Universal Correlation between the Ejected Mass and Total Flare Energy for Solar and Stellar Cold Plasma Ejection

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collaborators

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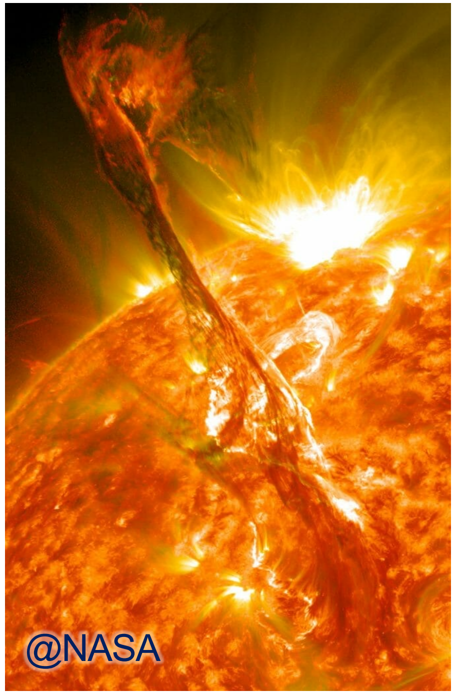
Hinode-15/IRIS-12 (9/22)

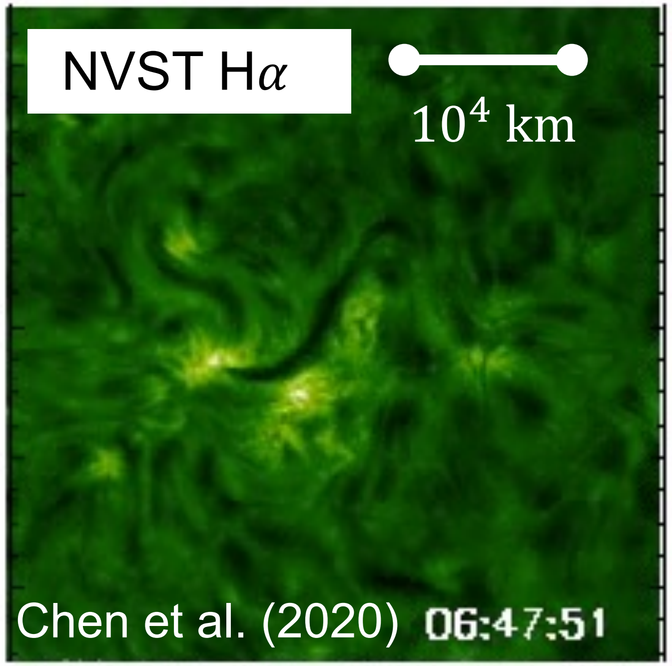
Cold plasma ejections with flares of various scales

Filament eruption/ Surge



- Cold plasma ejection accompanied by solar flare ($10^{28} - 10^{32}$ erg)
- Length: $10^4 - 10^5$ km

Small ejections with flare (minifilament eruption)



Chen et al. (2020)

- Cold plasma ejection accompanied by small-scale flare ($10^{24} - 10^{27}$ erg)
- Length:$10^3 - 10^4$ km

Although spatial scales are different, physical mechanisms are considered to be common.

(e.g., Sakajiri et al. 2004; Ren et al. 2008; Innes et al. 2009; Kontogiannis et al. 2020)

Ejection mass vs flare energy

- **CMEs:**

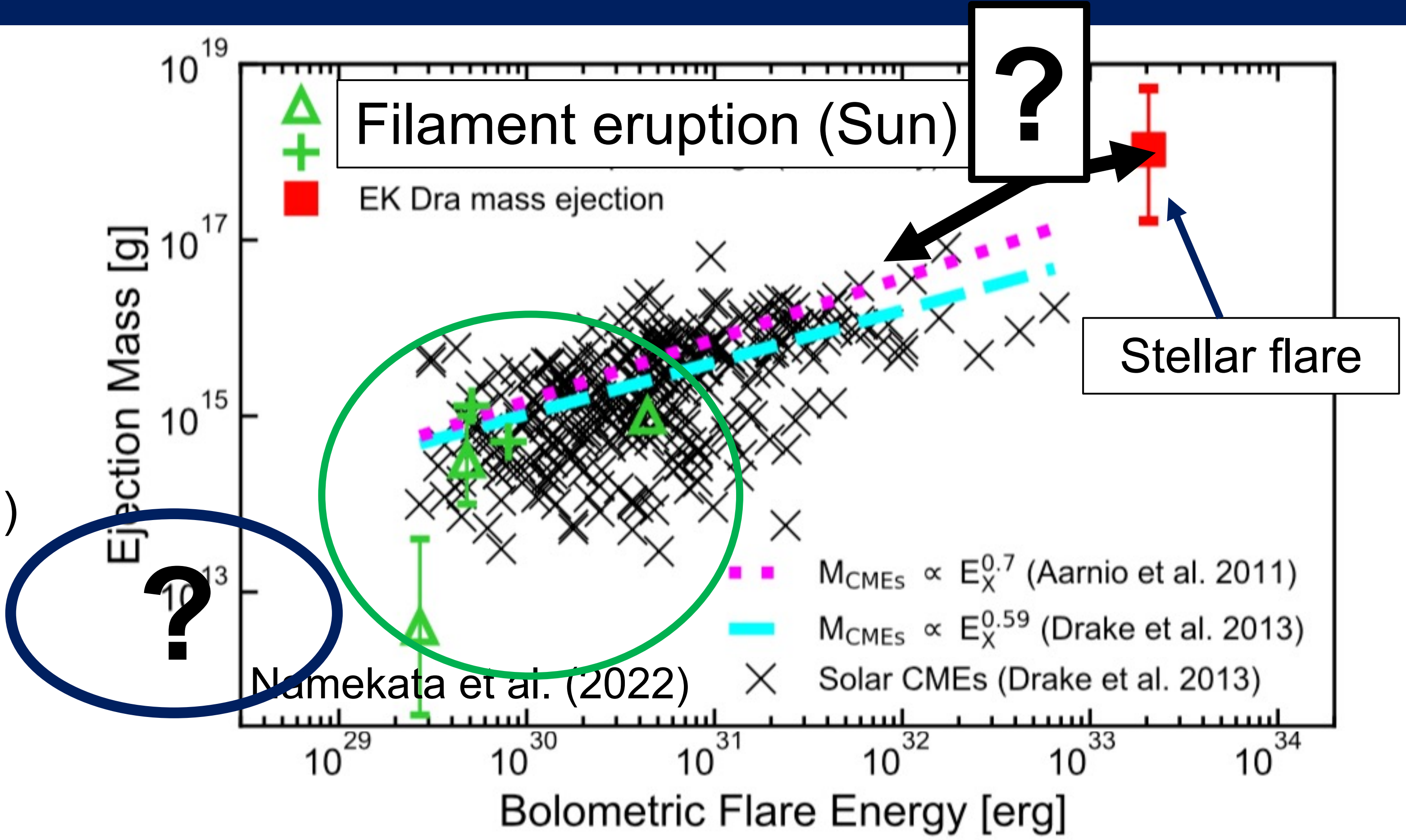
different temperature and height observed by coronagraphs

- **Filament eruptions:**

Only five cases (Namekata et al. 2022)

- **minifilament eruptions:**

No cases



<u>We need more samples on cold plasma ejections on the Sun.</u>

SMART/SDDI @ Hida Observatory of Kyoto University

full-disk Hα observation with imaging spectroscopy

Ichimoto et al. 2017

- **wavelength**: H$\alpha \pm 9$ Å at 73 points with 0.25 Å
- **temporal resolution**: 12 s
- **pixel size**: 1.23"

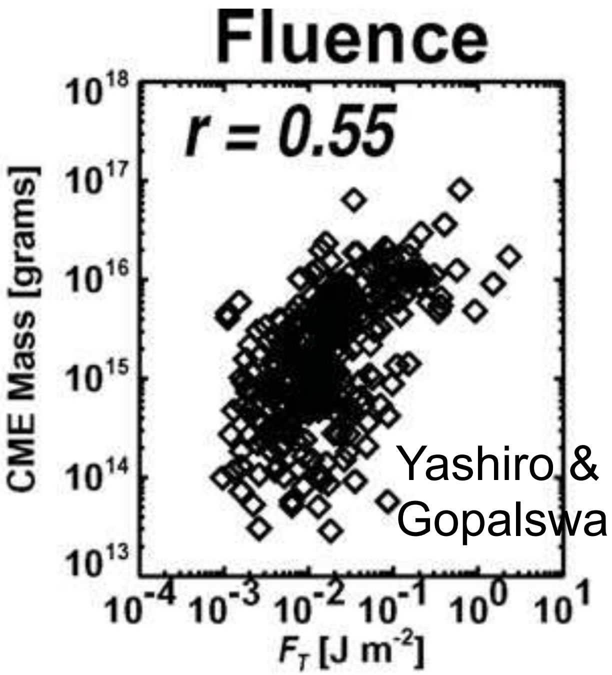
We can easily capture the spectra of cold plasma ejections of various sizes.

Purpose of this study

Purpose

- Estimates of **ejection mass** and **flare energy** for various sizes of cold plasma (filament) ejections in the Sun

- Compare solar analysis results with **stellar results**



Yashiro & Gopalswamy (2009)

✓ We performed **statistical Hα line spectral analysis** for **mass ejections with small flares in the quiet region** and for **large filament eruptions** by using SMART/SDDI.

✓ We constructed **a scaling law** between the total flare energy and the ejection mass of the cold plasma.

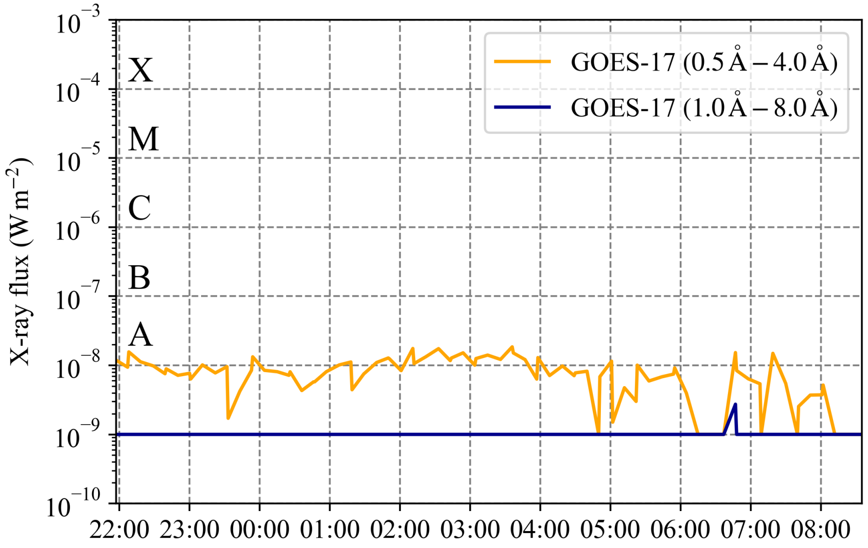
Observational data and event selection

Small ejections in the quiet region

- SMART/SDDI 1-day data for 2019 9/7.
- We visually checked the eruption component from the difference image between the blue and red sides of the Hα wing.
- We limited to only those showing EUV brightening in SDO/AIA and near the disk center.

We analyzed 25 cold plasma ejections with small flares.

GOES X-ray flux (2019/9/7)



Filament eruption

- We selected near the disk center events from the SMART/SDDI filament disappearance catalog (Seki et al. 2019).
- We analyzed 6 cases of active region filament and 4 cases of intermediate filament with flare.

How to determine the physical values of cold ejecta

- Determine the line-of-sight velocity, Doppler width, and optical thickness of the ejecta by the **cloud model** (Beckers 1964; Mein & Mein 1988).

- Determine the **density** and **mass** of the ejecta from the Doppler width and optical thickness using the method of Tsiropoula & Schmieder (1997).

$$n_2 = 7.26\times10^{12}\,\frac{\tau_0 \Delta\lambda_D}{d}\ \mathrm{cm}^{-3}$$ (second level hydrogen density)

↓ vertical slab model (Poland et al. 1971)

$$n_H = 5.0\times10^{8}\sqrt{n_2}\ \mathrm{cm}^{-3}$$ (hydrogen density)

- Determine the **kinetic energy** of the ejecta from the line-of-sight velocity and density.

How to estimate total flare energy (filament eruption)

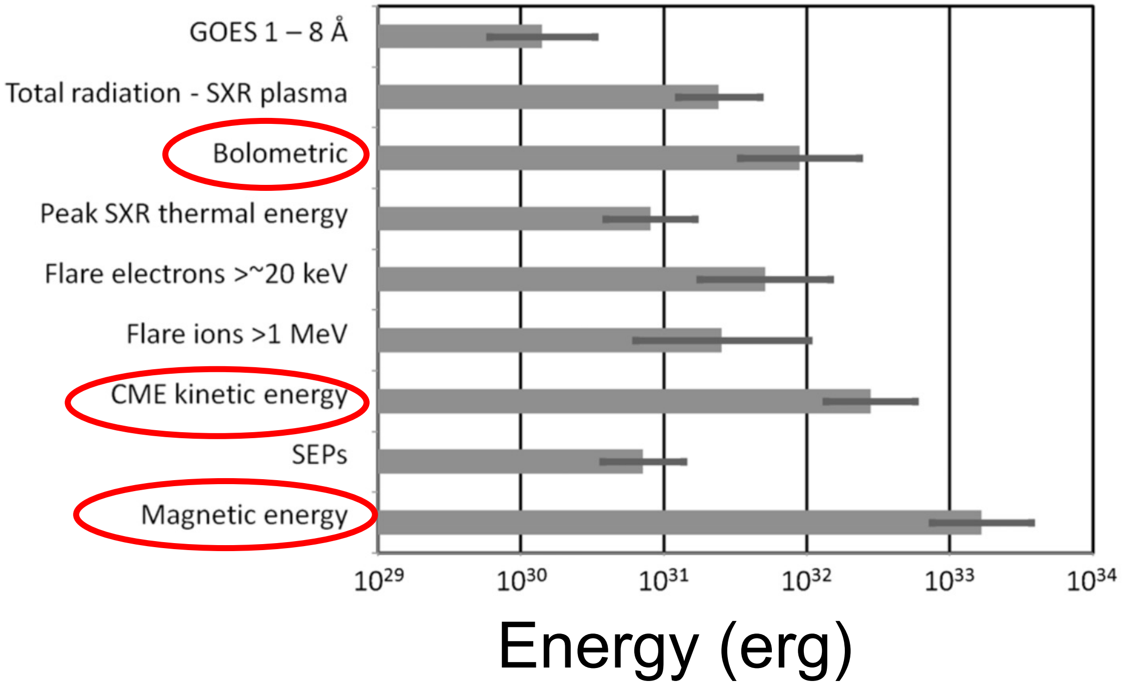
Filament eruption

- Assuming that the **M 1.0 flare corresponds to 10^{30} erg**, we obtained the bolometric energy of the flare.
  (Shibata et al. 2013; Namekata et al. 2022)

- We determined the kinetic energy from the components of the cold plasma motion.

- We assumed

Emslie et al. (2012)



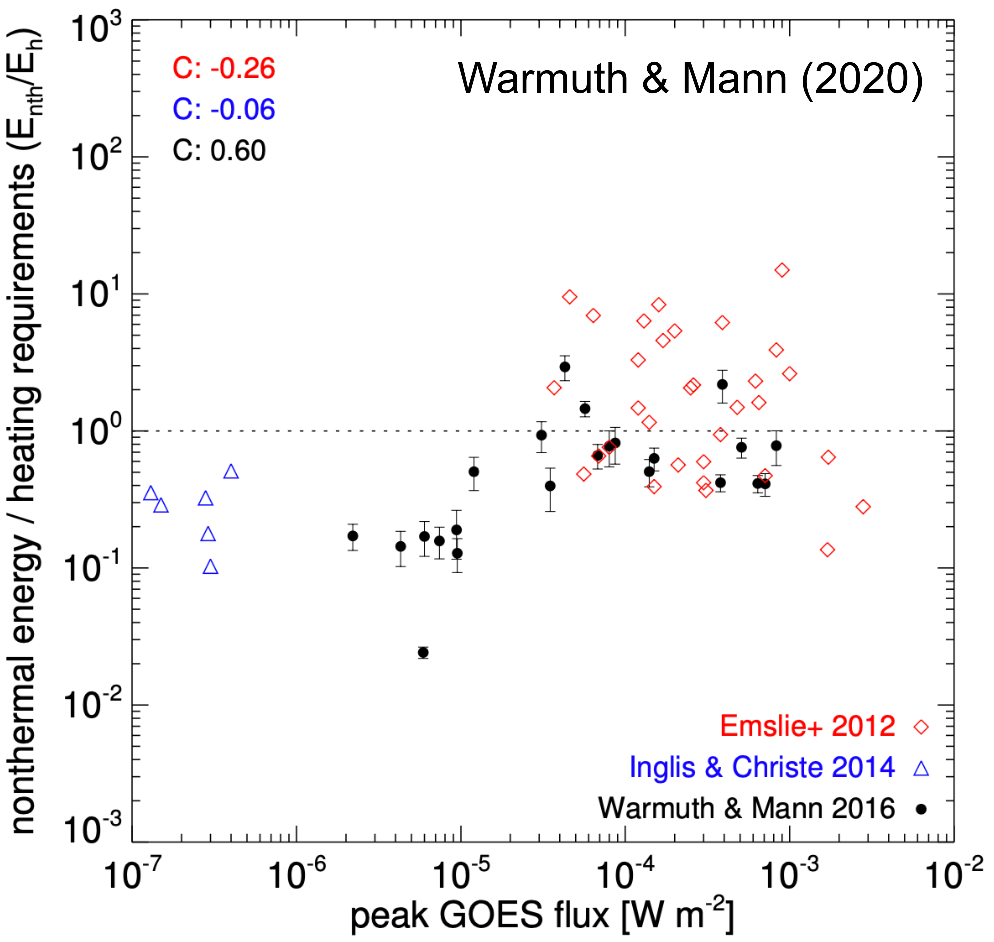
total flare energy = bolometric energy + kinetic energy

How to estimate total flare energy (small events)

Small ejections in the quiet region

- We performed differential emission measure **(DEM) analysis** from AIA to obtain the thermal energy of the flare associated with the ejection (Hanah & Kontar 2012).

- We assumed that nonthermal energy is negligibly small for small flares.
  (Warmuth & Mann 2020)

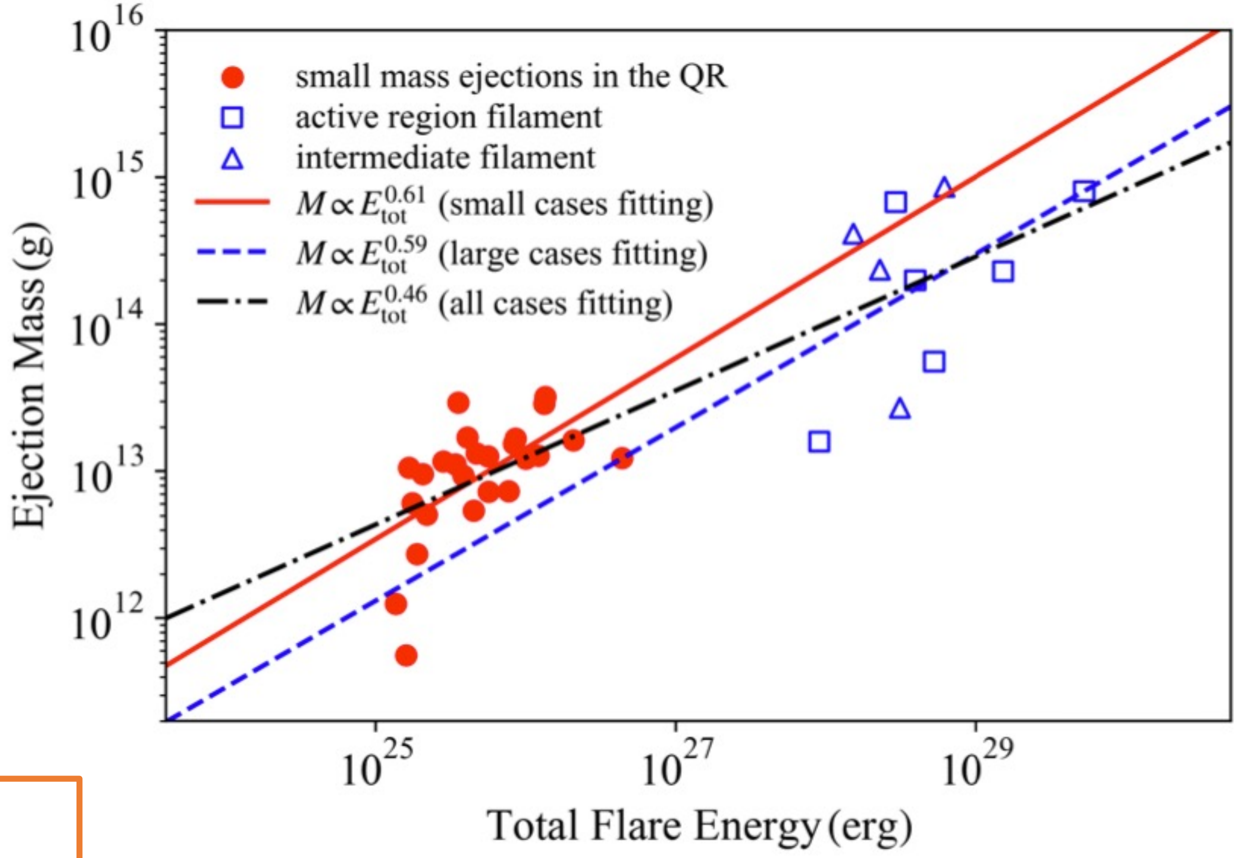


- We assumed

total flare energy = thermal energy + kinetic energy

Ejection mass vs total flare energy

	correlation coefficient	fitting
Small	0.6	$M \propto E_{\text{tot}}^{0.61}$
Large	0.49	$M \propto E_{\text{tot}}^{0.59}$
All	0.86	$M \propto E_{\text{tot}}^{0.46}$



Positive correlation between
Ejection mass vs total flare energy

Comparison with previous and stellar studies

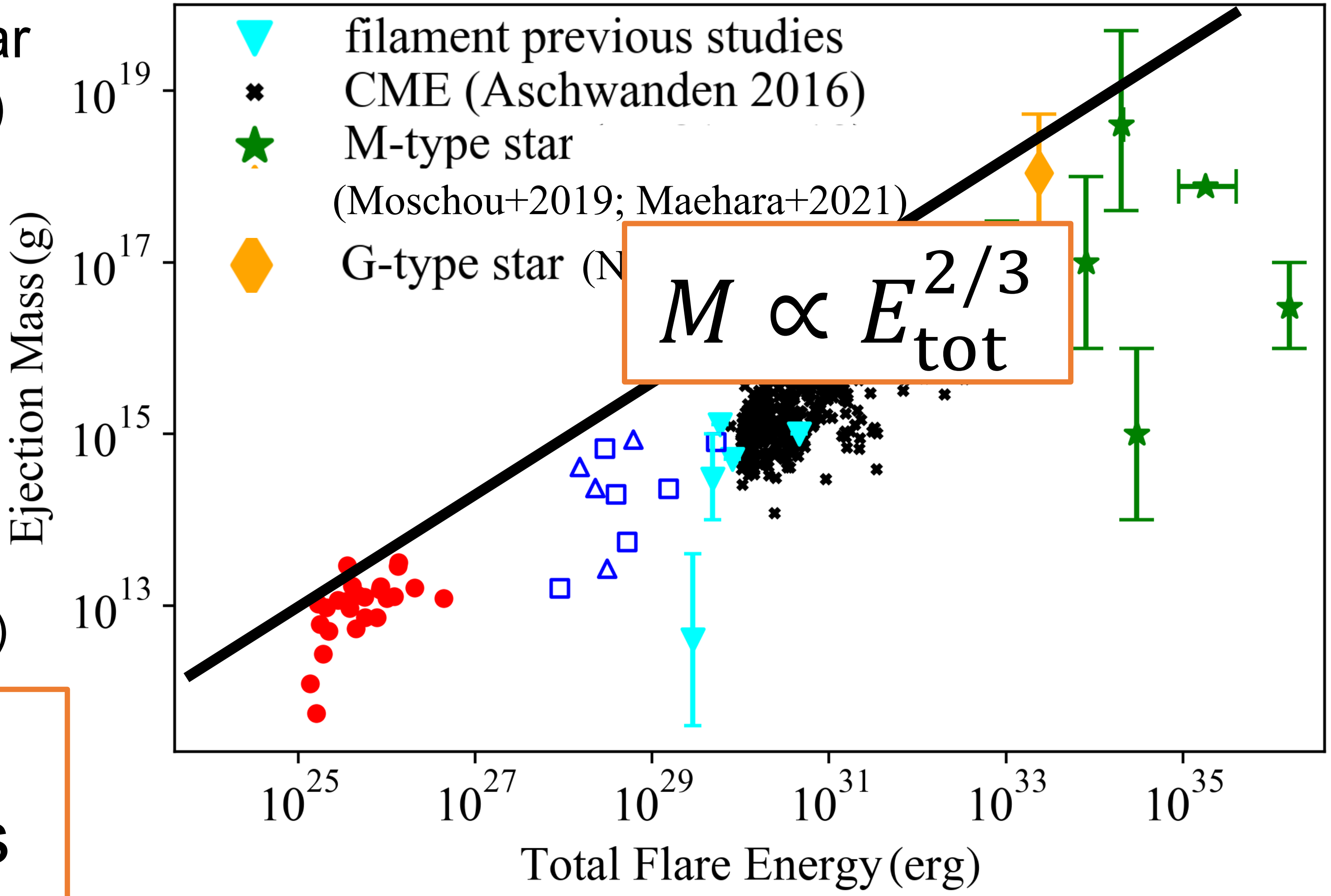
- $E_{\mathrm{tot}} = 100E_{\mathrm{X}} + E_{\mathrm{kin}}$ for M-type star (Moschou+2019; Maehara+2021)

$\left(\begin{array}{l} E_{\mathrm{X}}\text{: X−ray energy in the GOES 1−8 Å} \\ E_{\mathrm{kin}}\text{: kinetic energy of the ejecta} \end{array} \right)$

- $E_{\mathrm{tot}} = E_{\mathrm{bol}} + E_{\mathrm{kin}}$ for G-type star (Namekata+2022)

(E_{bol}: bolometric energy of white-light flare)

strong correlation over
a wide range of energies
$(10^{25} - 10^{35}\ \mathrm{erg})$



$$M \propto E_{\mathrm{tot}}^{2/3}$$

Derivation of theoretical Scaling law (mass M)

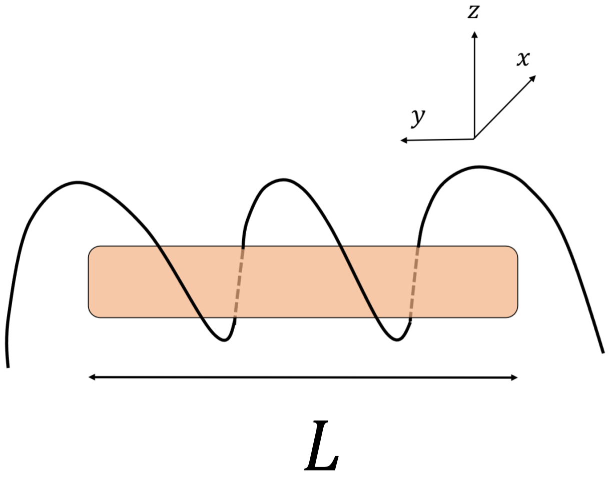
Assumptions

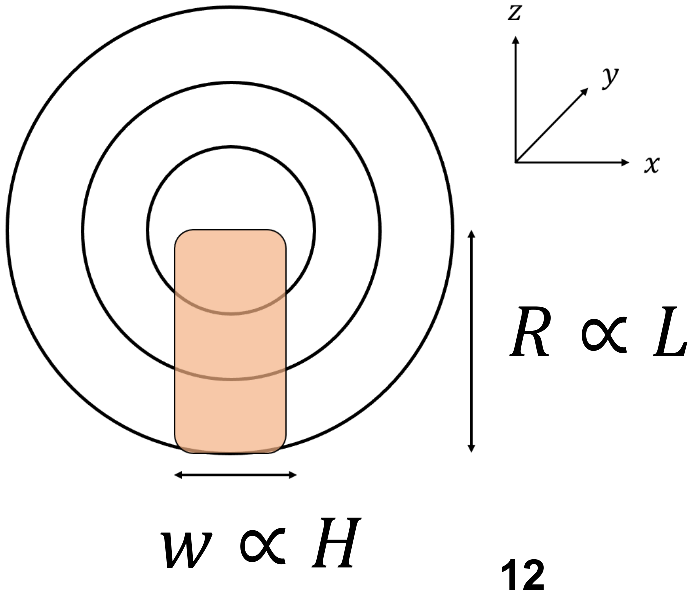
- The filament is approximated by a rectangle of length L, height R, and width w and is supported by a stable helical magnetic field.
- Height $R \propto L$
- Width $w \propto H$

(H: pressure scale height in the filament)

$$\boxed{M = f_v L R w \rho \propto H L^2 \propto L^2}$$

f_v: volume filling factor, ρ: typical density



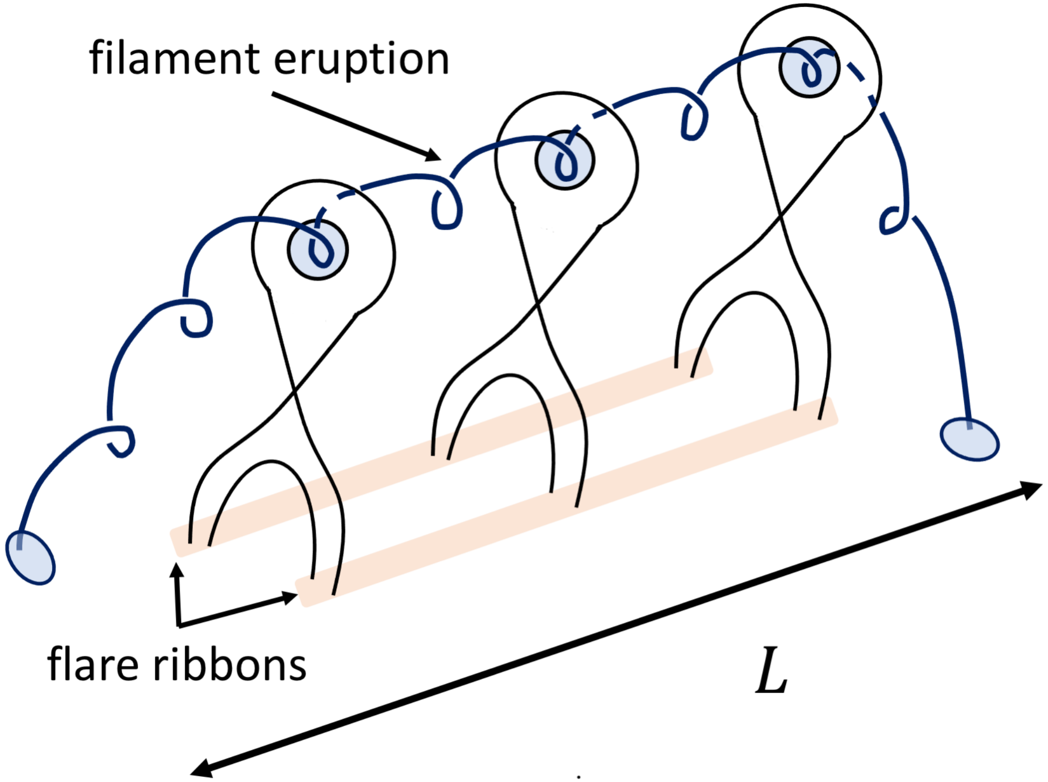


Derivation of theoretical Scaling law (total flare energy E_{tot})

Assumptions

- total flare energy can be estimated by the total amount of magnetic energy contained in a cube of length L.

$$\boxed{E_{\mathrm{tot}} = f\,\frac{B_{\mathrm{corona}}^2}{8\pi}L^3}$$



f: conversion rate from magnetic energy
B_{corona}: coronal magnetic field ambient to the filament

Scaling law for ejection mass vs total flare energy

- $M = f_v L R w \rho = f_v \frac{4\beta_x^{-1/2}(x=0)}{\pi} \frac{B_\psi}{B_y} \rho H L^{2}$
- $E_{\mathrm{tot}} = f \frac{B_{\mathrm{corona}}^2}{8\pi} L^3$

$$\begin{aligned} M \sim 1.5 \times 10^{13} \times \left(\frac{f_v}{0.3}\right) \left(\frac{\beta_x(x=0)}{10^{-3}}\right)^{-1/2} \left(\frac{f}{0.1}\right)^{-2/3} \\ \times \left(\frac{B_\psi / B_y}{0.5}\right) \left(\frac{H}{250\ \mathrm{km}}\right) \left(\frac{\rho}{10^{-13}\ \mathrm{g\ cm^{-3}}}\right) \\ \times \left(\frac{B_{\mathrm{corona}}}{50\ \mathrm{G}}\right)^{-4/3} \times \left(\frac{E_{\mathrm{tot}}}{10^{28}\ \mathrm{erg}}\right)^{2/3} \ (\mathrm{g}) \end{aligned}$$

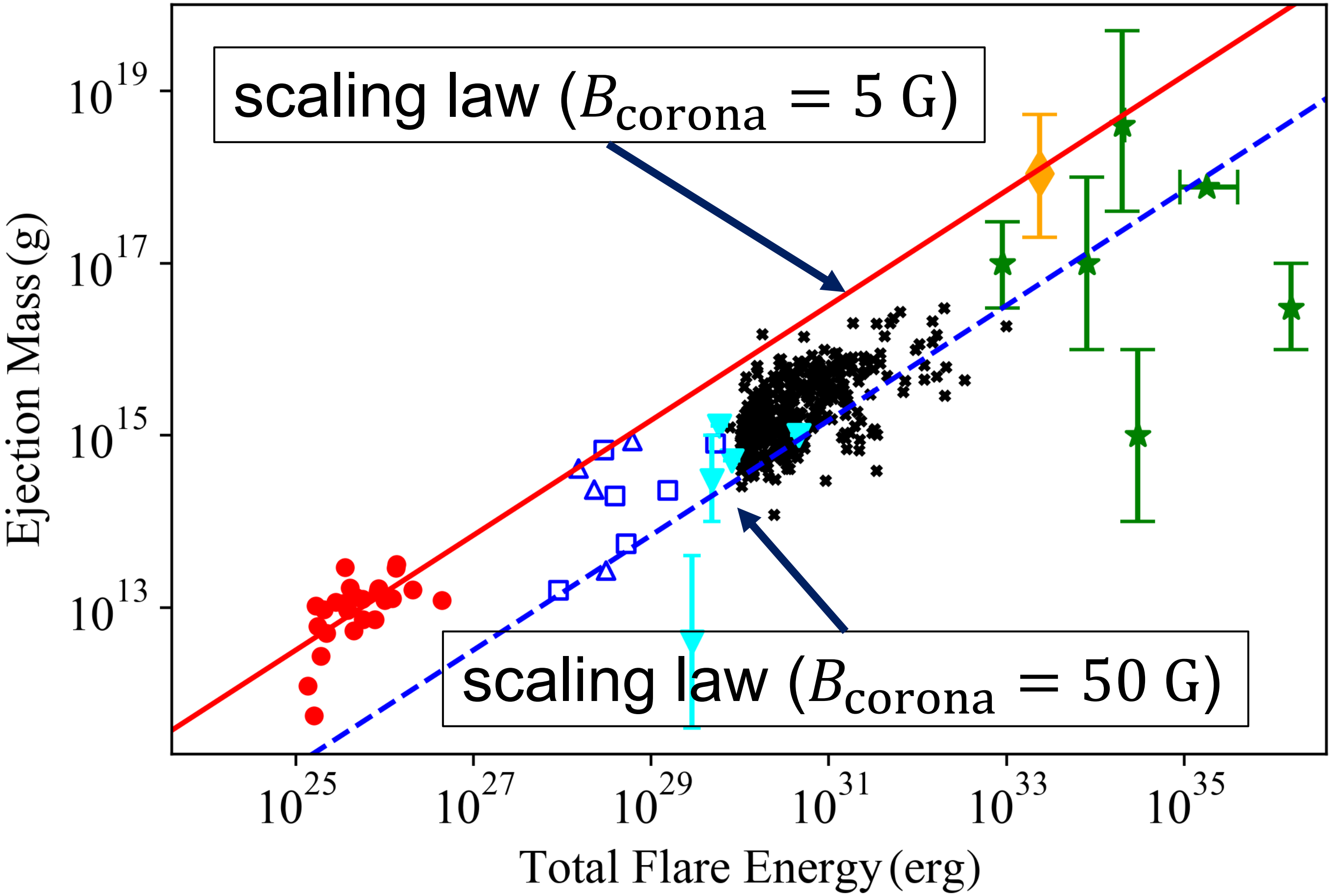
Comparison with Scaling law and observation

- The scaling law explains the observation by considering coronal magnetic field difference.

⇩

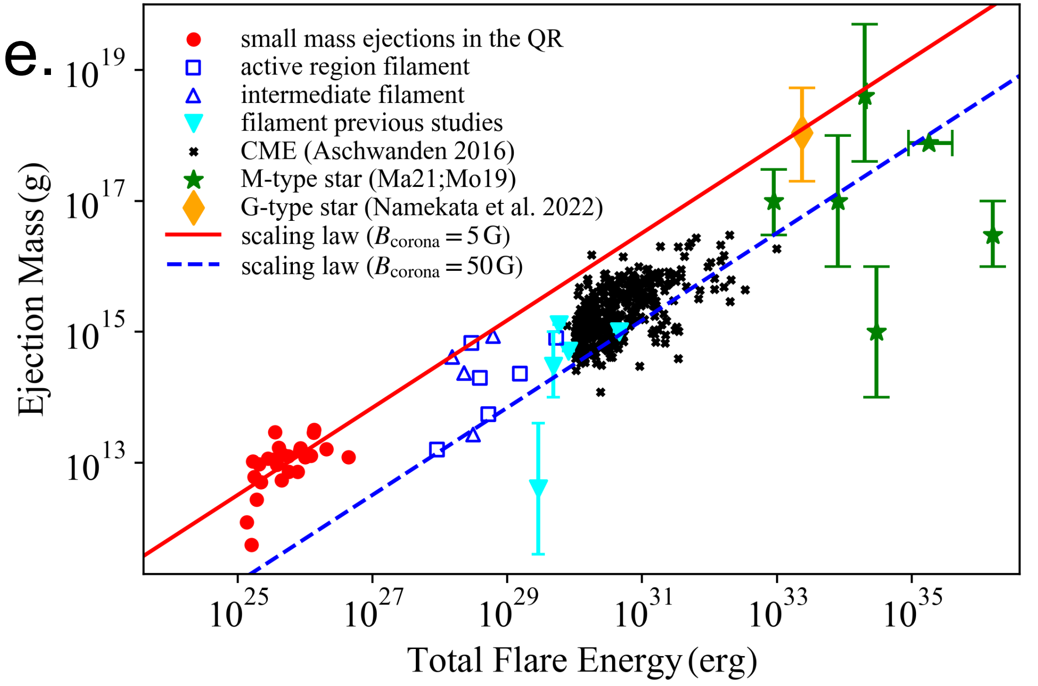
✓ a common mechanism regardless of their scale

✓ supports the interpretation of stellar filament eruptions (Namekata et al. 2022)



Summary

We studied the relationship between **ejected mass** and **total flare energy** for cold plasma ejections with flares of various scales on the Sun by using SMART/SDDI.



✓**Positive correlation** over 10 orders of energy range.

✓New **scaling law** for ejected mass and total flare energy for cold plasma ejections.

✓The plasma motions estimated from the blue shift associated with stellar flares are also roughly consistent with the scaling law.

(→support the interpretation as **stellar filament eruption**)