The Sun and Space Weather

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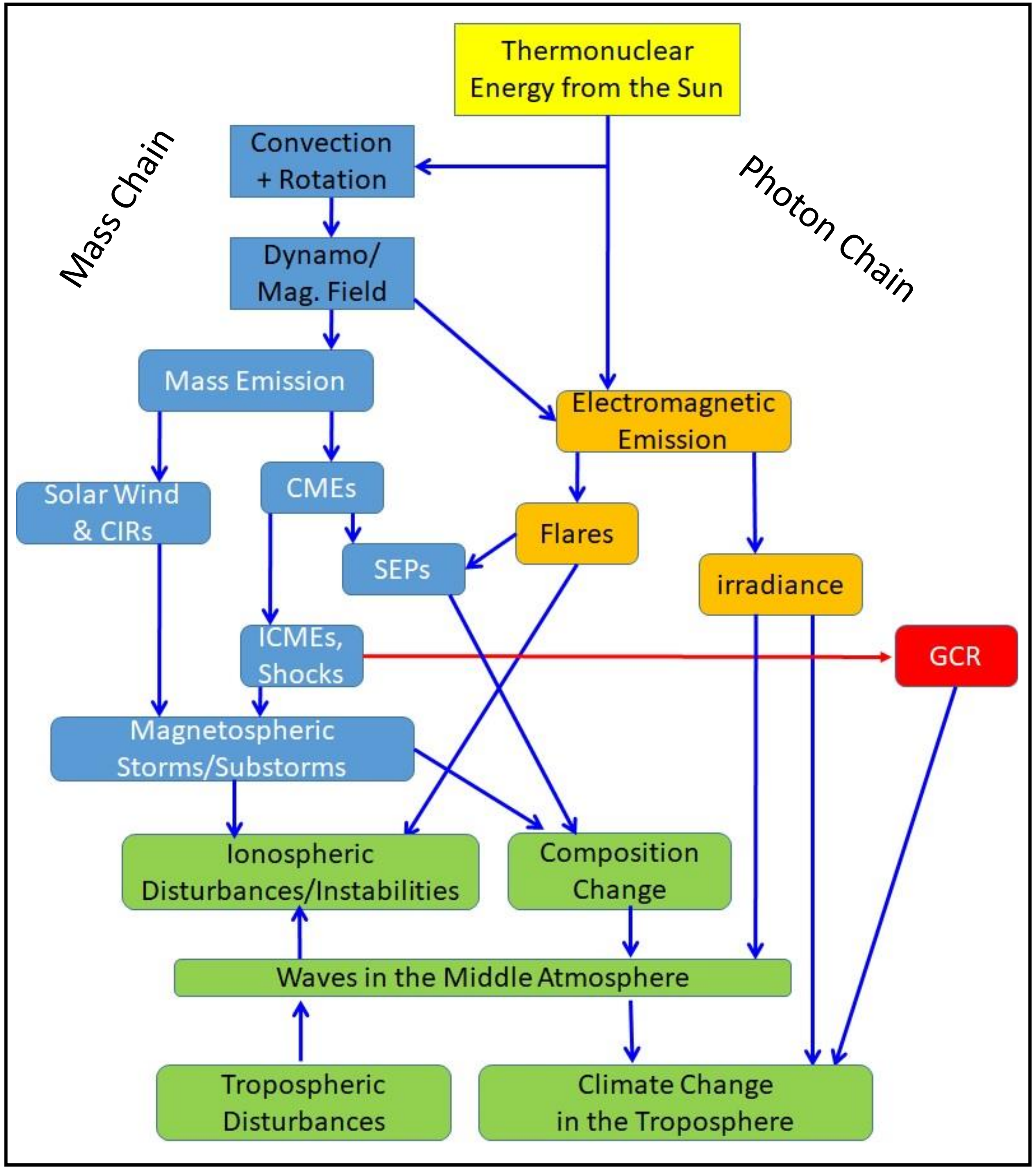
Recent Reviews

- Space weather: the solar perspective, M. Temmer LRSP 18, 4, 2021 (434 references). https://ui.adsabs.harvard.edu/abs/2021LRSP...18....4T/abstract
- Earth-affecting solar transients: a review of progresses in solar cycle 24, J. Zhang et al., PEPS 8, 56, 2021 (890 References) https://ui.adsabs.harvard.edu/abs/2021PEPS....8...56Z/abstract
- The Sun and Space Weather, N. Gopalswamy Atmosphere, 13, 1781, 2022 (205 references) https://ui.adsabs.harvard.edu/abs/2022Atmos..13.1781G/abstract
- History and development of coronal mass ejections as a key player in solar terrestrial relationship, N. Gopalswamy, Geoscience Lett. 3, 8, 2016 (191 references), https://ui.adsabs.harvard.edu/abs/2016GSL.....3....8G/abstract



Source of Energy

Nuclear fusion: 600 million tons of H burns to yield 596 million tons of He every second

Missing 4 million tons (4 billion kg) becomes energy

$E = mc^2$ (c^2 joules per kg = 9×10^{16} J/kg)

4 billion kg → 3.6×10^{26} J per second (W)

Mass Chain:

Consequence of solar dynamo (convection + rotation)

Release of magnetic energy

Coronal Mass ejections (CMEs) closed field regions

High speed streams open field regions →

Corotating interaction regions (CIRs)

Magnetic field transported with plasma: magnetic storms

Energetic particles from CME-driven shocks, flares

EM Chain:

Flares superposed on steady EM radiation

Galactic Cosmic Rays (GCRs):

Modulated by CME, CIR magnetic fields

Contribute to Inner Van Allen Belt

Upward chain:

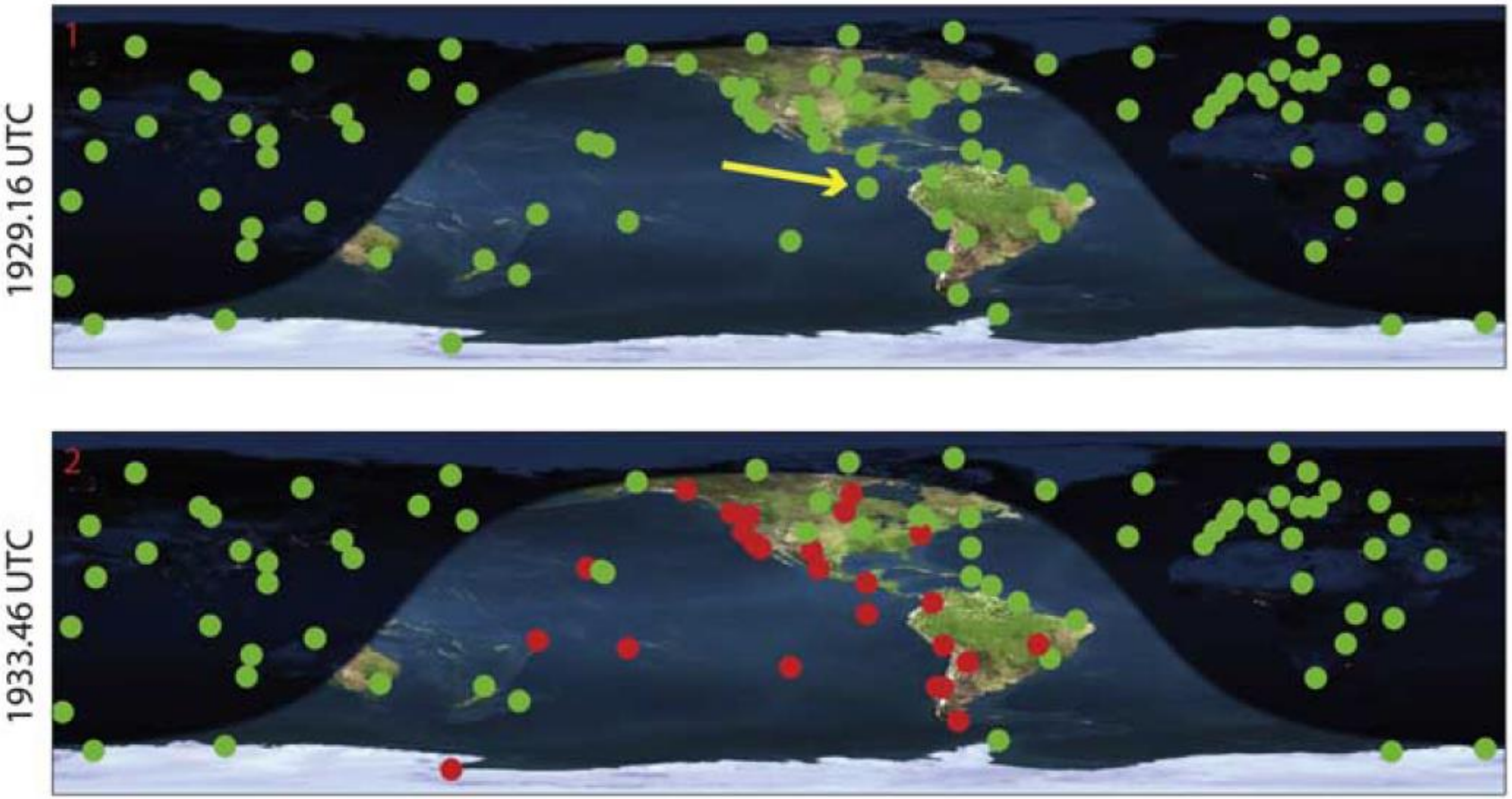
Ionospheric disturbances/irregularities

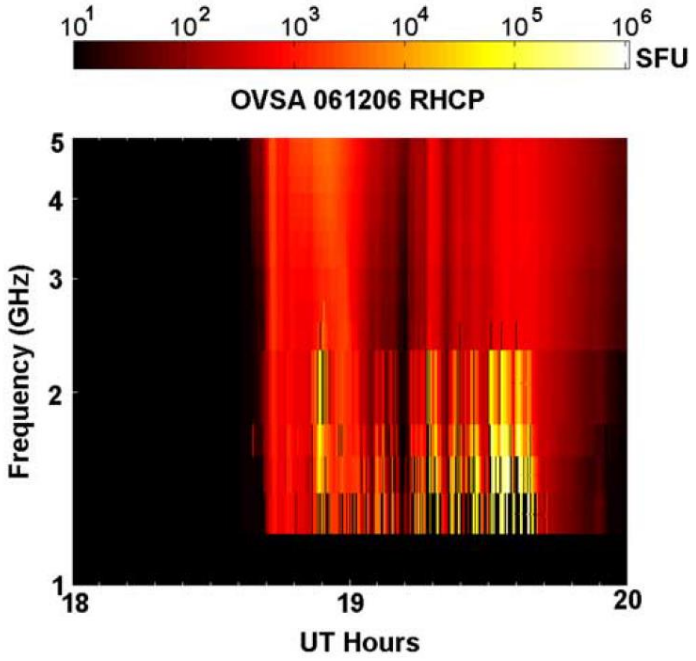
Contributions from flares & CMEs

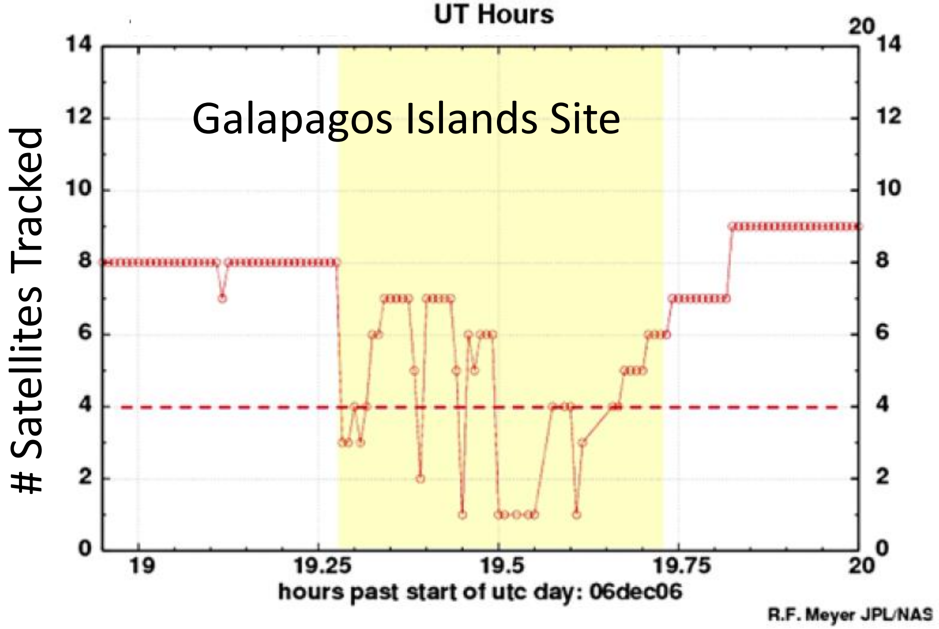
Solar Radio Burst Affecting GPS

Microwave bursts are due to electrons accelerated in flaring regions

IGS Network Dual Frequency Code Observations, 6 December 2006







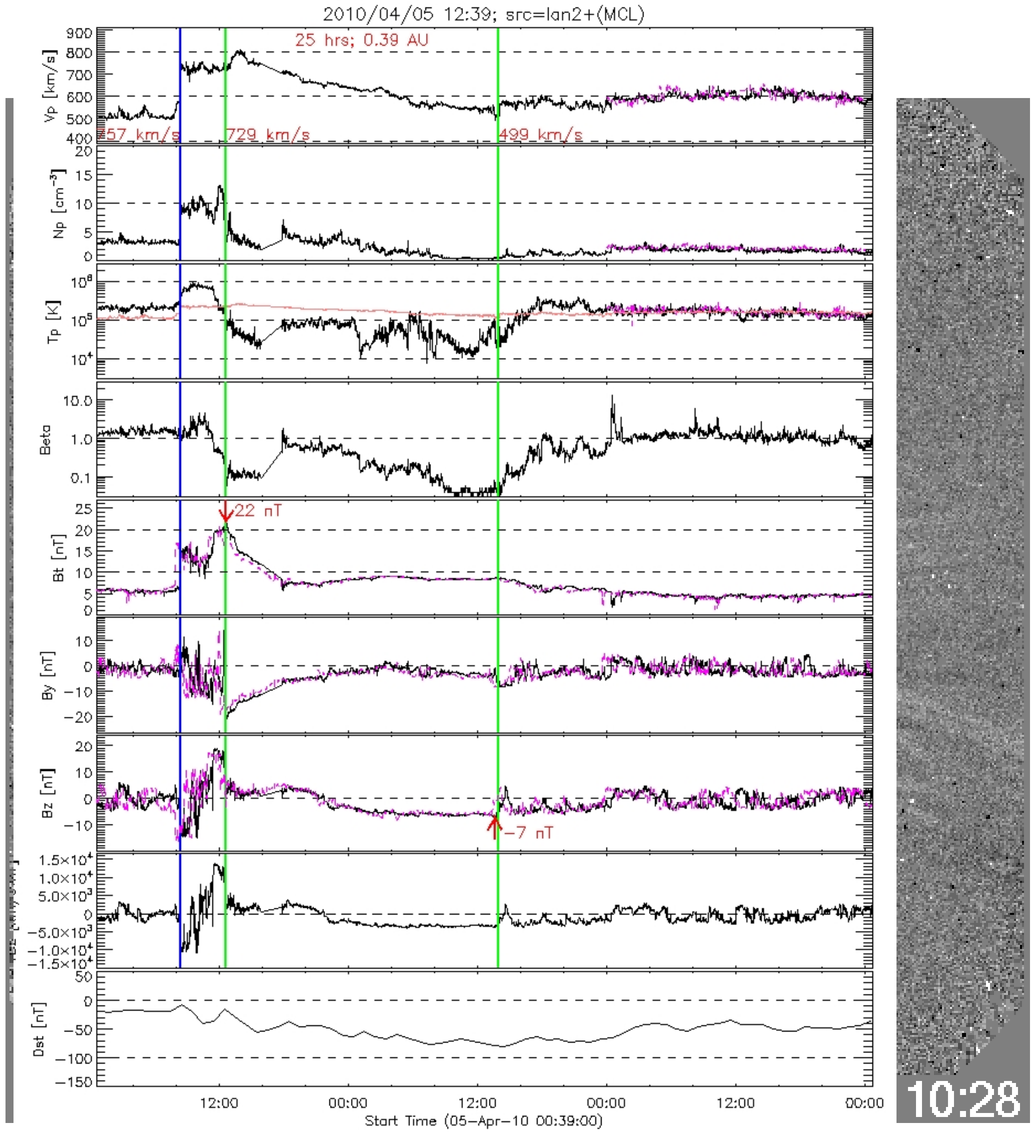
- Solar Radio Bursts affect the entire sunlit hemisphere
- Different from the frequent but localized ionospheric irregularities
- Civilian dual frequency GPS receivers were the most severely affected

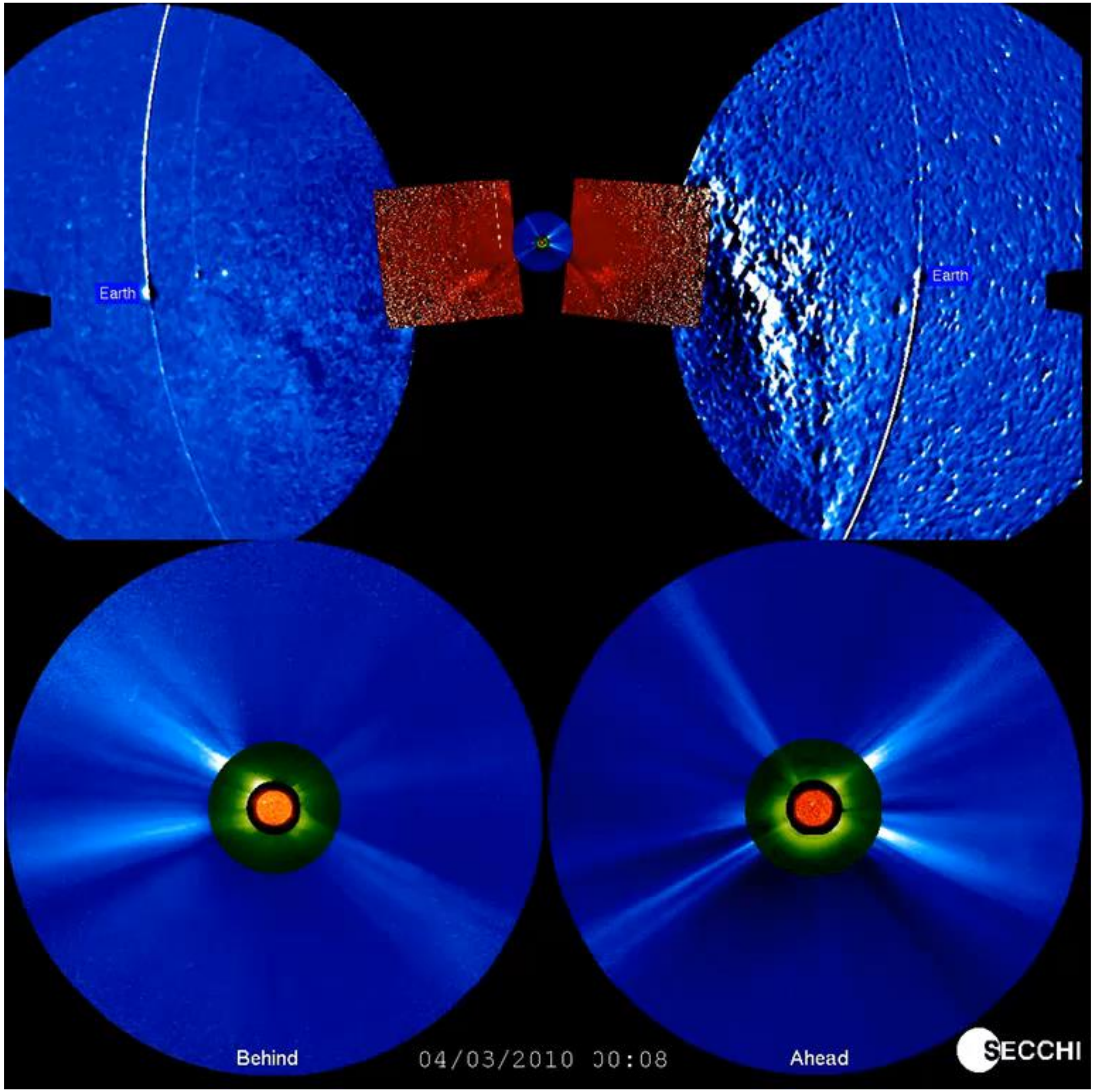
Corrections require ≥4 satellites tracked

Cerruti et al. 2008 SpaWea

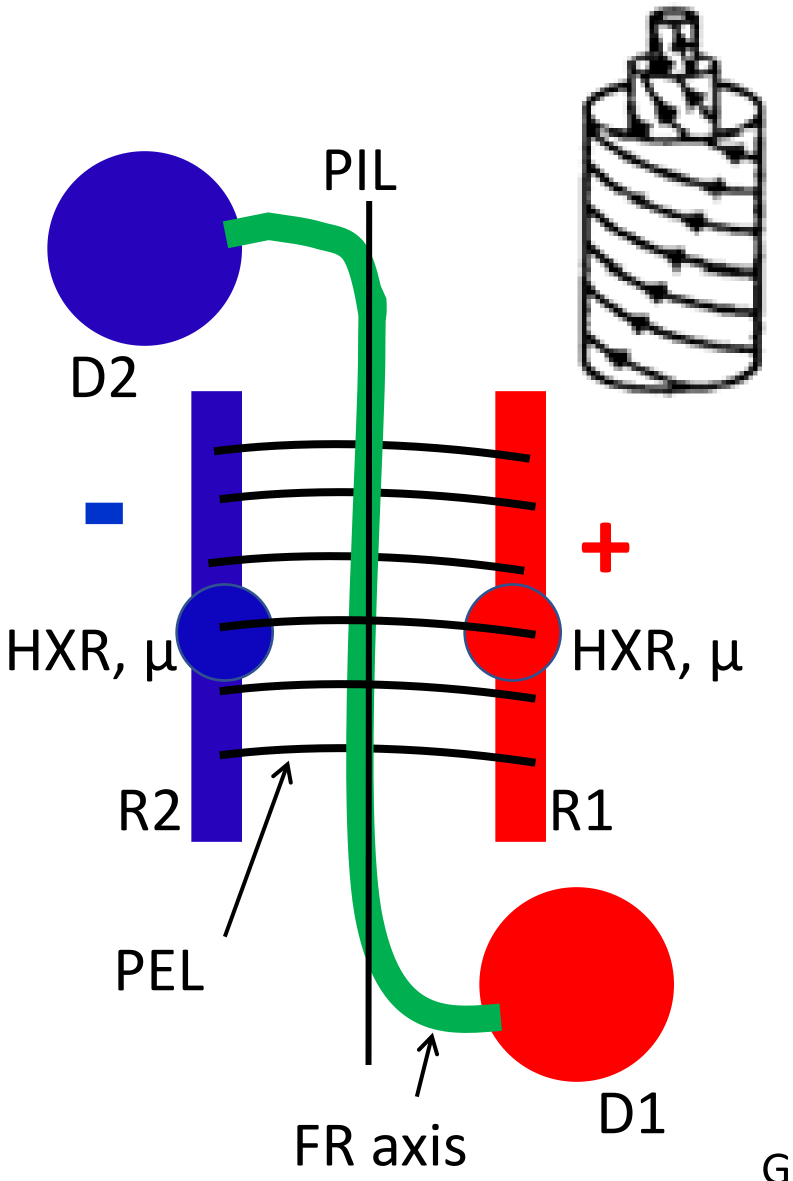
A CME Impacting Earth

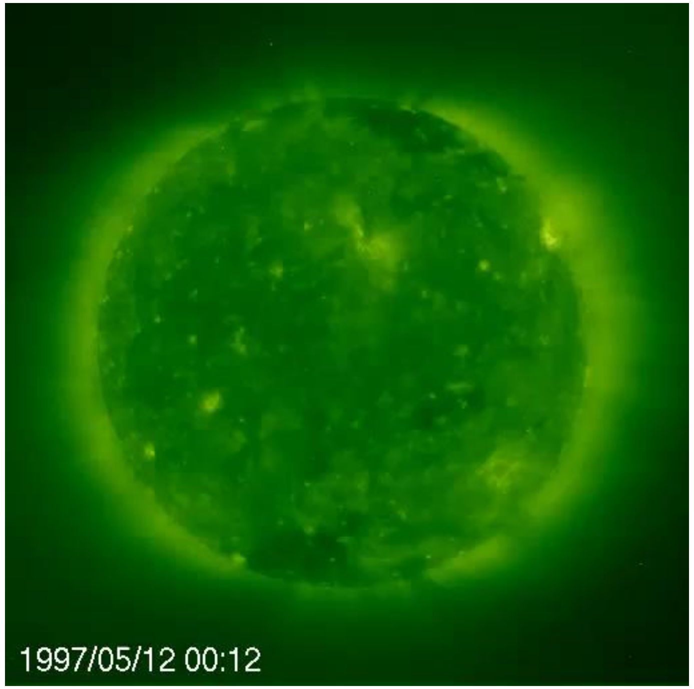
Benefit of extending the FOV to the whole heliosphere



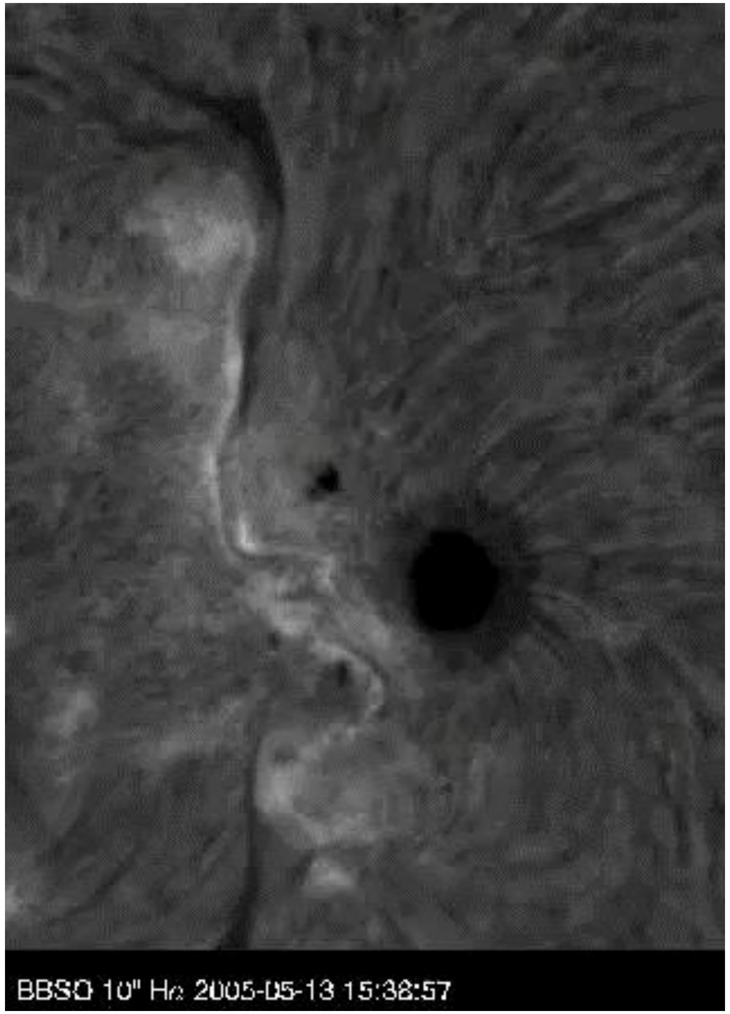


Eruption Geometry





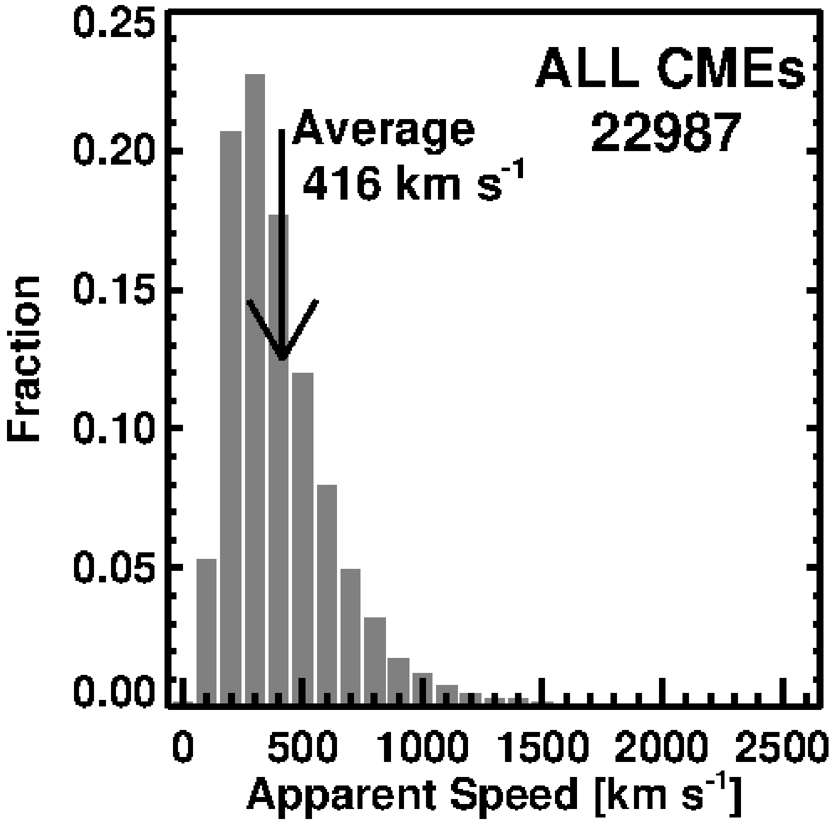
Gopalswamy 2009

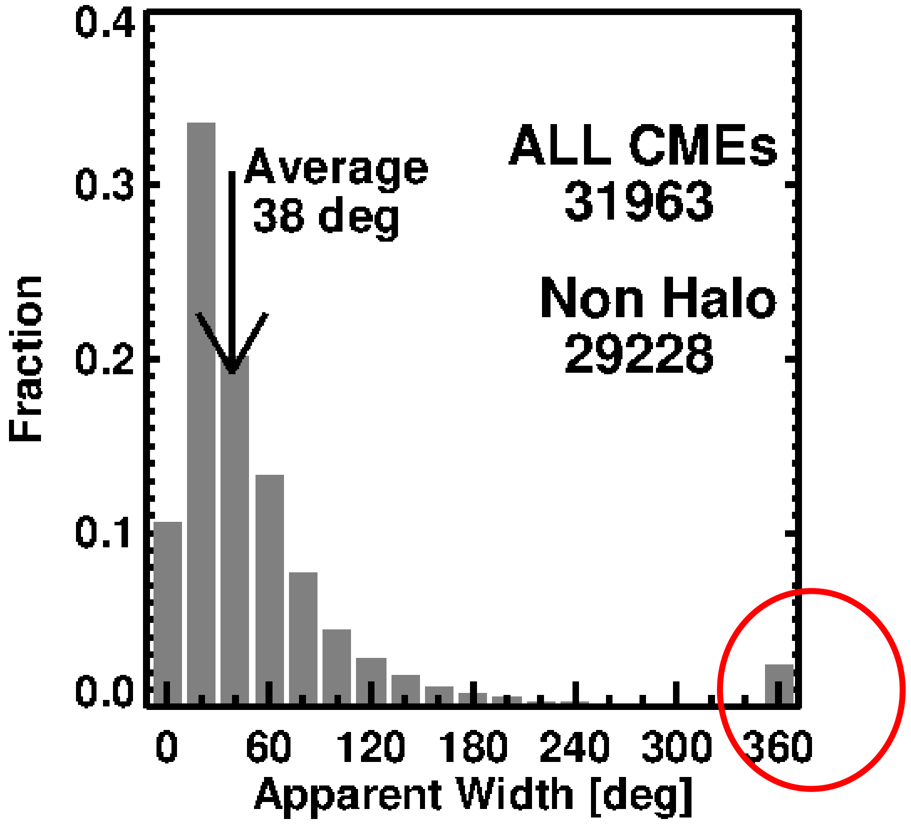


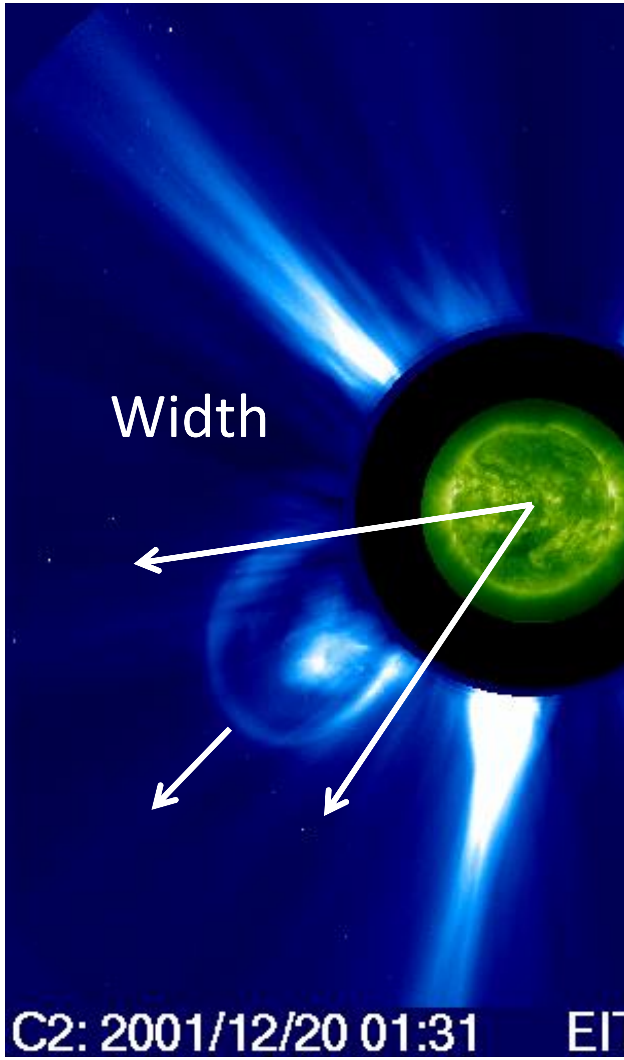
courtesy: V. Yurchyshyn

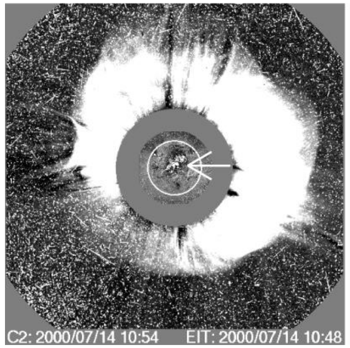
EUV, H-alpha

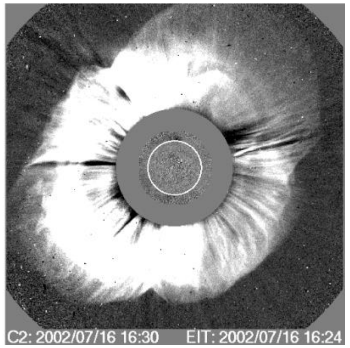
CME Kinematic Properties





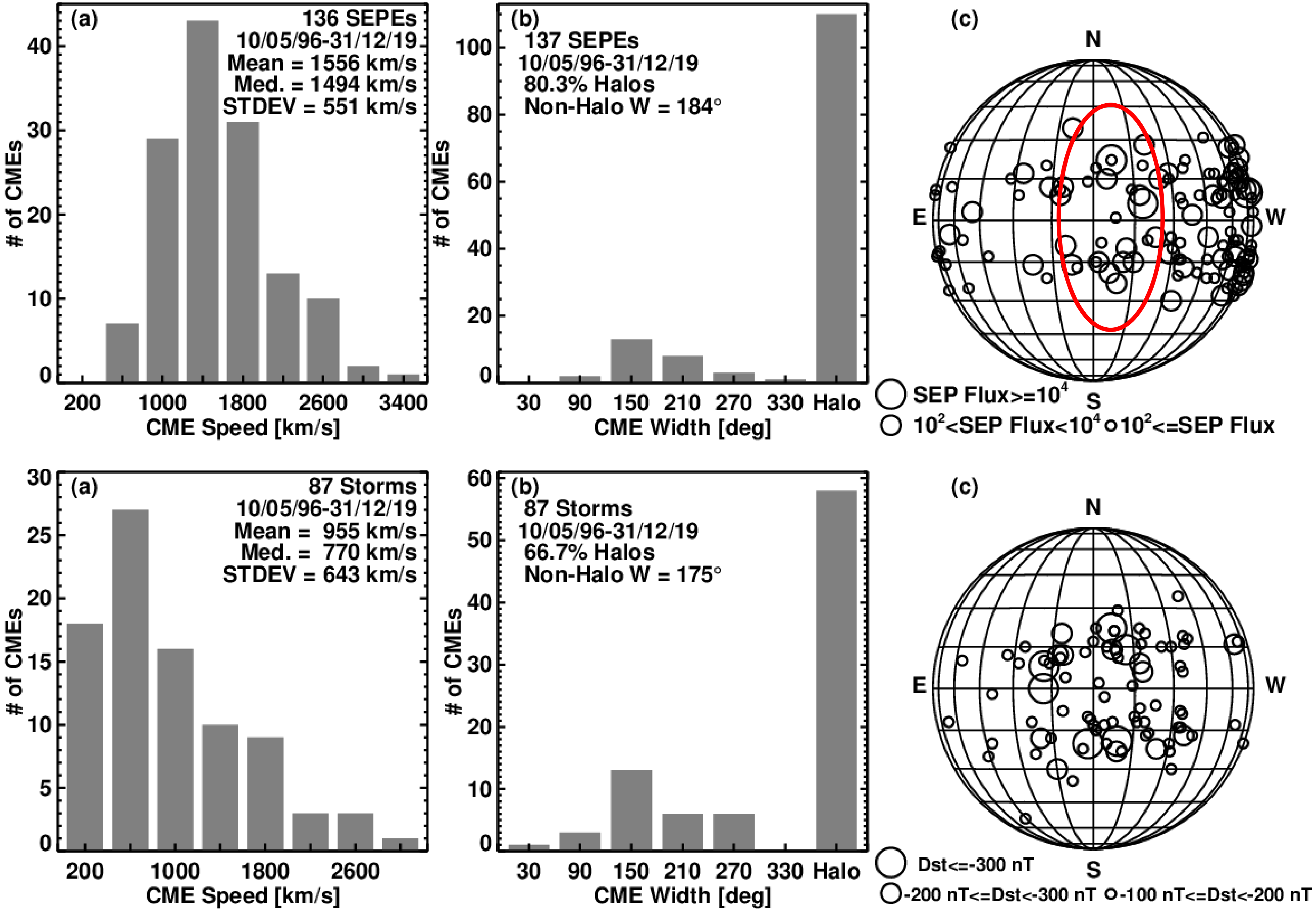






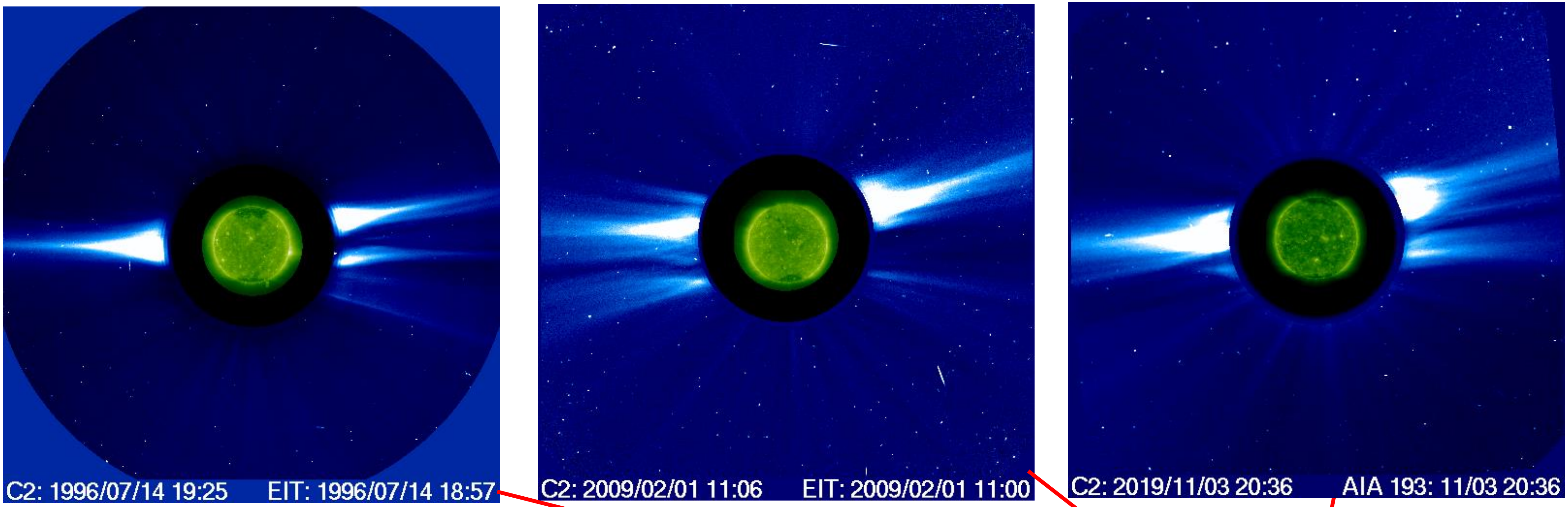
SEP Events

Shock-driving CMEs

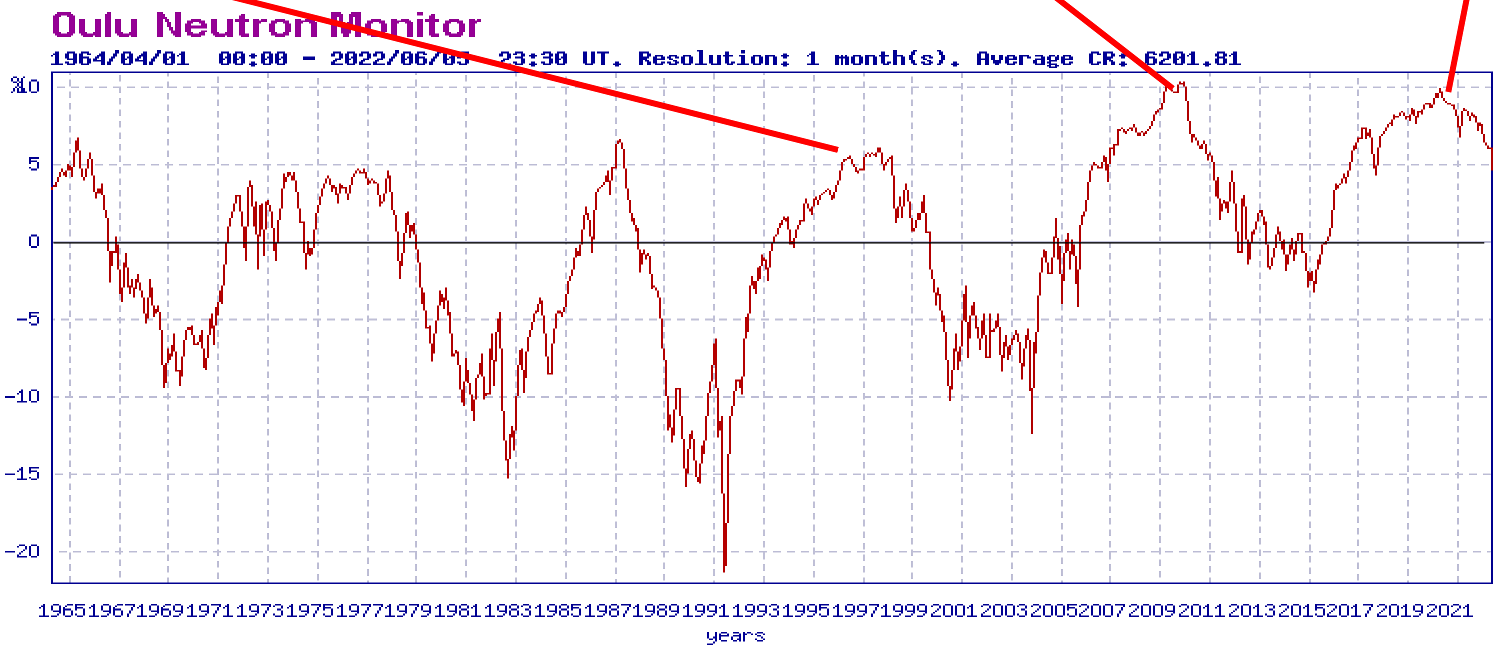


GM Storms

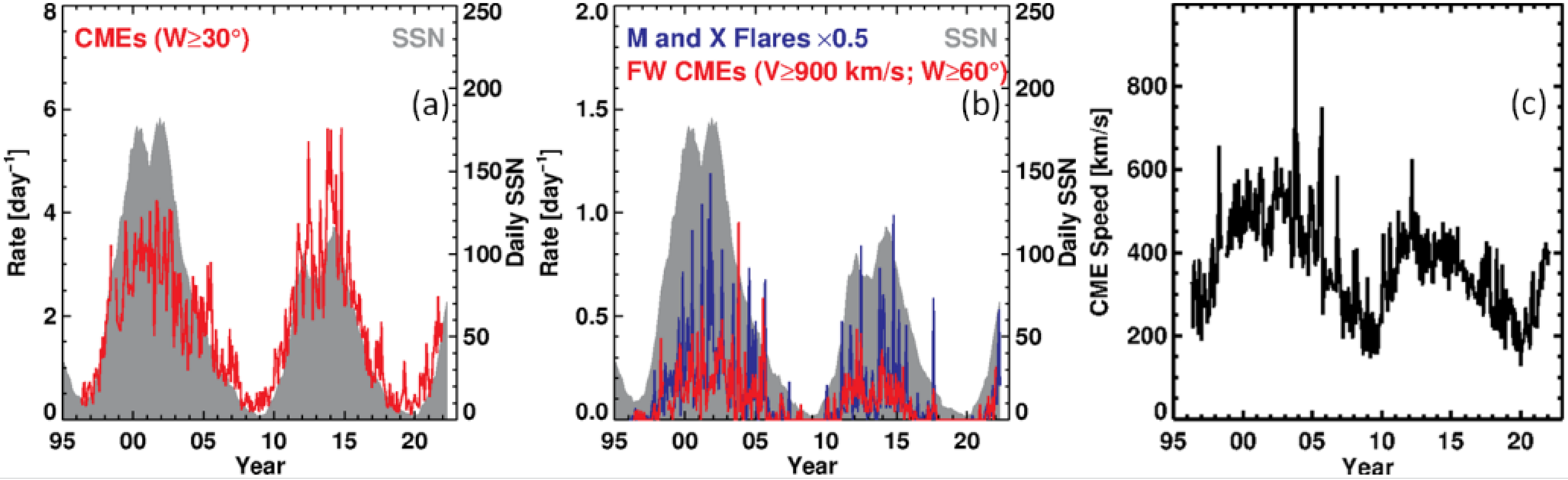
CMEs with Bz <0 in Flux Rope &/ Sheath



High level of cosmic rays at Earth during solar min
Anticorrelation with SSN
CMEs deflect cosmic rays away (Forbush decrease)

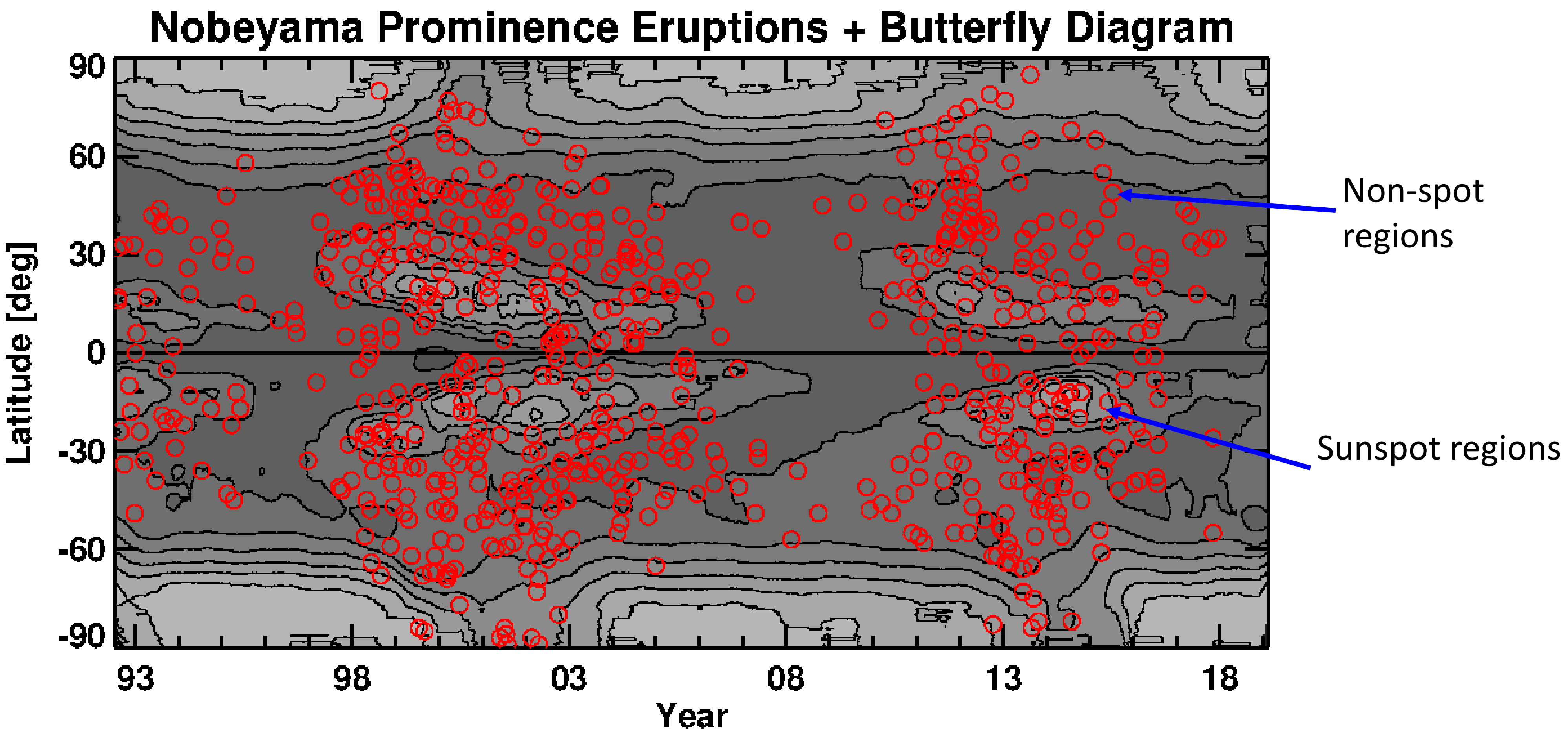


Solar Cycle Variation



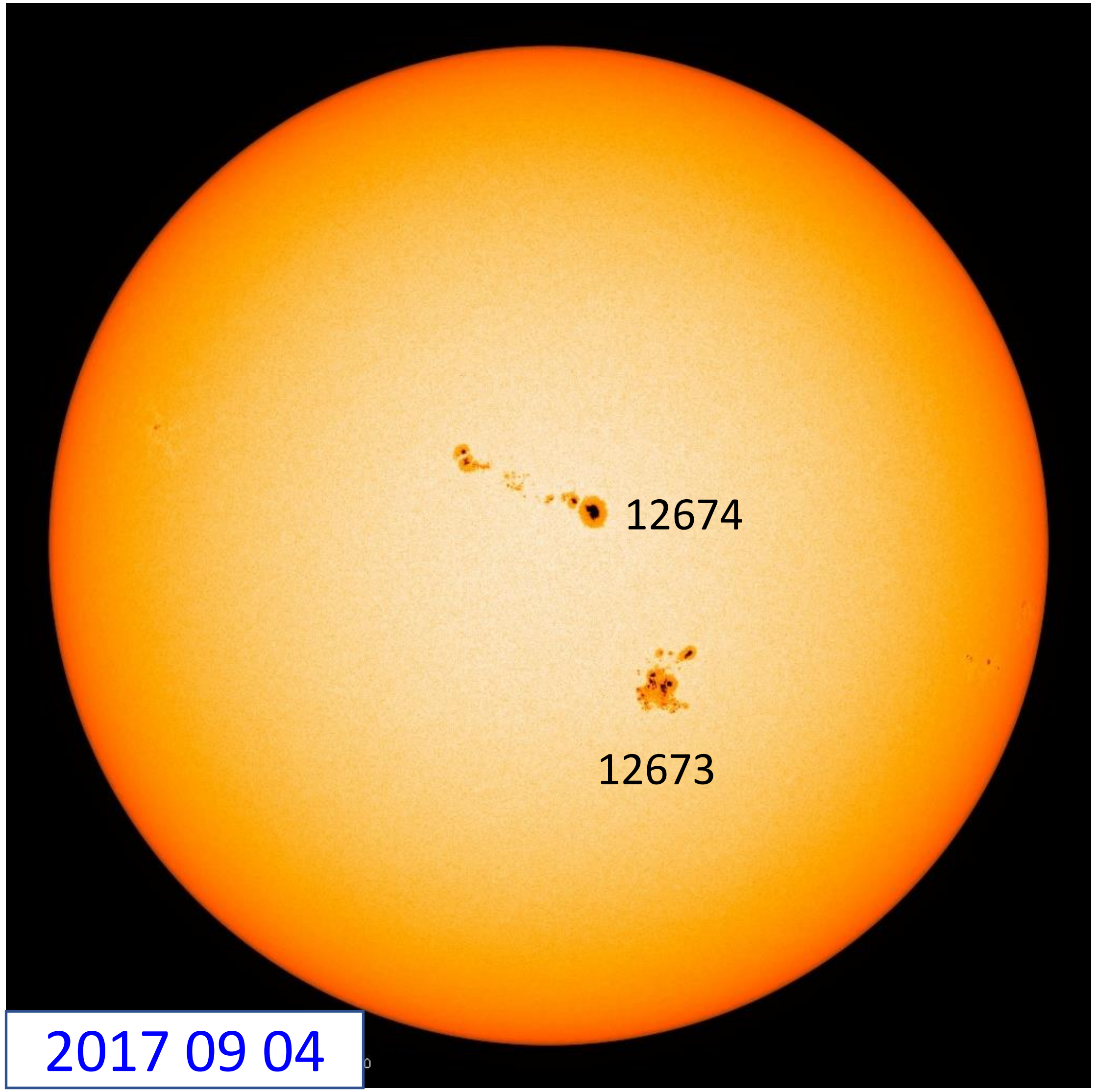
CME occurrence rate and speed are higher during maxima
SSN – CME rate relationship depends on CME energy
Mild Space Weather in SC 24; likely in Sc 25 as well

CME source regions

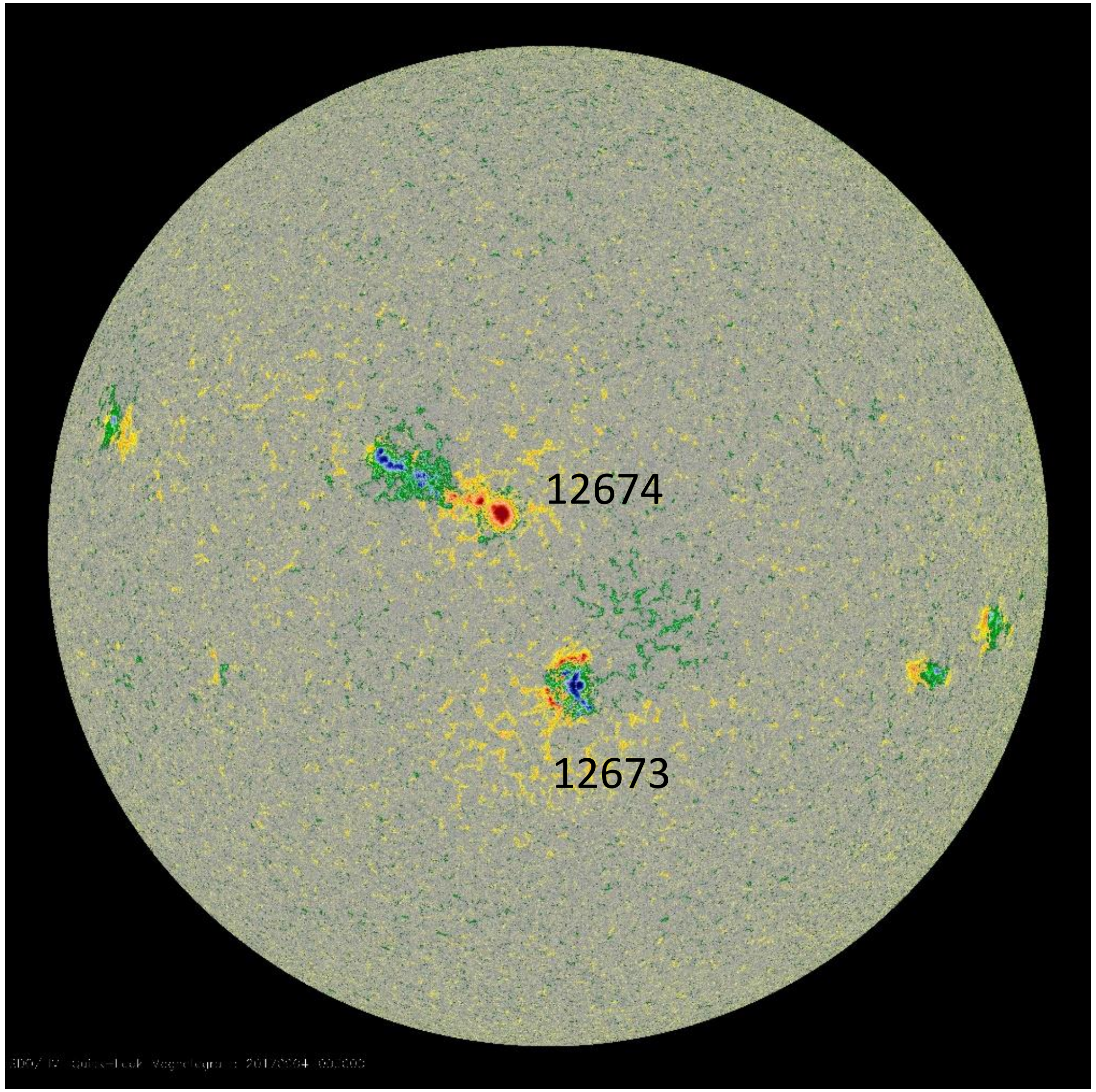


Locations of prominence eruptions (PEs) automatically detected from Nobeyama Radioheliograph images

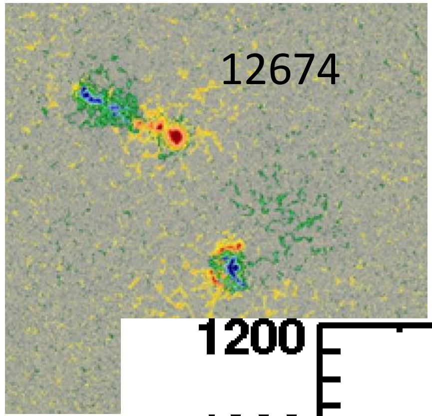
Regions with different CME productivity (Sep 2017)



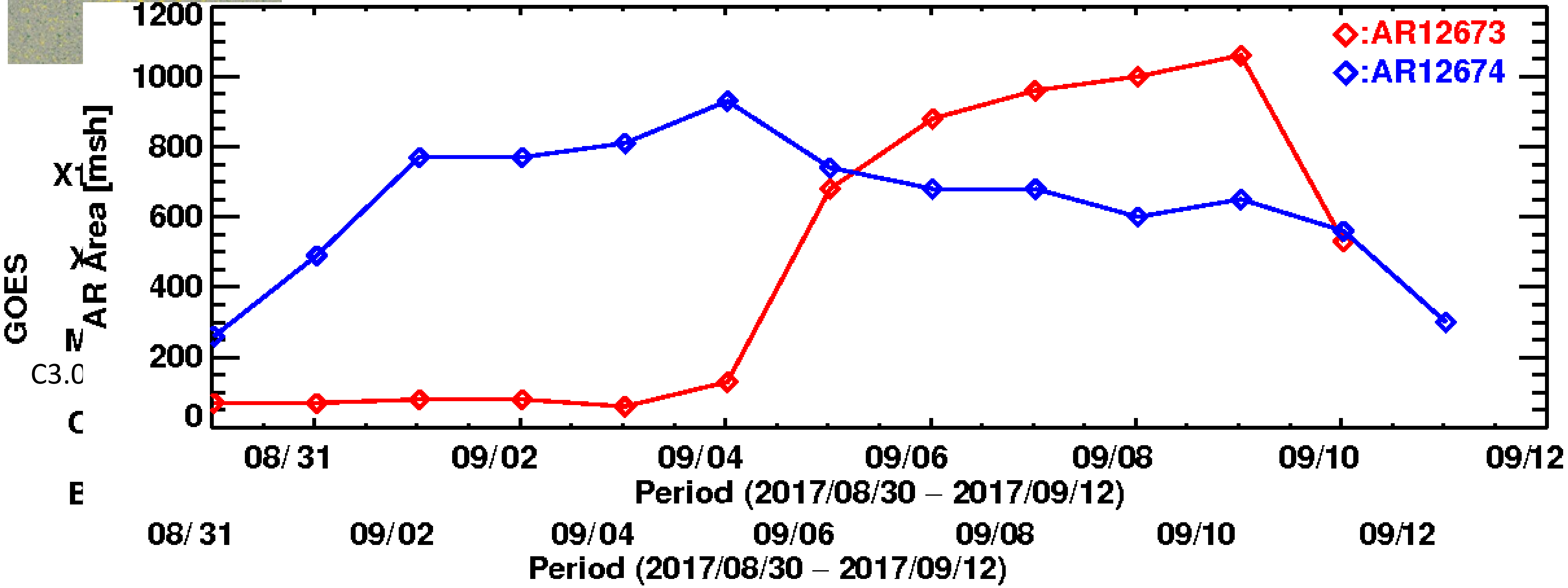
SDO/AIA Continuum



SDO/HMI Magnetogram



Flares & CMEs in ARs 12673 & 12674



Space weather events occurred from AR 12673 when the region rotated from the disc center to the west limb. The Sep 06 CME caused both a major mag storm & a large SEP event. The Sep 4 CME had a large SEP event and minor storm; Sep 10 CME had a GLE; Sep 6 & 10 CMEs had sustained gamma-ray emission

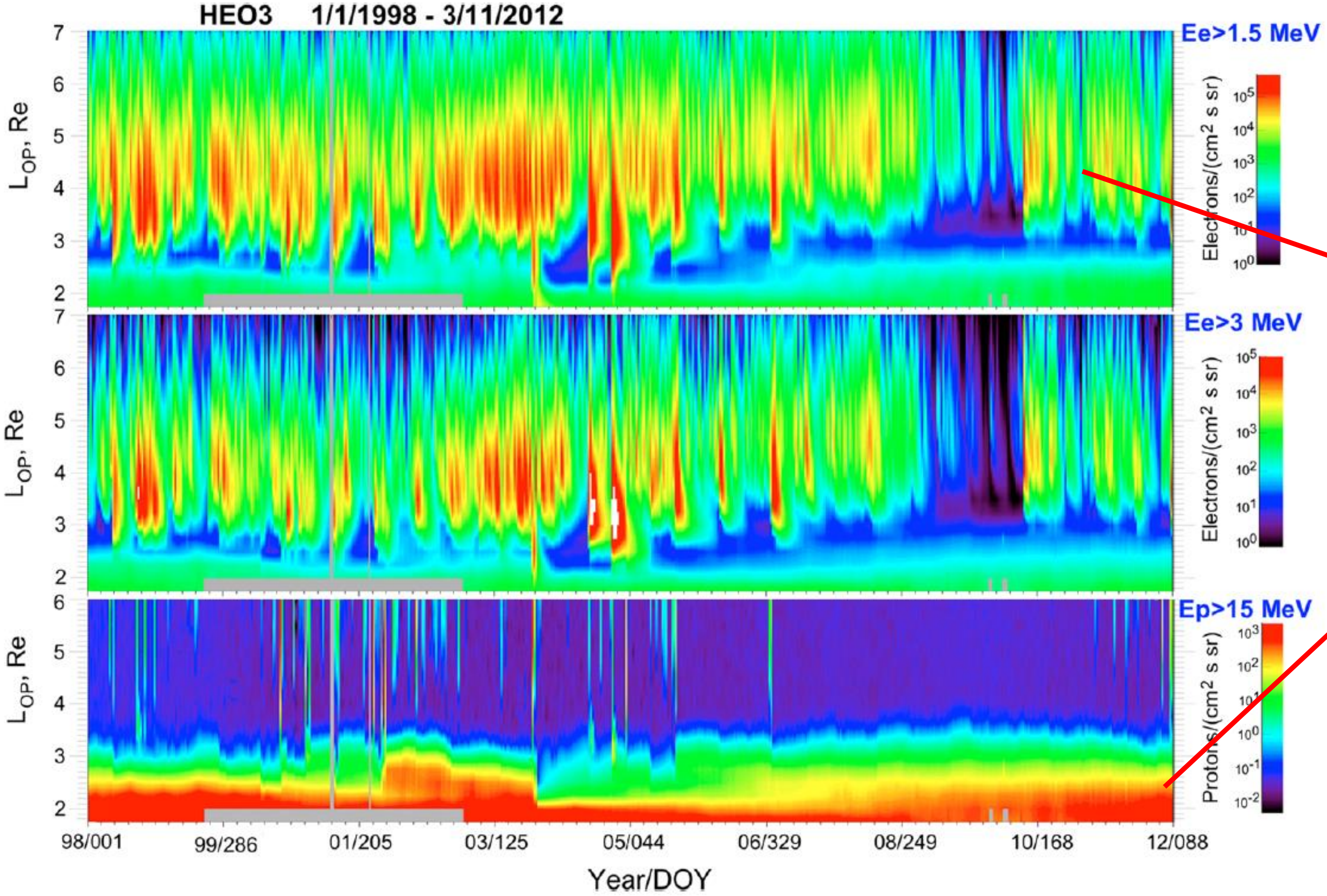
Hazards from Energetic Particles

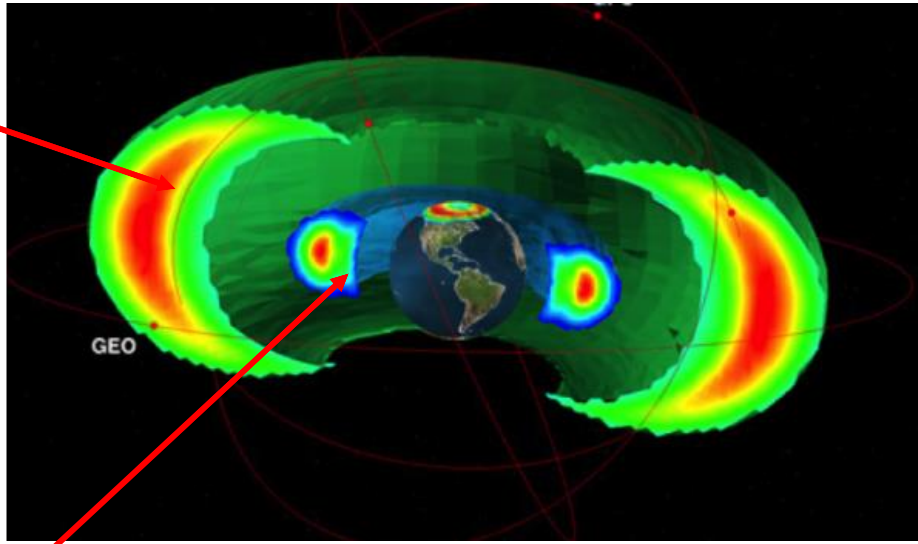
Particles	Effects	Sources
Electrons 10-100 keV	S/C charging	Trapped particles
Electrons > 100 keV	Deep dielectric charging, solar cell damage	Trapped particles
Electrons > 1 MeV	Radiation damage (ionization)	Trapped/quasi trapped
Protons 0.1-1 MeV	Surface damage to materials	Trapped particles
Protons 1-10 MeV	Disp. damage in solar cells	Trapped particles, IP shocks*
Protons >10 MeV	Ionization, disp. damage; sensor background	Rad belt, SEPs, GCRs
Protons > 30 MeV	Damage to biological systems	Rad belt, SEPs, GCRs
Protons > 50 MeV	Single event effects	Rad belt, SEPs, GCRs
Ions >10 MeV/nuc	Single event effects	SEPs, GCRs
GeV particles (GLEs**)	Single event effects, hazard to humans in polar flights and in deep space	SEPs, GCRs

Feynman and Gabriel 2000

**Ground Level Enhancement (GLE) in SEPs; *ESP events

Van Allen belts

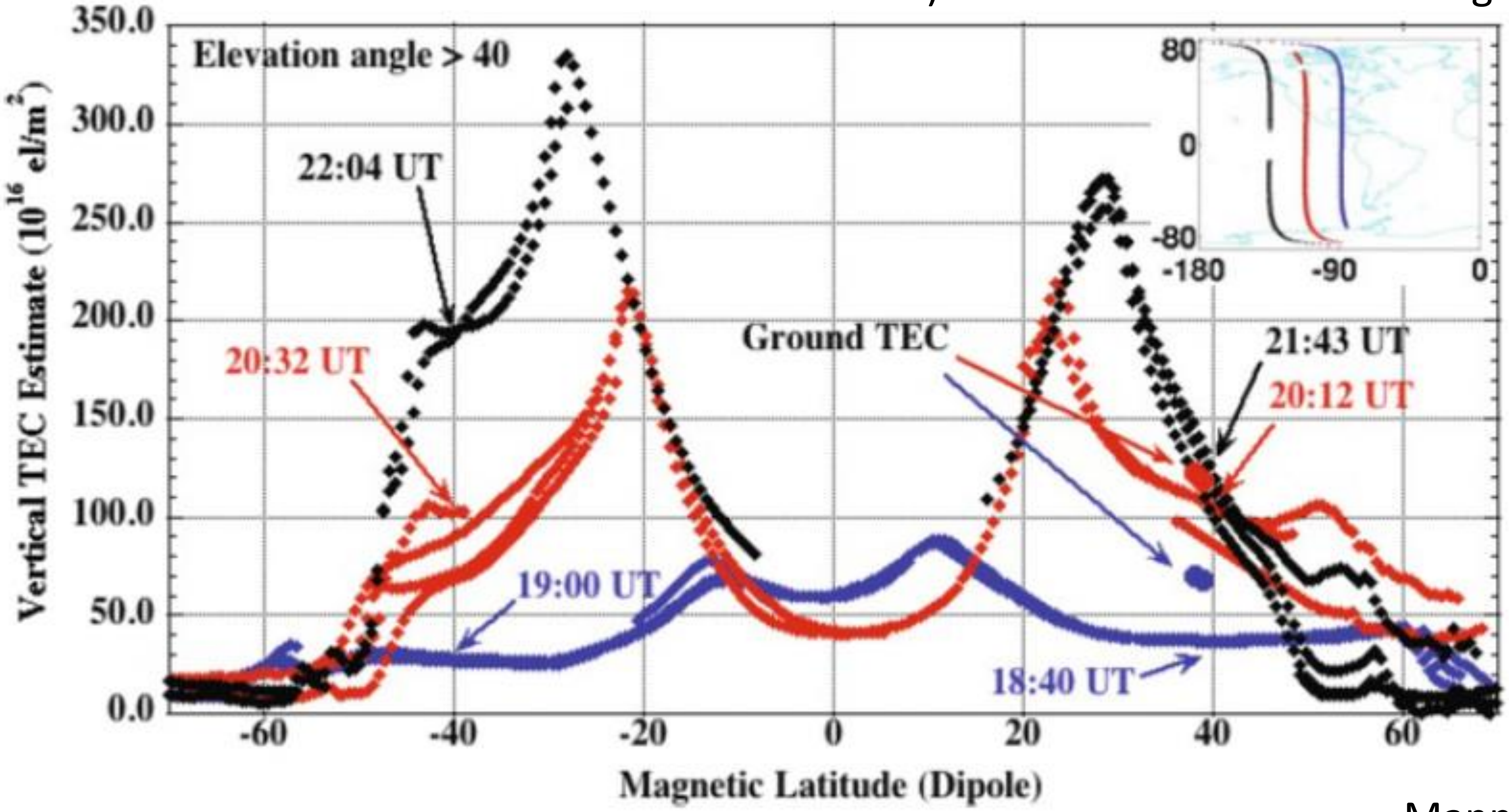




Earth's radiation belts
(Van Allen belts)

CME Impact on the Ionosphere: Super-fountain Effect

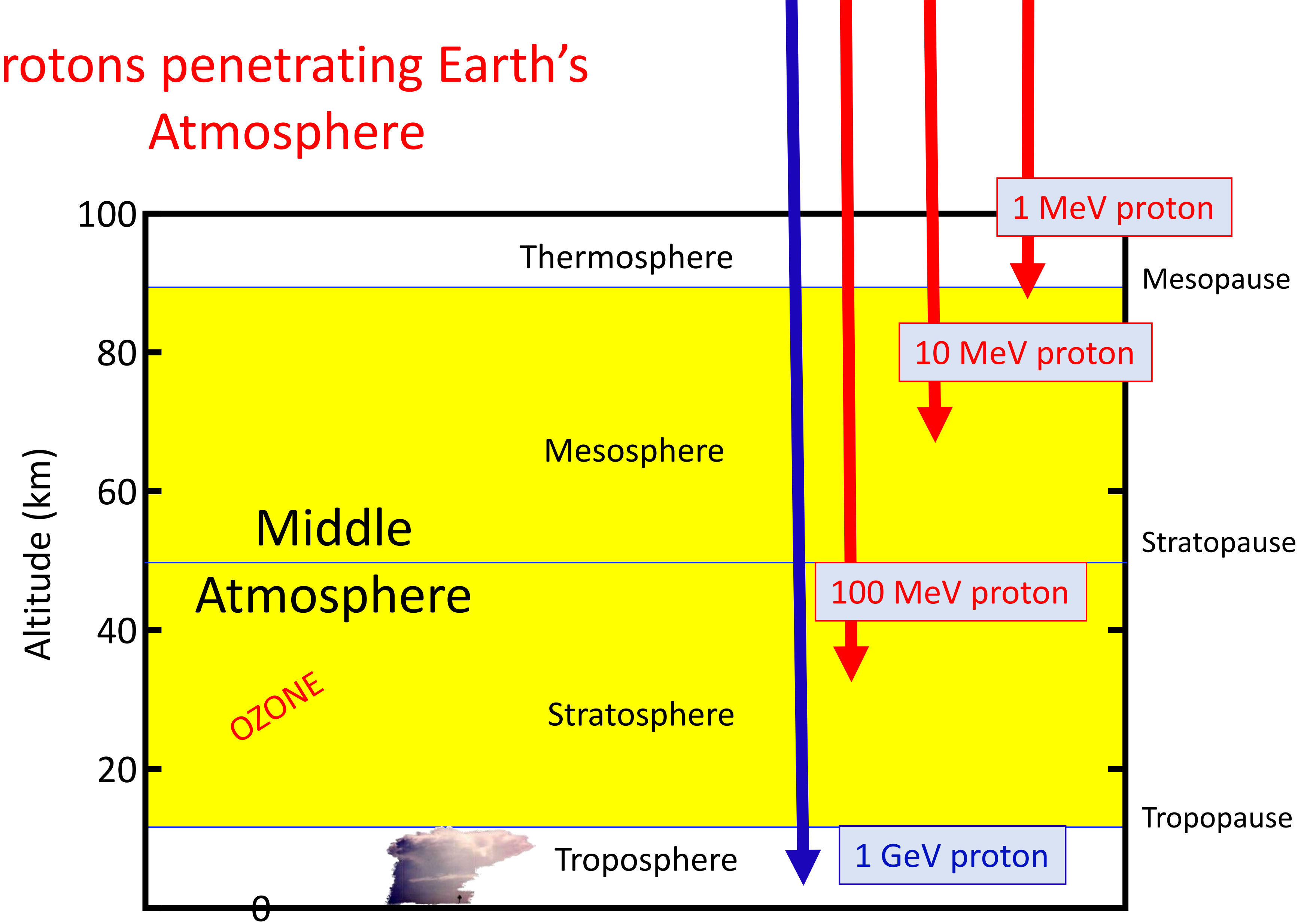
The vertical TEC above the CHAMP satellite (approximately 400-km altitude) for the 30 October 2003 magnetic storm

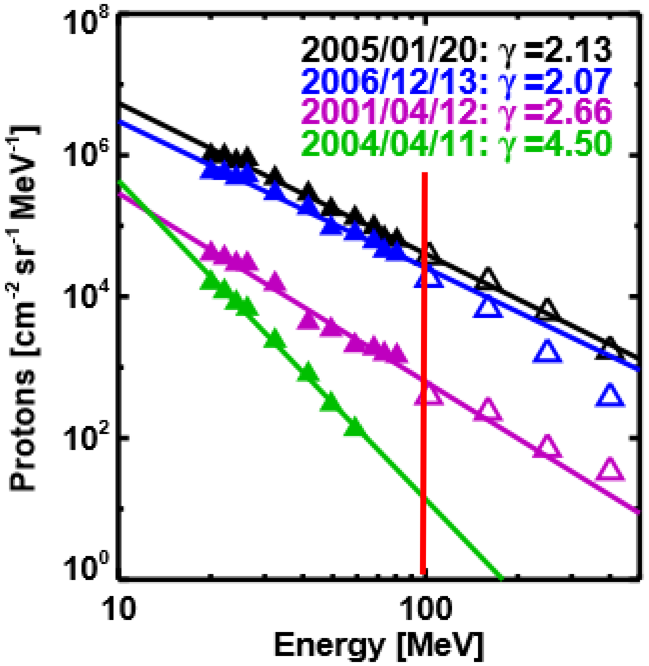


Mannucci et al. 2015

- TEC enhances by a factor of 5
- The enhancement spreads to mid latitudes (up to ~50 deg from <20 deg)

Protons penetrating Earth's Atmosphere



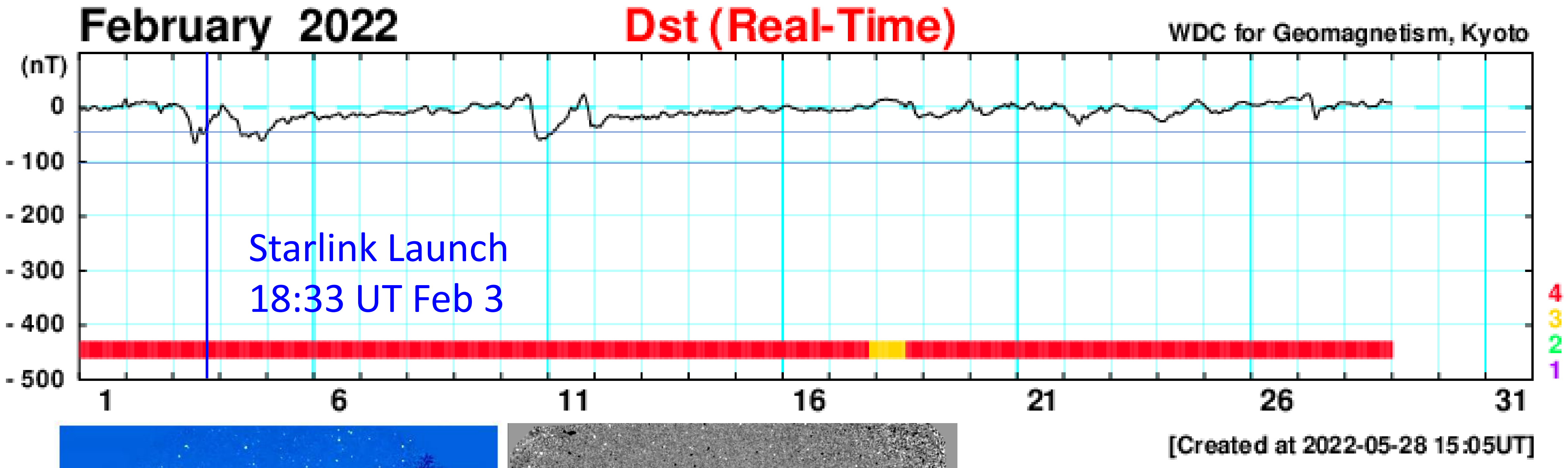


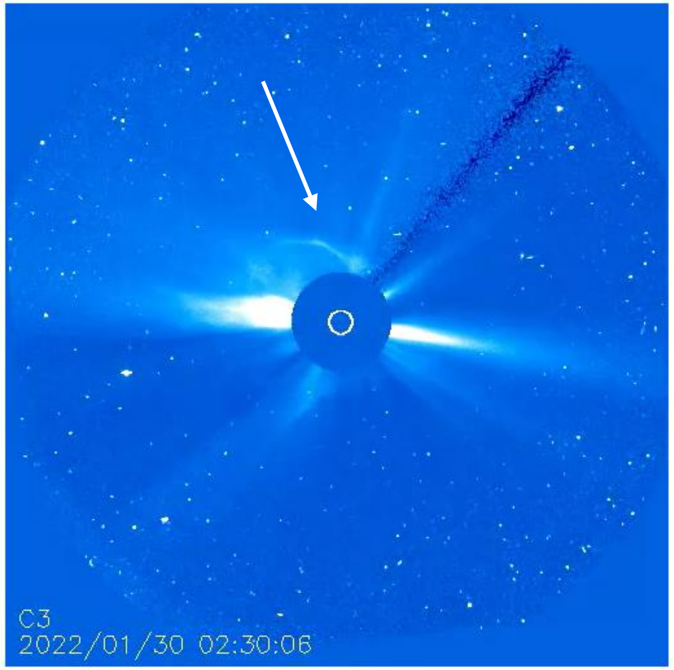
The spectrum of energetic particles decides the space weather impact

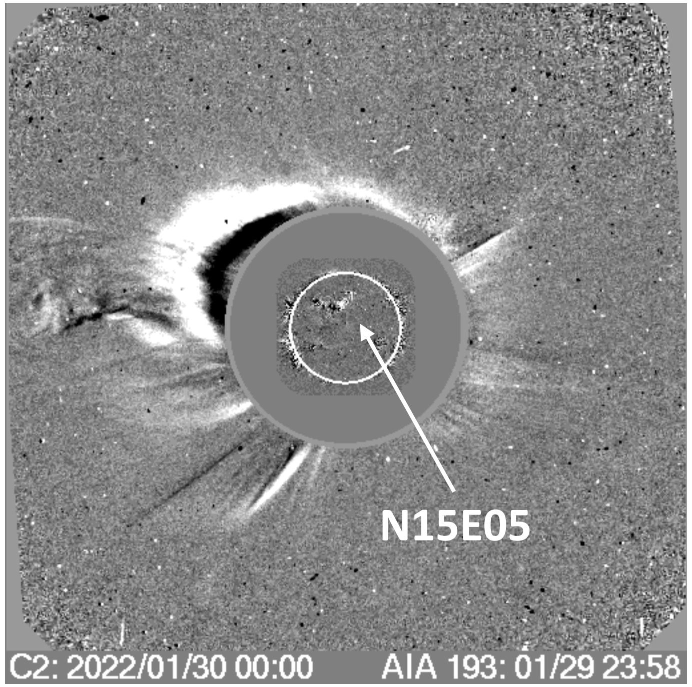
100 MeV protons penetrate to the stratosphere and can destroy ozone.

GeV particles can affect airplane crew/passengers in polar routes

Courtesy: C. Jackman







The moderate geomagnetic storm resulted in an elevated thermospheric density and hence the atmospheric drag over an extended period that led to the premature deorbit of the 38 satellites.

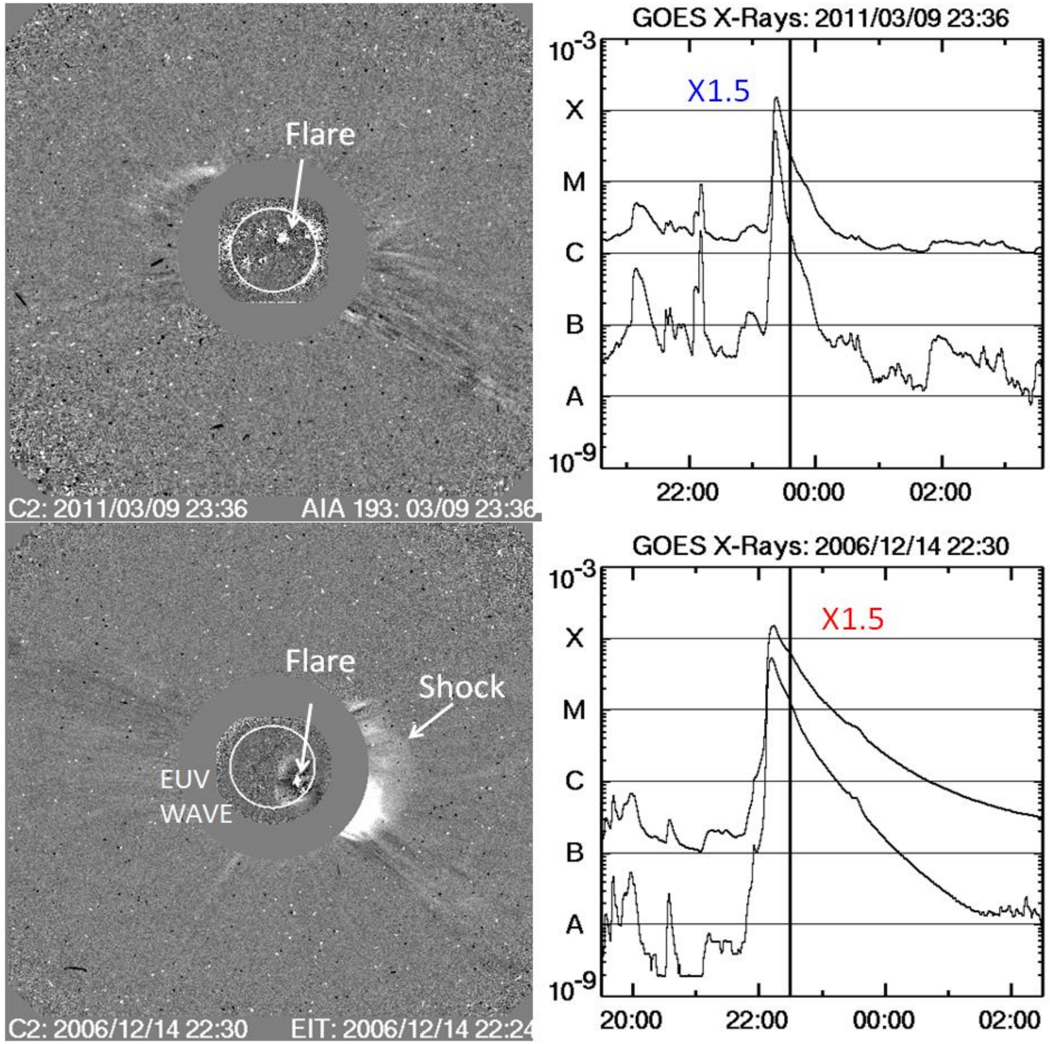
Dang et al. 2022; Zhang et al. 2022; Fang et al. 2022; Lin et al. 2022; Gopalswamy et al. 2023

Summary

- Space weather is a unique field of research with scientific and practical importance of global relevance
- Most of the space weather is a consequence of variable energy flow from the Sun
- Upward energy flow from Earth and galactic cosmic rays contribute to space weather
- Coronal mass ejections, high speed streams, solar flares, and solar energetic particle events are the primary transients relevant for space weather

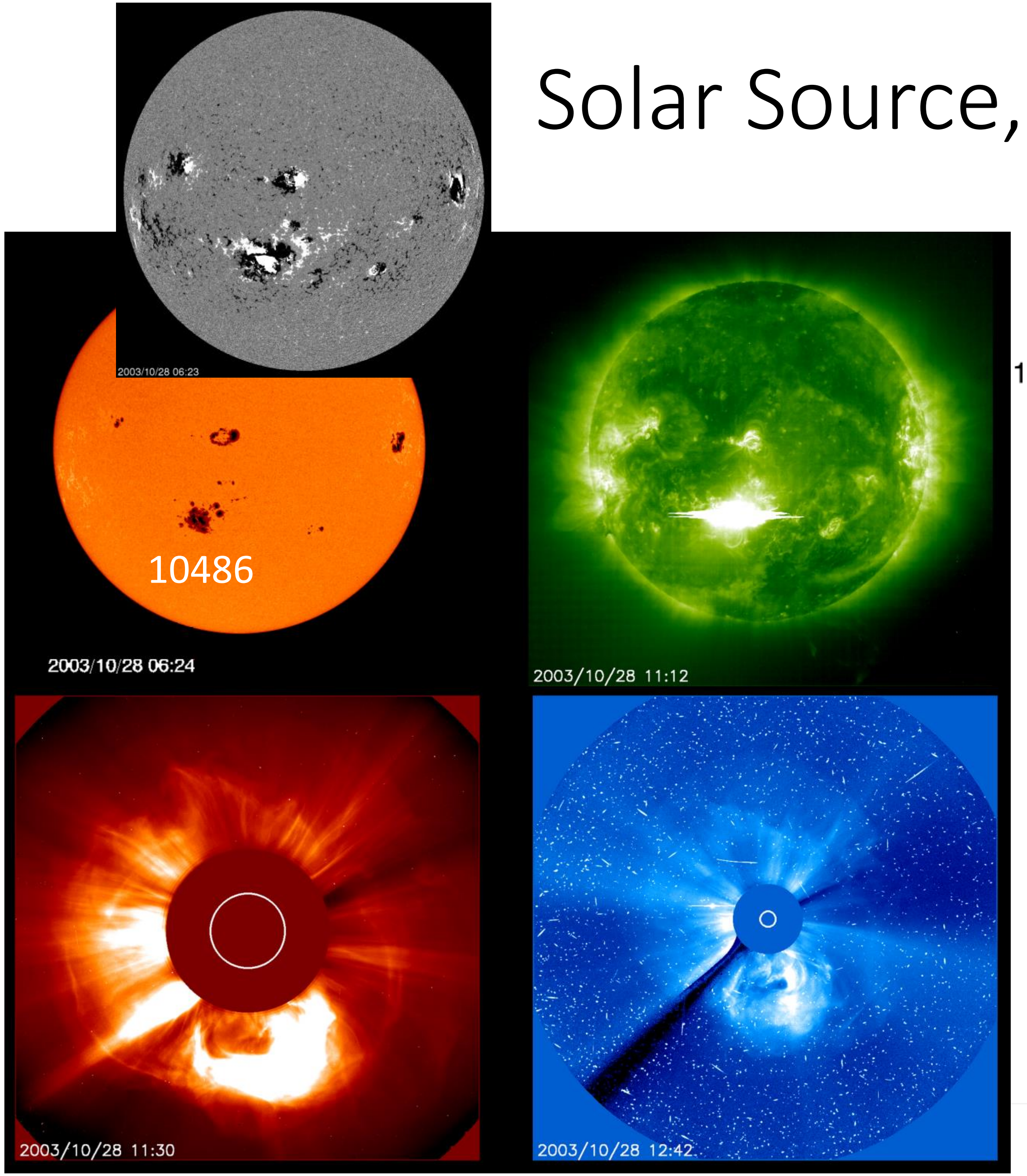
EUV, White light, X-rays

Confined and Eruptive flares



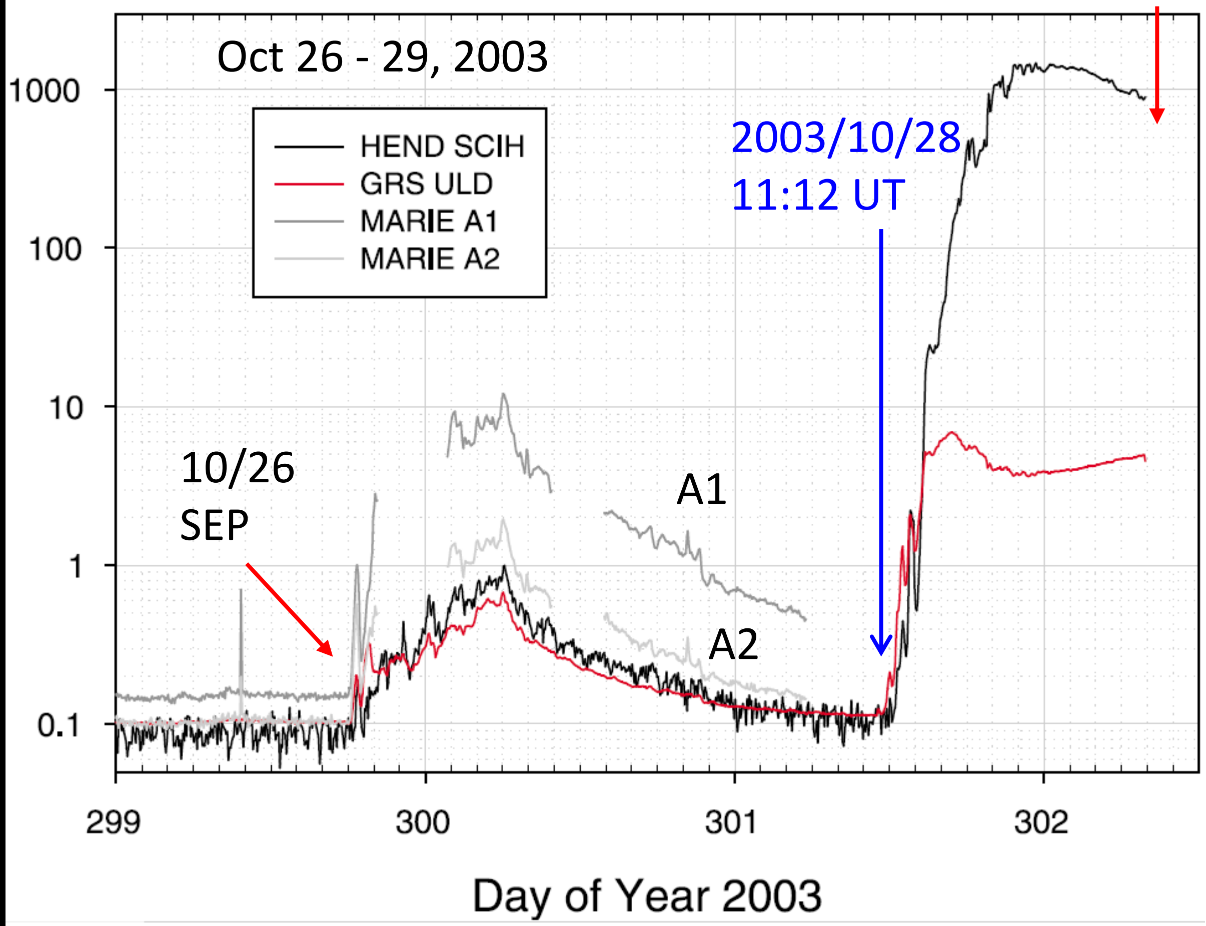
- The confined flare is not associated with mass motion – just electromagnetic emission (in EUV image taken by SDO/AIA)
- The eruptive flare has surrounding disturbances in EUV including (from SOHO/EIT) a CME and its shock (from SOHO/LASCO)
- The GOES soft X-ray light curves show that flare intensities are very similar (X1.5)
- Recent investigations show that many eruptive flares are preceded by confined flares (Nindos et al. 2020; Gopalswamy et al. 2009)

Solar Source, Flare, CME, Consequences



MARIE on Mars Odyssey died

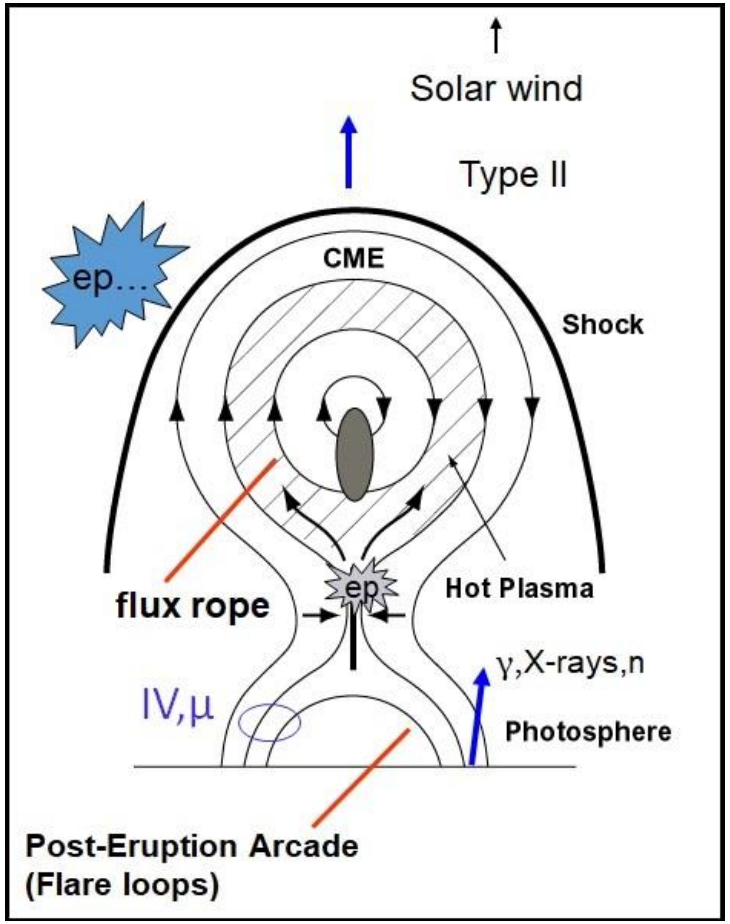
Safe mode



Visible, EUV

Zeitlin+2010

Common Eruptive Signatures & Consequences

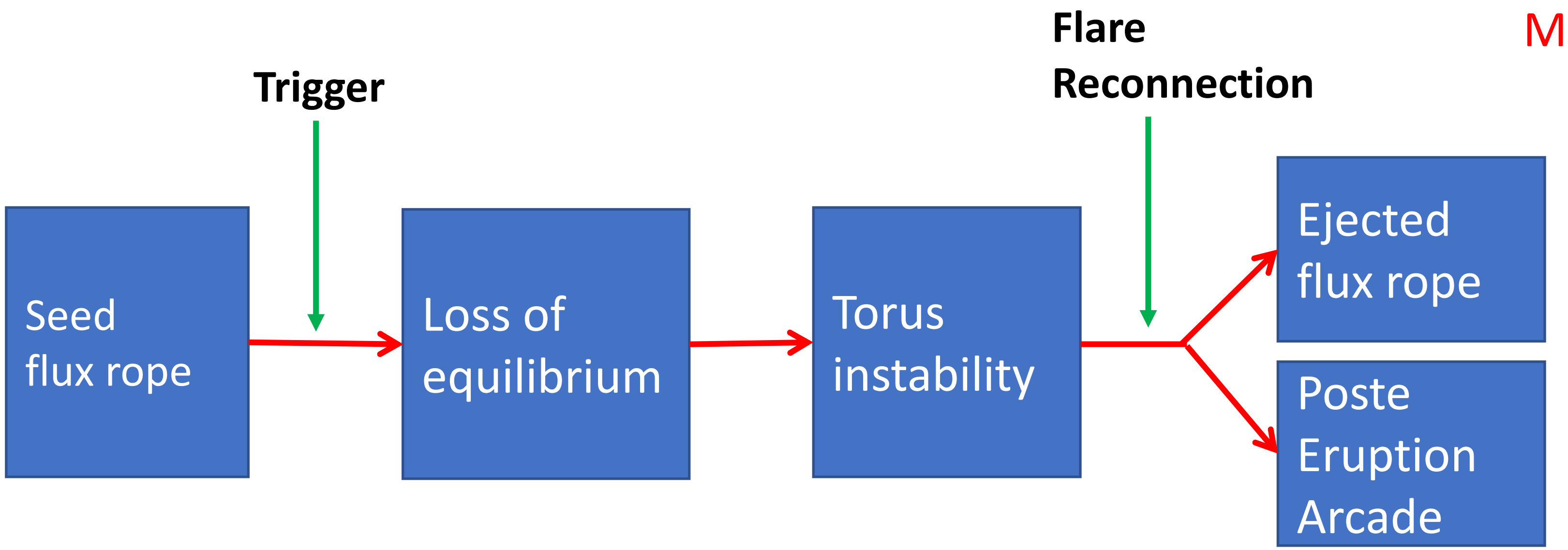


- Prominence/filament eruptions
- Flare ribbons
- Post-eruption arcades, Type IV Bursts
- Hard X-ray, Microwave foot points
- Coronal dimming (flux rope)
- Coronal Mass ejections (Flux rope, prominence core, shock sheath)
- Shocks (H-alpha, EUV, microwaves, type II bursts, SEP events)
- Long-duration Type III bursts
- In-situ (SI/SSC, charge state signatures, ESP events, GIC, geomagnetic storms)
- Ionospheric disturbances
- Atmospheric disturbances

Initiation

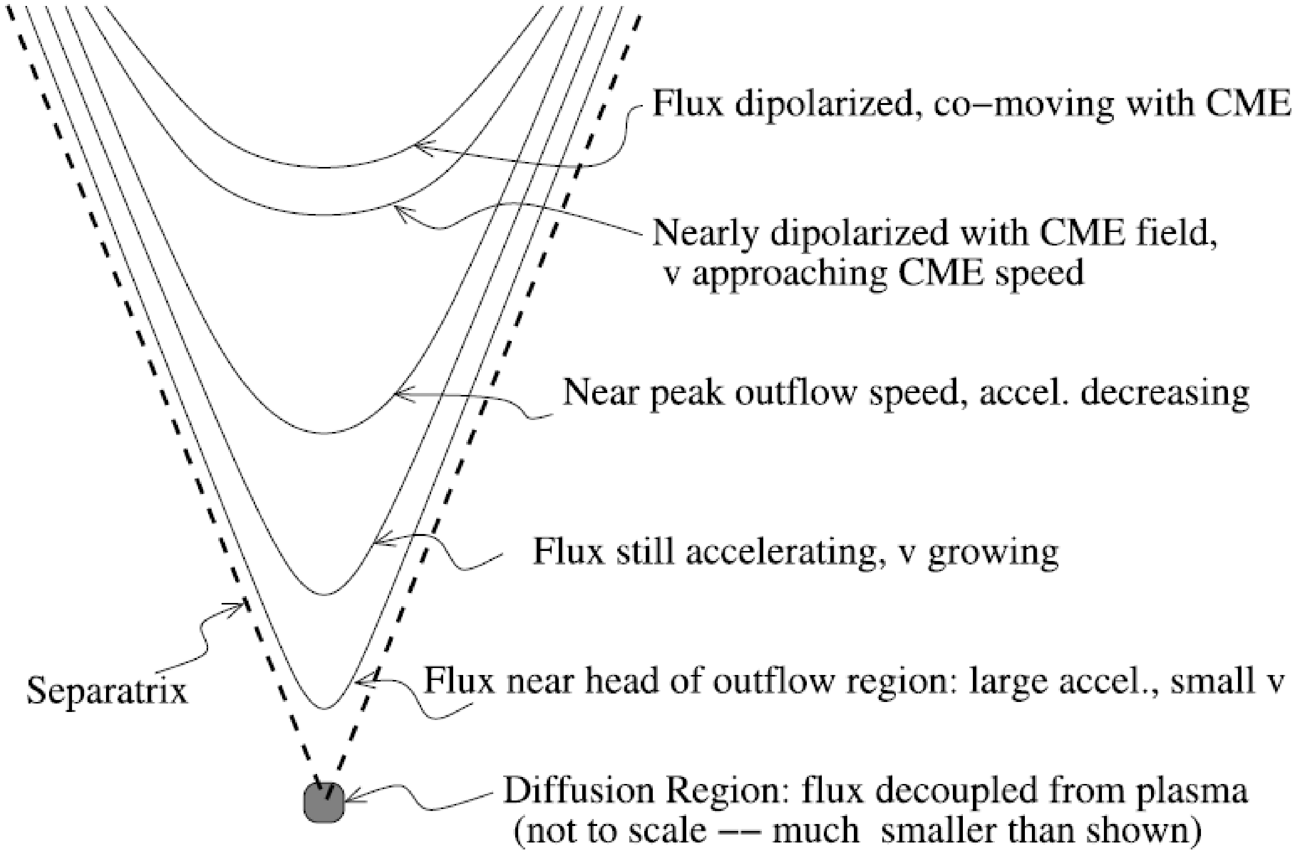
Further evolution determined by drag, deflection, rotation and Expansion
Magnetic cloud at 1 au

Pre-eruption structure and evolution (energy storage)

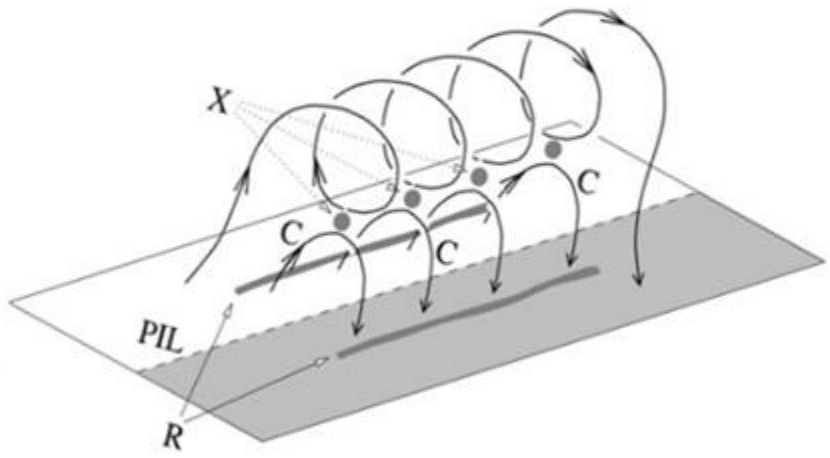


Filament
Hot flux rope
Formed due to slow reconnection

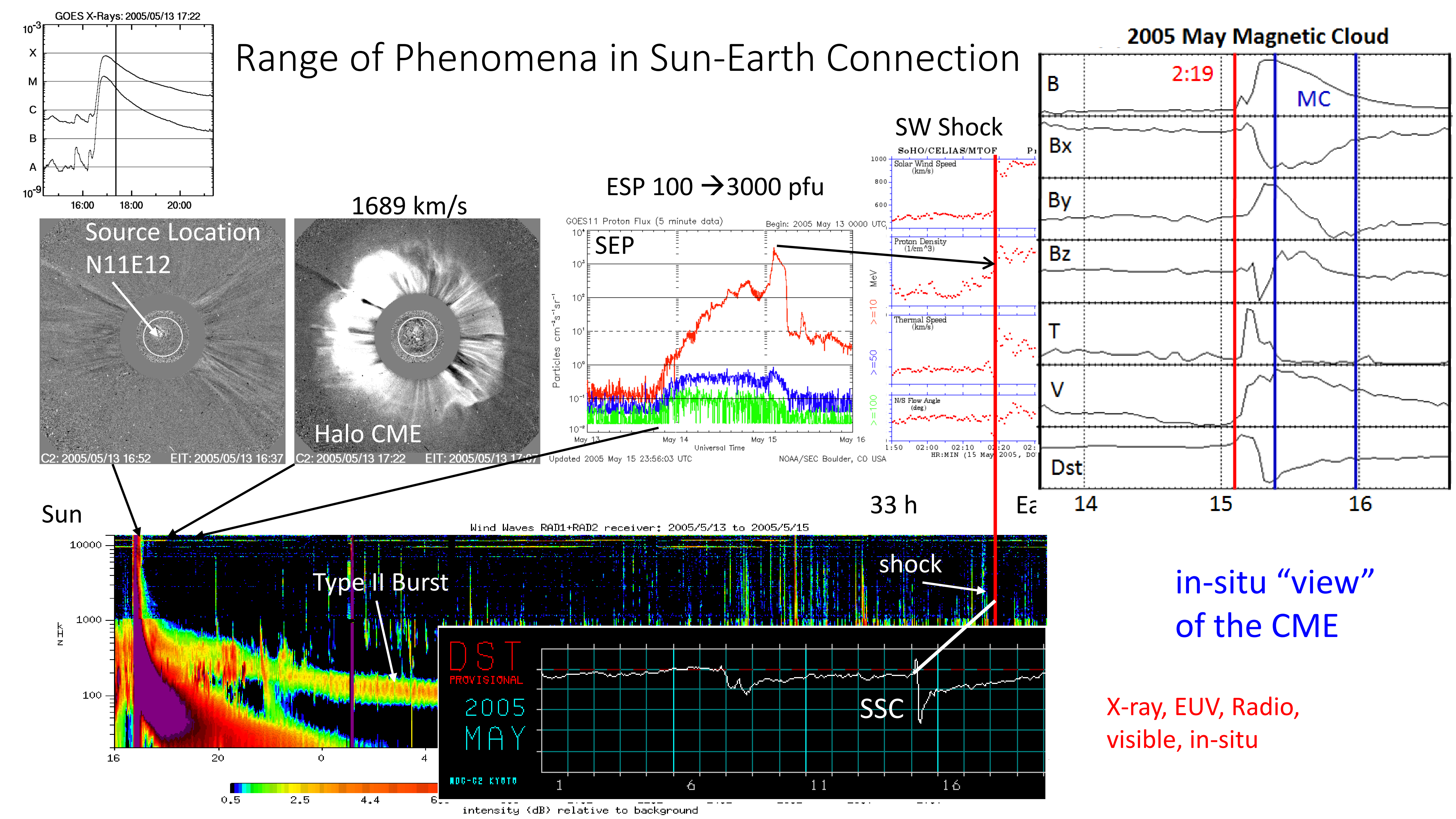
Details of Flux Rope Acceleration



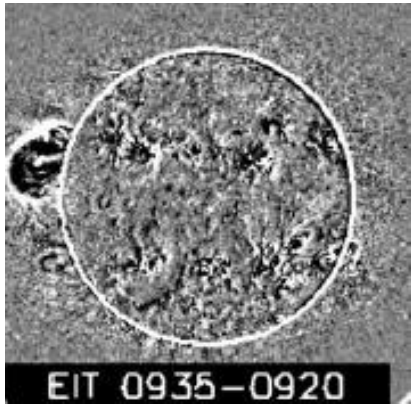
Welsch 2018



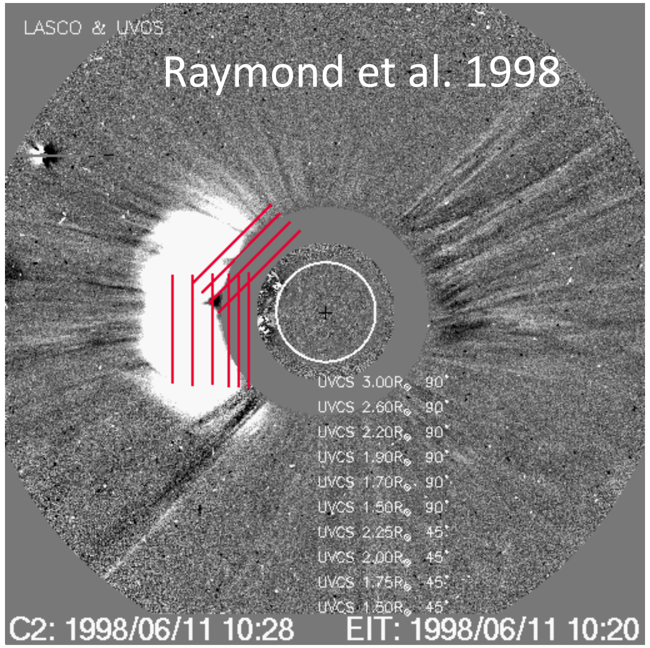
Longcope et al. 2007


Range of Phenomena in Sun-Earth Connection
GOES X-Rays: 2005/05/13 17:22
X
M
C
B
A
16:00
18:00
20:00
1689 km/s
Source Location
N11E12
Halo CME
C2: 2005/05/13 16:52
EIT: 2005/05/13 16:37
C2: 2005/05/13 17:22
ESP 100 → 3000 pfu
GOES11 Proton Flux (5 minute data)
Begin: 2005 May 13 0000 UTC
SEP
Particles cm⁻²s⁻¹sr⁻¹
May 13
May 14
May 15
May 16
Universal Time
Updated 2005 May 15 23:56:03 UTC
NOAA/SEC Boulder, CO USA
>=10
>=50
>=100
MeV
SW Shock
SoHO/CELIAS/MTOF
Solar Wind Speed (km/s)
Proton Density (1/cm^3)
Thermal Speed (km/s)
N/S Flow Angle (deg)
2005 May Magnetic Cloud
2:19
MC
B
Bx
By
Bz
T
V
Dst
14
15
16
33 h
Sun
Wind Waves RAD1+RAD2 receiver: 2005/5/13 to 2005/5/15
Type II Burst
shock
kHz
10000
1000
100
intensity (dB) relative to background
DST PROVISIONAL
2005 MAY
WDC-C2 KYOTO
SSC
in-situ "view" of the CME
X-ray, EUV, Radio, visible, in-situ

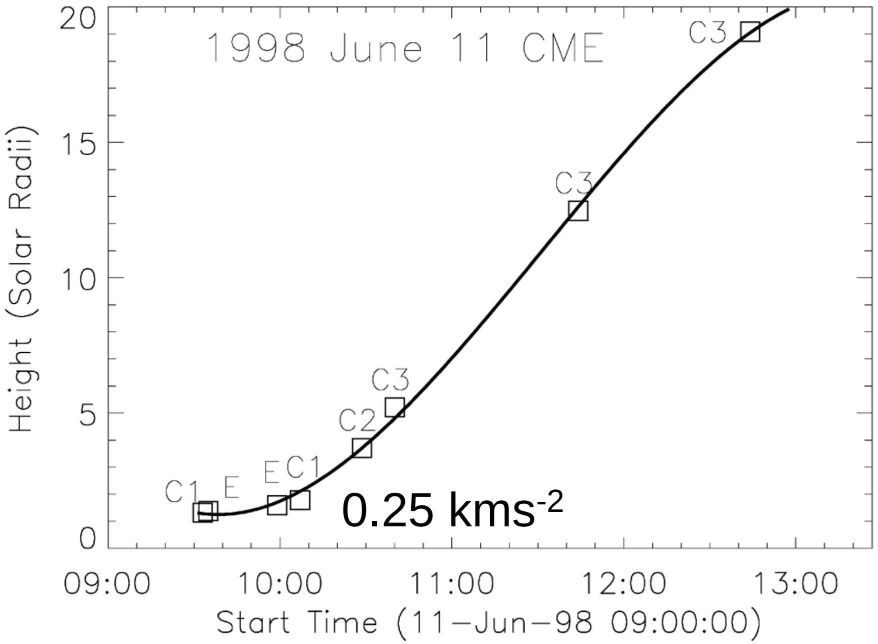
CME Kinematics from LASCO, EIT

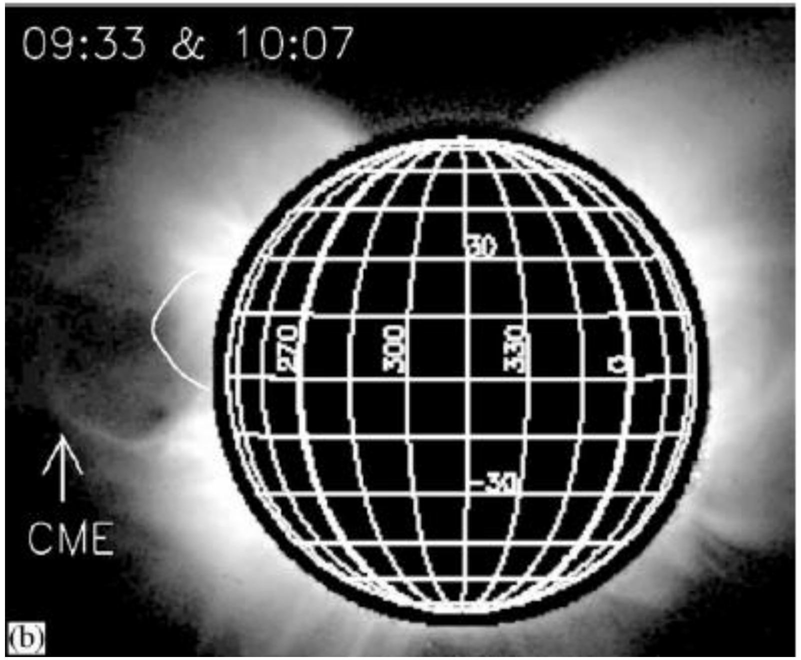


EUV, UV, visible

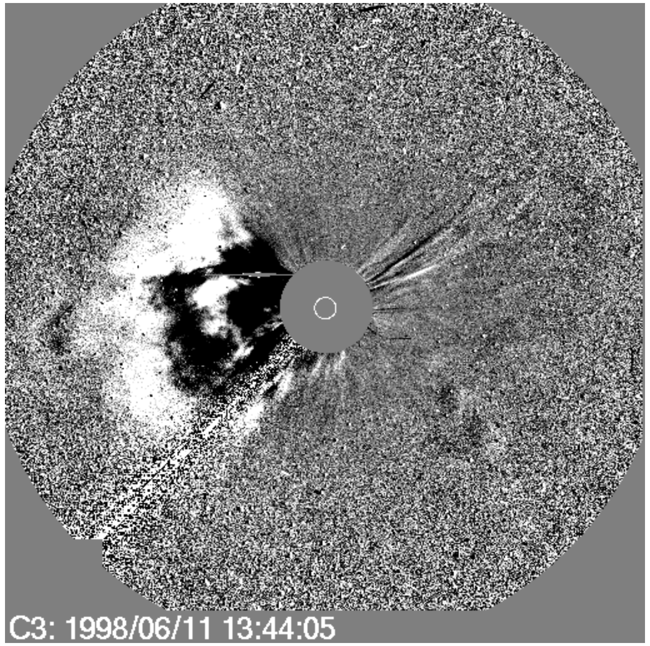


Gopalswamy & Thompson 2000





$$h = 3.1 - 0.1t + 1.5\times10^{-3}t^2 - 3.4\times10^{-6}t^3$$

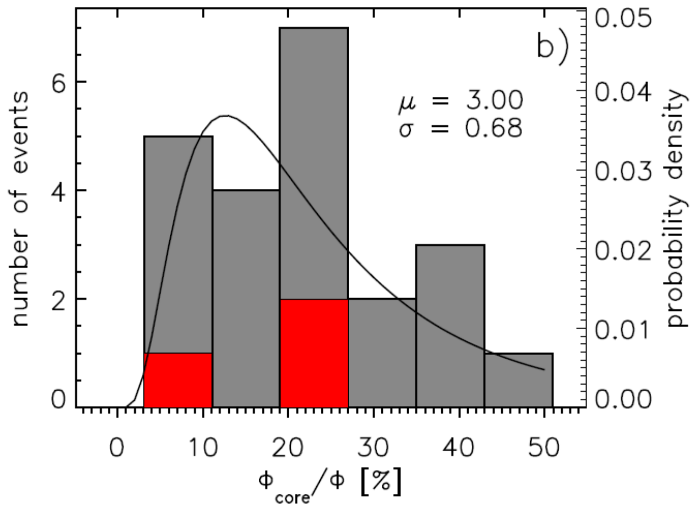


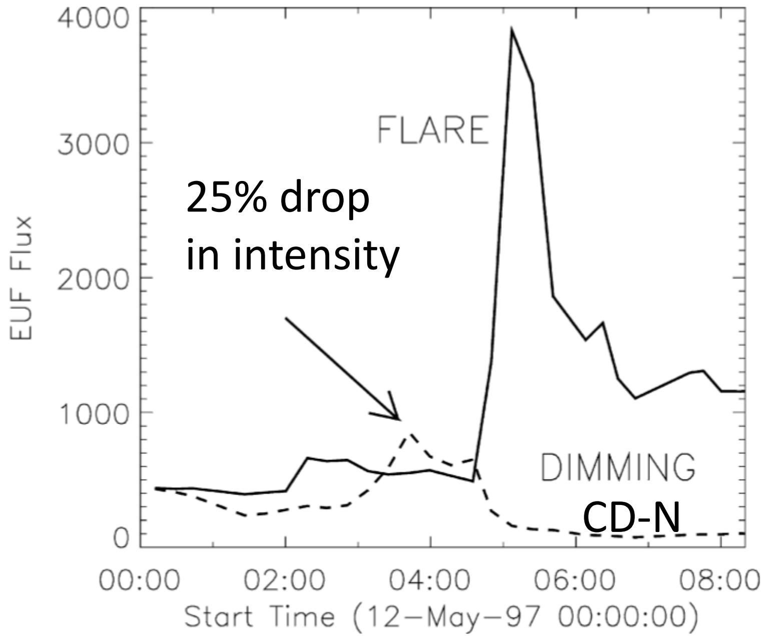
3rd order polynomial indicating early acceleration (a_p = +0.25 kms^{-2}) and later deceleration (-36 ms^{-2})

Dimming

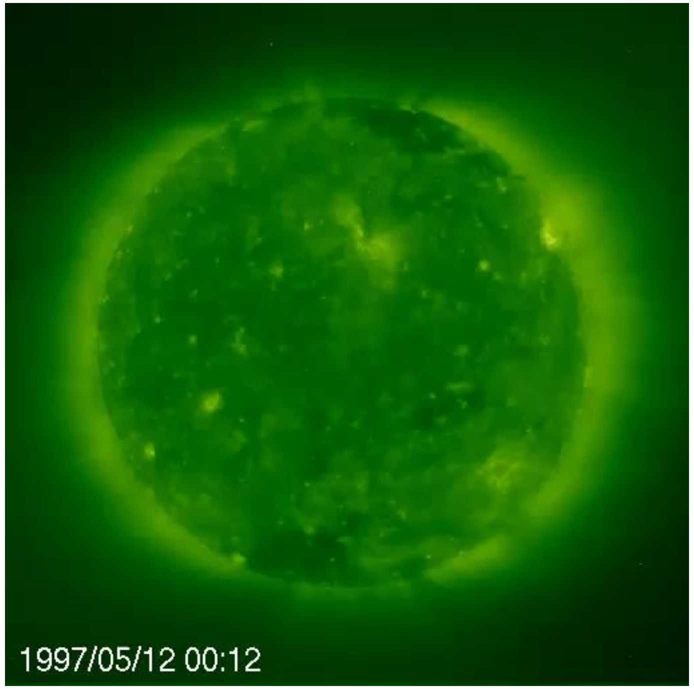
- Core dimming & Secondary dimming
- CD: feet of erupted flux rope
- SD: due to expansion of overlying loops
- Tertiary dimming? due to sweeping by waves

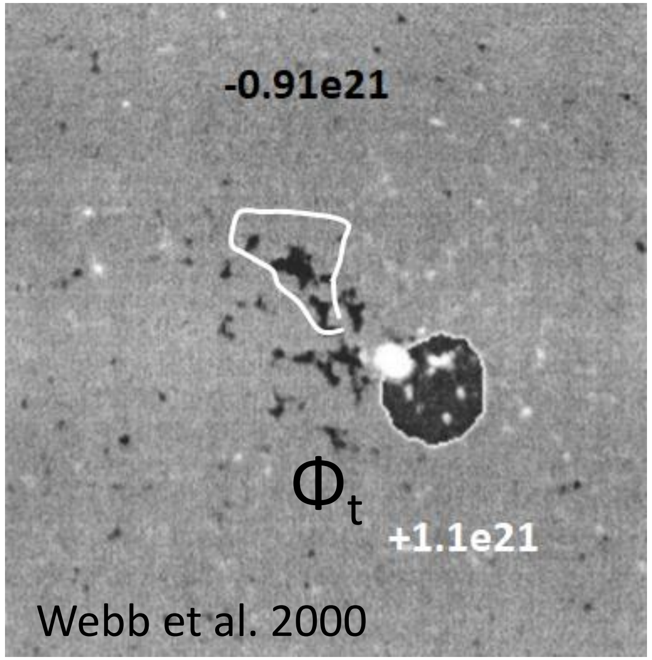
(Rust et al. 1983; Hudson et al. 1996; Thompson et al. 1998; Gopalswamy 1999; Webb et al. 2000; Gopalswamy and Thompson 2000; Mandrini et al. 2005; Warmuth 2015; Dissauer et al. 2018)

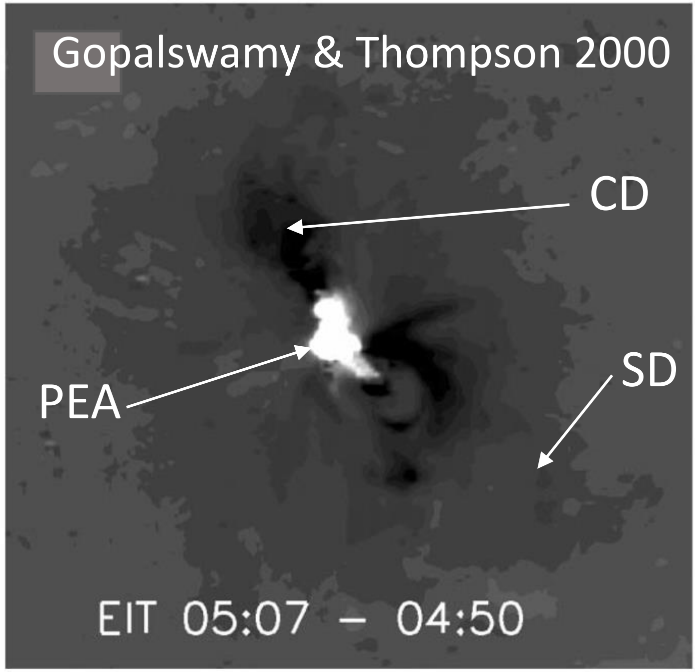




CME onset ~ Flare onset







Galactic Cosmic Rays

- https://cdaw.gsfc.nasa.gov/movie/make_javamovie.php?date=20191103&img1=lasc2aia193