Satellite anomalies and their socioeconomic impacts in case of a disastrous solar flare

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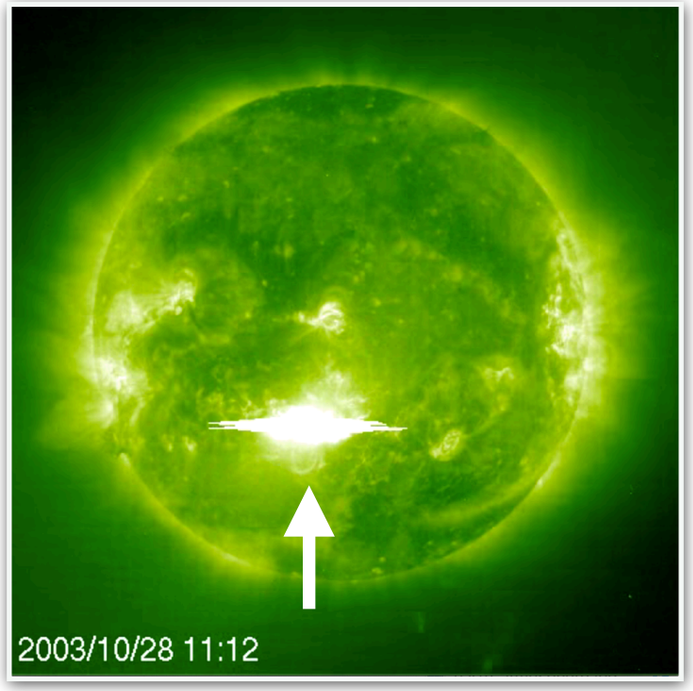
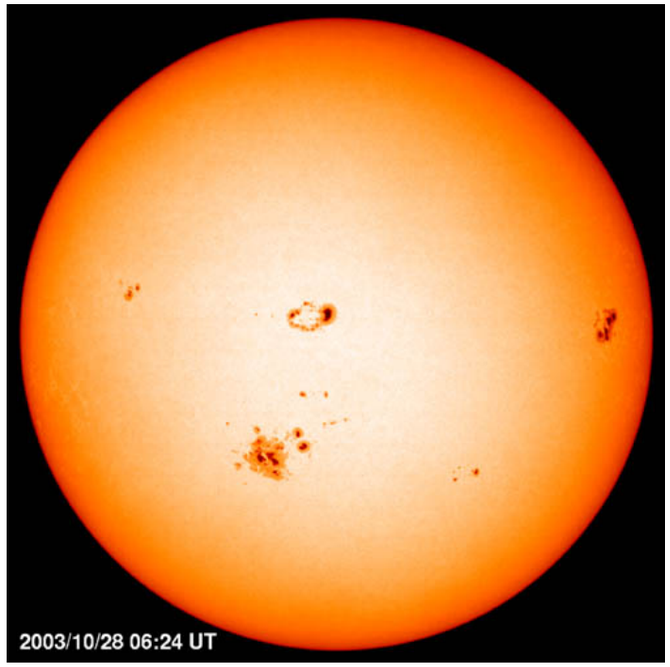
Space weather?

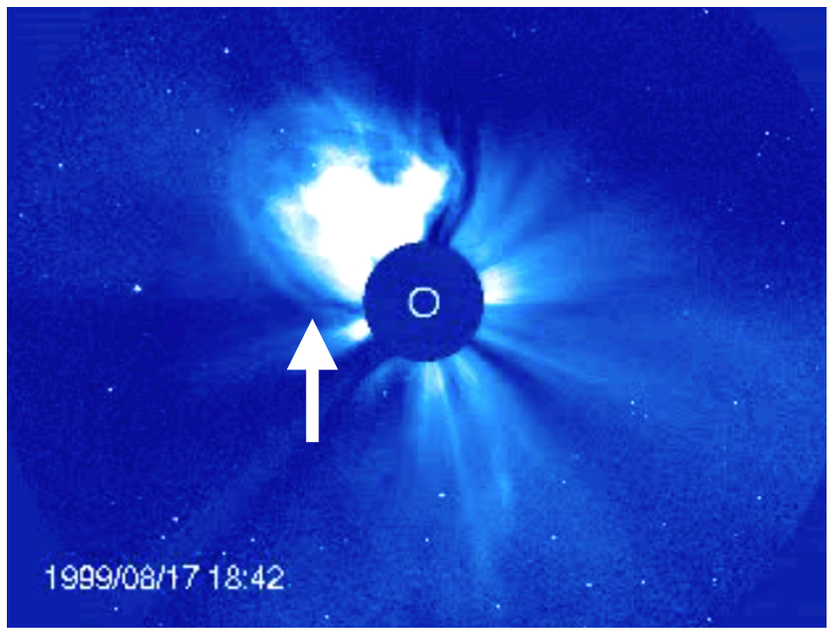
- Space weather is "**severe disturbances** of the upper atmosphere and of the **near-Earth space environment** that are driven **by the magnetic activity of the Sun**" (National Research Council 2008).
- The Sun often produces a sudden eruptive phenomena called **solar flare** and emits strong **electromagnetic waves** in almost all the wavelengths, the huge **bulk of plasma**, and **protons and electrons almost in light speed**.



Flare in extreme ultraviolet
SOHO/EIT
2003 Oct 28



Sunspot in visible light
SOHO/MDI
2003 Oct 28



Coronal Mass Ejection
SOHO/LASCO C3
1999 Aug 17

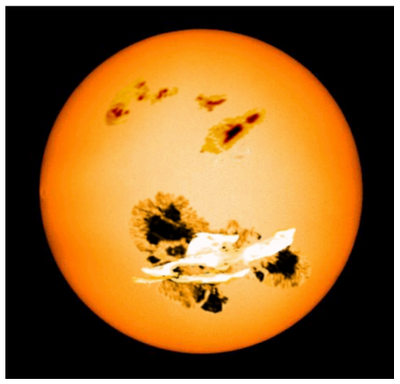
Space weather impacts

- Space weather can bring adverse effects on the human society such as **communication error** (<— EM waves), a huge **blackout** (<— bulk of plasma), a **spacecraft anomaly** (<— nearly light-speed plasma), and **radiation exposure** (<— nearly light-speed plasma).
  - **Satellite anomaly**: In case of "Halloween event" (**X17.4**-class flare), **47** satellites reported anomalies, **1** was a total loss, and **10** suffered a loss of service for > 1 day.
  - **Blackout**: In 1989 on March, all the **electricity** supply **stopped** throughout Quebec state in Canada for **9 hours** because of the huge flare. 6 millions people were affected.
  - **Economic impact:** In case of the worst case ever observed (Carrington event in 1859) (Oughton et al. 2018): $ 0.6–2.6 trillion (Lloyd's of London 2013), $ 1–2 trillion (NRC 2008), $ 0.001–0.02 trillion (Abt associates 2017)
  - cf. total direct economic loss brought by all the disasters in 2005–2015 all over the world was > $1.3 trillion (UNDRR sendai framework 2015).

Note: Flares are classified into B < C < M < X classes according to the peak intensity of soft X-ray flux. For example, X17.4-class flare means that the peak intensity was $17.4*10^{-4}$ watts/m^2, whose energy corresponds to 10^{33} erg (cf. the energy of M10 earthquake is 10^{27} erg).

Superflare

Notsu et al. 2019, ApJ

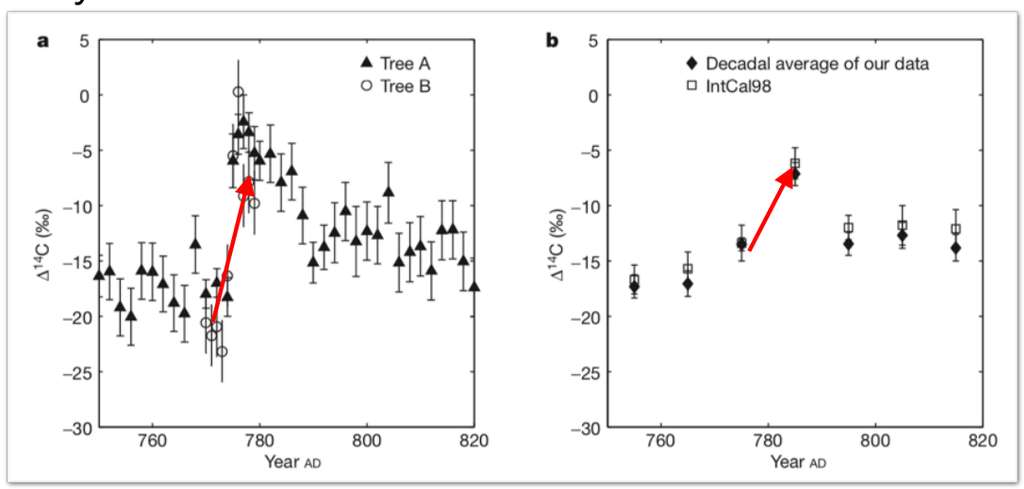


imaginary picture of super flare sunspot

Other indirect evidences of superflare

- ^{14}C content in Japanese tree rings

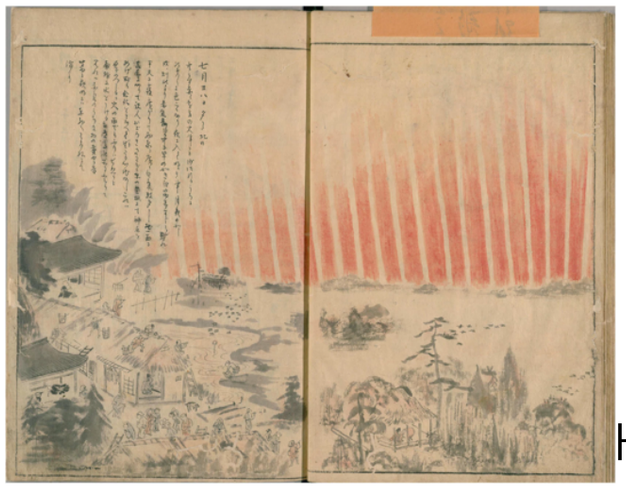
Miyake et al. 2012



https://www.amazon.com/KEPSWET-Yellow-Non-Slip-Carpet-Bedroom/dp/B01G8JL9ZG

Sudden increase in ^{14}C
→ lots of particles came from space

- Historical records in Japan



Some records of aurora recorded at low latitude eastern asia (Japan) were found.

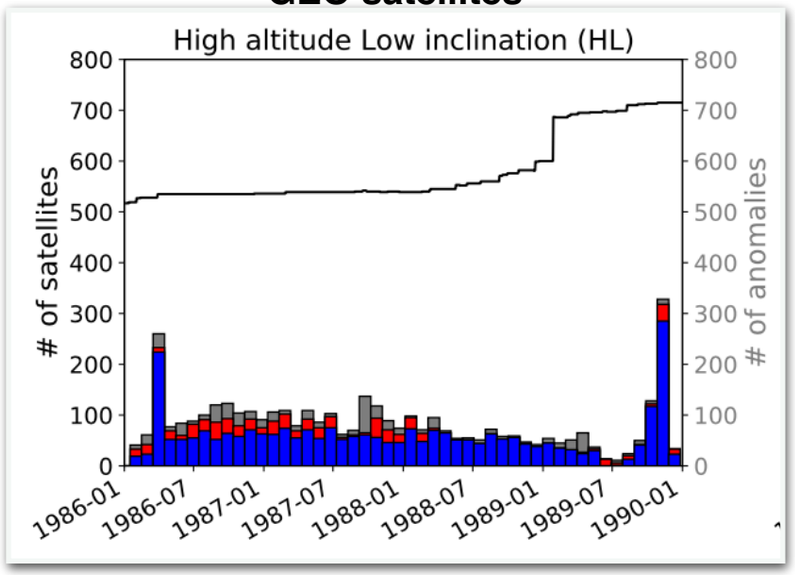
Hayakawa et al. 2017

How severe damage could be if a disastrous solar flare should happen?

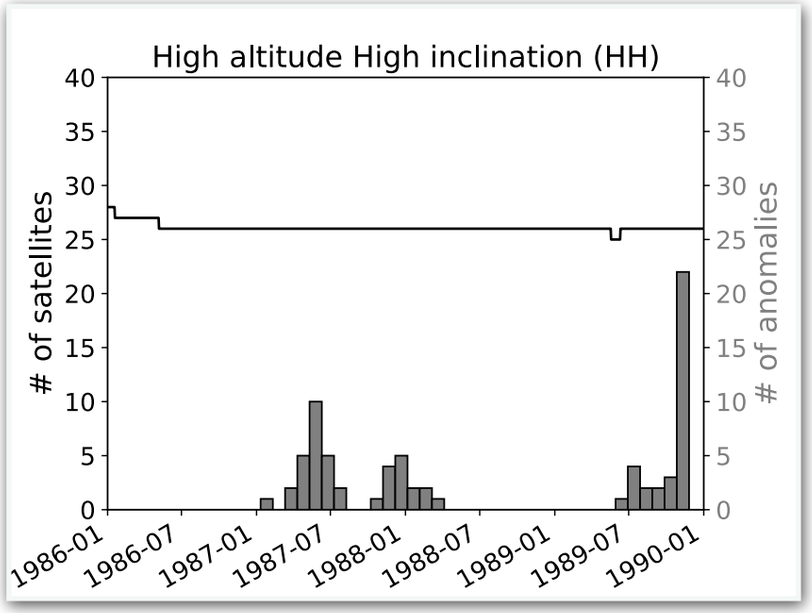
Data

- # of satellite anomalies and of operational satellites

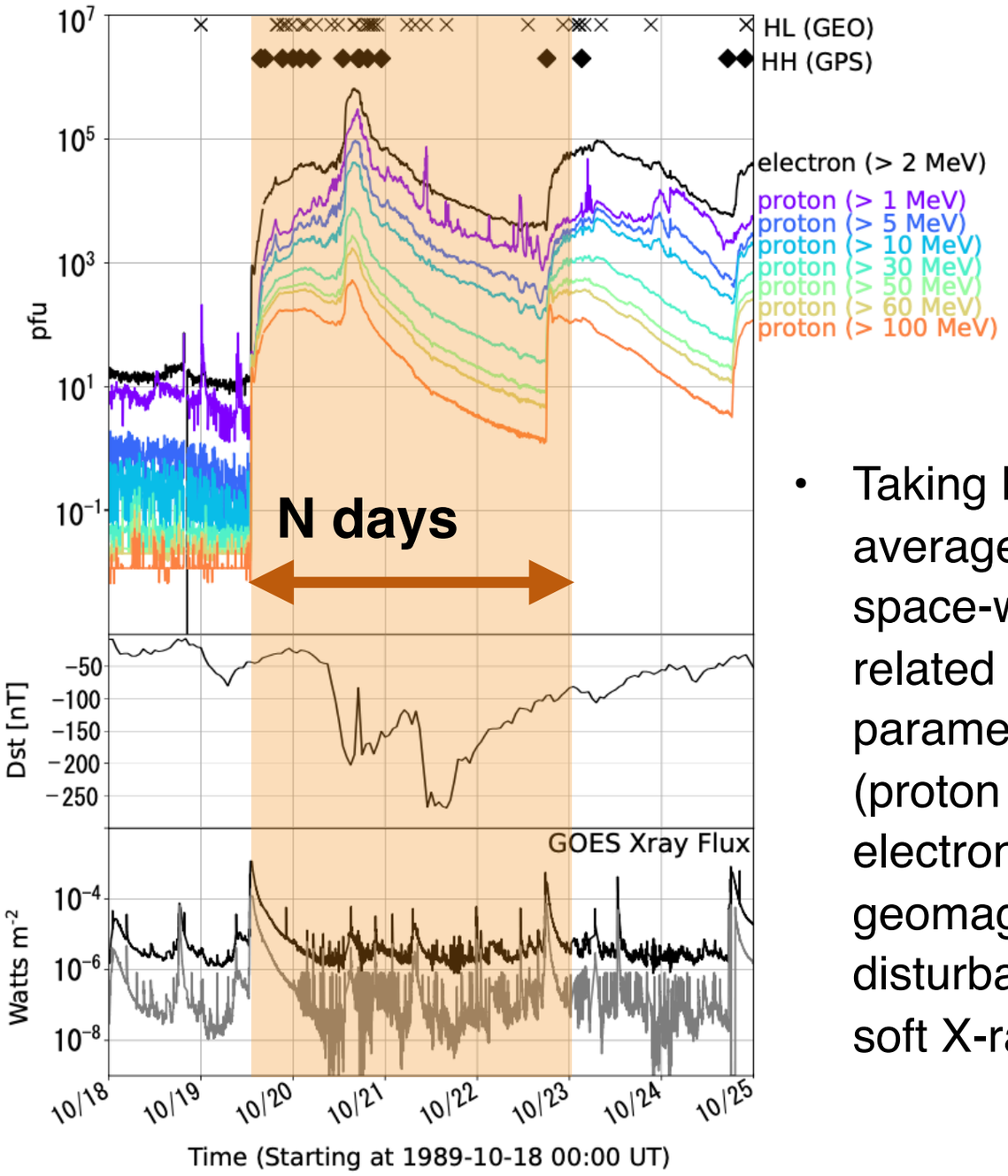
GEO satellites



GPS satellites



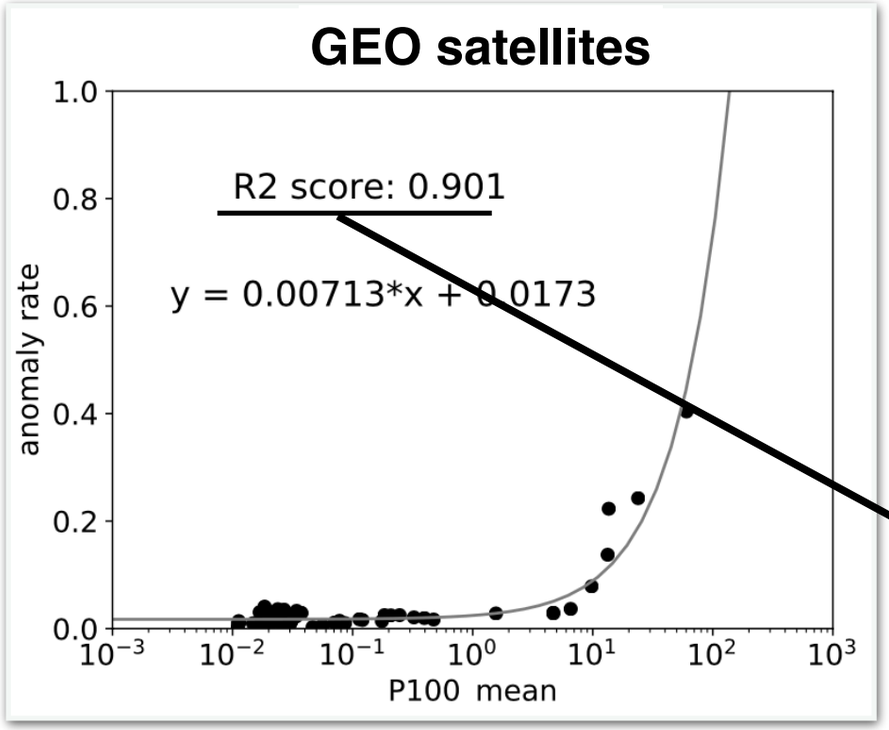
- Space-weather-related physical parameters



- Taking N-days average of space-weather-related physical parameters (proton flux, electron flux, geomagnetic disturbance, soft X-ray flux)

- 91 samples: X-class flare events from 1986 to 1990.

Result — Simple regression to all anomalies



$$R^2 = 1 - \frac{\sum(y_{true} - y_{pred})^2}{\sum(y_{true} - \overline{y_{true}})^2},$$

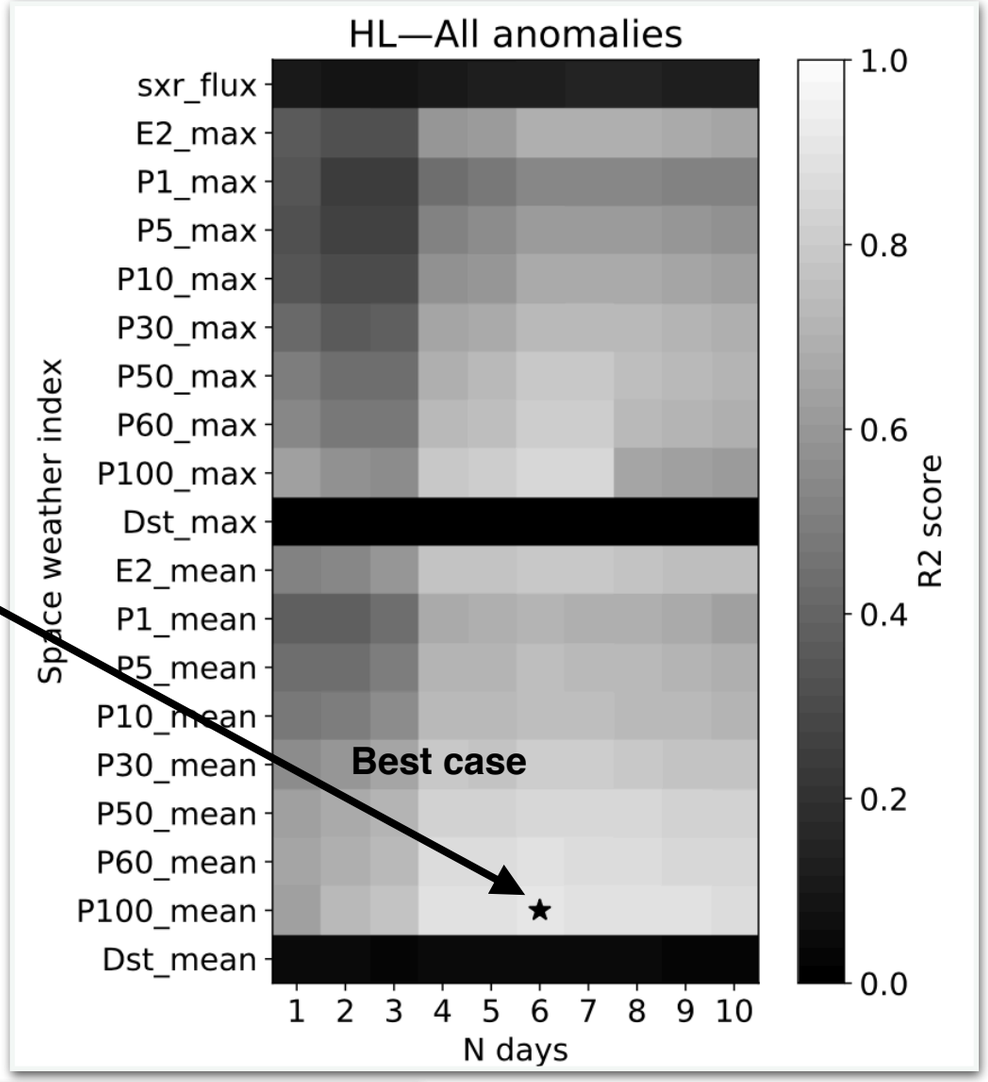


Table 1: The best R^2 scores for anomaly types or attributions and the prediction of satellite-anomaly rates in cases of X100 and X1000-class solar flare.

Orbit	Type or Attribution	R^2 score	Anomaly rate (X100)	Anomaly rate (X1000)
HL (GEO)	all	0.902	4.62	31.3
HL (GEO)	SE	0.910	4.57	31.0
HL (GEO)	SEU	0.895	4.22	28.6
HH (GPS)	all	0.931	7.07	48.1

- The rates are **~8 (X100) or ~50 times (X1000) larger** than the worst cases ever observed.

Summary

- For the purpose to **evaluate** the possible impact on **satellite anomalies** in case of a solar **superflare**, **single linear regressions of satellite-anomaly rate on space-weather indices** with different sampling windows was conducted.
  - The satellite-anomaly rate: the ratio of the total number of anomalies to that of operational satellites.
  - The space-weather physical parameters: SXR peak flux, the average and maximum of electron flux with its energy above 2 MeV, proton fluxes with 7 different energy ranges, and Dst index.
- As a result, the **satellite-anomaly rate** for all the anomalies (soft error, single event upset) was **correlated quite well (R2 score ~ 0.9)** to t**he average of proton flux with its energy higher than 100 MeV for 6 days.**
- Assuming the upper limit of the space-weather indices in case of X1000-class flare, the predictions of the **satellite-anomaly rates** showed that SE could occur on GEO satellites **~30 incidents** per satellite and on **GPS** satellites **~48 incidents** per satellite.
- Our results suggests that in case of a superflare, it could be anticipated that **all the satellites** suffer from anomalies, and the damages could be **~50 times severer** than the worst cases ever observed.