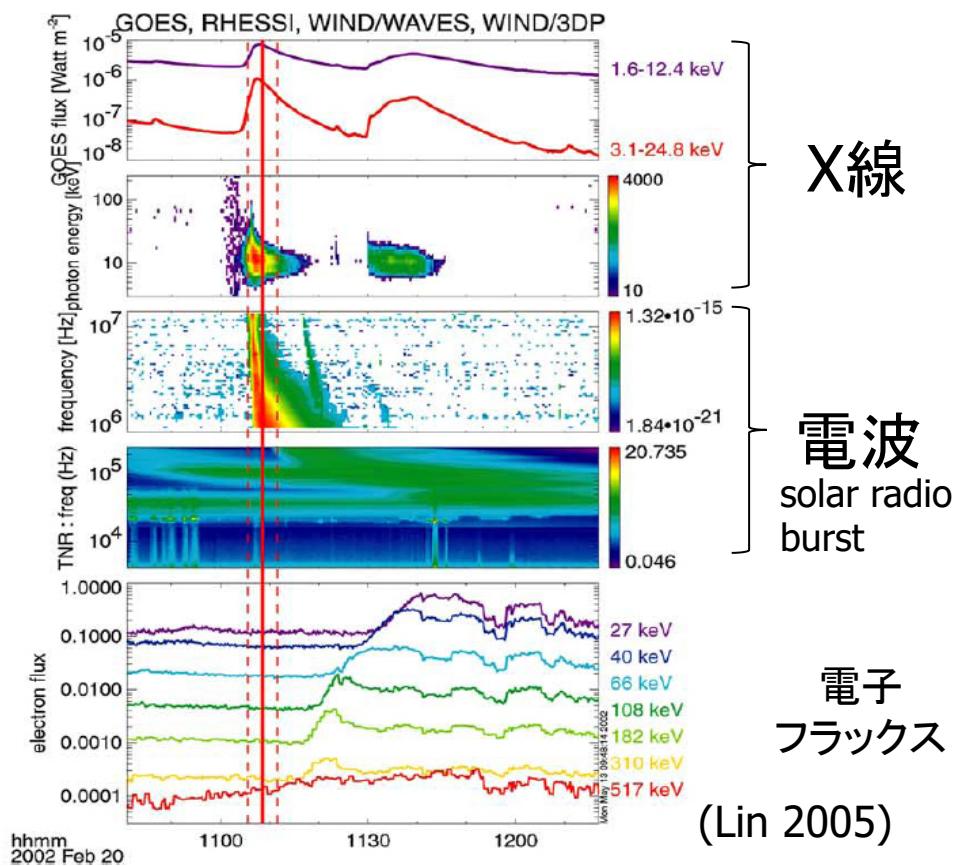
Solar Flare and Filament Eruption (observed by NASA/SDO)



太陽コロナと核融合(トカマク)プラズマの類似性 (2)

突発的エネルギー解放ダイナミクスの発生

太陽フレア



X線

電波
solar radio
burst

電子
フラックス

トカマク・ディスラプション

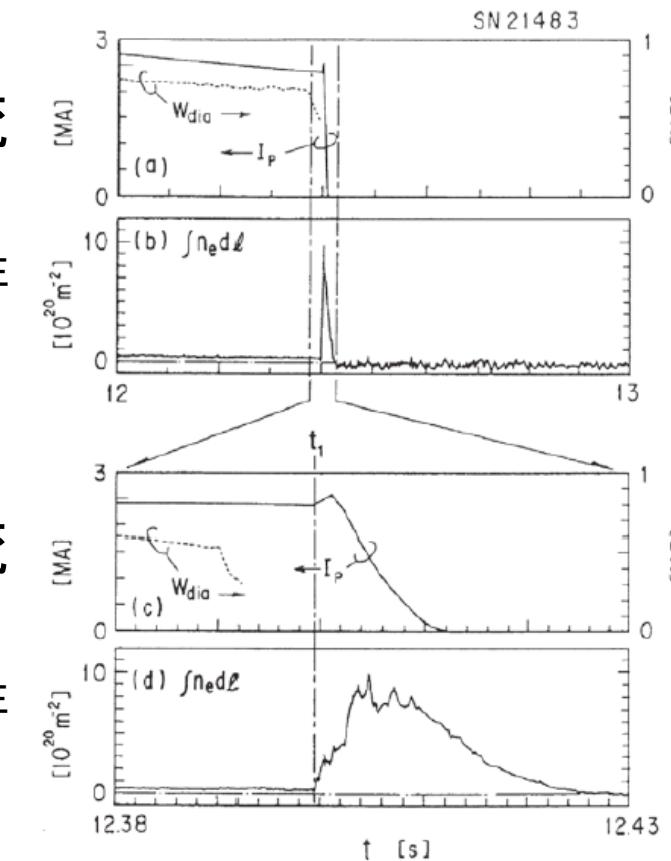
電流

電子柱
密度

電流

電子柱
密度

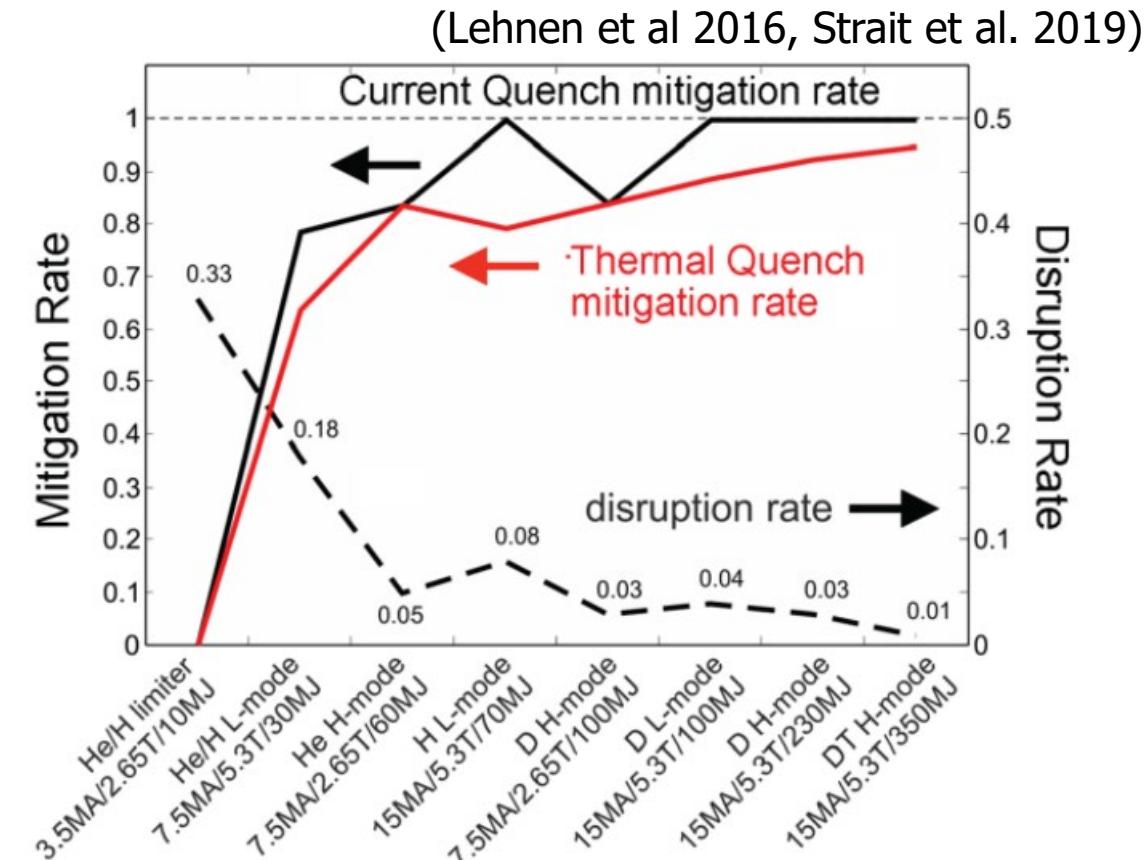
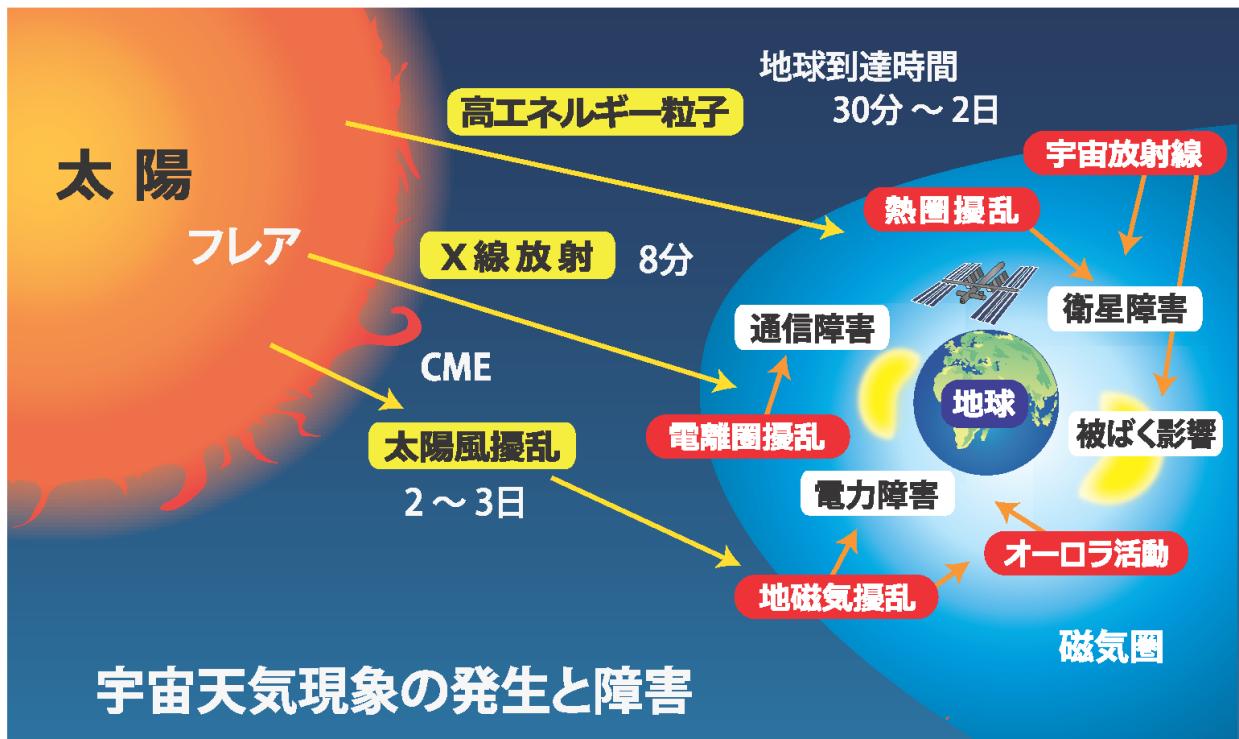
熱エネル
ギー



MHD不安定性、磁場擾乱、磁気リコネクション

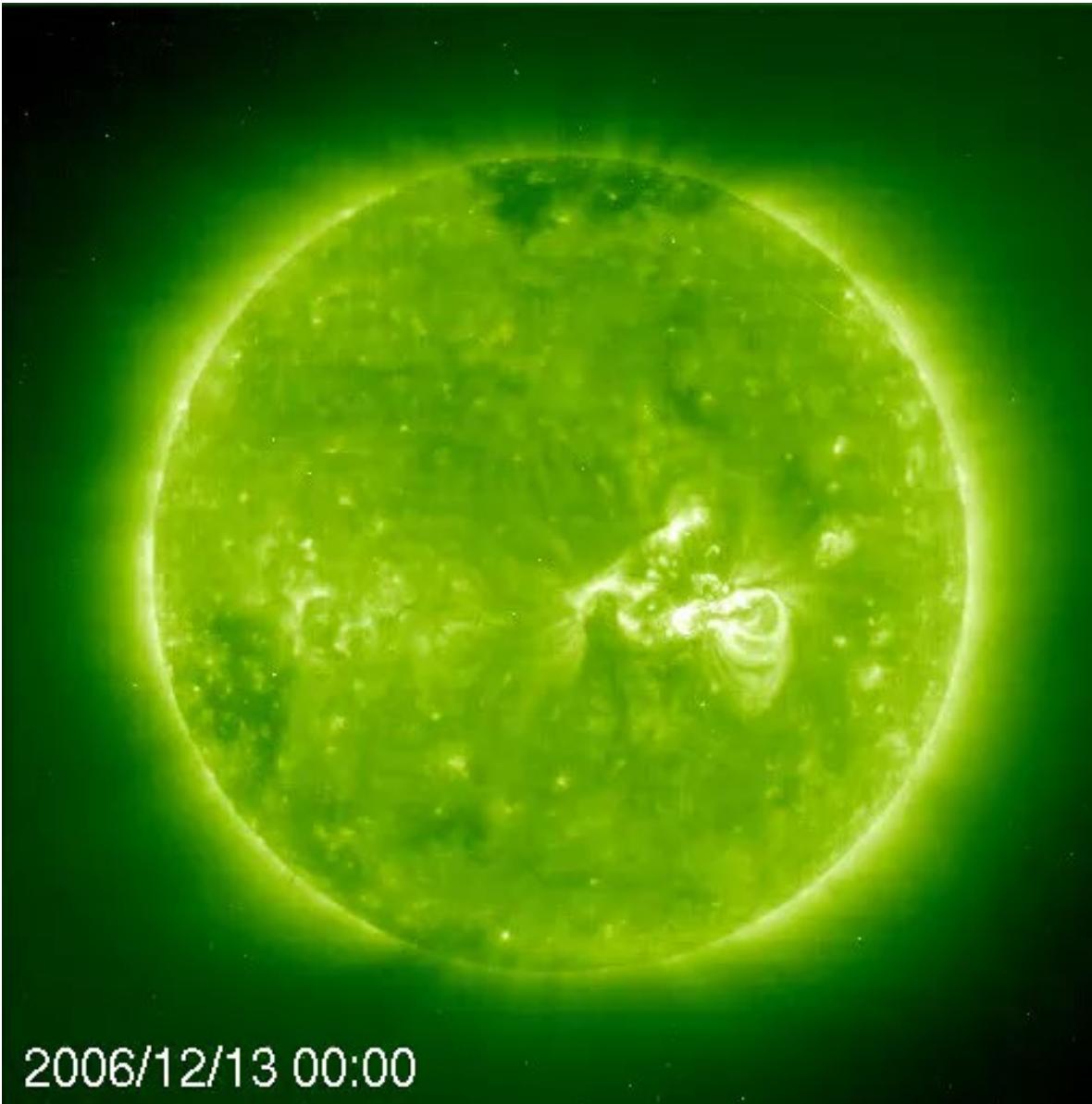
太陽フレアと核融合(トカマク)プラズマの類似性 (3)

予測研究の重要性



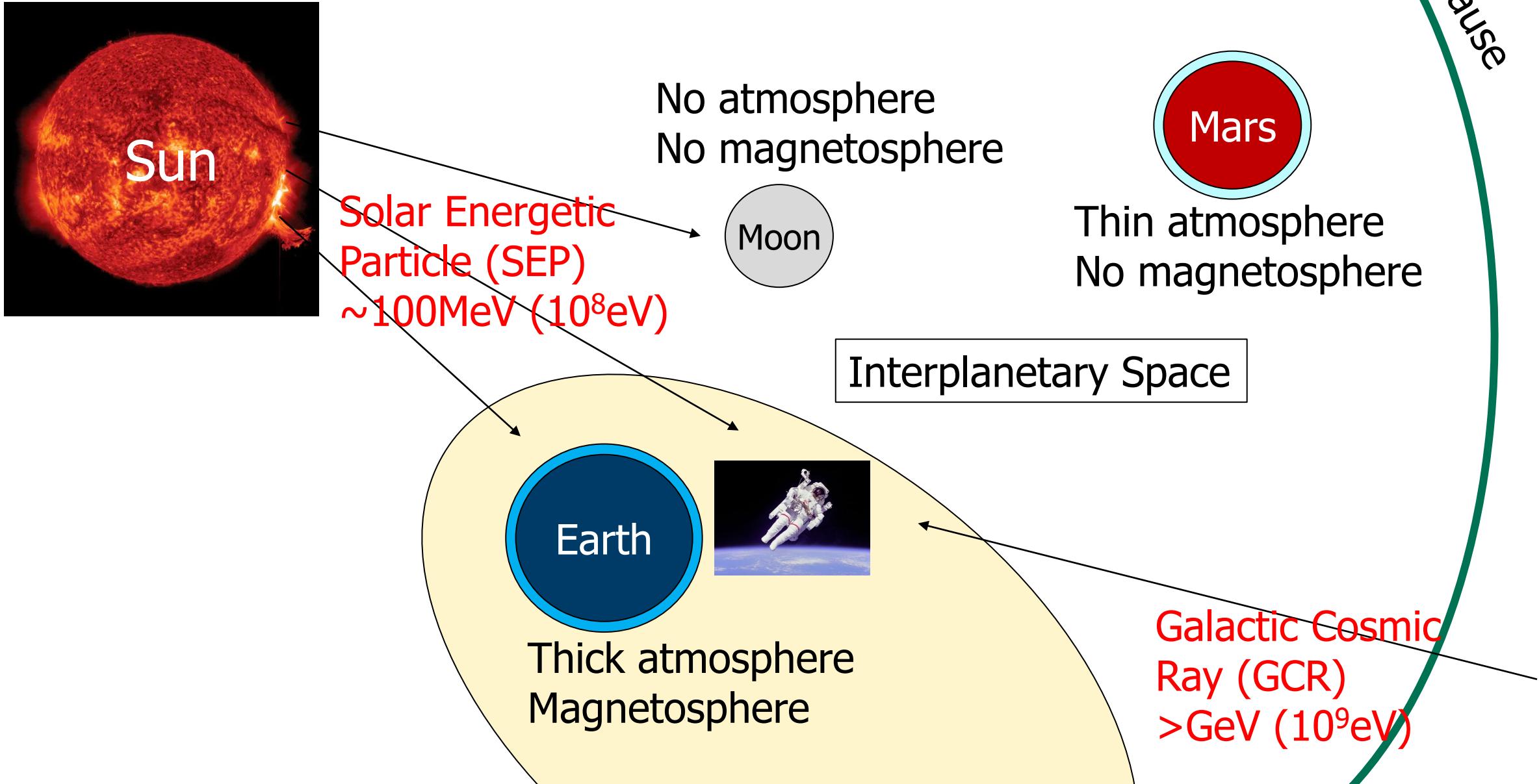
ITERのオペレーションモードとディスラプションの許容率及び要求される緩和率

Solar Particle Events (SPE)



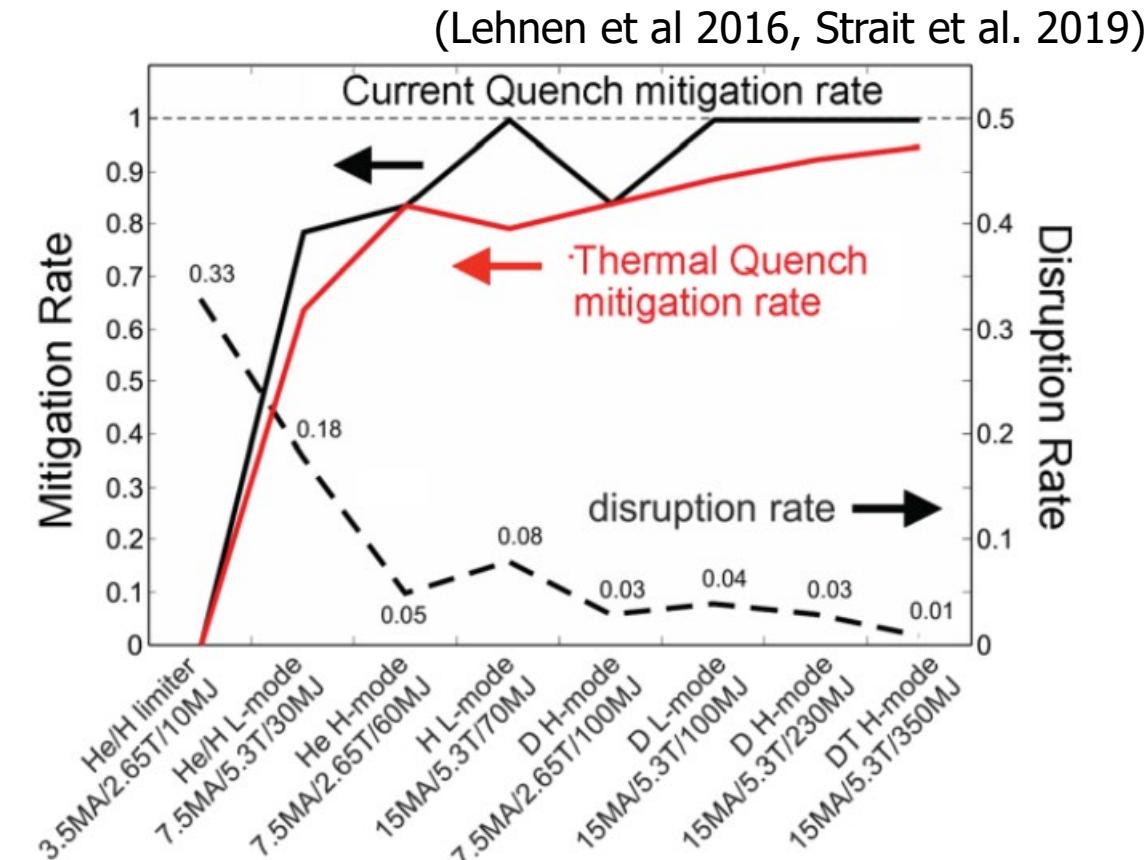
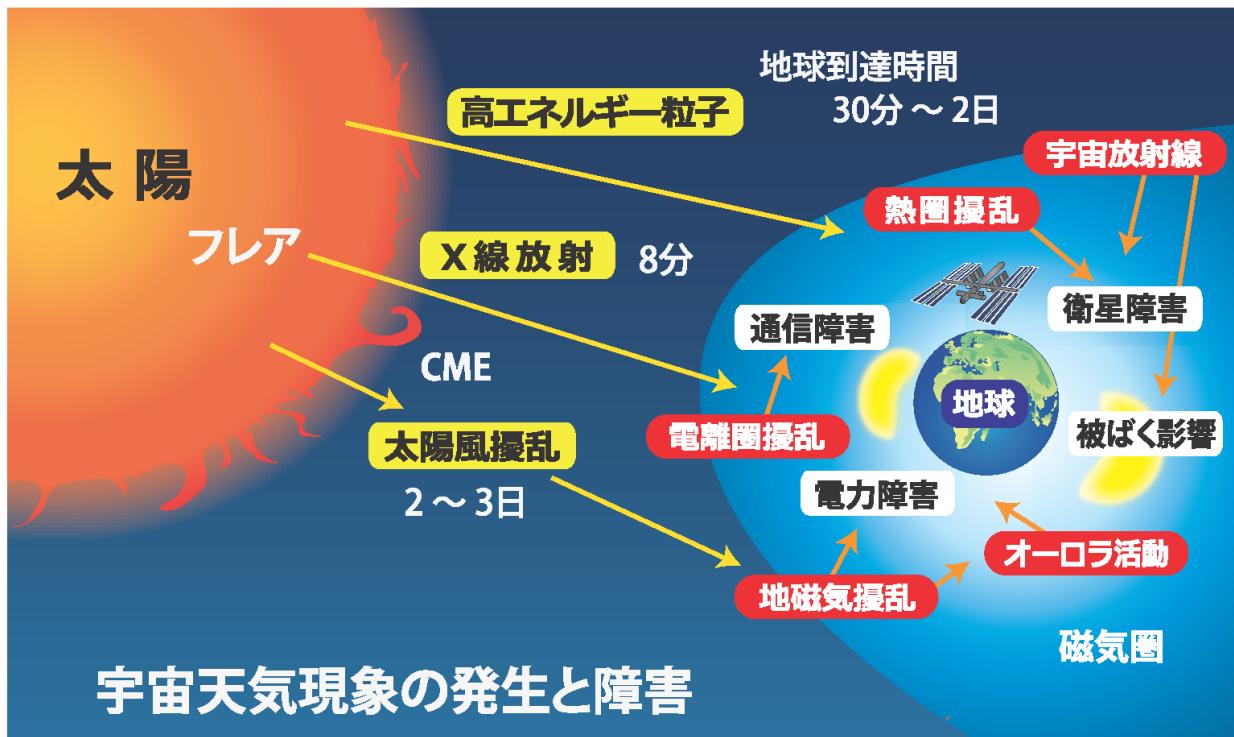
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Space Radiation Health Risk



太陽フレアと核融合(トカマク)プラズマの類似性 (3)

予測研究の重要性



ITERのオペレーションモードとディスラプションの許容率及び要求される緩和率

予測研究の方法(ex., 太陽フレア)

- 経験予測
 - 過去の観測データより黒点や活動領域(ex., 磁場)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。
 - 機械学習を用いた有効な予測パラメタと探索
- 物理予測
 - 適切な物理理論(MHD不安定性理論)に基づいて導かれた予測パラメタに基づく予測
- データ駆動モデル、データ同化モデル
 - 観測・測定データを使った物理数値モデルに基づく予測

機械学習による予測パラメタの探査 (Bobra & Couvidat, 2015)

THE ASTROPHYSICAL JOURNAL, 798:135 (11pp), 2015 January 10

BOBRA & COUVIDAT

Support Vector Machine
(Cortes & Vapnik 1995)による
フレア領域と非フレア領域の磁
場パラメタ分離

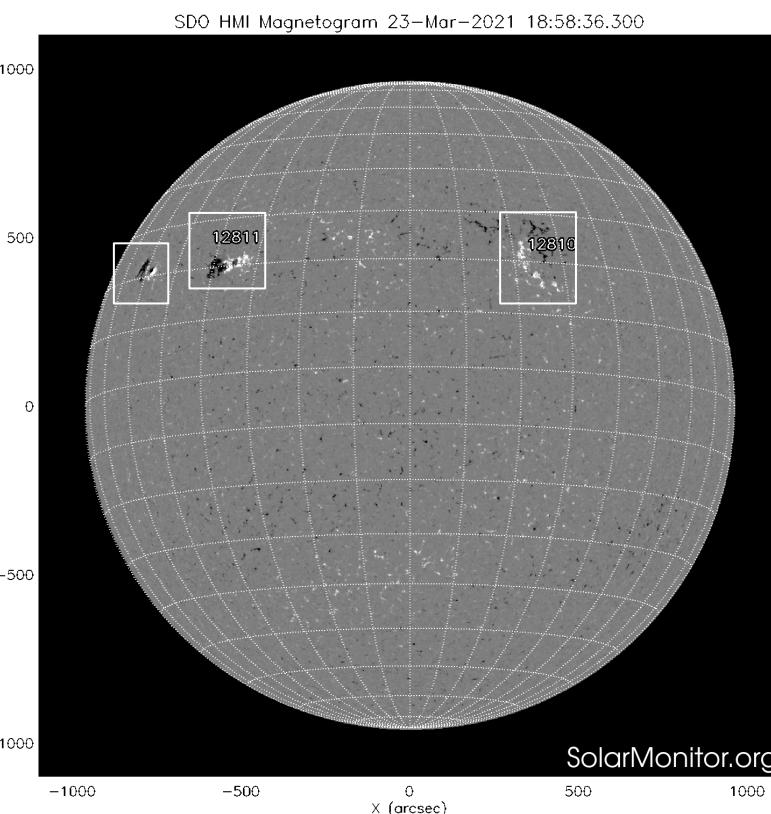


Table 1
SHARP Active Region Parameter Formulae

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
SAVNCP	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	$\Phi = \sum B_{LoS} dA$ 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
SHRGIT45	Fraction of Area with shear $> 45^\circ$	Area with shear $> 45^\circ$ / 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)	$H_c \propto \frac{1}{N} \sum B_z \cdot J_z$	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, α	$\alpha_{\text{total}} \propto \frac{\sum J_z \cdot B_z}{\sum B_z^2}$	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

機械学習によるディスラプションの予測

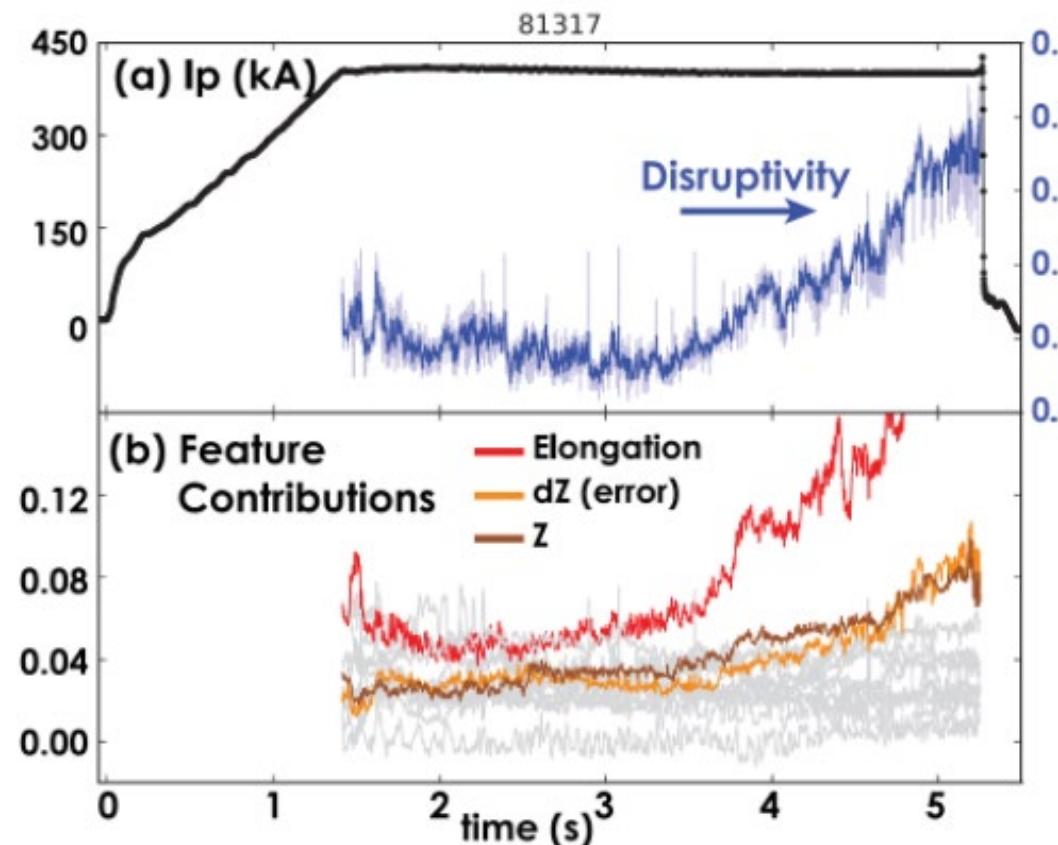


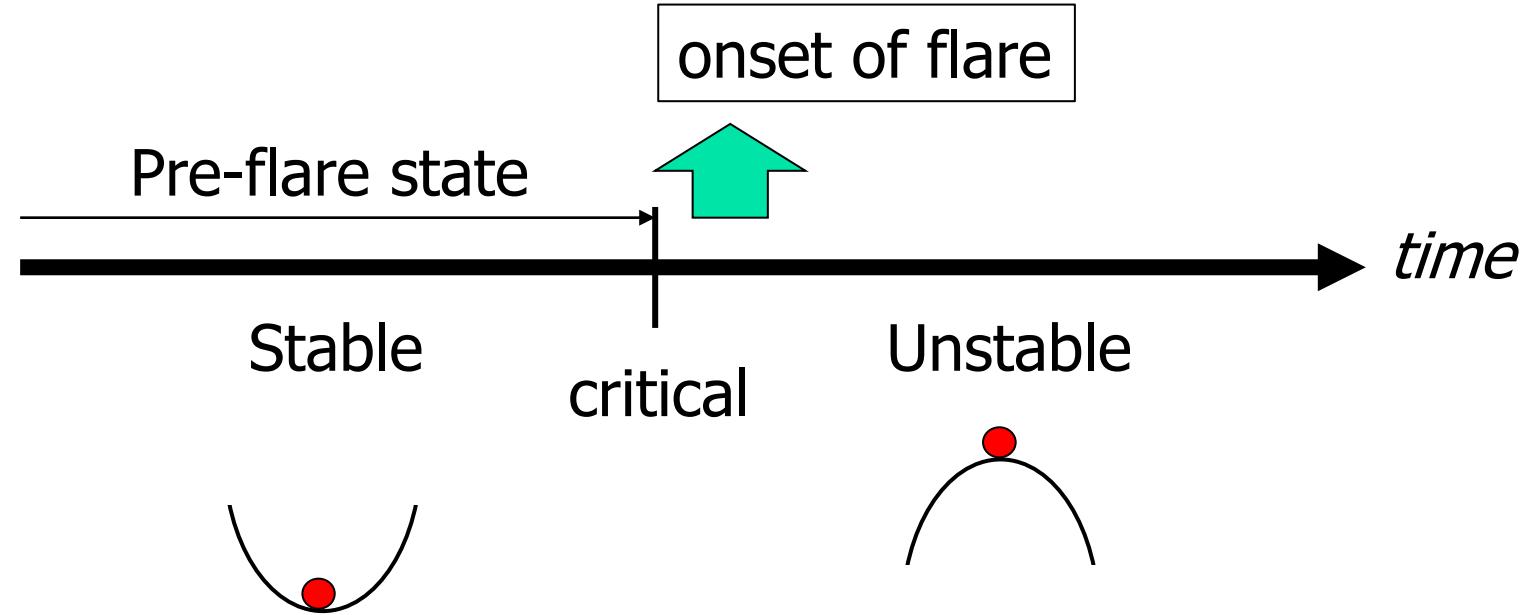
Figure 8. (a) Disruptivity signal (blue curve) from a Random Forest machine-learning algorithm rises as an EAST discharge approaches a vertical displacement event (VDE) instability. (b) Relative importance of the 13 input signals. Rising traces indicate high importance for discharge elongation, vertical position, and vertical control error. Reproduced with permission from [59].

(Granetz et al. 2019)

予測研究の方法(ex., 太陽フレア)

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 - 観測・測定データを使った物理数値モデルに基づく予測

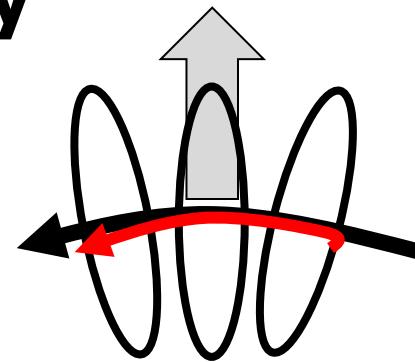
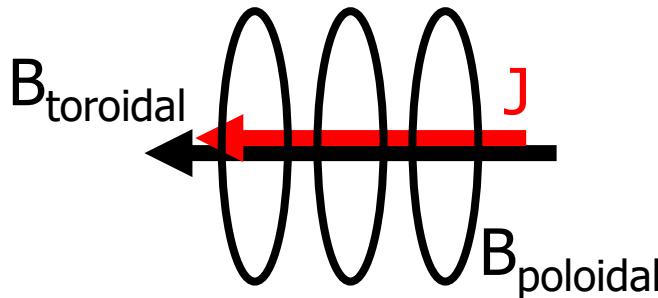
太陽フレアの物理予測(不安定性仮説)



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

Kink and Torus Instabilities

kink mode instability



Twist number

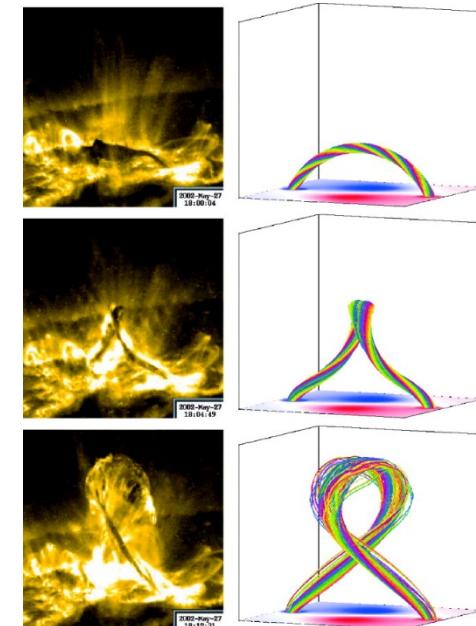
$$T_w = \frac{d\Phi_{\text{poloidal}}}{d\Phi_{\text{toroidal}}} > o(1)$$

Kruskal+1954

Hood & Priest 1979, 1981

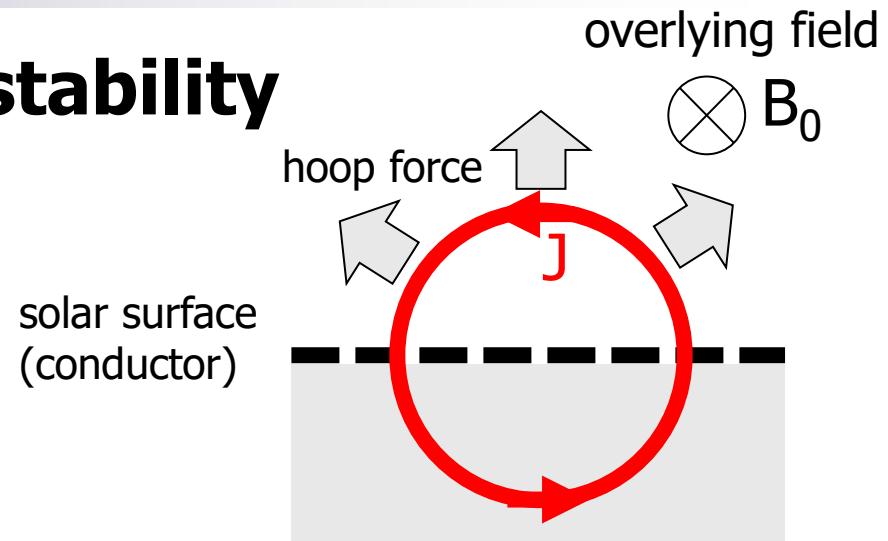
Török & Kliem 2005

Török, Kliem & Titov 2004



Török & Kliem 2005

torus instability



Decay index

$$n = -\frac{R}{B_0} \frac{dB_o}{dR} > o(1)$$

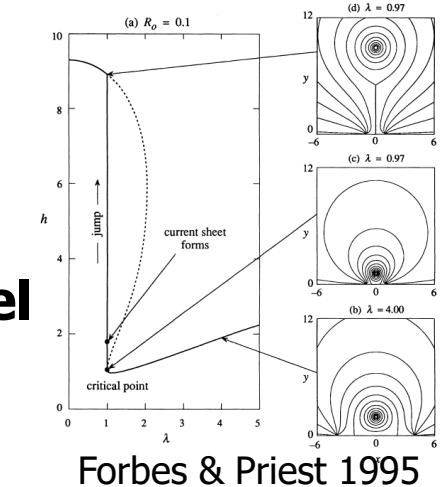
Shafranov 1966

Kliem & Török 2006

Demoulin & Aulanier 2010

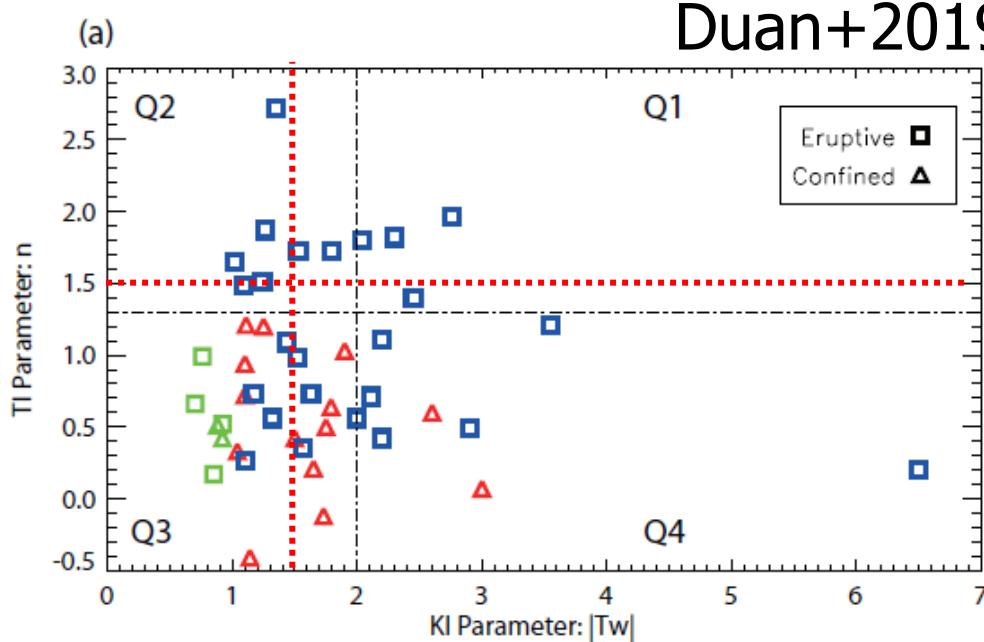
Loss of Equilibrium Model

Forbes & Priest 1995



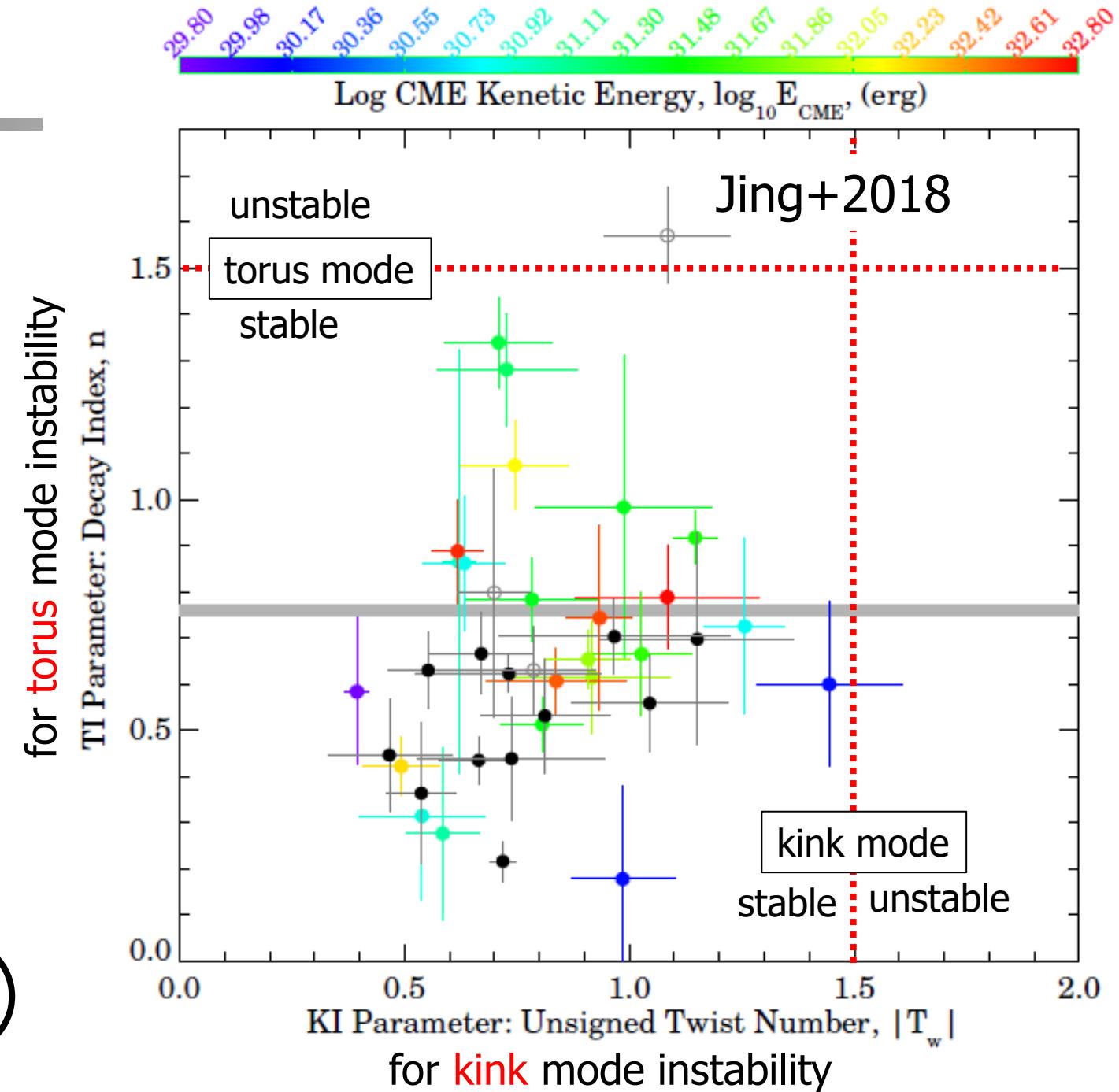
Forbes & Priest 1995

Stability Analysis



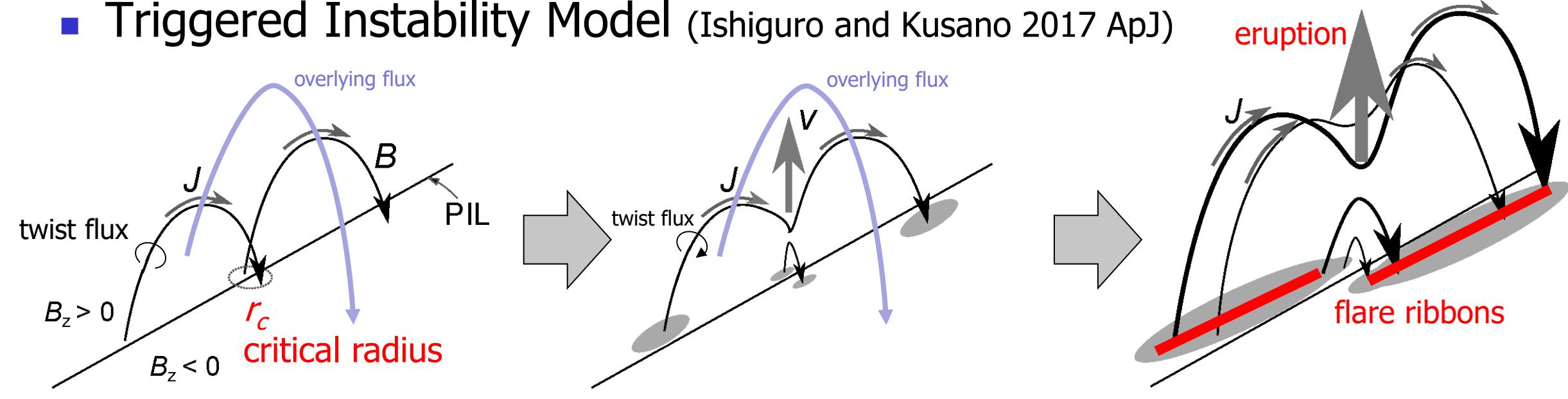
There is no clear correlation between the critical condition of kink and torus instabilities and the onset of large flares.

Something was missed. ☹



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)

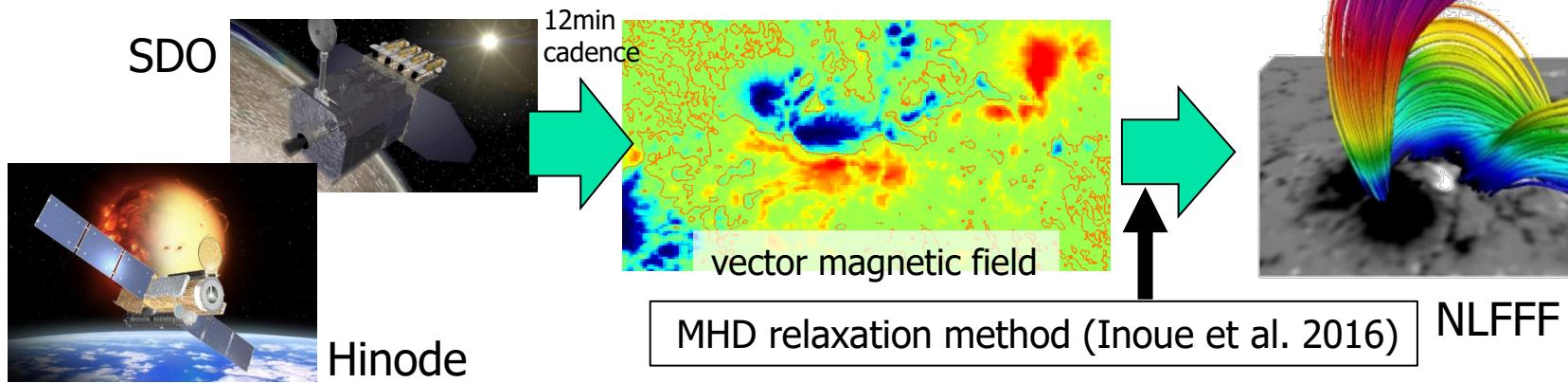
Onset of Flare

The critical condition
of D-A instability

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

magnetic twist
twist flux
overlying magnetic flux

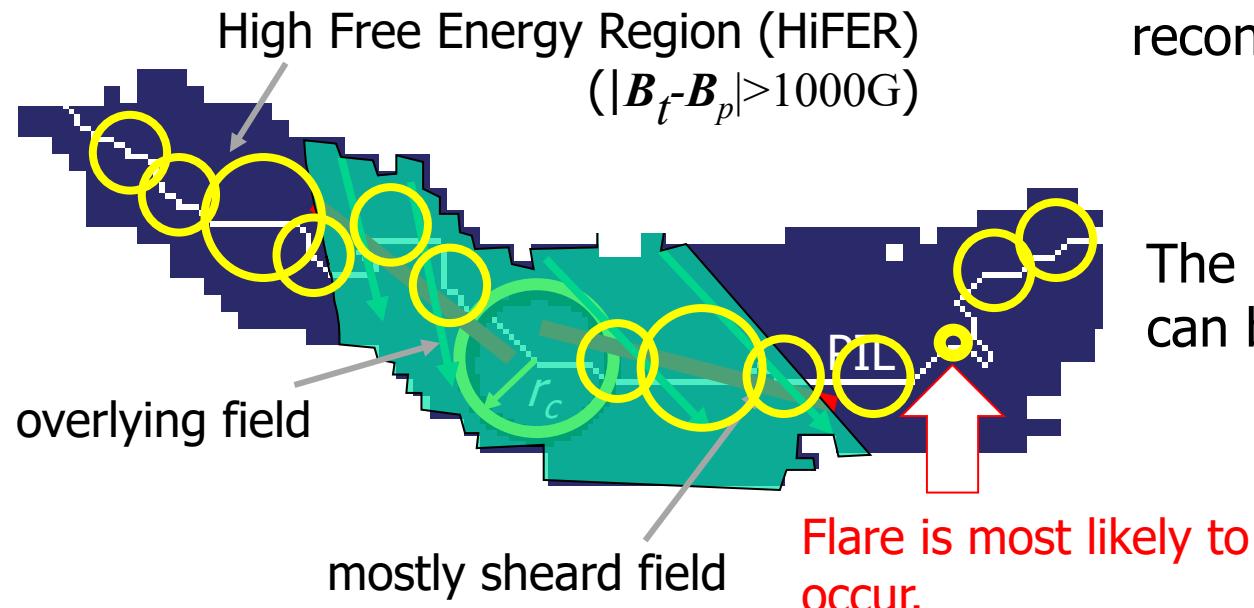
Flare Prediction (κ -scheme)



Magnetic Twist on Magnetic field Line at Any Foot-points

$$T_w = \frac{1}{4\pi} \int \alpha dl$$

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



The critical size of trigger-reconnection

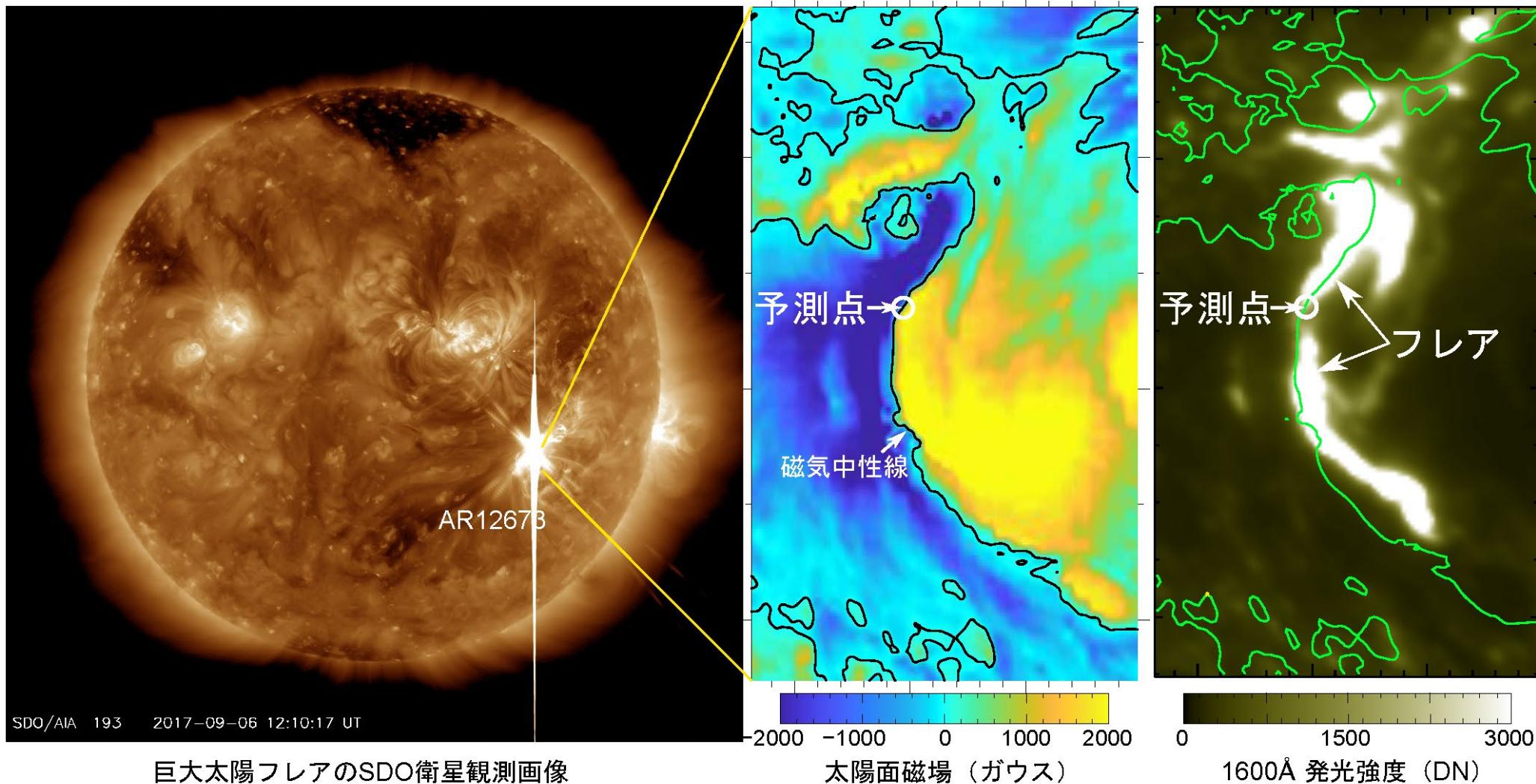
$$r_c$$

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

The minimum free-energy which can be released by the DAI.

$$E_r = \frac{S^{1/2}}{8\pi} \int |B_h - B_p|^2 dS$$

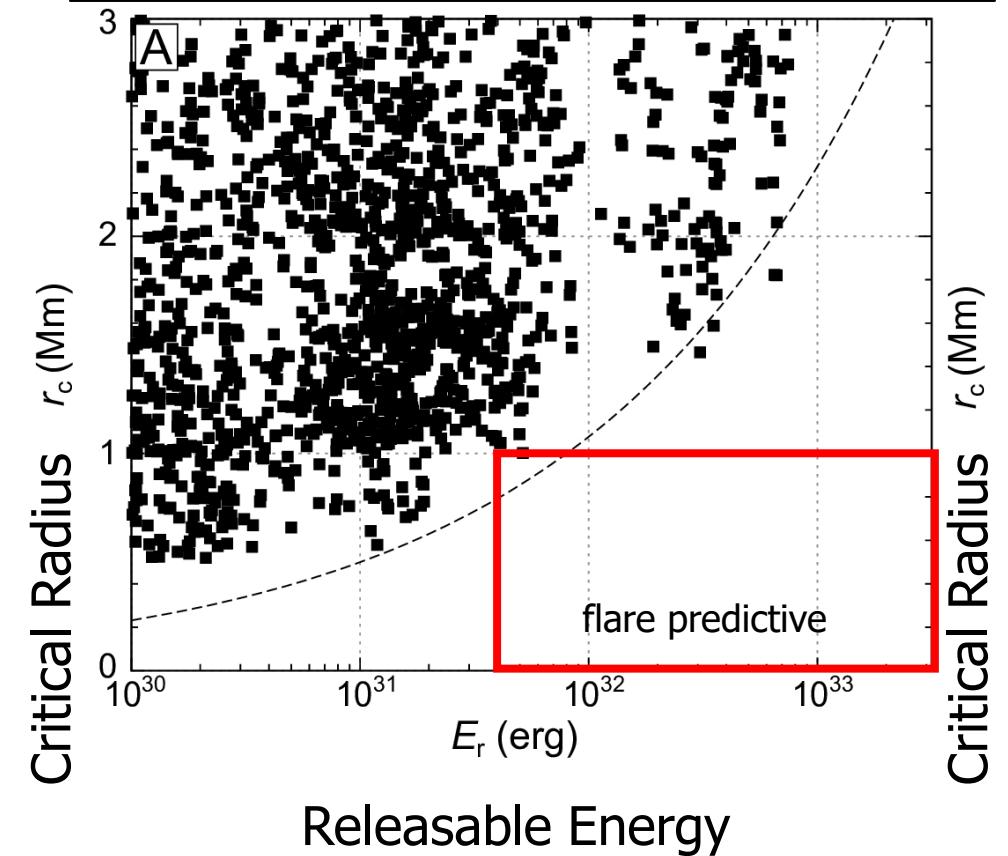
κ -schemeの予測結果



κ -schemeの統計的検証

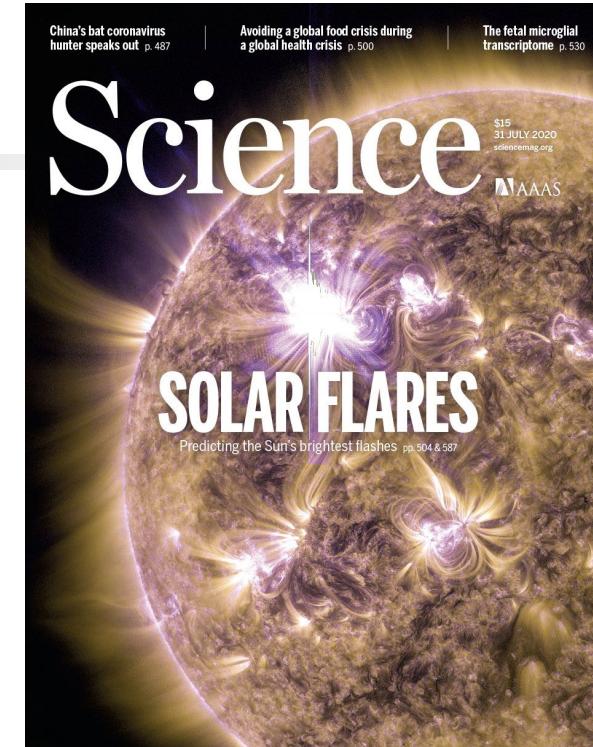
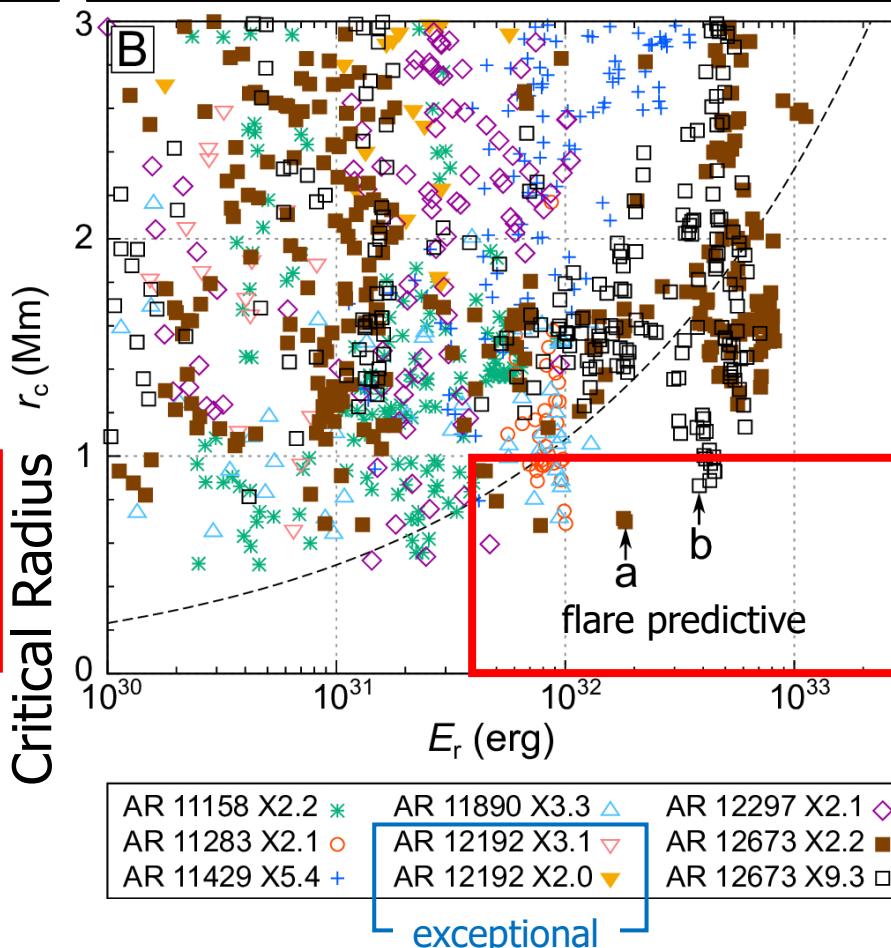
Group 1: Non-flaring regions

- 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.

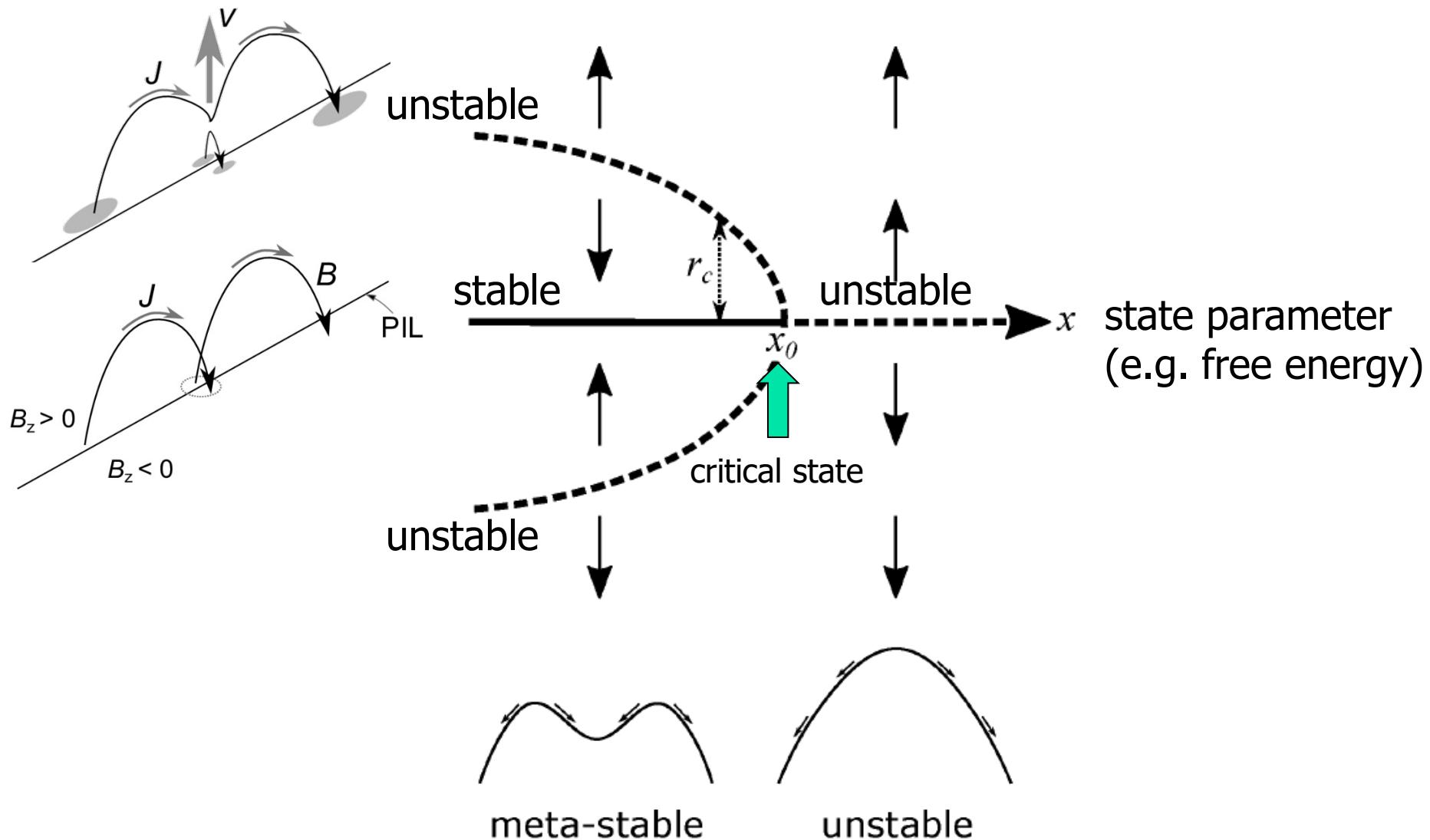


Kusano et al. 2020, Science
DOI: 10.1126/science.aaz2511

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

$r_c < 1$ Mm and
 $E_r > 4 \times 10^{31}$ erg
before their flares.

Sub-critical Bifurcation



まとめ

- 太陽コロナと核融合(トーラス)プラズマは共通性の高いプラズマである。
- 特に、太陽フレアとトカマク・ディスラプションはMHD不安定性・磁気擾乱現象に起因した突発的なエネルギー解放現象としての物理的共通性がある。さらに、共に現象の予測が重要であるという意味で研究の方向性にも共通性がある。
- それゆえ、「**プラズマ突発現象の予測研究**」を通した天文学と核融合研究の融合は発展性のある重要な課題
 - 機械学習を利用した多パラメタ空間における非線形ダイナミクスの予測
 - MHD理論に基づく物理予測
 - データ駆動モデル・データ同化モデルを用いた数値予測、アルゴリズム開発