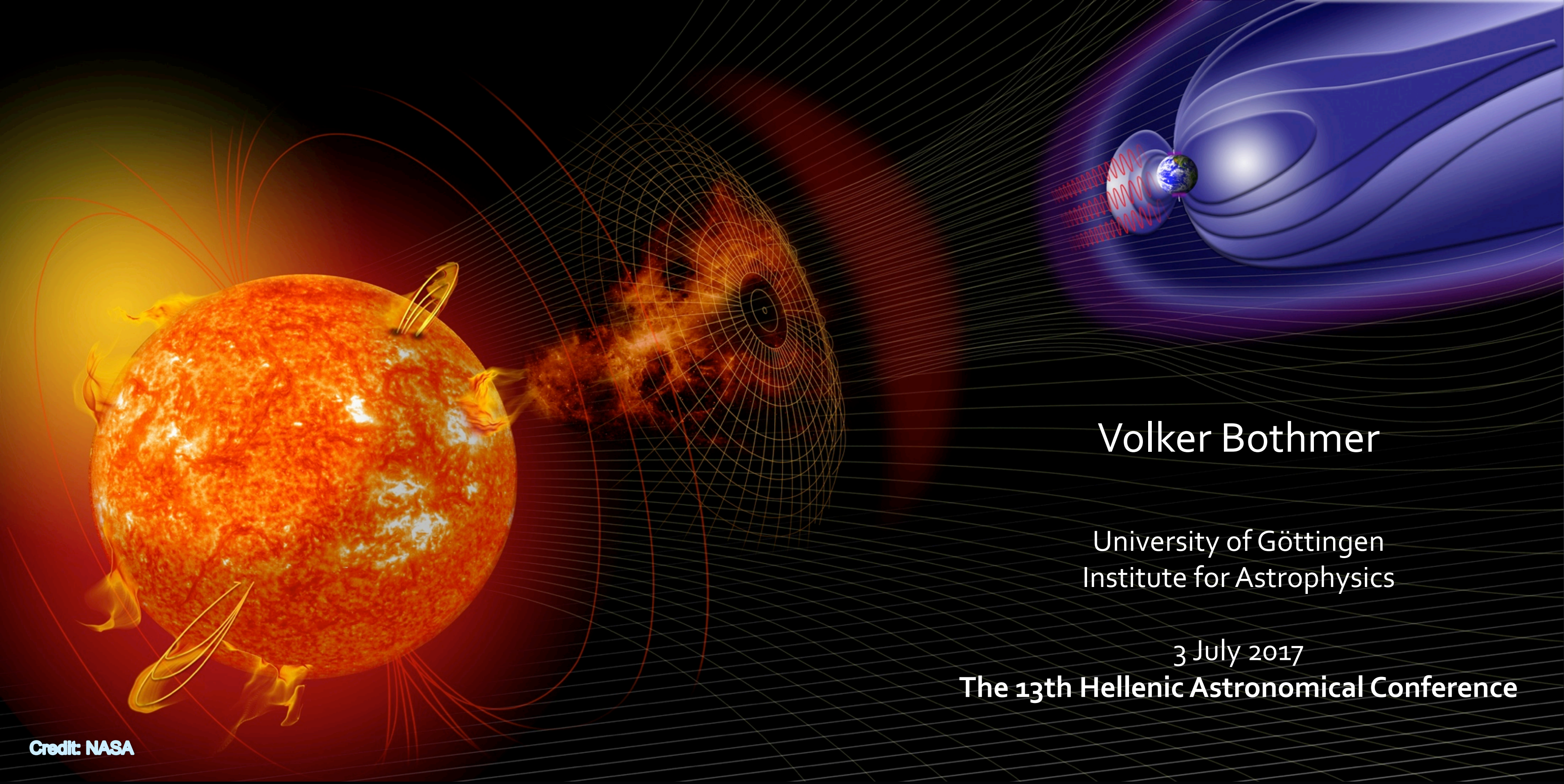



Volker Bothmer

University of Göttingen
Institute for Astrophysics

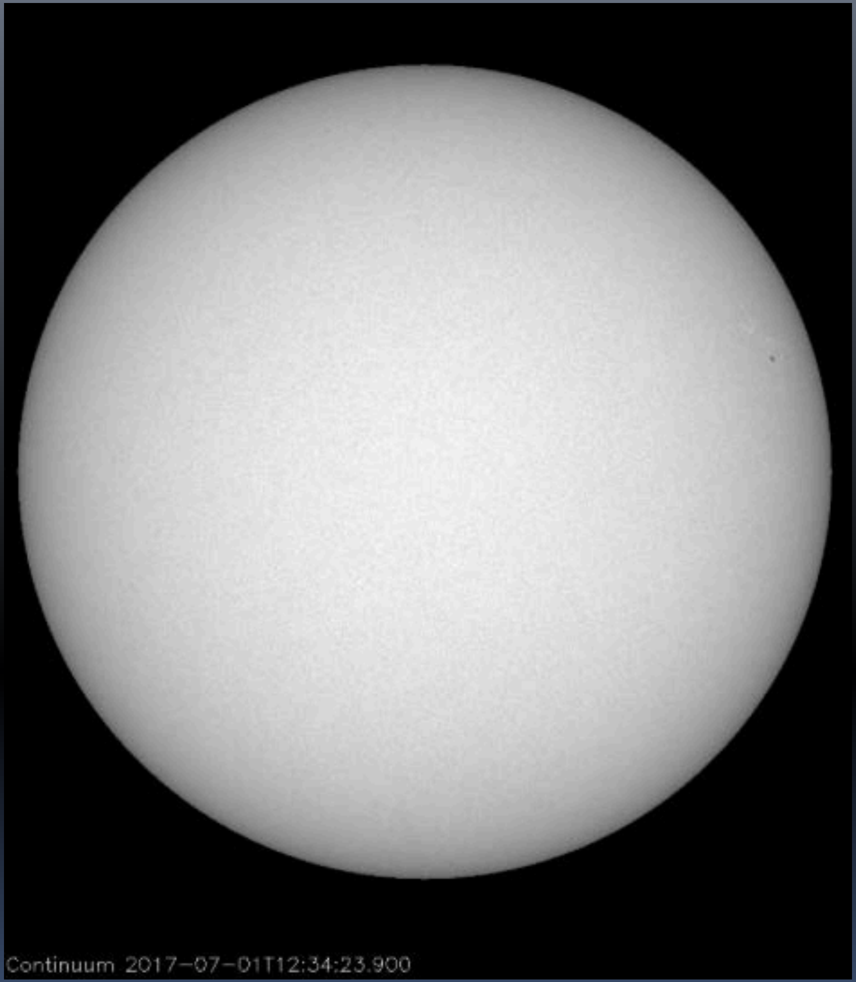
3 July 2017
**The 13th Hellenic Astronomical Conference**

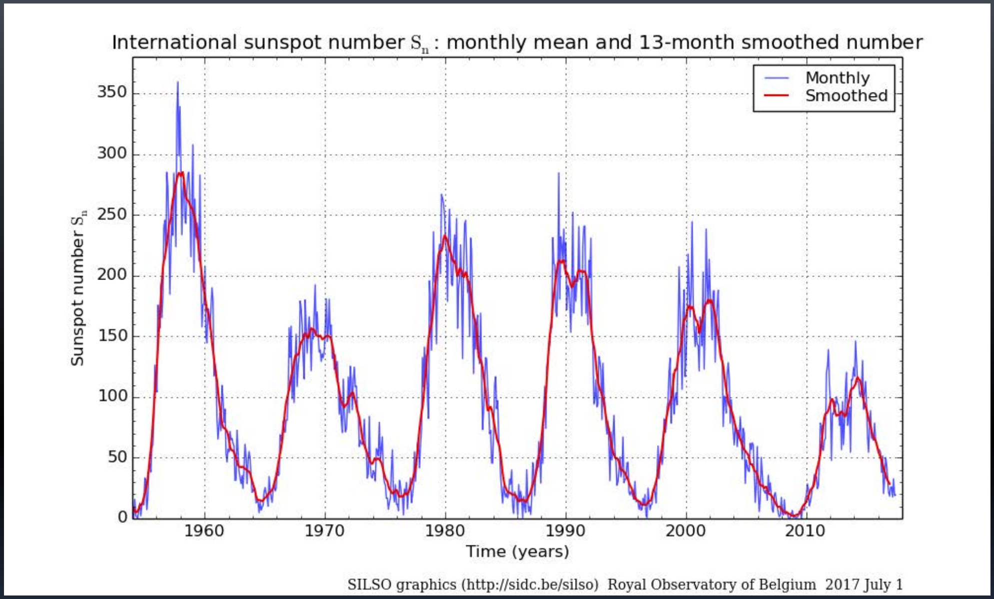
# HELIOPHYSICS AND SPACE WEATHER – CHALLENGES AND PERSPECTIVES

# Outline

- Introduction to Heliophysics – From Mariner to SDO
- Space Weather and the Forecast
- Challenges and Perspectives – Solar Probe, Solar Orbiter & Lagrange
- Conclusions

# The Sun Today



# Coronal structures indicate the expansion of the solar atmosphere into space

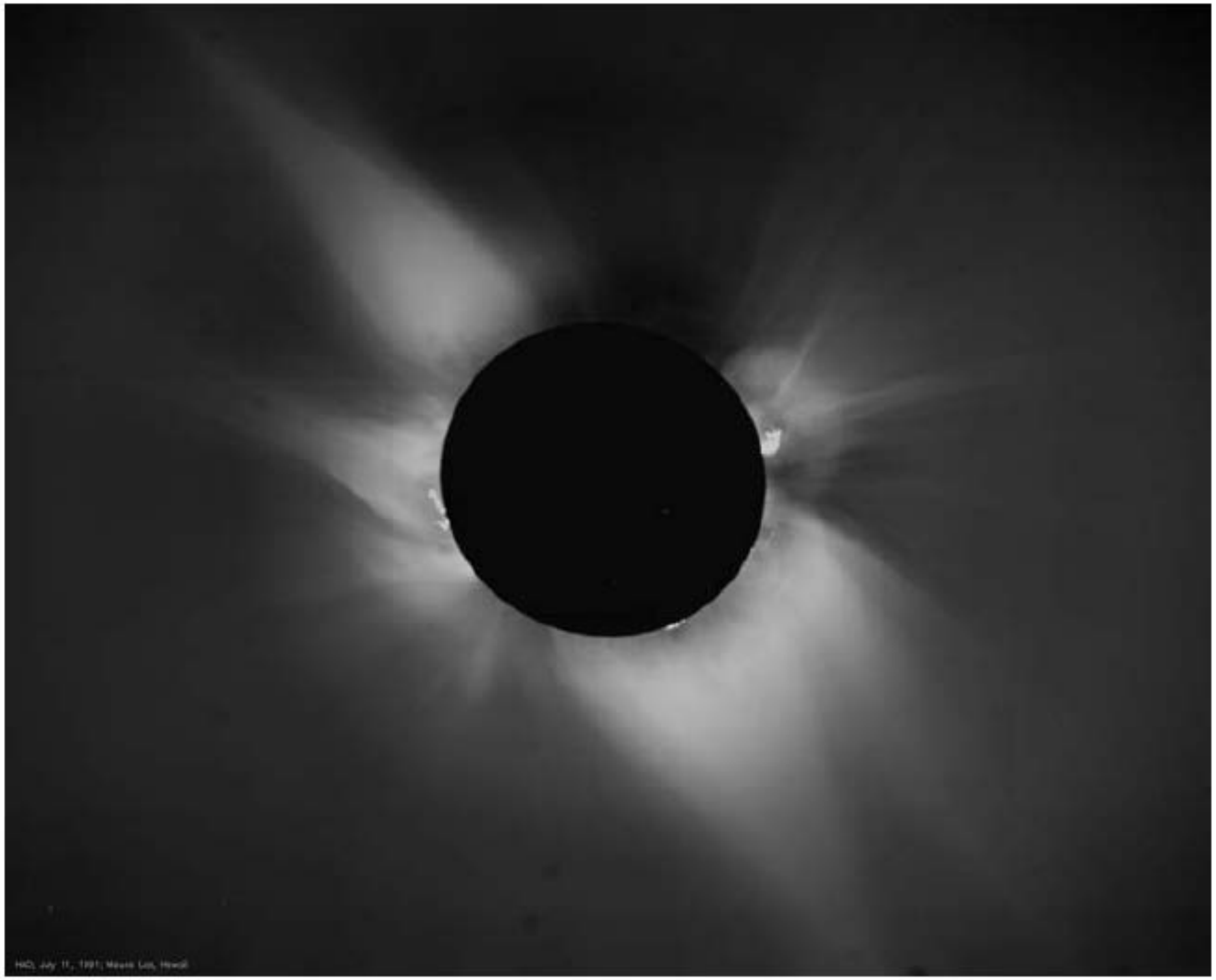
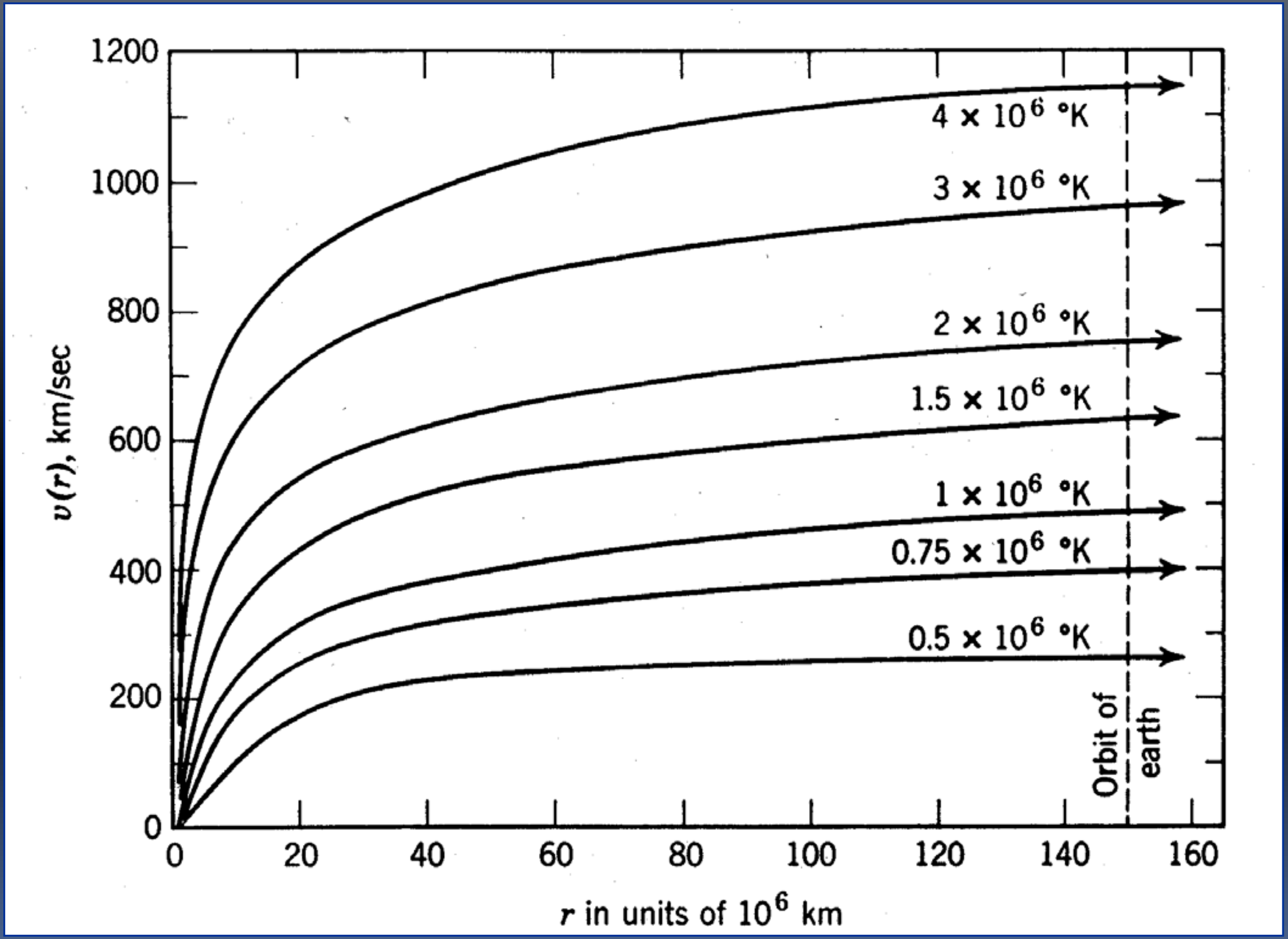


**Fig. 1.2.** The solar corona as seen during the total solar eclipse on July 11, 1991. Courtesy: High Altitude Observatory (HAO), Boulder, USA.

# The existence of the solar wind was deduced theoretically from HD equations by Parker in 1958



# The Earth's atmosphere shields part of the solar EM Spectrum – Need for space exploration

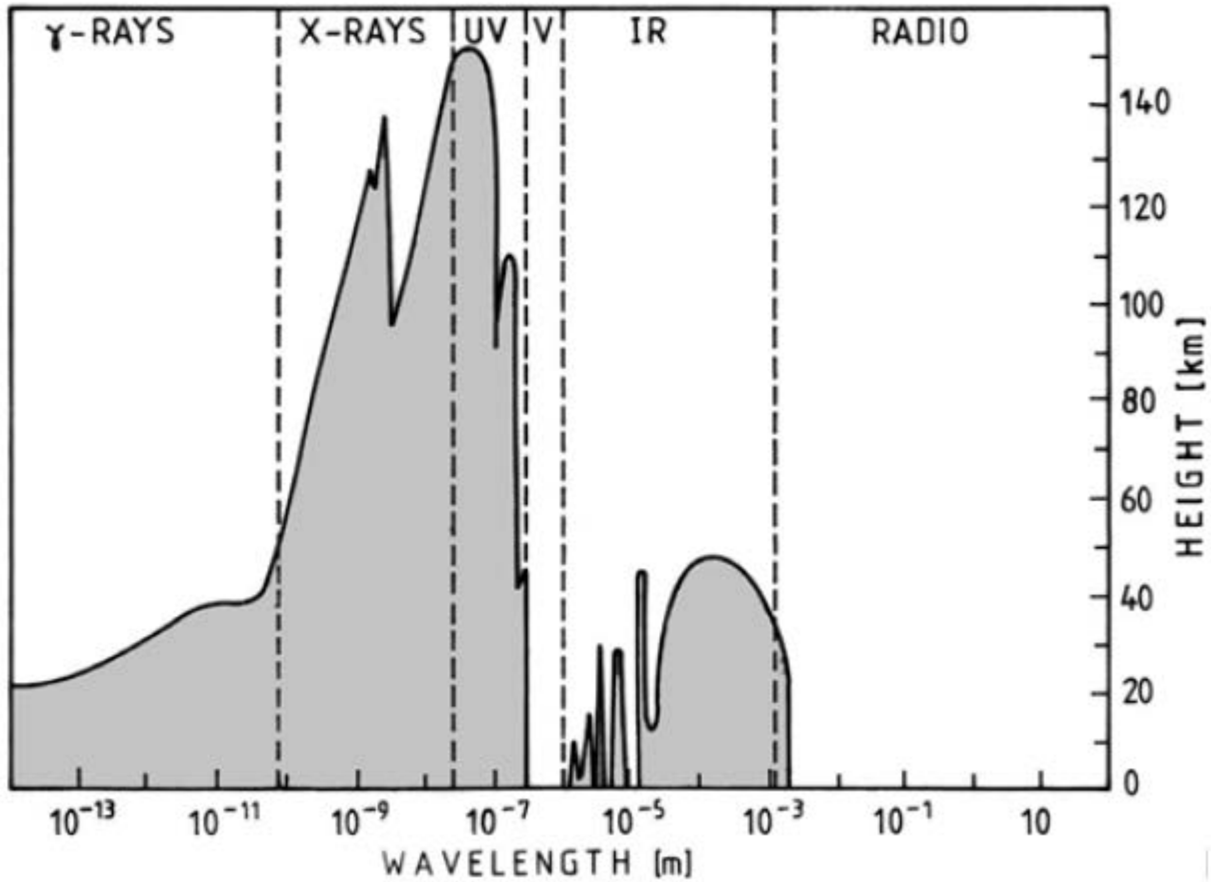



**Figure 3.3.** Absorption of solar radiation by the Earth's atmosphere. The shaded areas provide the height above ground where the incoming intensity is reduced to 50% of its original strength. After Nicolson (1982), adapted by Stix (2004).

# The advent of the space age: In 1962 Mariner 2 records the solar wind

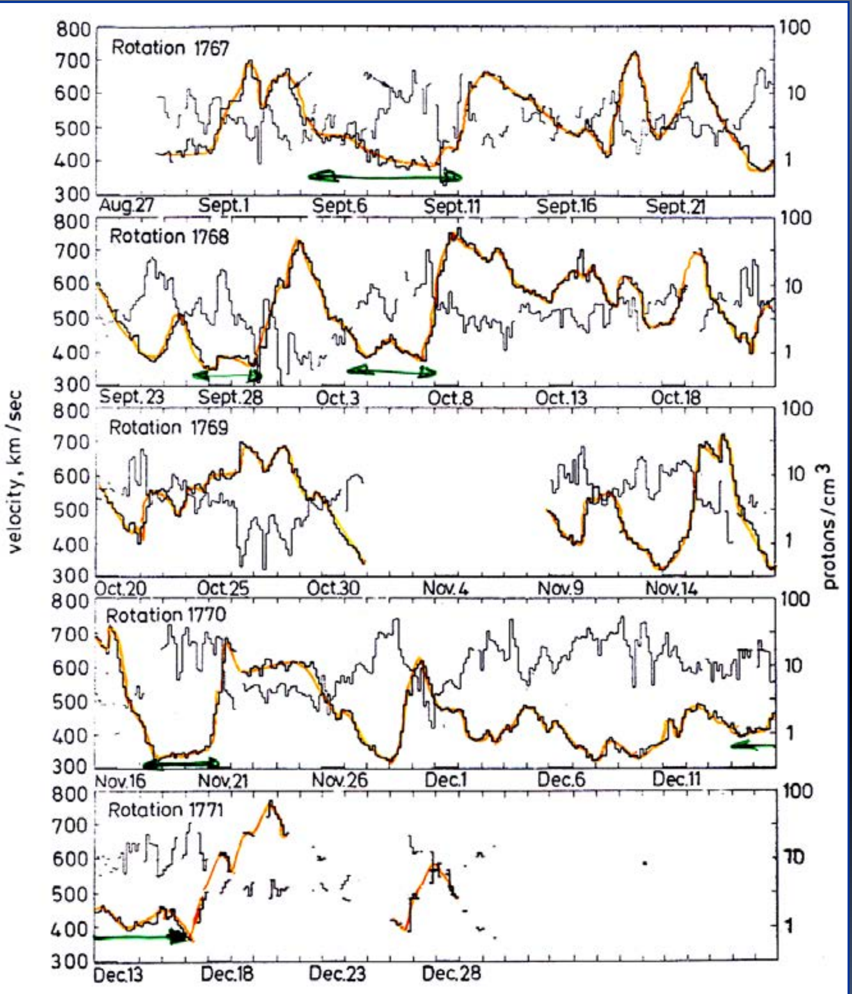



Fig. 1.5 Three-hour averages of the solar wind proton density and flow speed observed by Mariner 2 in 1962 [1.21]. The time coordinate has been broken into 27-day solar rotation periods


Dylan, 1962

Neugebauer und Snyder (1962)

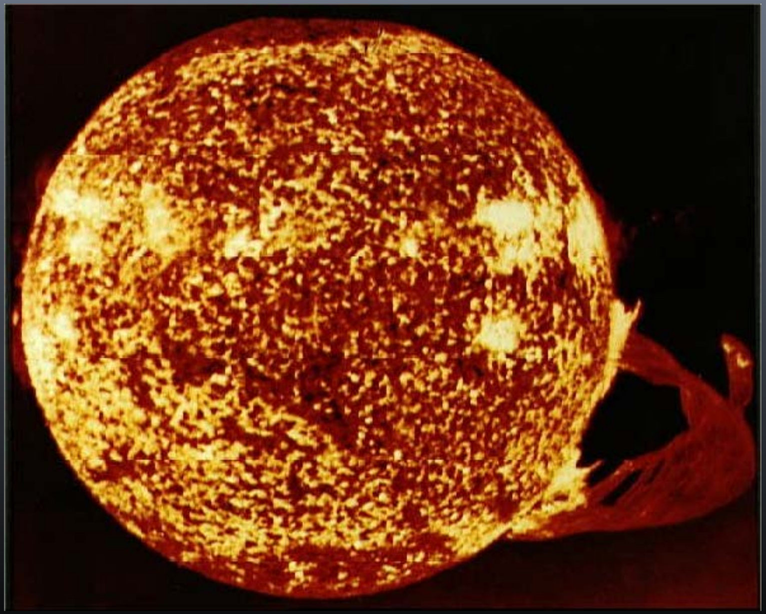
# Solar wind sampling on moon – Apollo 11, 20 July 1969

I.

II.

Images: NASA

# 1973-1974: Skylab Observations



A CME Observed with the Coronagraph

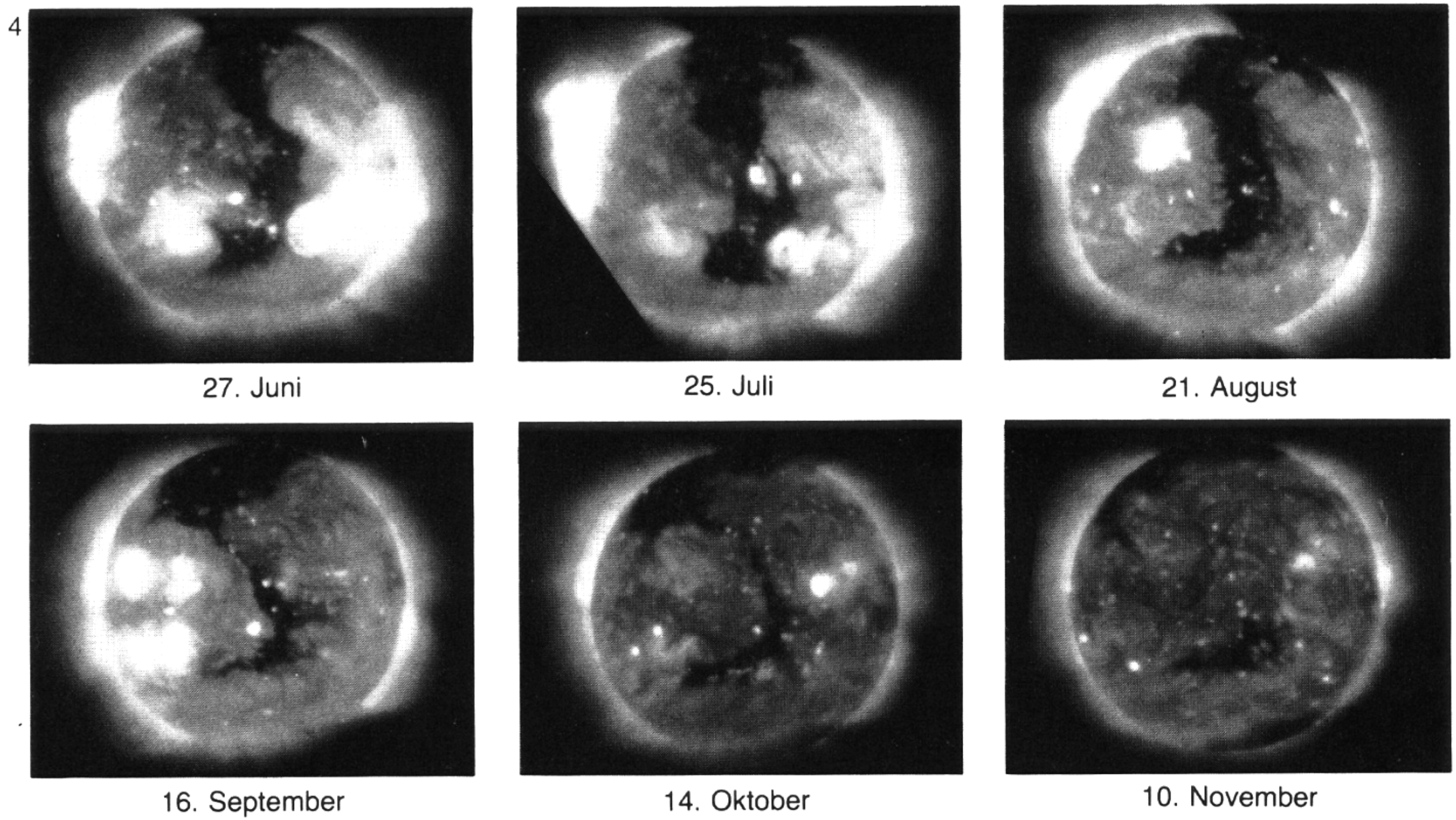
on board Skylab in 1973

- 2.0 - 6 solar radii; Film detector (5“ resolution)
- ~100 CMEs observed, established importance (and beauty); statistics; associations
- Weakness: limited film capacity, 3 short duration missions

<u>What is a CME</u>?

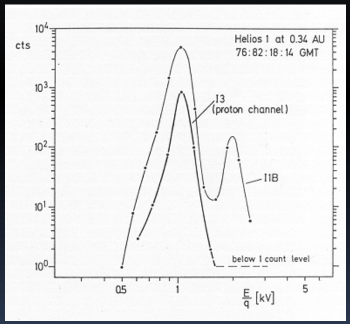
A new, discrete, bright feature appearing in the field of view of the coronagraph and moving outwards over a period of minutes to hours (Munro et al., 1979)

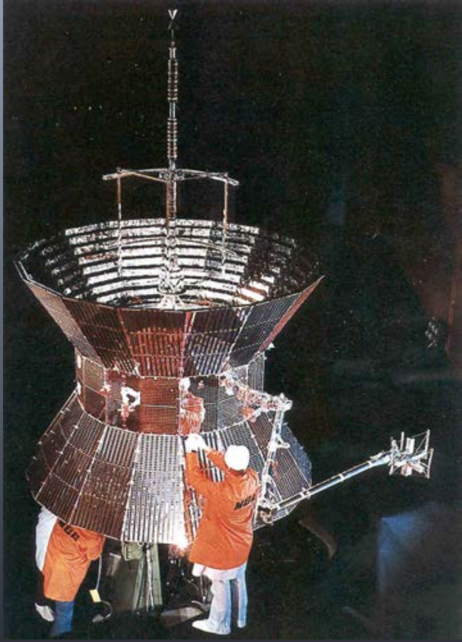
# SKYLAB: Coronal Hole Extensions in 1974



# Solar wind characteristics at 1 AU based on Helios 1,2 measurements

| | |
|---|---|
| Plasma bulk velocity V | 300 – 800 km/s |
| Proton density $N_P$ | 10 $cm^{-3}$ |
| Proton temperature $T_P$ | $4 \cdot 10^4$ K |
| Electron temperature $T_E$ | $1.5 \cdot 10^5$ K |
| Magnetic field strength B | 4-5 nT |
| Plasma composition | 95% Protons, 4% Helium ions, very few heavy elements, same number of free electrons (quas neutrality) |

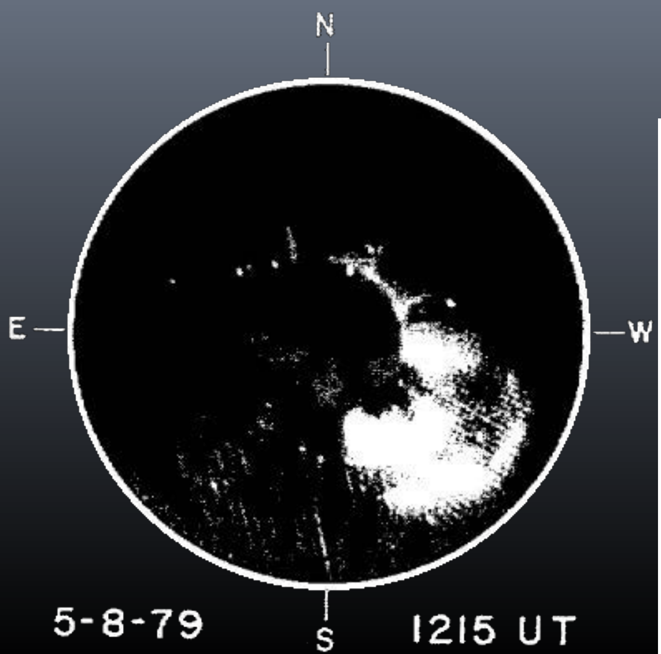


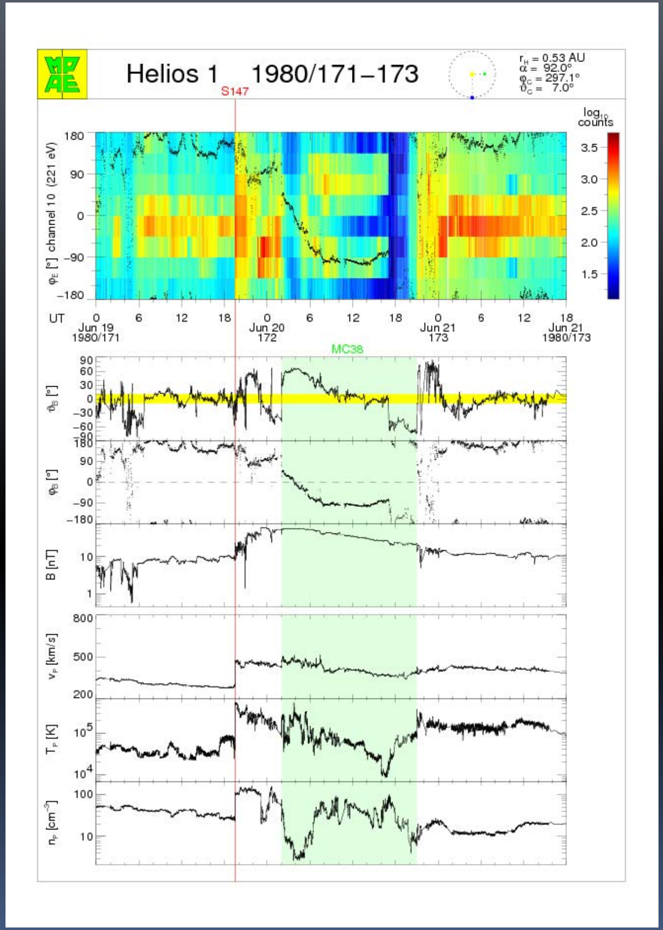
Helios-Orbit:

0.29 – 1 AU

# Correlated Analysis of Remote Sensing and In-Situ Observations with P78-1 and Helios 1 & 2

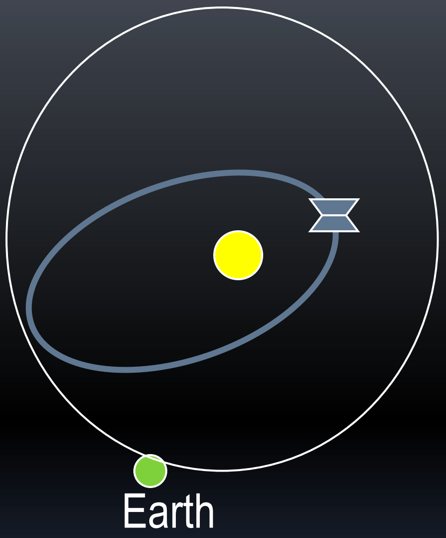



Solwind Coronagraph on board P78-1 (1979-1985)




Burlaga: Magnetic Clouds

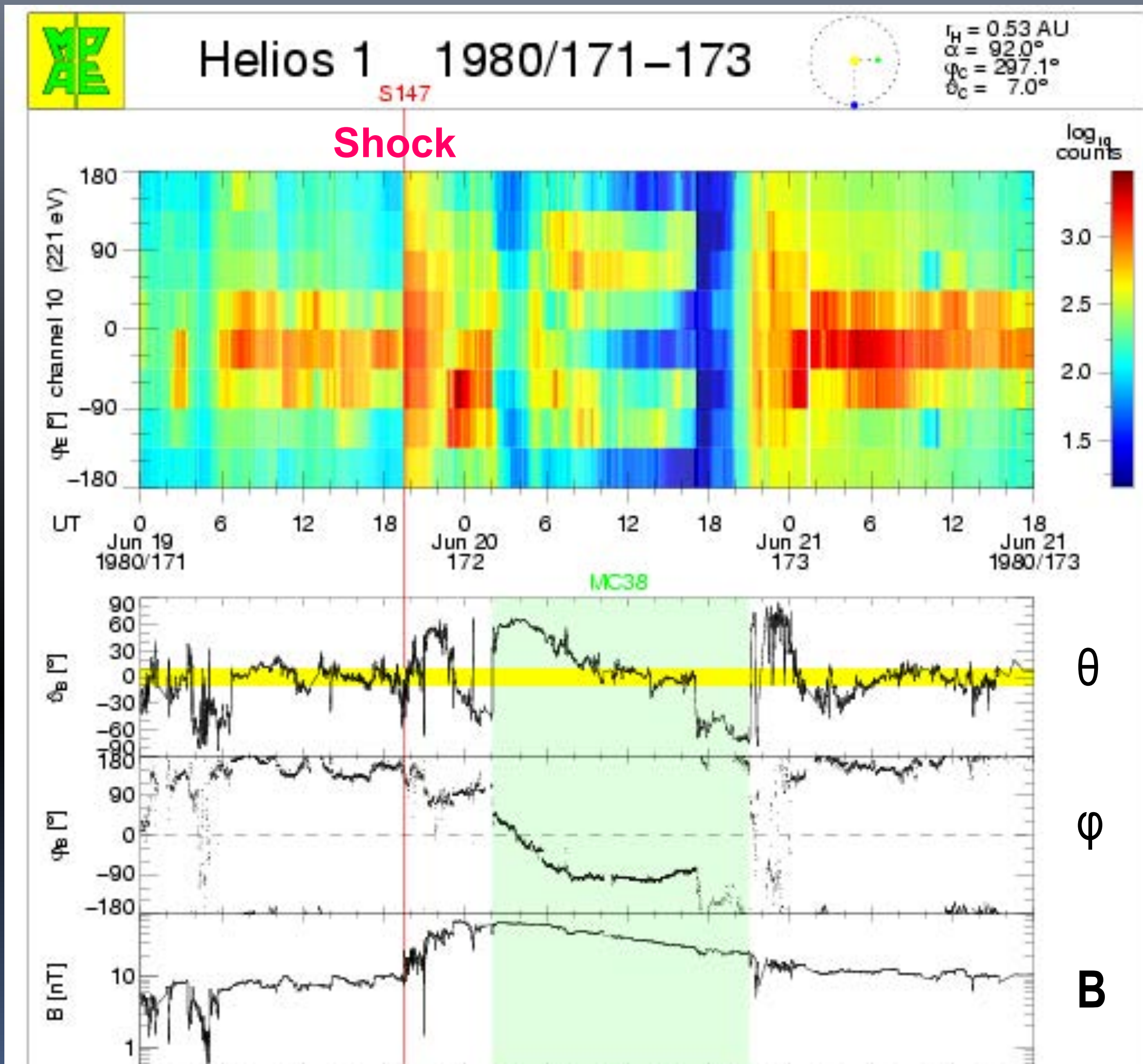
Helios-Orbit: 0.29 - 1 AU




The Helios 1 & 2 Spacecraft

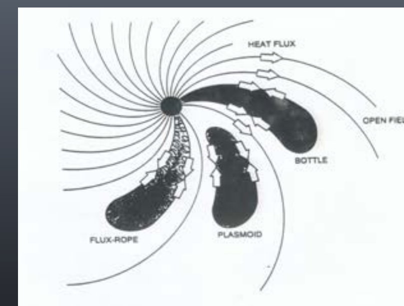
(1974-1986)

# A Magnetic Cloud (Helical Flux Rope CME in the Solar Wind) Measured by Helios 1 following a S/C Directed CME




1 Day

Suprathermal Electrons
(E=221 keV)




*Phillips et al., Solar Wind 7, 1992*

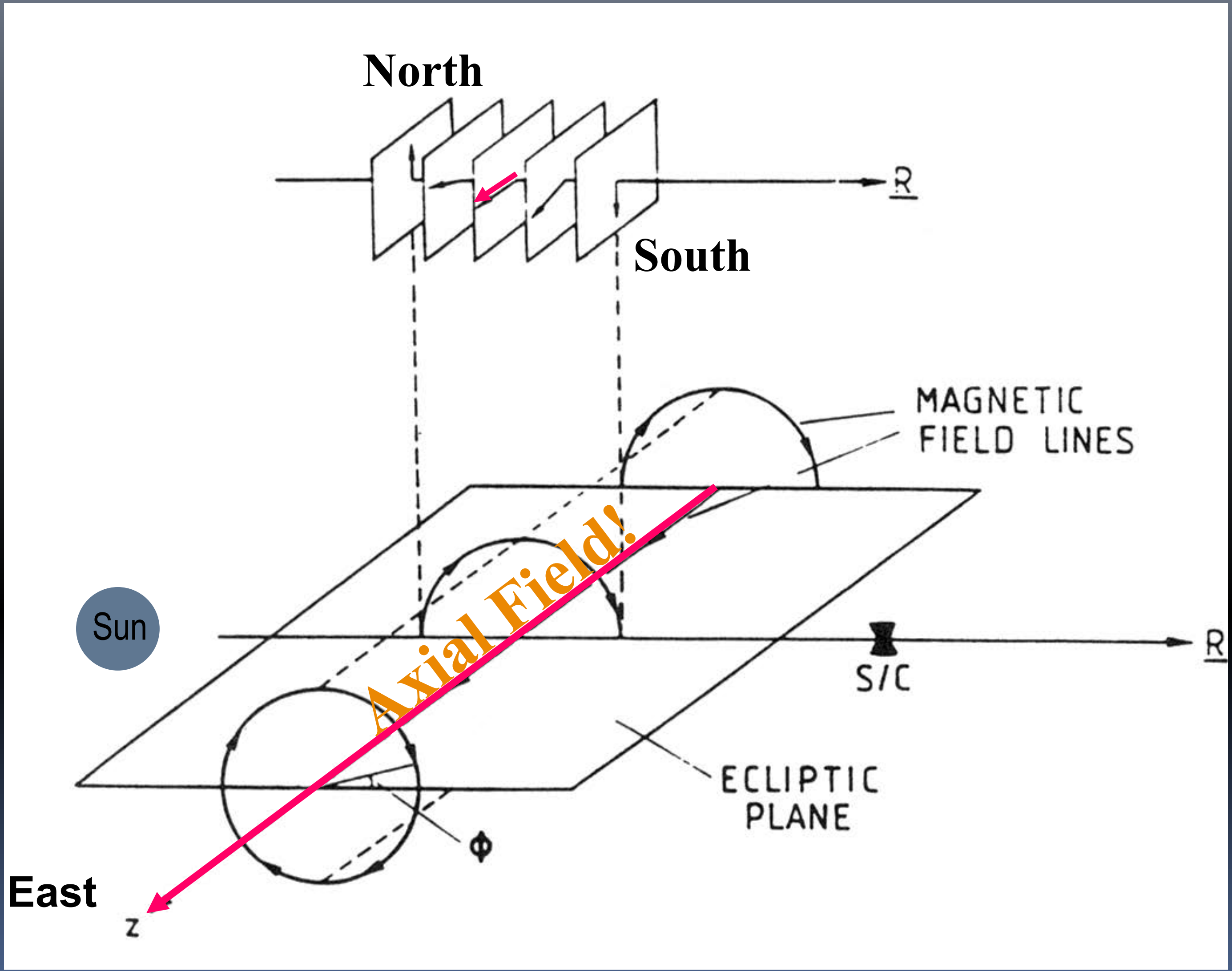
IMF Polar (NS) Direction

IMF Azimuthal (EW) Direction

IMF Strength

*Bothmer, Solar Wind 9, 119-126, 1999*

# Explanation for the Magnetic Structure of a CME in the Solar Wind




In Principal,

the Cylinder can

be Arbitrarily

Inclined

with Respect

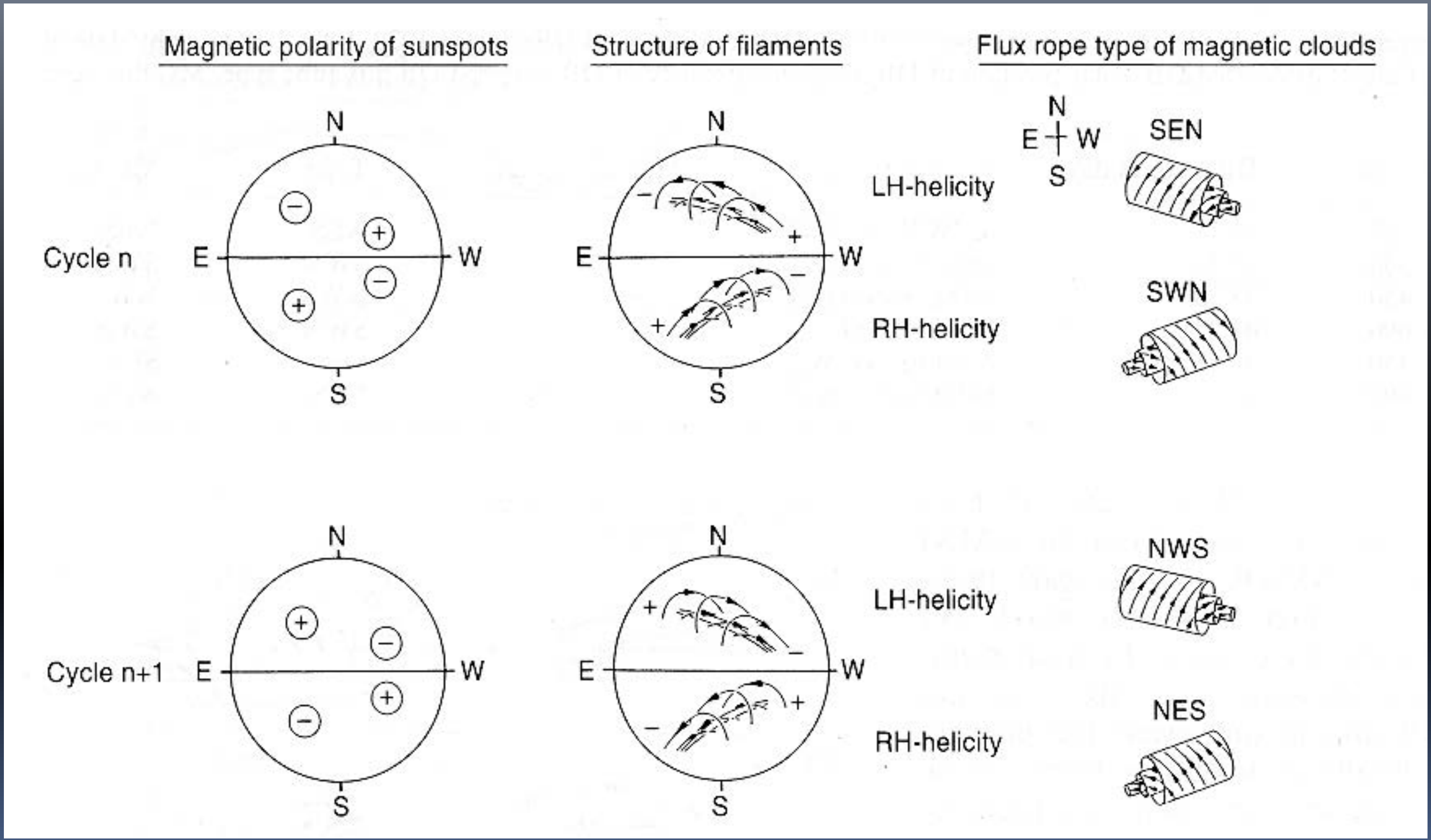
to the

Observer!

Helical
Structure!

*Goldstein, 1983; Bothmer & Schwenn, Ann. Geophys., 16, 1-24, 1998*

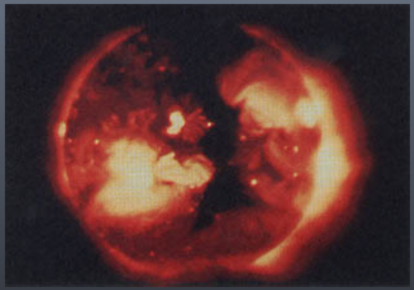
# The B&S Scheme for FR CMEs



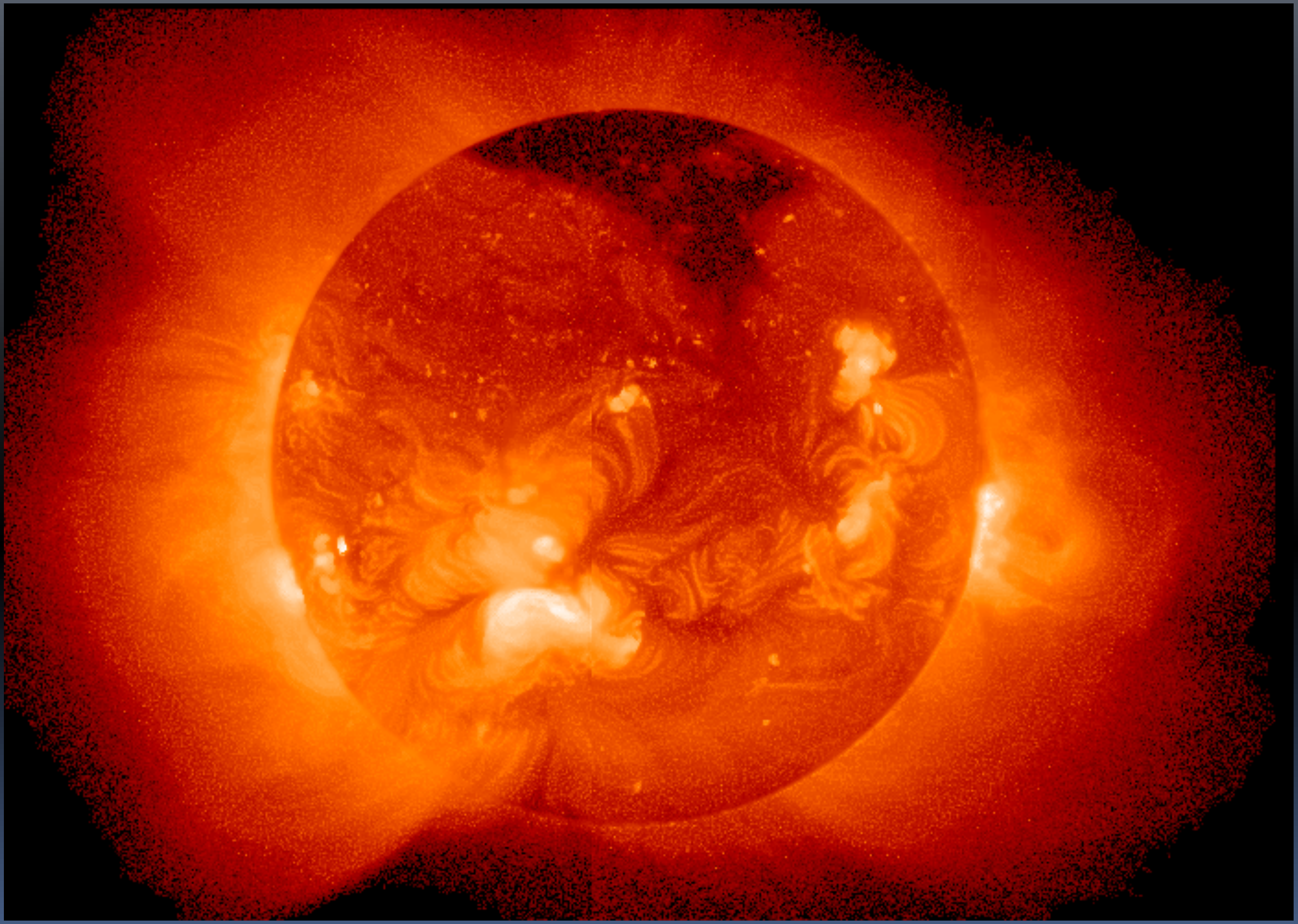

Quadrupolar Fields not Included

Bothmer & Schwenn, 1998

# The Sun's hot outer atmosphere, the EUV corona, is only visible from space

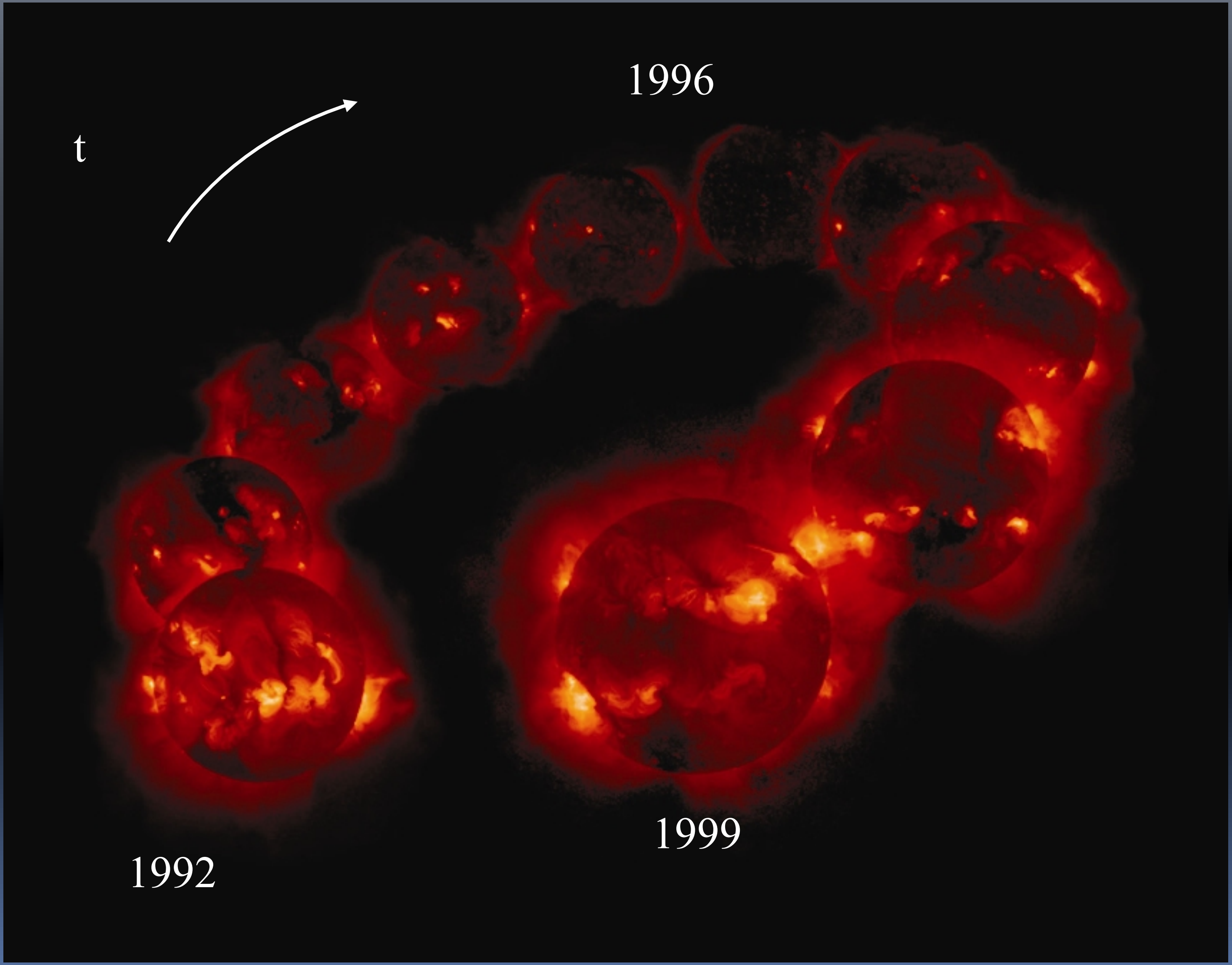


SKYLAB 1974



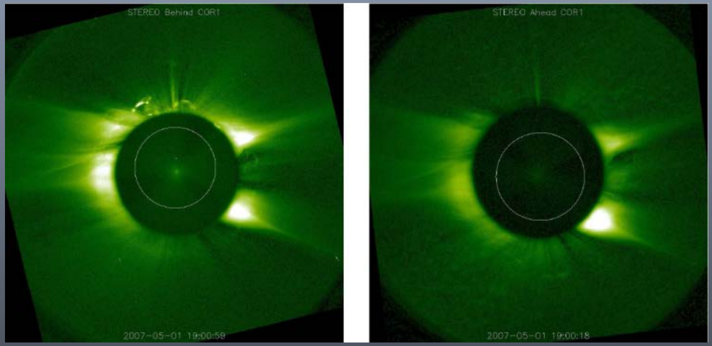
Yohkoh/SXT, 1992 August 26, 2 S/C pointings (E & W), 3-5 Million K

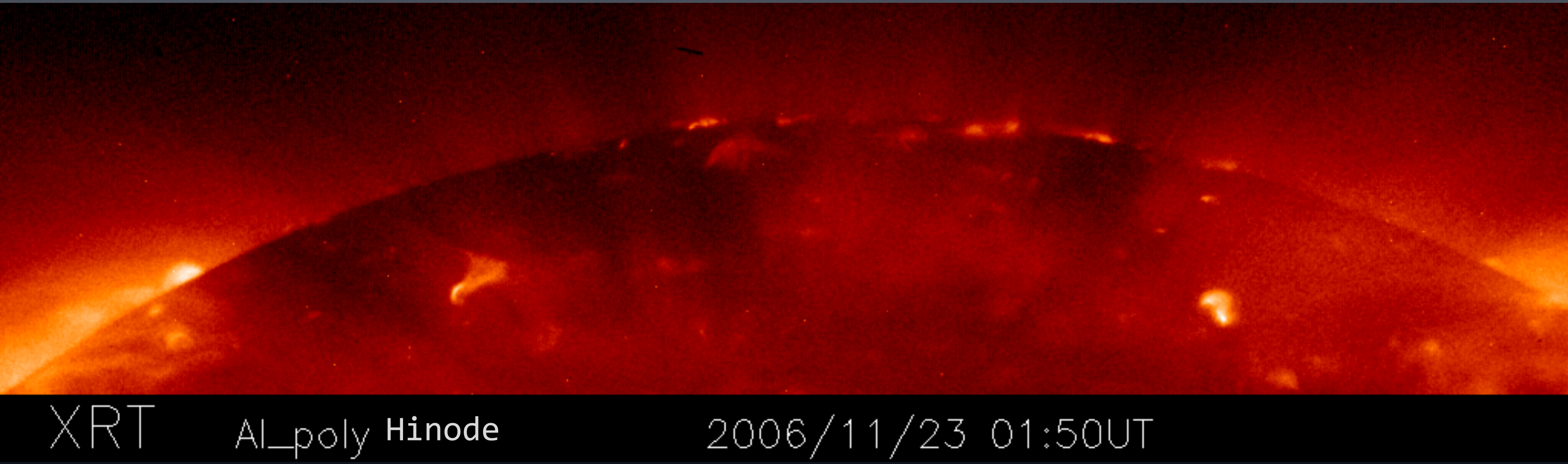
# Solar cycle variation of the Sun's soft X-ray (0.25-4 keV) intensity (a factor of ~ $10^2$): Yohkoh 92-99



# Coronal Jets as Manifestations of Photospheric Variability on Small-Scales

Missions to achieve observations at new scales: Hinode, Solar Orbiter

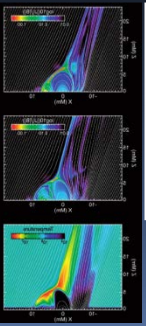


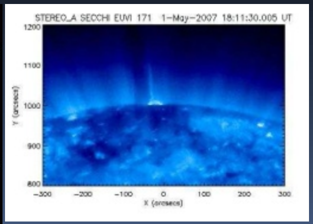




Reconnection

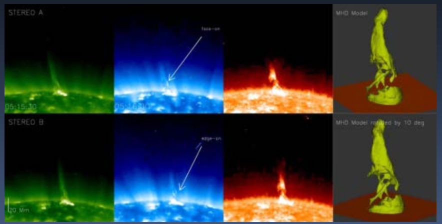
Untwisting

Small-Scale CMEs

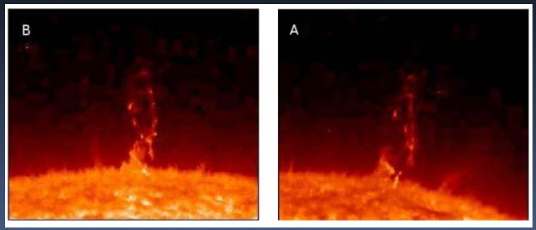




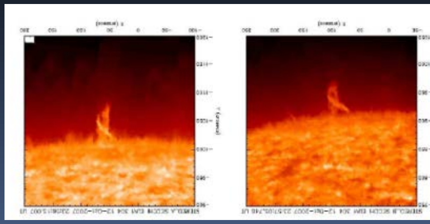

Nisticò et al. (2009)



Patsourakos et al., ApJ L. (2008); Pariat et al. (2008)




Nisticò et al. (2009)

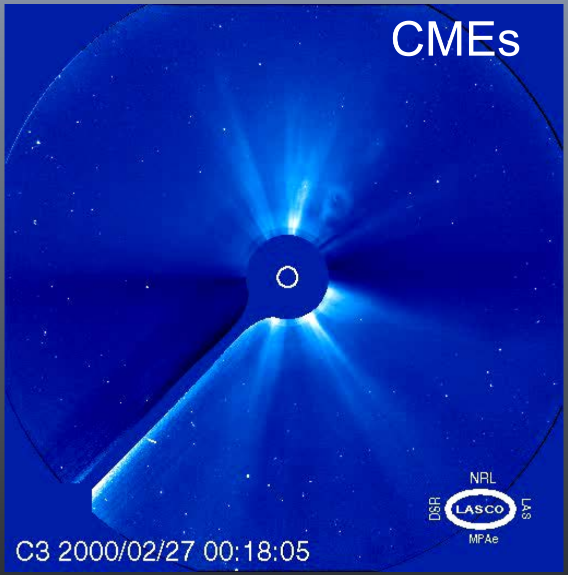


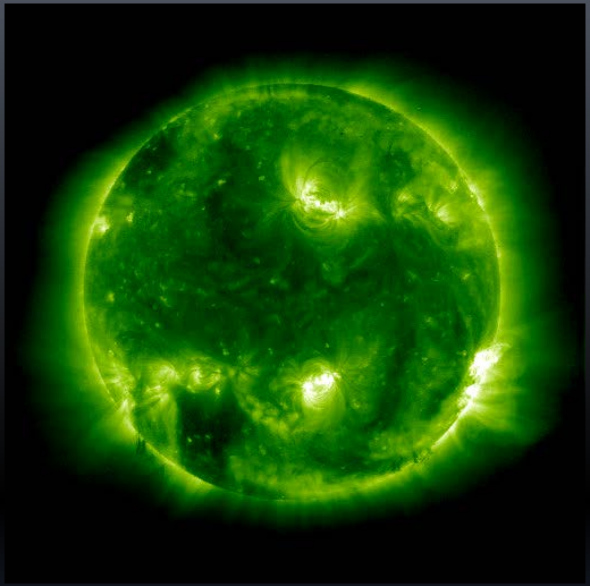
Bothmer and Nisticò (2009); Innes et al. (2008)

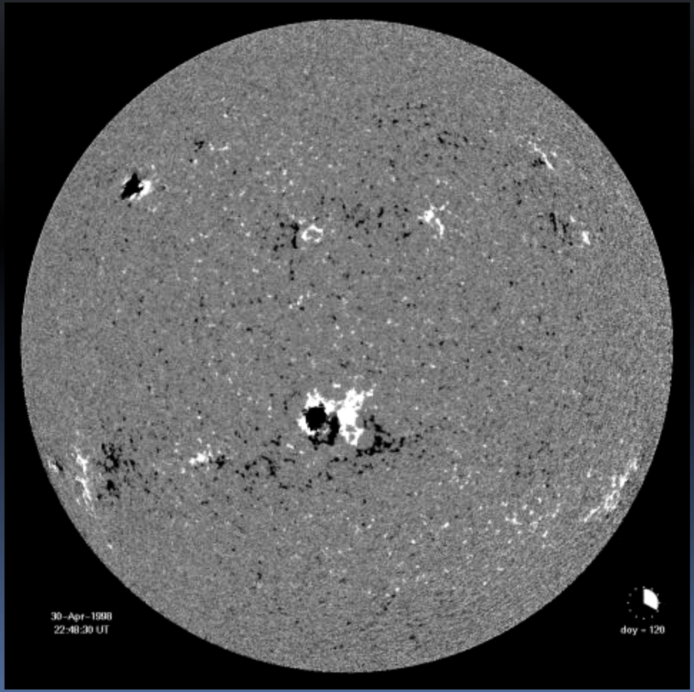
Moreno Insertis et al. (2008); Yokoyama & Shibata (1996)

STEREO high res. Campaign, 171 Å, 75 seconds

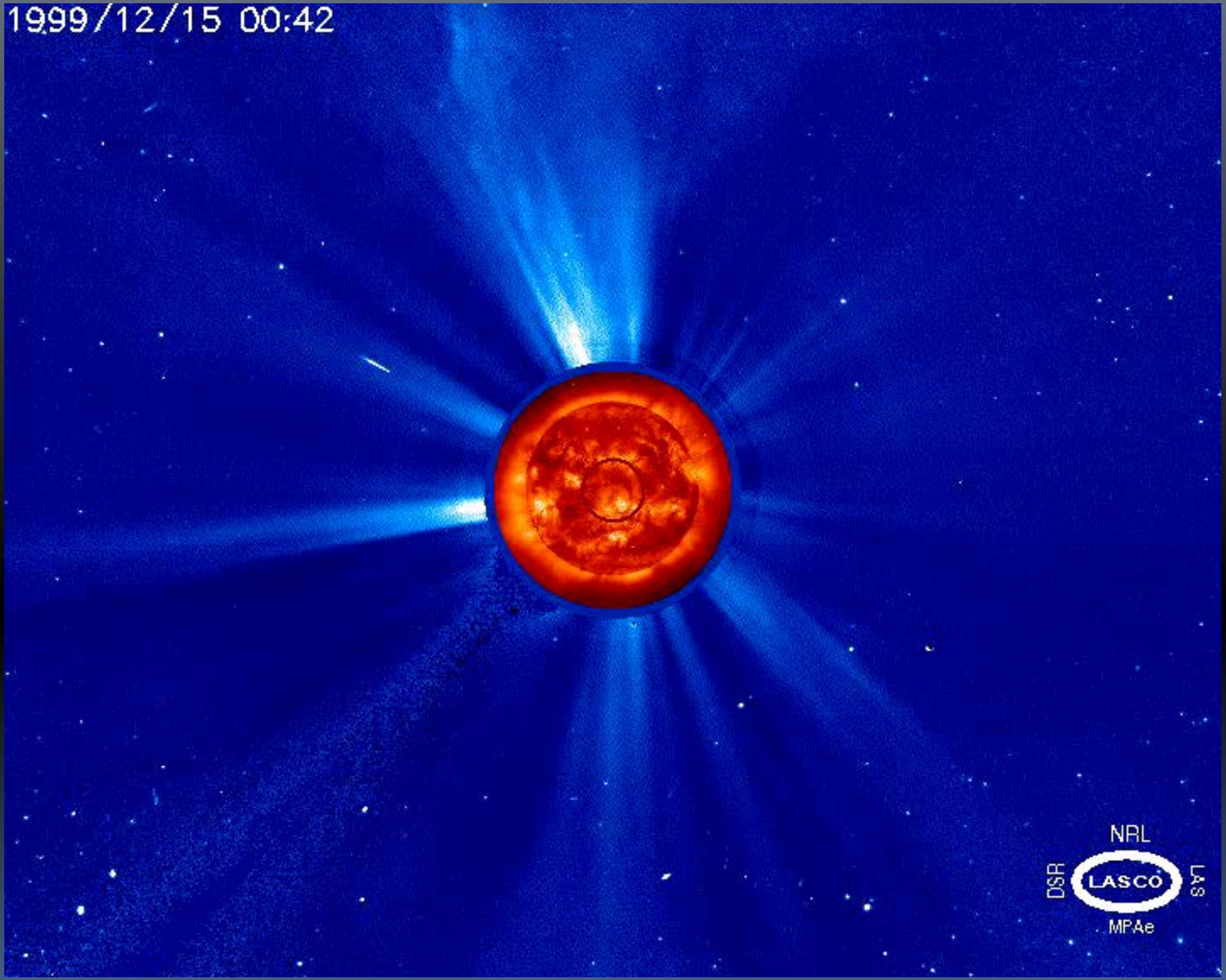
# The variable magnetic field of the Sun is the driver of solar activity and coronal structure





# The Dynamic Corona Observed with SOHO/LASCO/EIT - December 1999 to January 2000



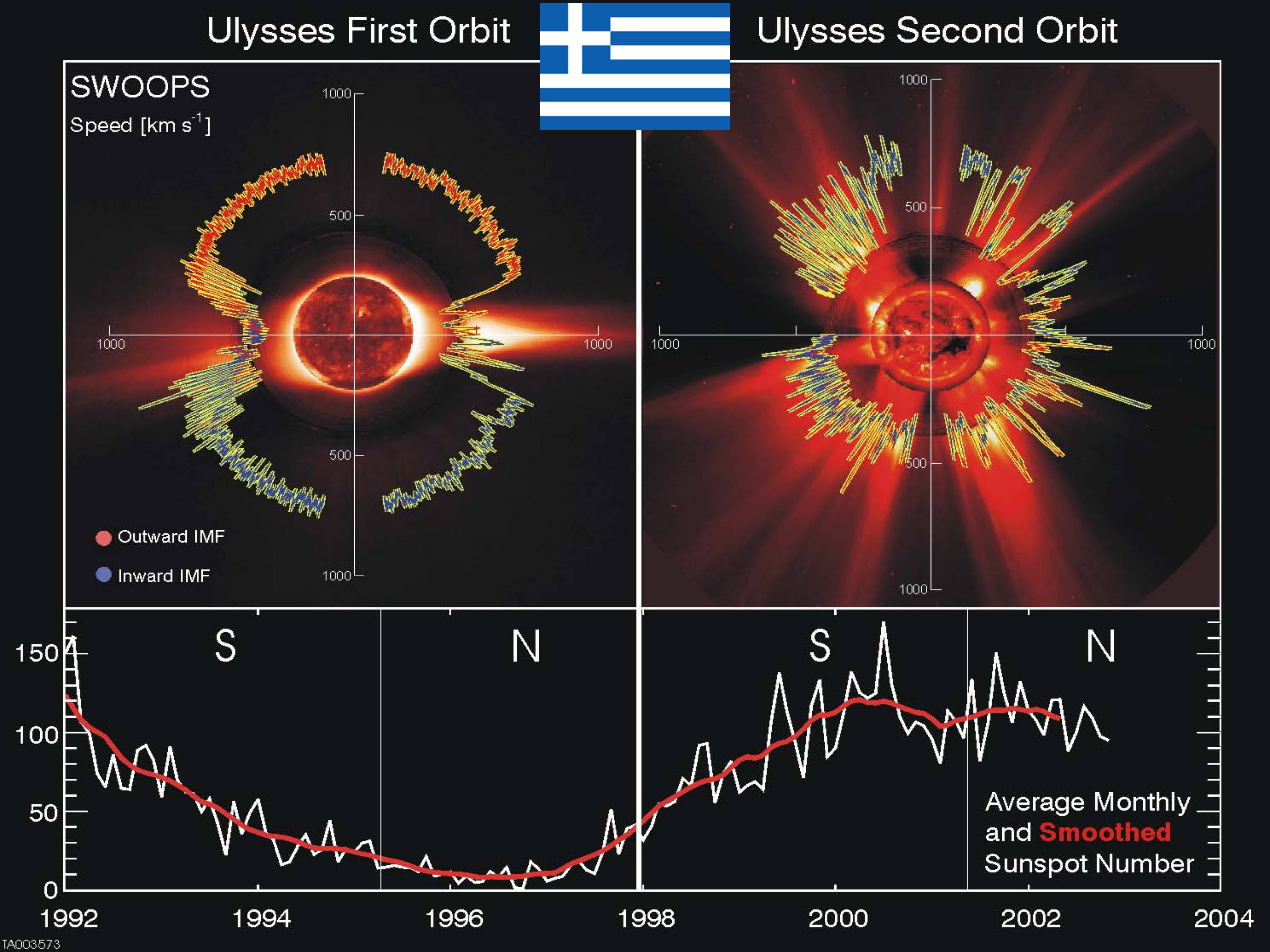

SOHO has observed >10.000 CMEs during 1996-2007.

Coronal Mass Ejections (CMEs) occur on variable spatial- and time-scales.

Speeds: 300->3.000 km/s

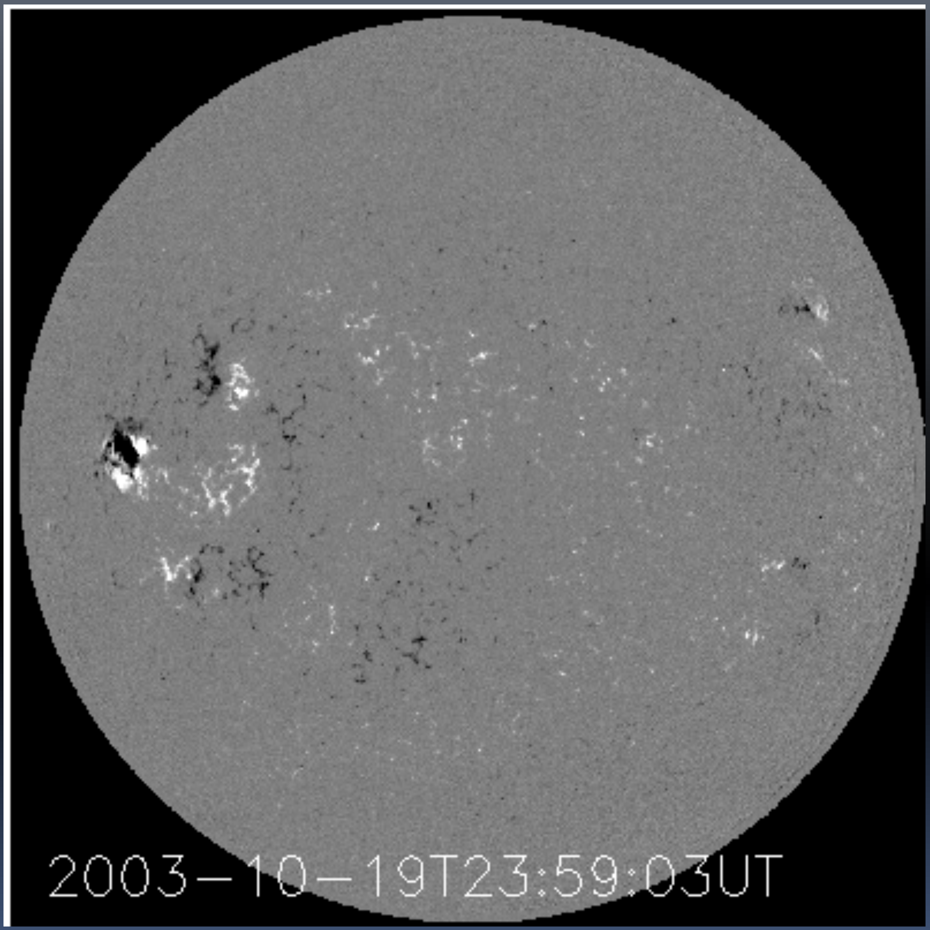
About 50 CMEs with speeds > 3.000 km/s per cycle

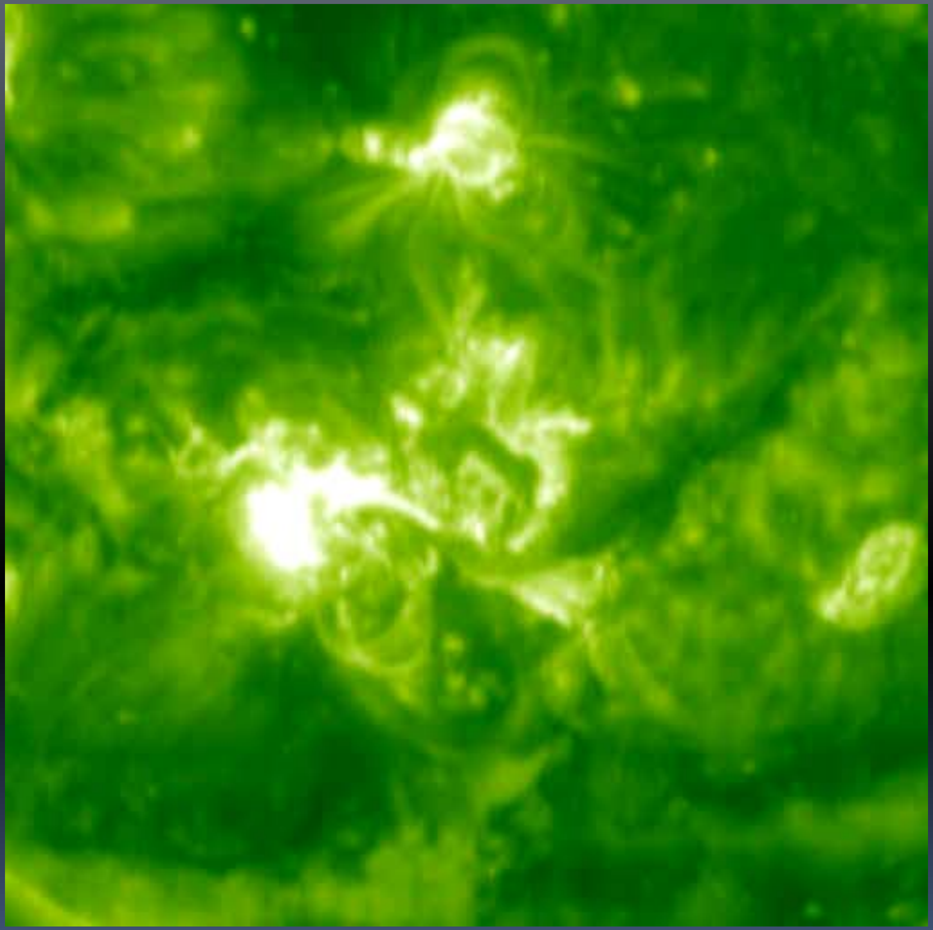
Courtesy: B. Podlipnik



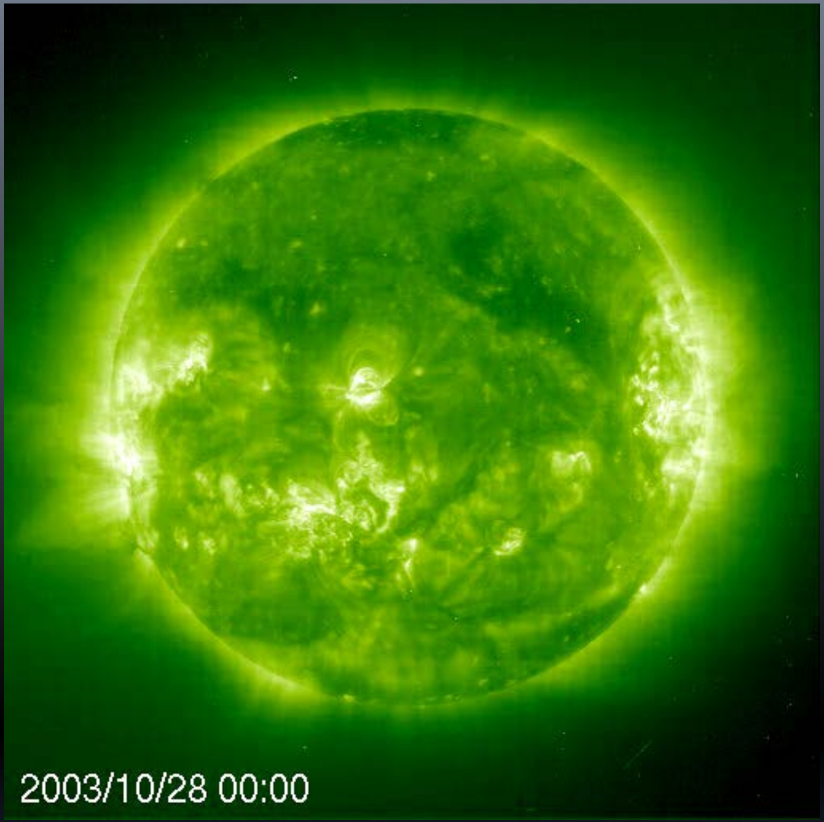
Ulysses First Orbit
Ulysses Second Orbit
SWOOPS
Speed [km s-1]
1000
500
500
1000
1000
1000
Outward IMF
Inward IMF
1000
500
500
1000
1000
1000
S
N
S
N
150
100
50
0
1992
1994
1996
1998
2000
2002
2004
Average Monthly
and Smoothed
Sunspot Number
TA003573

# Solar photospheric magnetic field can evolve dramatically in a few hours – October 2003



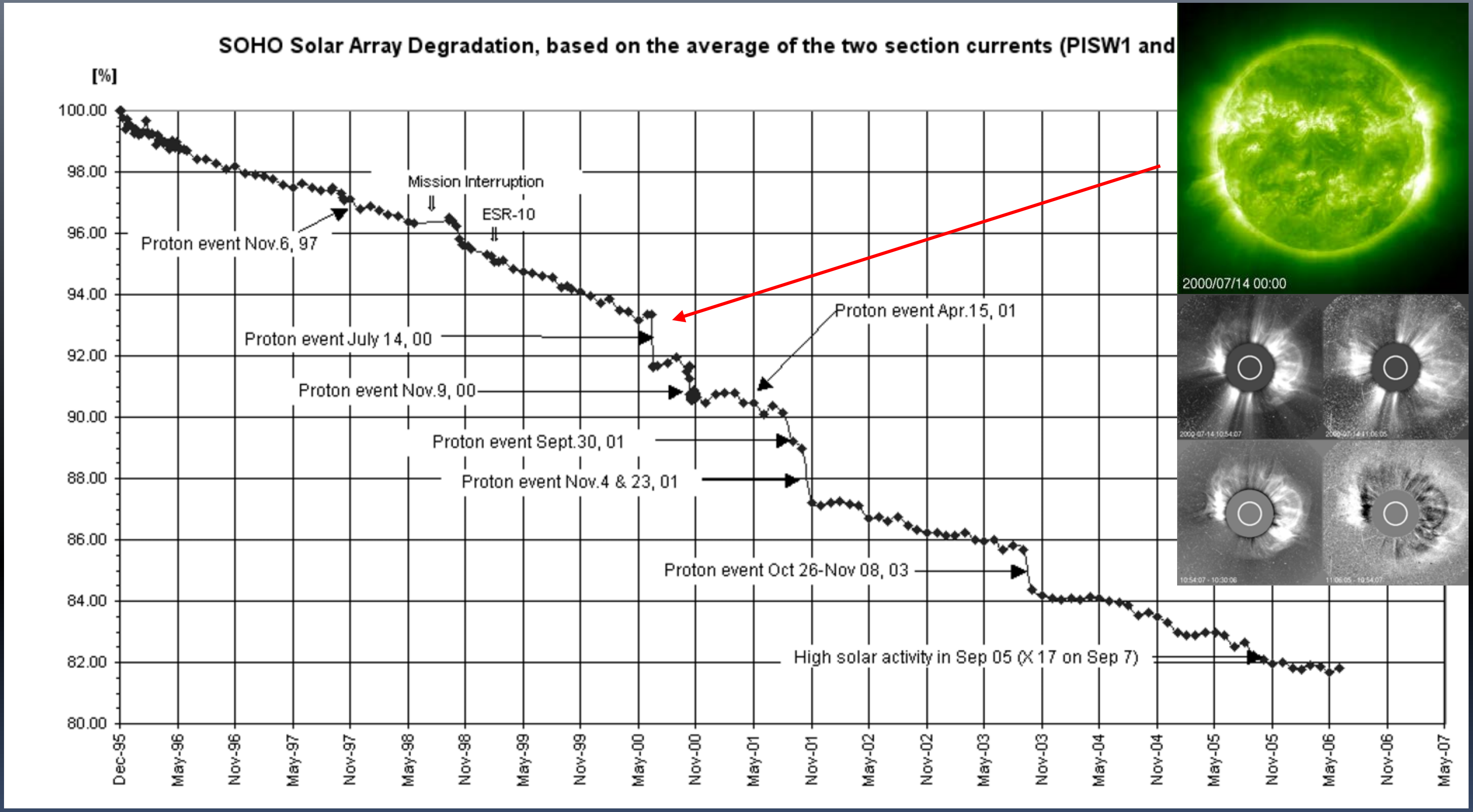



# Strong Flare/CME/SEP event on 28 October 2003, SOHO/EIT 19.5 nm




## Radiation Hazard to Astronauts, Airline Crews and Passengers

# SEP effects on SOHO solar cells



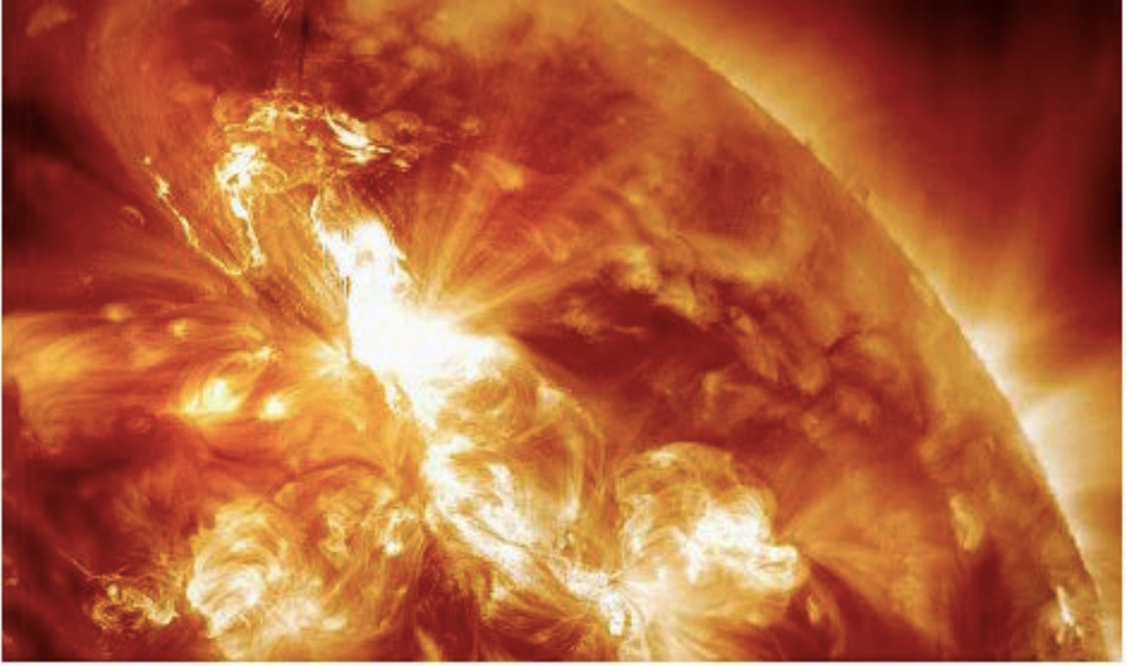

SEPs cause problems for stat trackers, electronic devices (e.g. Nozomi)

Brekke et al., 2006

# Space Weather on Mars


- Human radiation hazards due to solar energetic particles (SEPS) and cosmic rays (CRs)
- Effects of SEPs and CRs on solar cells and electronic devices
- Effects of dust particles on solar cells

# Space Weather Effects of Radio Waves



A solar flare erupting from the sun. Photo: AP Photo/NASA

## 'Solar storm' grounds Swedish air traffic

Published: 04 Nov 2015 17:01 GMT+01:00
Updated: 04 Nov 2015 17:25 GMT+01:00

Share Tweet Share reddit

**Planes were grounded at some of Sweden's busiest airports on Wednesday afternoon because of a "solar storm" interfering with air traffic control radar systems, authorities said.**

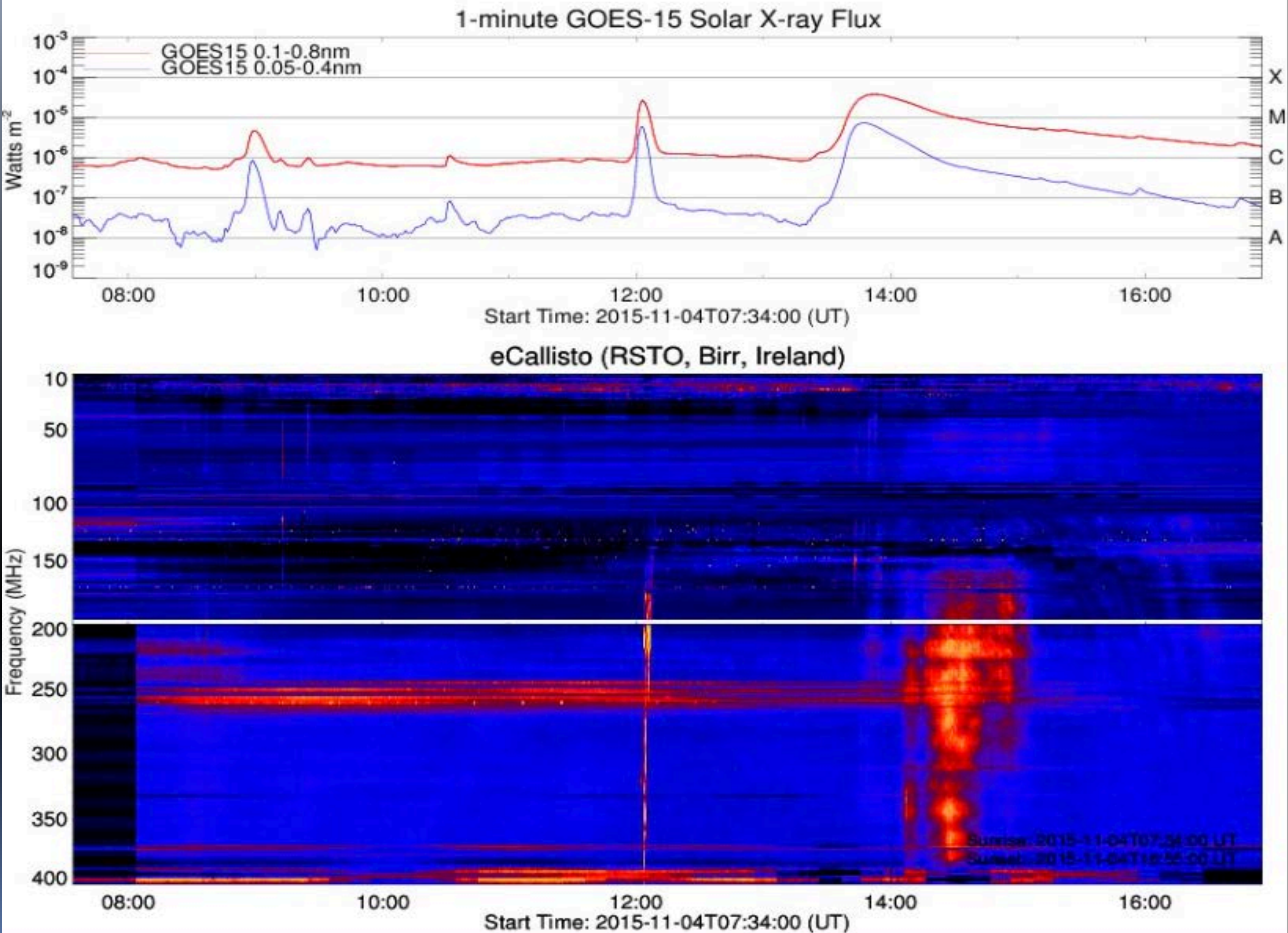
No aircraft were allowed to take off from airports in southern and central Sweden due to a massive geomagnetic solar flare storm causing problems for radar systems.

Ulf Wallin, press spokesperson at Swedavia, the organization managing Sweden's airports, told TT that airports at Landvetter in Gothenburg and Arlanda and Bromma in Stockholm were affected.

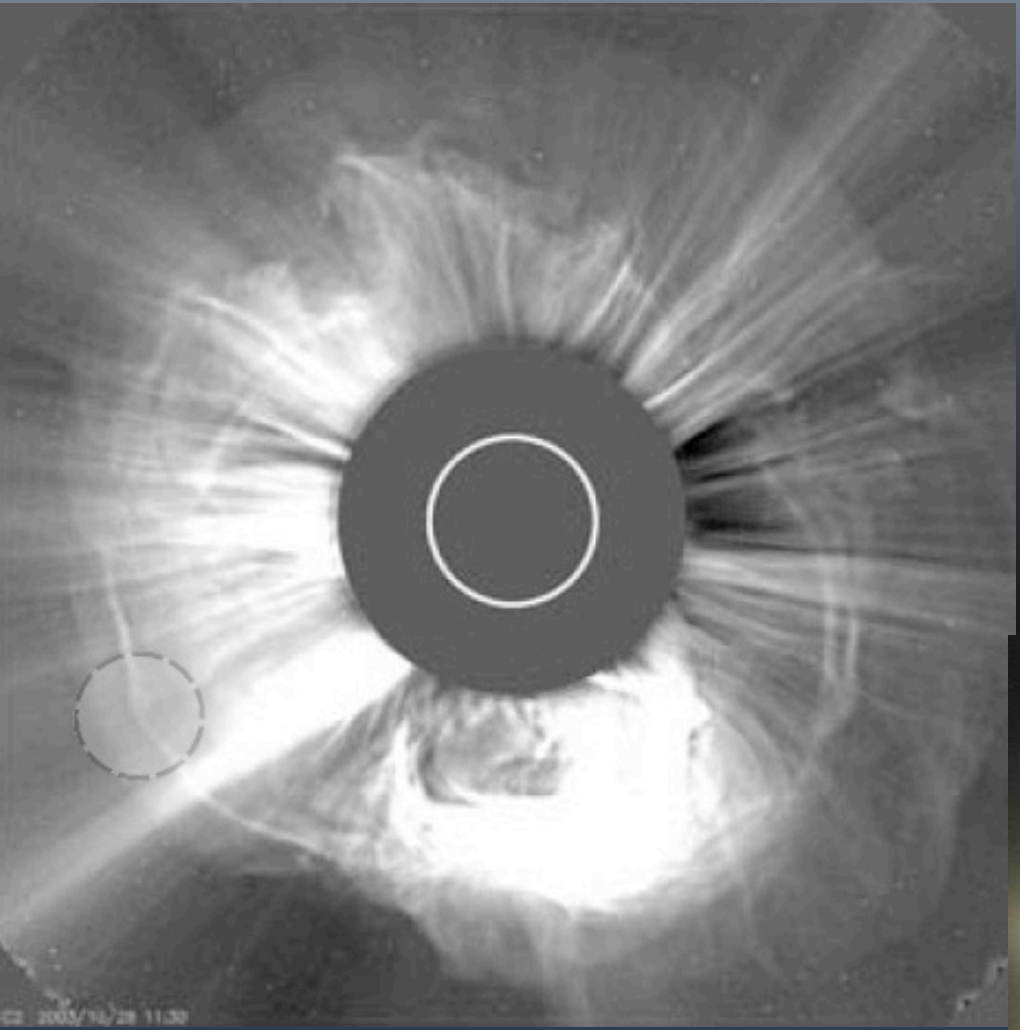
"Those airplanes that are in the air are allowed to land at the airports they're going to, but no planes are taking off," he said.

The problems began at around 3.30pm on Wednesday. An hour later, traffic had begun to return to normal, but it was not known when airports would be operating at full capacity again, said Per Fröberg, press spokesperson for Luftfartsverket, responsible for air traffic control in Sweden.

"[The solar storm] has meant that we haven't been able to see the airplanes on our radar screens. We are starting to get the systems up and running again but it's unclear when everything will be back to normal," he told the Aftonbladet tabloid.


1-minute GOES-15 Solar X-ray Flux
GOES15 0.1-0.8nm
GOES15 0.05-0.4nm
Watts m$^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
$10^{-8}$
$10^{-9}$
X
M
C
B
A
08:00
10:00
12:00
14:00
16:00
Start Time: 2015-11-04T07:34:00 (UT)
eCallisto (RSTO, Birr, Ireland)
Frequency (MHz)
10
50
100
150
200
250
300
350
400
08:00
10:00
12:00
14:00
16:00
Start Time: 2015-11-04T07:34:00 (UT)

# The associated CME observed with SOHO/LASCO/C2

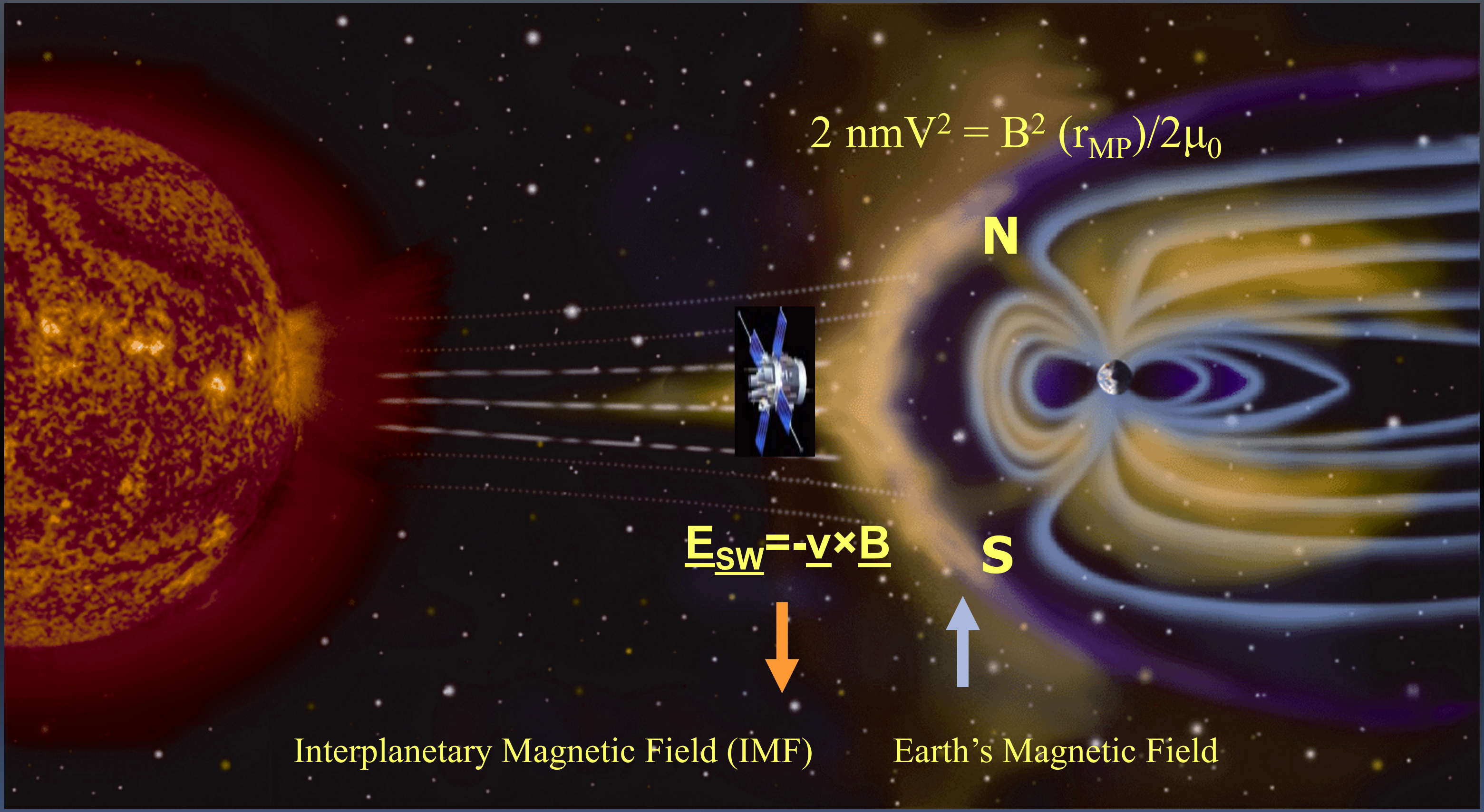


Halo CME
V ~ 3000 km/s

Tropospheric Halo

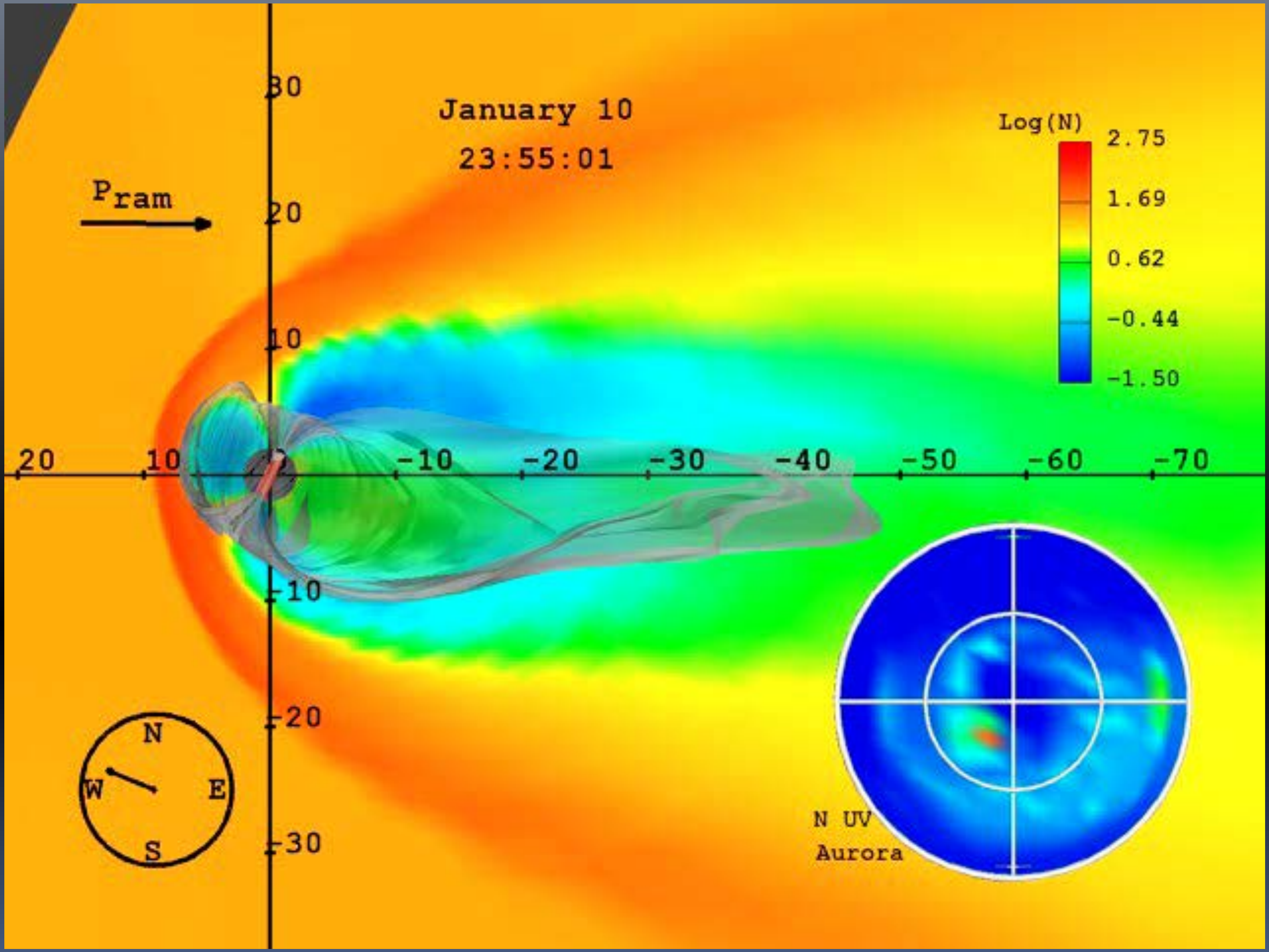
# Increased Geomagnetic Activity Requires Magnetic Reconnection Processes

Distance Sun – Earth = 1 AU ≈ 150 Million Kilometers




„Magnetic Reconnection“

# Solar Wind Impact on Earth‘s Magnetosphere

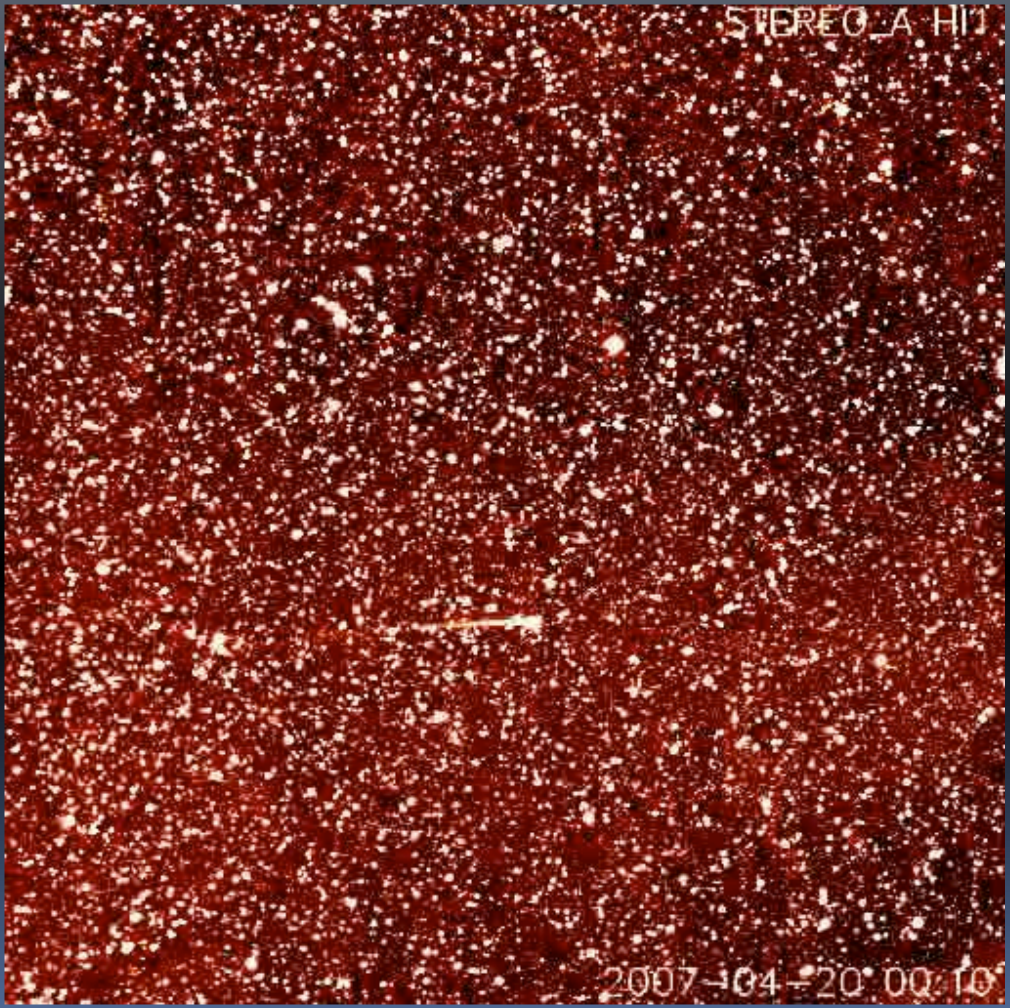



Goodrich et al. 1997

# Comet Encke – Tail disruption through CME impact - HI 1 A, 20$^{th}$ April 2007

**Period: 3.3 Years; Perihel: 0.338 AU**

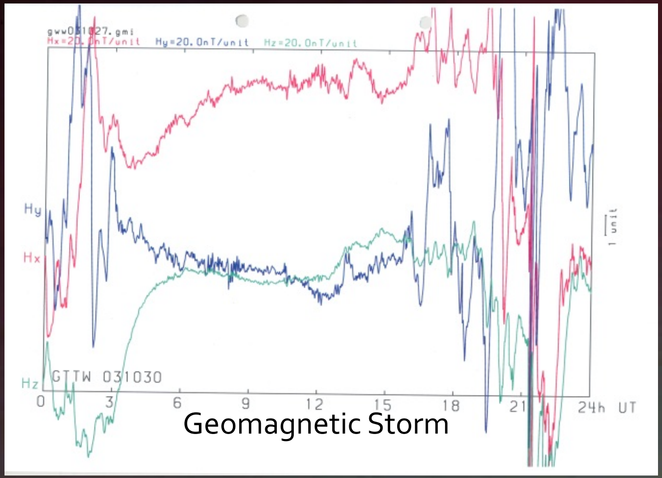
**FOV ~ $42 \cdot 10^6$ km (0.28 AU)**



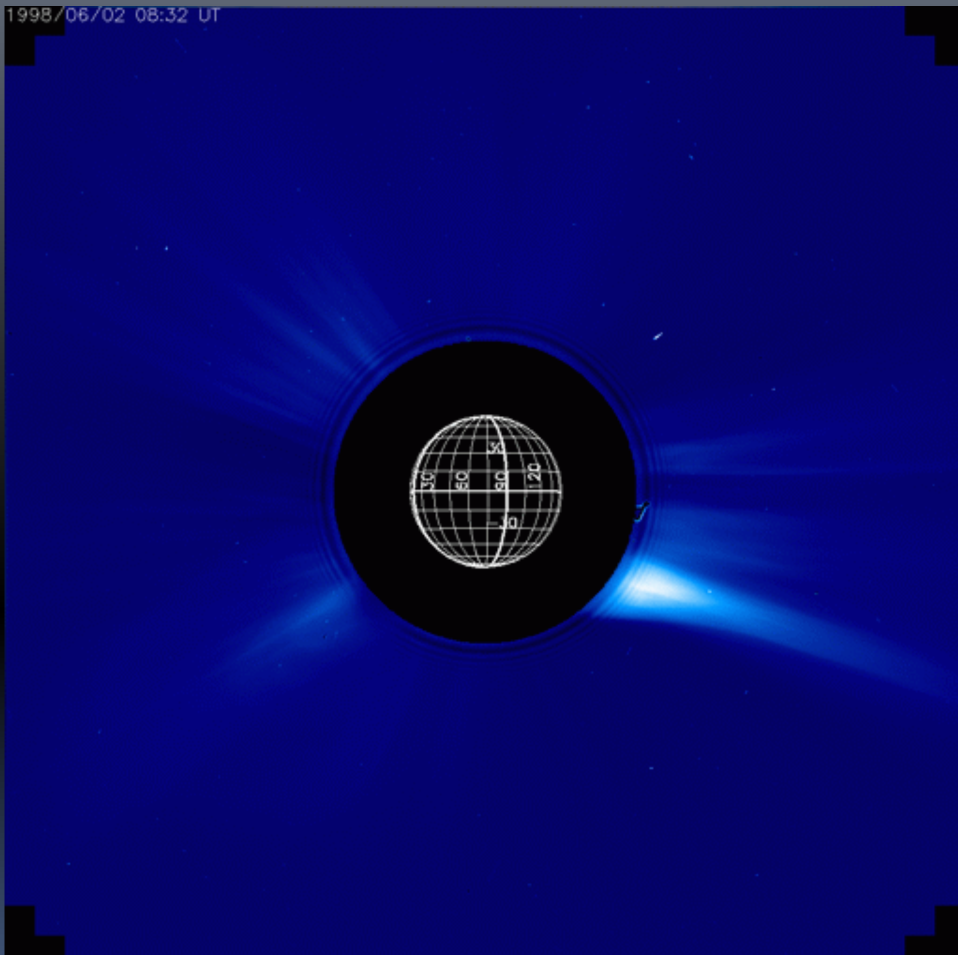

Vourlidas et al., ApJ 2007

Aurora in the sky at Göttingen on 30 October 2003 and associated geomagnetic fluctuations.

- SOHO halo CME alert on 28 October
- Estimated arrival time based on CMEspeed
- Identification of CME arrival in ACE real-time data
- Aurora expected after 10 pm on October 30
- watched in my garden around midnight




# Unprecedented Observations of CMEs with SOHO



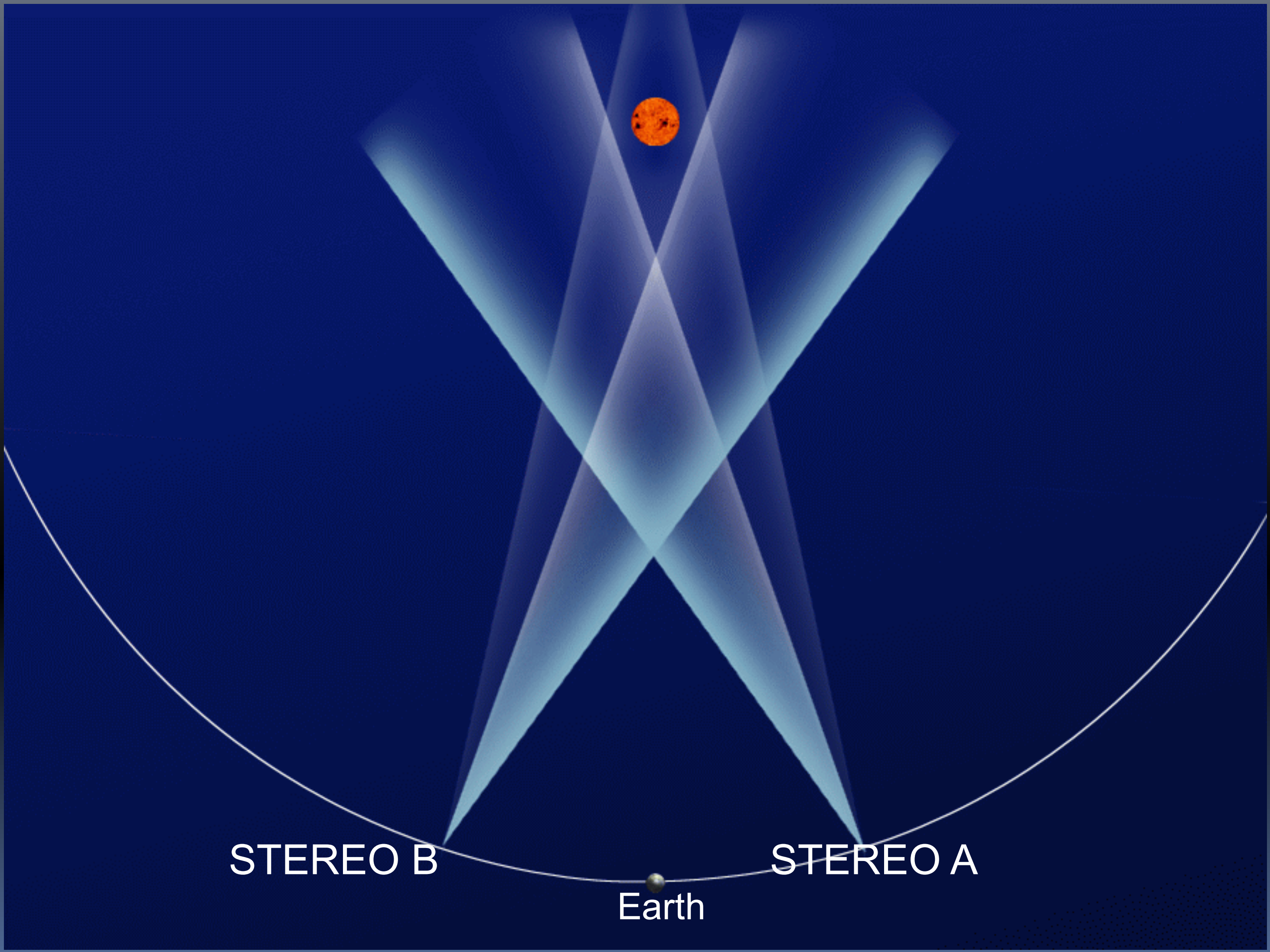

Note the CME's three part structure!

## Basic Properties

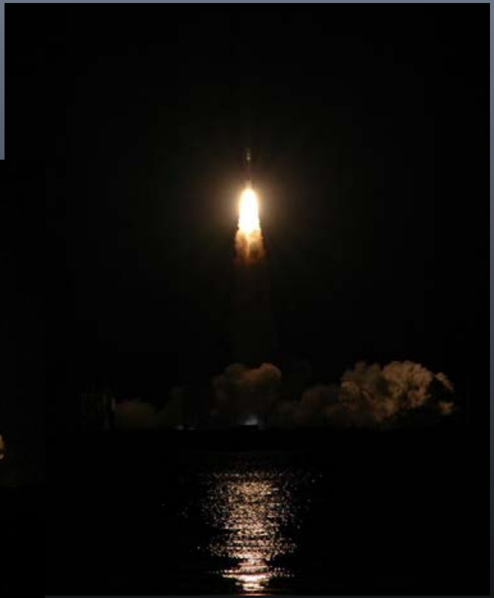
- Frequency:
  - 3.5 Events per Day in Maximum
  - 0.2 Events per Day in Minimum
- Mass: $5x10^{12}$ bis $5x10^{13}$ kg
- Velocities:
- 20 km $s^{-1}$ (sub-sonic) up to over 2500 km $s^{-1}$ (sub-alfvénic)
- CMEs with V>400 km/s cause shocks
- Time until arrival at Earth:

  Hours (>12) to Several Days
- Kinetic Energy: $10^{23}$ to $10^{24}$ J

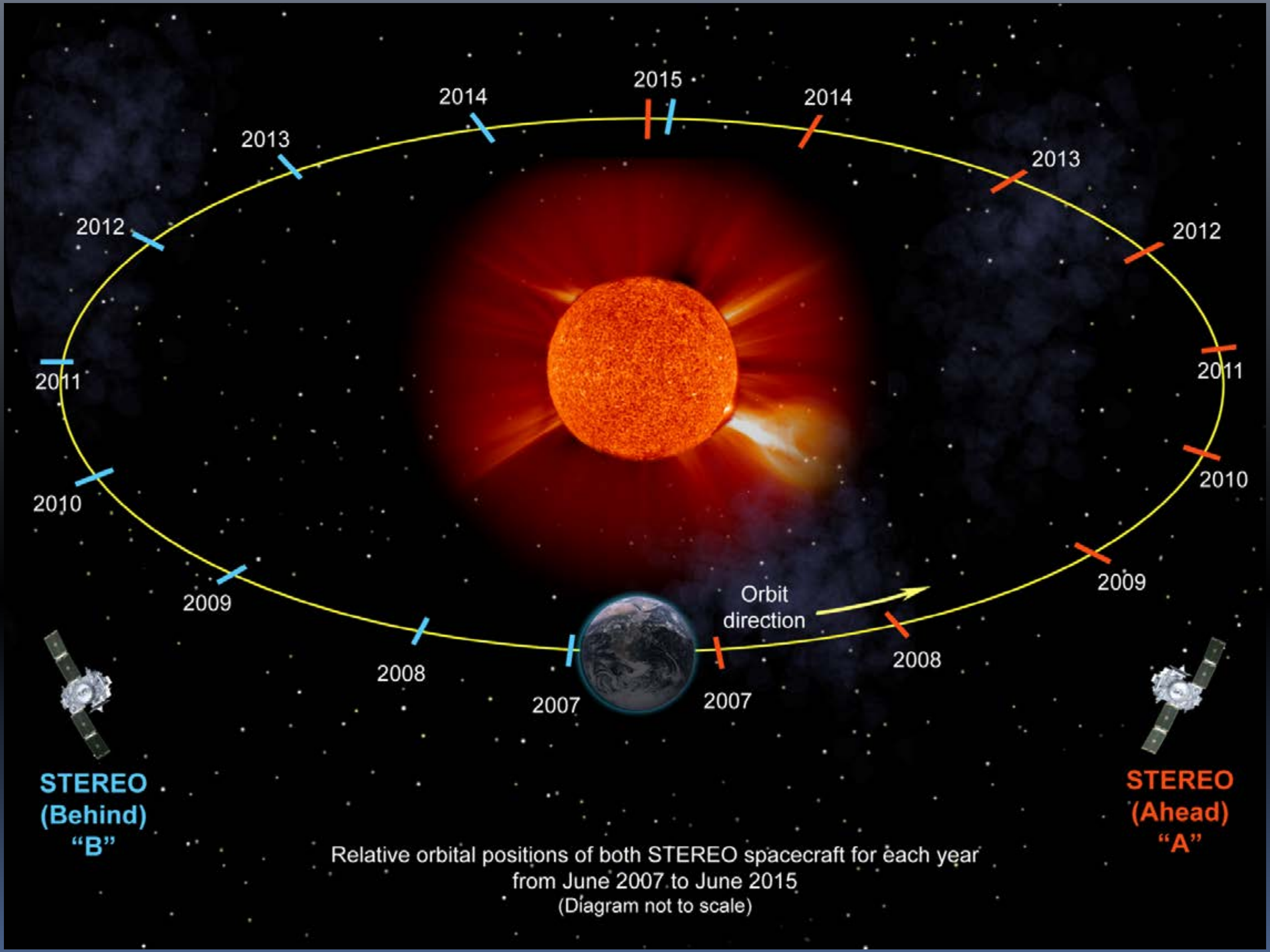
# Stereoscopic Observations of the Sun-Earth System



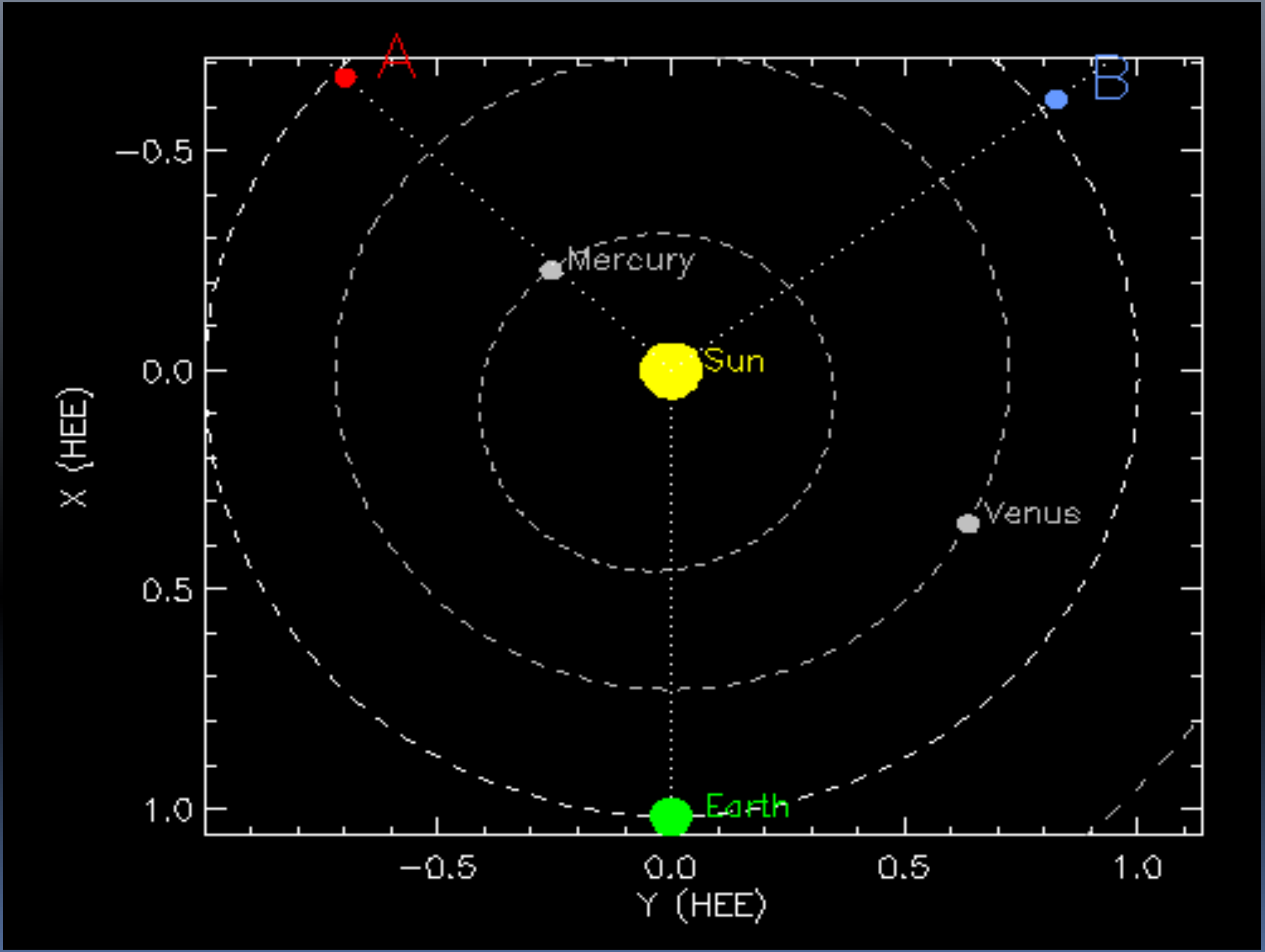
# Launch of STEREO on 25th October 2006, 20:52 L.T.

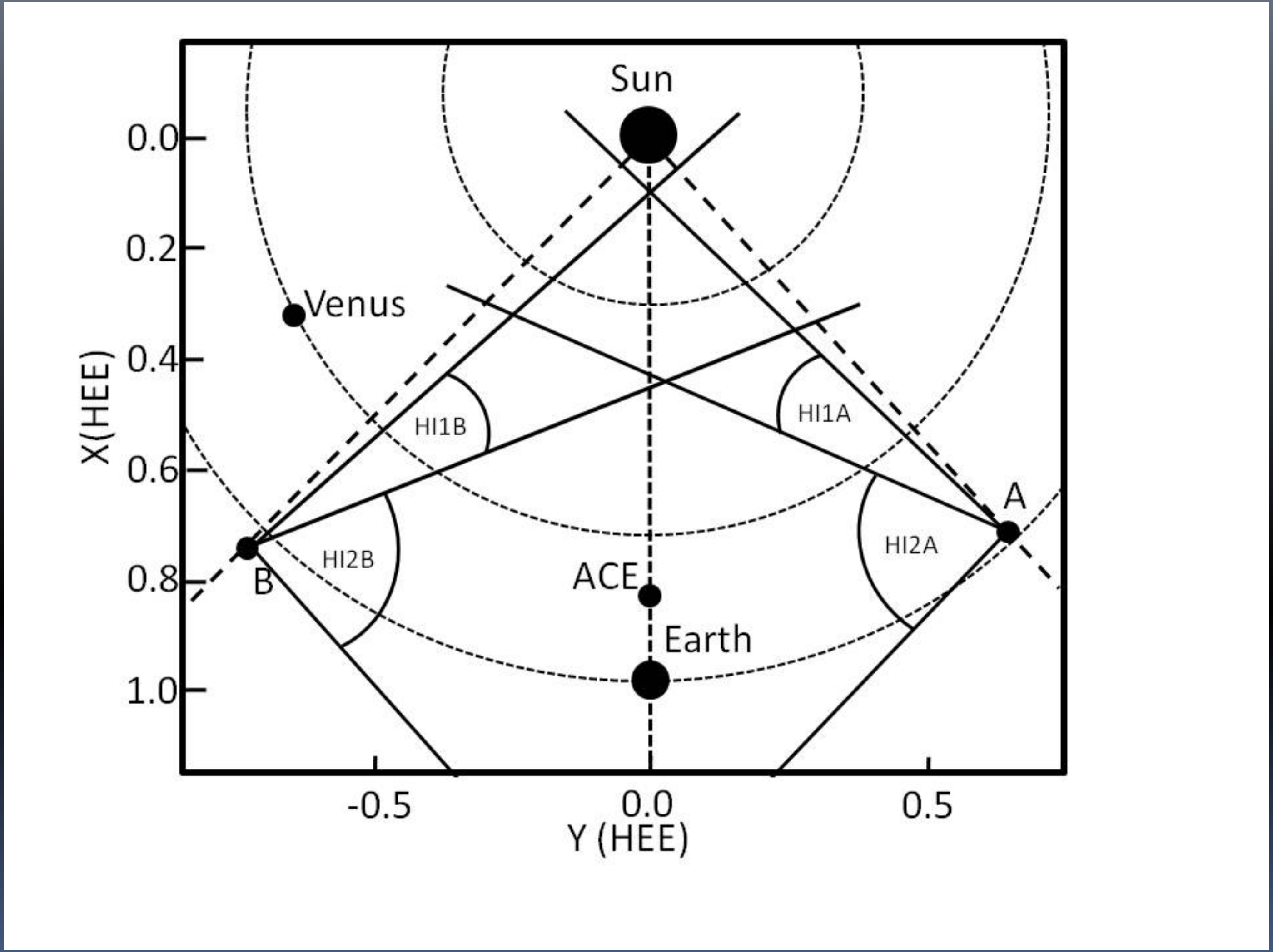
# STEREO Orbit



# Status of STEREO

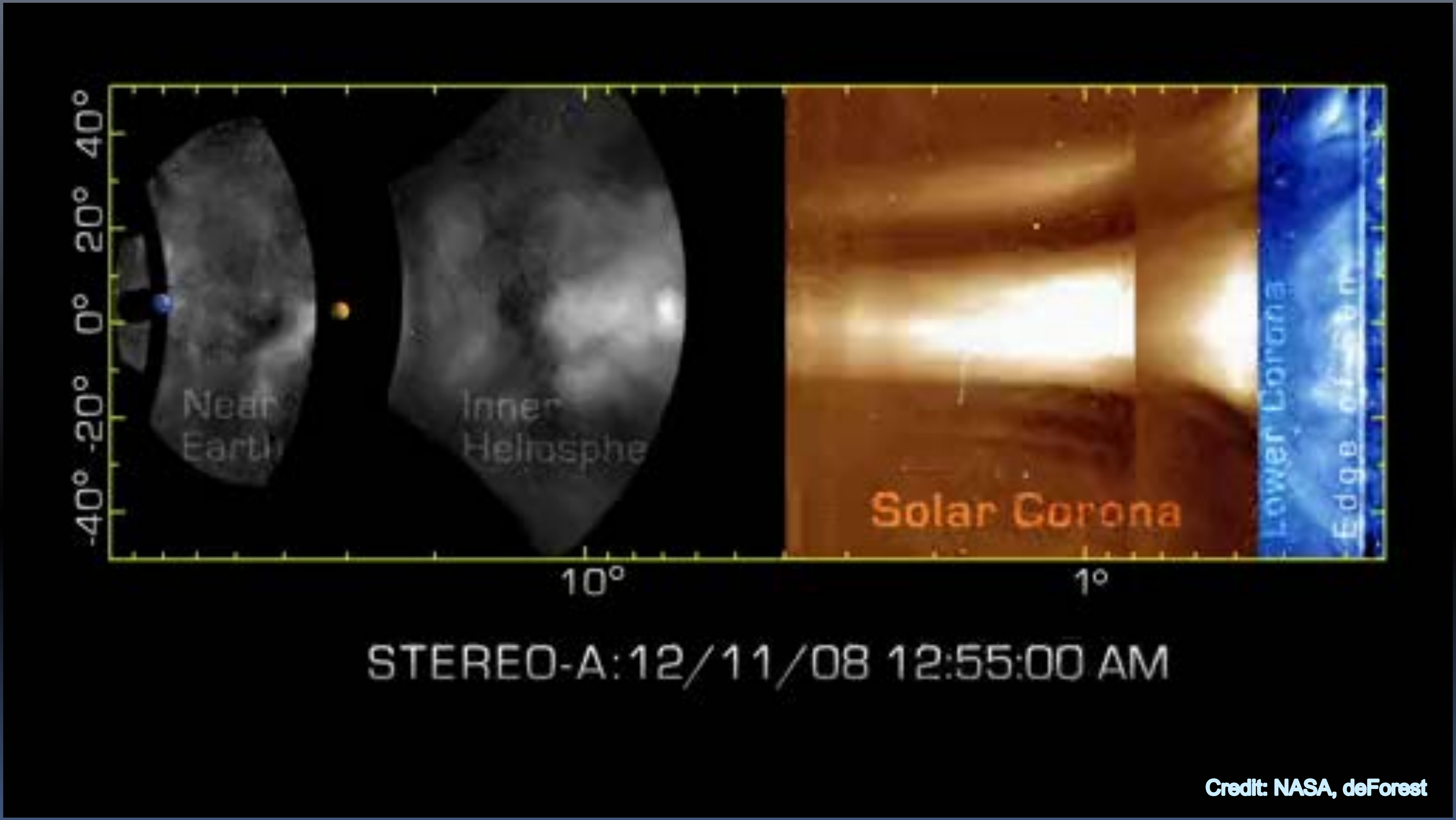


# December 2008 – First CME Tracked All Away Along the Sun-Earth Line

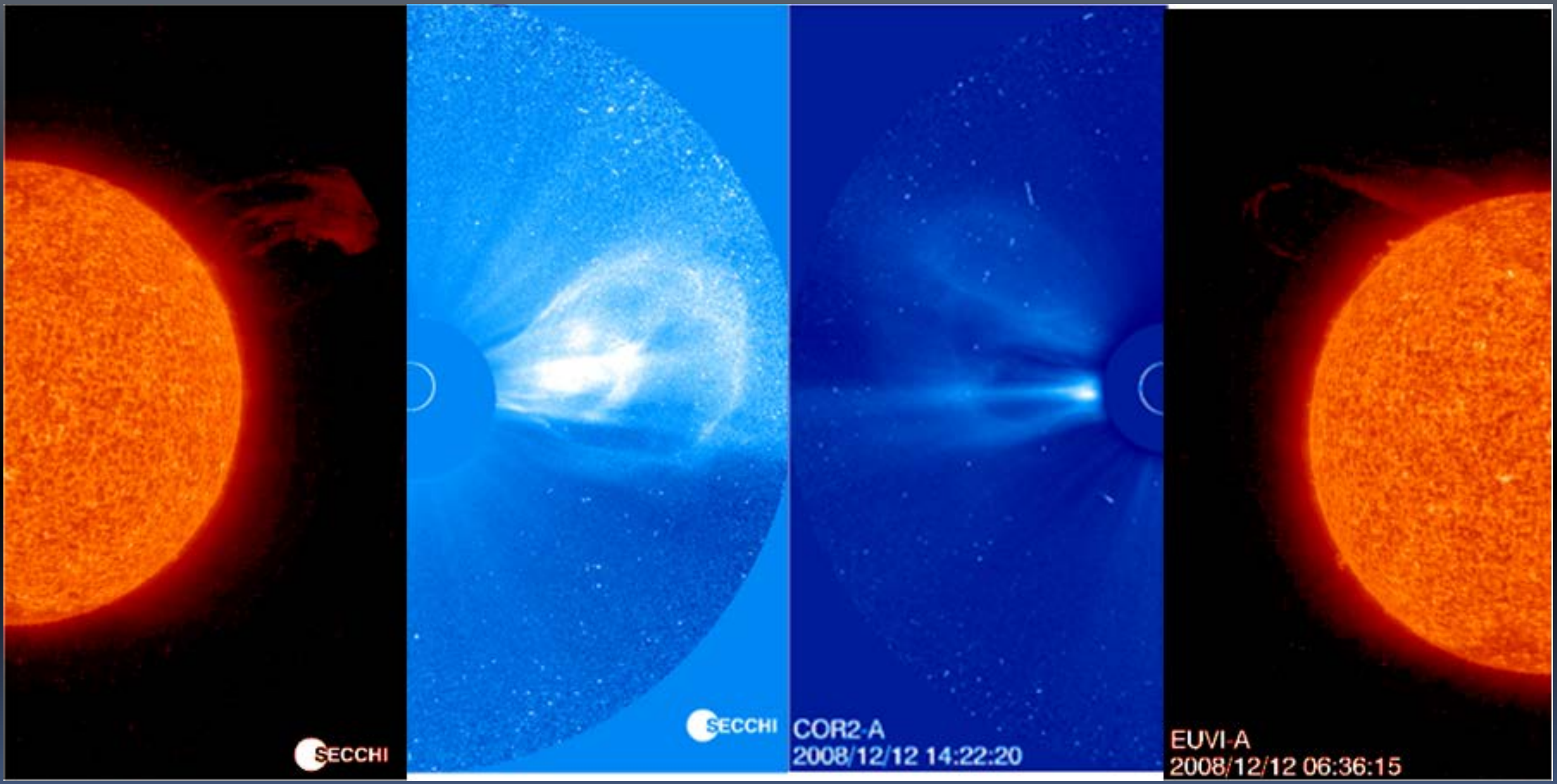



Davis et al., 2009

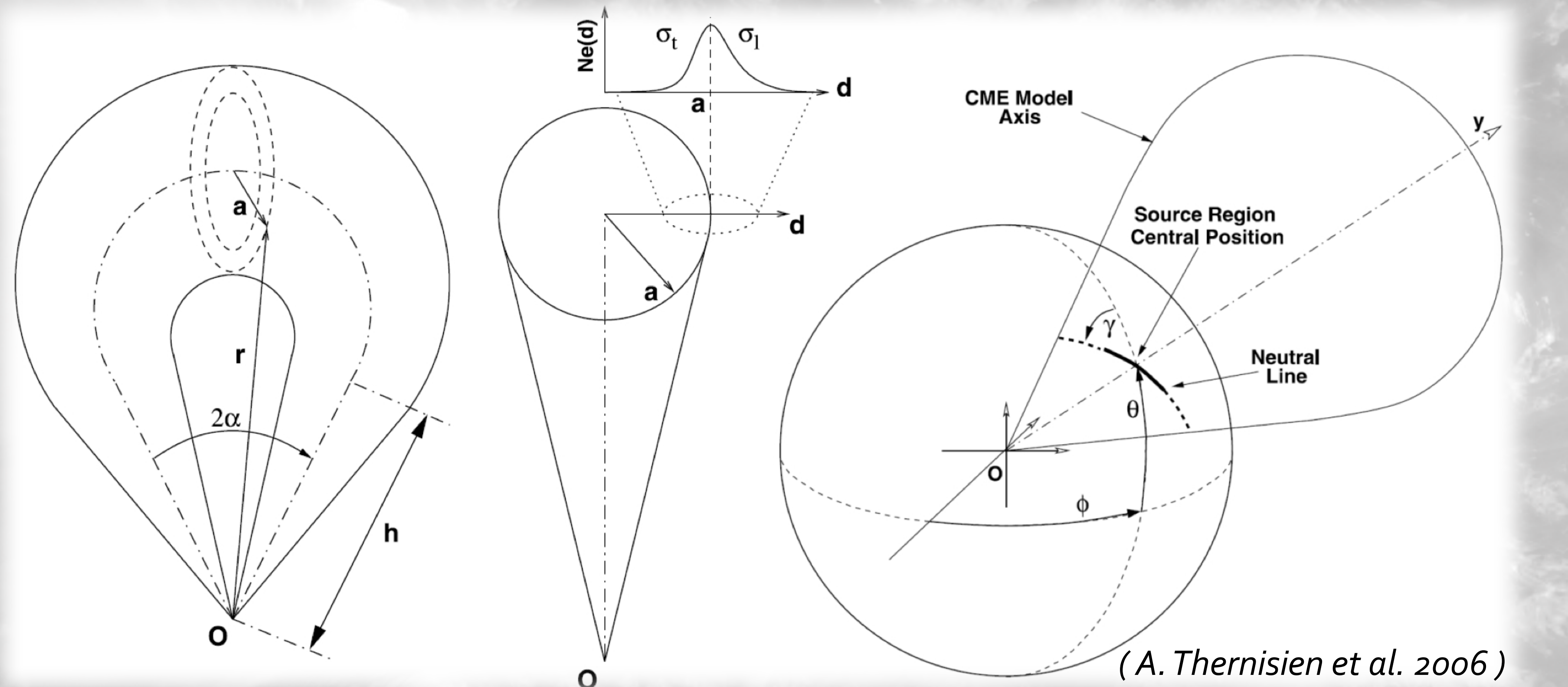
# CME tracked Sun to Earth



# STEREO SECCHI/EUVI A, B 304 Å and COR 2 A, B Observations



# The Graduated Cylindrical Shell Modell




*( A. Thernisien et al. 2006 )*

## Position on Sun:

*Longitute:* ϕ; *Latitude:* θ

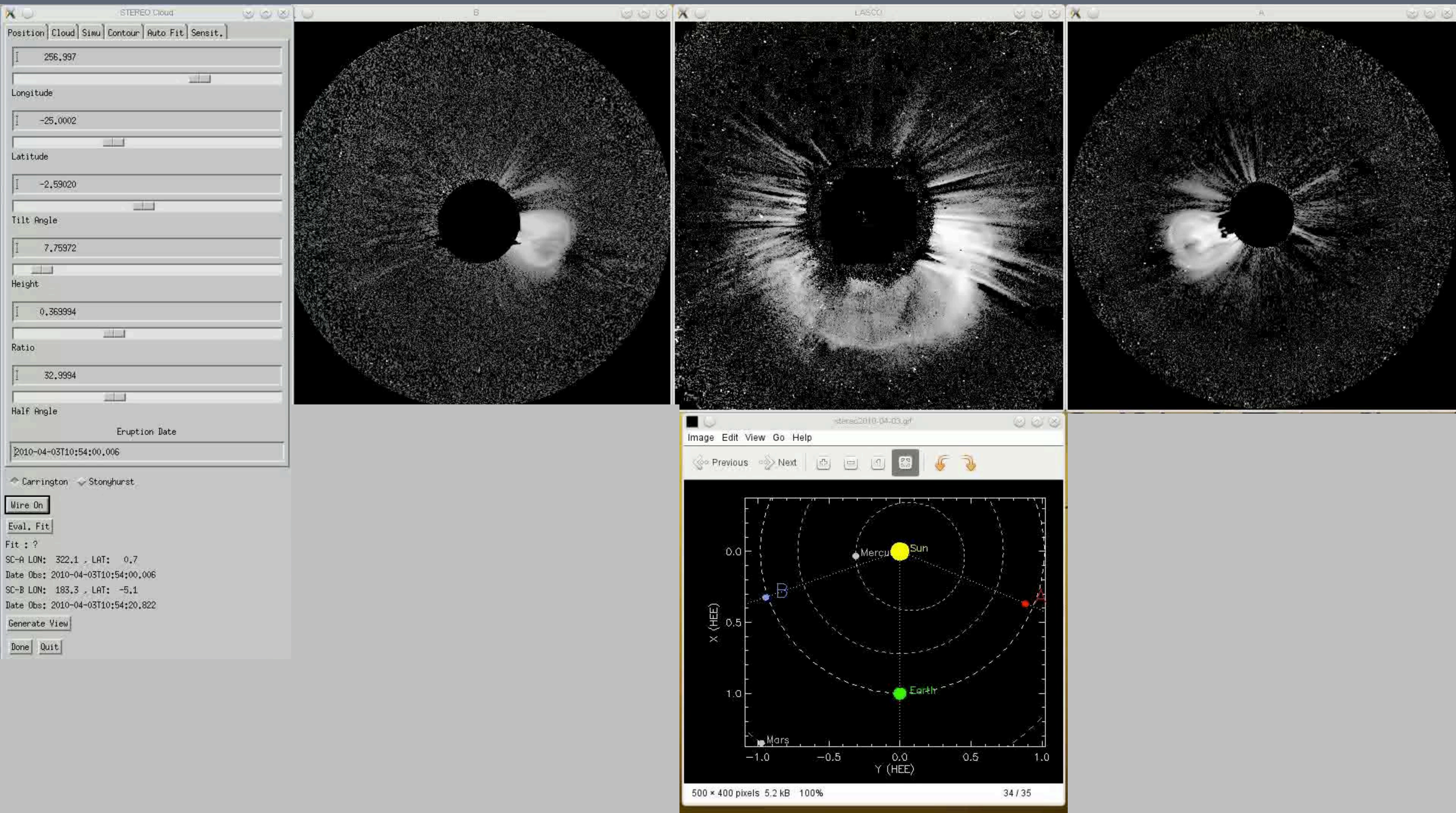
## Electron model:

*Gaussian width of density profile inside GCS:* $\sigma_t$
*Electron density:* $N_e$
*Gaussian width of density profile outside GCS:* $\sigma_l$

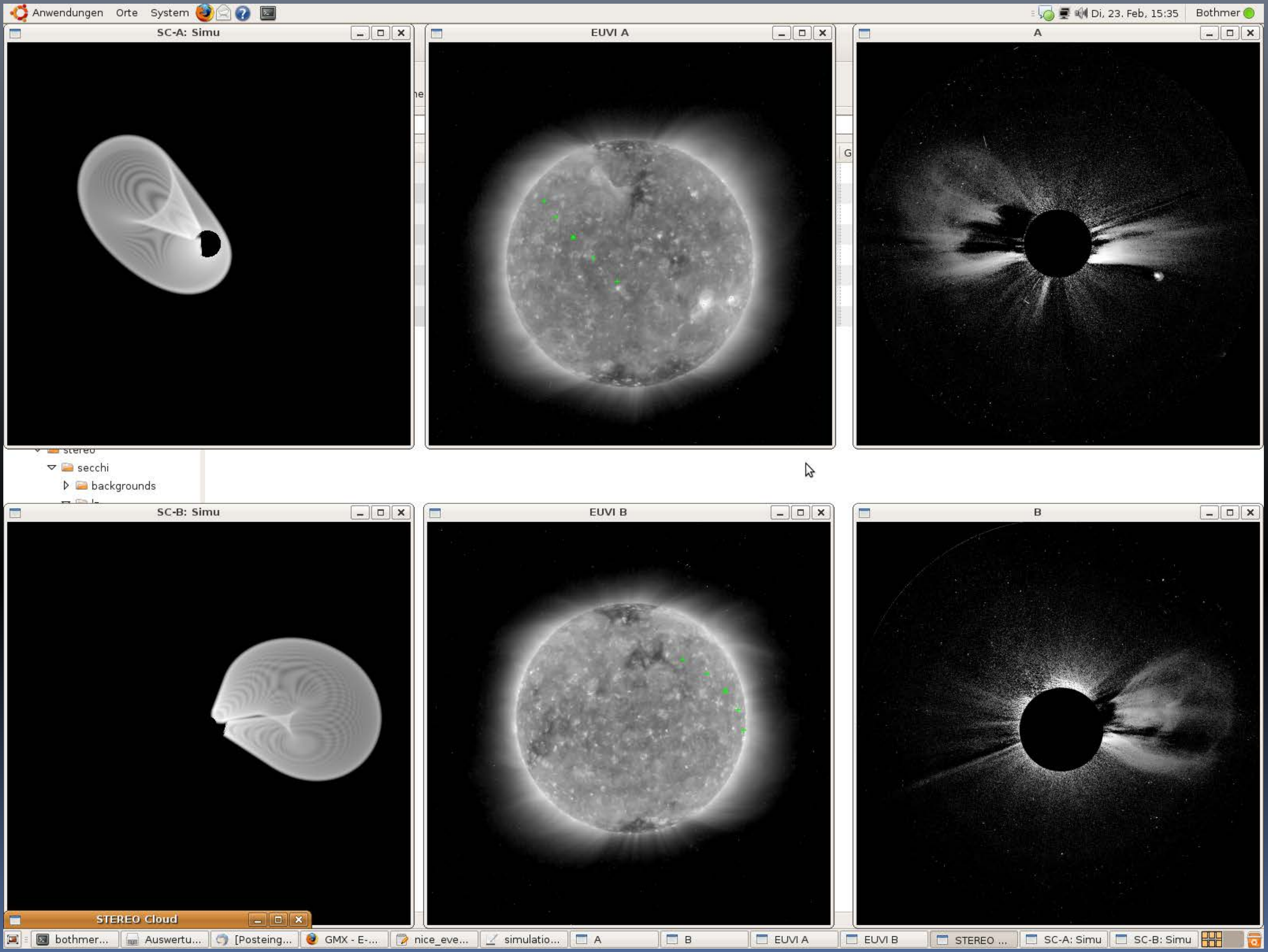
## Geometrical parameter:

*Angle between both legs:* 2α
*Radius of cross-section:* a
*Distance between sun center & boundary point of GCS:* r
*Height of the legs:* h
*Tilt angle:* γ
*Distance between O (sun center) & leading edge:* $h_{front}$

# Sample GCS Modelling

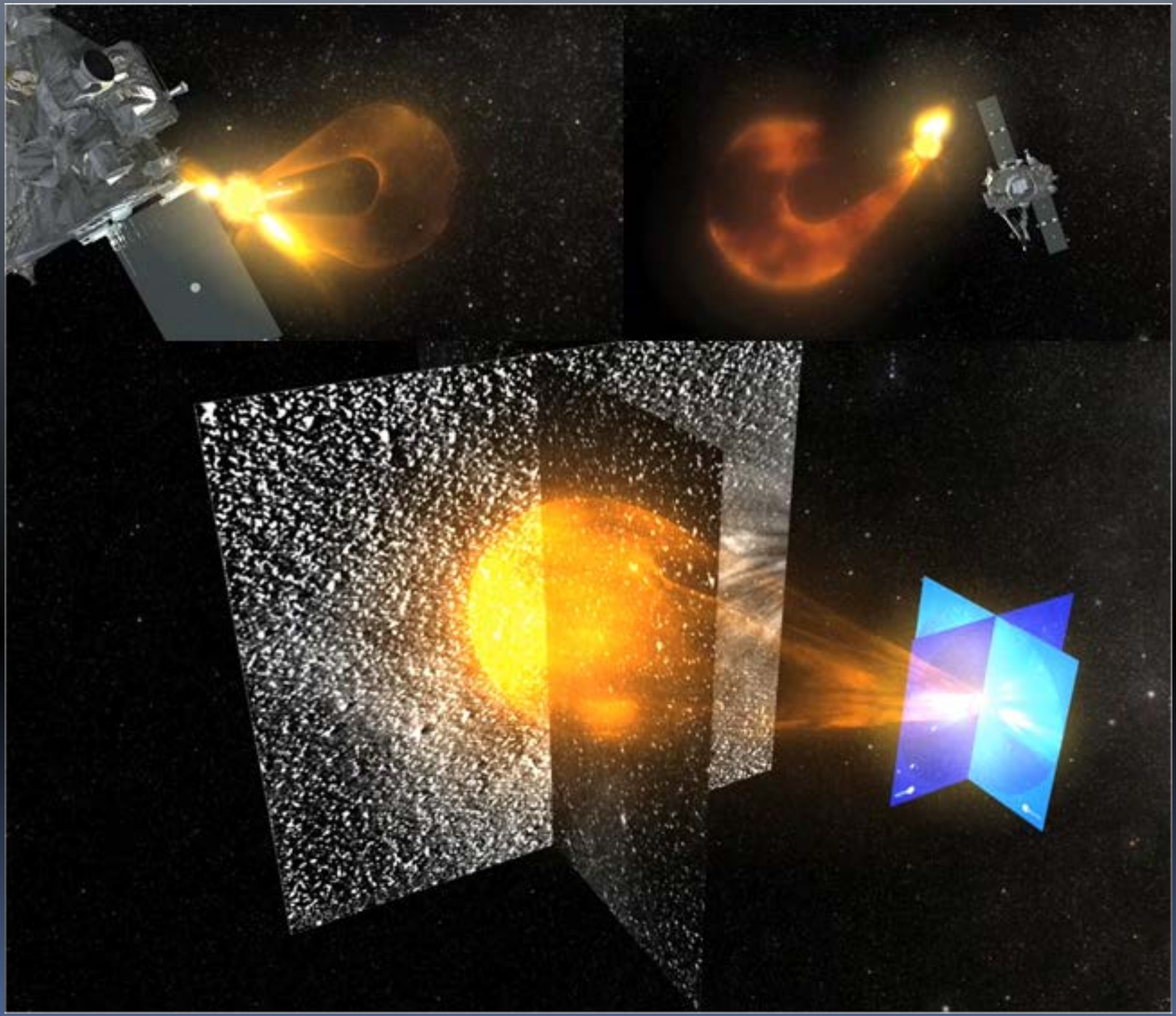


# CME Modelling: Dec. 12, 2008



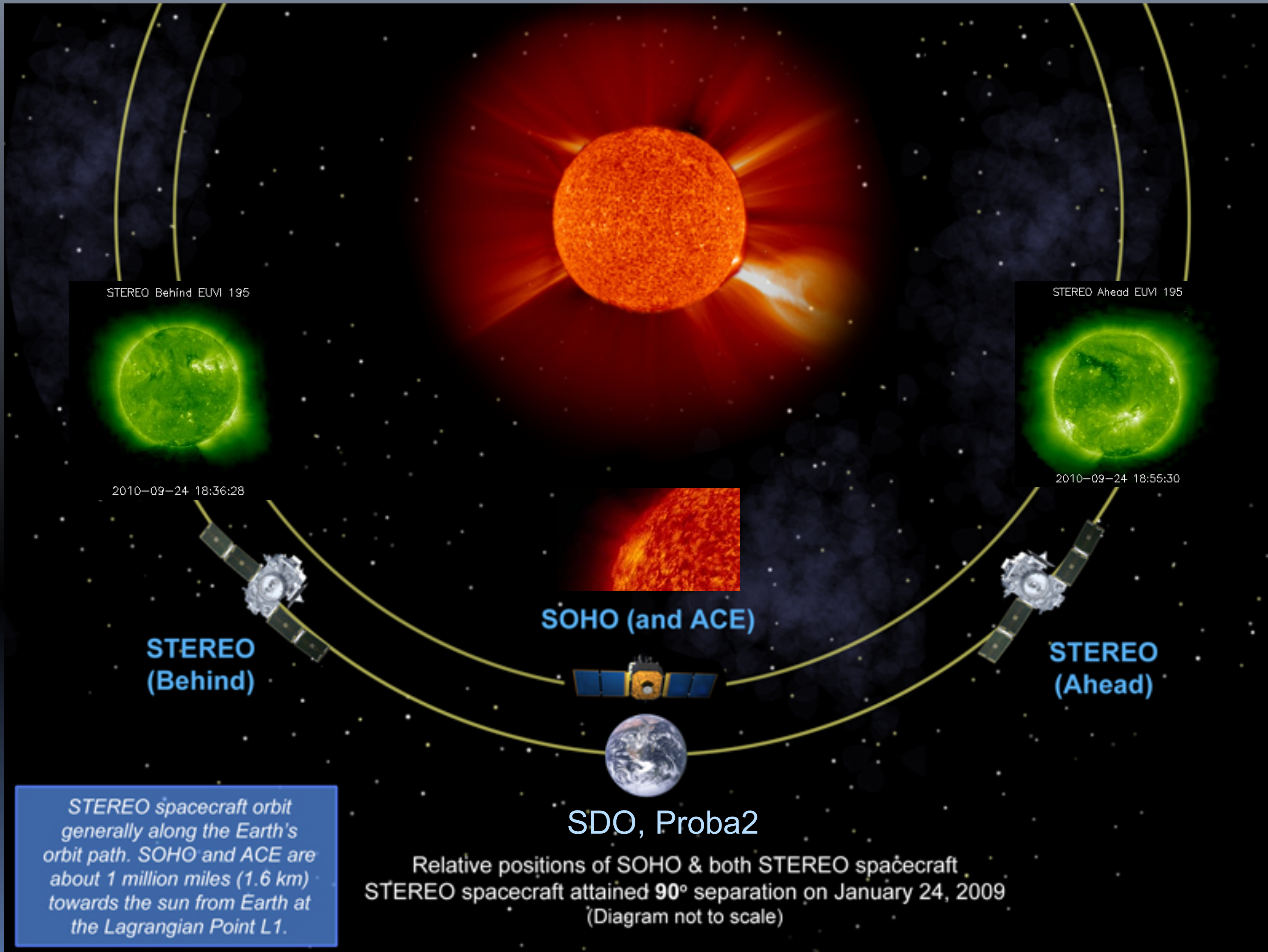

Credit: E. Bosman

# CMEs can be modelled as large-scale magnetic flux ropes

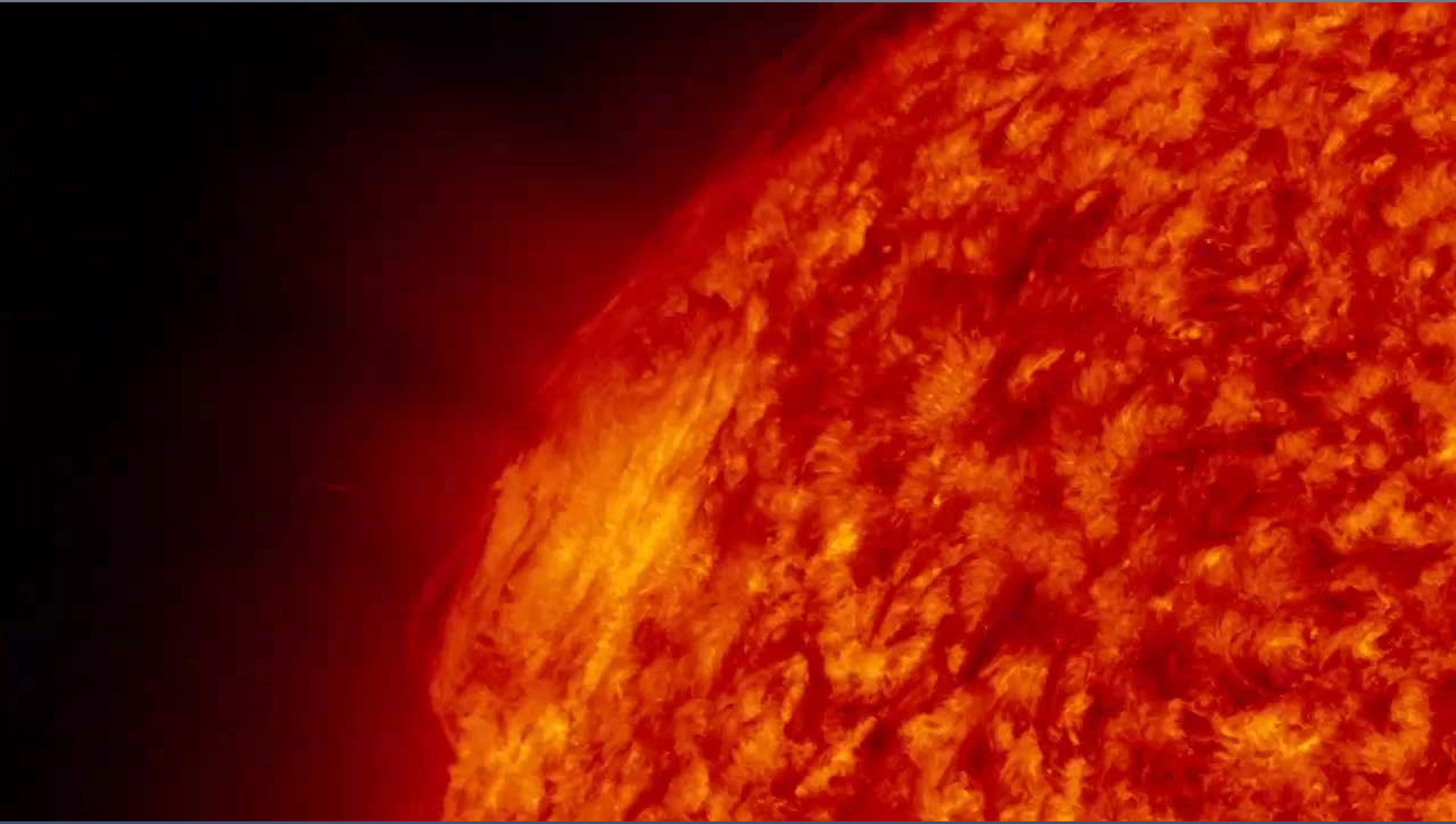


STEREO/SECCHI Consortium

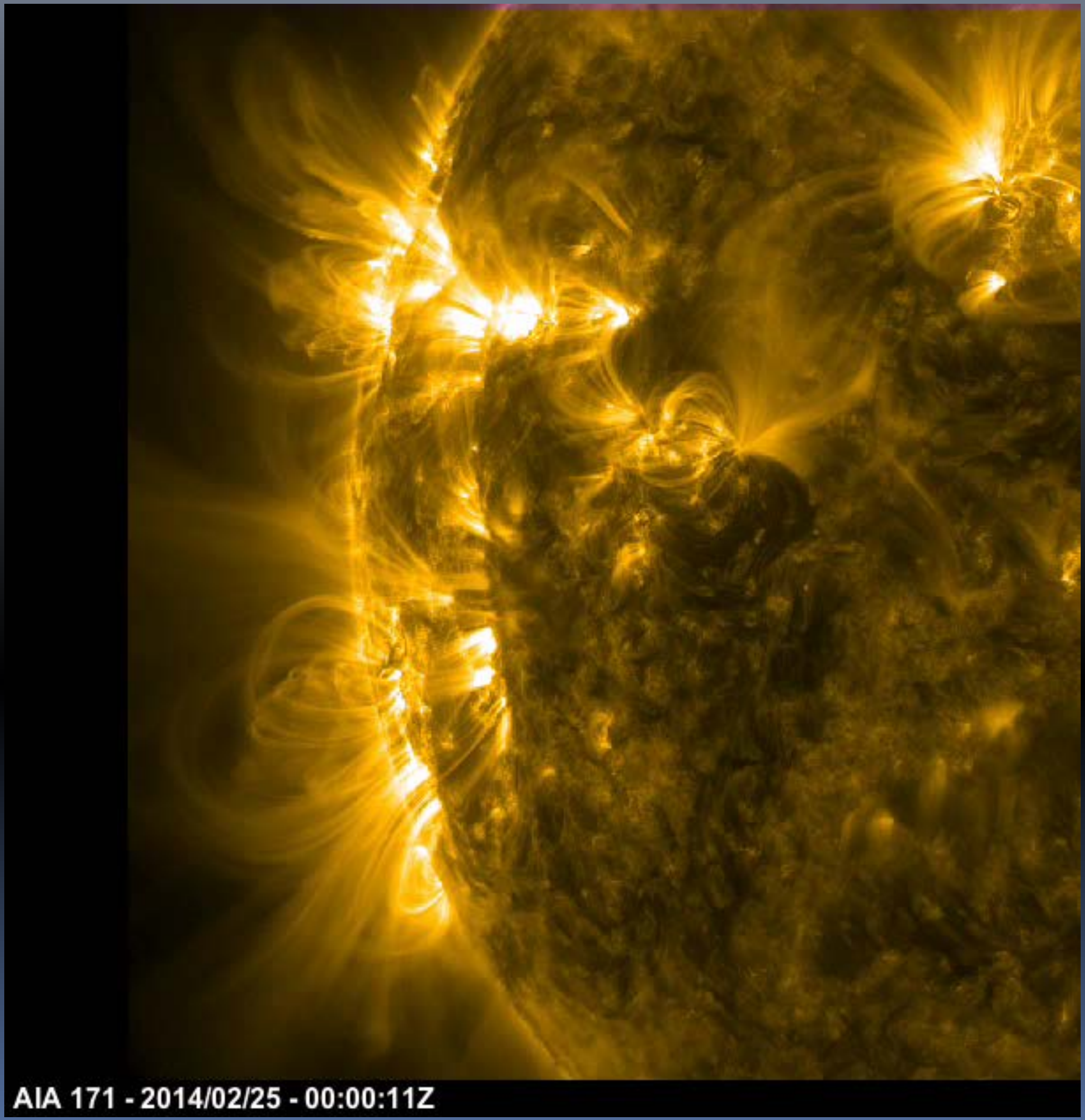
# Multi-Point Observations



# High Resolution Observationswith SDO



# Lateral expansion of CMEs – SDO/AIA 171

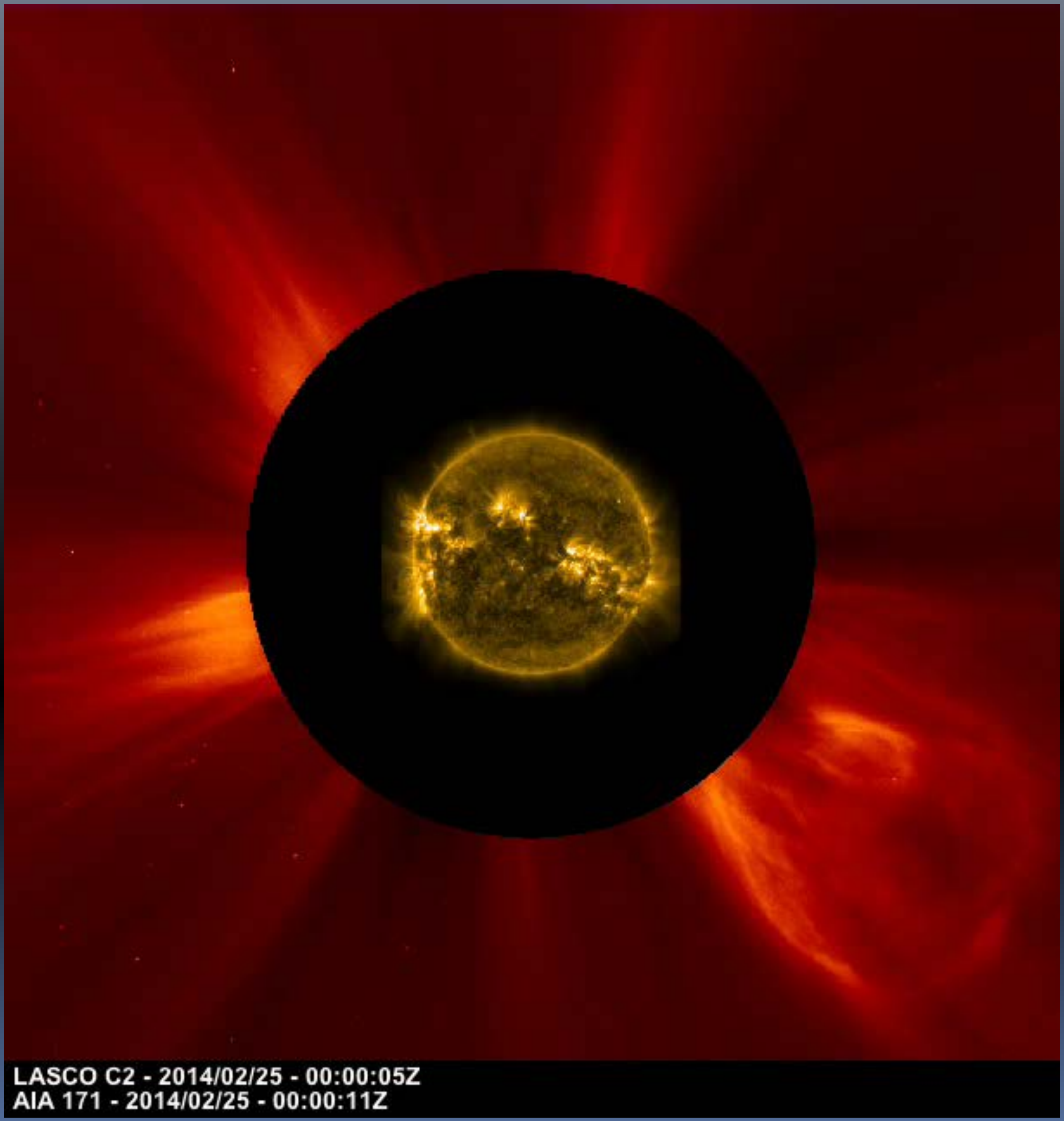



Credit: SDO/AIA

# The associated low coronal EUV wave

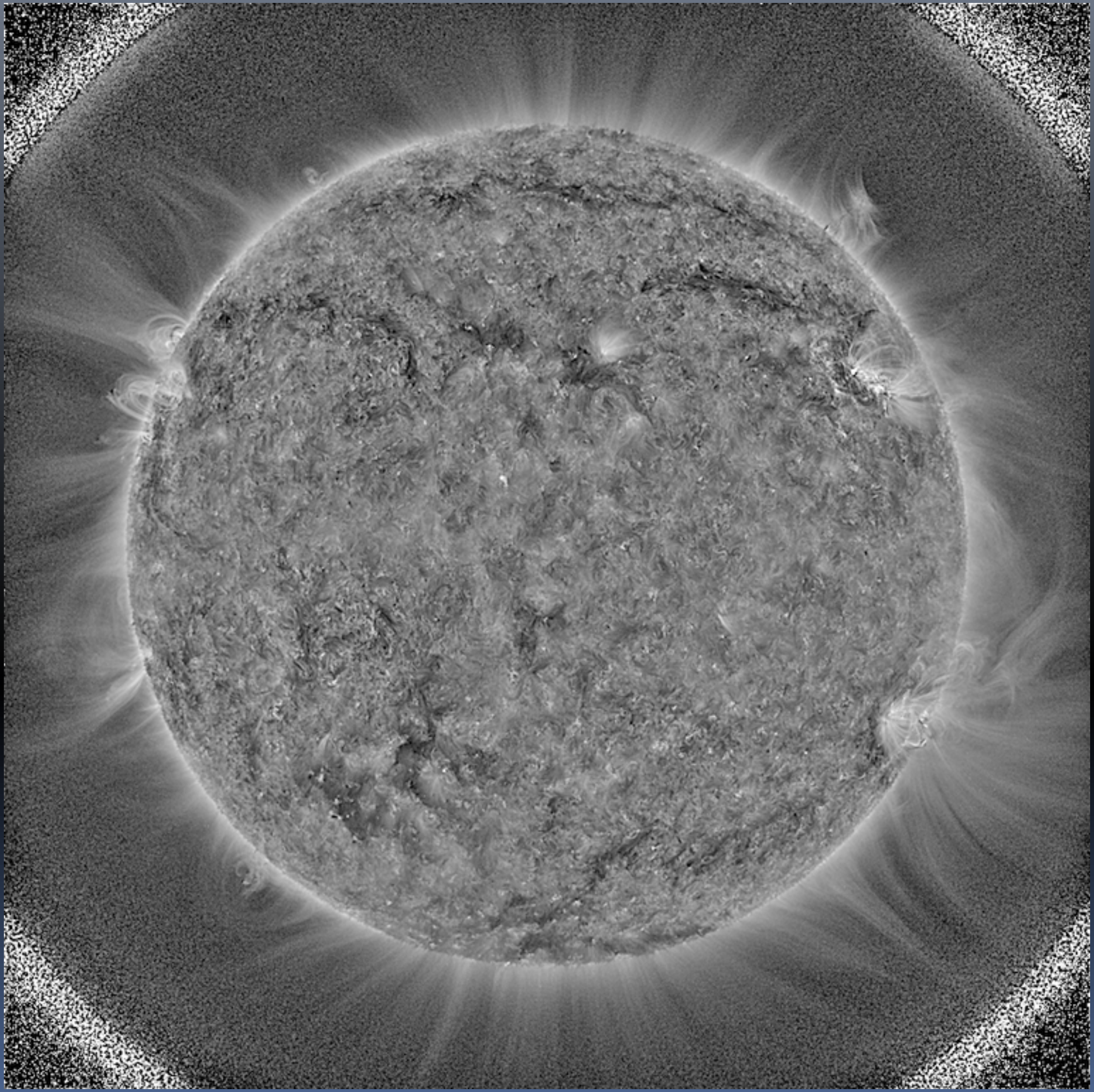

Credit: SDO/AIA, SIDC, AFFECTS

# Near-Sun rapid CME-Evolution



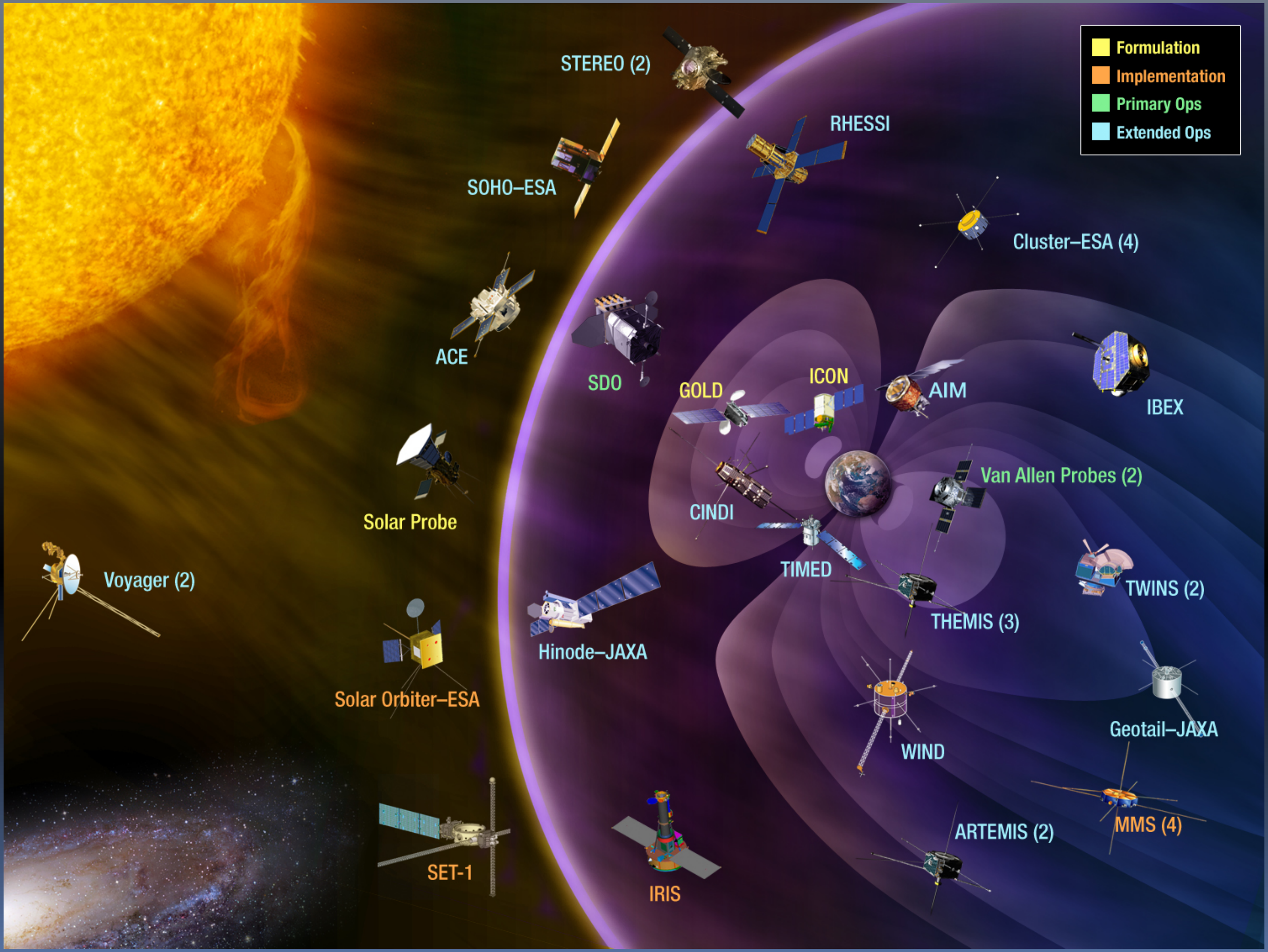

Credit: SDO, SOHO

# Flows Seen Over the Full Sun (SDO)



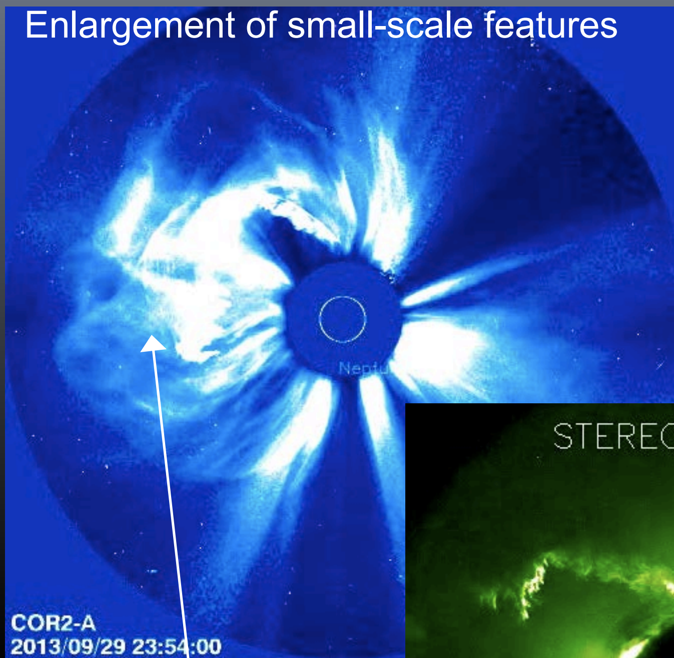
**171 Å**
**~0.6-0.9 MK**

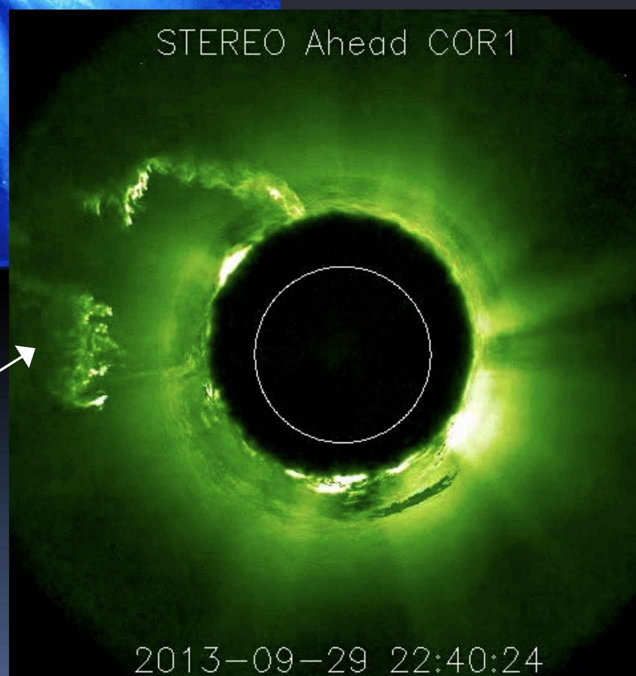
# The Helophysics Observatory

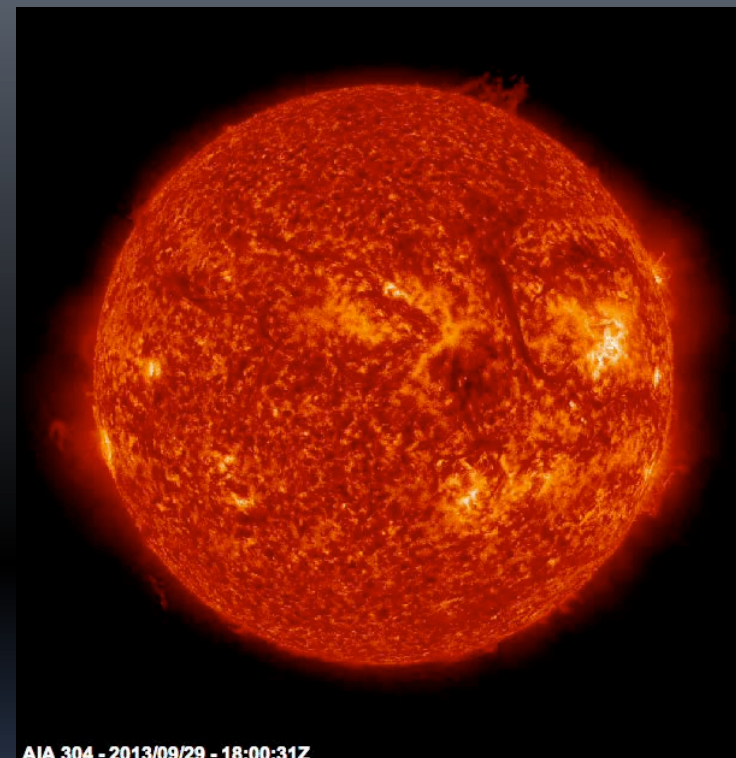


# AFFECTS Trailer

# CME on 29 September 2013 - SDO, STEREO/SECCHI/COR2 & COR1 A observations

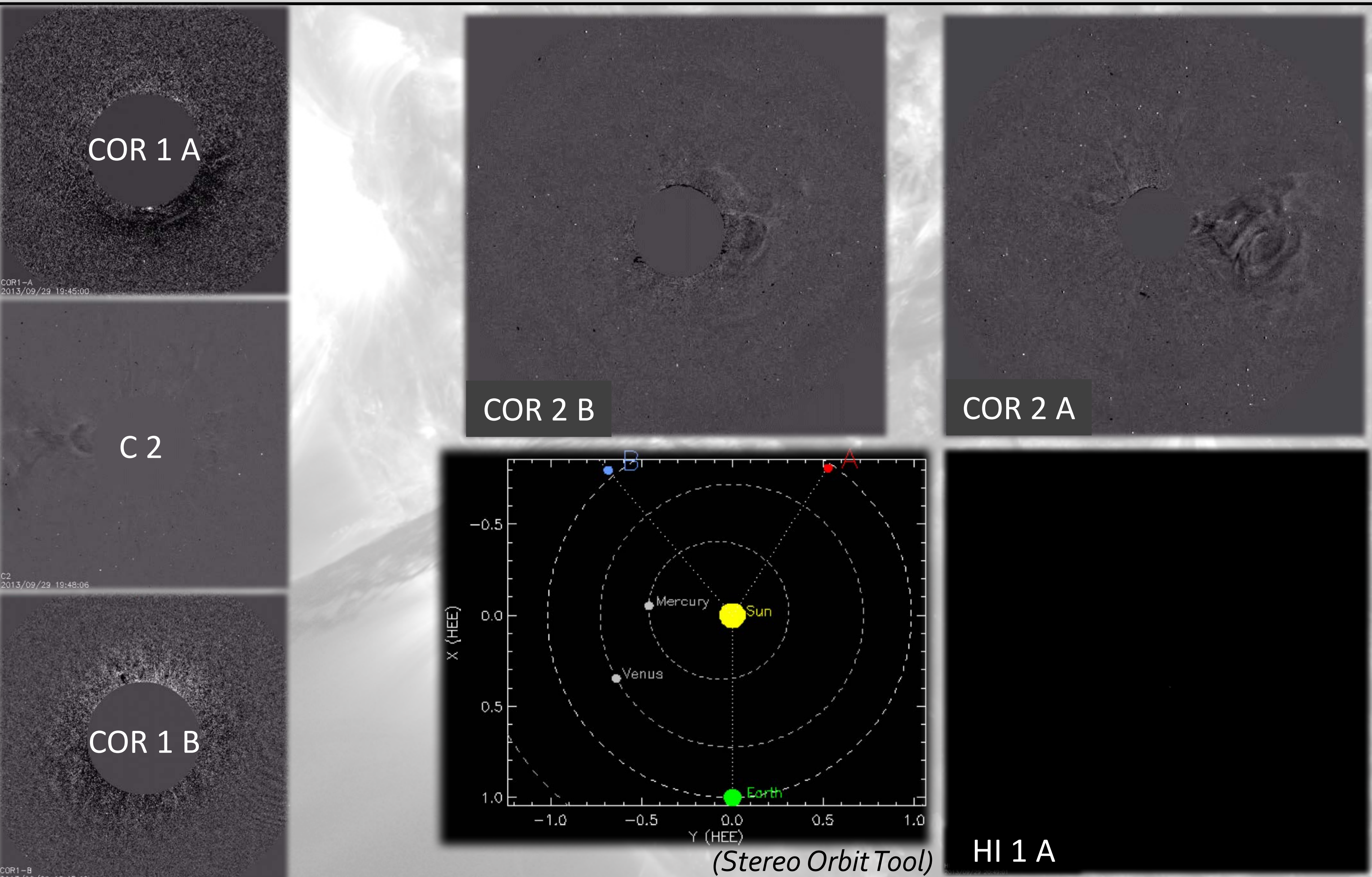


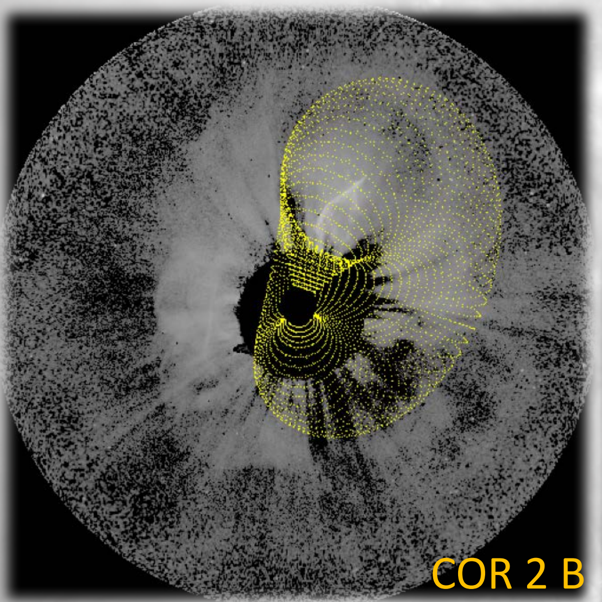

Expansion of fine-scale features
- Arrival times will depend on observer‘s position wrt CME SR

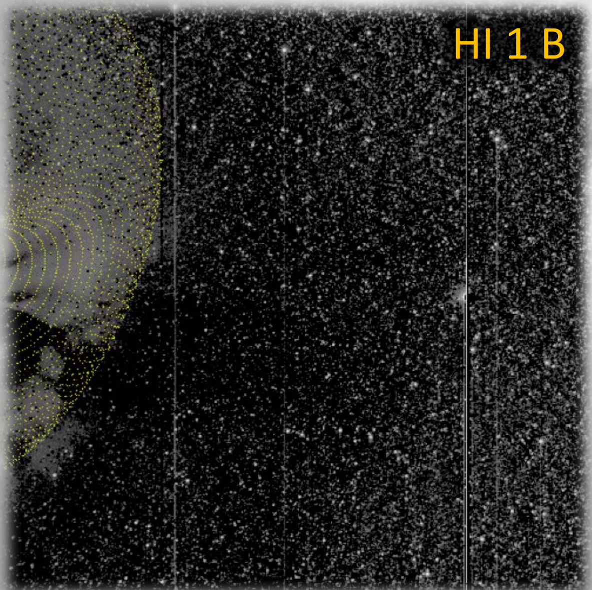
# CME on 29 September 2013



Institut für Astrophysik Göttingen

# GCS Modelling of Multipoint Observations



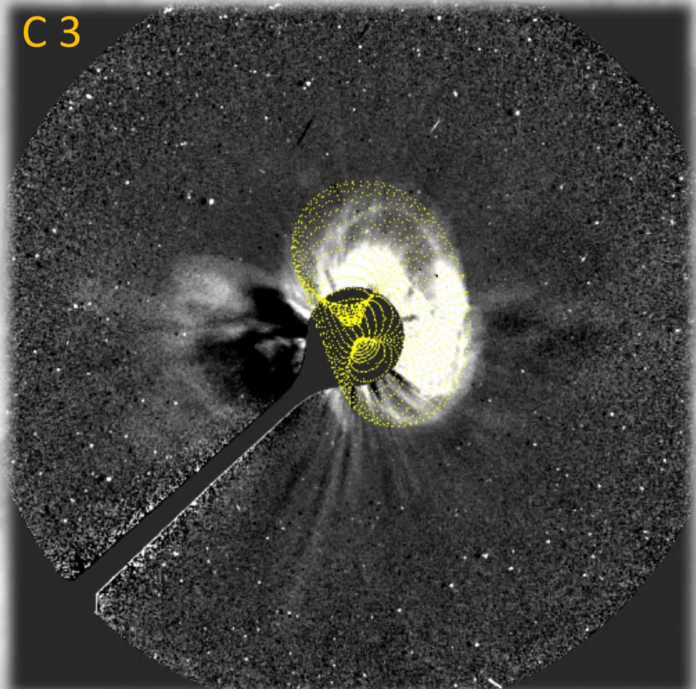




**Position on Sun:**

Φ = 12°  θ = 25.12°

Associated C1.2 Flare at:

Φ = 33°  θ = 10°

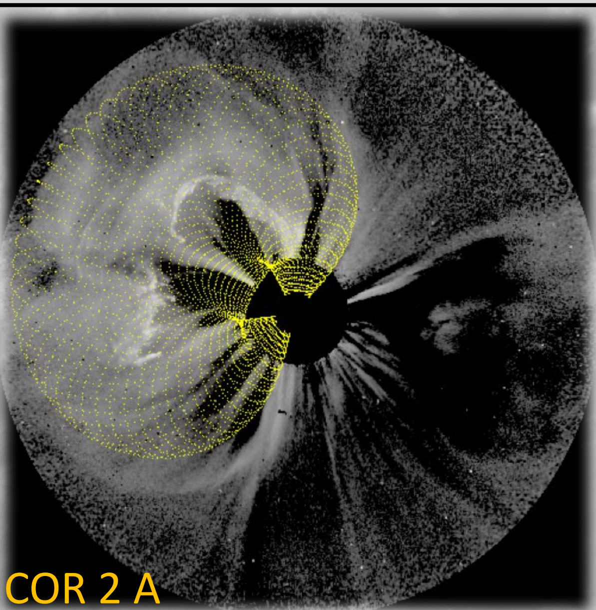


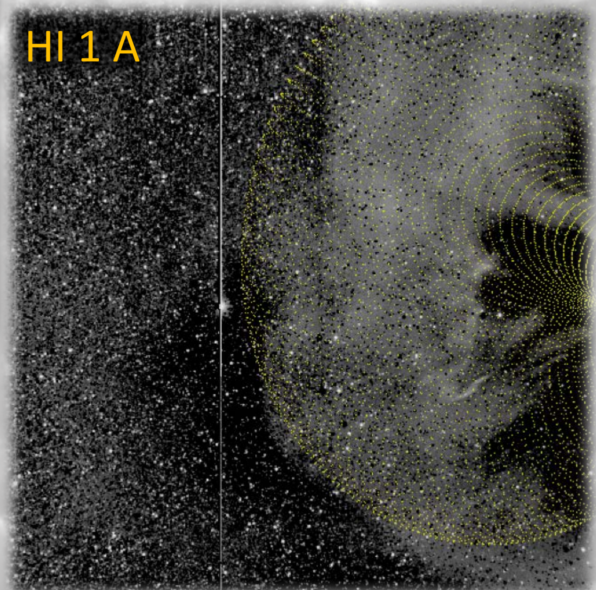

**Geometrical parameter:**

α = 63°

γ = -74.87°

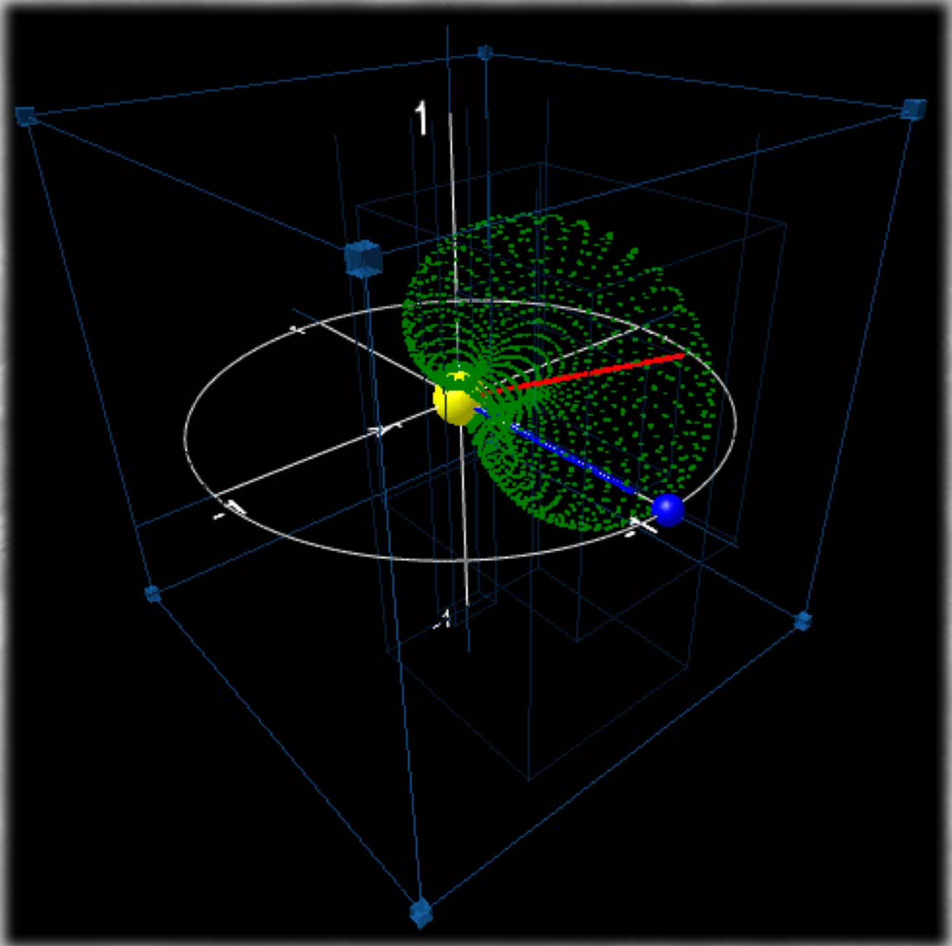
κ = a/r = 0.54



# Forecast bases on 3D CME Modelling & CME Propagation

- Which part of the CME hits earth?
- Assuming self similar expansion of the CME!
- Calculate Expansion factor using GCS parameters.
- Combining the EF with the arrival time in L1 we can calculate the distance of the APEX for this time.



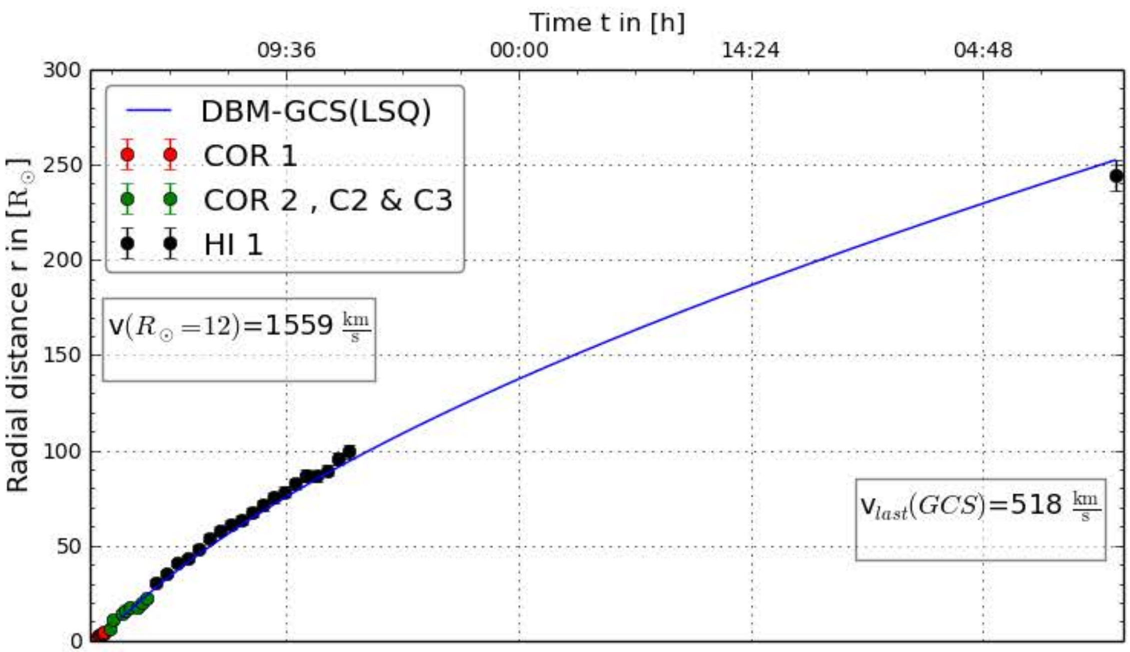

**Event from 29. Sep. 2013:**

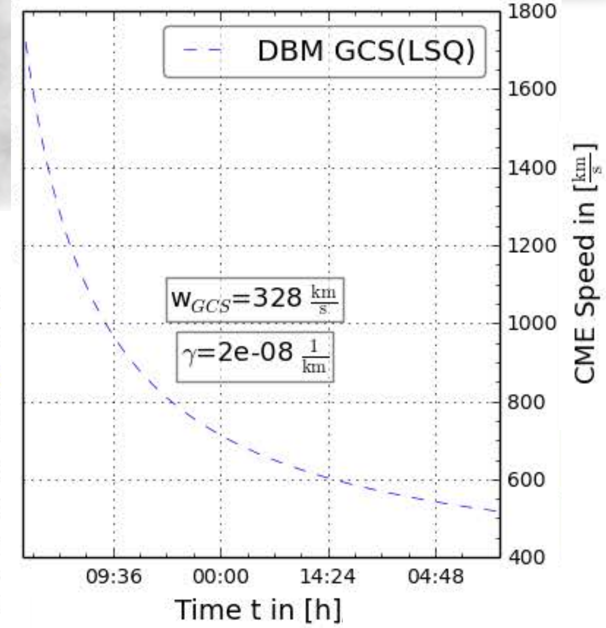
$$EF = \frac{h_{Earth}}{h_{Apex}} = \frac{v_{Earth}}{v_{Apex}} = 0.88$$

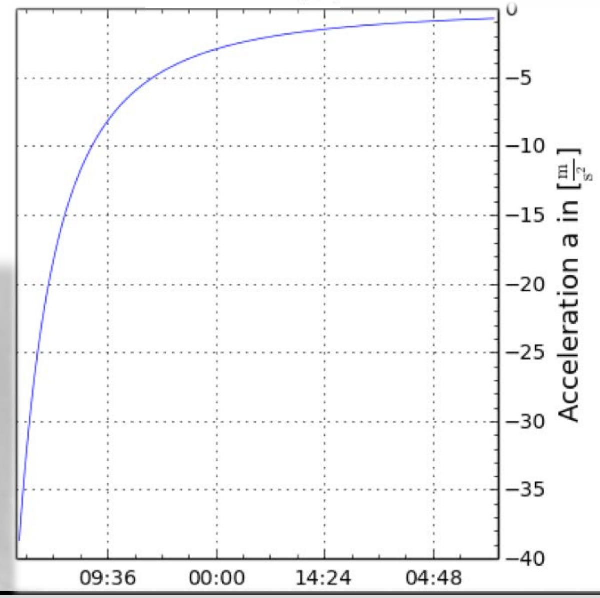
# Final Drag fit

**Expansion factor:** $EF = \frac{v_{Earth}}{v_{Apex}} = 0.88$

$$v_{Earth} = 456 \,{}^{\mathrm{km}}/_{\mathrm{s}}$$



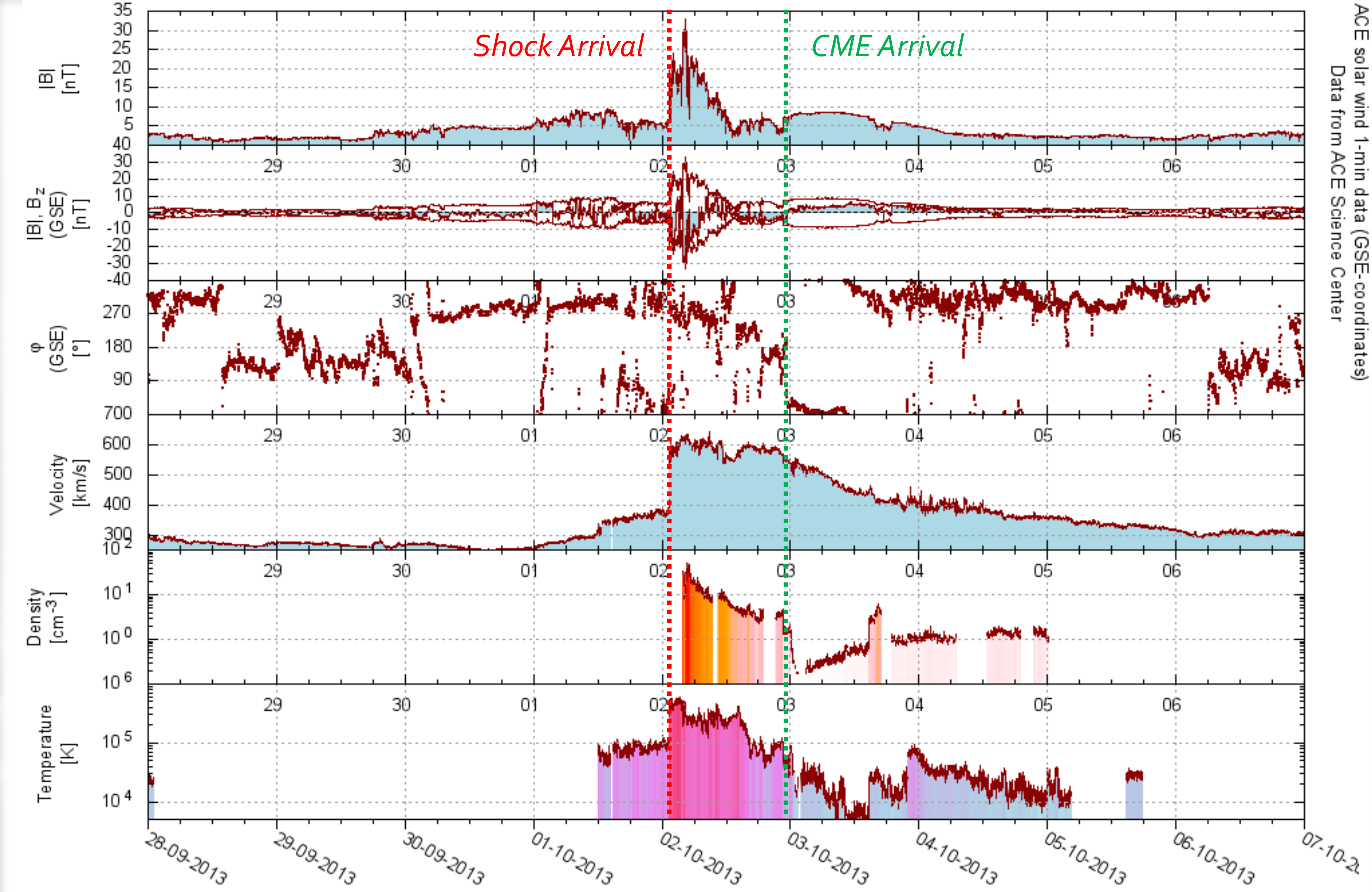

**Measurements from ACE:**

Solar Wind speed: $w = 280 - 300 \,{}^{\mathrm{km}}/_{\mathrm{s}}$

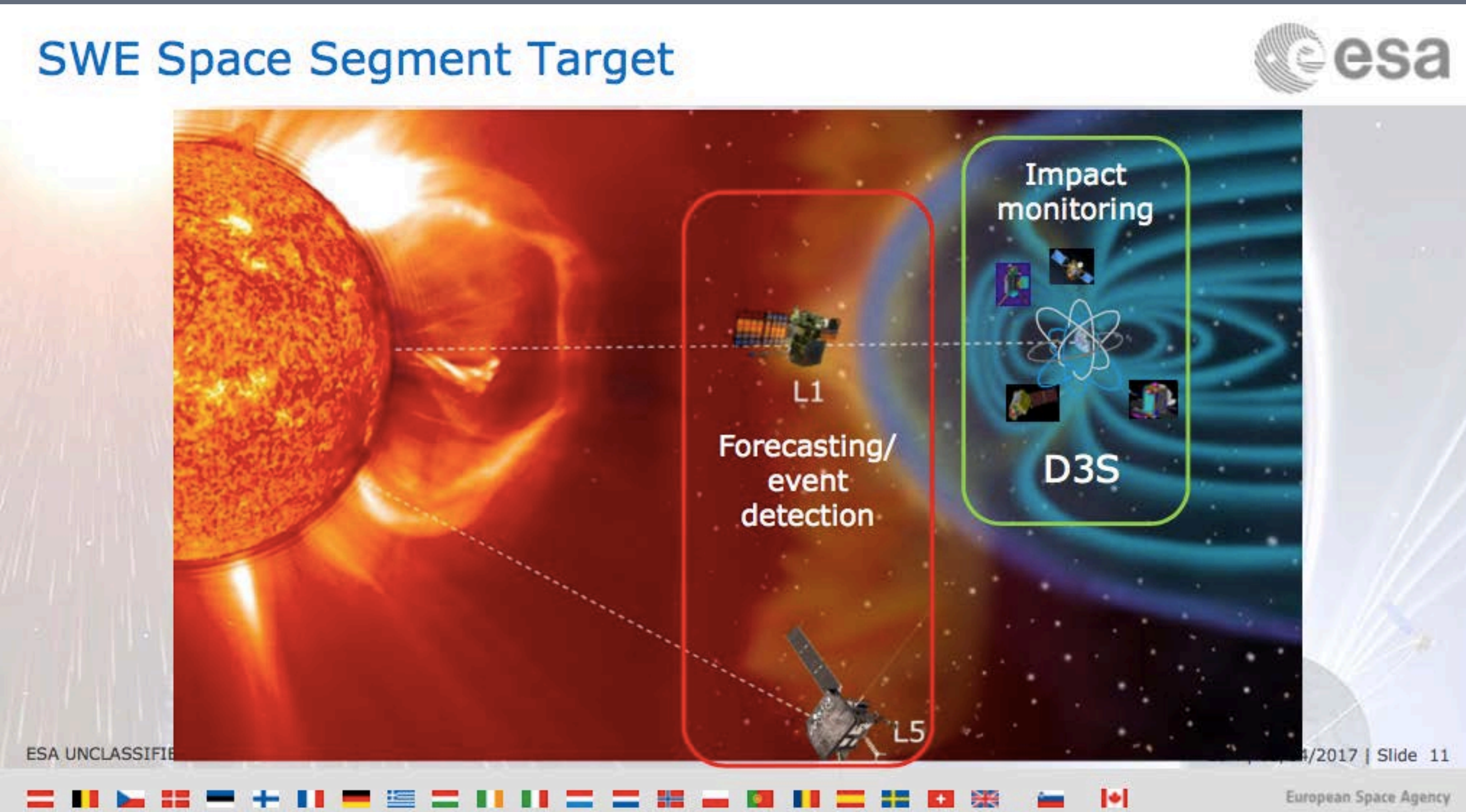
CME arrival speed: $v_{CME} \sim 550 \,{}^{\mathrm{km}}/_{\mathrm{s}}$

**CMEs decelerate between Sun and Earth!**

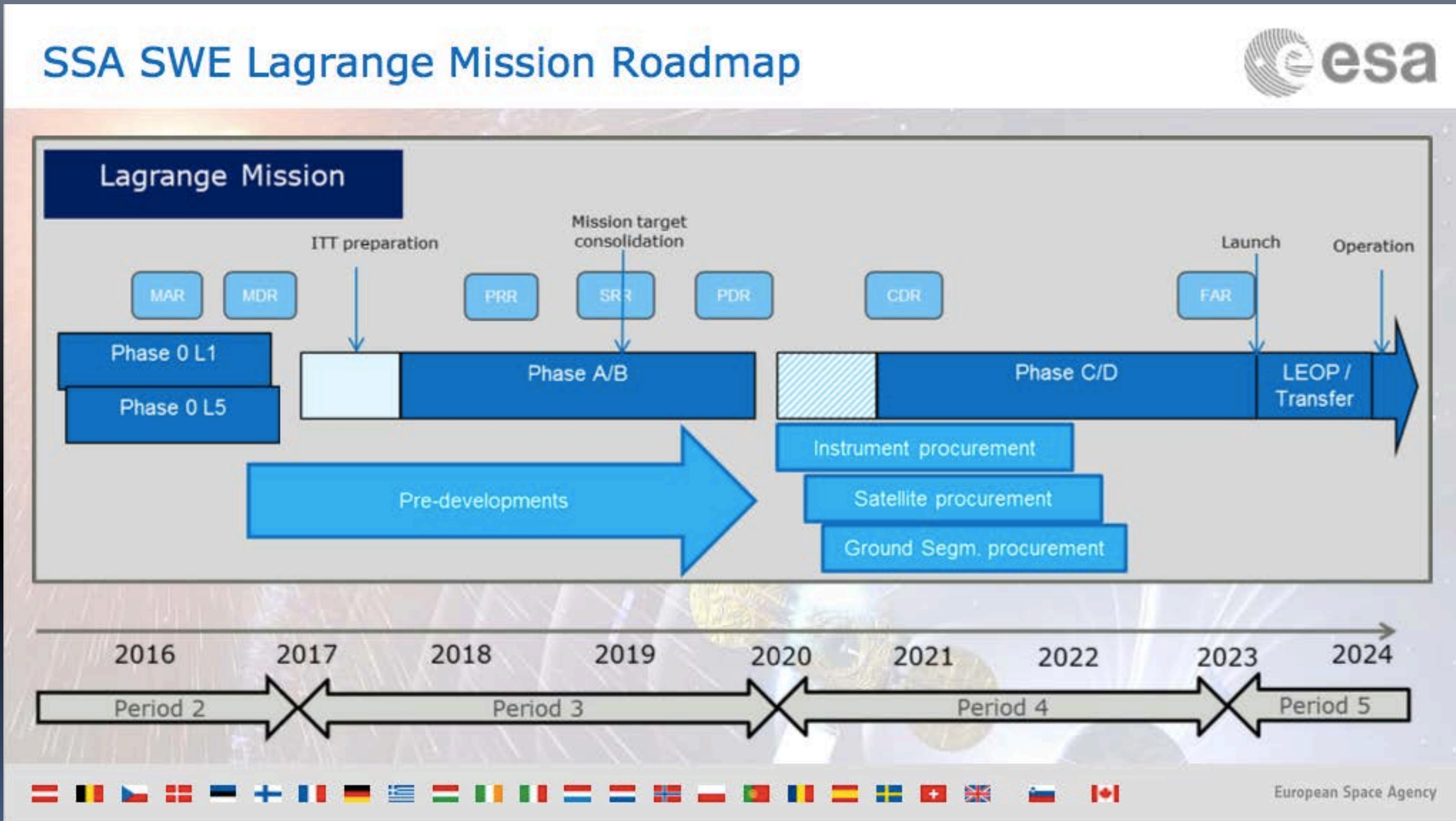
# CME Signature in ACE Solar Wind Data

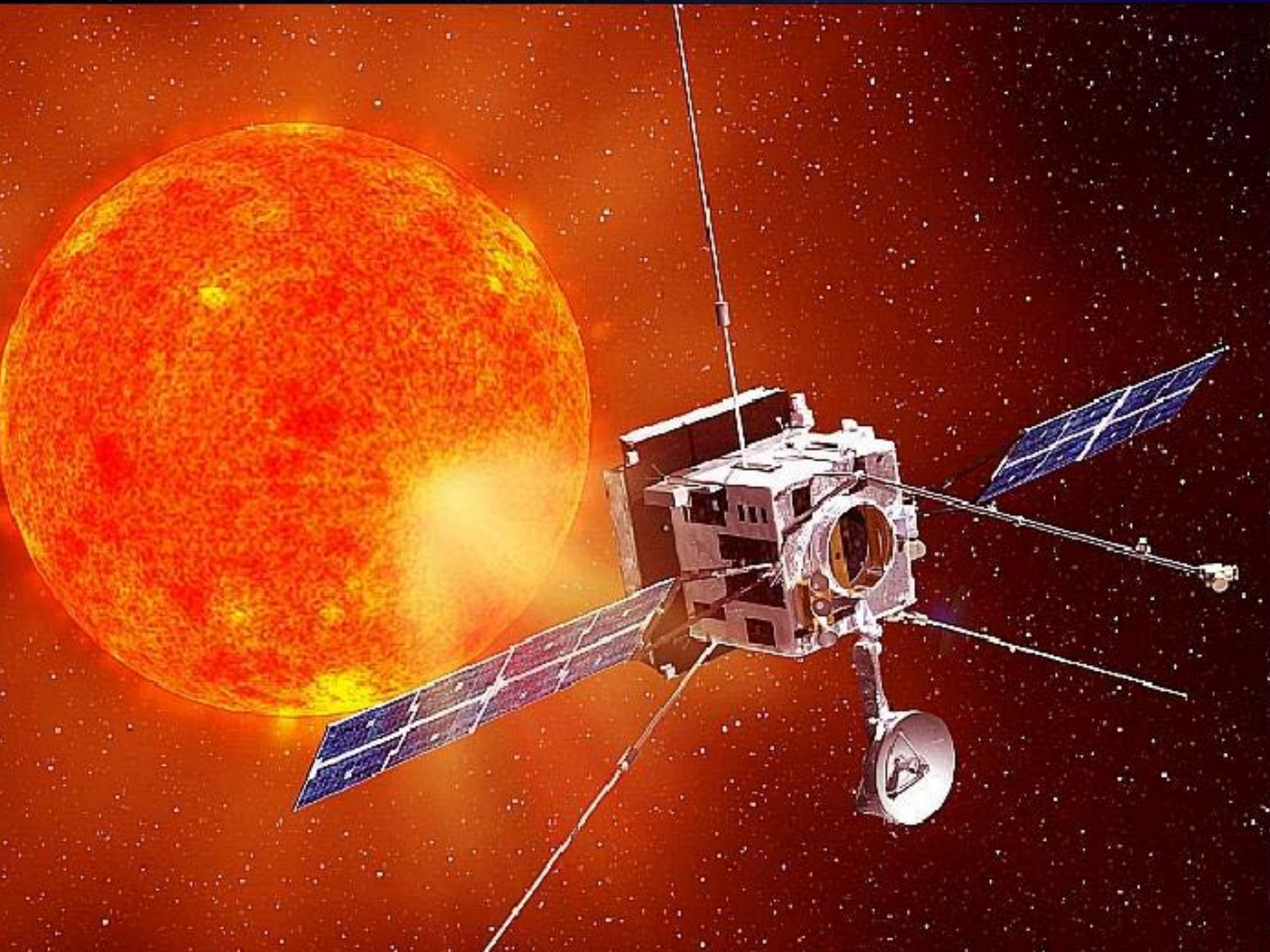


# ESA Space Weather Plans in SSA - Lagrange

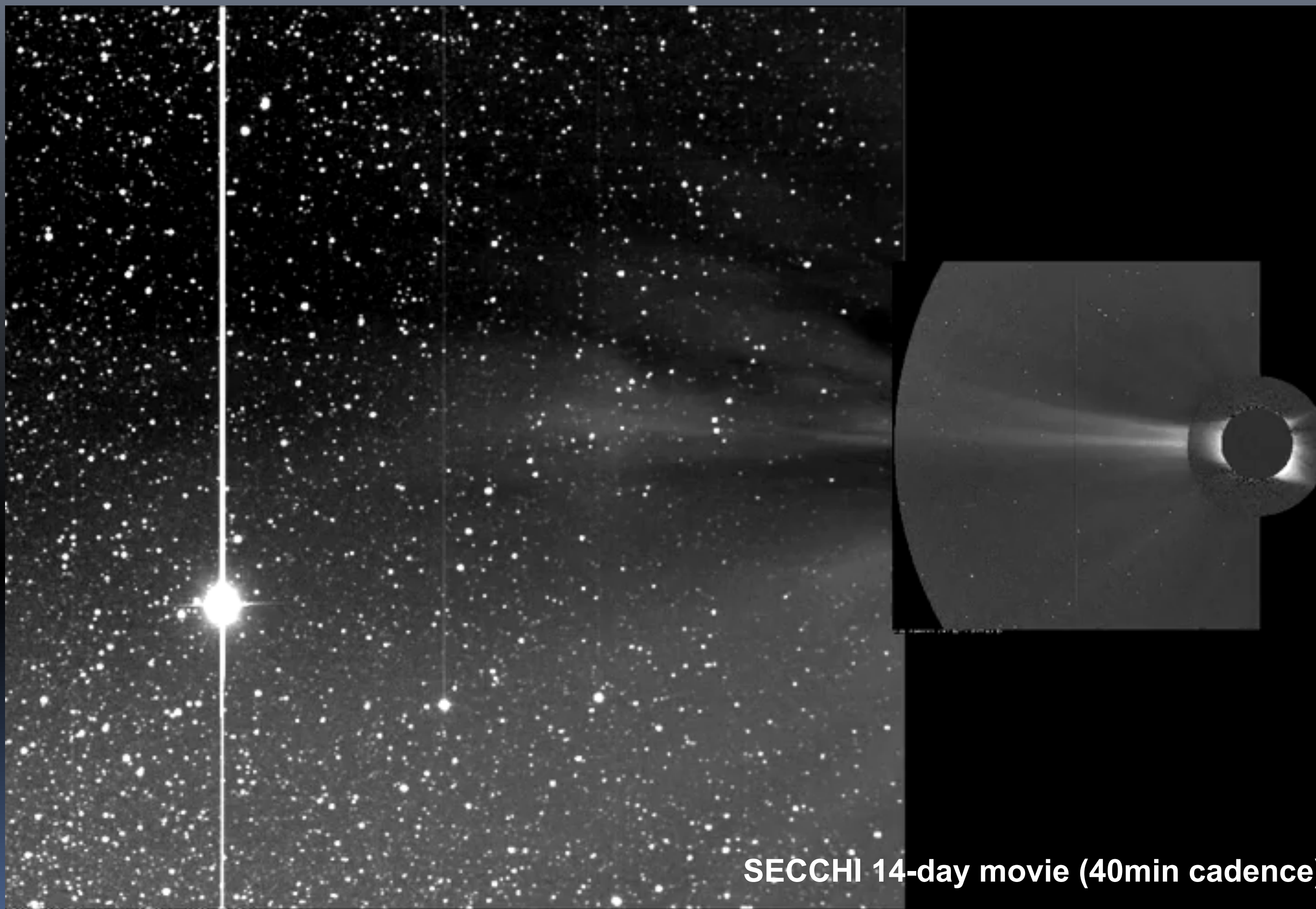


# Timeline

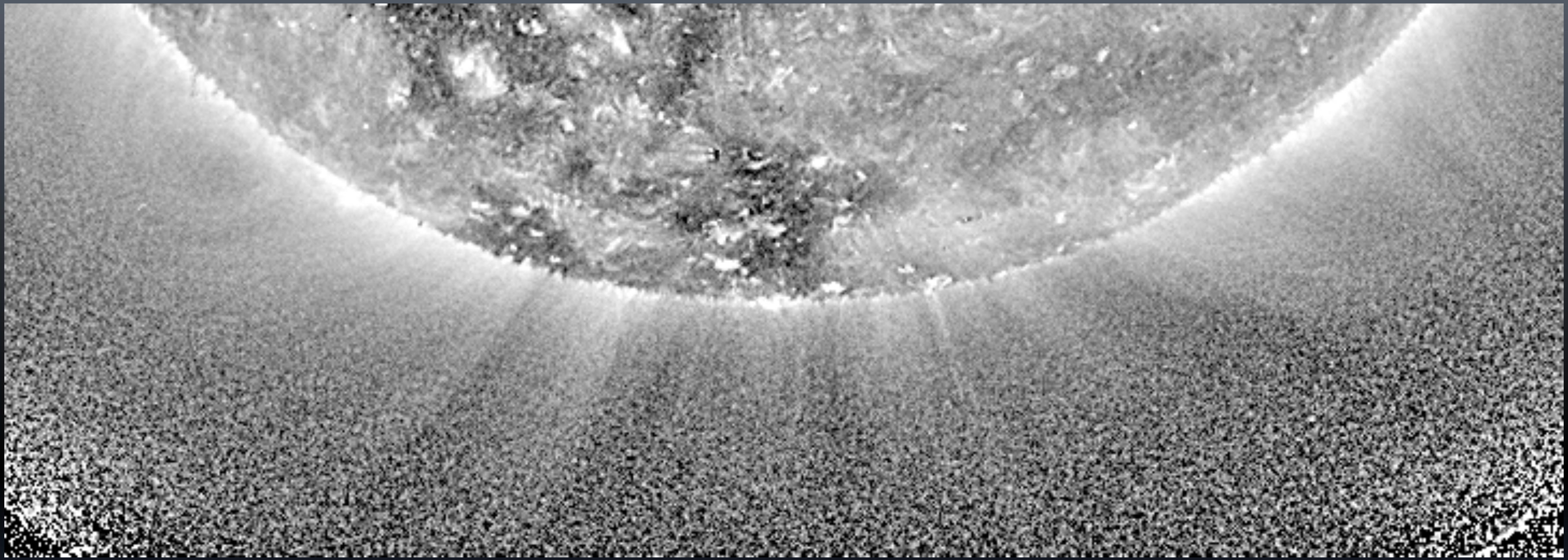

SSA SWE Lagrange Mission Roadmap
esa
Lagrange Mission
ITT preparation
Mission target consolidation
Launch
Operation
MAR
MDR
PRR
SRR
PDR
CDR
FAR
Phase 0 L1
Phase 0 L5
Phase A/B
Phase C/D
LEOP / Transfer
Pre-developments
Instrument procurement
Satellite procurement
Ground Segm. procurement
2016
2017
2018
2019
2020
2021
2022
2023
2024
Period 2
Period 3
Period 4
Period 5
European Space Agency



# Imaging the solar wind with STEREO



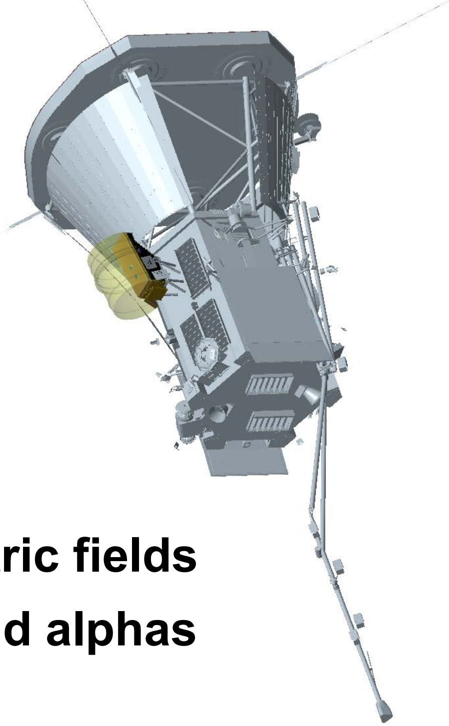
# Outflows in Coronal Hole (SDO)



193 Å
~1.4 MK

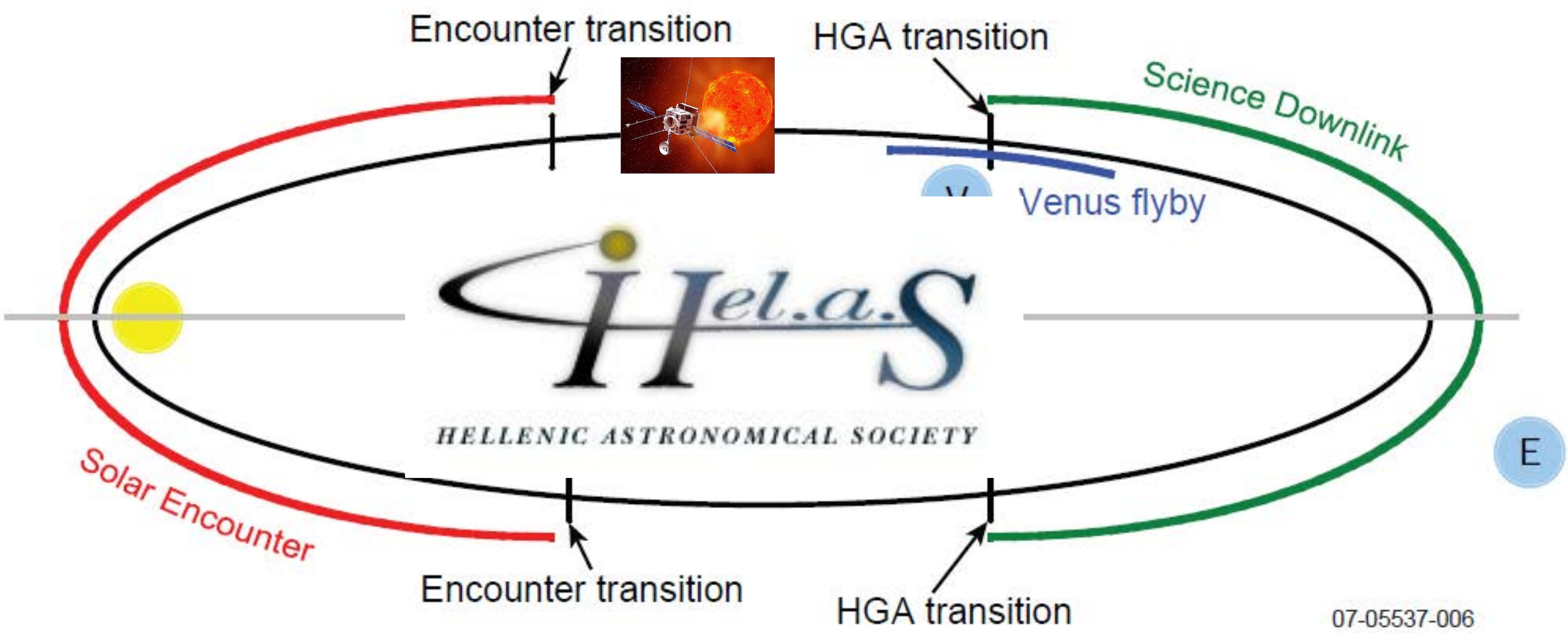

N
E
APL
APL
CRAFTSMAN
CRAFTSMAN

# What is PSP?



- **Goes to the last unexplored region of the solar system and enter the solar corona as close as 9.86 Rs**
- **Will answer fundamental questions of Heliophysics:**
  - **The heating of the solar corona**
  - **The origin, structure and evolution of the solar wind**
  - **Origin of solar energetic particles**
- **Investigations:**
  - **FIELDS: measurements of magnetic fields, AC/DC electric fields**
  - **SWEAP: measurements of flux of electrons, protons and alphas**
  - **ISΘIS: measurement of solar energetic particles**
  - **WISPR: measurement of coronal structures**
  - **Observatory Scientist**

# PSP Mission Scenario – Observations from 0.25 AU to 9.86 $R_S$



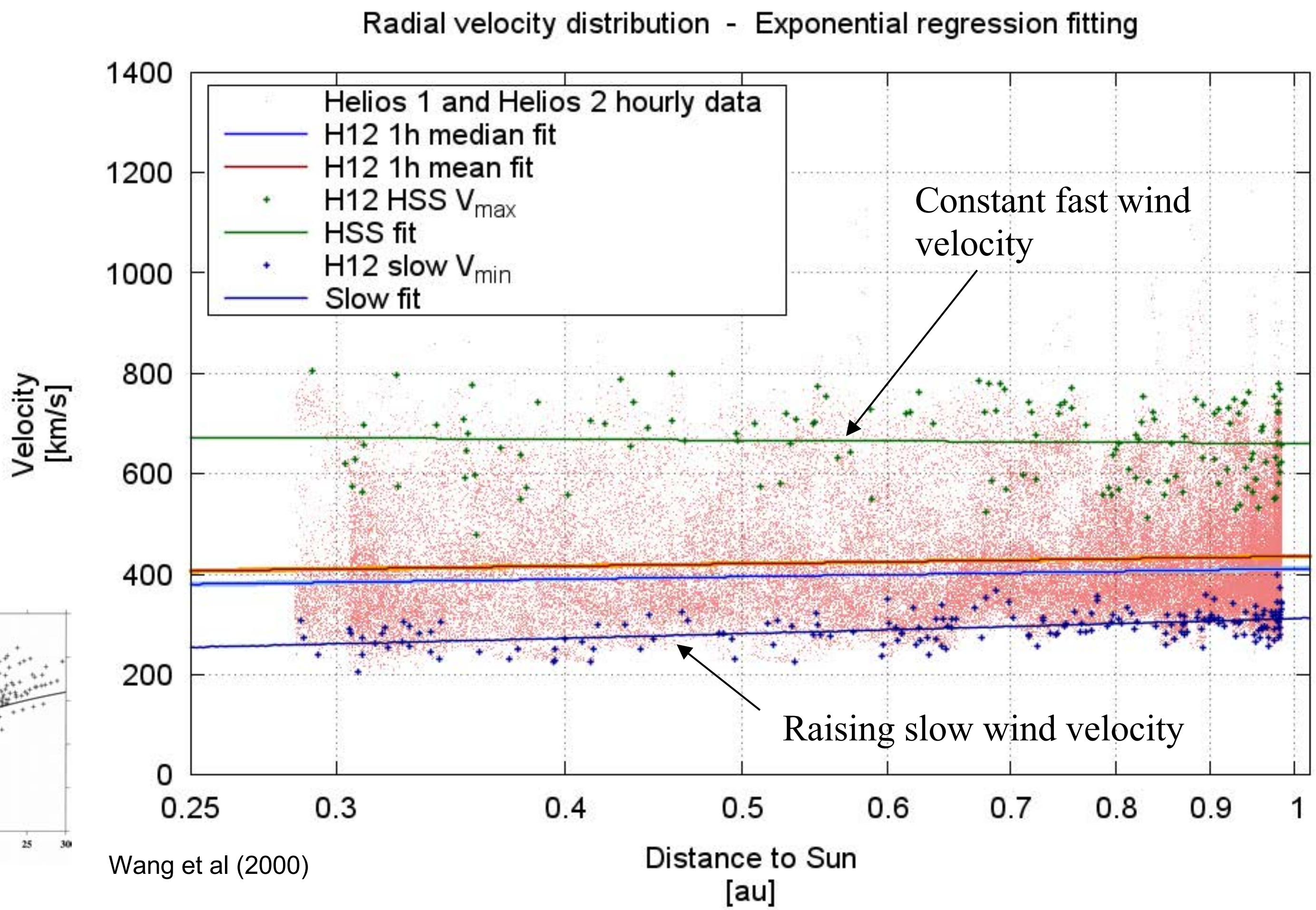

$V_{PSP}$~200 km/s
$V_{Helios}$~70 km/s

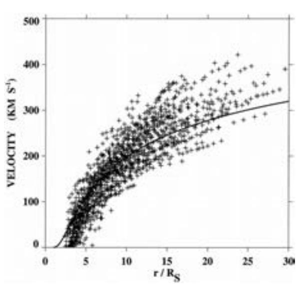
# Results from solar wind extrapolations (CGAUSS)

- **Helios structure selection**
  - **138 fast wind streams ($V_{max}$)**
  - **184 slow wind streams ($V_{min}$)**

Extrapolation to 0.04 au

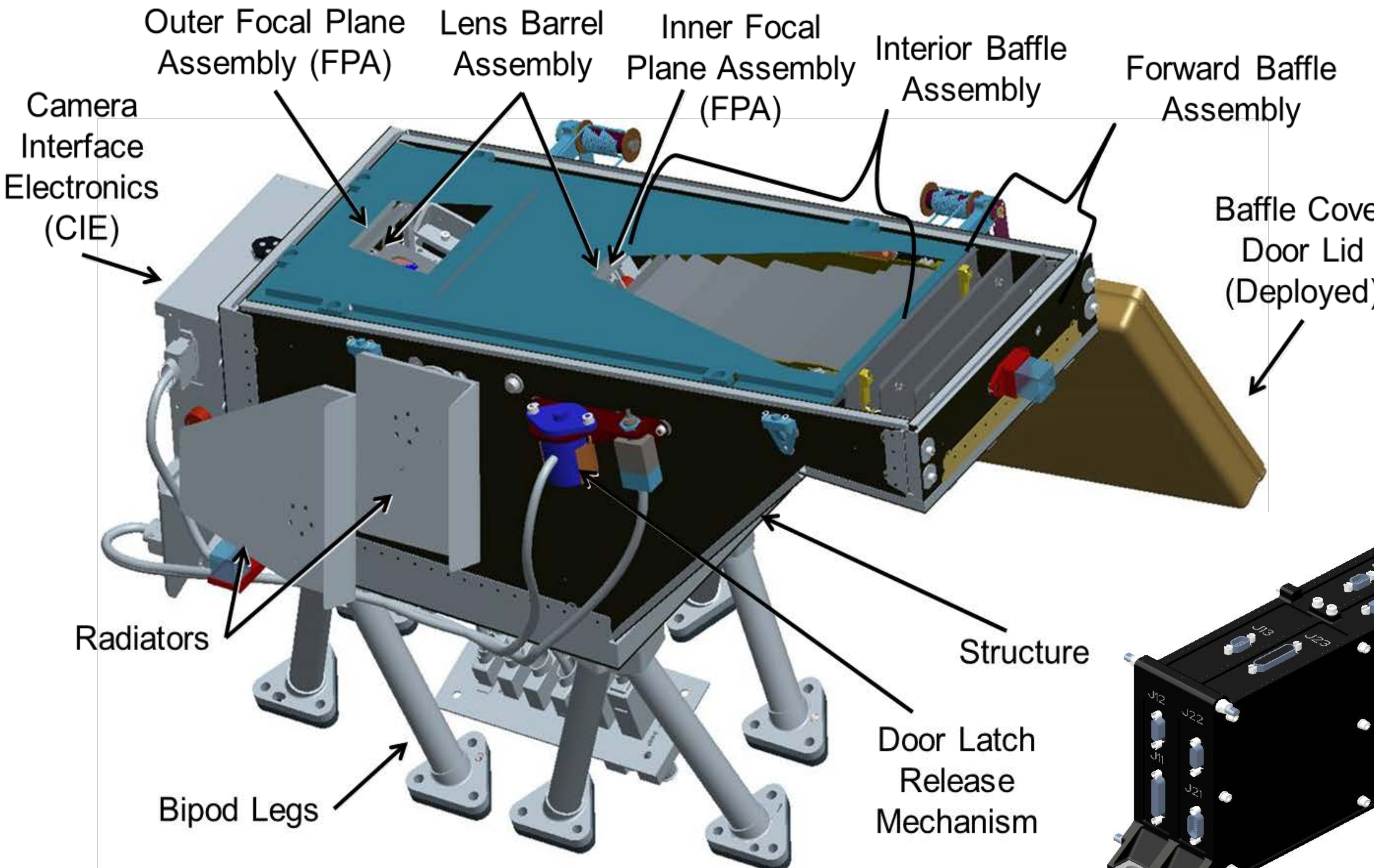
- Fast: $V_{max}$ = 689 km/s
- Slow: $V_{min}$ = 195 km/s

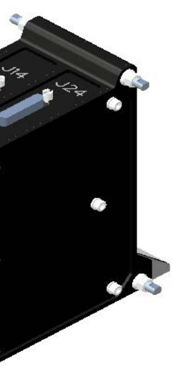


Wang et al (2000)

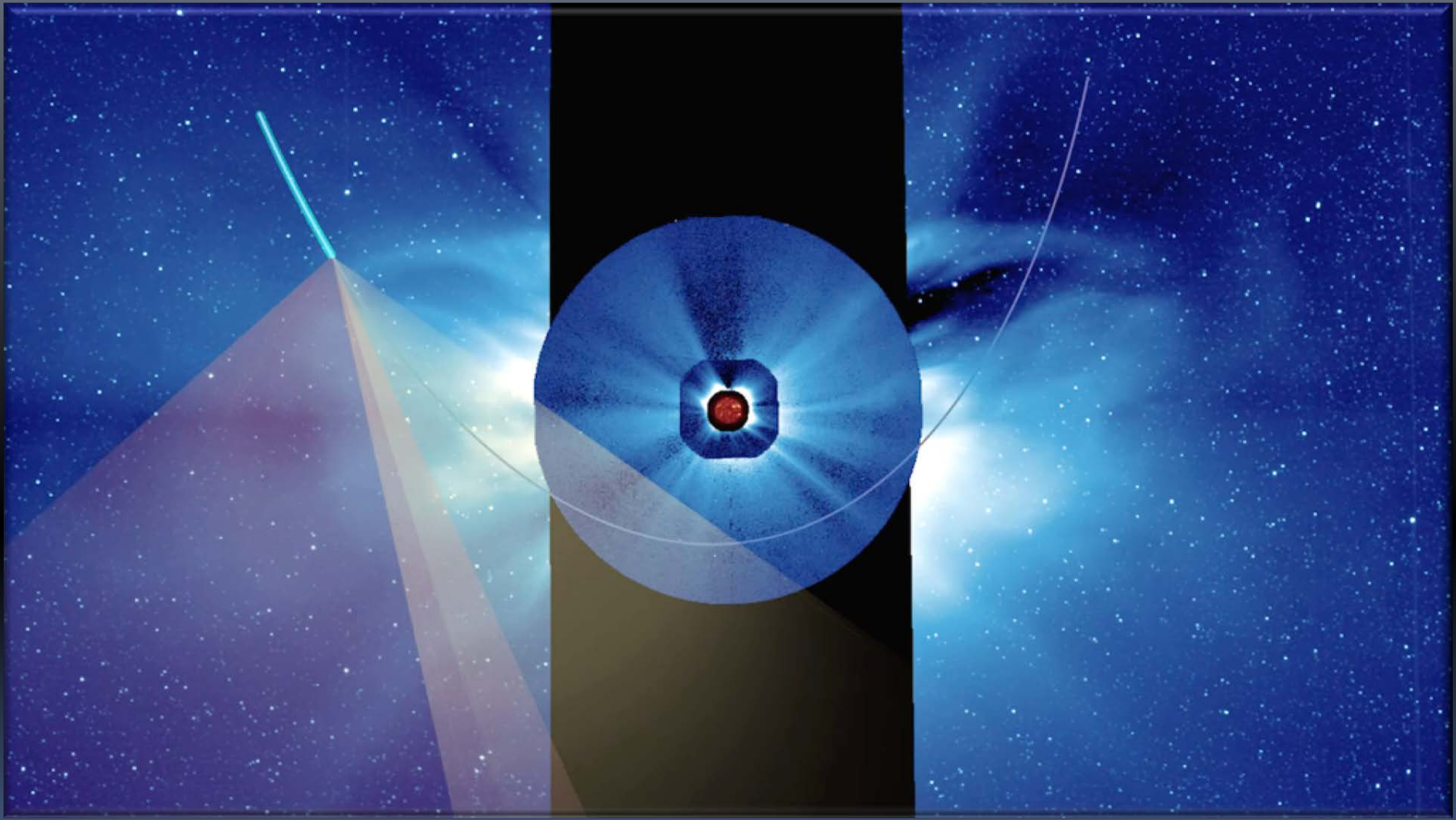
# What is WISPR (Wide Field Imager for Solar Probe Plus) Instrument Overview



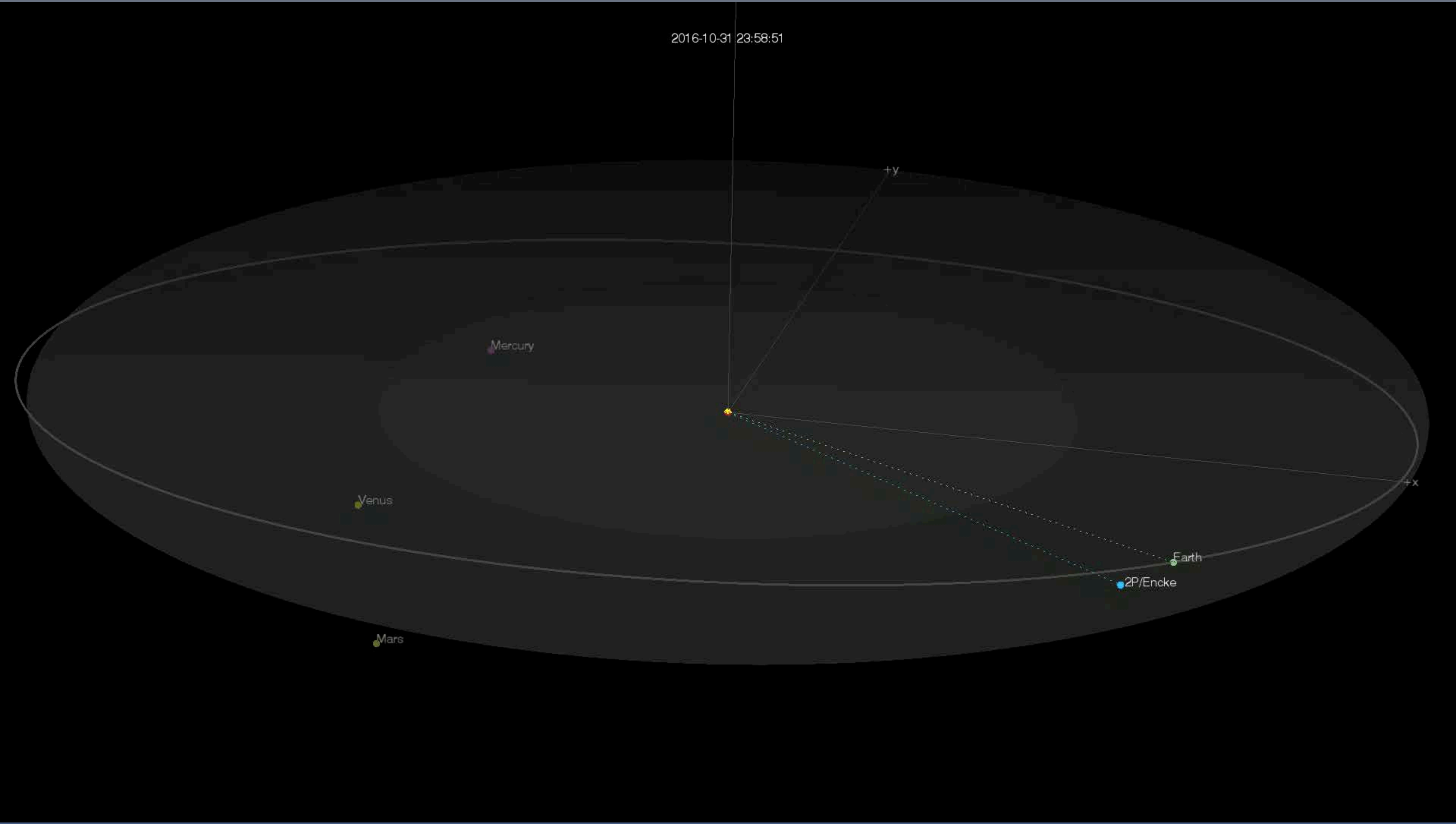

WISPR IDPU

# Simulation of WISPR Observations During a 10 $R_s$ PSP Perihelion



WISPR Consortium

# PSP and SO Orbit Plannings



# Conclusions

- Multipoint space observations have provided unique insights into heliospheric physics – what we call today the heliophysics observatory
- The solar wind outflow and CMEs are intimately connected to the photospheric magnetic fields
- Reliable space weather forecasts require a precise understanding of the underlying science – 3D topology, expansion, drag
- The challenging new missions Solar Probe, Solar Orbiter and Lagrange will certainly provide new breakthroughs

# Hellas 2017 - Efcharisto