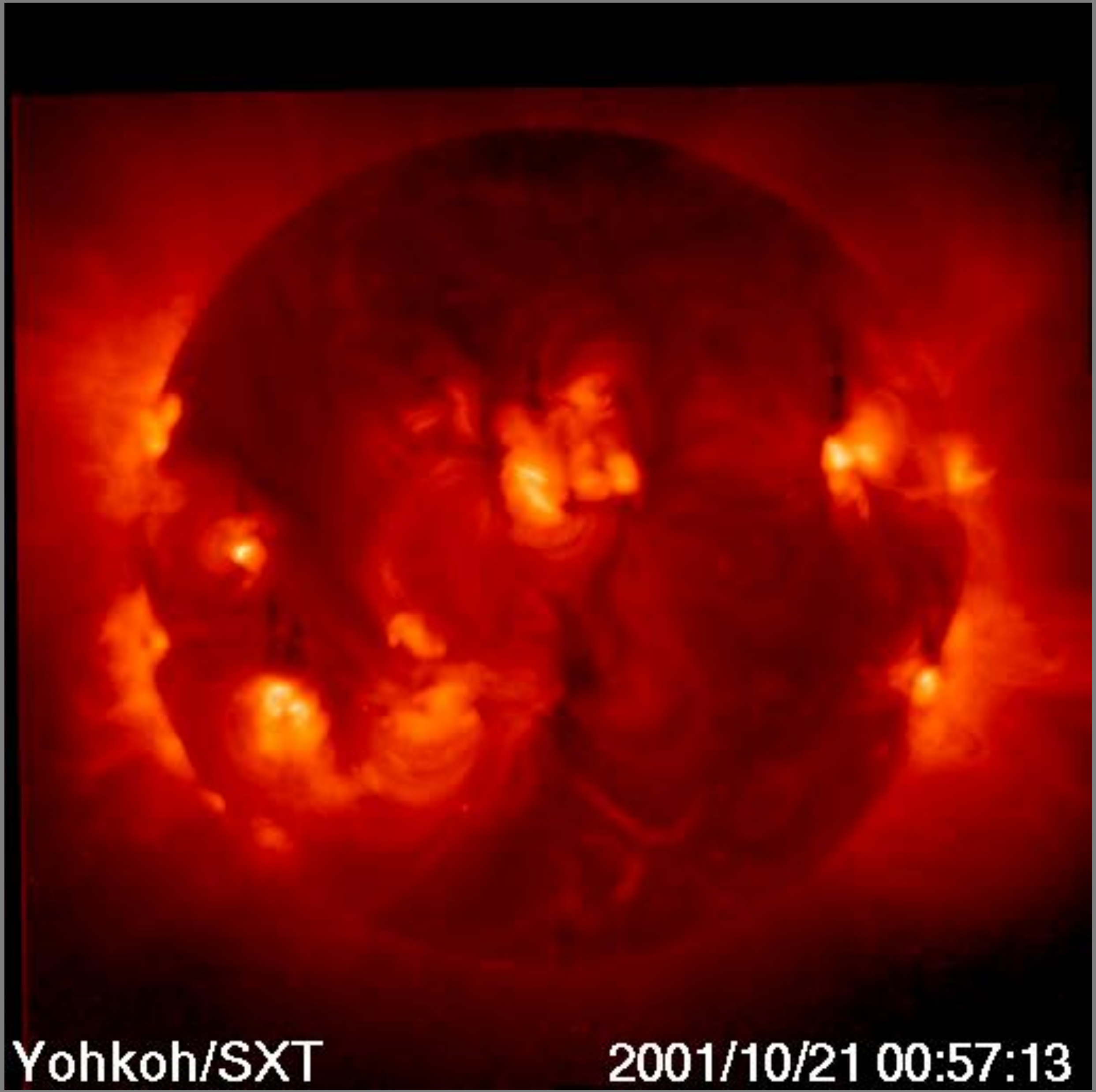
宇宙線 x 恒星フレア
＝ 若い太陽や太陽型星の宇宙線環境

行方 宏介/Kosuke Namekata

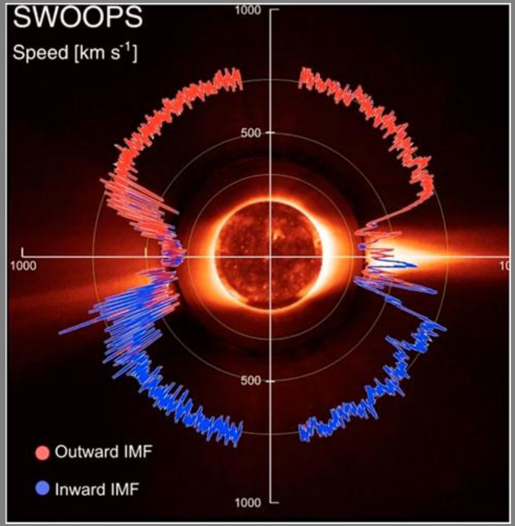
Kyoto University/The Hakubi Center for the Advanced Research,
NASA/Goddard Space Flight Center (JSPS Overseas Fellow),
The Catholic University of America

宇宙線 x □□□ 研究会 13:30-14:30JST (30+30 min)
2026年3月30日(月) (=0:30-1:30EDT 3月29日(日))

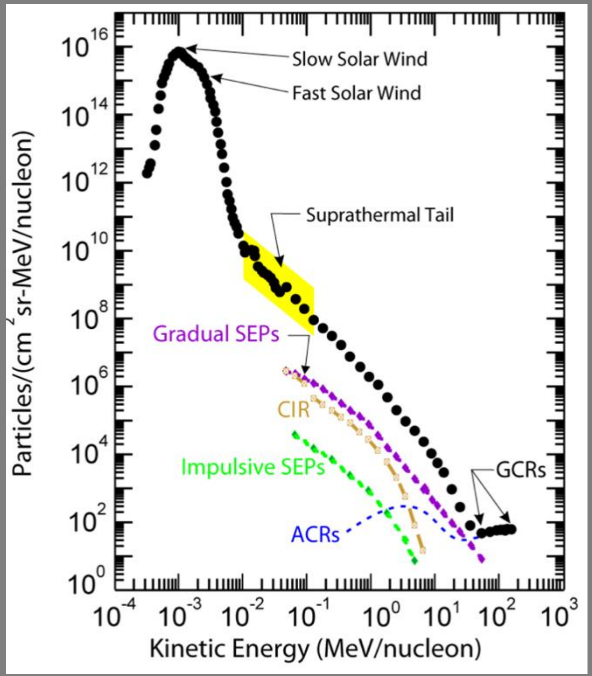
The Sun/Stars is a Source of Particles

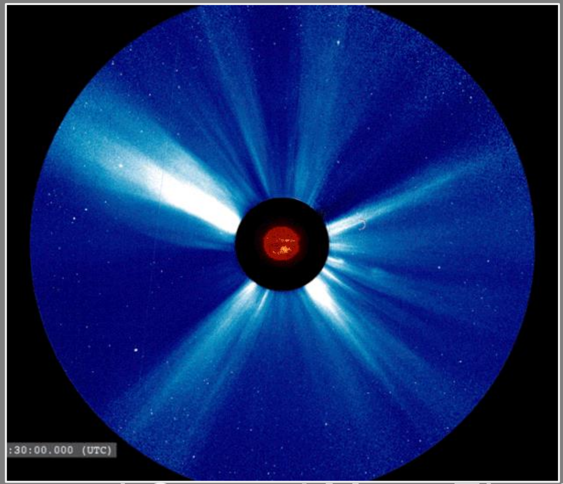


Solar Wind (0.5 – 5 keV)



McComas et al., 2013





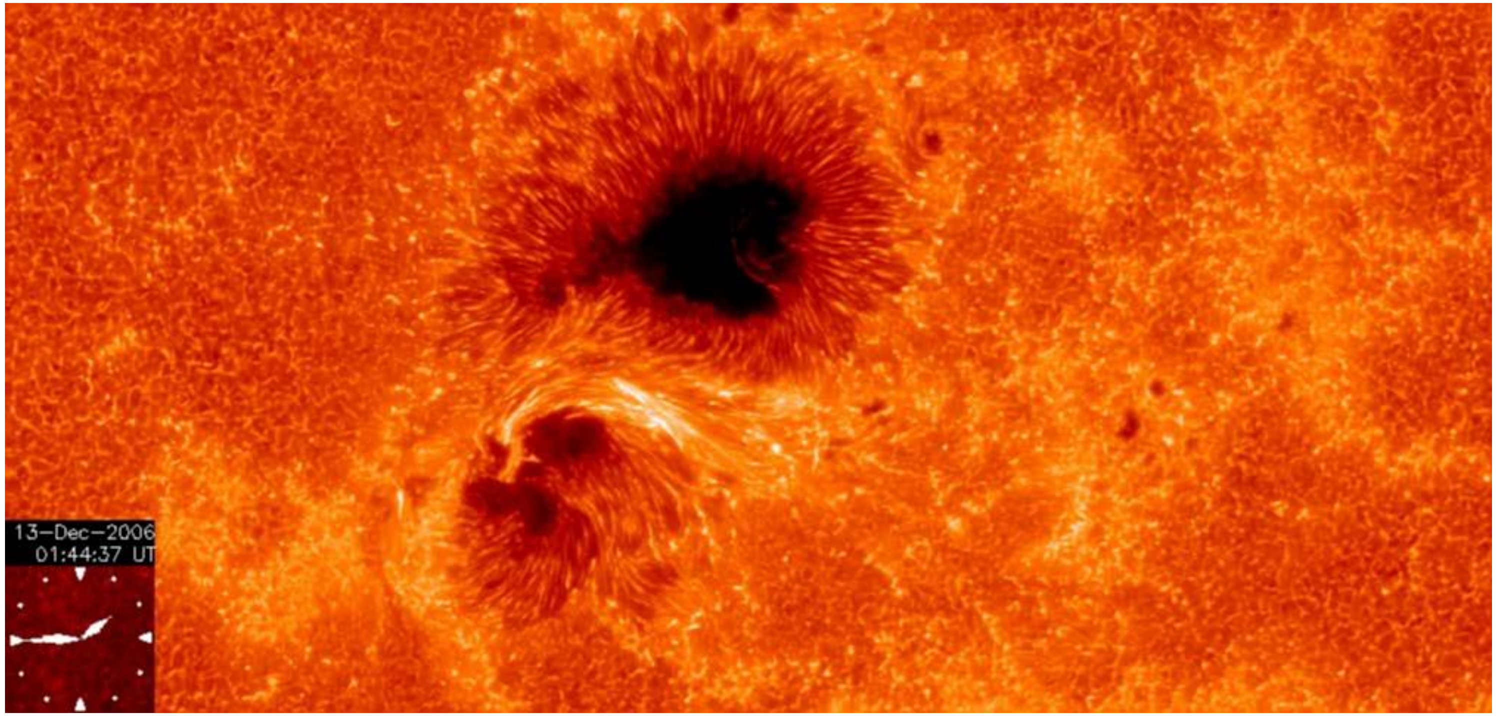
NASA STEREO

→ **Today I will focus on this side**

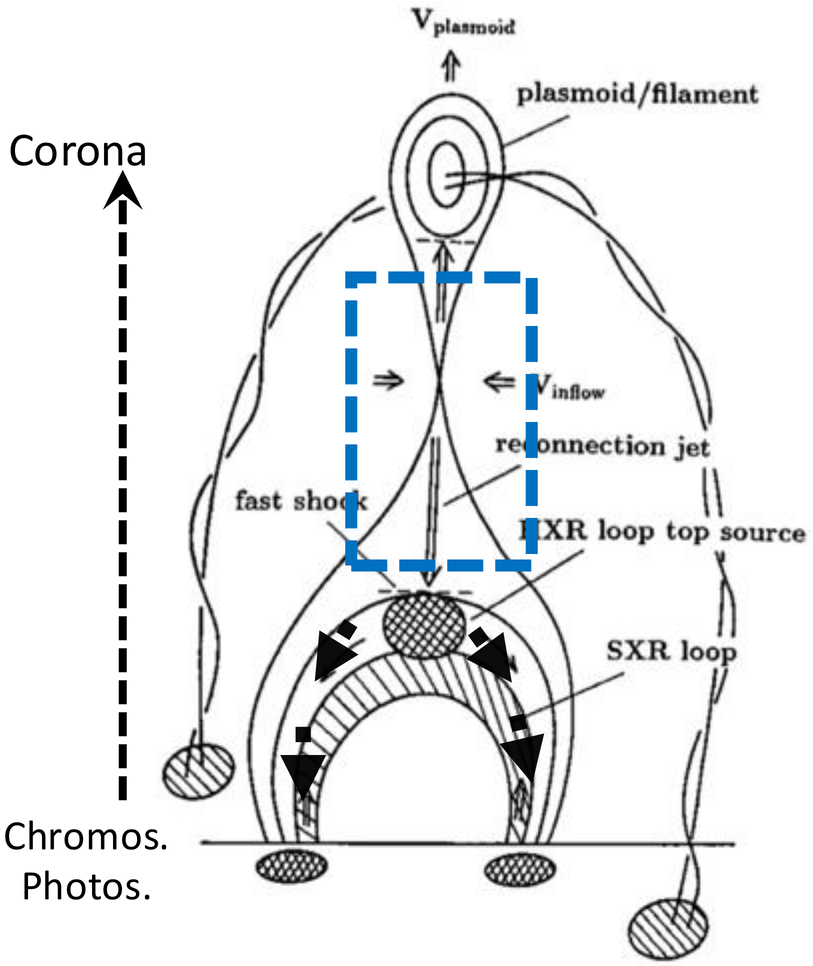
Flares and Coronal Mass Ejections-related Energetic Particles (SEPs) (100 keV – 数 GeV)

Research Field: Solar/Stellar flares

- Triggered by the magnetic reconnection.
- Energy: $10^{29\text{-}32}$ erg (=$10^{22\text{-}25}$ Joule)
- Impulsive SEPs (=Solar Energetic Particles) with unknown mechanism



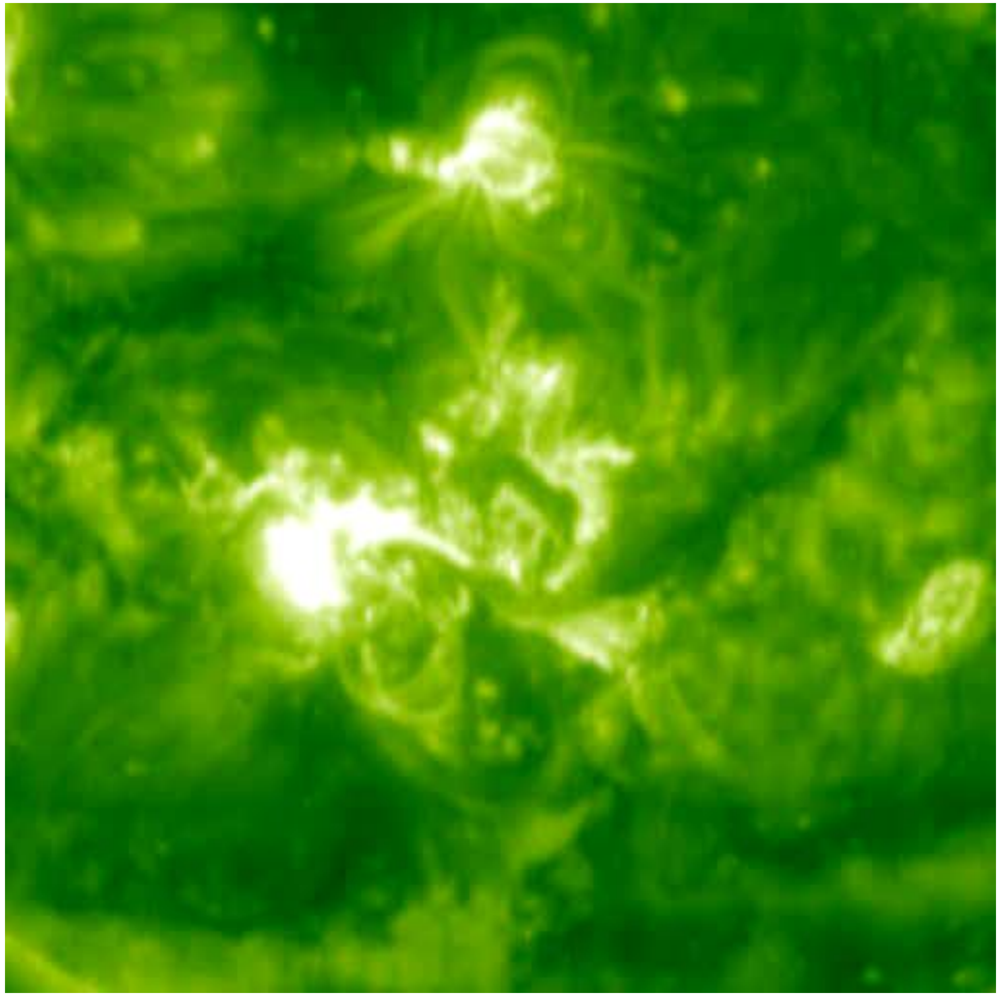
Unified picture of solar flares



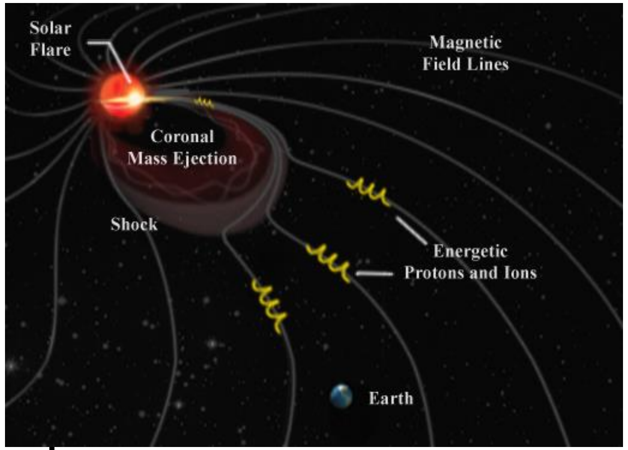
Shibata+1995

Coronal mass ejections (CMEs) and Particles from the Sun

Coronal Mass Ejections (CME) occur associate with flares

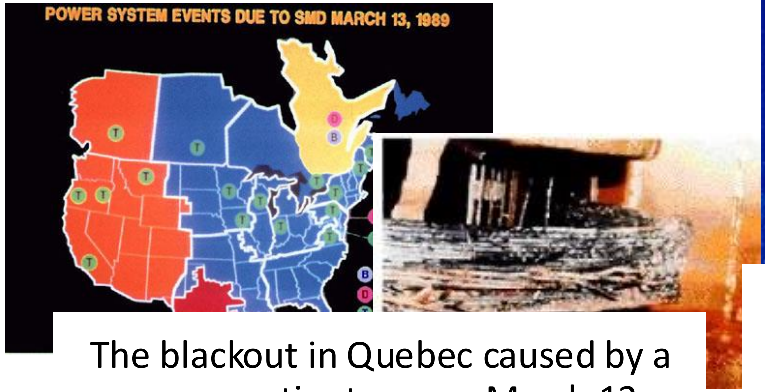


Gradual SEP: keV-GeV High energy particles are accelerated in CME shockwaves.

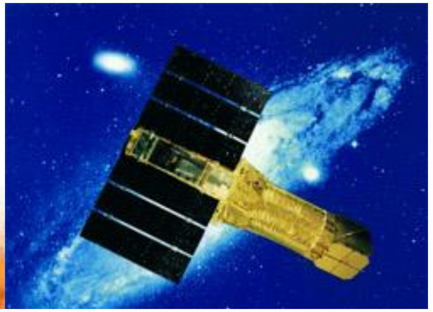


©V. Airapetian

Space weather



The blackout in Quebec caused by a geomagnetic storm on March 13, 1989



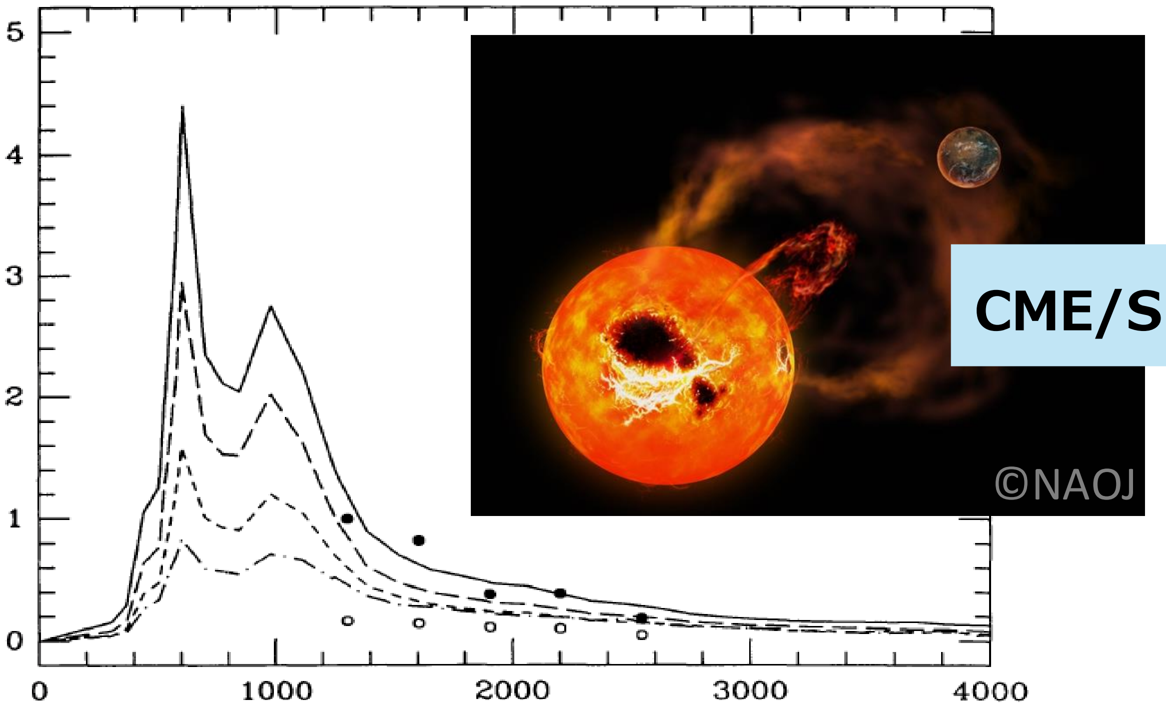
The X-ray observation satellite "Asuka" malfunctioned due to a solar flare

Stellar Flares and Potential Impact on Exoplanets

- In 2010s : Many types of stars in the universe are known to show stellar flare
  - ✓ Can CMEs/SEPs influence “exo”space weather?
  - ✓ What is the particle environment around different stellar-type environement?

Flares on Cooler stars [Hawley & Pettersen 1991]

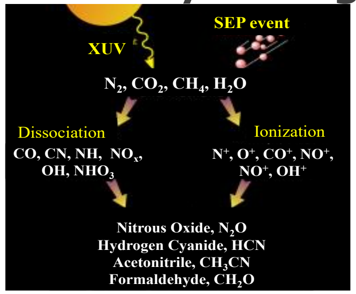
Stellar Flux



Time [sec]

CME/SEP

Chemistry Change



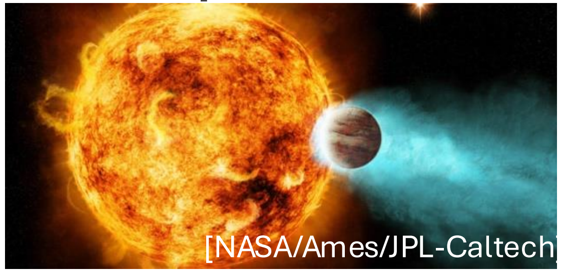
[cf. Airapetian+16]

Stellar mass & angular momentum evolution

[Cranmer+17]

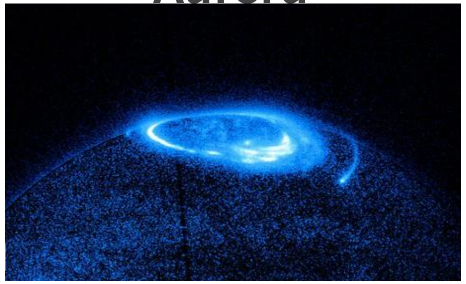
©Airapetian’s presentation

Atmospheric erosion



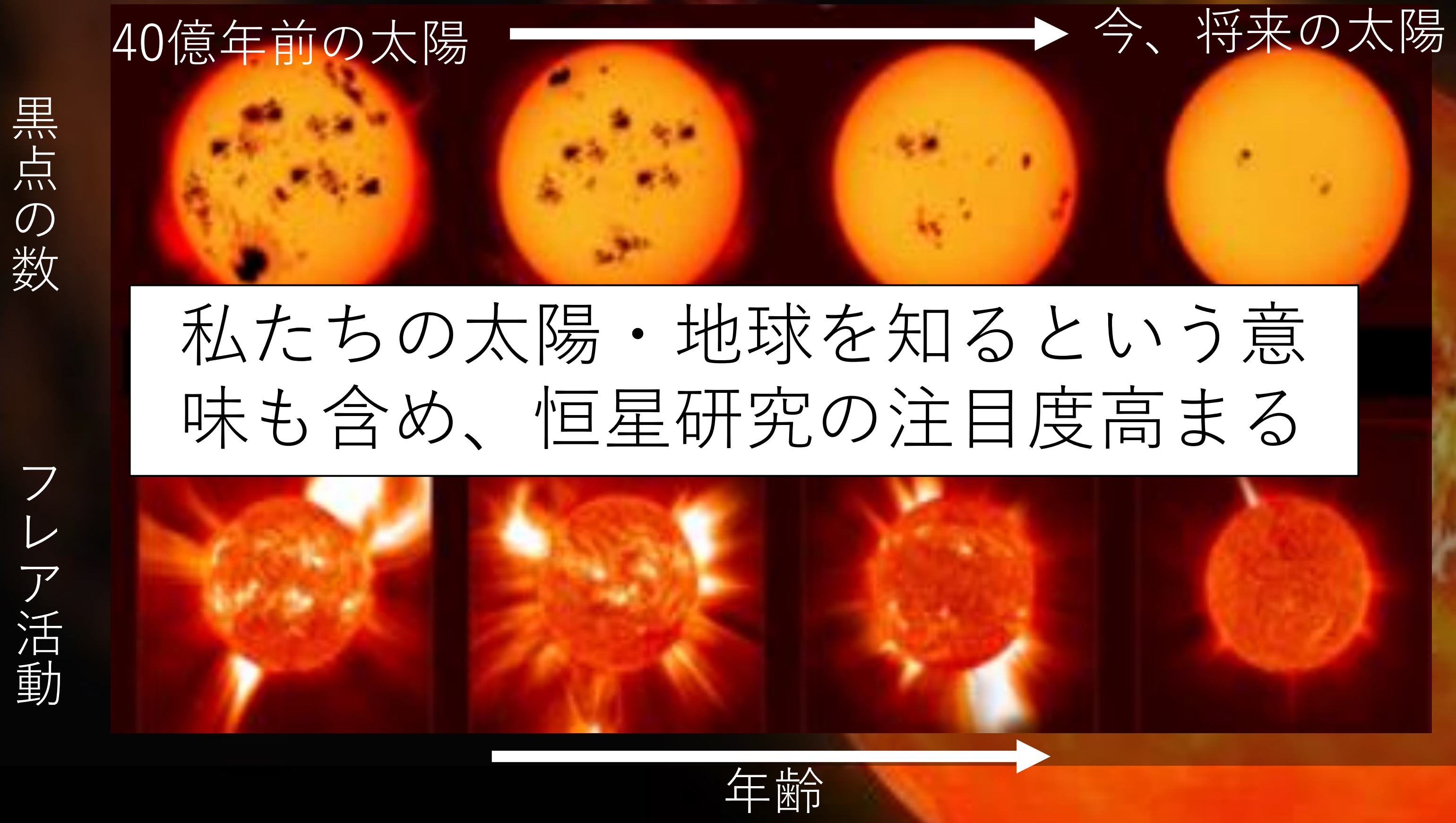
[cf. Hazra & Vidotto+22]

Aurora



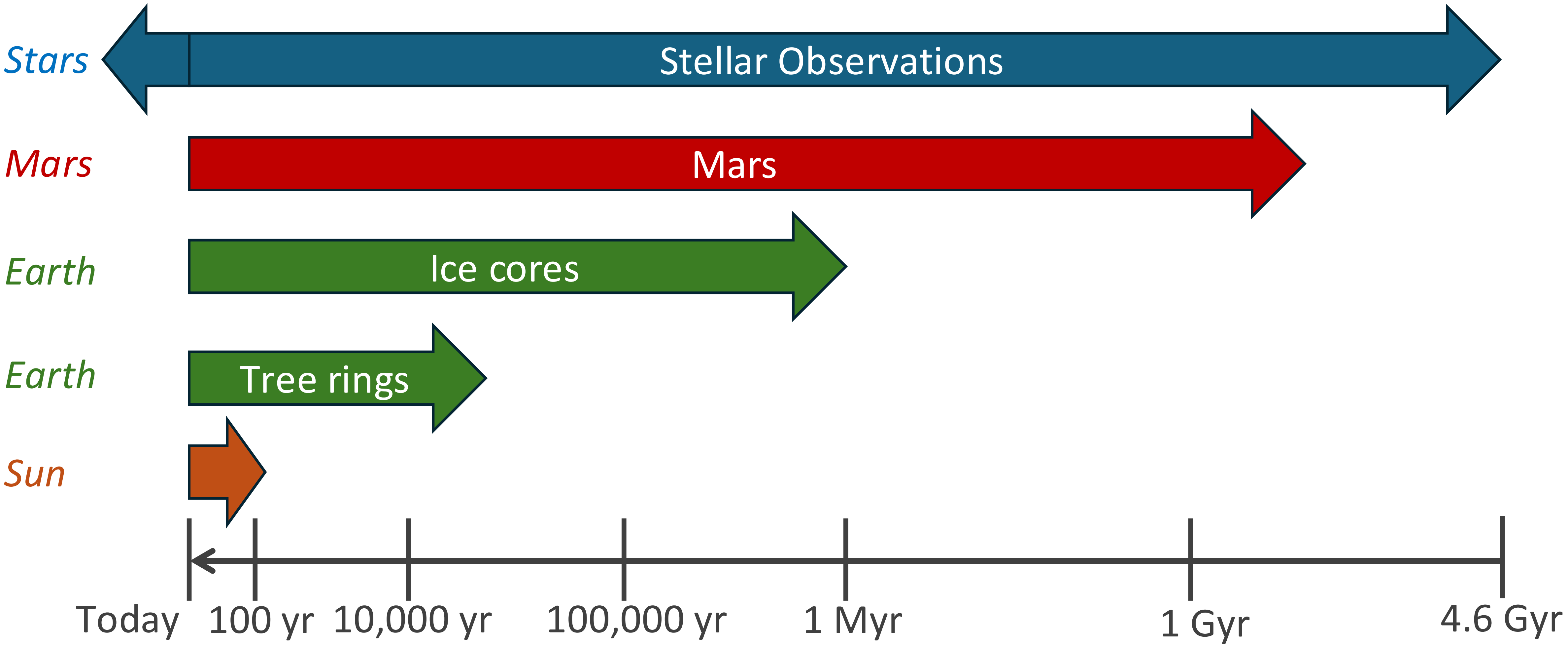
近年のトレンド: “Stars as the Sun” Concept

- 過去170年の太陽観測では46億年の「粒子環境の進化」は解明不可
- 宇宙にある**「様々な年齢の太陽型星」での恒星フレア**を見れば、**太古の、近い過去の、または将来の太陽の活動性**を知れる



私たちの太陽・地球を知るという意味も含め、恒星研究の注目度高まる

Inferring Sun's Particle Environment from Stars



From KISS workshop, cf. Loyd et al. 2025

Key Questions

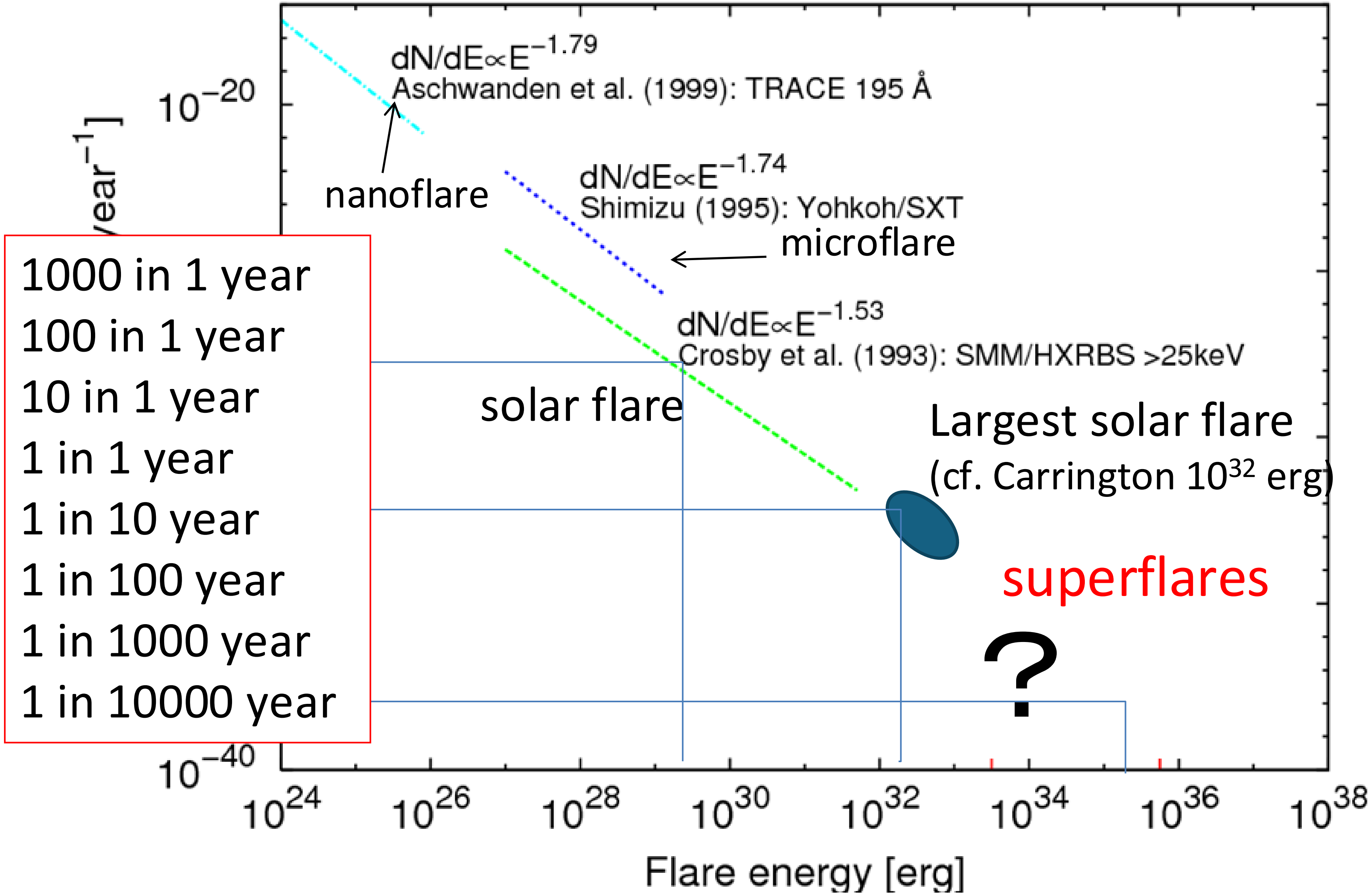
Questions:

- *What is the maximum energy limit and frequencies of flares/CMEs/SEPs on our Sun and young Suns?*

Difficulties:

- Particles are difficult to observe.
- Estimates from flares/CMEs are the only way.

Can superflares (>10^{33} erg) occur on the Sun?



- Frequency-energy relation shows a universal power law: $dN/dE \propto E^{-1.5 \sim -1.9}$

✓ Largest flare (10^{32} erg) occur once in 10 years

<u>Questions</u>

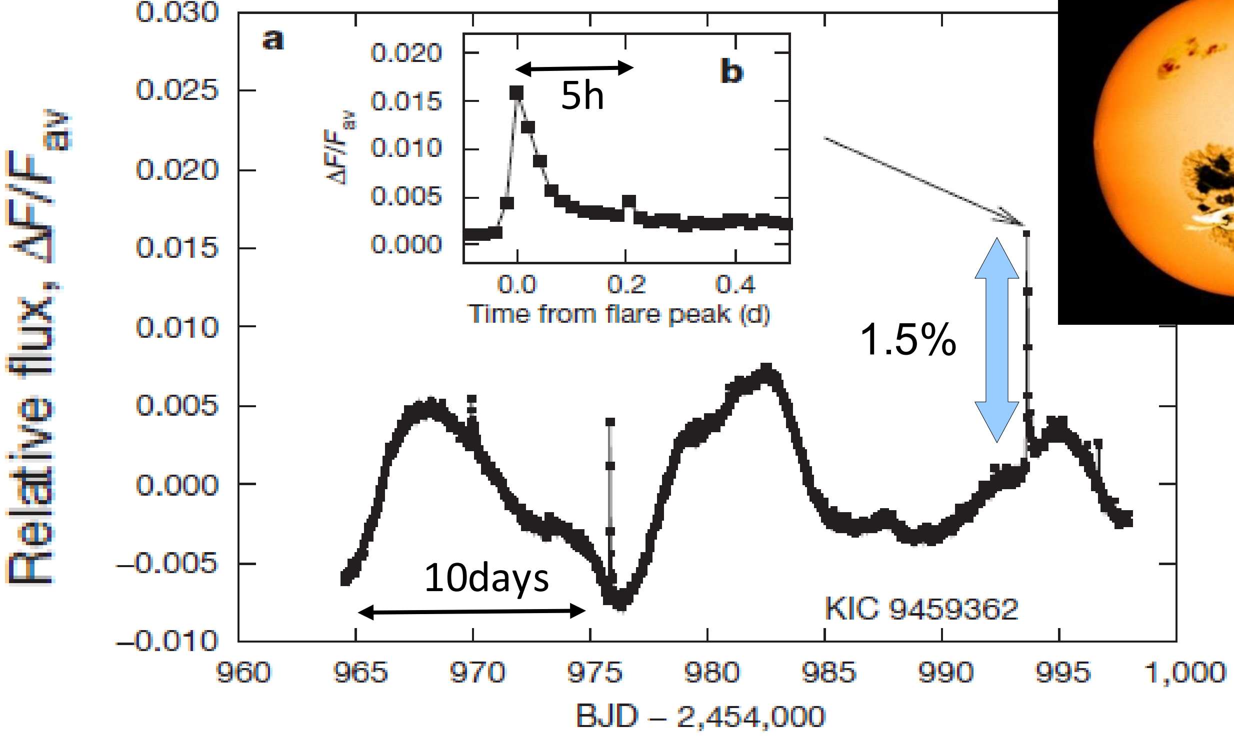
- Can “superflares” occur on our 4.6-Gyr-age Sun?
- What is the flare rate from the young Sun?

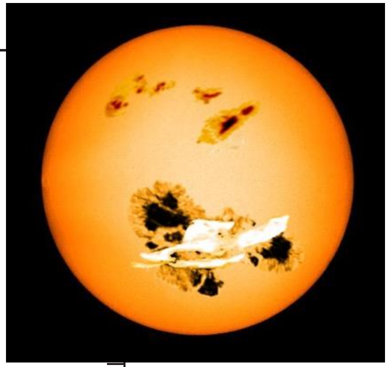
→ Observe many young Sun-like stars!!

Discovery of Superflare on Matured Sun-like Stars

- >2000 superflares ($10^{33\text{-}36}$ erg) were discovered on Sun-like stars after 2012.

Fig. Lightcurve of superflare

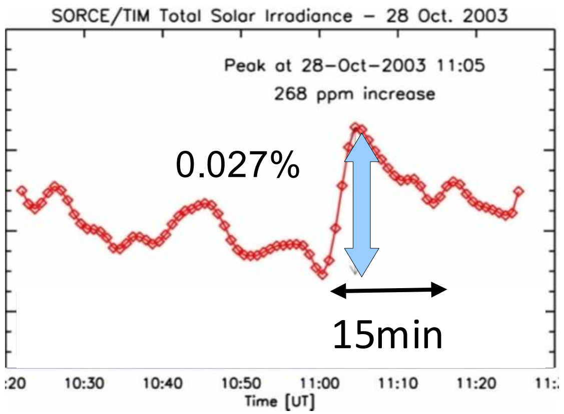




Maehara et al. (2012), Nature

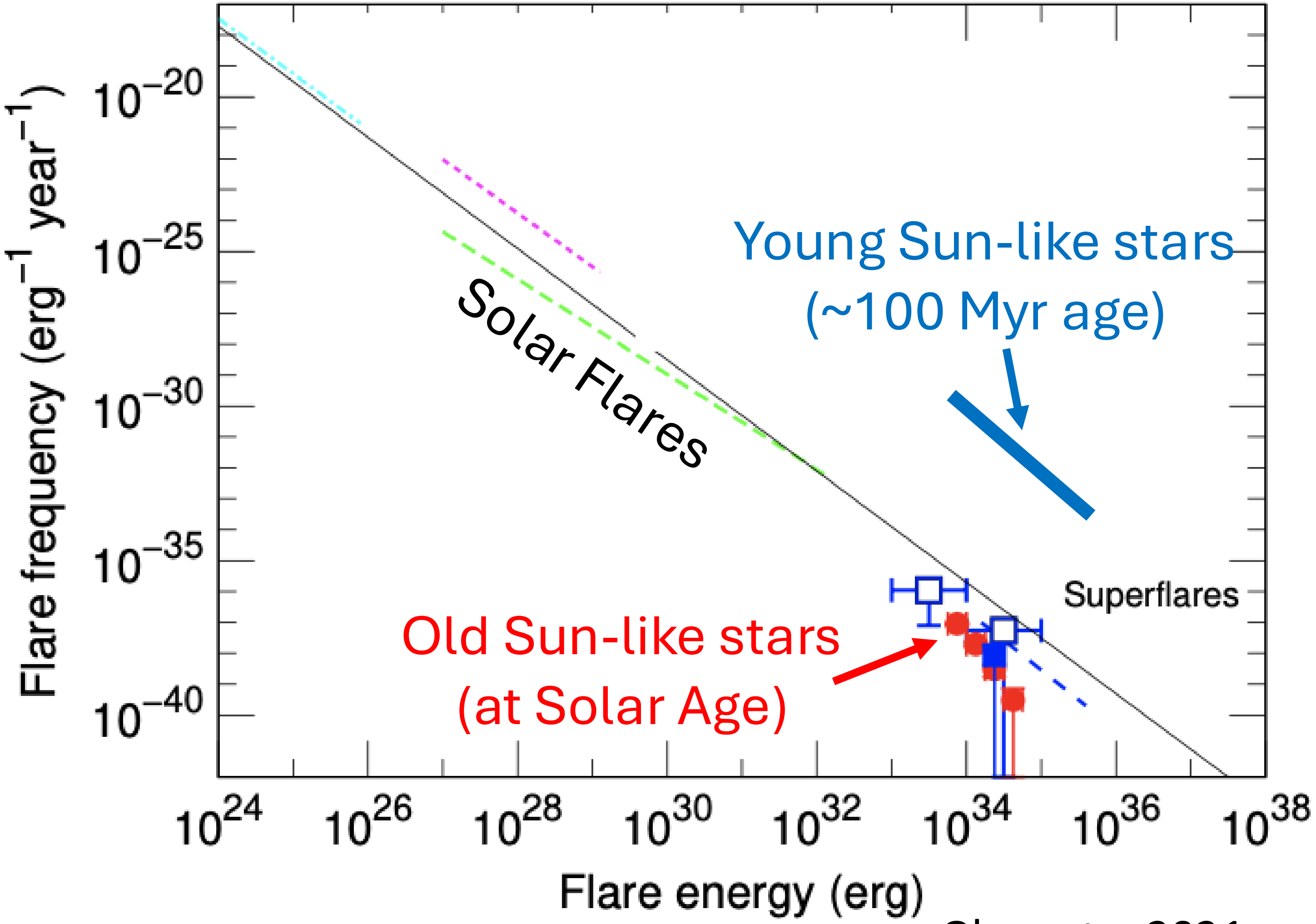
Maehara et al. 2012 Nature,
Shibayama et al. 2013 ApJS
Maehara et al. 2015 EPS,
Notsu et al. 2019, ApJ
Okamoto et al. 2021, ApJ
Vasilyev et al. 2024, Science

Largest solar flares



Kopp et al. (2005)

Flare Frequency of the Sun-like stars



Okamoto+2021

- <u>Solar Age (~ 4.6 Gyr)</u>

✓ Sun-like stars at solar age produce superflares once in 100-1000 yrs, consistent with solar statistics

→ The Sun can produce superflares in 100-1000 yrs??

- <u>Young Age (~100 Myr)</u>

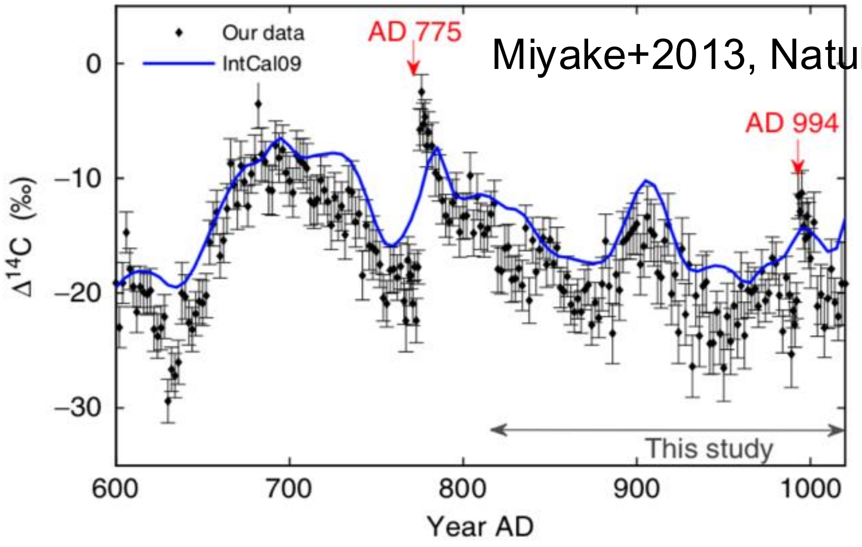
✓ Young Sun produce superflares ~once in a day.

→ The young Sun might have affected the earth environment dramatically!!

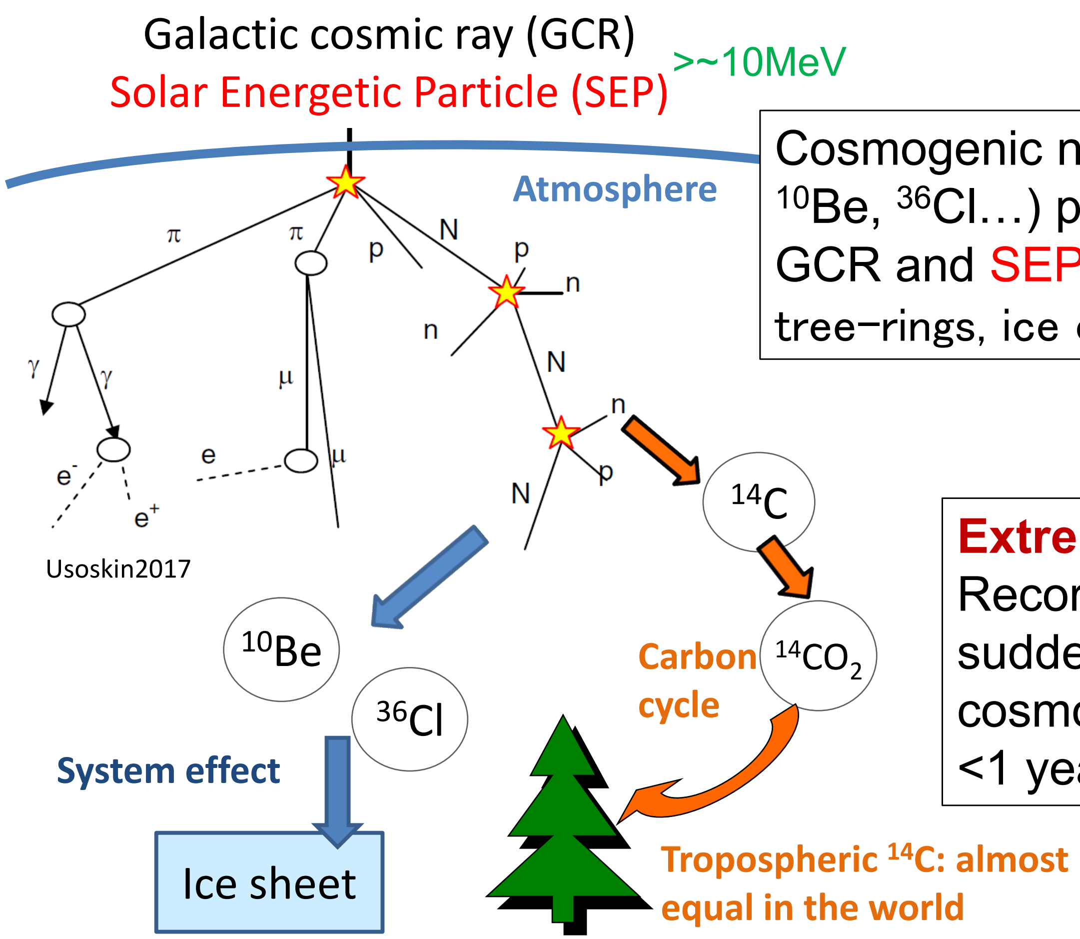
地球地上の同位体からの極端宇宙天気現象

- 過去数万年の太陽の極端宇宙天気現象を示唆する年輪・アイスコアの同位体と矛盾ない ⇒ 過去、太陽でもスーパーフレア/巨大SEPイベントが発生した可能性を支持

- Tree rings (^{14}C)
  - Miyake et al. (2012, 2013), etc
- Ice core (^{10}Be, ^{36}Cl time changes)
  - Mekhaldi et al. (2015), etc



Miyake+2013, Nature



Cosmogenic nuclides (^{14}C, ^{10}Be, ^{36}Cl…) produced by GCR and SEP → Recorded in tree−rings, ice cores,…

Extreme SEP event
Recorded as a sudden increase of cosmogenic nuclides <1 year

©F. Miyake

Young Sun's Role to Solve the "Fain Young Sun Paradox"??

- Massive SEPs (and e^- air shower) can generate in the early Earth/Mars atmosphere:
  - ✓ Greenhouse gas → solution to "FYSP" ??
  - ✓ Prebiotic chemistry & amino acid [Kobayashi+23] → origin of life?

Ion pair production per 1.25 NO_x

$N_2 + e^- \rightarrow 2N(^4S) + e^-$

$N(^4S) + O_2 \rightarrow NO + O(^3P)$

$N(^2D) + O_2 \rightarrow NO + O(^3P)$

$N(^4S) + NO \rightarrow N_2 + O(^3P)$

$H_2O + Ion^+ \rightarrow H + OH + Ion^+$

$NO + NH \rightarrow N_2O + H$ laughing gas

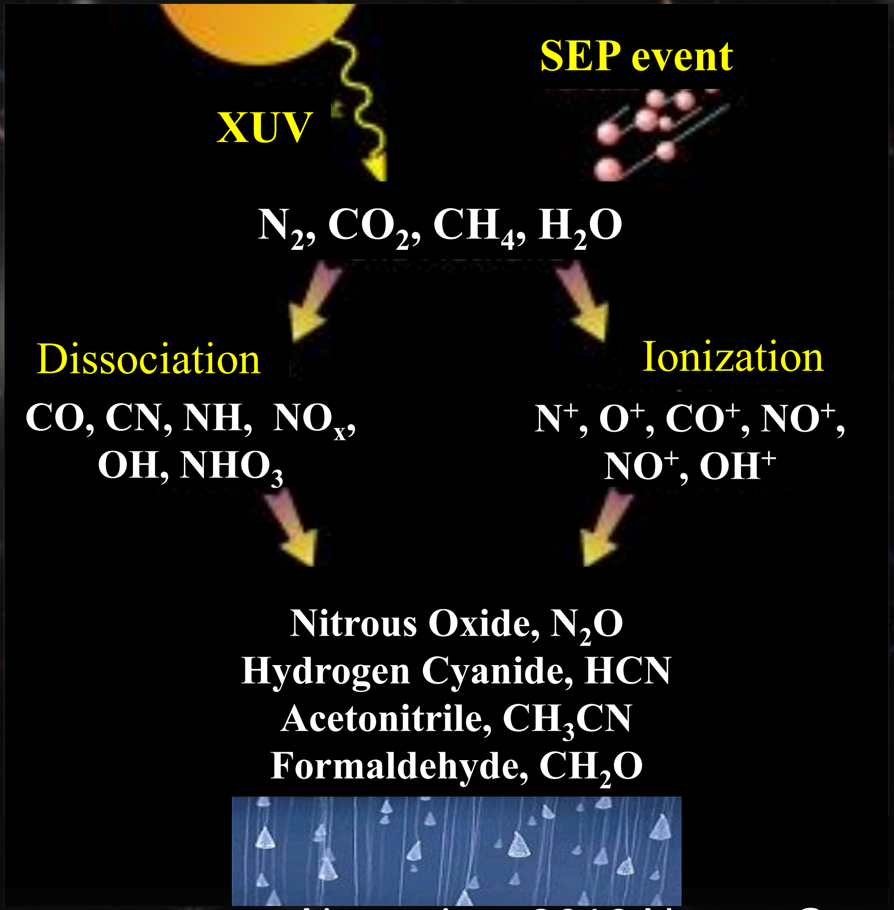
$NO + CH \rightarrow HCN + O$

$CH + CN \rightarrow HCN + H$

$CH_2 + N(^4S) \rightarrow HCN + H$

$CH_3 + N(^4S) \rightarrow HCN + H + H$

$HCN + H_2O \rightarrow H_2NCOH$ formamide

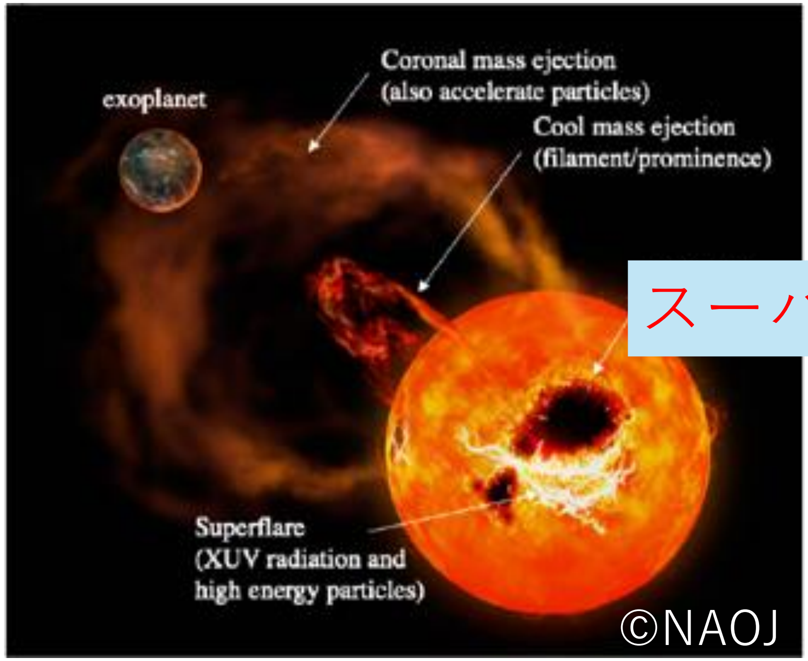


Airapetian+2016 Nature Geoscience

NASA/JWST

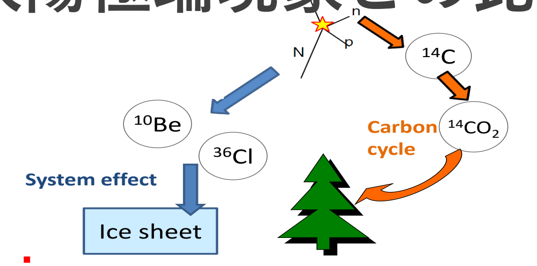
Next Questions in 2020s: Do superflares produce huge CMEs?

- 太陽型星スーパーフレア観測、太陽系・系外惑星系研究を結びつけるには恒星での<u>CME・SEPイベントの特徴づけが期待される</u>

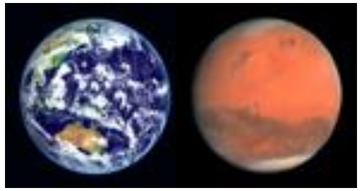


スーパーCME

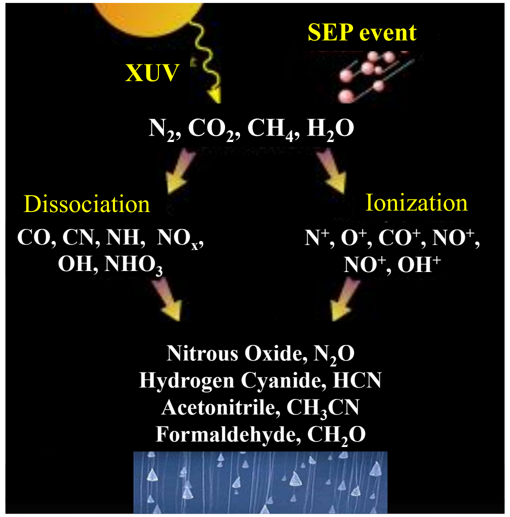
太陽極端現象との比較



系外惑星へ影響



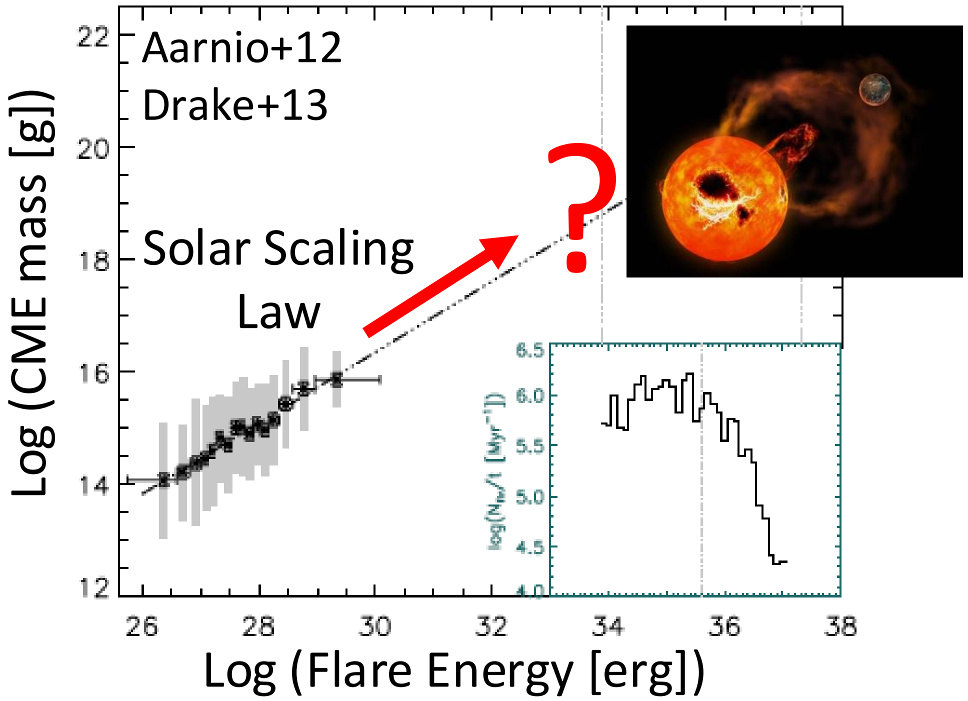
若い太陽への影響



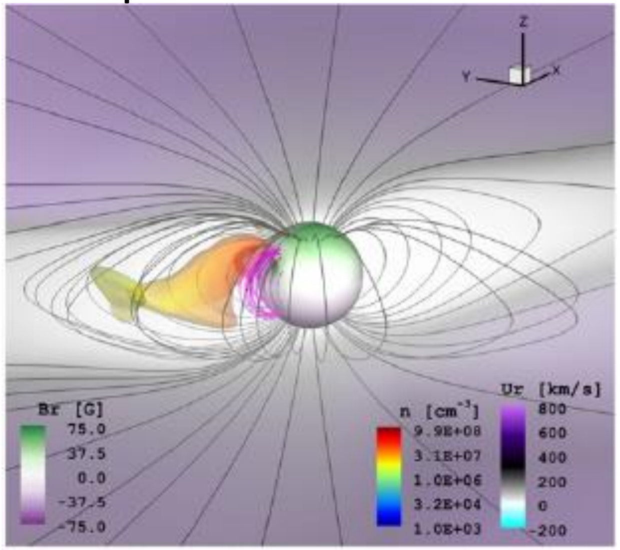
Do Young Sun-like Stars Produce Huge CME/SEP Event?

- Solar flare-CME relationship predicts frequent, gigantic CMEs from active stars.
- On the other hand, theoretical study suggests strong stellar magnetic field & different topology can change what stellar CMEs looks like [e.g., Alvarado-Gomez+2018, Sun+2022].

⇒ No Observational Evidence: "Missing CME Problem"



Strong magnetic field and/or dense coronal wind can change the eruptions and observational signature?



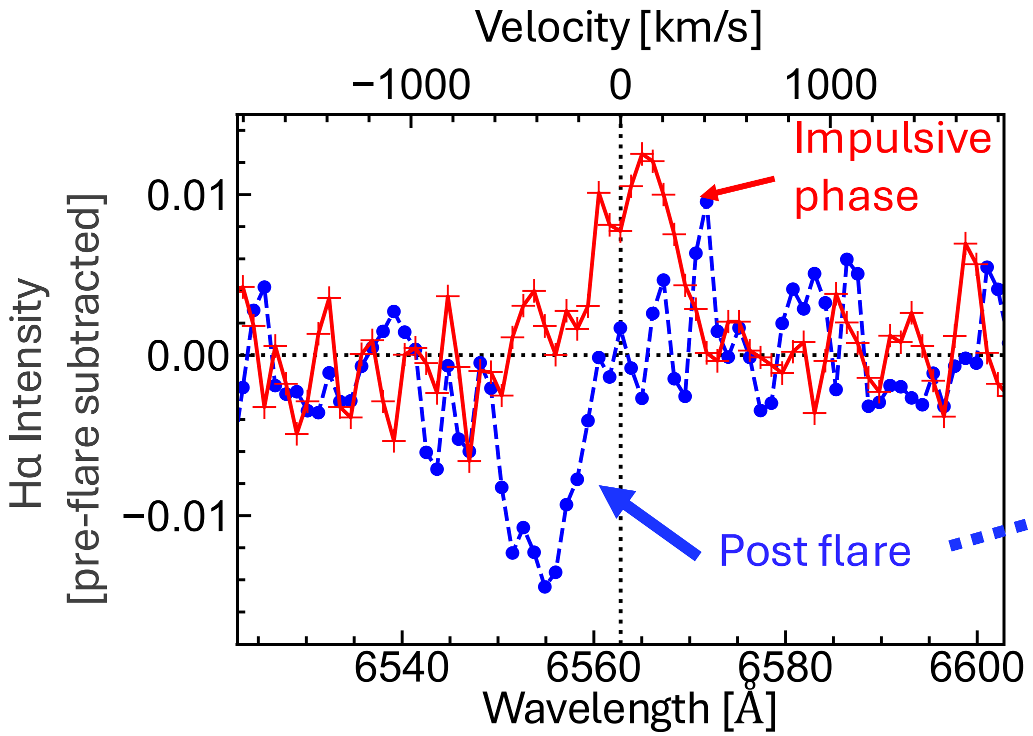
E.g. magnetic suppression (by Alvarado-Gómez+18)

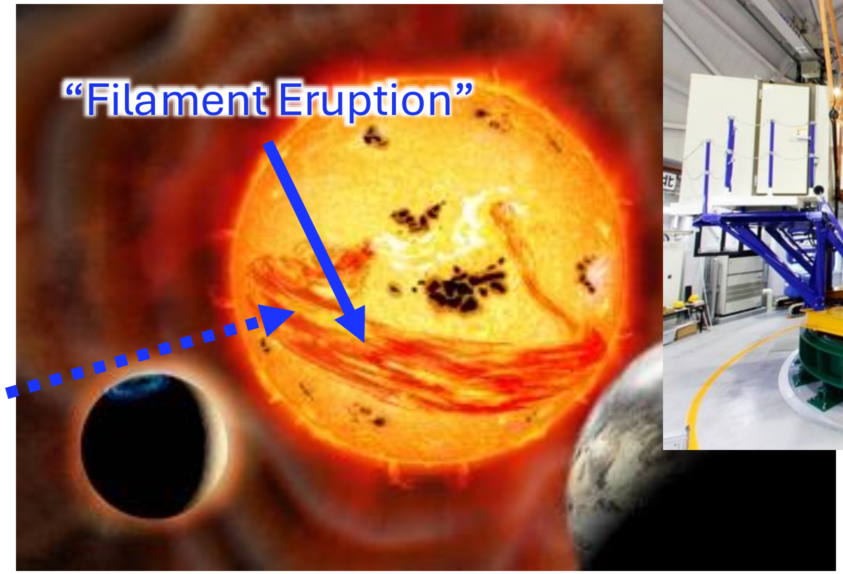
Recent Observations: Frequent, Huge CME Occurrence

- First discovery of a massive CME signatures (as a rapid Doppler-Shift signature) from superflares on a young Sun-like star.

  ⇒ The missing CME problem was almost solved.

- Frequency ~ up to 1 events / 5 days → **Very high**





Imaginary picture of our findings (©NAOJ)

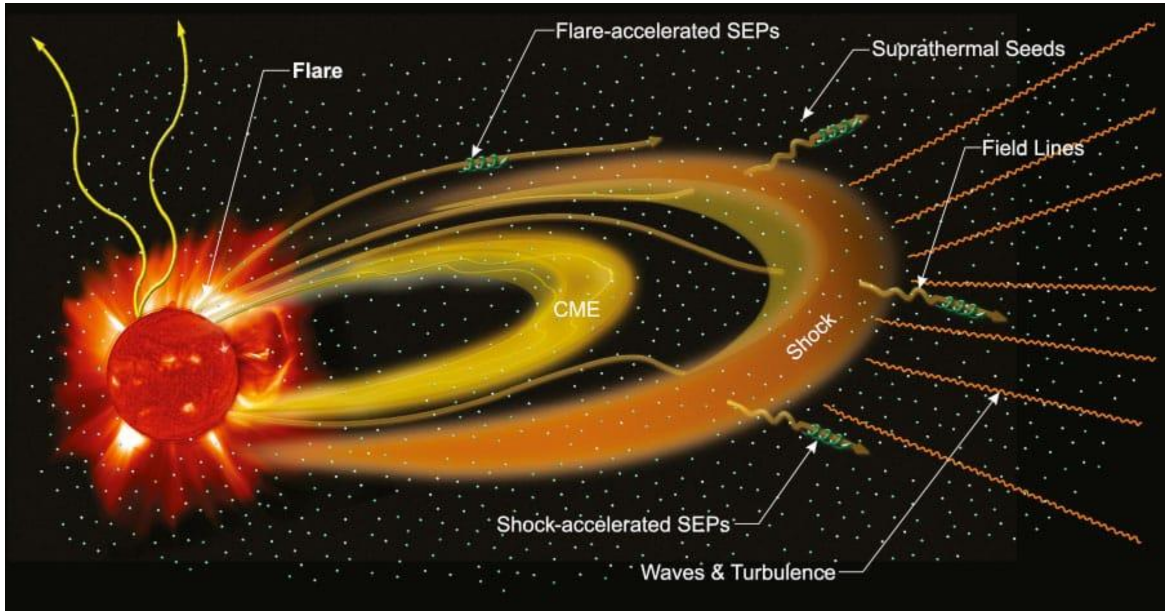
Namekata K.+ 2022 Nature Astronomy, 6, 241

Namekata K.+ 2026 Nature Astronomy, 10, 64

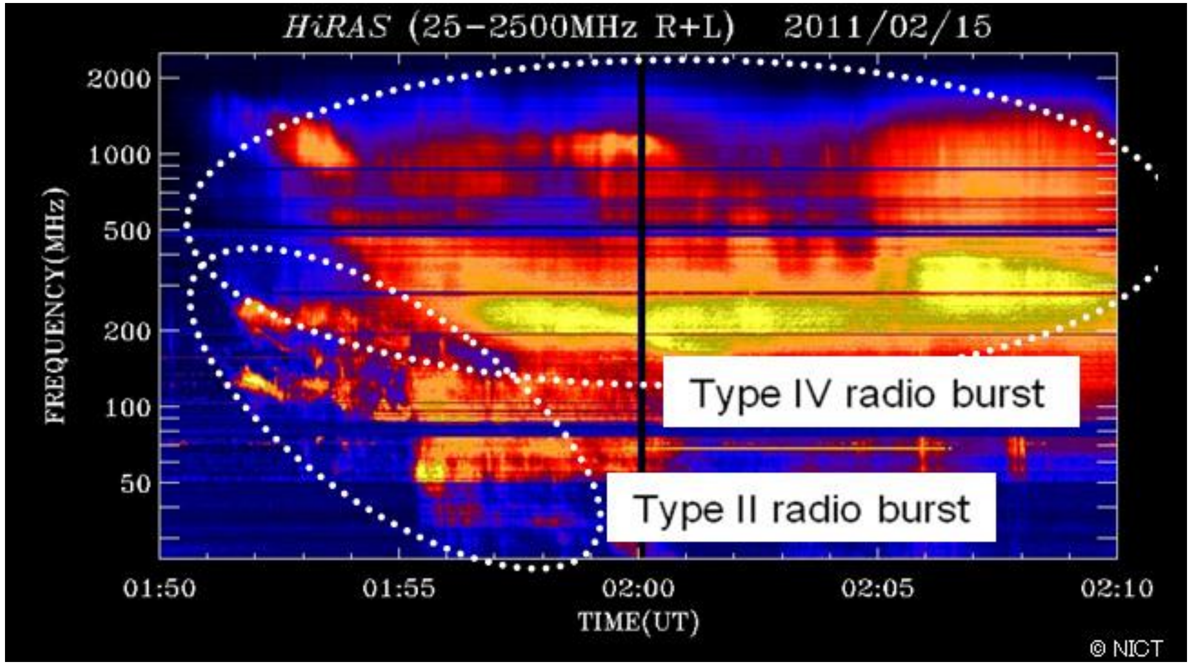
The Occurrence of Shockwave as a Source of SEP??

- Radio MHz observation can detect shockwave (type-II radio burst).

↔ Missing in stellar observations



Solar radio observations

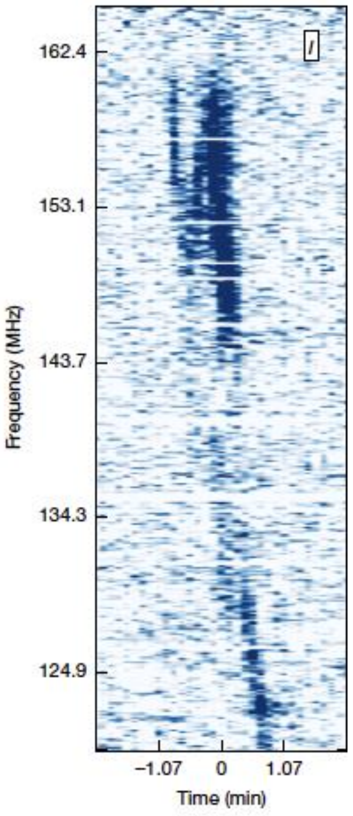


Recent Discovery of CME-Shockwave from Low-Mass Stars

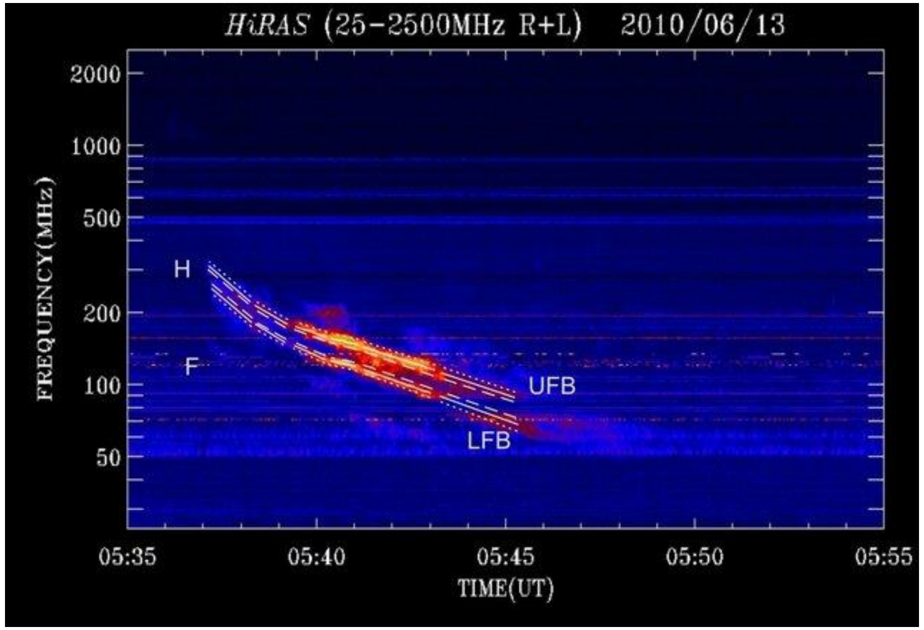
Article

Radio burst from a stellar coronal mass ejection

Challingham+2025, Nature



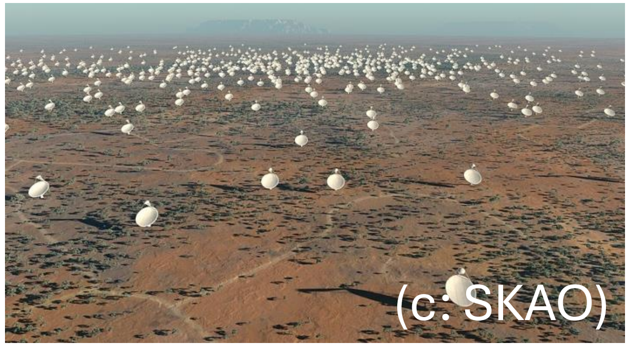
Solar radio burst



- <u>A shockwave occurrence</u> was confirmed for the first time.
- [late-20s~30s] SKA (2027~) can be a game changer in shockwave/SEP detection

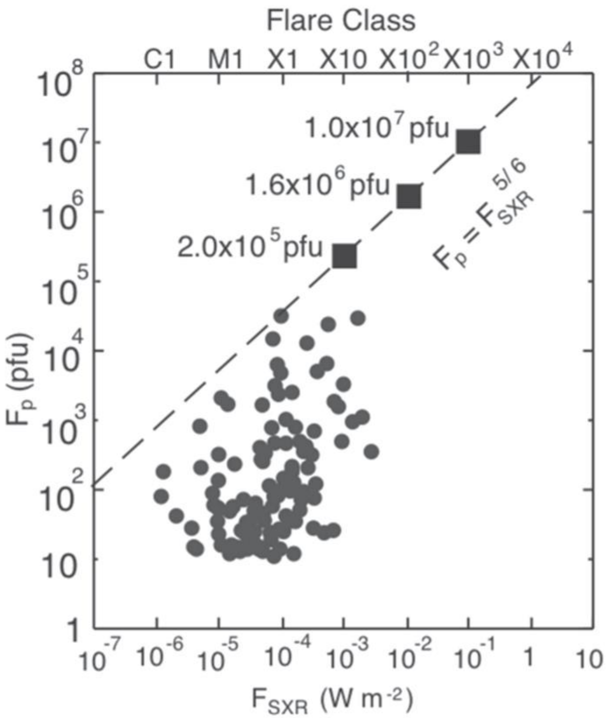
SKA(-Low)

- 2027~
- Frequency : 50-350 MHz
- South hemisphere

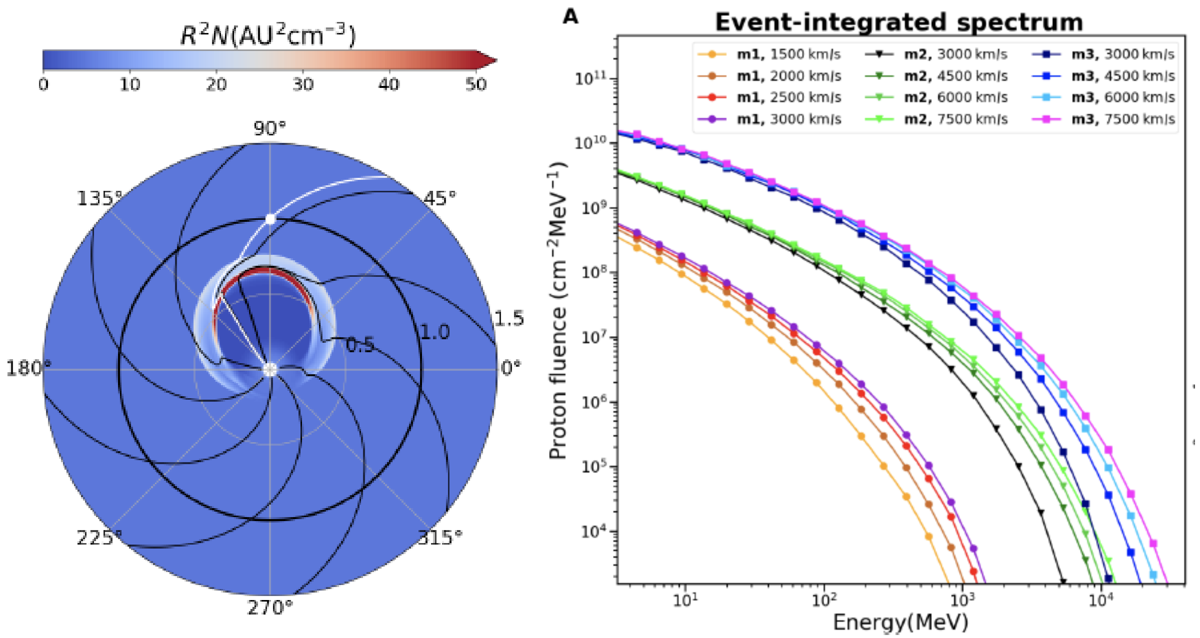


Path Toward the Particle (SEP) Environment

- Directly observing SEP is SO HARD
- Solar scaling laws have large uncertainty [cf. Takahashi et al. 2016]
- Several trials and ideas:
  - ✓ Data-driven CME/SEP model? [cf. Hu et al. 2022, Science Advances]
  - ? <u>Future:</u> CME imprint or aurora in exoplanet atmosphere? (e.g. JWST)



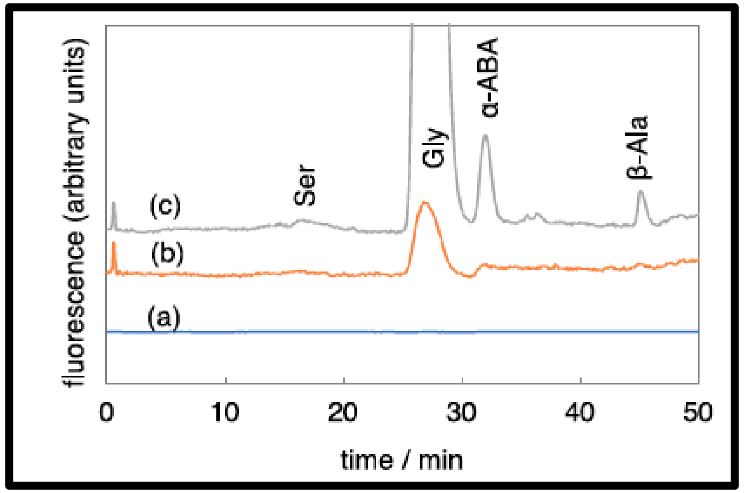
From Takahashi et al. 2016



Hu et al. 2022, Science Advances

Recent Experimental Study Simulating the early Earth/Mars

- Gas chemical reaction to 2MeV proton beam irradiation at Laboratory, led by Japan's group [Kobayashi+23, 26]
- Input: Observed flare/CME frequency & simulated SEP
- Result: Amino acid & Greenhous gasses



Protons@Tandem Accelerator (Tokyo Tech)

Starting materials
- Gas mixture:

CO_2, N_2, CO, H_2 (H_2O) with various mixing ratio

Proton irradiation
- Tandem accelerator
- Tokyo Tech: 2.5 MeV
- Tokyo City Univ: 2.0 MeV

<u>Future in 2020s/30s</u>

- Case for Exoplanetary atmosphere?
- With Constraint from JWST observations [led by Kajikiya-san (Science Tokyo)]

International Team & Review Paper on Stellar Particles

- Interdisciplinary team workshop on stellar particles
- From solar-stellar astrophysics and exoplanetary-planetary physics

Review Paper

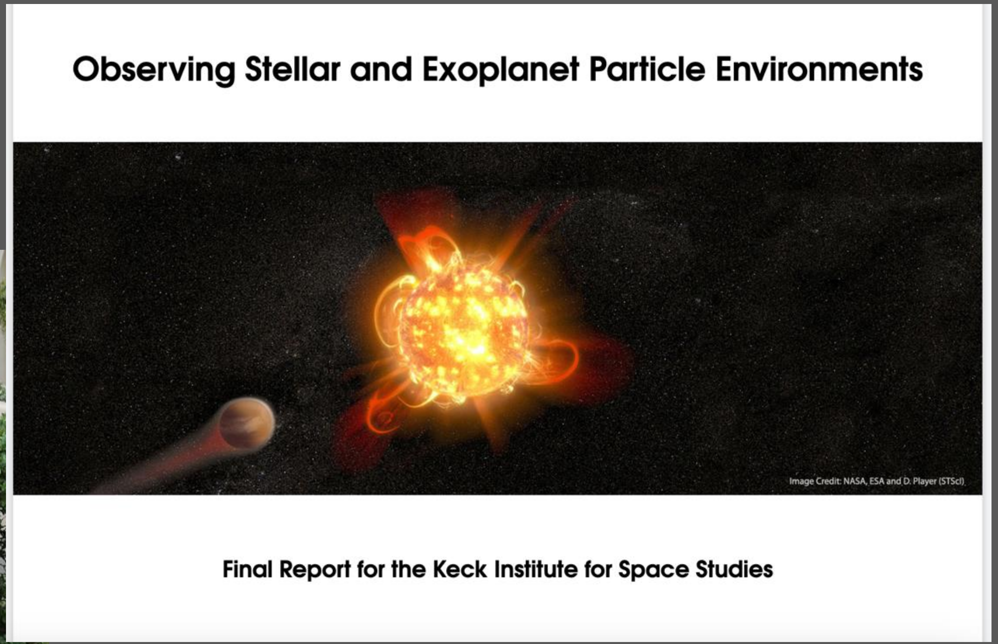

Observing Stellar and Exoplanet Particle Environments

Image Credit: NASA, ESA and D. Player (STScI)

Final Report for the Keck Institute for Space Studies

Workshop: “Blazing Paths to Observing Stellar and Exoplanet Particle Environments”

Loyd et al. (including K. Namekata) 2025
“The Exospace Weather Frontier”
https://authors.library.caltech.edu/records/gmhk5-amp17

Summary

- 2020-30年代は恒星CMEがより観測・特徴づけられる時代。系外惑星研究だけでなく、太陽系研究とのシナジーを最大化し進めたい。