ASTR-6000 Seminar
COLLAGE: Coronal Heating, Solar Wind, & Space Weather

March 17, 2022
Space Weather
The Interplanetary Space Environment

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Outline

1. **Space Climate vs. Space Weather**

2. **Solar sources of space weather: photons, plasma, and charged particles**
   - Solar Extreme Ultraviolet (EUV) irradiance
   - Review of solar wind structures: High Speed Streams (HSS) and Co-rotating Interaction Regions (CIRs)
   - Solar Magnetic Eruptions (SMEs)
     - Flares: from gamma rays to radio emission
     - Coronal Mass Ejections (CMEs)
     - Energetic particle production

3. **The interplanetary space environment: a "planet agnostic" viewpoint**
   - Solar wind influences
   - CMEs impacts
   - Radiation storms

Planets and people come in next week…

1. Space Climate vs. Space Weather

Space Climate

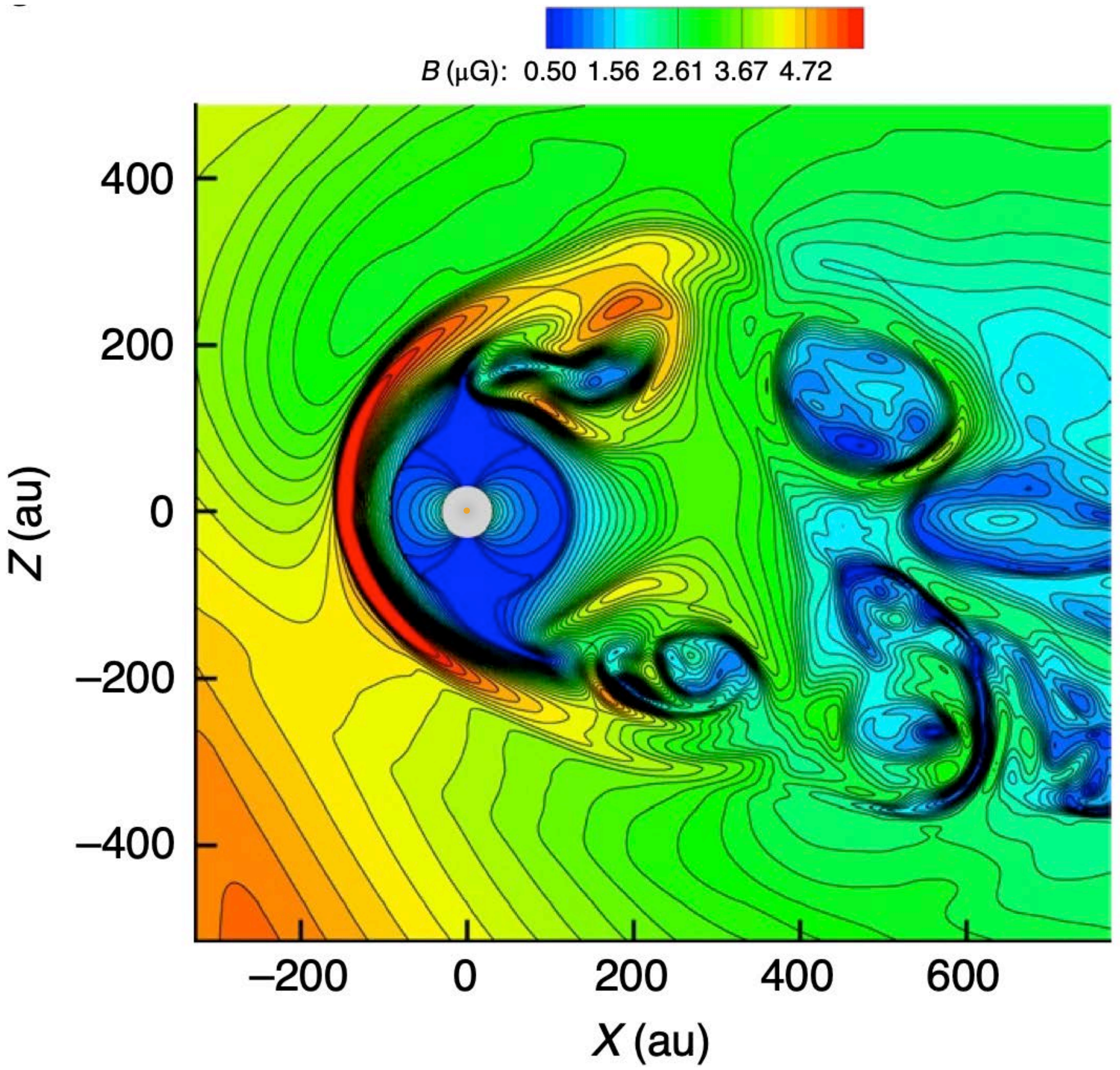
- The variable physical conditions in interplanetary space, over time spans of *a solar cycle (10—12 years) or longer.*

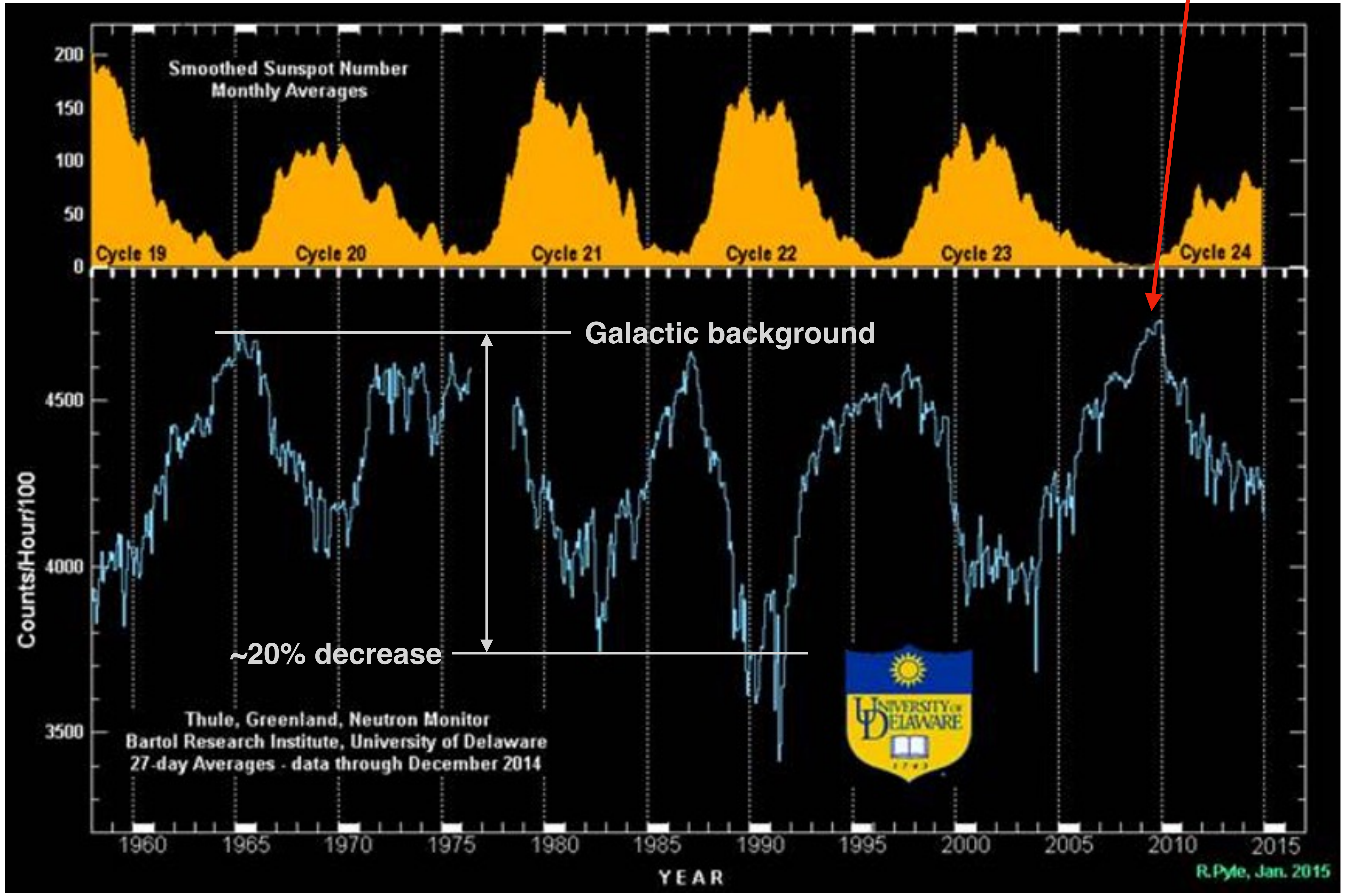
Space Climate: Galactic Cosmic Ray flux

GCRs are modulated in anti-phase with the sunspot cycle

Largest GCR background since measurements started: Cycle 23-24 deep minimum

The changing magnetic Heliosphere changes the influx of energetic charged particles

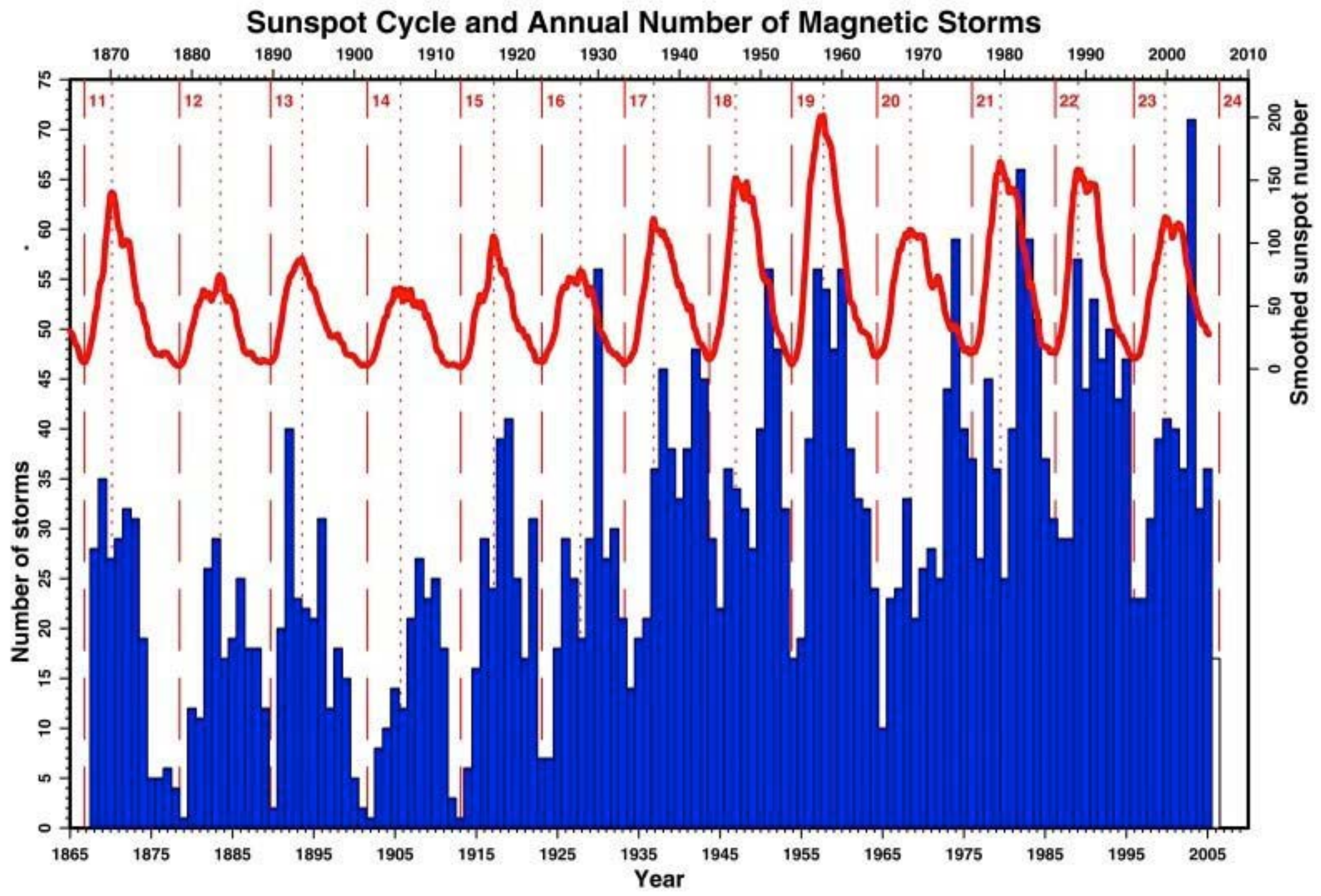




Ofer et al., Nature Astronomy, 2020:
https://doi.org/10.1038/s41550-020-1036-0

Space Climate: Geomagnetic storm occurrence

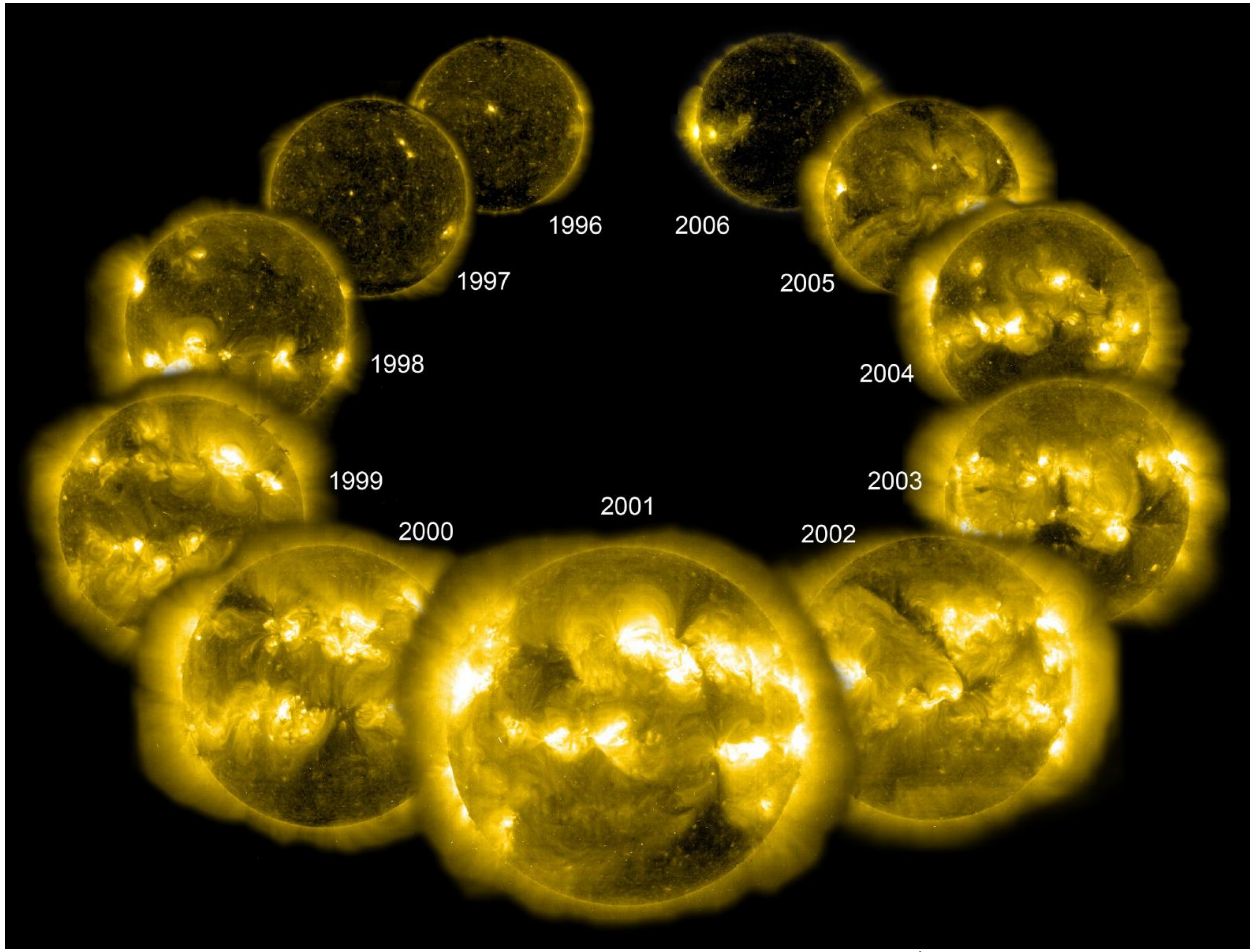
Geomagnetic storm occurrence correlates in phase with the sunspot cycle



Edward Sabine was the first to point out this correlation in 1852, but it was dismissed as a coincidence by many of the prominent astronomers and physicists of the day (George Airy, Lord Kelvin, …)

Space Climate: EUV irradiance variability

Extreme Ultraviolet (EUV) irradiance varies in phase with the sunspot cycle

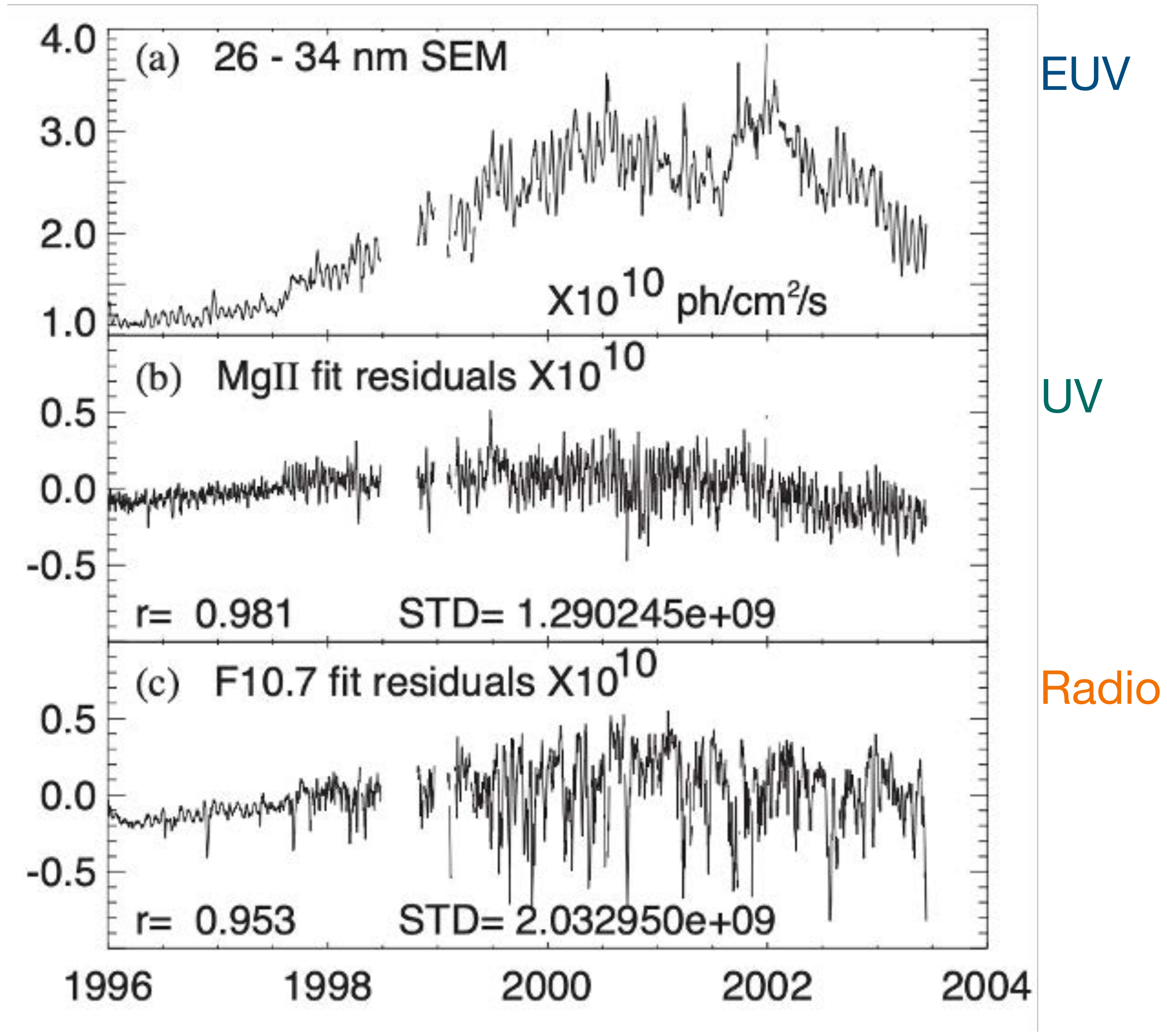


SOHO Extreme Ultraviolet Telescope (EIT) 284 Å bandpass

EUV variability: 2—4X variation (global average)
10—100X peak variation during flares

Other indicators of solar EUV spectral irradiance variation:

- Mg II 2800 Å core-to-wing ratio
- F10.7cm radio emission

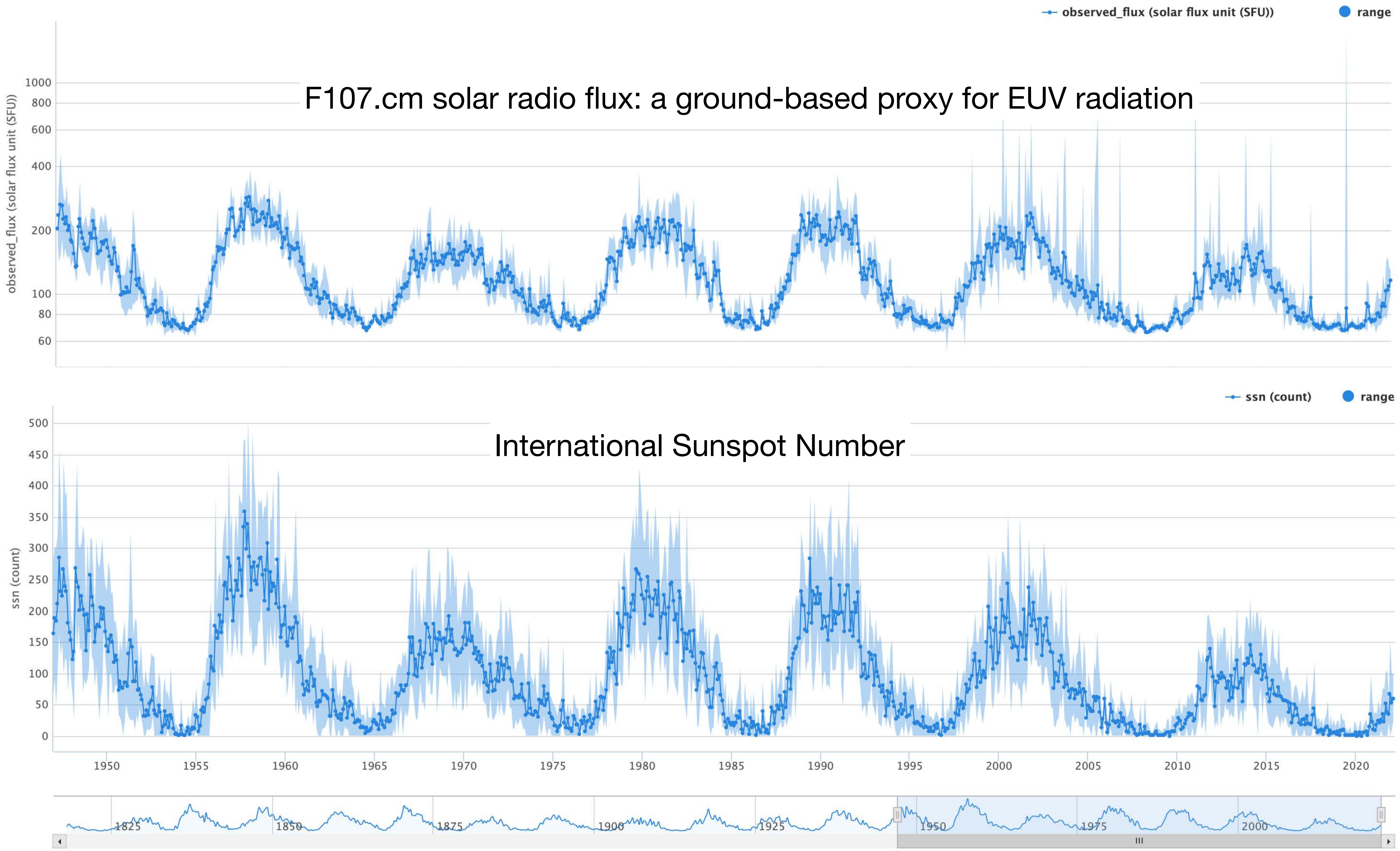


Floyd et al., Journ. Atm. & Sol. Terrest. Phys., **67**, 3, 2005, https://doi.org/10.1016/j.jastp.2004.07.013

Space Climate: EUV irradiance variation

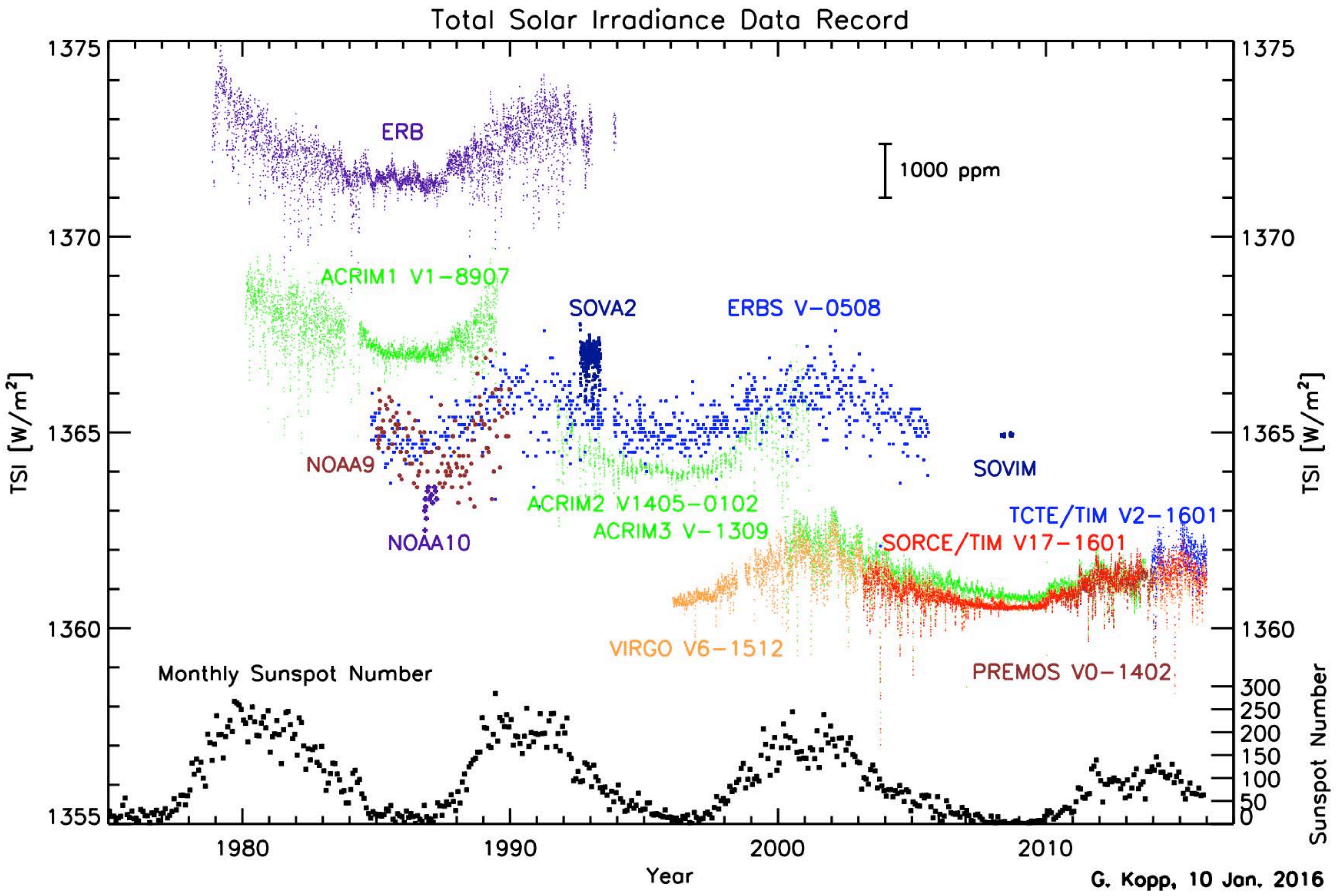
F10.7cm radio flux is most commonly used in atmospheric/ionospheric modeling

1 sfu = $10^{-22}\ W \cdot m^{-2} \cdot Hz^{-1}$

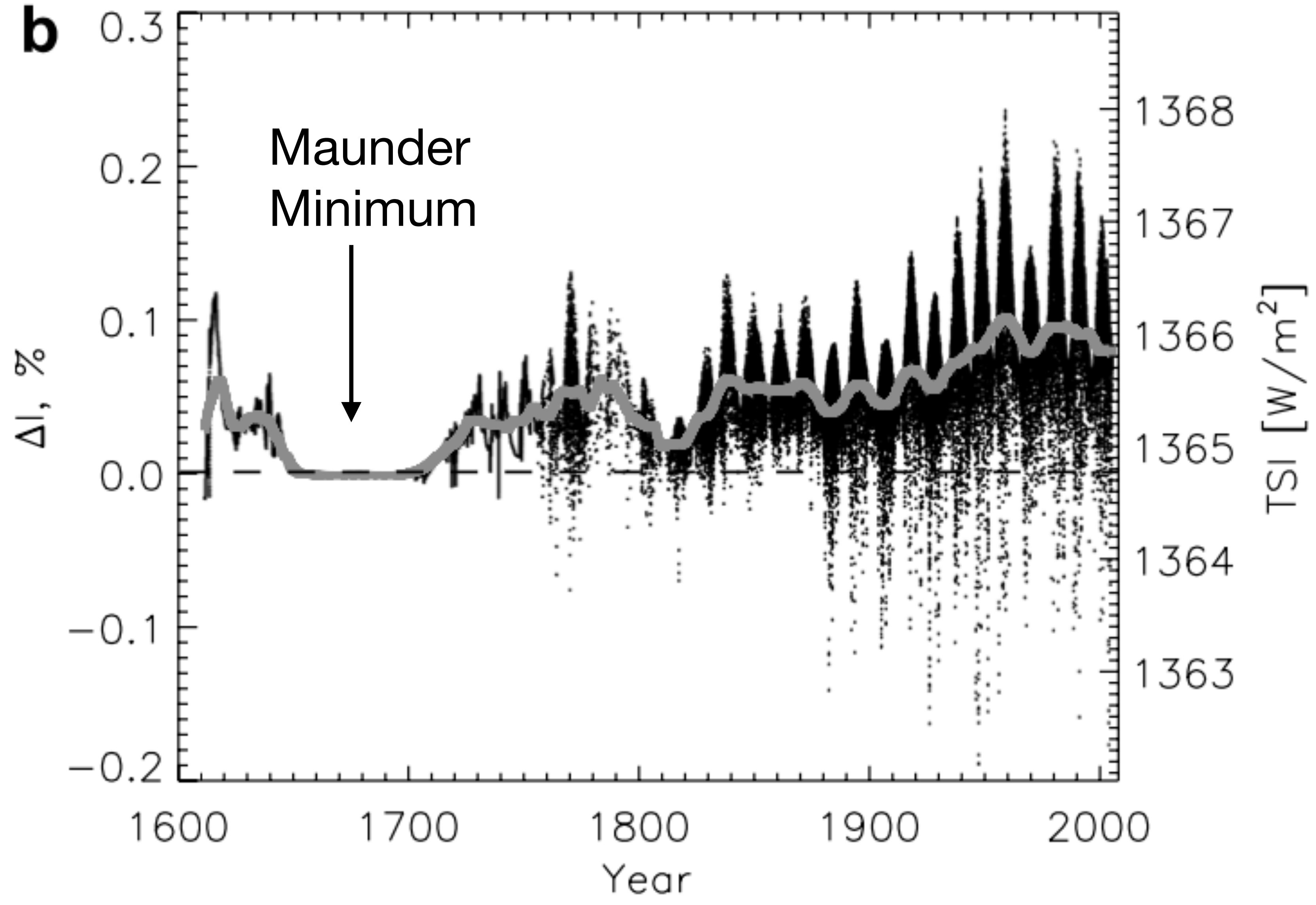


Space Climate: Total Solar Irradiance variation

TSI is modulated at the 0.1% level in phase with the sunspot cycle



The globally averaged Sun is brighter when there are more sunspots



Evidence of longer-term TSI variation with sunspot cycle magnitude

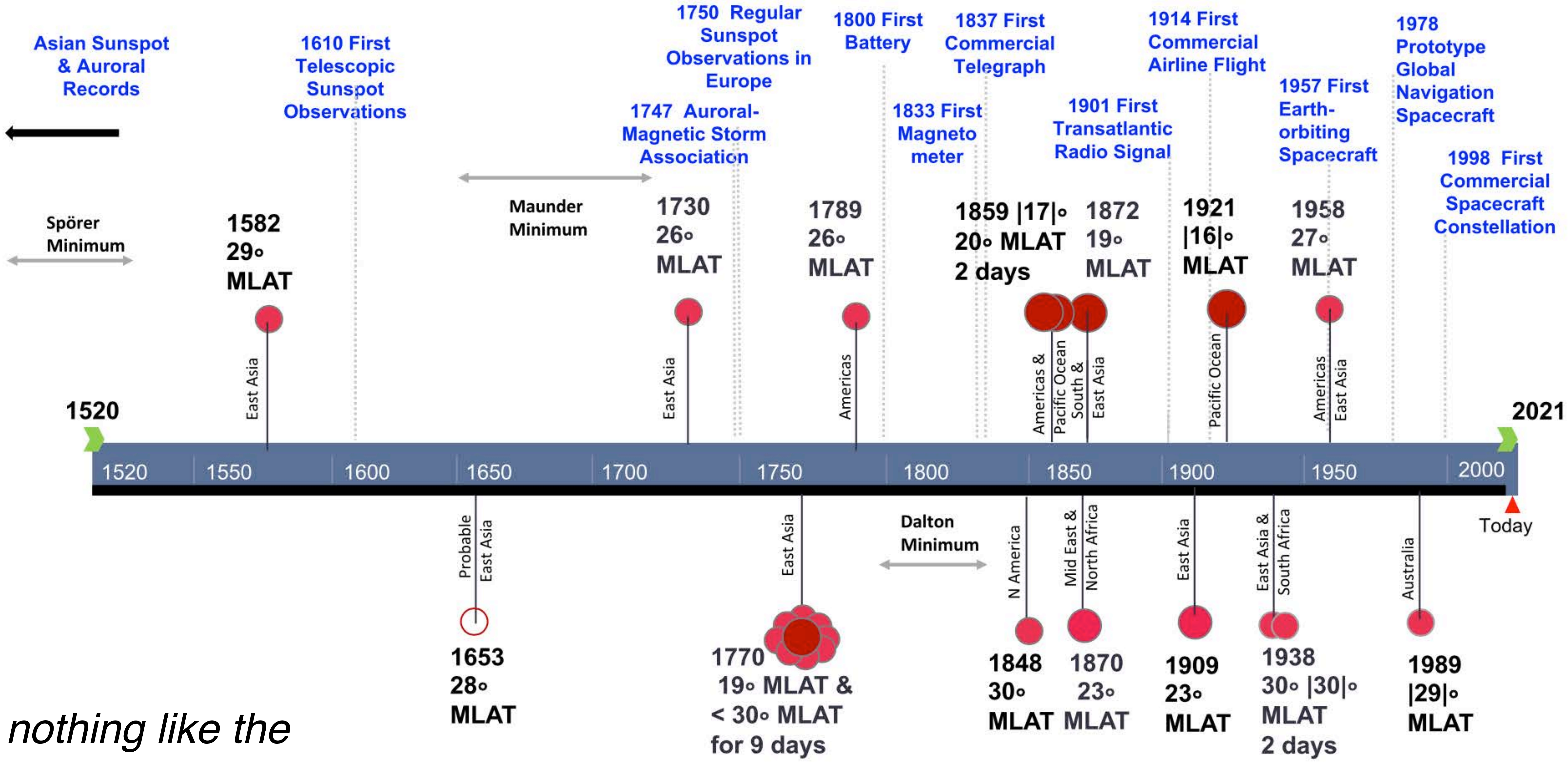
Balmaceda, et al., Adv. Space Res., 40, 2007, https://doi.org/10.1016/j.asr.2007.02.077.

Kopp et al., Sol. Phys., **11**, 291, 2016, https://doi.org/10.1007/s11207-016-0853-x

Space Climate: evidence for longer-term variation

Geomagnetic storm activity not seen in the modern era

500 Years of geomagnetic storms with aurora visible lower than 30° magnetic latitude



We have seen nothing like the superstorm series of 1770 in the modern era

Knipp et al., Journ. Space Weath. Space Clim., **11**, 29, 2021, https://doi.org/10.1051/swsc/2021011

1. Space Climate vs. Space Weather

Space Weather

- The variable physical conditions in interplanetary space, over time spans of *minutes to days*, due primarily to the variable level of magnetic activity on the Sun.

Space weather exists around magnetic stars regardless of whether they have inhabited planets or not.

- The physical phenomena associated with the interactions of the variable interplanetary space environment with planetary systems: **Stellar-Planetary System Science**.

A list of phenomena that occur due to Sun-Earth interactions, e.g., "aurora borealis", GICs, etc.

- The impact of the variable space environment on humans and human-made technology.

"If it doesn't do anything, it's not important."

- A **predictive science** that is not necessarily dependent on "understanding" the physics of the underlying phenomena.

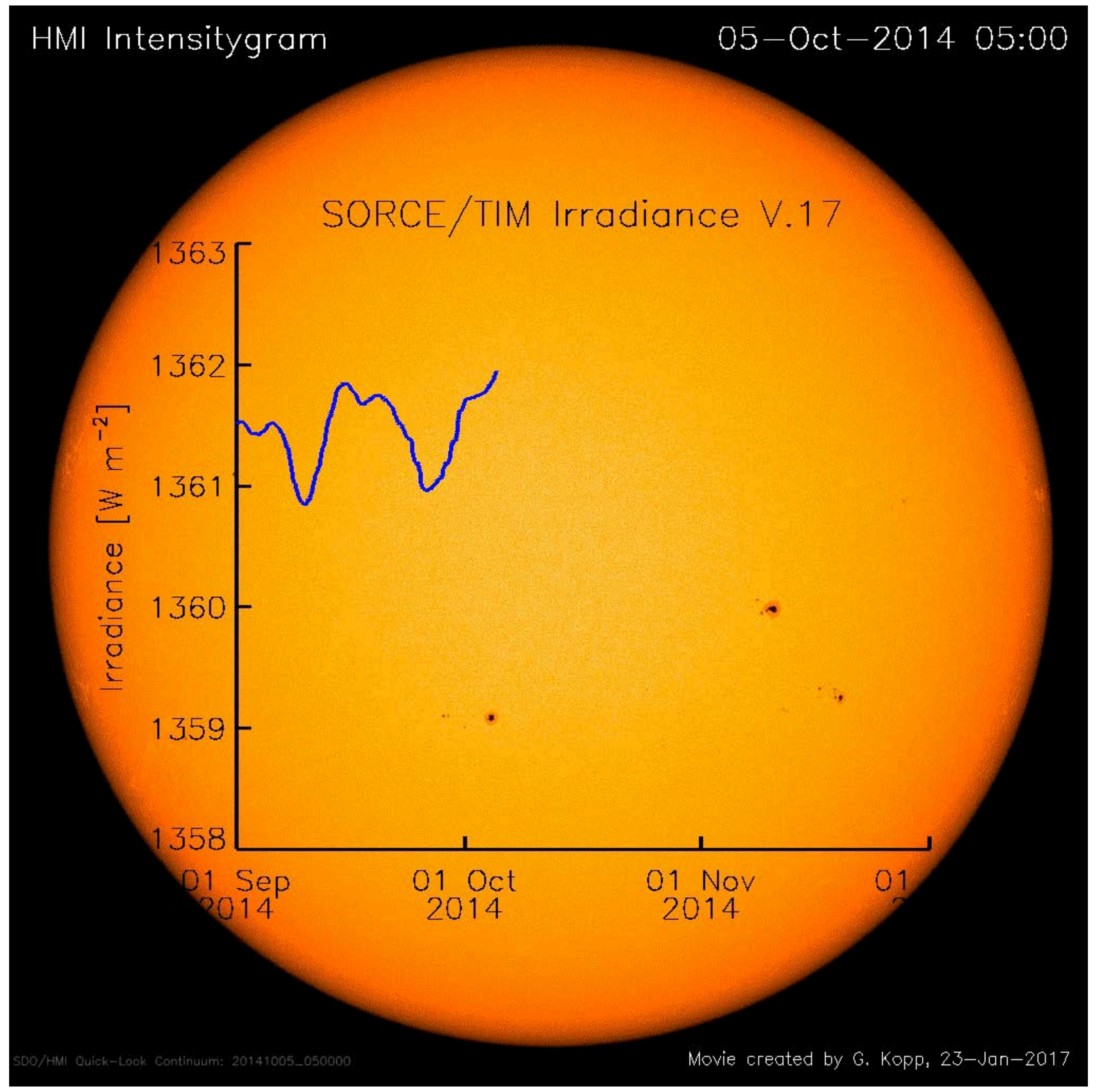
Hurricane storm surge is not fully understood. NOAA doesn't care - they still predict it using empirical models and tools because it has impacts.

2. Solar sources of space weather

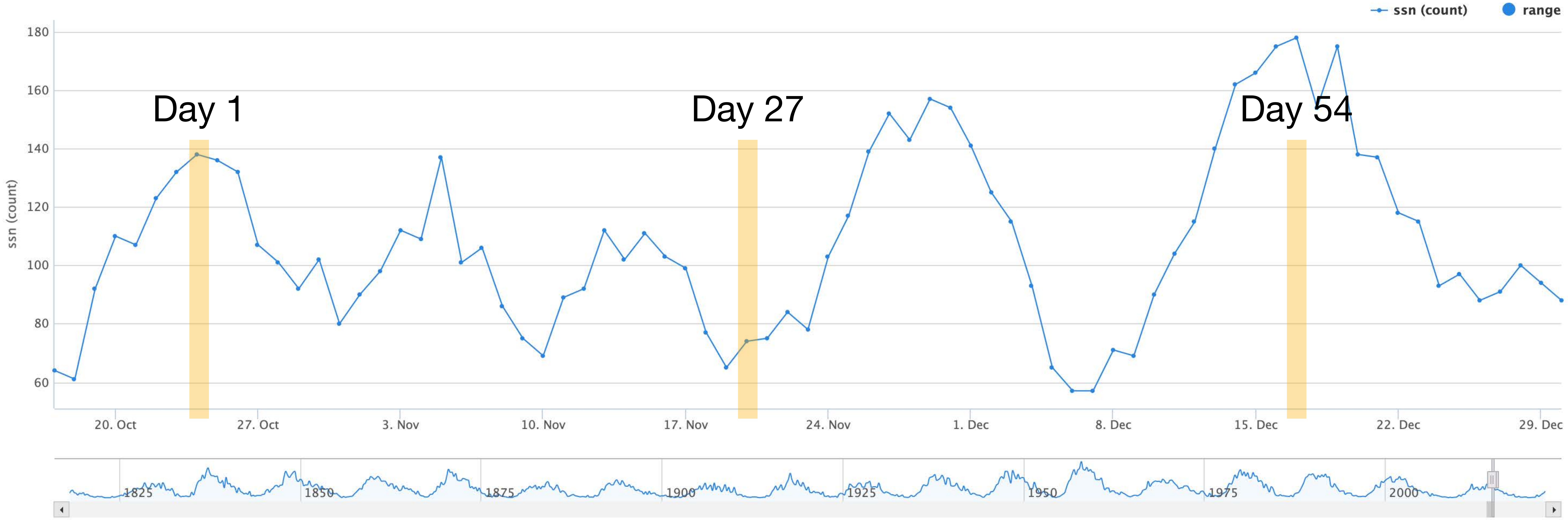
- Extreme ultraviolet (EUV) irradiance variations — **Photons**
- Solar wind structures in interplanetary space — **Plasma**
- Solar magnetic eruptions (SMEs) — **Photons, Plasma, and Charged particles**

Extreme Ultraviolet variability due to Active Regions

EUV irradiance shows rotational modulation due to passage of ARs



TSI for October 2014
0.23% max variation

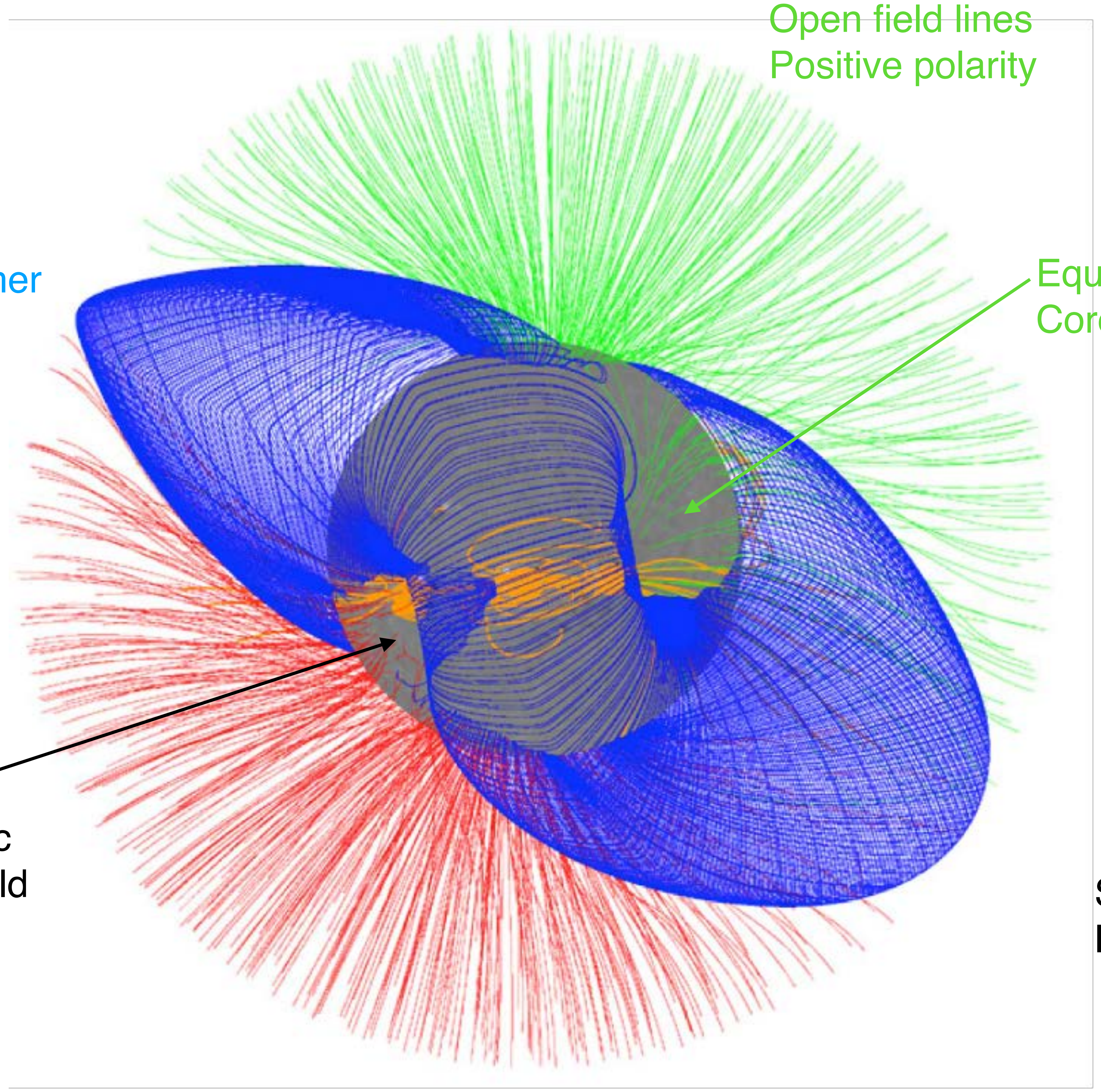


EUV proxy for October — December 2014
300% max variation

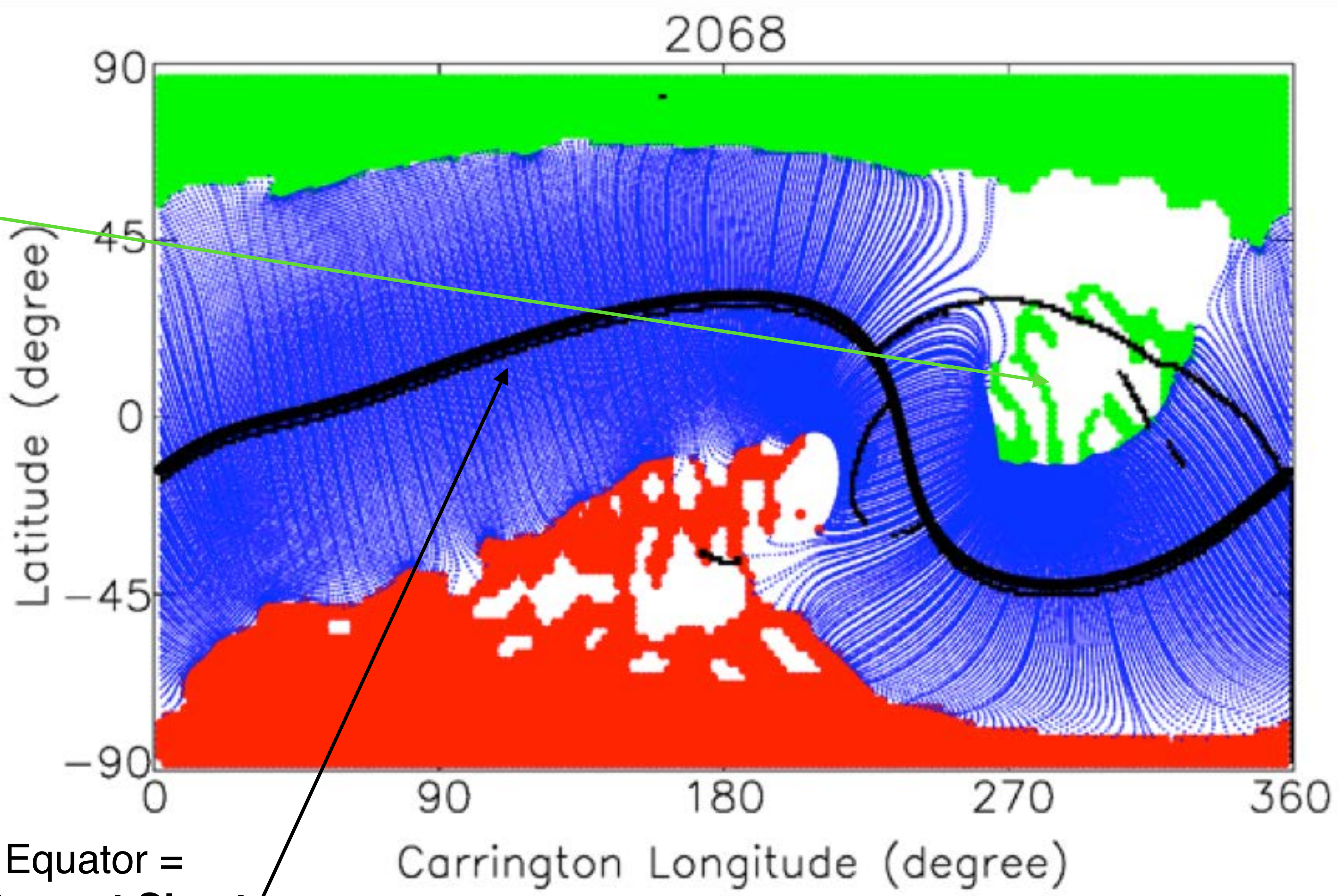
LASP Interactive Solar IRradiance Datacenter: https://lasp.colorado.edu/lisird/data/penticton_radio_flux/

Review of solar wind characteristics

The global solar magnetic field determines the interplanetary solar wind structure



Potential Field Source Surface (**PFSS**) Model of the solar magnetic field

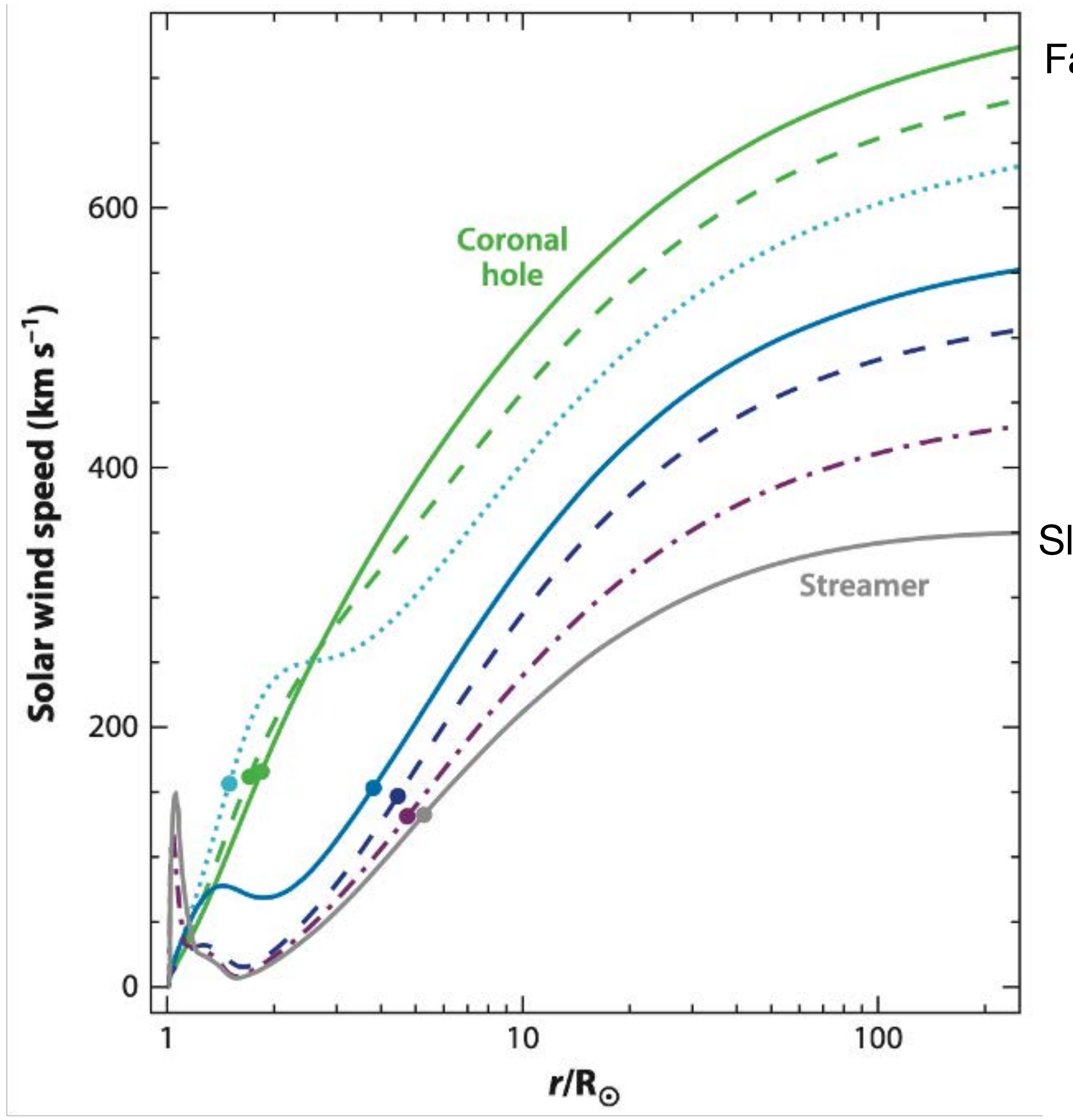


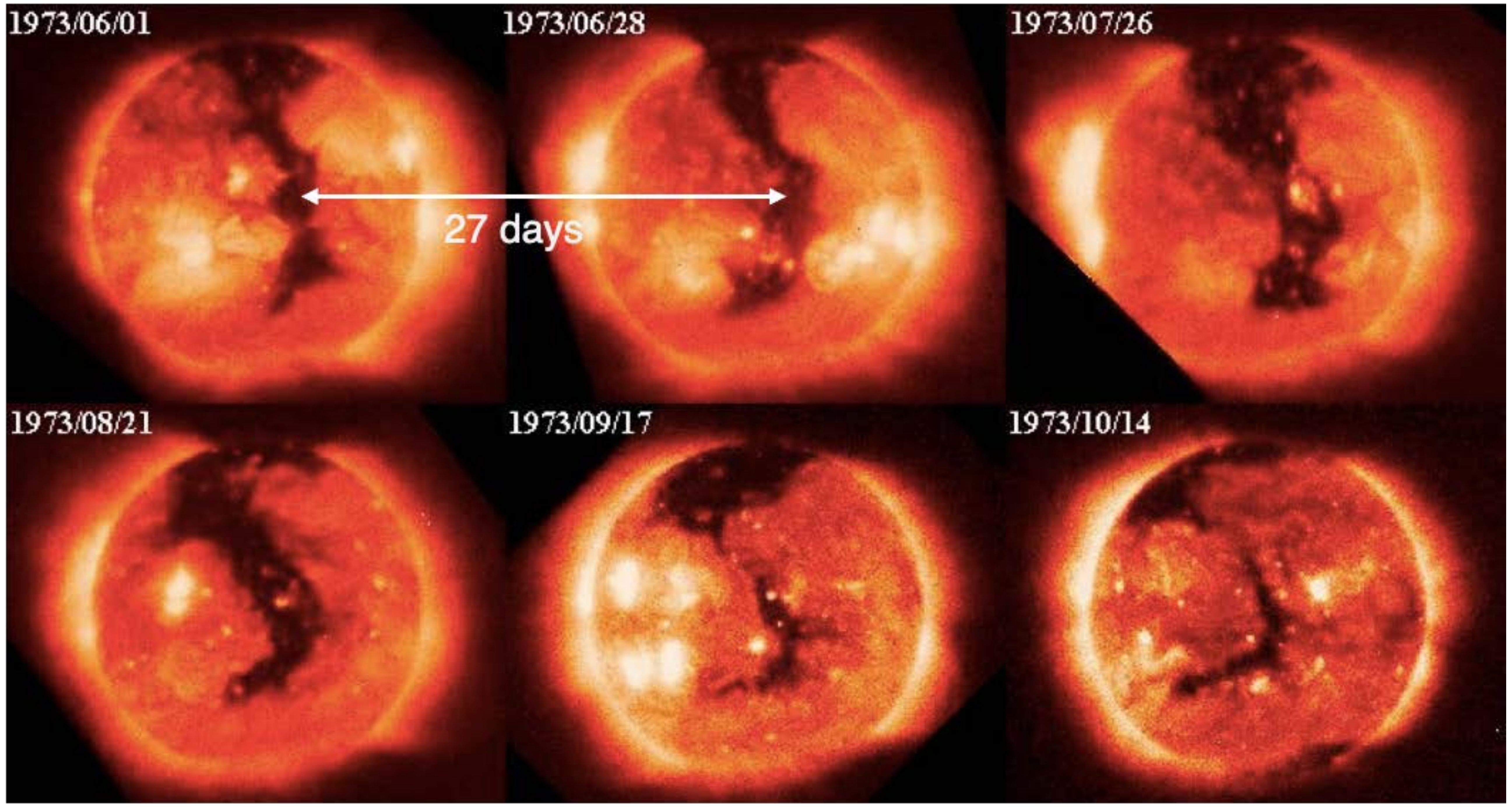
PFSS Model "unwrapped" onto cylindrical map projection

Petrie et al., Sol. Phys., **274**, 2014, https://doi.org/10.1007/s11207-010-9687-0

Review of solar wind characteristics

High Speed Streams (HSSs) and Co-rotating Interaction Regions (CIRs)





Skylab X-ray telescope discovers "**coronal holes**" — open field regions in the global solar magnetic field and sources of "High Speed Streams" (HSS) of solar wind.

Note acceleration out to/beyond 1 AU

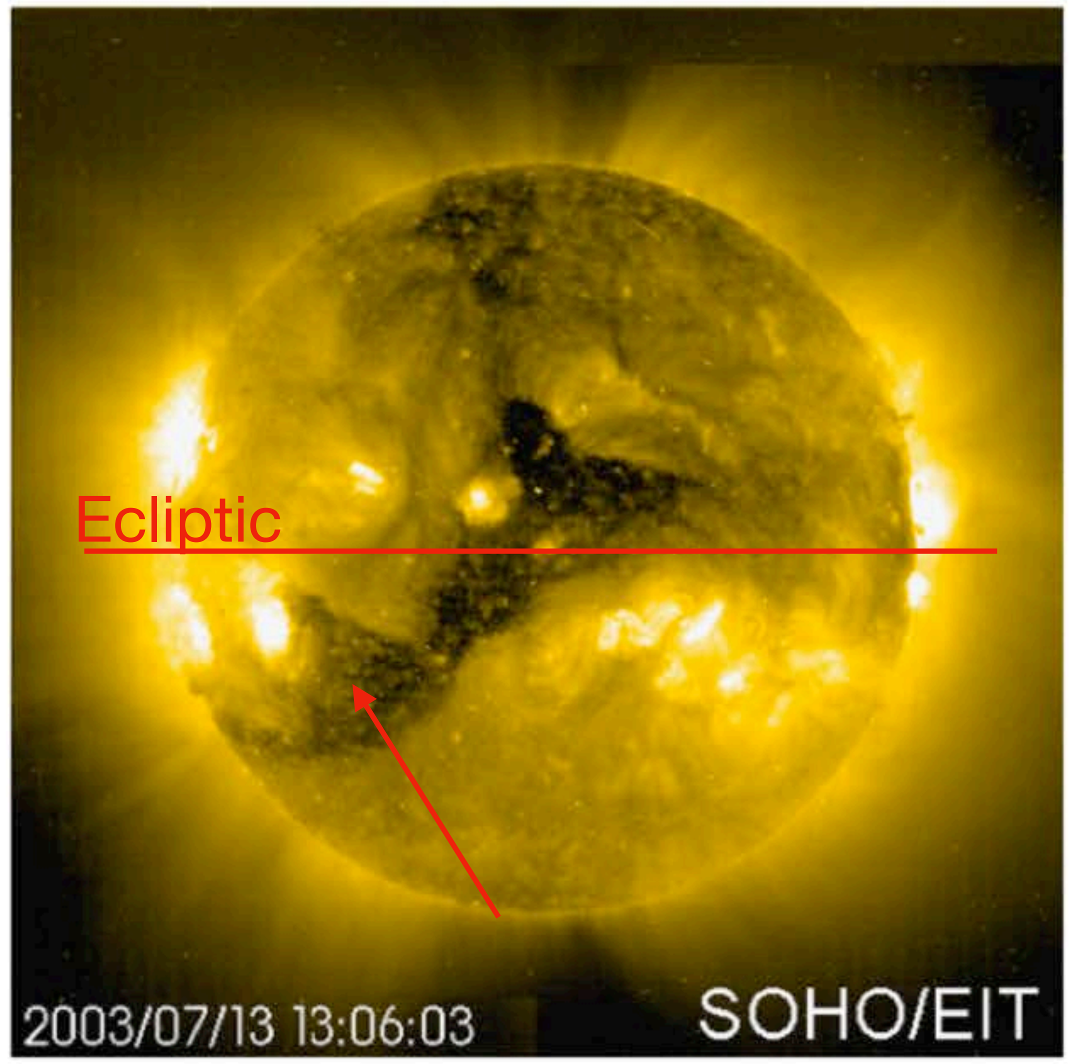
Note 27-day recurrence over > 4 months due to solar rotation

Cranmer & Winebarger., Ann. Rev. Astron. & Astrophys., 2019, https://doi.org/10.1146/annurev-astro-091918-104416

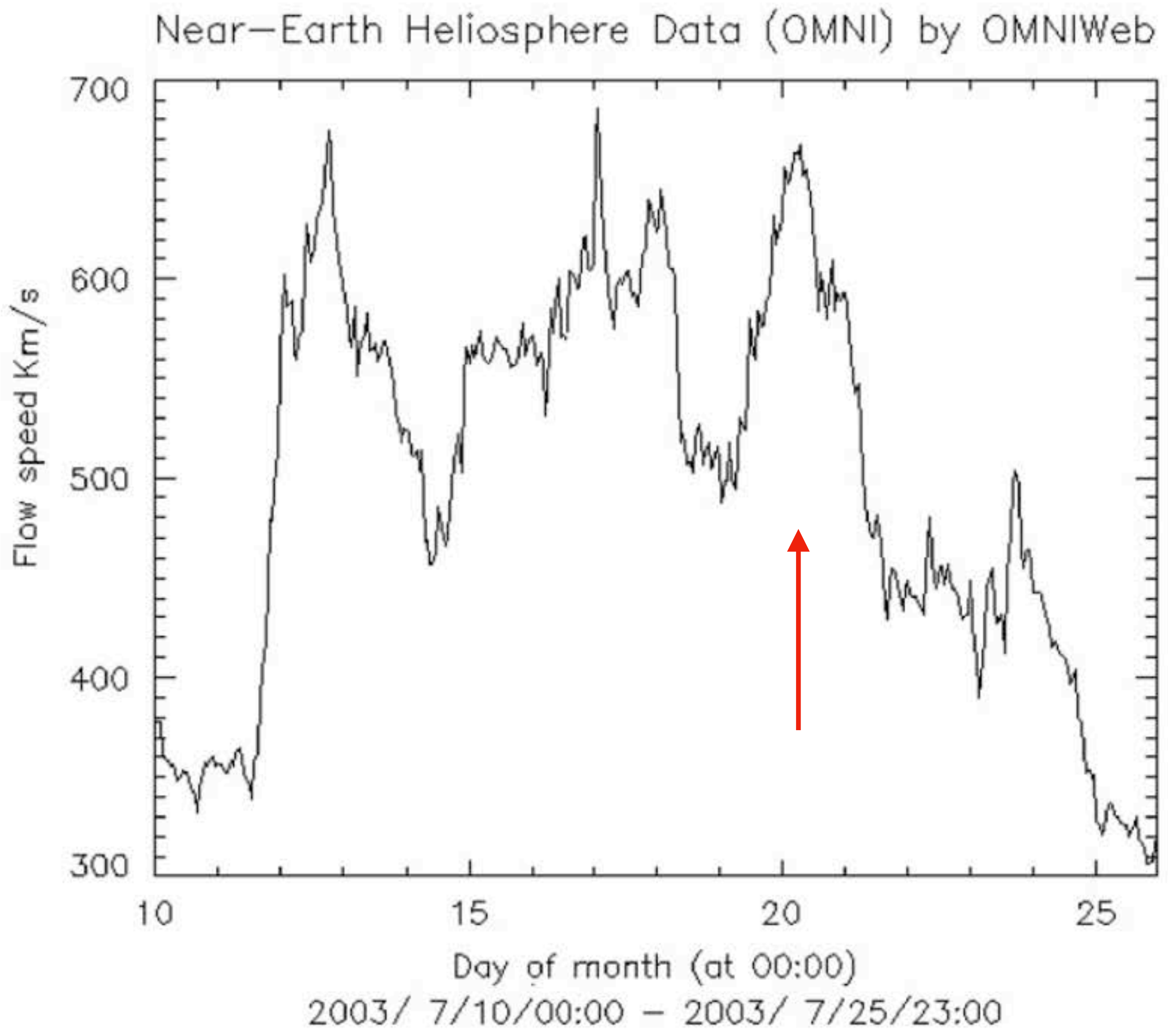
Review of solar wind characteristics

High Speed Streams (HSSs) and Co-rotating Interaction Regions (CIRs)

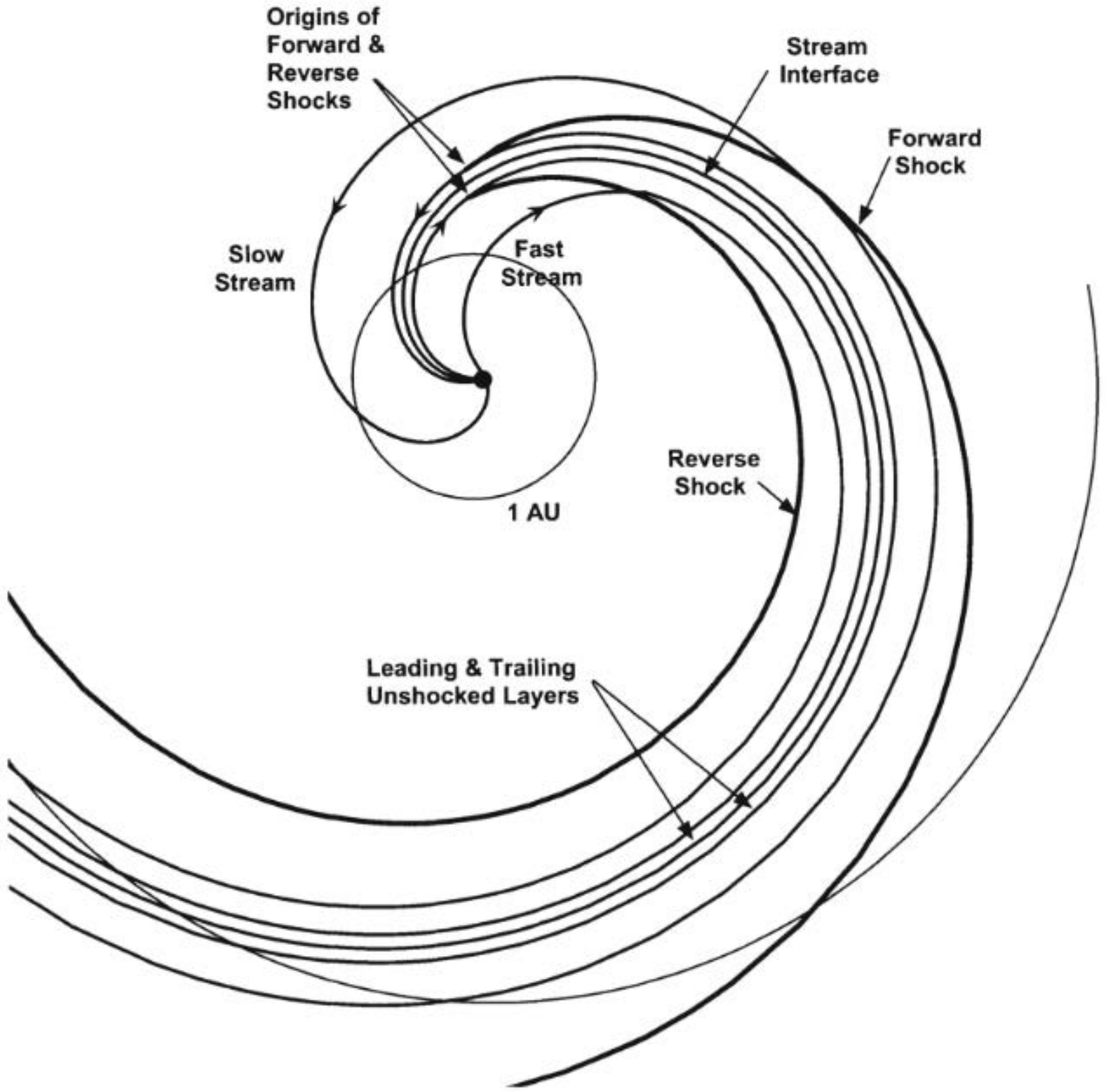
Also called “Stream Interaction Regions” (SIRs) in some literature



Trans-equatorial coronal hole



Solar wind speed at L1 in the ecliptic impacted by CH even at higher latitudes



CIR formation: at 1 AU the interface shocks are typically not fully formed - “weak shock”

Gopalswamy et al., Journ. Atm. Sol.-Terr. Phys., **70**, 2008, https://doi.org/10.1016/j.jastp.2008.06.010

Solar Magnetic Eruptions (SMEs)

Largest eruption of SC 24
NOAA SUVI
195 Å
10-Sept-2017
(rotated 90° West limb up)

SMEs

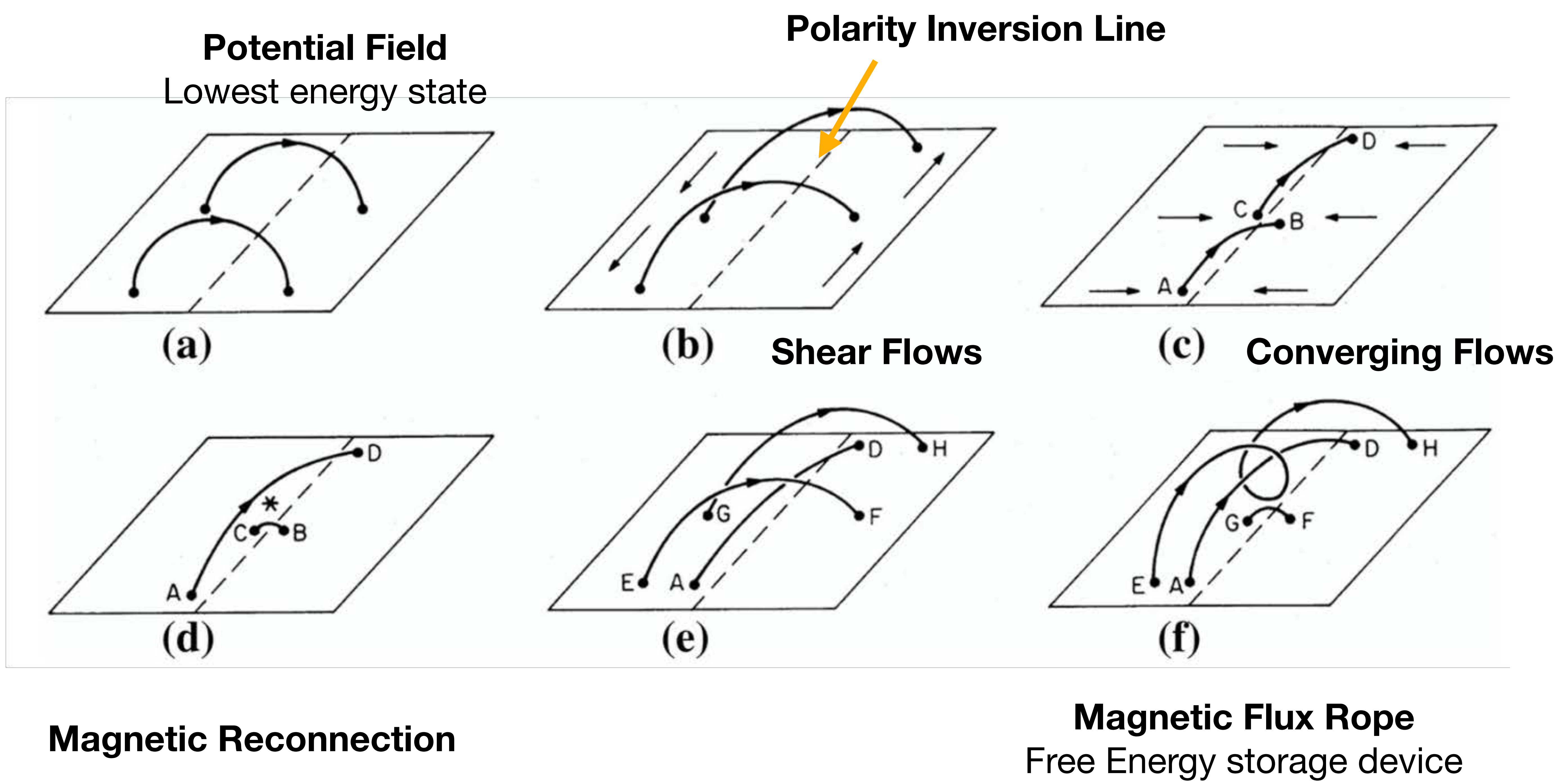
A unifying concept rooted in magnetic reconnection that explains flares, CMEs, and Solar Energetic Particles

- Basic elements of the concept:
  - Hypothesis: a necessary prerequisite for a magnetic eruption is the formation of a "**Magnetic Flux Rope**" (MFR) in the solar chromosphere or corona.
  - MFRs are formed over **Polarity Inversion Lines** (PILs) where convective motions in the photosphere (and possibly pressure-driven flows in the chromosphere) twist magnetic field lines into "**non-potential**" configurations.
  - Non-potential magnetic field configurations can store "**Free Energy**" that can be converted to kinetic energy of the coronal plasma to accelerate particles and drive CMEs.
  - Free Energy in the MFR builds up over time as the convection and shearing flows continually add twist and writhe (aka **Helicity**) to the magnetic field.
  - **Magnetic reconnection** triggers the eruption, releasing the twist in the field and converting the magnetic free energy.

Magnetic Flux Rope Formation

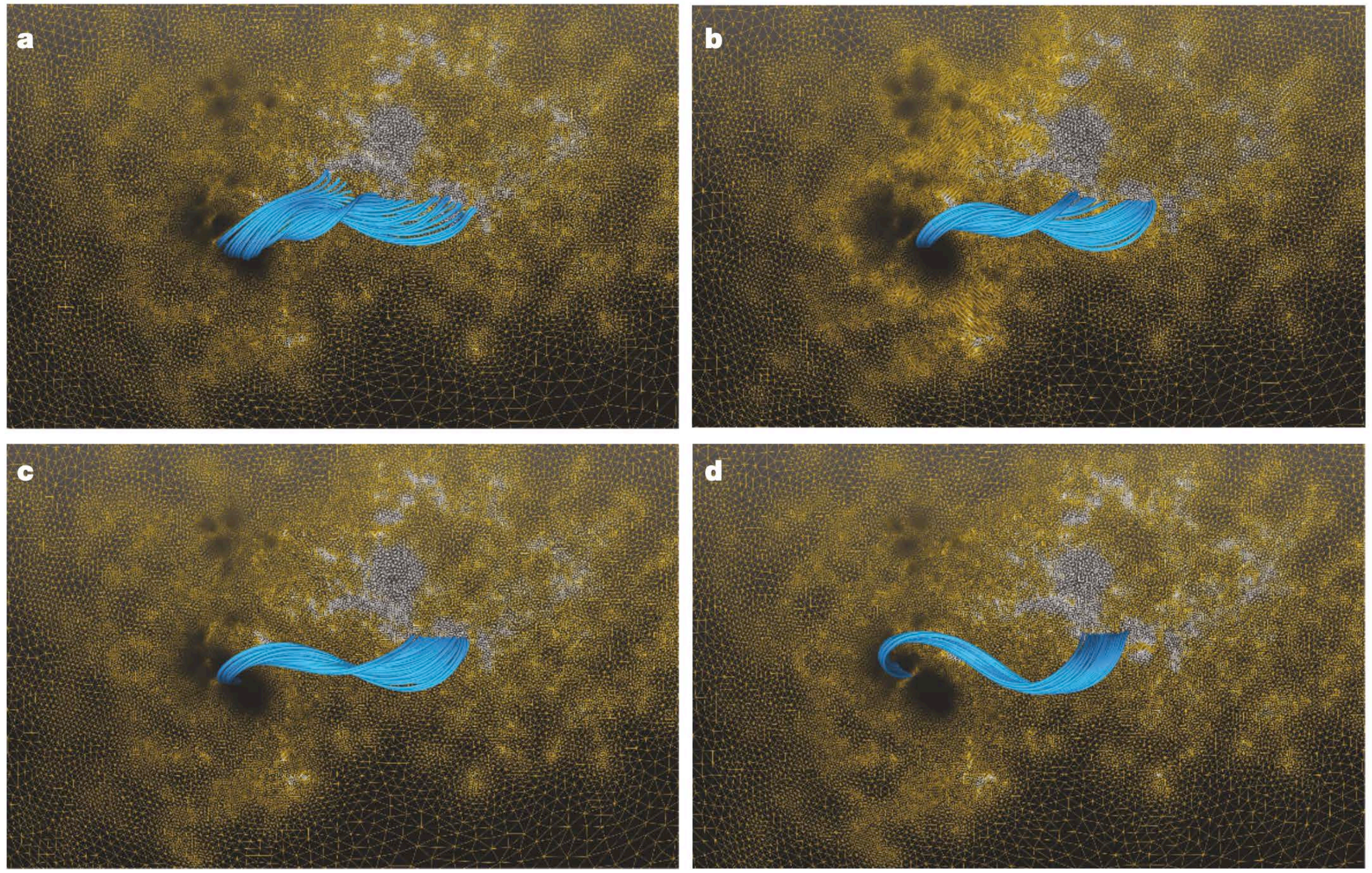
Analytic and Ideal MHD simulations

Analytical model of shearing and cancellation of field lines across a Polarity Inversion Line (PIL)



van Ballegooijen & Martens, ApJ, **343**, 971,1989

Ideal MHD model of MFR formation on actual magnetic field data from October 2014

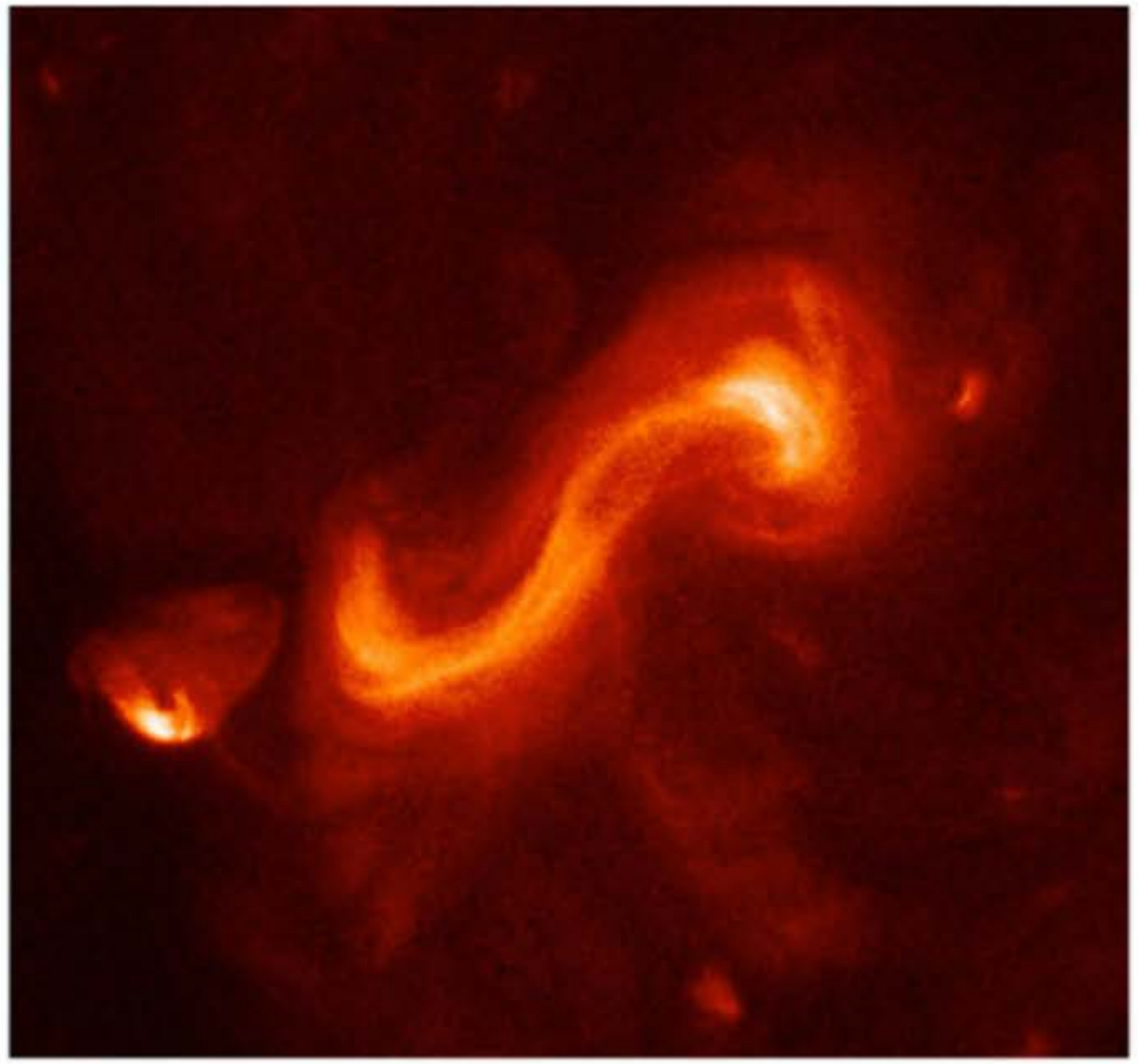


Amari et al., Nature, 2018, https://doi.org/10.1038/nature24671

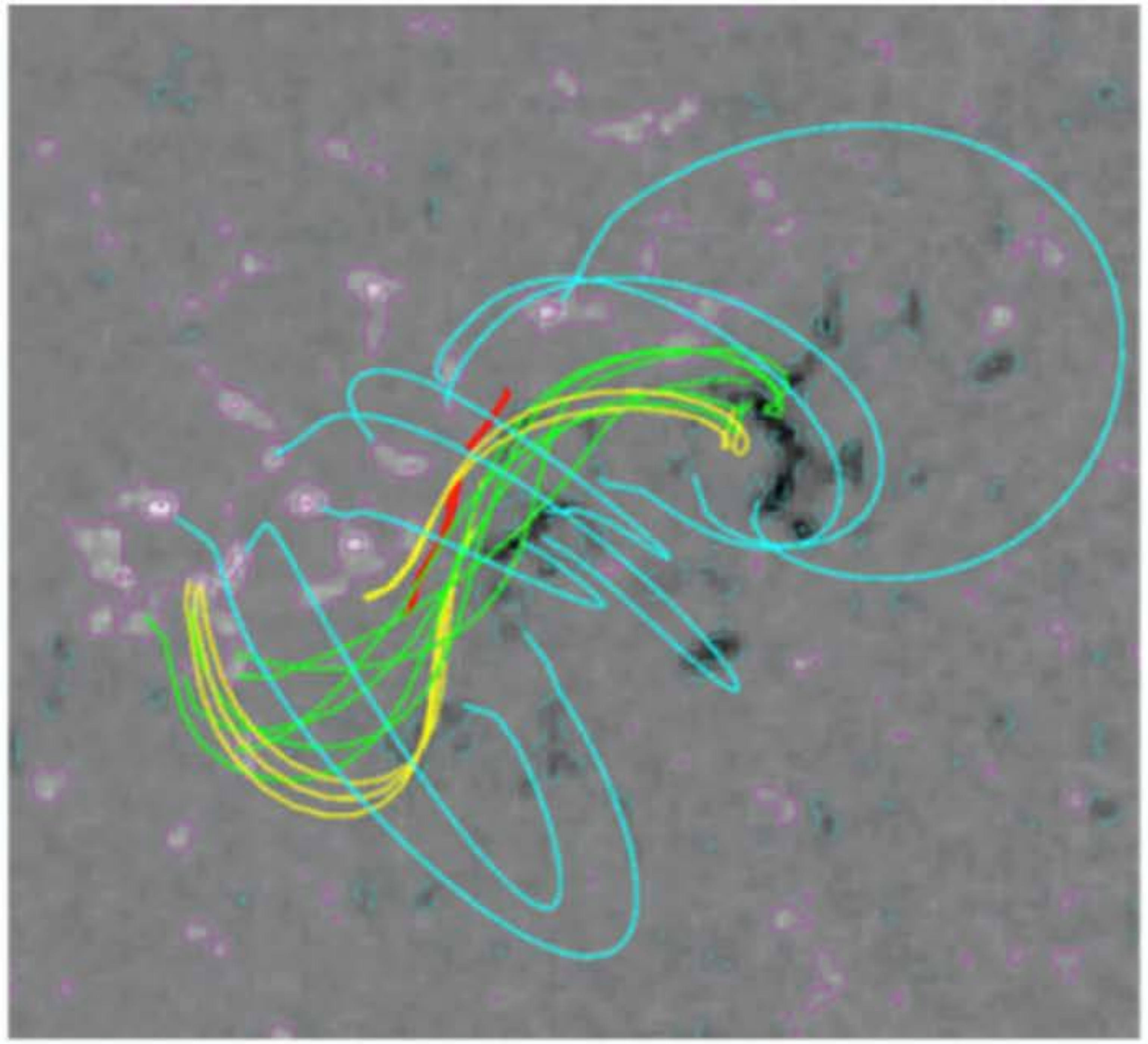
Magnetic Flux Rope Formation

Observations: 12-Feb-2007 eruption

Hinode XRT observation of
“X-ray sigmoid”



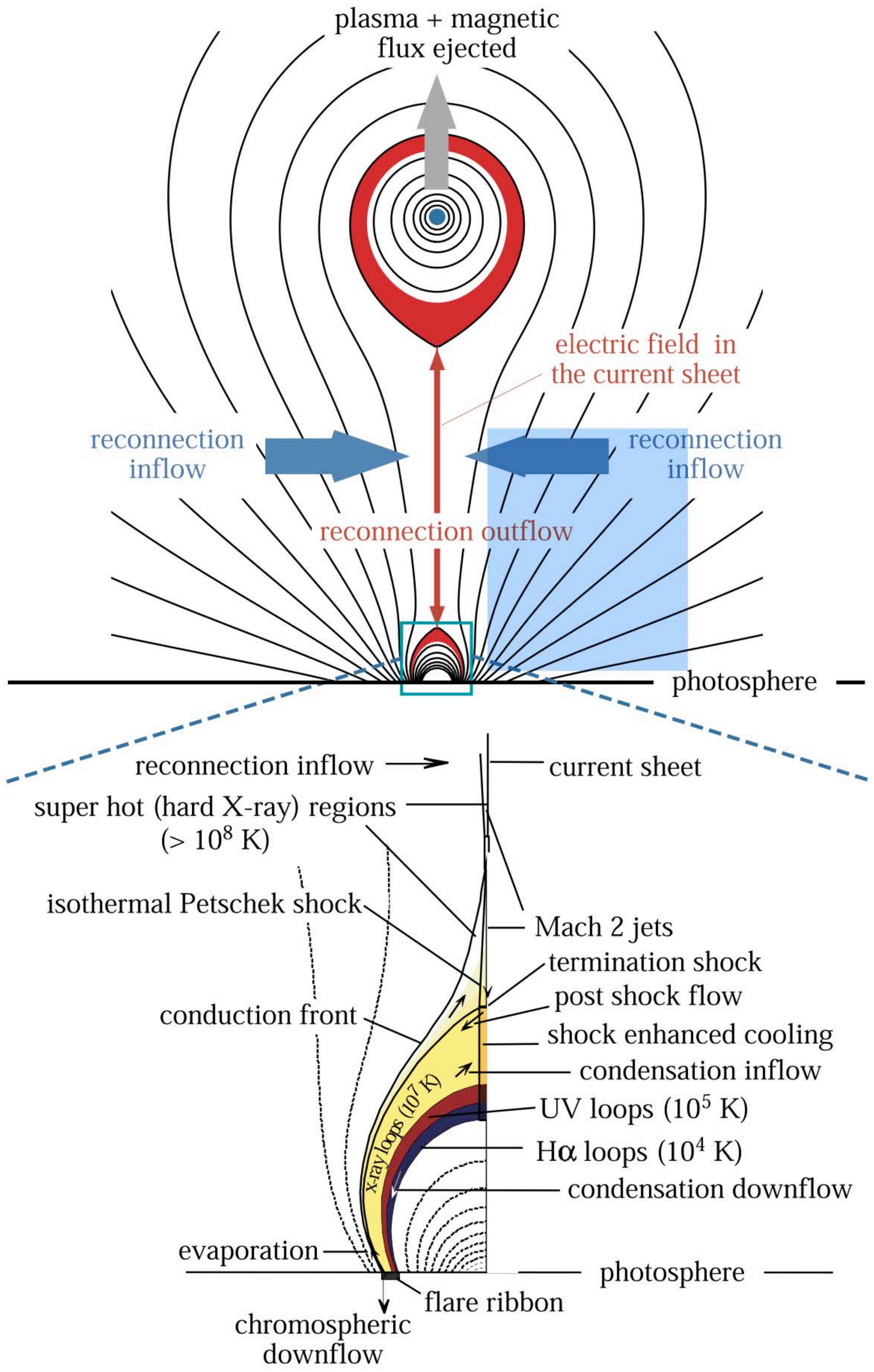
Non-linear Force Free Field (NLFFF) model
based on Hinode/SOT magnetogram



Toriumi & Wang, Living Rev. Sol. Phys., 2019, https://doi.org/10.1007/s41116-019-0019-7

SMEs: don't call them "Flares"

The standard SME model & event sequence



Ko et al., ApJ, **594**, 2003, https://doi.org/10.1086/376982

1. Magnetic flux rope formation over polarity inversion line in sunspot active region or quiet sun filament channel

2. Energy build-up in MFR due to continued shearing/twisting and/or injection of additional flux.

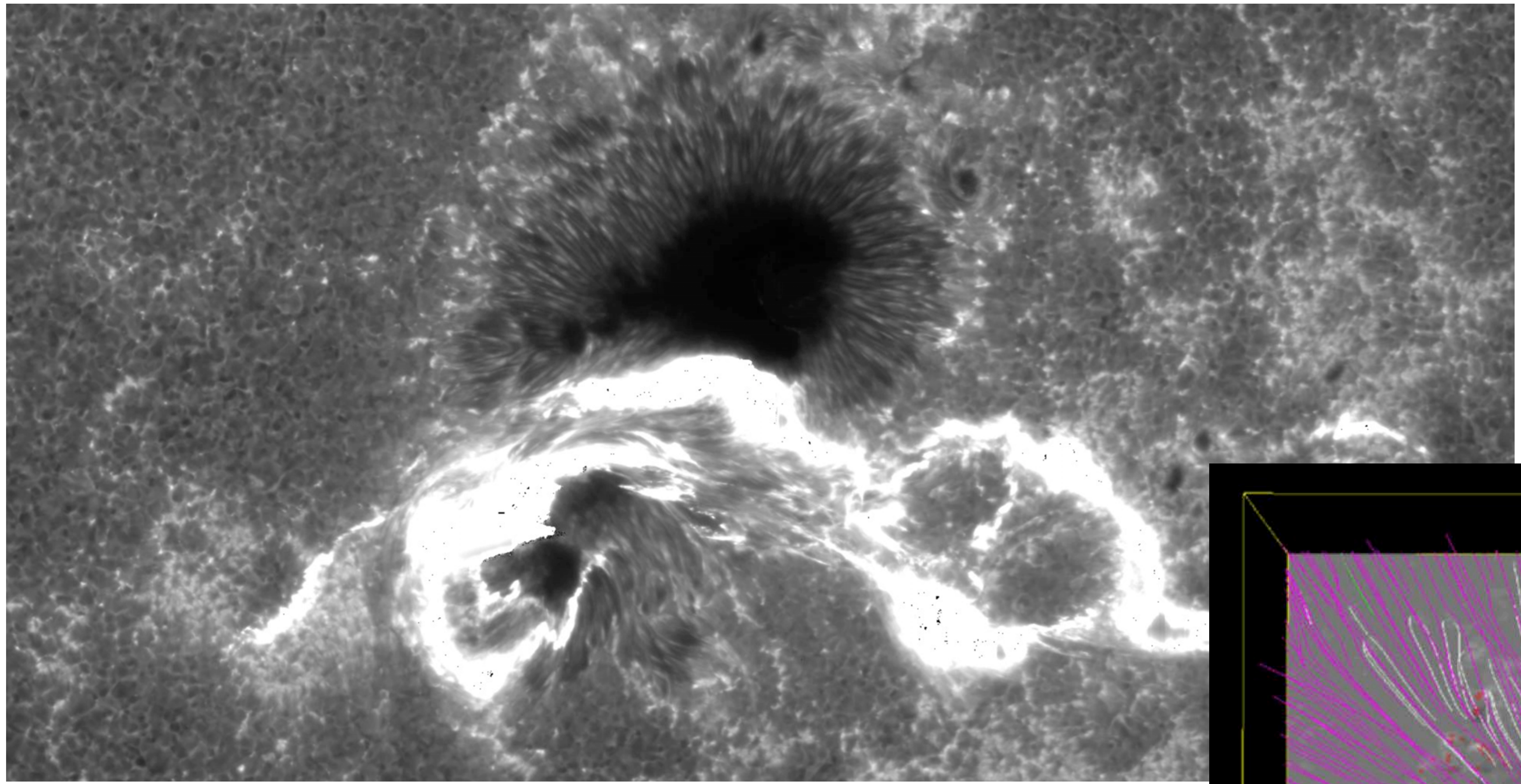
3. Plasma instability (e.g., torus kink instability) triggers eruption of MFR. Reconnection with overlying field allows escape into ICME ("break out").

4. Reconnection below MFR in current sheet region accelerates plasma downward into chromosphere leading to prompt hard X-ray and gyrosynchrotron emission (*impulsive phase*).

5. Chromospheric heating and evaporation form "flare ribbons" and inject X-ray emitting plasma into magnetic loop arcade (*gradual phase*).

Solar Magnetic Eruptions

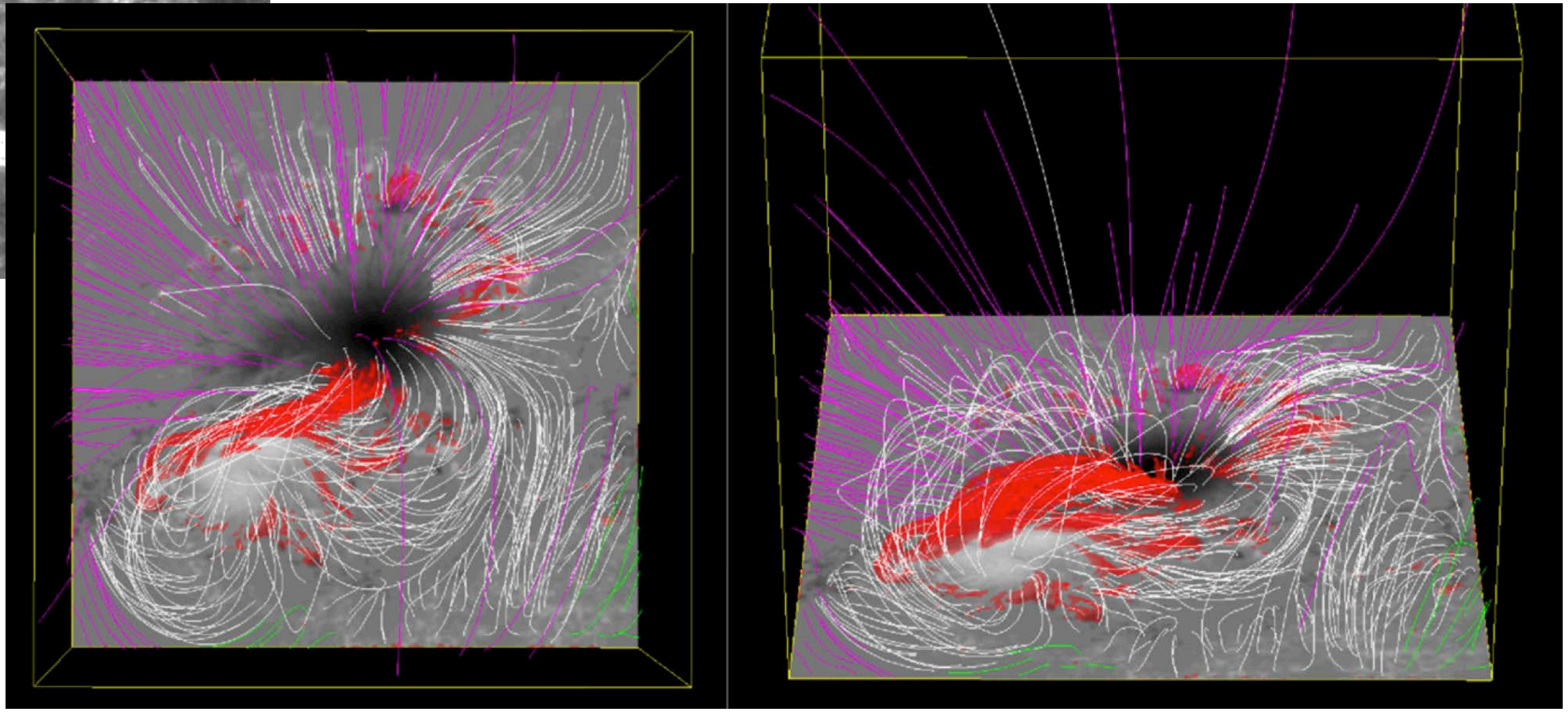
Magnetic Flux Ropes develop along sheared neutral lines



13-Dec-2006
Hinode/SOT CaII H-line 396nm
NOAA AR 10930 X3.4 flare

Non-Linear Force-Free Field (NLFFF)
extrapolation from photospheric magnetogram

Red isosurface = maximum electric current = core of MFR



Schrijver et al., ApJ, **675**, 2008, https://doi.org/10.1086/527413

Solar Magnetic Eruptions

Flaring surrounds a sheared polarity inversion (neutral) line

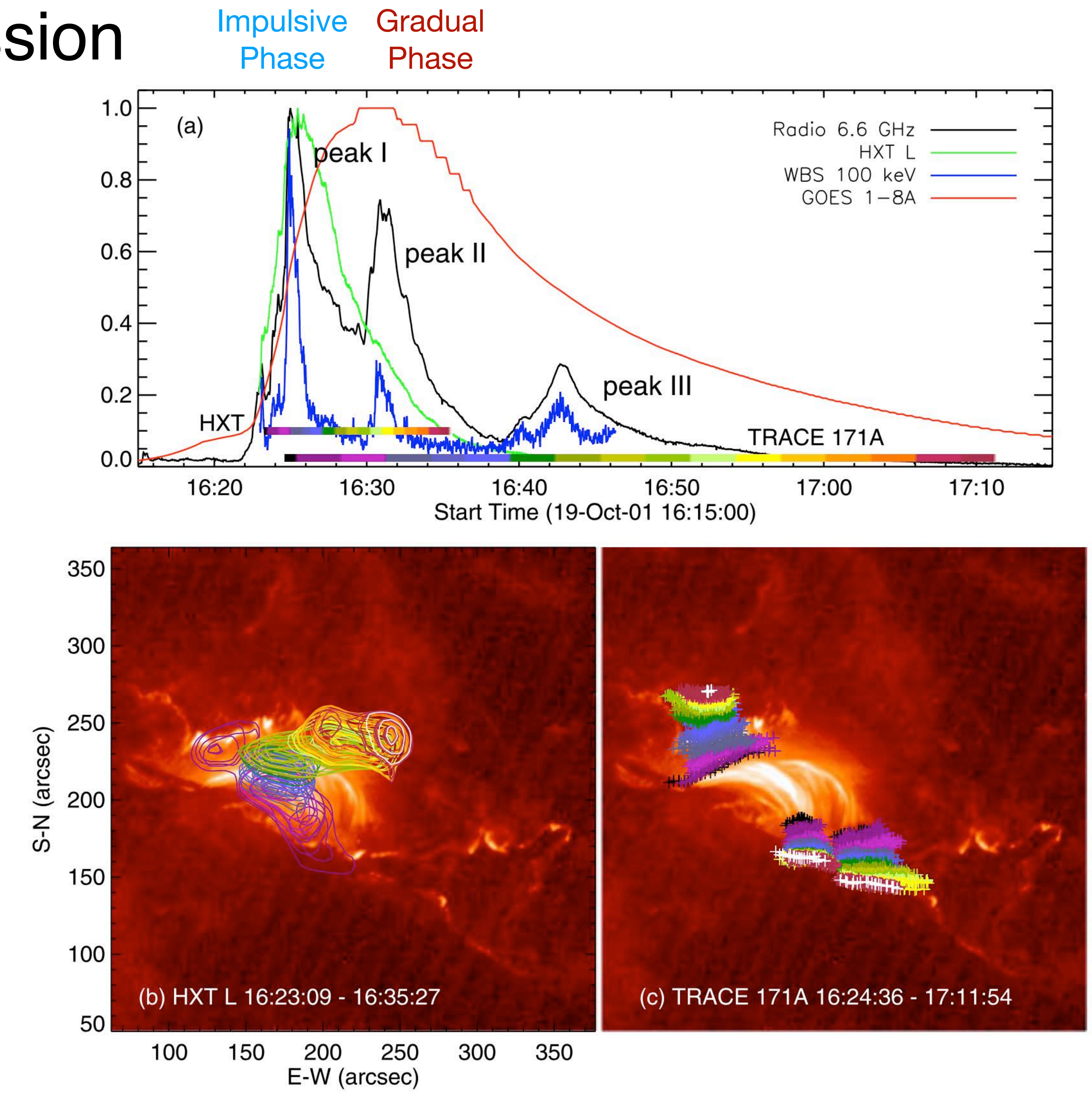
Solar Flares

Flares can have gamma ray to radio emission

- (a) Time evolution of electromagnetic radiation from solar eruption on 19-Oct-2001.
- **Impulsive phase** is defined by first peak in “hard X-rays” (100 keV, blue) or by 6.6 GHz radio peak (black).
  6.6 GHz is the electron gyrofrequency for a 2,400 gauss magnetic field.
- **Gradual phase** is defined by the peak in “soft X-rays” (GOES 1—8 Å, red)

- Bottom left image (b) shows hard X-ray contours (12—23 keV) from the Yohkoh Hard X-ray telescope (HXT) over TRACE 171 Å EUV image of the flare site color coded by time in the upper plot.
- Bottom right image (c) shows time history of EUV flare ribbons color coded by time in the upper plot.

- You will sometimes hear flares called “hard” and “soft” which is a reference to the relative flux in hard X-rays vs. the flux in soft X-rays.



Fletcher et al., Space Sci. Rev., 2011, https://doi.org/10.1007/s11214-010-9701-8

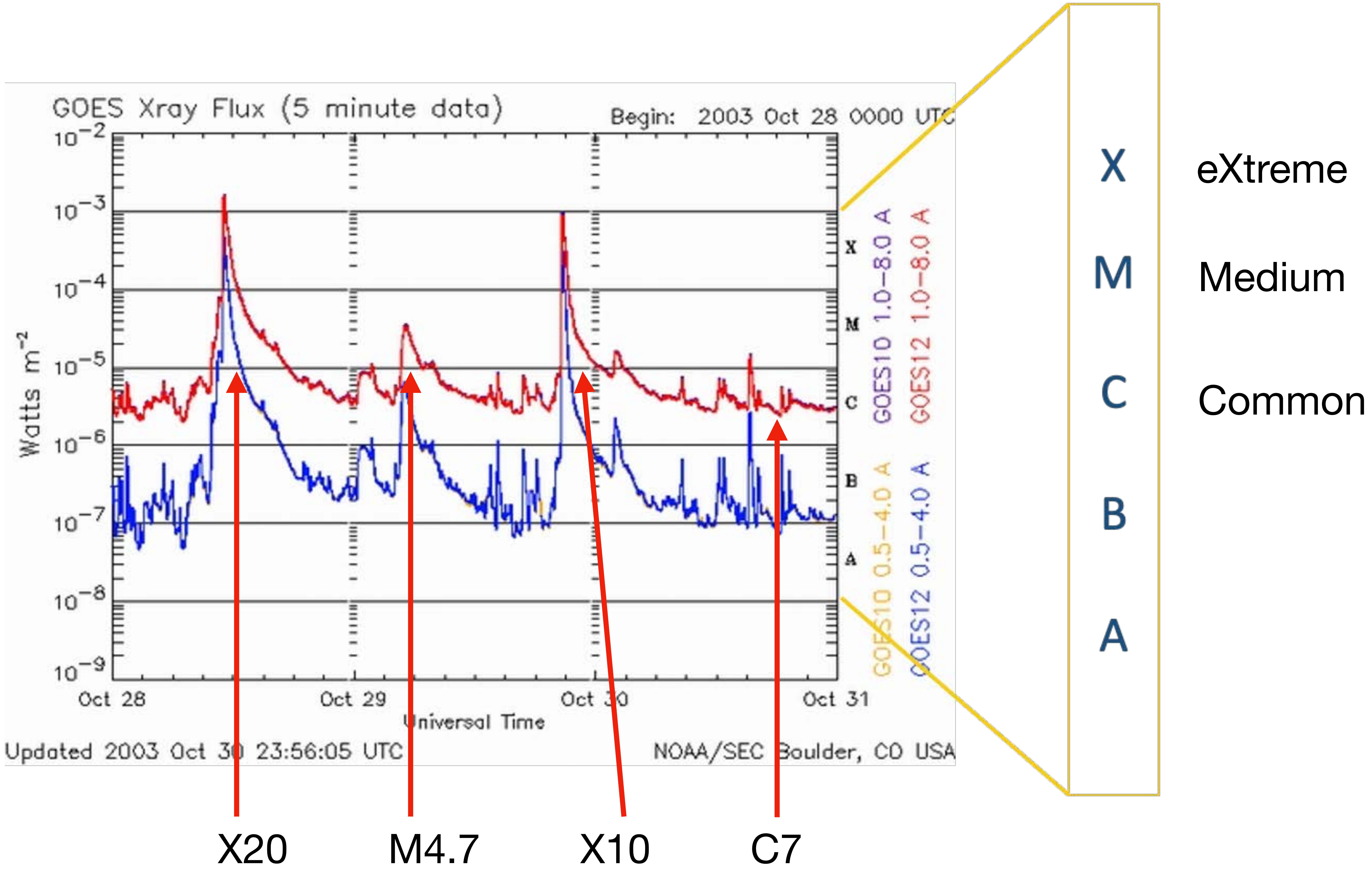
Solar Flares

Flares can have gamma ray to radio emission, but are classified by X-ray irradiance

Flares are classified by 1.0—8.0 Å logarithmic intensity peak (red curve).

Note: GOES has no spatial resolution – full Sun flux only.

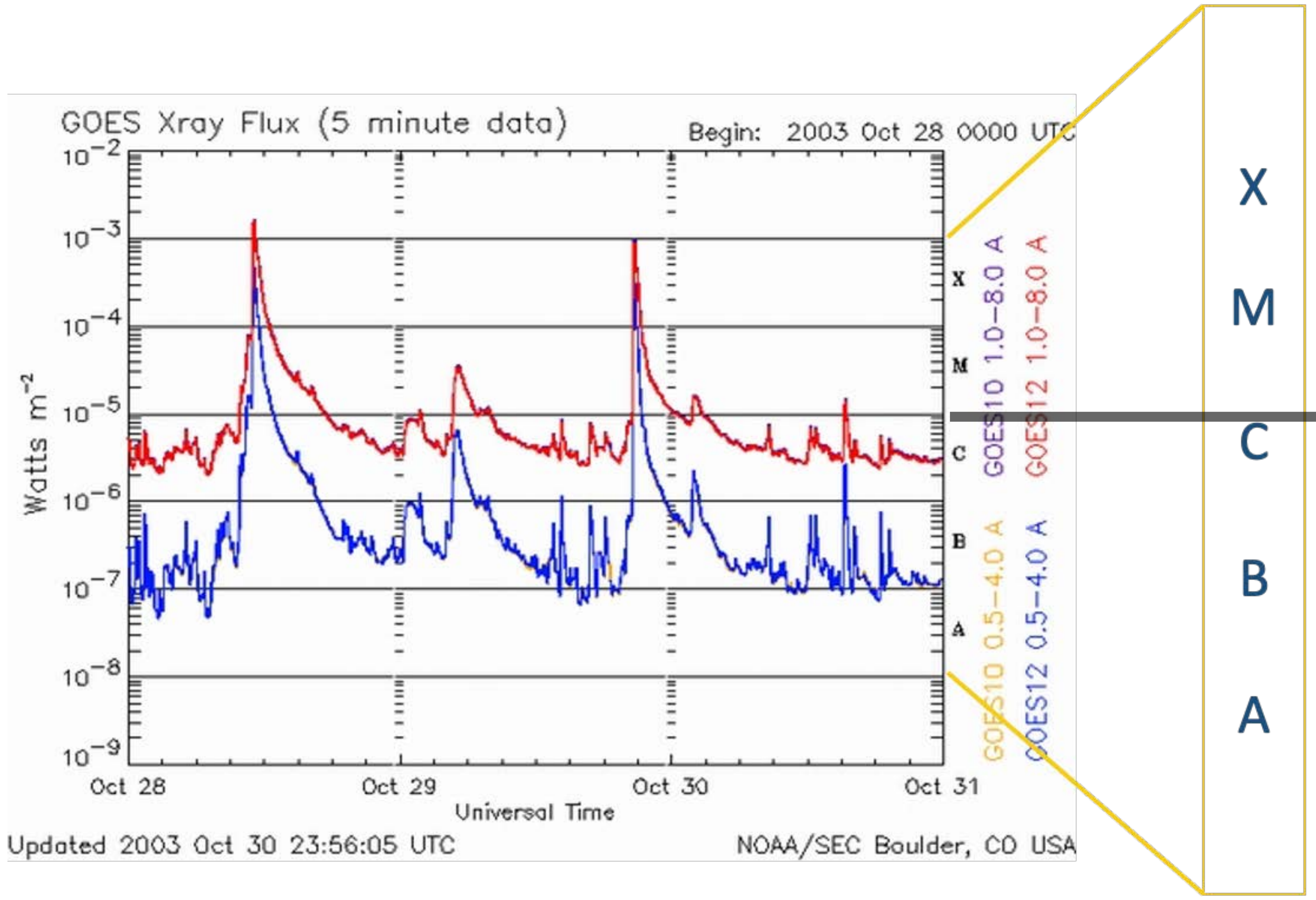
GOES data do not reveal which active region on the Sun originated a flare.



Solar Flares

NOAA Space Weather Prediction Center (SWPC) R-scale descriptions

Scale	Description	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
R 5	Extreme	**HF Radio:** Complete HF (high frequency) radio blackout on the entire sunlit side of the Earth lasting for a number of hours. This results in no HF radio contact with mariners and en route aviators in this sector. **Navigation:** Low-frequency navigation signals used by maritime and general aviation systems experience outages on the sunlit side of the Earth for many hours, causing loss in positioning. Increased satellite navigation errors in positioning for several hours on the sunlit side of Earth, which may spread into the night side.	X20 (2×10^{-3})	Less than 1 per cycle
R 4	Severe	**HF Radio:** HF radio communication blackout on most of the sunlit side of Earth for one to two hours. HF radio contact lost during this time. **Navigation:** Outages of low-frequency navigation signals cause increased error in positioning for one to two hours. Minor disruptions of satellite navigation possible on the sunlit side of Earth.	X10 (10^{-3})	8 per cycle (8 days per cycle)
R 3	Strong	**HF Radio:** Wide area blackout of HF radio communication, loss of radio contact for about an hour on sunlit side of Earth. **Navigation:** Low-frequency navigation signals degraded for about an hour.	X1 (10^{-4})	175 per cycle (140 days per cycle)
R 2	Moderate	**HF Radio:** Limited blackout of HF radio communication on sunlit side, loss of radio contact for tens of minutes. **Navigation:** Degradation of low-frequency navigation signals for tens of minutes.	M5 (5×10^{-5})	350 per cycle (300 days per cycle)
R 1	Minor	**HF Radio:** Weak or minor degradation of HF radio communication on sunlit side, occasional loss of radio contact. **Navigation:** Low-frequency navigation signals degraded for brief intervals.	M1 (10^{-5})	2000 per cycle (950 days per cycle)



"R" stands for "Radio blackout" due to historical association of solar flares with High Frequency (HF, 3–30 MHz) radio interference.

Note that only M1 flares or stronger generate any alerts.

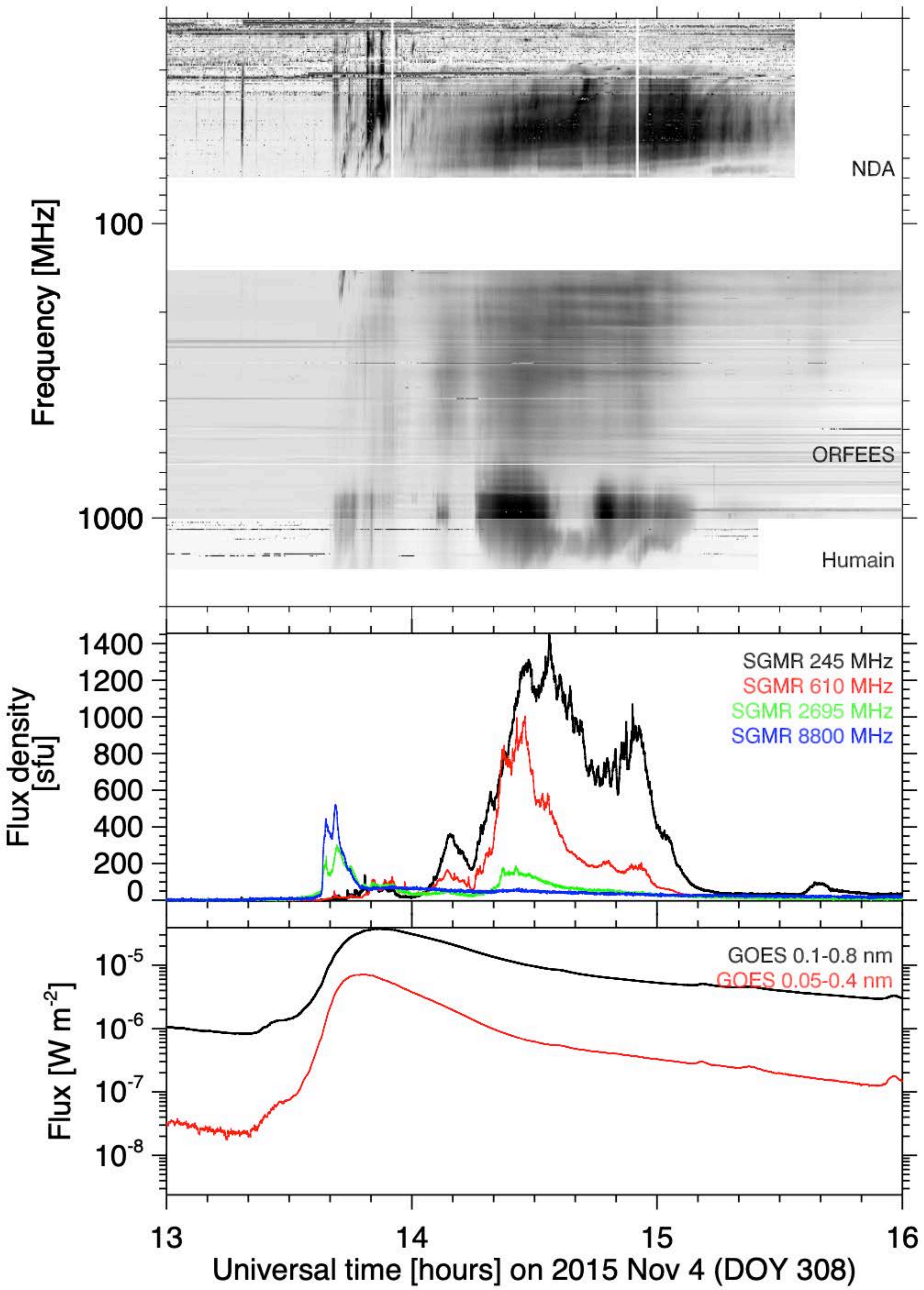
Solar "Radio Bursts"

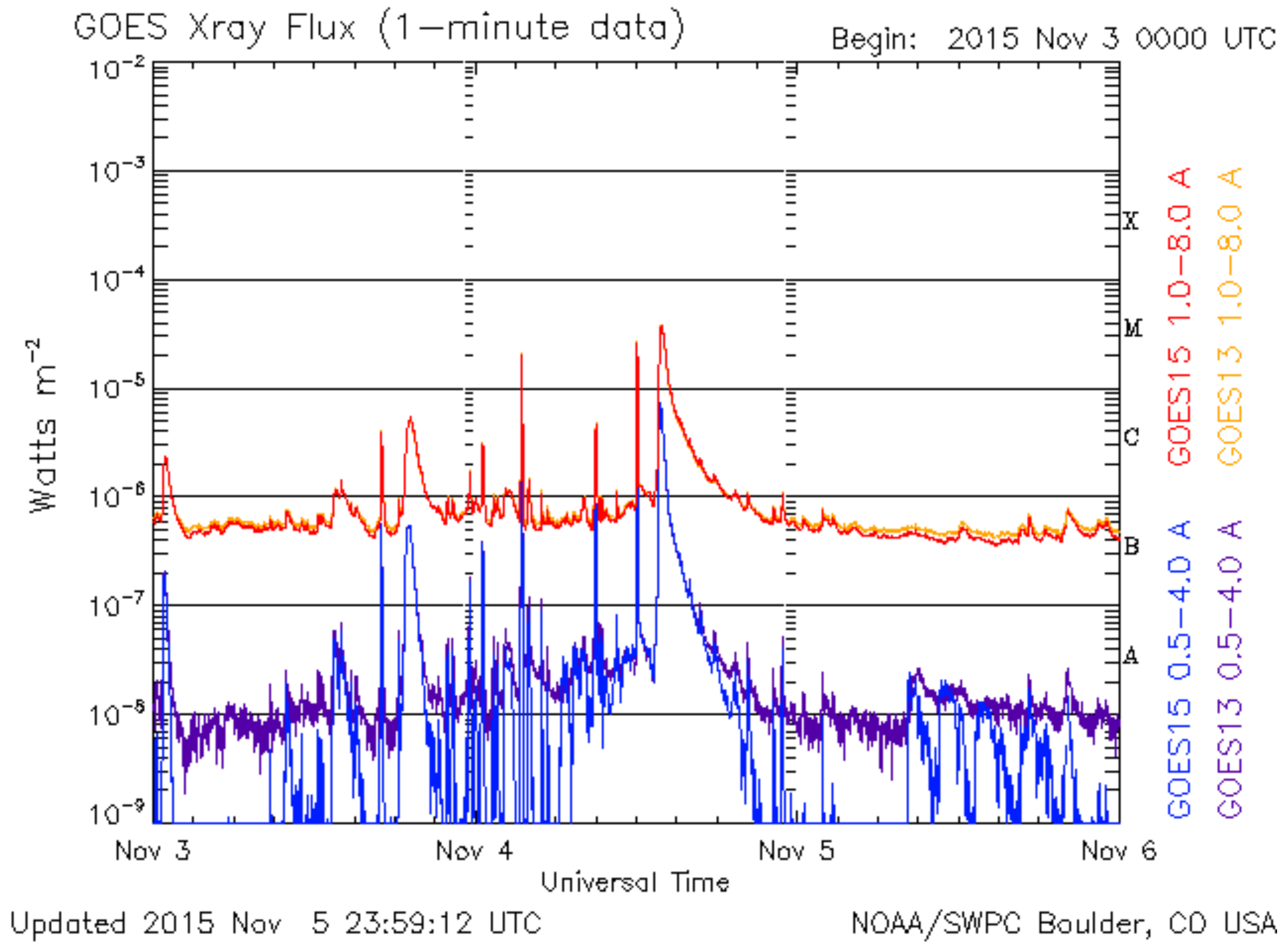
Flare photon emission in the ATC radar frequencies: 04-Nov-2015

Medium X-ray flare (M4) but it occurred at sunset in Sweden and Air Traffic Control radars were pointed directly at the Sun.

Note the very broadband radio signal recorded by the Sagamore Hill (SGMR) US Air Force solar radio telescope.

Duration: ~1.25 hours, corresponding to **impulsive phase**.






PHYS.ORG

Solar storm knocks out flight control systems in Sweden

November 4, 2015

Travellers wait in the terminal building at Stockholm's Arlanda on August 17, 2013

Aviation officials say a solar storm knocked out the air traffic control systems in Sweden on Wednesday, prompting them to close the country's airspace for more than an hour.

Solar “Radio Bursts”

Radio emission in the GPS L1 and L2 bands: AR 10930, 06-Dec-2006

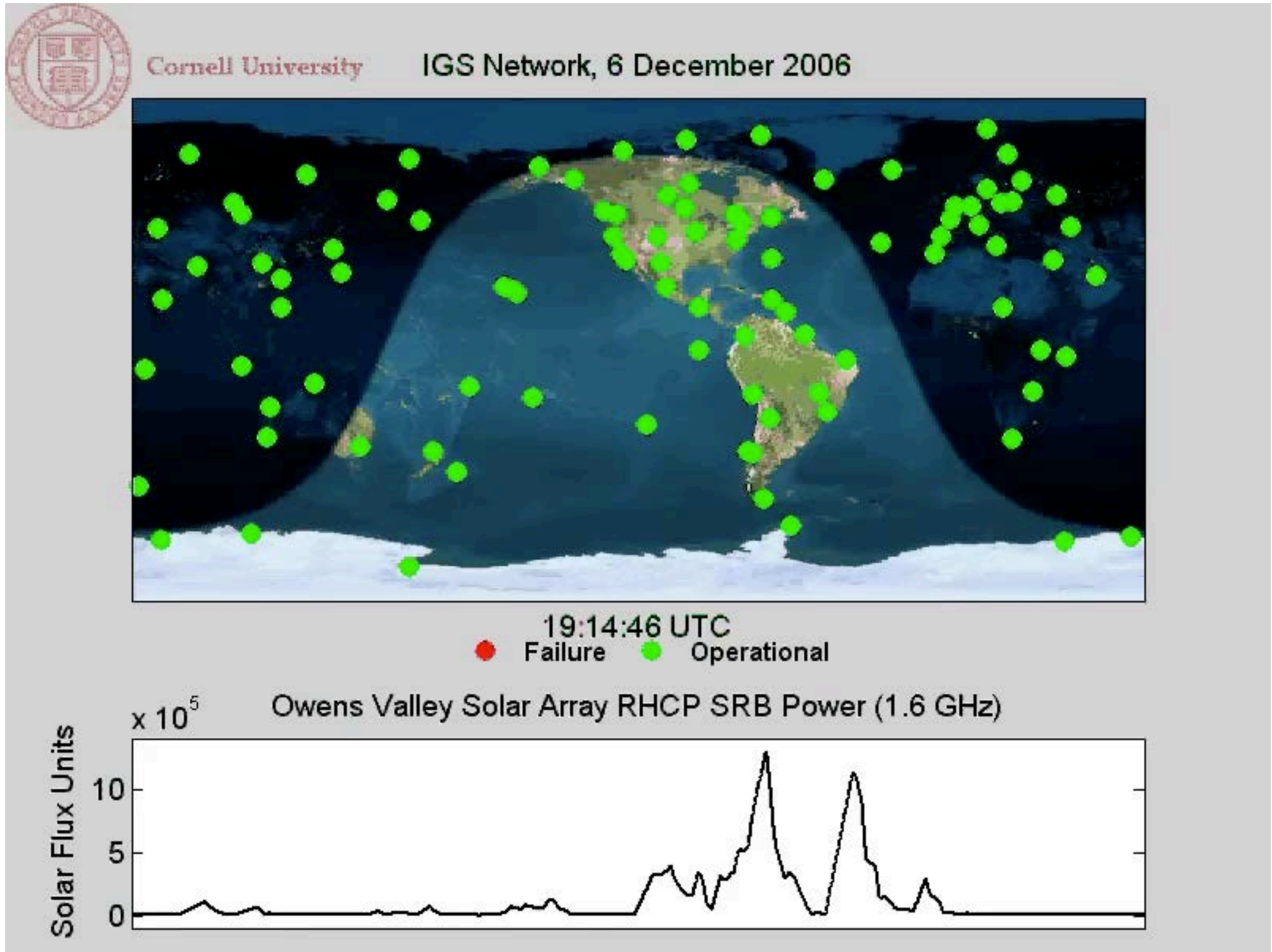
International GNSS Service (IGS) network

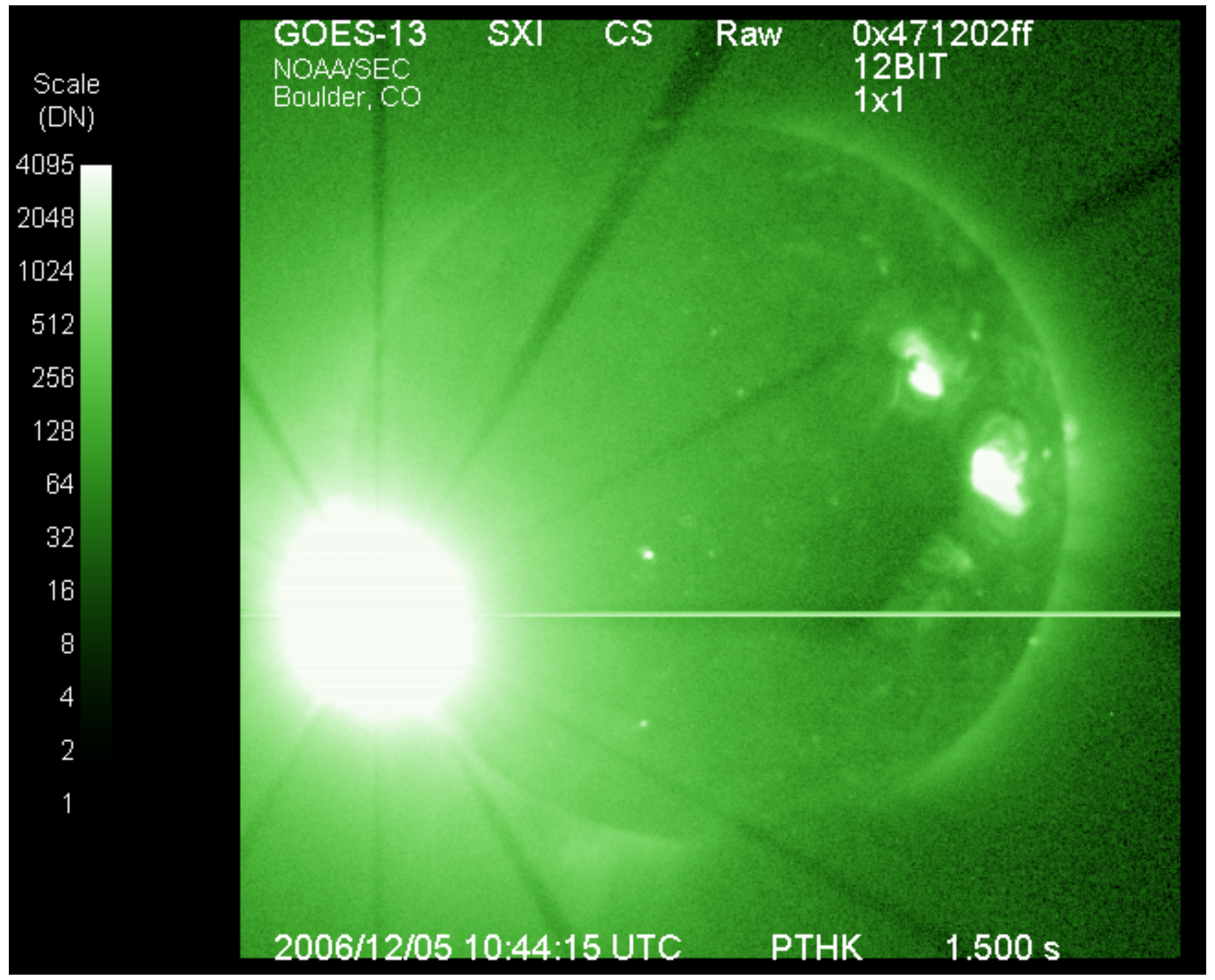
GNSS = Global Navigation Satellite System (e.g., GPS)

L1 band = 1575 MHz

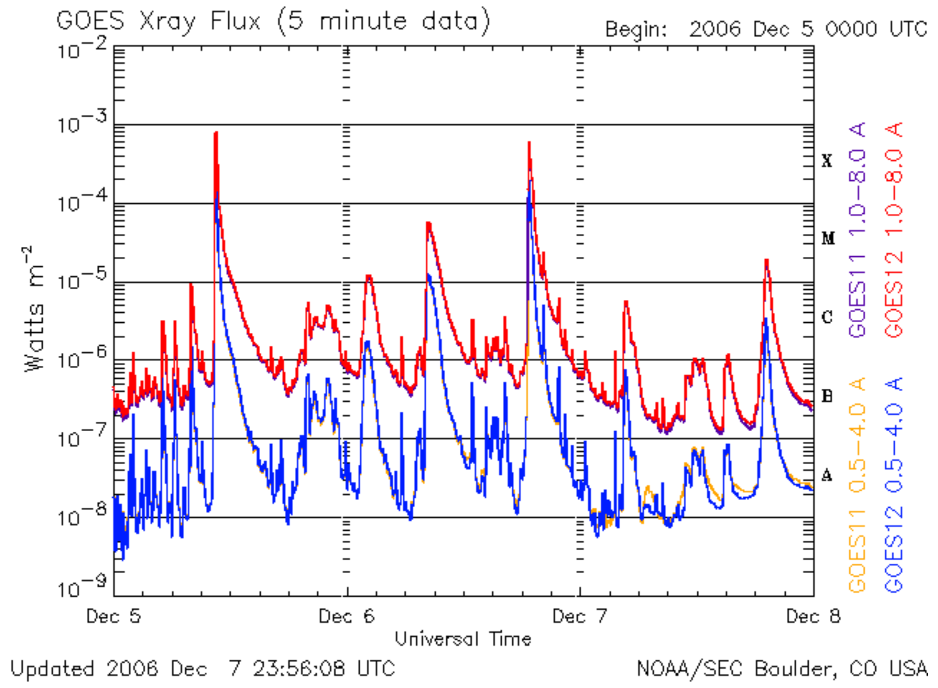
RHCP = right hand circular polarized

SRB = Solar Radio Burst



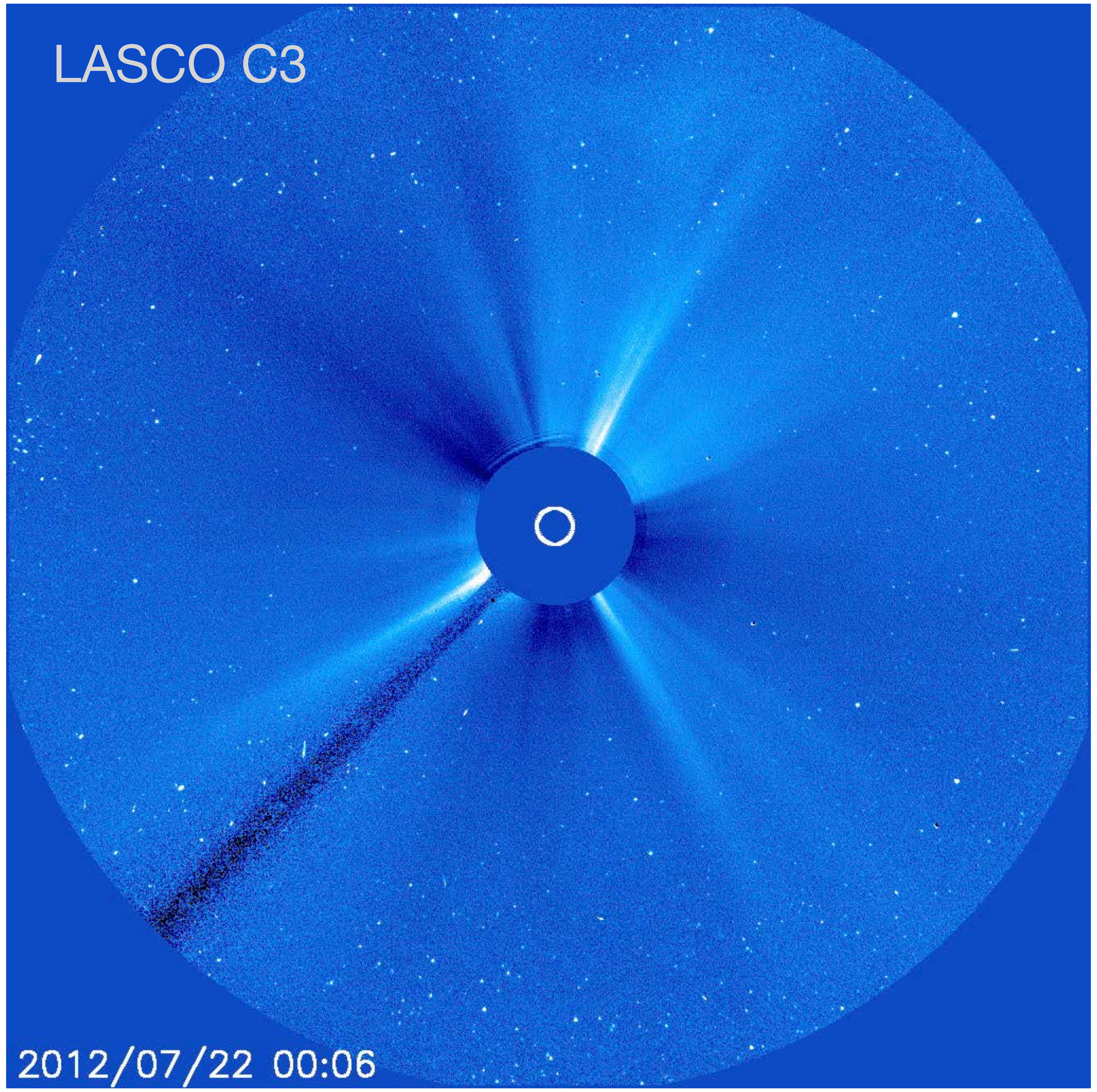


The same AR damaged the NOAA Solar X-ray Imager (SXI) instrument’s CCD camera during long-exposure testing

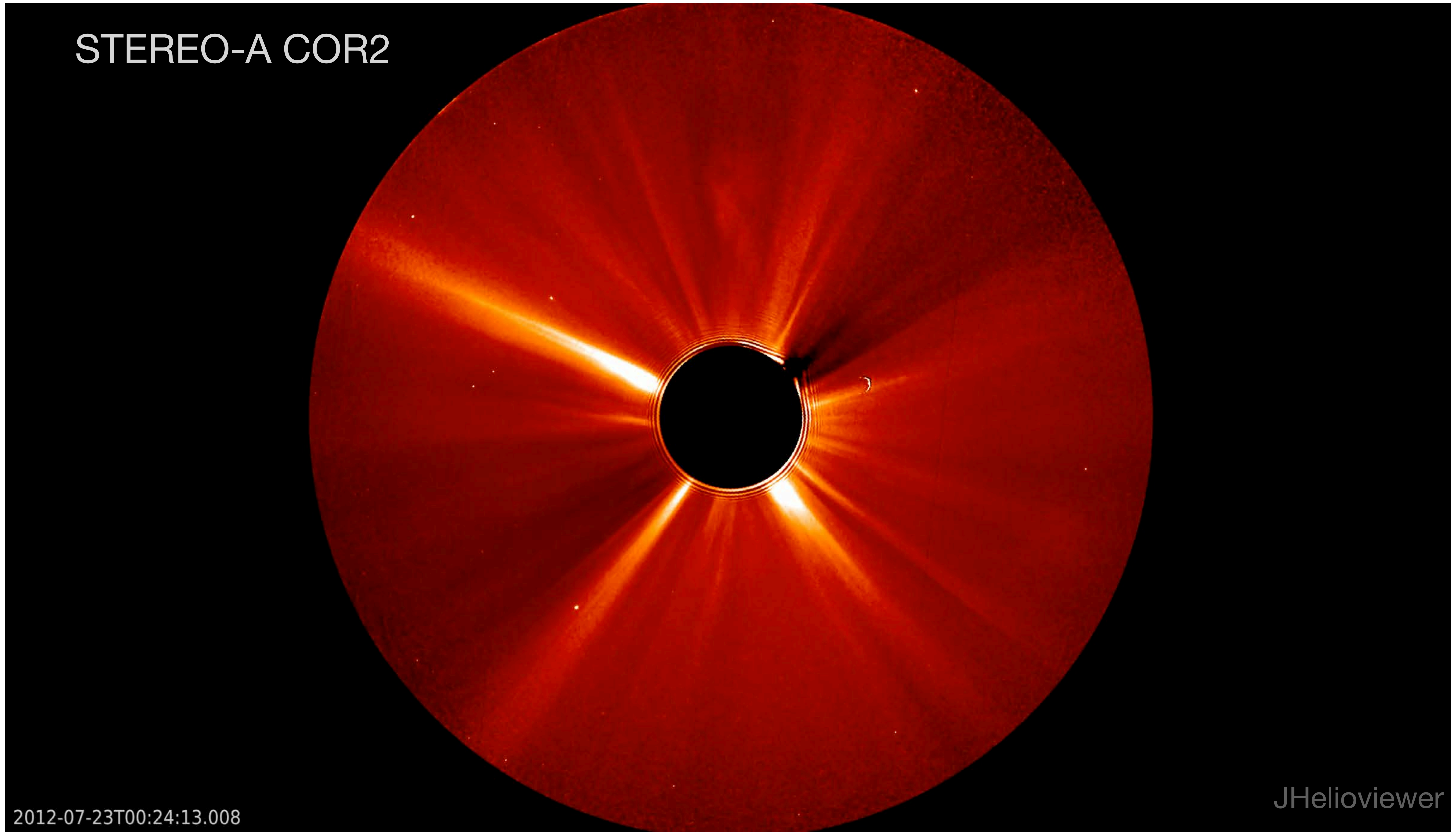


Coronal Mass Ejections drive the most severe events

23-24 July 2012 “Carrington event at STEREO-A”



Far-side CME
Estimated velocity: 2600±500 km s^{-1}

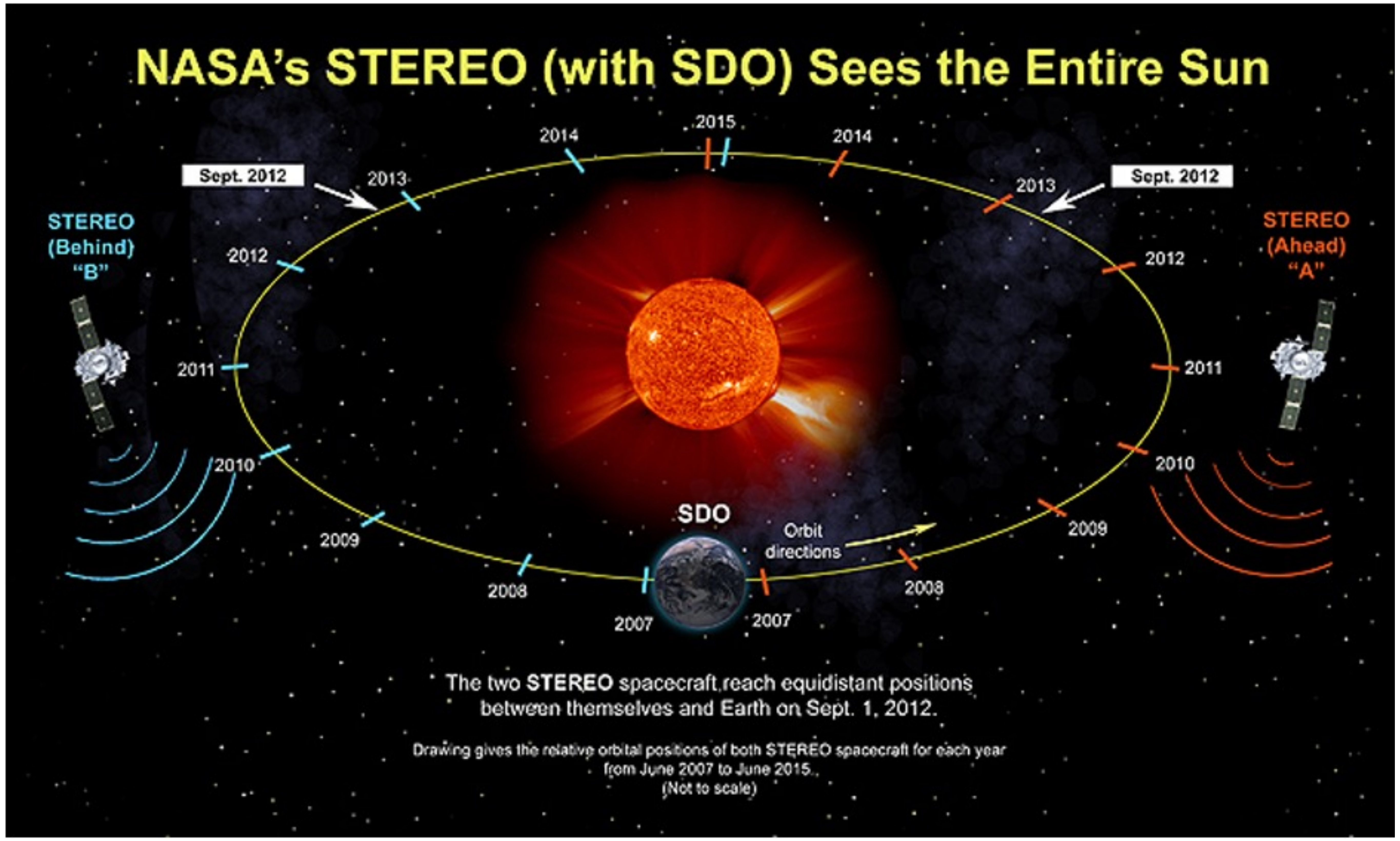


Halo CME at STEREO-A
Impact at STEREO-A at ~1AU in 18.6 h: comparable to 1859 Carrington event transit time

Baker et al., Space Weather, **11**, 2013, https://doi.org/10.1002/swe.20097

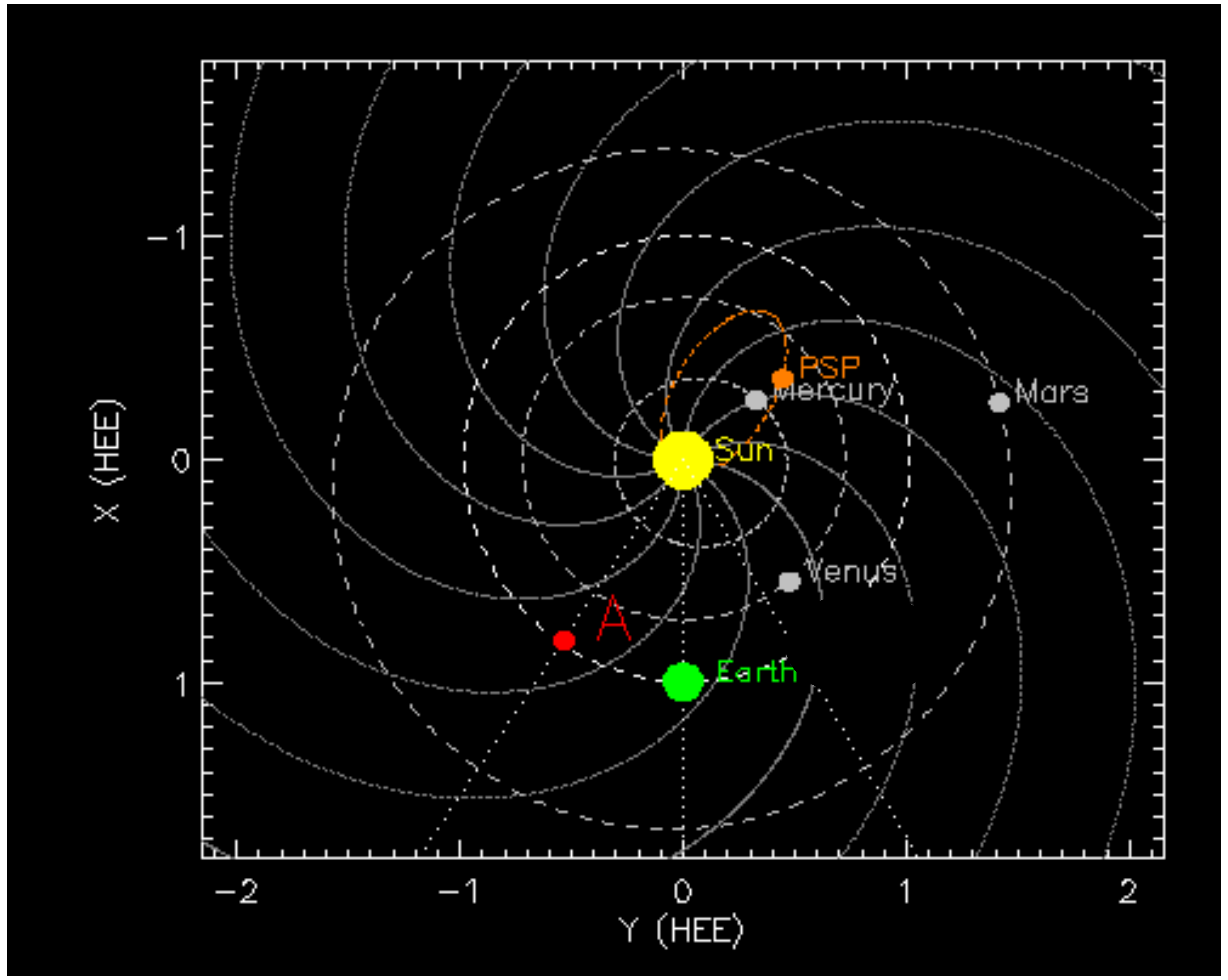
NASA's STEREO mission enabled multi-angle views of CMEs

2010—2015 was the "golden age" of CME observations



STEREO mission launched in October 2006

https://stereo-ssc.nascom.nasa.gov/cgi-bin/make_where_gif



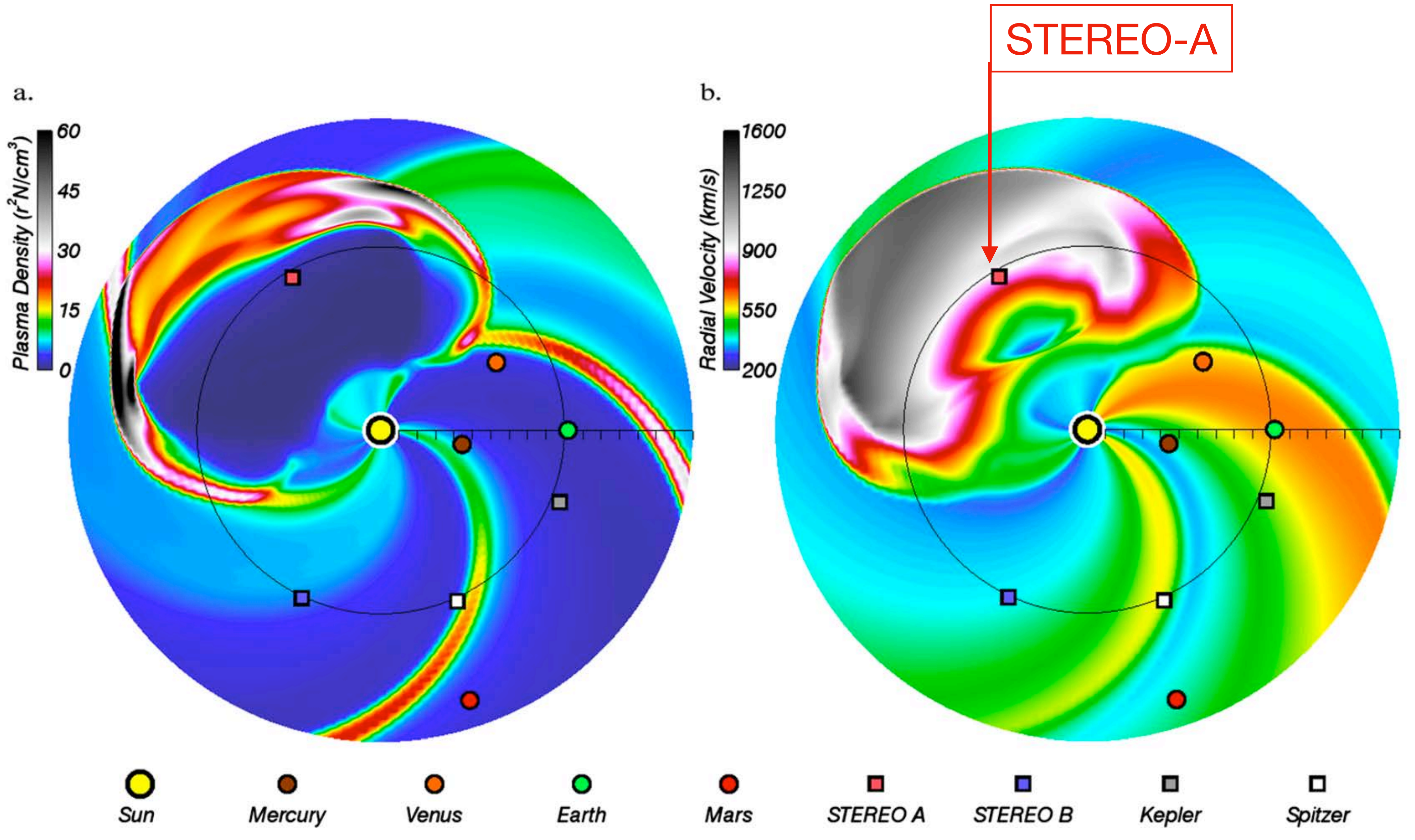
Location of STEREO spacecraft on 17-Mar-2022

STEREO-B lost in 2016

Coronal Mass Ejections drive the most severe events

23-24 July 2012 “Carrington event at STEREO-A”

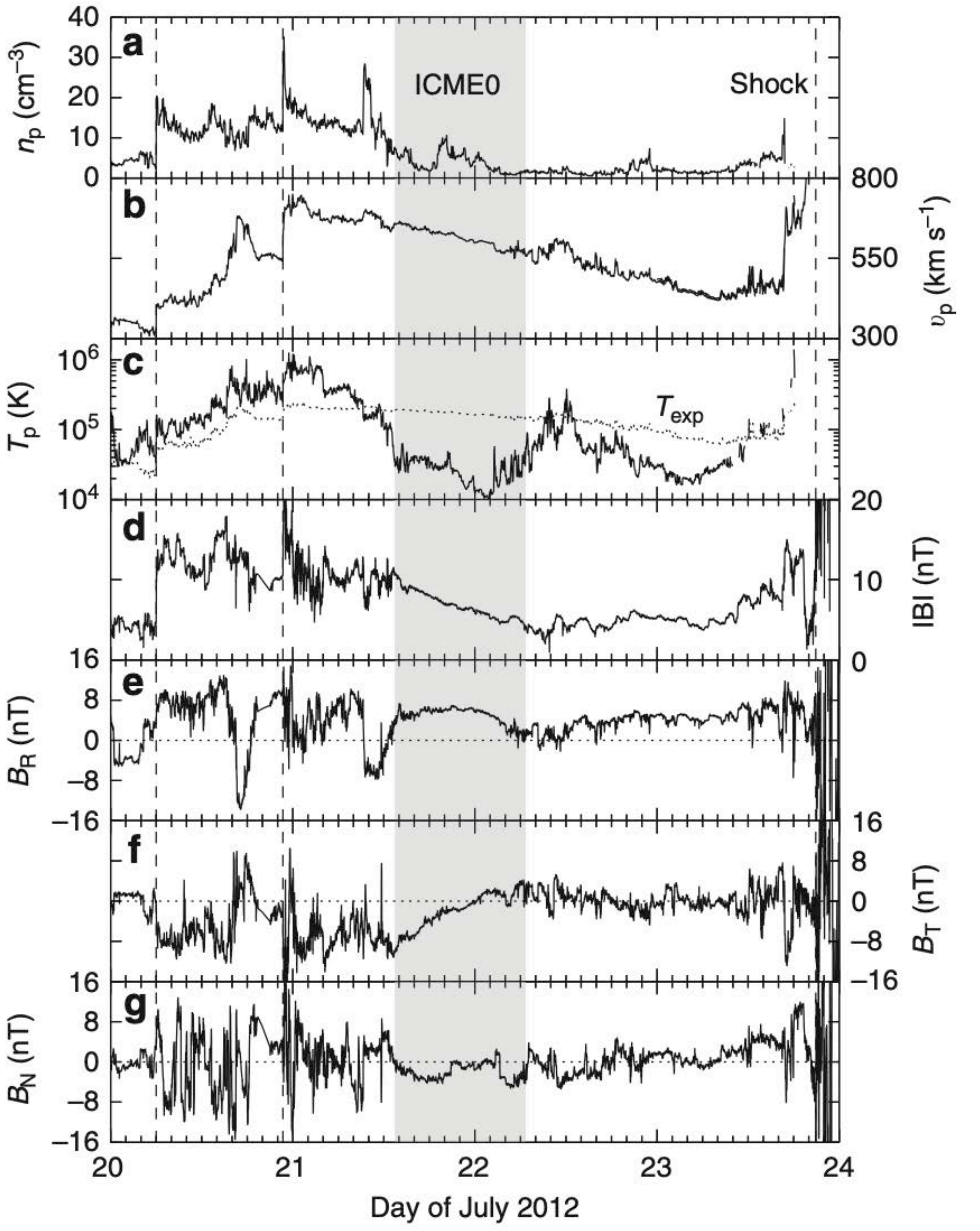
WSA-Enlil Model Simulation

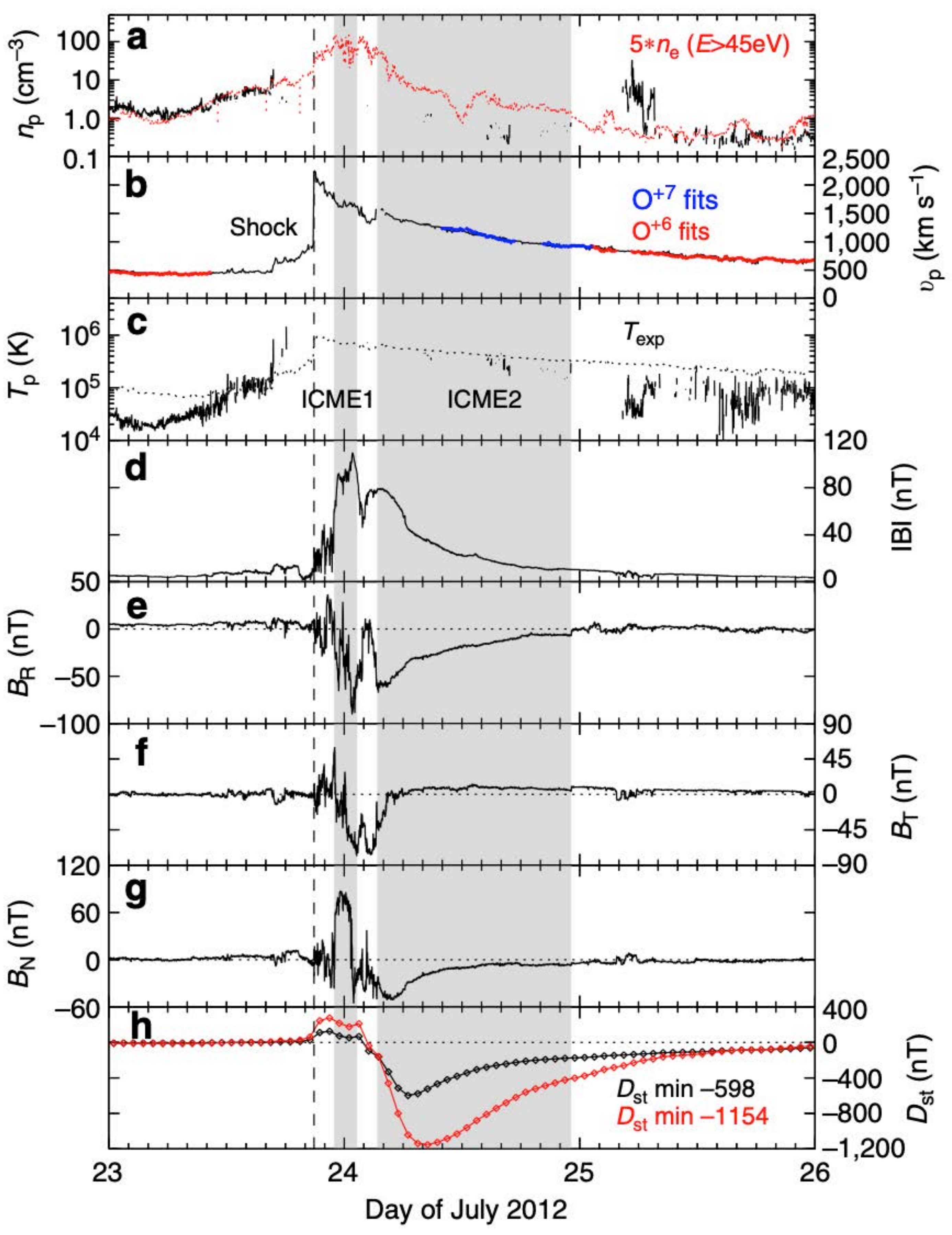


Plasma density

Plasma radial velocity

CME transit velocity: 2,150 km s^{-1}
(Sun-STEREO-A distance / 18.6 h)





Precursor CME arrival on 21-July

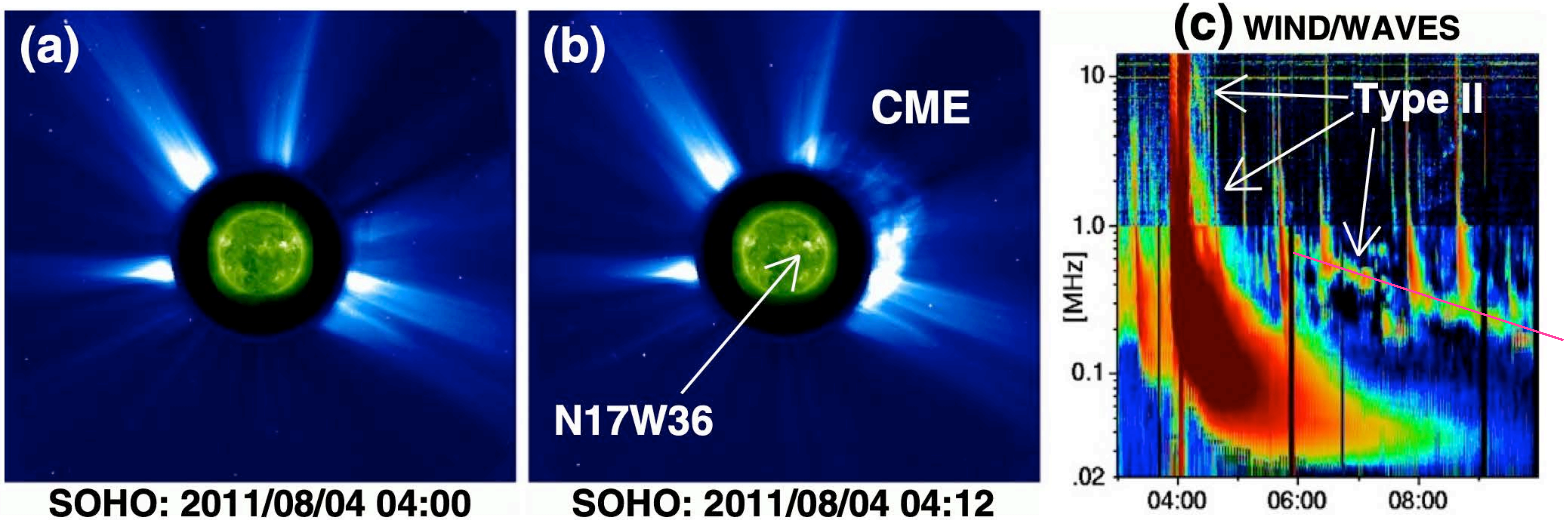
Extreme CME arrival on 24-July

Liu et al., Nature Comm., **5**, 2014, https://doi.org/10.1038/ncomms4481

Baker et al., Space Weather, **11**, 2013, https://doi.org/10.1002/swe.20097

Coronal Mass Ejections

CME “Type II” radio emission: a speed proxy



Slope correlates to CME speed within 3—10 R_{sun}

CME arrival time estimates based on Type II radio frequency decay speed estimates are highly inaccurate.

Deceleration between 10 R_{sun} and 1AU is common

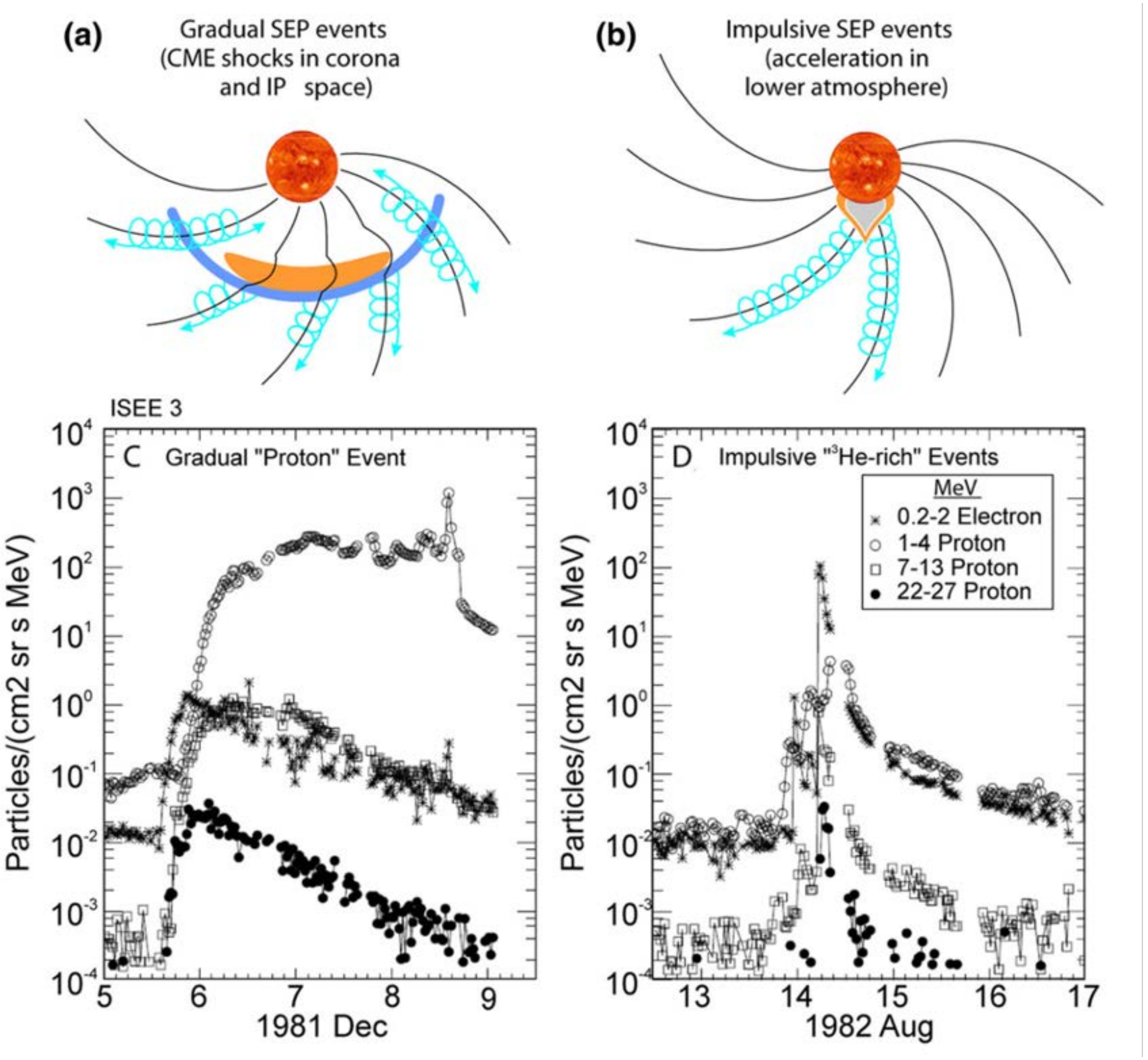
Gopalswamy et al., Earth Planets Space, **66**, 2014, https://doi.org/10.1186/1880-5981-66-104

Solar Energetic Particle (SEP) production

Impulsive ("flare site") and gradual (shock front) acceleration

- Solar Energetic Particles (SEPs) are protons and ions (primarily ^{3}He and α-particles) accelerated to relativistic energies of > 1 MeV per particle
- 2 MeV electron: v ~ 0.97c, 100 MeV proton: v ~ 0.4c

- Two types of SEP events: **Gradual and Impulsive:**
  - Gradual events originate at CME shocks in interplanetary (IP) space. Mostly protons.
  - Impulsive events originate at solar flare site in corona. Heavy ion enriched compared to gradual. Can include neutrons.



Desai & Giaclone, Living Rev. in Sol. Phys., 2016, https://doi.org/10.1007/s41116-016-0002-5

3. The Interplanetary Space Environment

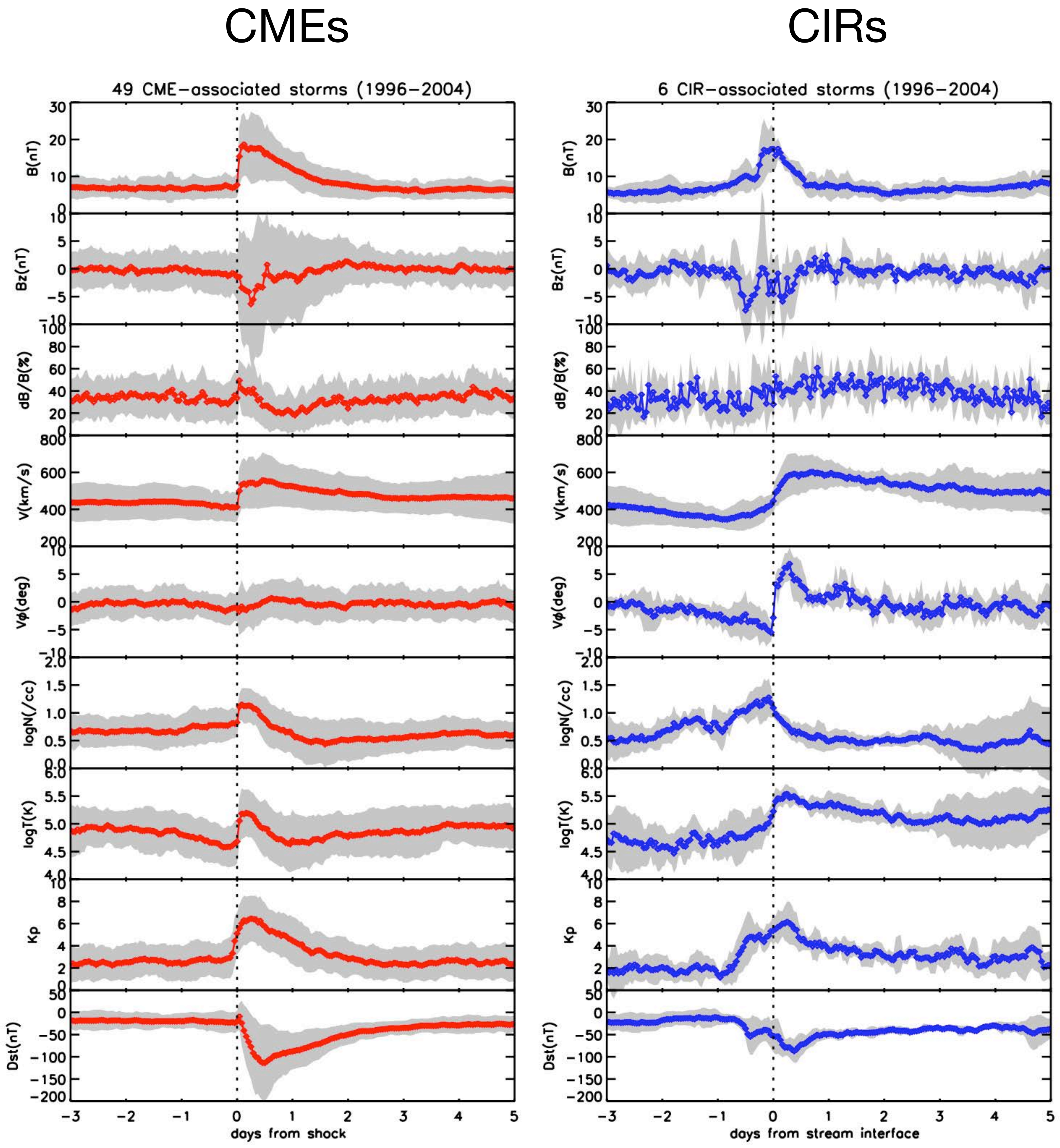
Space plasma characteristics of CMEs vs. solar wind Co-rotating Interaction Regions

Steep shock in magnetic field and proton velocity.

CME arrival defined by velocity and density shocks

Temperature rises rapidly and declines

In general, steeper and deeper decline in Dst



In general, no shocks (although some CIRs can produce fairly steep shocks in N and V)

CIR arrival defined by sudden change in Vϕ

Temperature rises more gradually and stays high

Kataoka & Miyoshi, Sp. Weath. Journ., 2006, https://doi.org/10.1029/2005SW000211

25-Oct-2016 Solar Wind HSS measured at L1

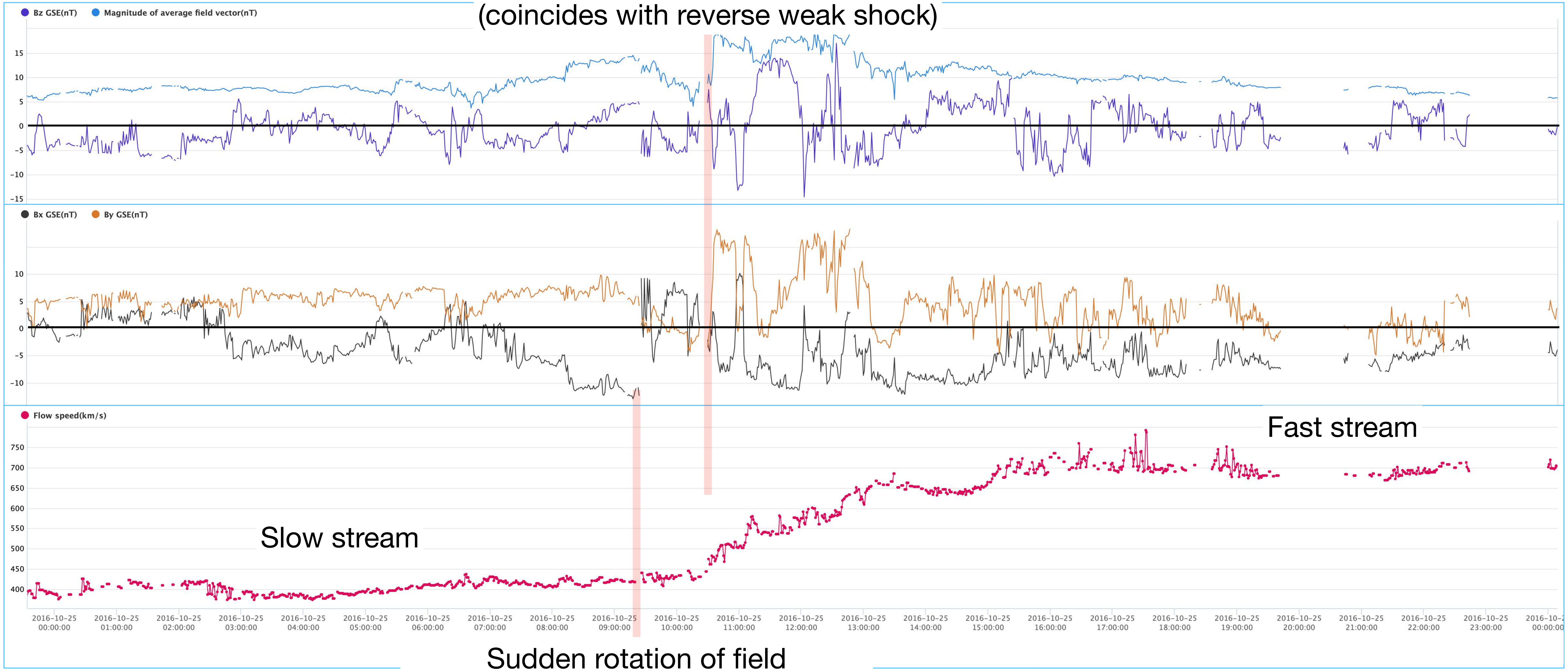
DSCOVR satellite Interplanetary Magnetic Field (IMF) data

|B| jump followed by turbulence
(coincides with reverse weak shock)

|B|
B_z

B_x, B_y

Flow
Speed



Sudden rotation of field
(coincides with forward weak shock)

Space Weather Data Portal: https://lasp.colorado.edu/space-weather-portal/home

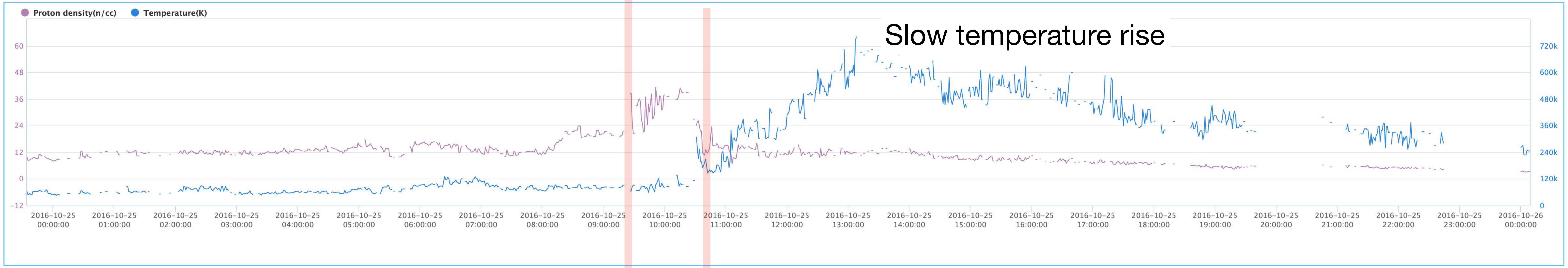
25-Oct-2016 Solar Wind HSS measured at L1

DSCOVR satellite Interplanetary Magnetic Field (IMF) data

Forward weak shock

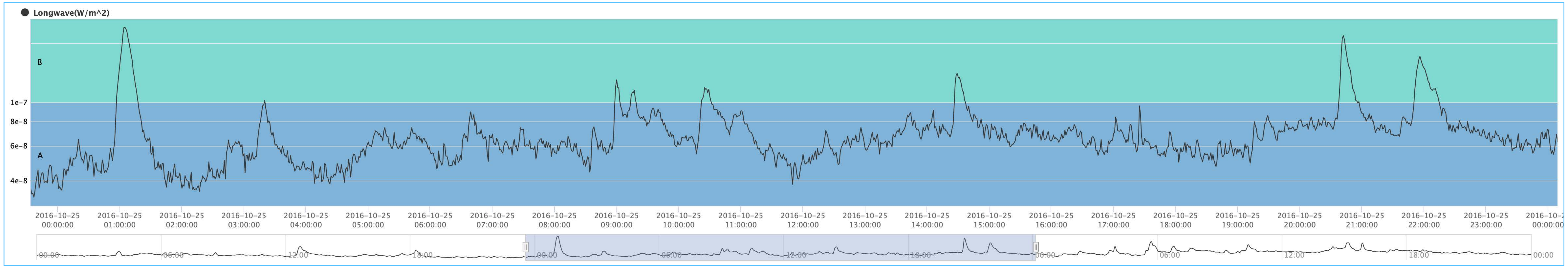
Density

Temp.



Reverse shock

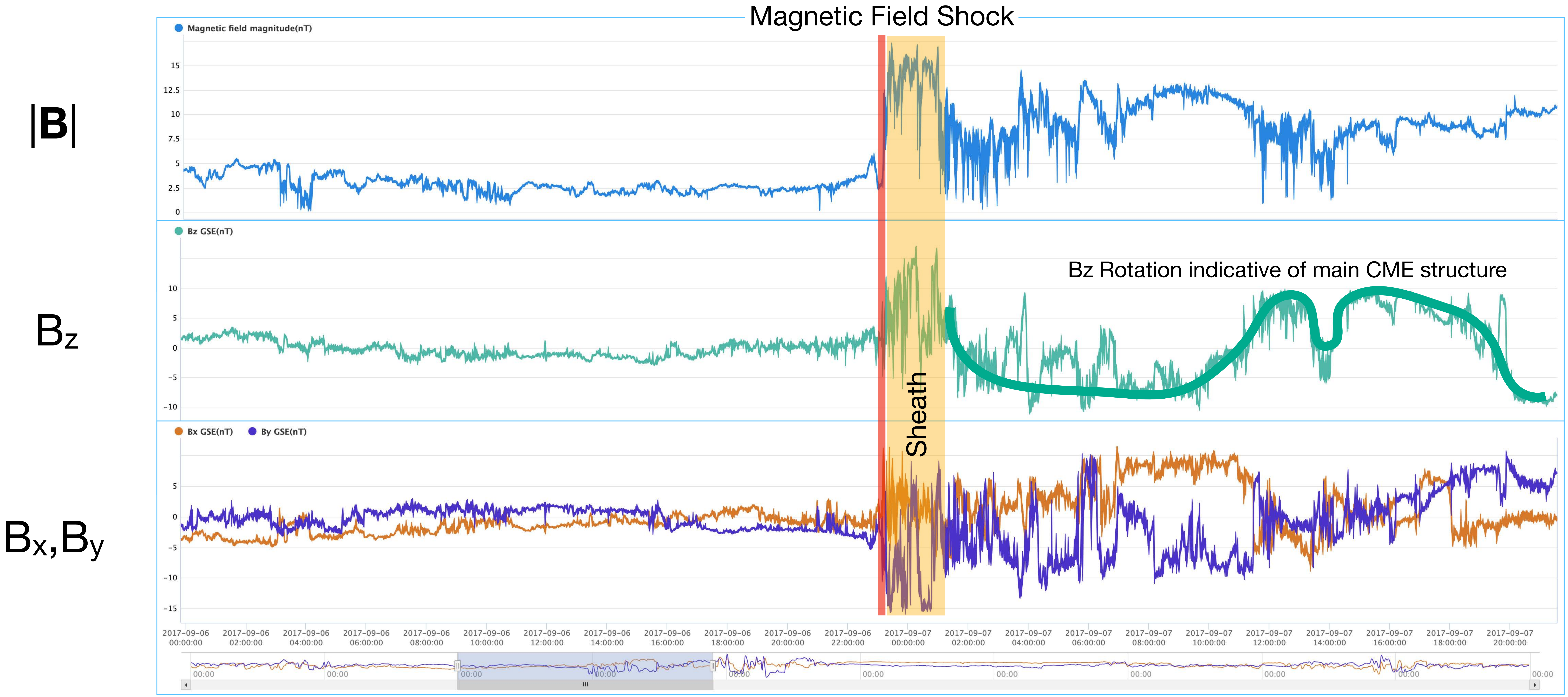
Solar Activity



No eruptive activity in previous 48 hours

08-Sep-2017 CME measured at L1

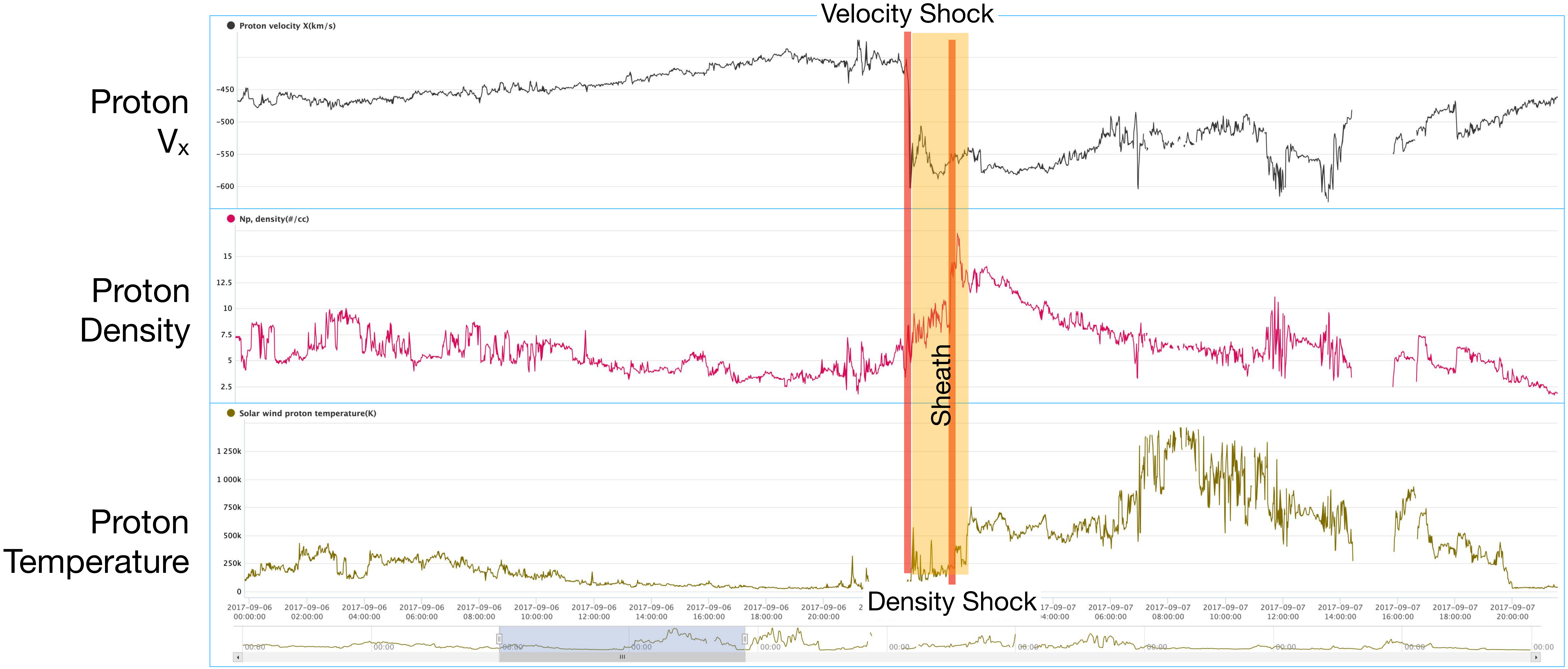
DSCOVR satellite Interplanetary Magnetic Field (IMF) data



Space Weather Data Portal: https://lasp.colorado.edu/space-weather-portal/home

08-Sep-2017 CME measured at L1

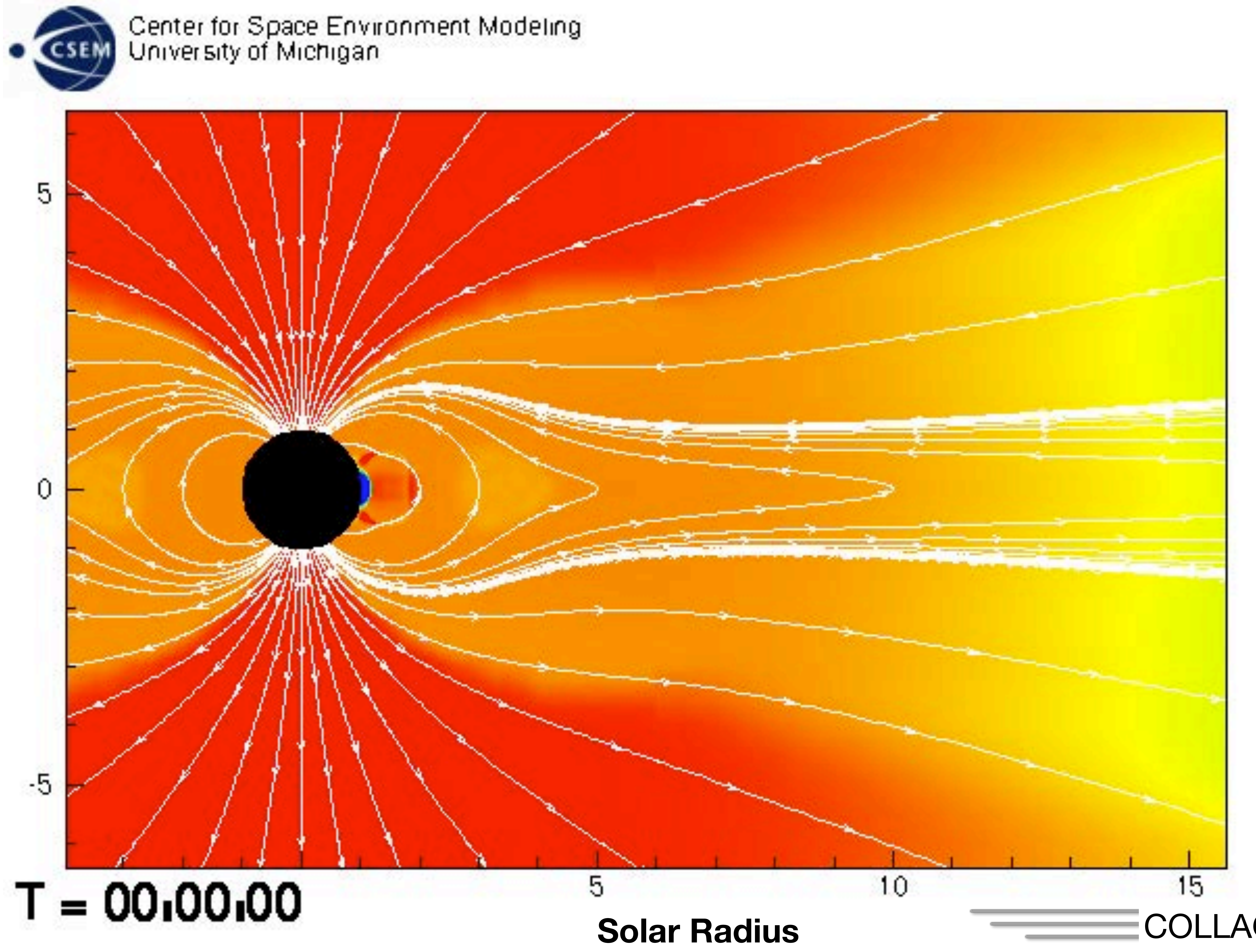
DSCOVR satellite solar wind plasma data



Space Weather Data Portal: https://lasp.colorado.edu/space-weather-portal/home

CME propagation through interplanetary space

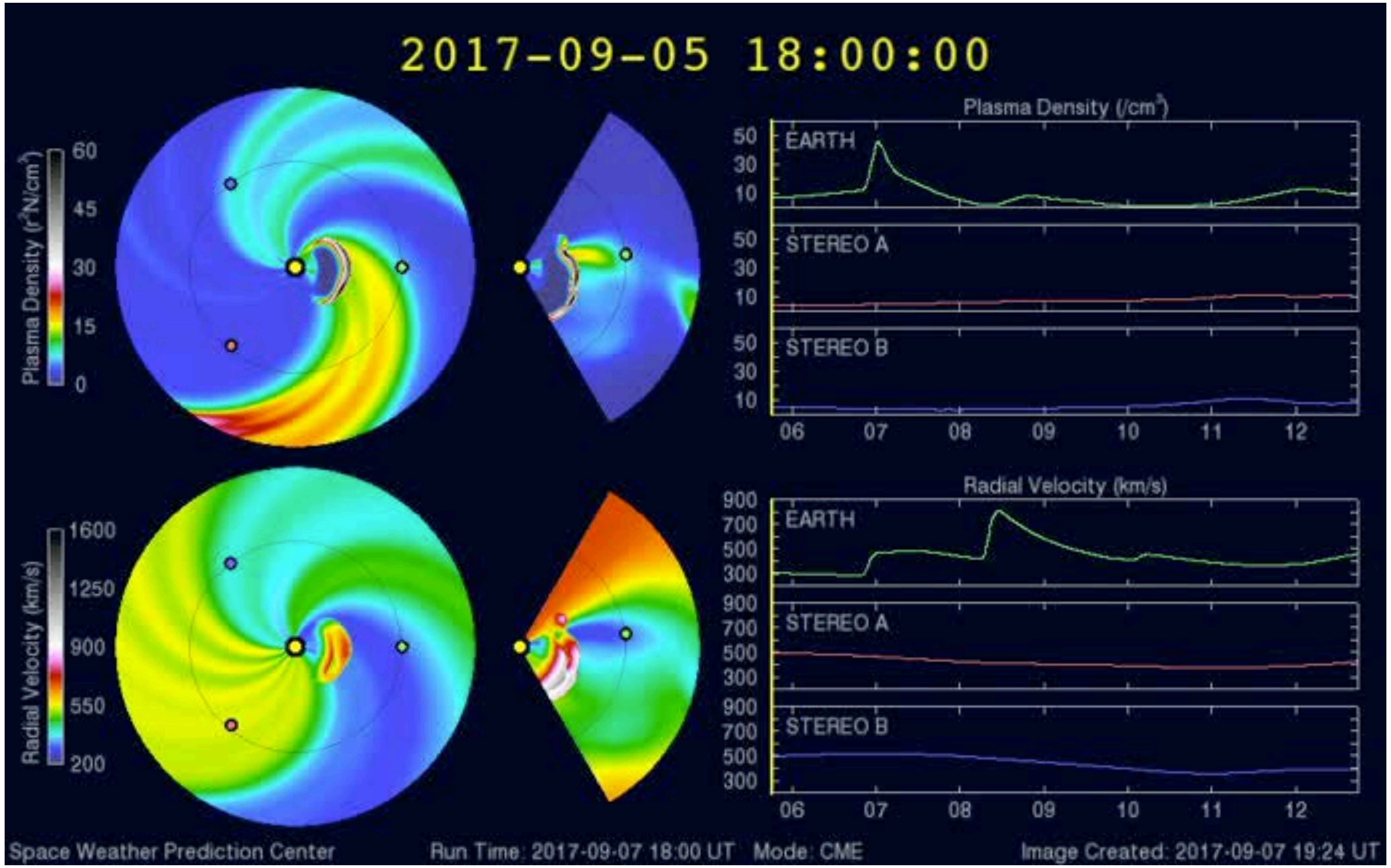
Ideal MHD model of large CME propagation to Earth



CME propagation in Interplanetary Space

WSA-Enlil operational forecasting model

- 3D Ideal MHD model of solar wind run by NOAA Space Weather Prediction Center (SWPC).
- Boundary conditions: synoptic photospheric magnetogram from NSO GONG network.
- Far side photospheric magnetic field simulated by ADAPT model (maybe).
- CMEs are modeled by *hydrodynamic* piston impulse with parameters input “by hand” base on coronagraph analysis of CME shape: **NO MAGNETIC FIELD**
- Used to estimate CIR and CME arrival times at Earth. Since no magnetic field, no Bz estimate.



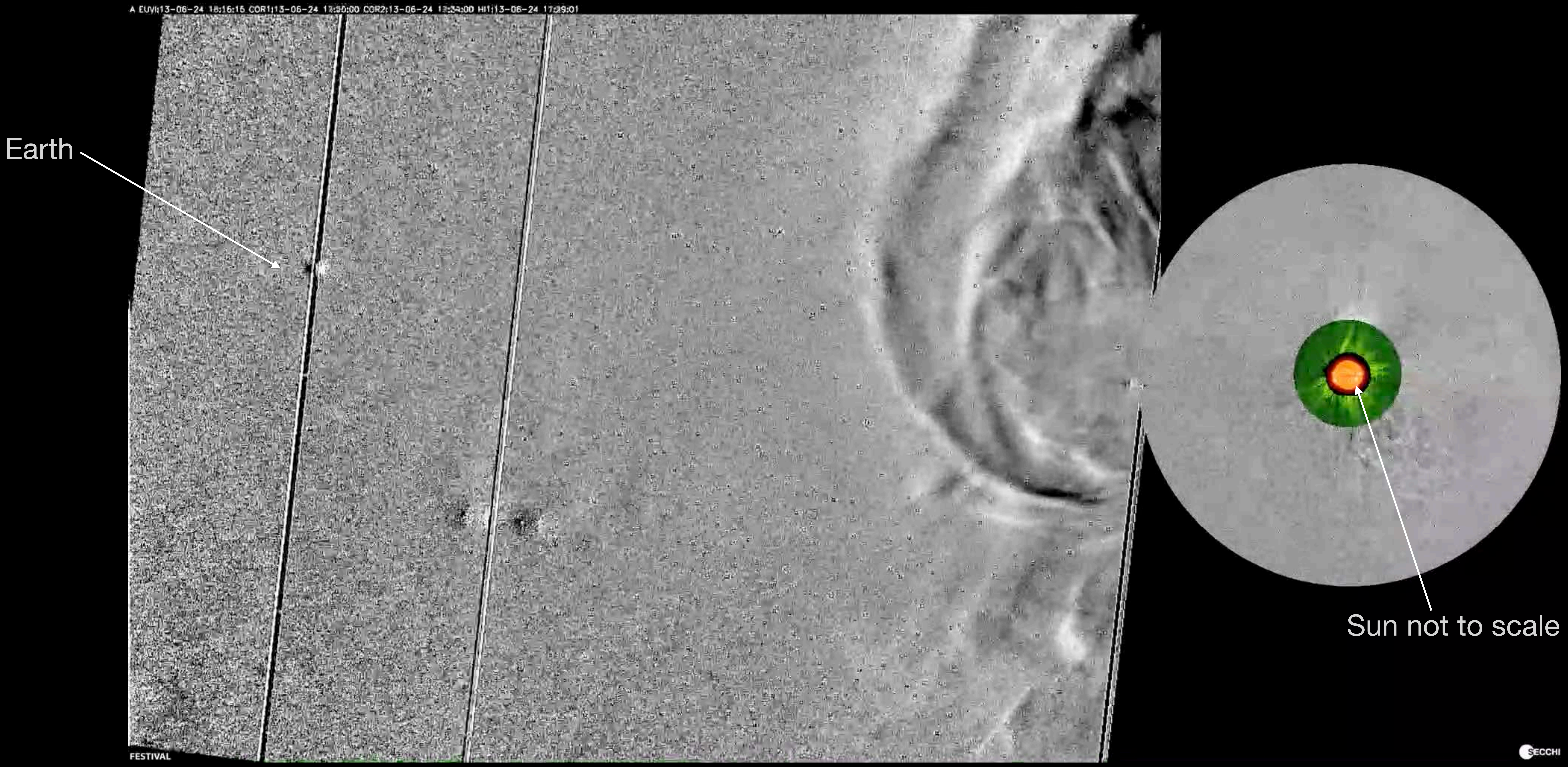
Plasma density

Plasma radial velocity

Ecliptic plane view   Earth meridional section   Time series at locations

CME propagation through IP space: complexity reigns

STEREO-A HI instrument 22—25 June 2013

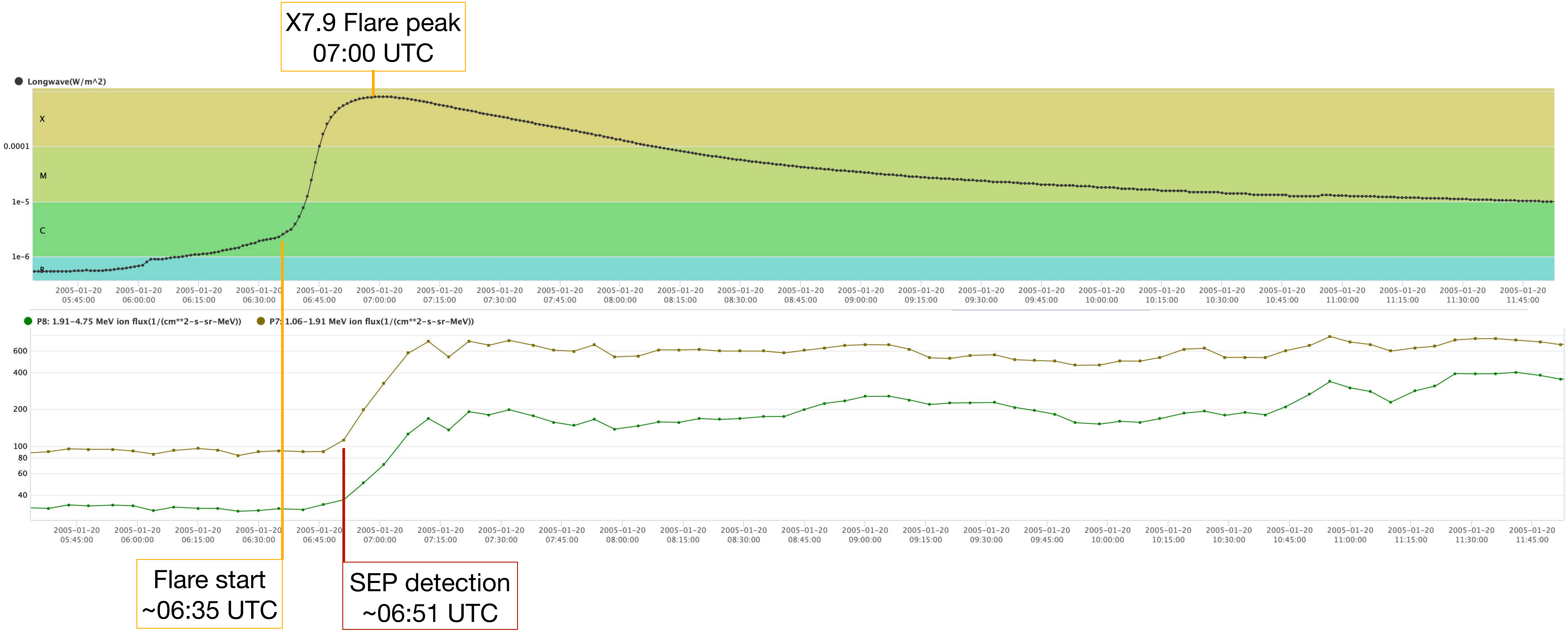


SEP detection in deep space

SEP events are actually *visible* in cameras (and eyes) in deep space

SEP detection in deep space

NASA ACE Mission at L1: 20-Jan-2005 radiation storm

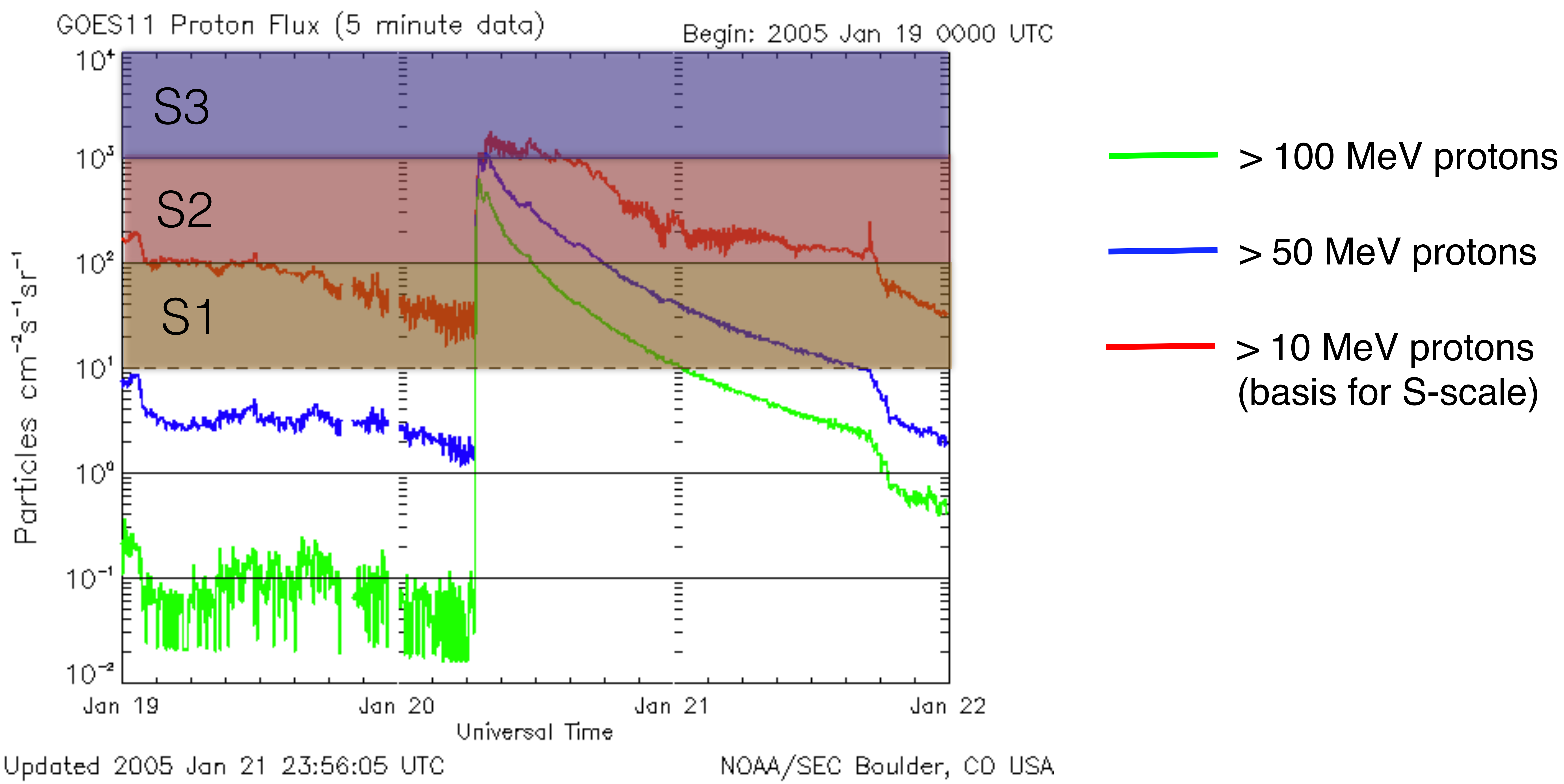


16-min travel time from Sun to L1: ~153,000 km/sec ~ 0.5 c

Space Weather Data Portal: https://lasp.colorado.edu/space-weather-portal/home

SEP Detection at Earth

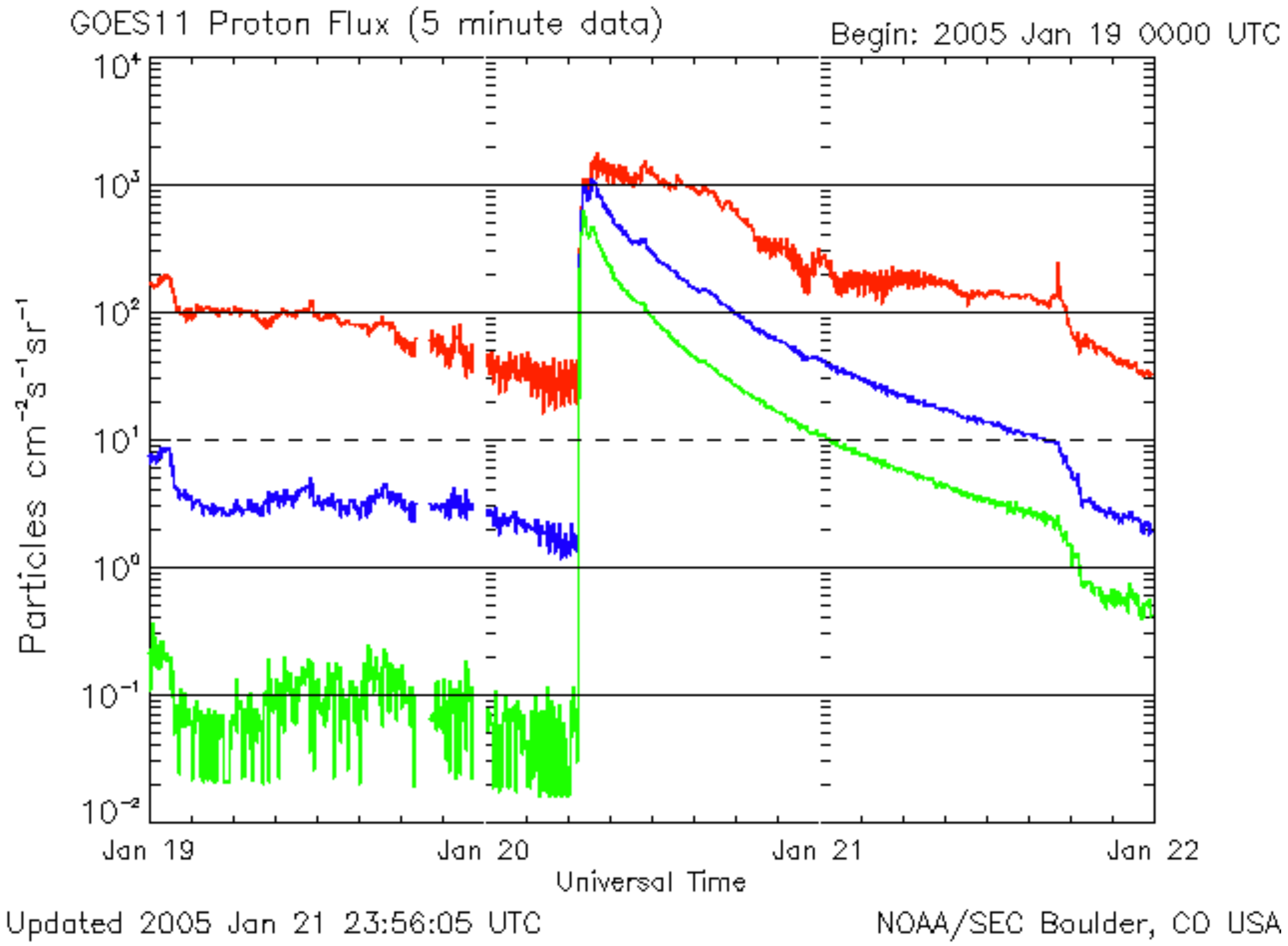
“Radiation Storms” are classified by the NOAA GOES/SEISS instrument suite



The 20-Jan-2005 **S3** storm caused one of the largest ground neutron fluxes since 1989

SEP Detection at Earth

NOAA Space Weather Prediction Center (SWPC) S-scale descriptions



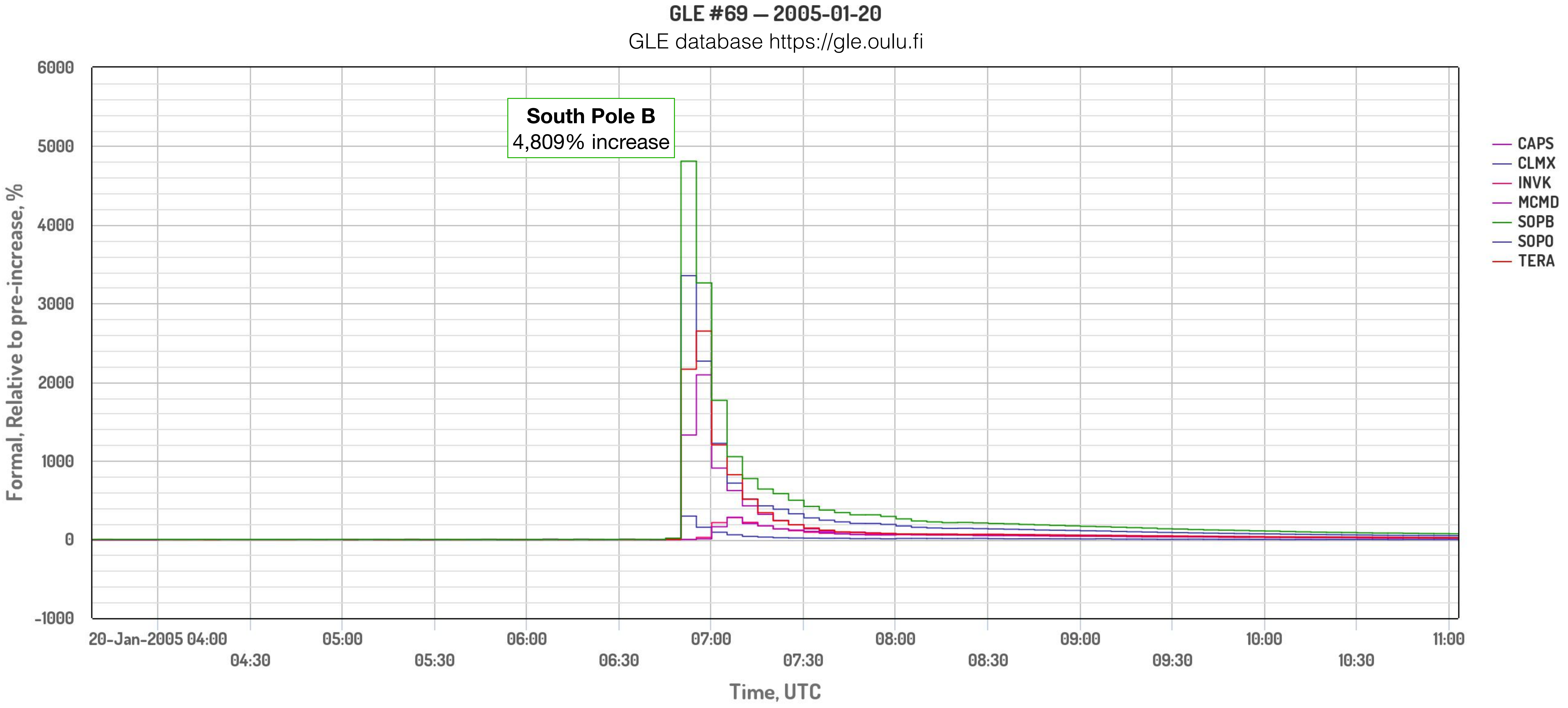
Scale	Description	Effect	Physical measure (Flux level of >= 10 MeV particles)	Average Frequency (1 cycle = 11 years)
S 5	Extreme	**Biological:** Unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. **Satellite operations:** Satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate sources; permanent damage to solar panels possible. **Other systems:** Complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult.	10^5	Fewer than 1 per cycle
S 4	Severe	**Biological:** Unavoidable radiation hazard to astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. **Satellite operations:** May experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded. **Other systems:** Blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.	10^4	3 per cycle
S 3	Strong	**Biological:** Radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. **Satellite operations:** Single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely. **Other systems:** Degraded HF radio propagation through the polar regions and navigation position errors likely.	10^3	10 per cycle
S 2	Moderate	**Biological:** Passengers and crew in high-flying aircraft at high latitudes may be exposed to elevated radiation risk. **Satellite operations:** Infrequent single-event upsets possible. **Other systems:** Small effects on HF propagation through the polar regions and navigation at polar cap locations possibly affected.	10^2	25 per cycle
S 1	Minor	**Biological:** None. **Satellite operations:** None. **Other systems:** Minor impacts on HF radio in the polar regions.	10	50 per cycle

S-scale description includes impacts on technological systems (Lecture 2).

Note that because this is a measurement at GEO, i.e., (usually) inside the bowshock, it underestimates the flux in interplanetary space.

SEP Detection at Earth

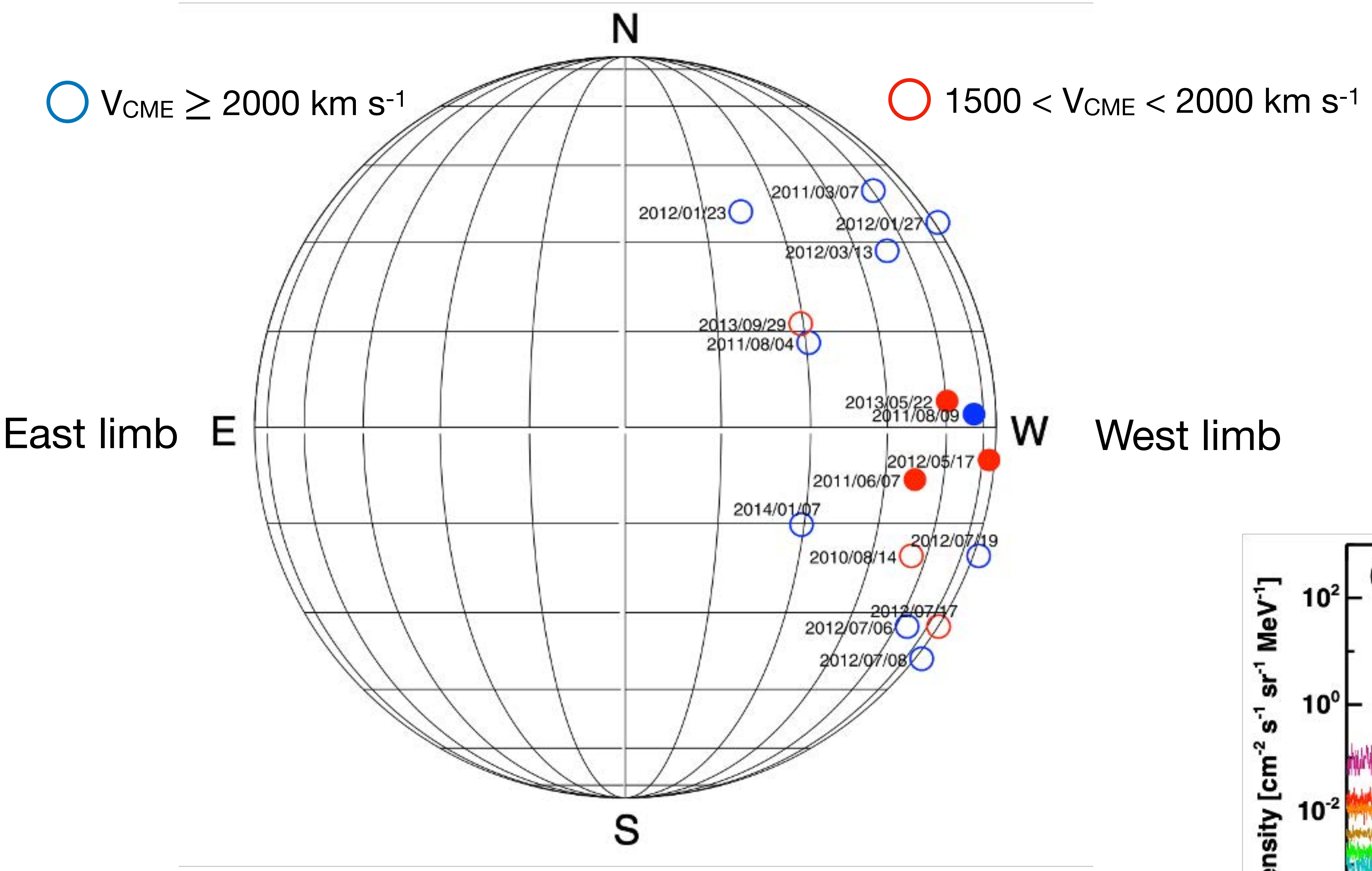
Ground-based neutron detectors: “**Ground-Level Events**” (**GLEs**)



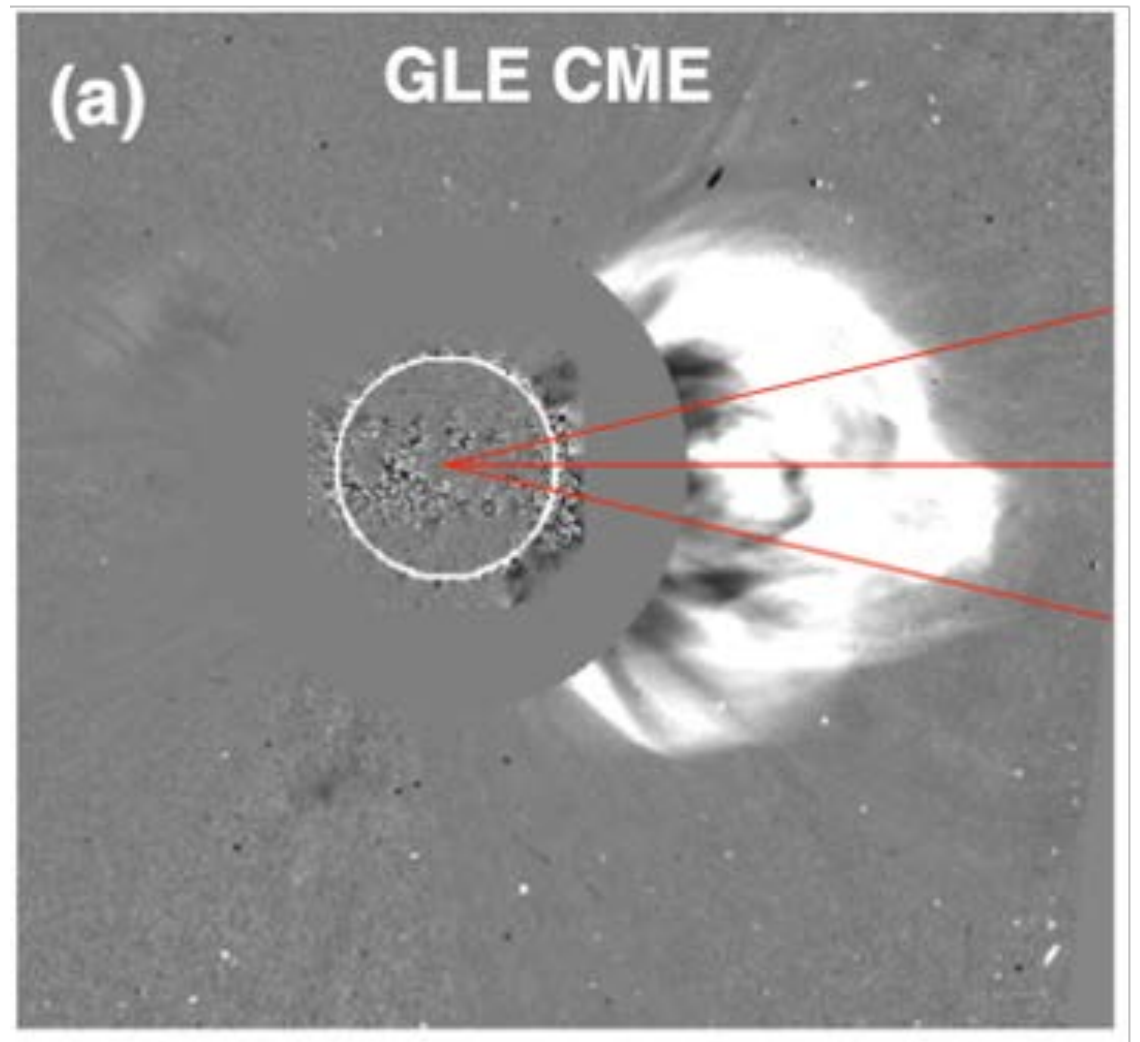
GLE neutrons require SEP proton energies > 1 GeV impacting the atmosphere

SEP detection in deep space

SEP events follow the Parker Spiral magnetic field: West limb events are more dangerous



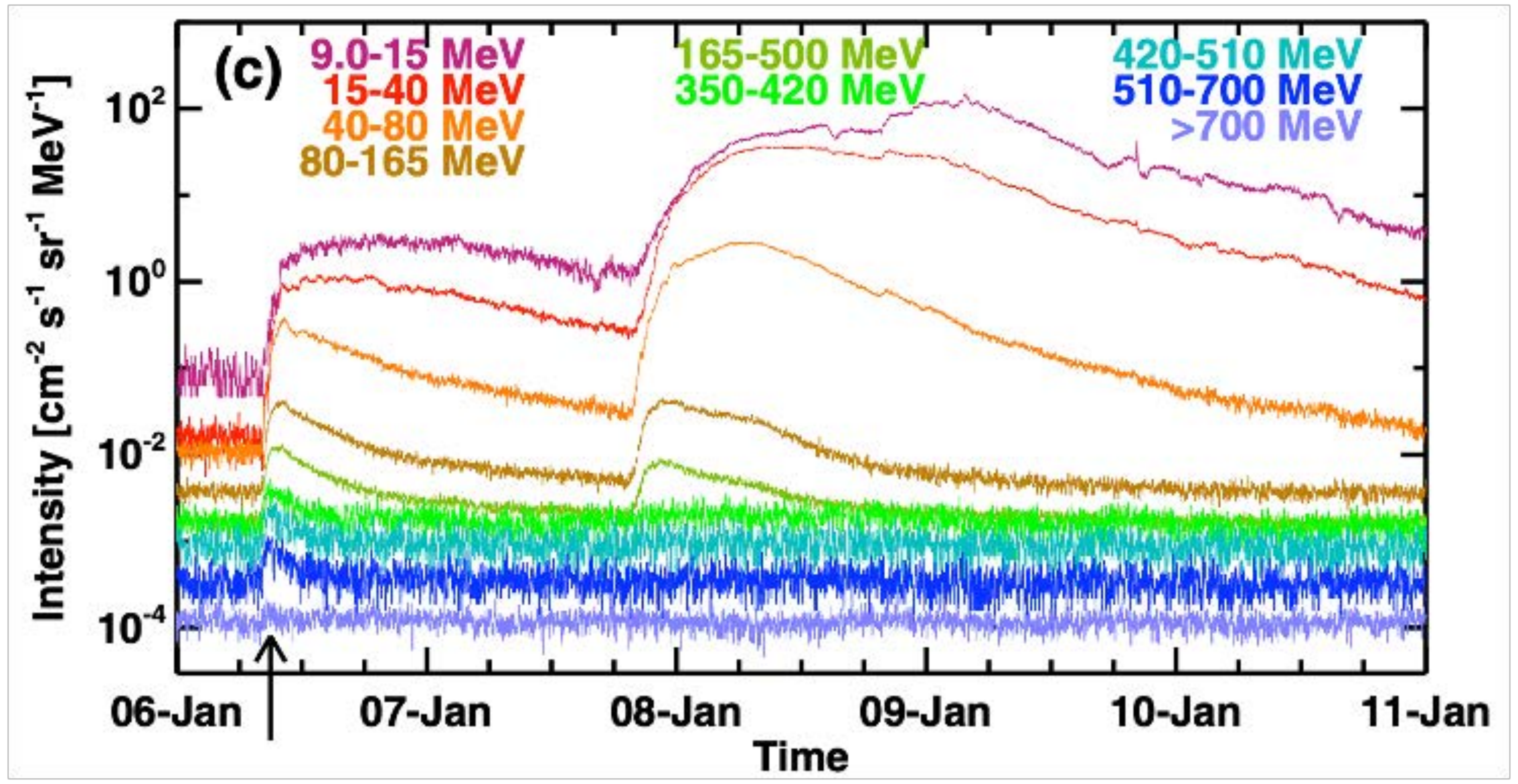
Solar Cycle 24 (to 2014) SEP events from M5+ Flares
Western Hemisphere Only



SOHO: 2014/01/06 08:12

Some SEP events can be caused by eruptions on the far side:

6-Jan-2014 event caused a **Ground Level Event (GLE),** i.e., neutrons detected on the ground at Earth



Gopalswamy et al., Earth Planets Space, **66**, https://doi.org/10.1186/1880-5981-66-104

SEP detection in deep space

Electrons are accelerated to higher velocities than protons and can provide warning of SEP events

10-Sep-2017 Radiation storm and GLE

ACE EPAM 5-minute data at L1

Space Weather Data Portal: https://lasp.colorado.edu/space-weather-portal/home

Reading for next week

Knipp, D. J., et al. (2016), "*The May 1967 great storm and radio disruption event: Extreme space weather and extraordinary responses*", *Space Weather*, **14**, 614–633,

https://doi.org/10.1002/2016SW001423