Magnetic field parameters determining the association of solar flares and CMEs

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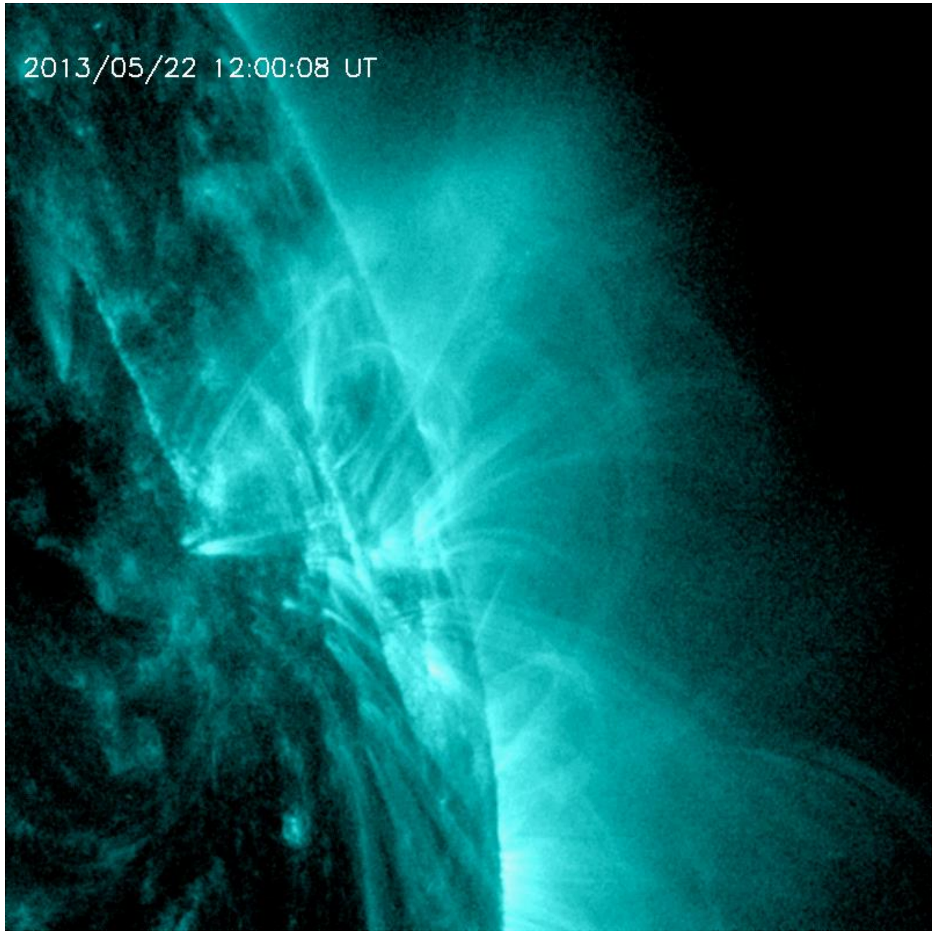
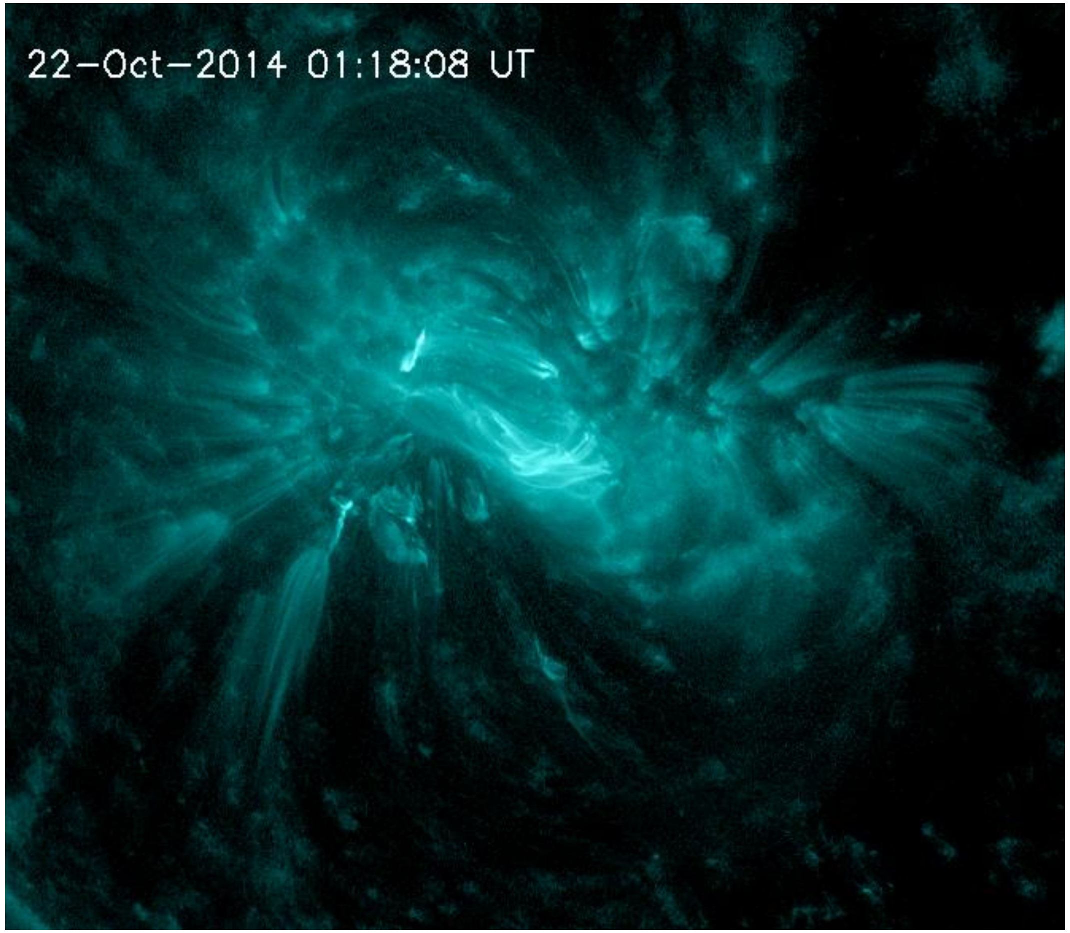
Background： eruptive and confined flares



Eruptive Flare



Confined Flare

Background： eruptive and confined flares

solar flares

eruptive flares with a CME
dominant contributors to adverse space weather at Earth

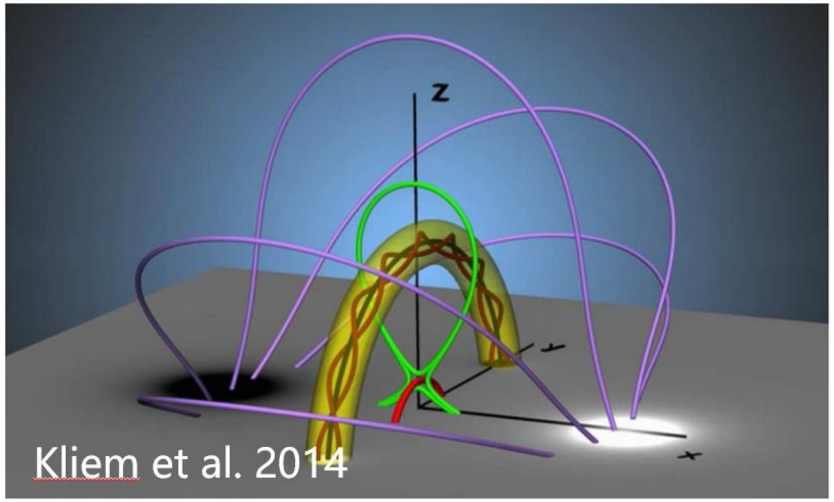
confined flares without a CME
have little influence to adverse space weather at Earth

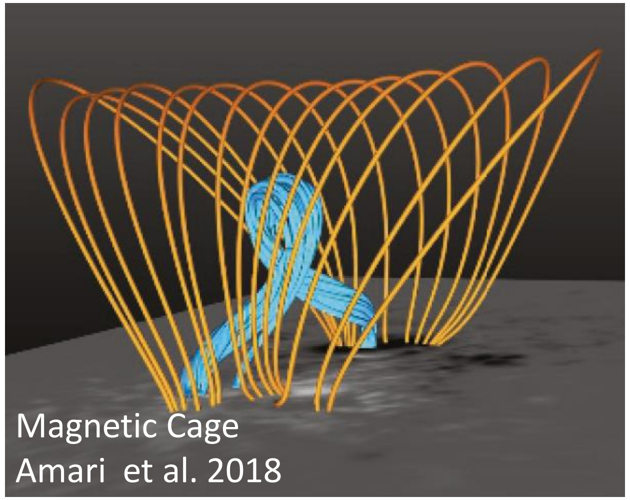
What are the factors determining the eruptive character of a flare?

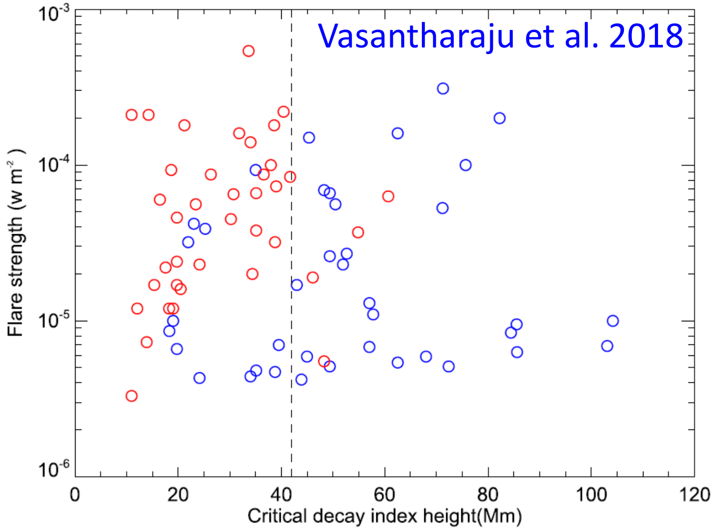
Our understanding of solar flare-CME association

- **important to forecast space weather in the near-Earth environment**
- **has important implications for understanding magnetic activities in other stars**

Constraint of overlying magnetic fields







Lorentz force ↓

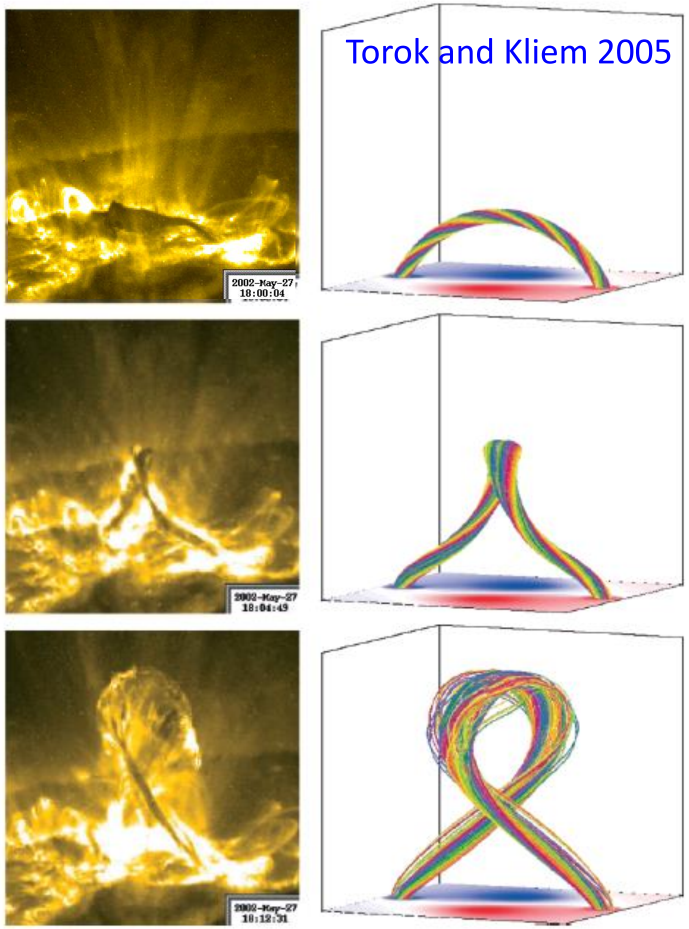
$$\rho_m \frac{d^2R}{dt^2} = \boxed{\frac{\mu_0 I^2}{4\pi^2 a^2 R}\left[\ln\left(\frac{8R}{a}\right) - \frac{3}{2} + \frac{l_i}{2}\right]} - \boxed{\frac{I B_e(R)}{\pi a^2}}$$

Hoop force ↑

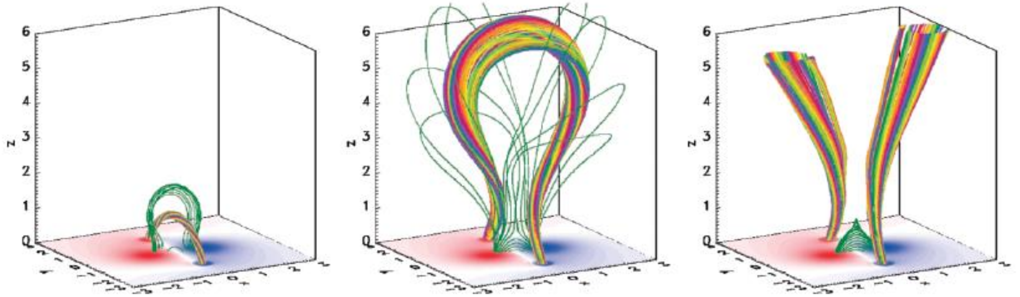
For confined flares, strapping magnetic field is stronger or does not decrease sufficiently fast with height

- Decay index has been used $n = -d \ln B_{hor}/d \ln h$ the critical height for torus instability h_{crit} corresponds to the height where $n_{crit} \approx 1.5$
- Confined flares tend to have larger h_{crit}, implying a stronger constraint of background magnetic fields overlying confined flares (Baumgartner et al. 2018; Vasantharaju et al. 2018)

Constraint of overlying magnetic fields



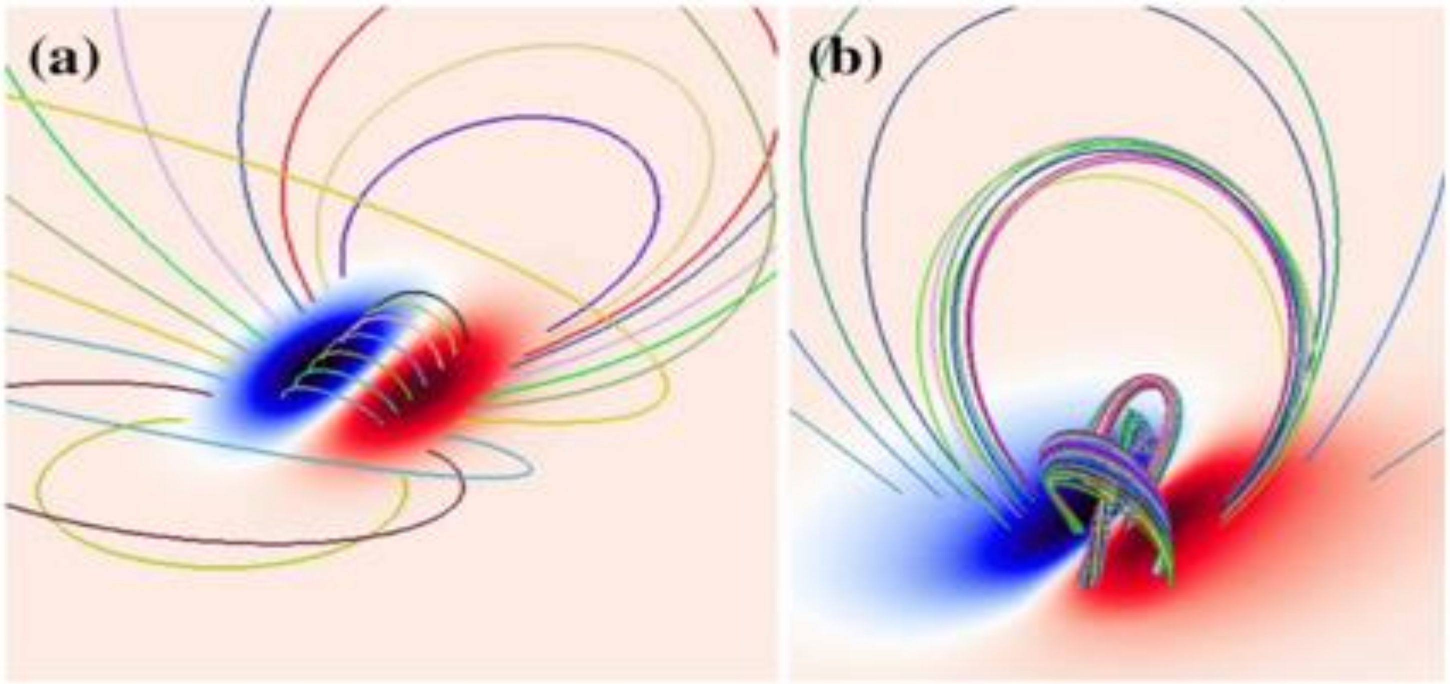
failed eruption with a strong confinement of overlying magnetic fields



full eruption with a weak confinement of overlying magnetic fields

- By decreasing the strapping magnetic fields above the flux rope, a failed eruption ➡ a full eruption (Torok and Kliem 2005)

Magnetic non-potentiality of ARs



Potential fields

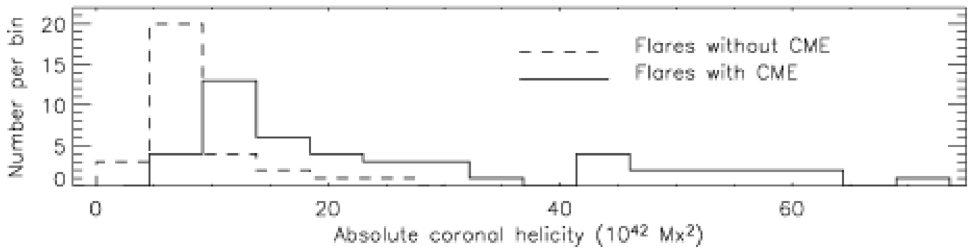
$\nabla \times \mathrm{B} = 0$

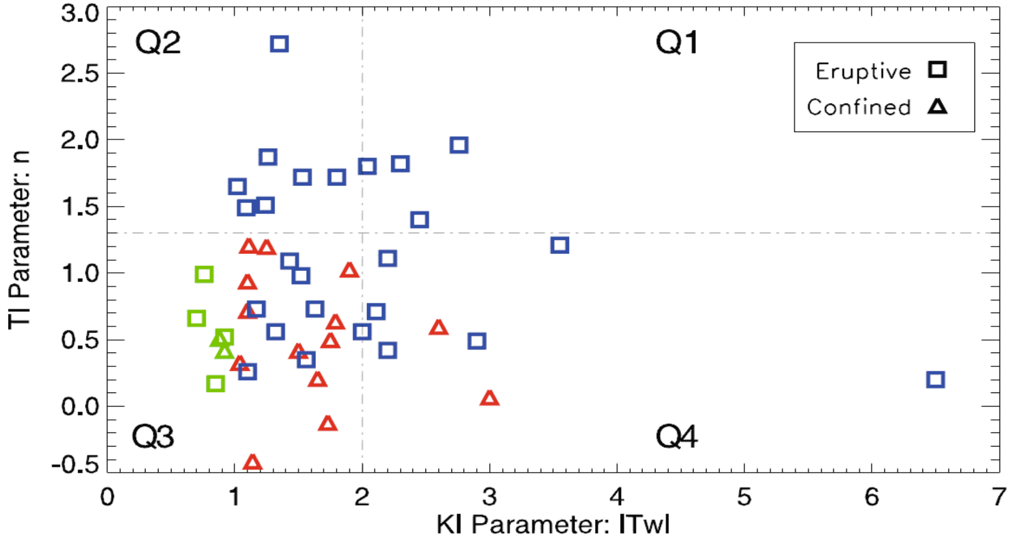
Non-potential fields

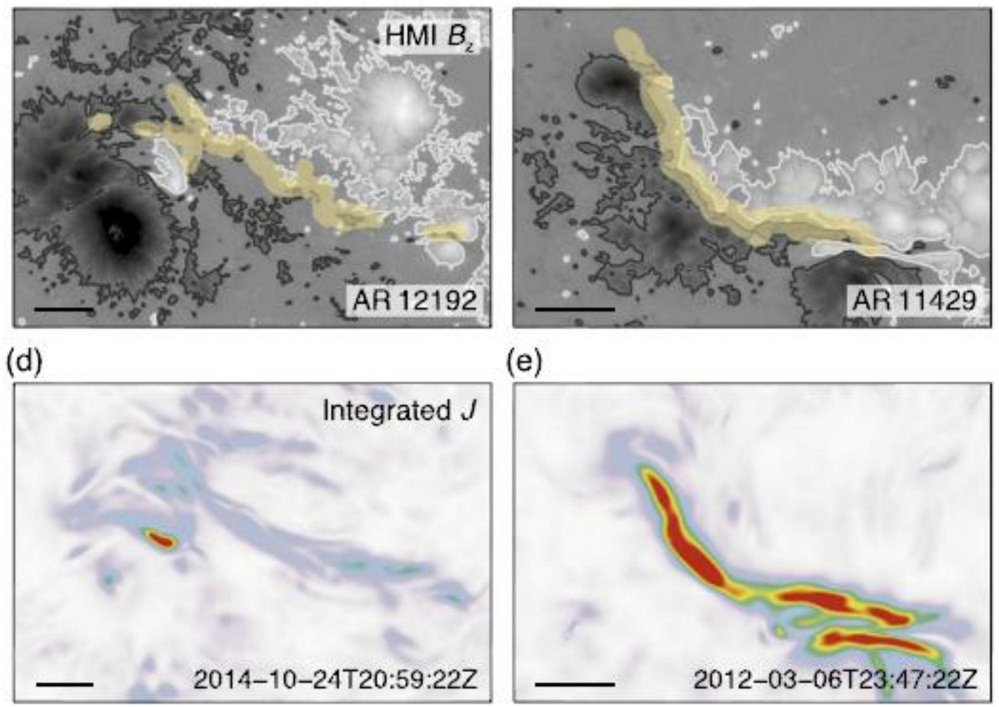
$\nabla \times \mathrm{B} = \mu J \neq 0$

- Magnetic non-potentiality: the degree to which the magnetic fields of an AR deviate from a potential field
- Non-potential parameters: free magnetic energy, magnetic helicity, current, current helicity, magnetic twists, etc.

Magnetic non-potentiality of ARs







- ➢ larger pre-flare coronal magnetic helicity for eruptive flares (Nindos and Andrews 2004; Gupta et al. 2021)
- ➢ larger magnetic twist number *Tw* of flux ropes and larger decay index *n* for eruptive flares (Duan et al. 2019)

- ➢ AR 12192 of 2014 October hosts the largest sunspot group since 1990, producing a total of 6 confined X-class flares
- ➢ Sun et al. (2015) found that AR 12192 shows weaker non-potentiality and stronger overlying magnetic fields

Two factors determining the eruptive character

- For confined flares, strapping magnetic fields overlying the flaring region is too strong or does not decrease sufficiently fast with height (Wang & Zhang 2007; Cheng et al. 2011; Chen et al. 2015; Thalmann et al. 2015; Baumgartner et al. 2018)

- Confined flares tend to have weak magnetic nonpotentiality of ARs, such as magnetic helicity, current helicity, magnetic twist number, etc. (Nindos & Andrews 2004; Tziotziou et al. 2012)

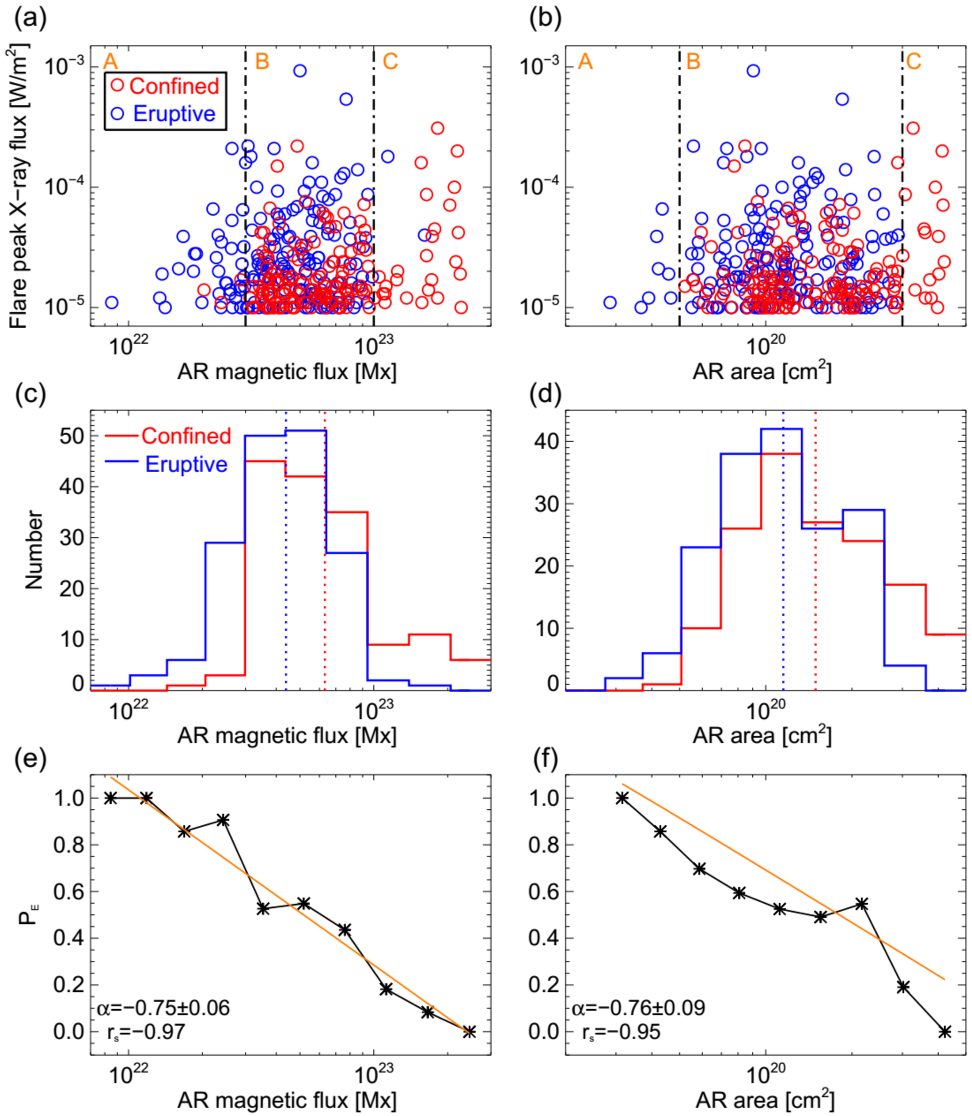
◆ Question: what is the key physical parameter determining the eruptive character of solar flares?

a key parameter Φ_{AR}

- We establish the eruptive/confined flare database and analyze 322 flares of GOES class ≥M1.0 during 2010–2019 observed by the SDO (Li et al. 2020, ApJ, 900, 128).
- 170 eruptive (155 M- and 15 X-) and 152 confined (146 M- and 6 X-).
- database1: https://doi.org/10.12149/101030

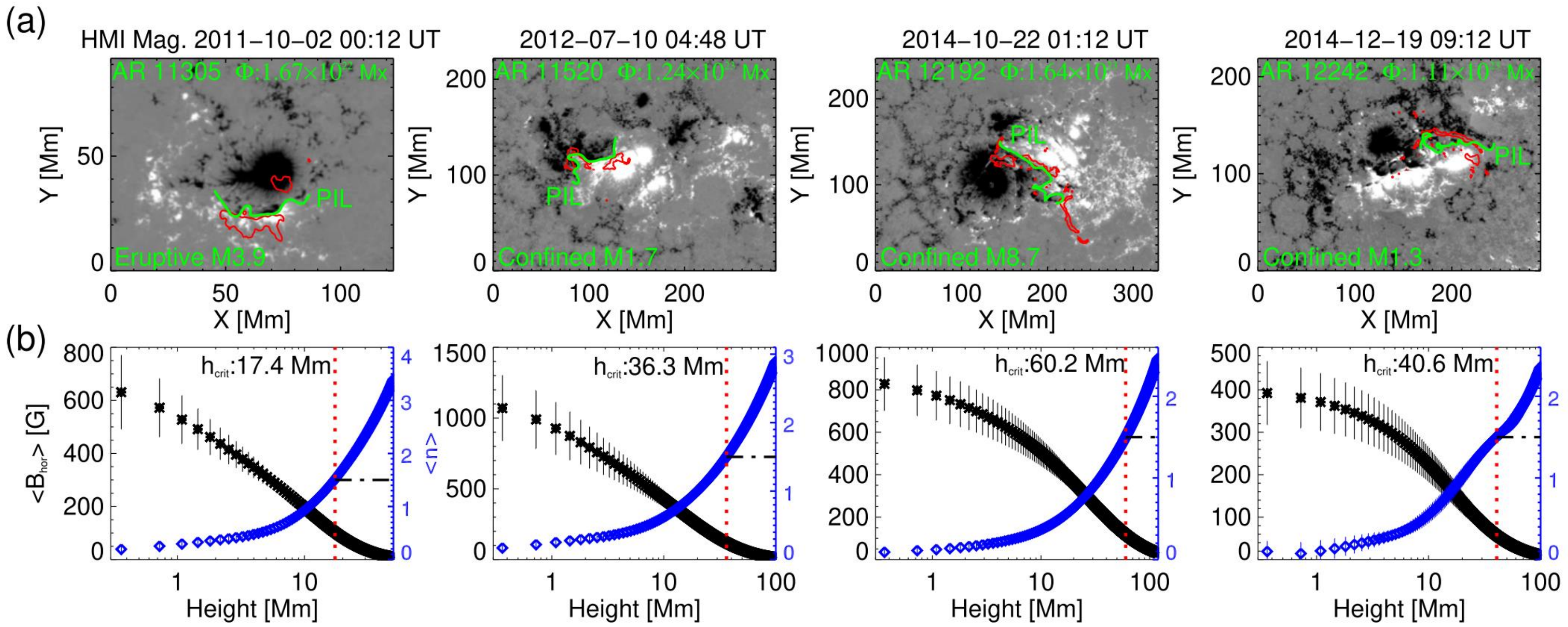
1	INDEX	KEY	Confined/Erupti	TSTART [	TPEAK [U	TFINAL [	IXPEAK [	LAT [deg	LON [deg	ARNUM	PHI_AR [	S_AR [cm
2	1	20100612_0030_11081_M2.0	E	2010-06-	2010-06-	2010-06-	2.00E-05	23	43	11081	1.84E+22	9.20E+19
3	2	20100807_1755_11093_M1.0	E	2010-08-	2010-08-	2010-08-	1.00E-05	11	-34	11093	3.03E+22	8.57E+19
4	3	20101016_1907_11112_M2.9	C	2010-10-	2010-10-	2010-10-	2.90E-05	-20	26	11112	3.53E+22	1.13E+20
5	4	20110213_1728_11158_M6.6	E	2011-02-	2011-02-	2011-02-	6.60E-05	-20	-4	11158	2.21E+22	4.35E+19
6	5	20110215_0144_11158_X2.2	E	2011-02-	2011-02-	2011-02-	2.20E-04	-20	10	11158	3.07E+22	5.59E+19
7	6	20110216_0735_11158_M1.1	C	2011-02-	2011-02-	2011-02-	1.10E-05	-20	30	11158	4.16E+22	9.06E+19
8	7	20110216_1419_11158_M1.6	C	2011-02-	2011-02-	2011-02-	1.60E-05	-20	32	11158	4.04E+22	9.06E+19
9	8	20110307_1345_11166_M1.9	E	2011-03-	2011-03-	2011-03-	1.90E-05	11	-27	11166	4.50E+22	1.31E+20
10	9	20110309_1035_11166_M1.7	E	2011-03-	2011-03-	2011-03-	1.70E-05	11	1	11166	3.73E+22	7.72E+19
11	10	20110309_1317_11166_M1.7	C	2011-03-	2011-03-	2011-03-	1.70E-05	9	6	11166	3.72E+22	7.44E+19
12	11	20110309_2313_11166_X1.5	C	2011-03-	2011-03-	2011-03-	1.50E-04	8	9	11166	4.04E+22	7.76E+19

a key parameter Φ_{AR}



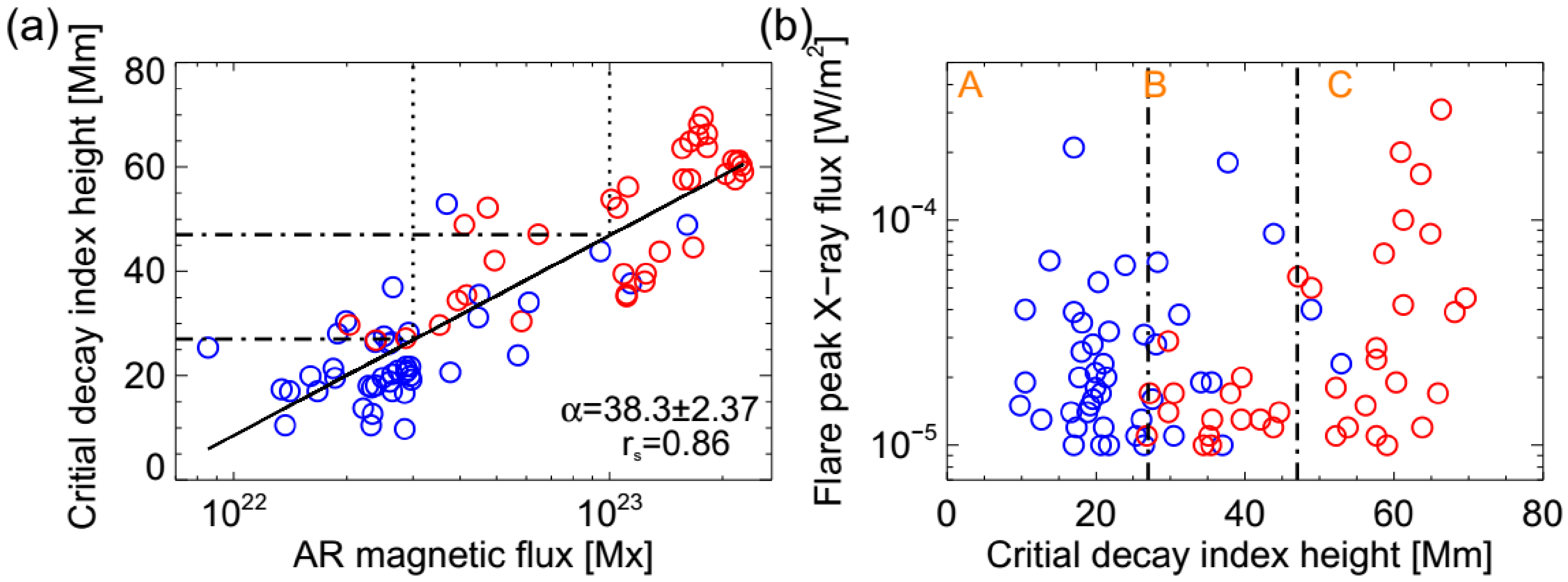
- In ARs with Φ_{AR} <3.0 ×10^{22} Mx, about 92% (36 of 39) of events are eruptive.
- In ARs with Φ_{AR} >1.0 ×10^{23} Mx, about 93% (26 of 28) of events are confined.
- Flare-CME association rate has a strong anti-correlation with $\Phi_{AR,}$ implying that an AR containing a large flux has a lower probability that the flares will be associated with a CME.

a key parameter Φ_{AR}



- The critical height for torus instability h_{crit} corresponds to the height where n_{crit} ≈1.5
- The eruptive flare in AR 11305 with a small Φ_{AR} has h_{crit} of ∼17 Mm, lower than confined flares in larger ARs (36–60 Mm)

a key parameter Φ_{AR}

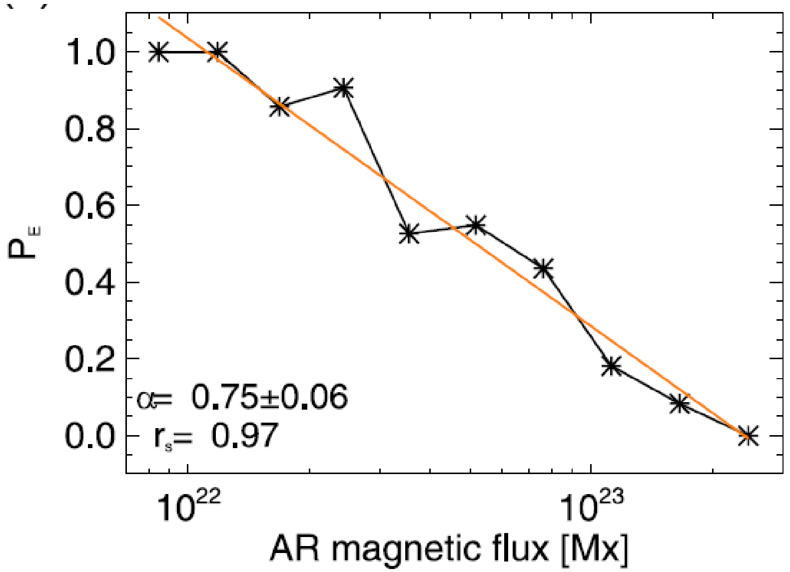


- h_{crit} has a strong positive correlation with Φ_{AR} at correlation coefficient r_s of 0.86

$$h_{\mathrm{crit}} = (38.31 \pm 2.37)\log|\Phi_{\mathrm{AR}}| + (-834.53 \pm 53.92),$$

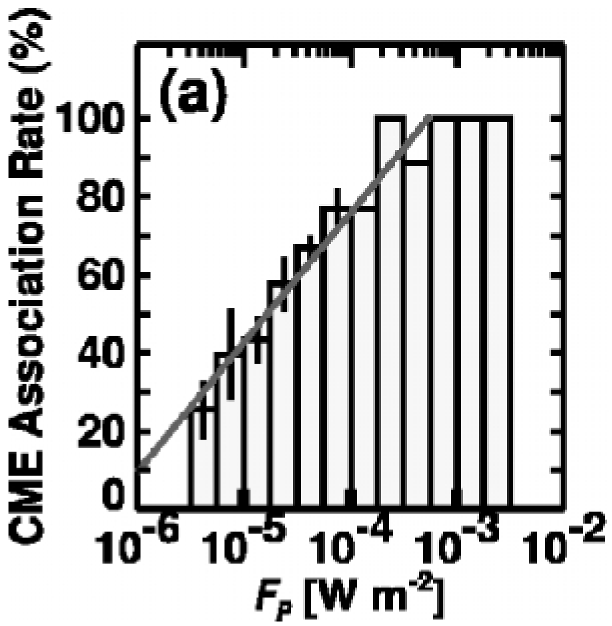
➢ ARs with a larger Φ_{AR} tend to have a stronger constraining magnetic fields

Motivation



Li et al. 2020, ApJ

versus



Andrews 2003; Yashiro et al. 2006

Question: what is the flare-CME association rate R as function of both the flare class F_{SXR} and the total flux Φ_{AR} of ARs?

flare-CME association rate with Φ_{AR} and F_{SXR}

- Database 2: 719 ≥C5.0 flare events (251 eruptive,468 confined)
  http://doi.org/doi:10.12149/101067 (Li et al. 2021, ApJL, 917, L29)

Table 1: Number of Eruptive and Confined Flares in all ARs and ARs with largest Φ_{AR}

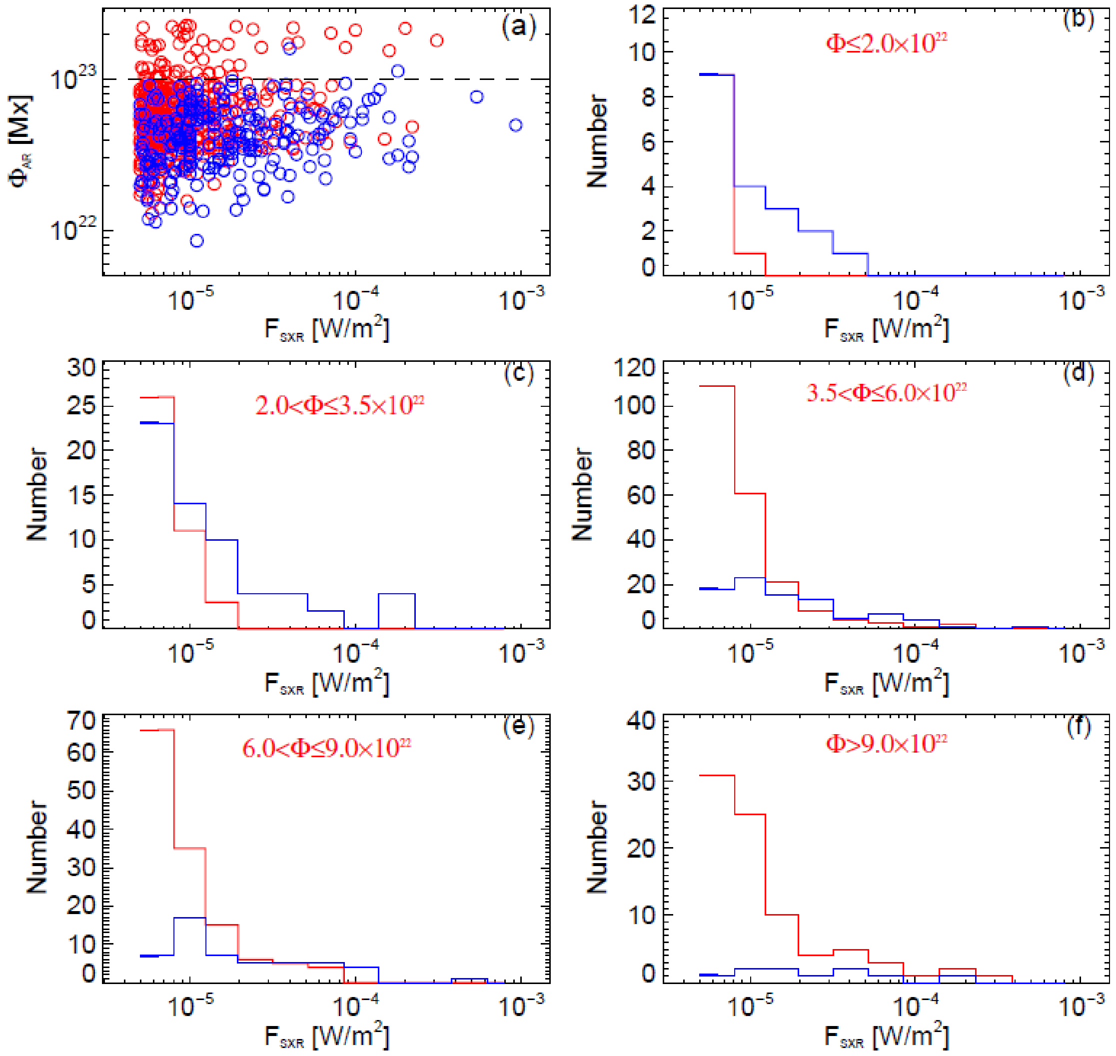
Class	Eruptive[1]	Confined[1]	R[2]	Eruptive[3]	Confined[3]	R[2]
C	82	315	21%	1	40	2%
M	154	147	51%	6	30	17%
X	15	6	71%	1	4	20%
Total	251	468	35%	8	74	10%

[1]For all ARs

[2]Flare-CME association rate

[3]For ARs with largest $\Phi_{AR} > 9.0\times10^{22}$ Mx

Flare-CME association rate with Φ_{AR} and F_{SXR}



- We divide Φ_{AR} into 5 subintervals and seperately calculate the number distributions for confined (red) and eruptive (blue) events in 5 different Φ_{AR} subintervals.

flare-CME association rate with Φ_{AR} and F_{SXR}

- for each Φ_{AR} subinterval, R clearly increases with F_{SXR}

$$R = \alpha \log F_{SXR} + \beta, \quad (4)$$

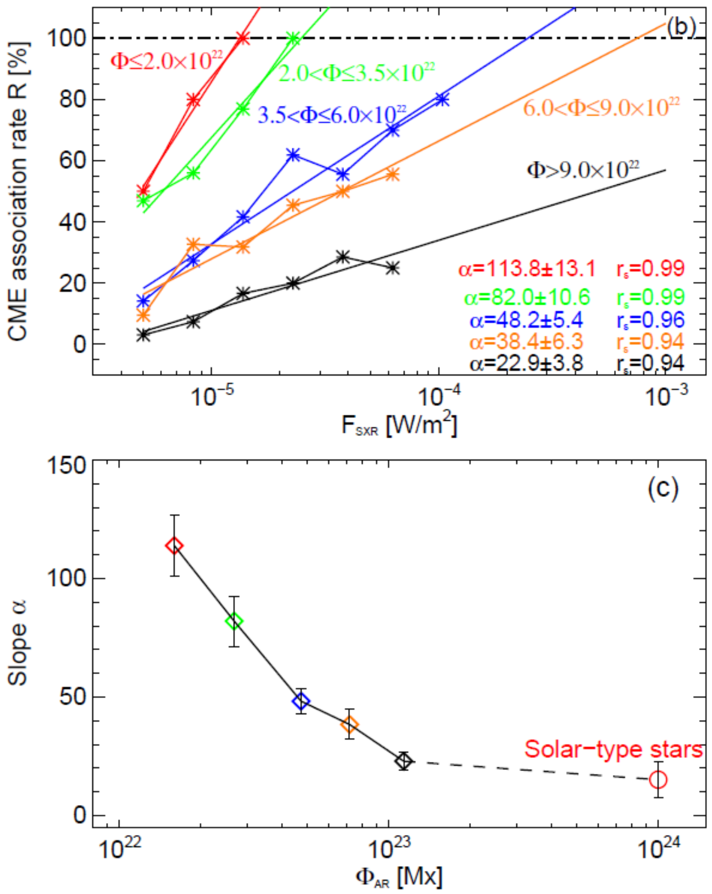
larger flares are more likely associated with a CME

- the slope of *R* reveals a steep monotonic decrease with Φ_{AR} , implying that flares of the same GOES class but originating from a larger AR are much more likely confined.

- Assuming Φ_{AR} in solar-type stars as 1.0×10^{24} Mx (Maehara et al. 2012; Shibata et al. 2013)

$$R = (15.1 \pm 7.8) \log F_{SXR} + 80.0.$$

no more than 50% X100-class superflares are associated with stellar CMEs



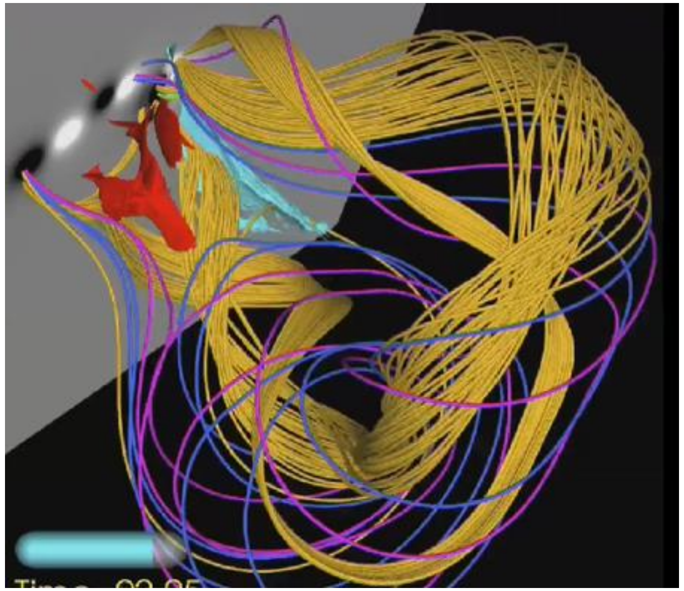
a new parameter α / Φ_{AR}

- Φ_{AR} describes the strength of the background field confinement and is an important quantity describing the eruptive character of a flare

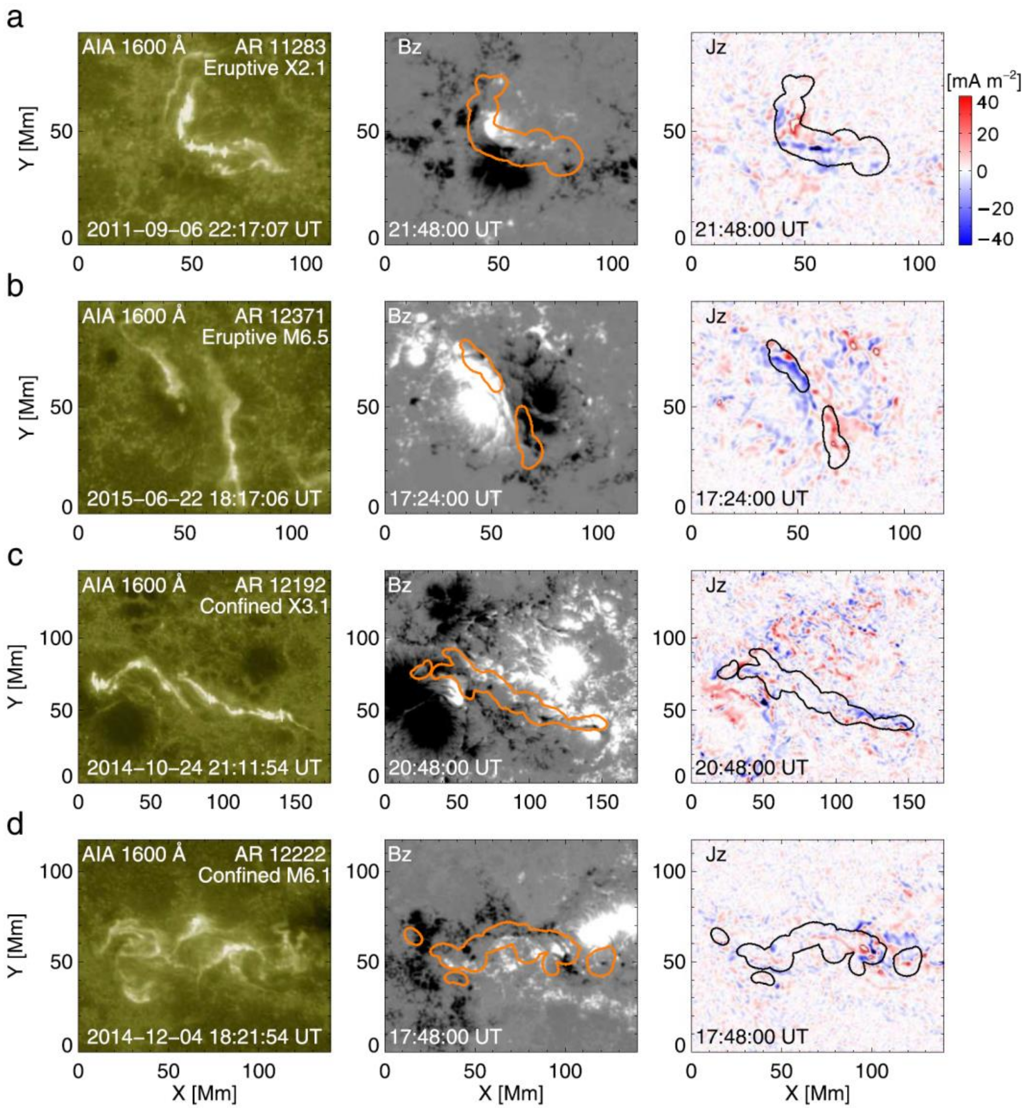
Questions:

How to combine the two factors, i.e., the constraint of overlying magnetic fields and the magnetic non-potentiality of ARs?

Parameters	Description	Unit	Formula
Φ_{AR}	Total unsigned flux	Mx	$\Phi_{AR} = \Sigma \lvert B_z \rvert dA$
J_z	Mean vertical electric current density	$mA\ m^{-2}$	$J_z = \frac{1}{N\mu}\Sigma(\nabla \times \mathbf{B})_z$ [b]
α	Mean characteristic twist parameter	Mm^{-1}	$\alpha = \frac{\mu \Sigma J_z B_z}{\Sigma B_z^2}$
ρ_{free}	Magnetic free energy density	$erg\ cm^{-3}$	$\rho_{free} = \frac{1}{8\pi} \lvert \mathbf{B}_{obs} - \mathbf{B}_{pot} \rvert^2$
Ψ	Mean shear angle	degree	$\Psi = \arccos \frac{\mathbf{B}_{obs} \cdot \mathbf{B}_{pot}}{\lvert B_{obs} B_{pot} \rvert}$

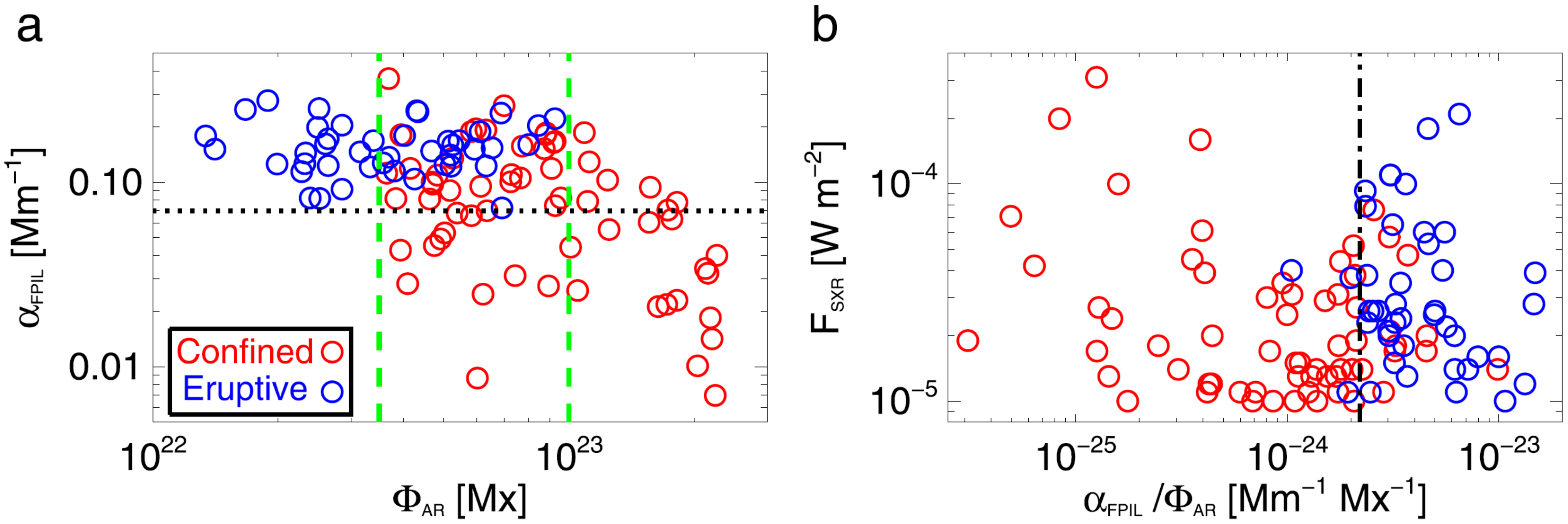


a new parameter α / Φ_{AR}



- We have identified a flaring polarity inversion line (FPIL) mask to demarcate the core of an AR (Sun et al. 2015)
- The vertical electric current density J_Z and the mean characteristic twist parameter α_{FPIL} within the FPIL mask are calculated for 106 flares

a new parameter α / Φ_{AR}



- The events with $\alpha_{FPIL} < 0.07\ Mm^{-1}$ are all confined
- For the new parameter $\alpha_{FPIL} / \Phi_{AR}$, about 93% (40 of 43) of eruptive events have values $\geq 2.2 \times 10^{-24}\ Mm^{-1}\ Mx^{-1}$, and ~83% (52 of 63) of confined flares have smaller values than the threshold

Summary and Discussion

- We find that Φ_{AR} can be used to quantify the background field confinement overlying the flaring region.
- The slope of the flare-CME association rate reveals a steep monotonic decrease with increasing Φ_{AR}, implying that a large magnetic flux tends to confine eruptions.
- We estimate that the flare-CME association rate in “superflares” is no more than 50%.

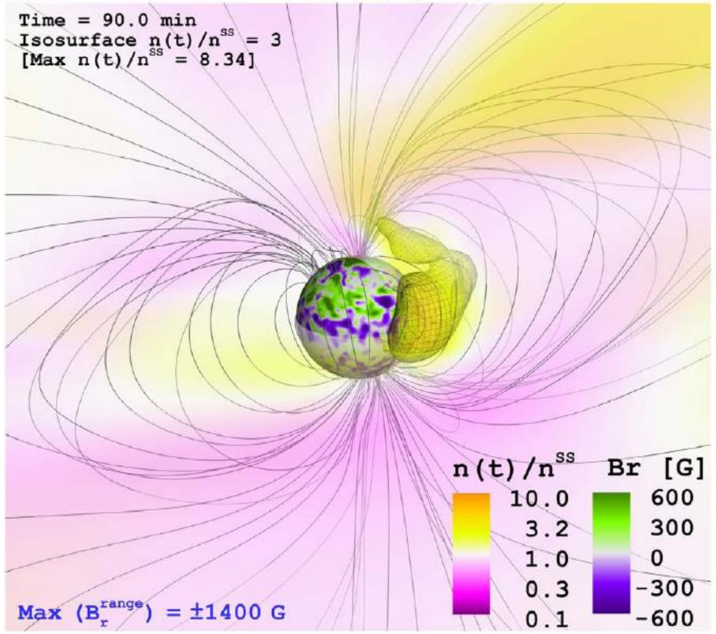
Summary and Discussion

- The new parameter α / Φ_{AR} has a better performance in distinguishing between eruptive and confined flares.
- We suggest that the relative measure of magnetic nonpotentiality over the restriction of the background field largely controls the capability of ARs to produce eruptive flares.

Summary and Discussion

- The occurrence rate of stellar CMEs and their associated kinetic energies are reduced significantly (Moschou et al. 2019; Vida et al. 2019).

- Our findings imply that numerous "superflares" may be confined because of a very strong overlying strapping fields in larger stellar ARs (stellar spots).



Alvarado-Gomez et al. (2019)

Thank you very much for your attention

If you have questions/comments, please send to

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