



Linking CMEs to Associated Solar Phenomena

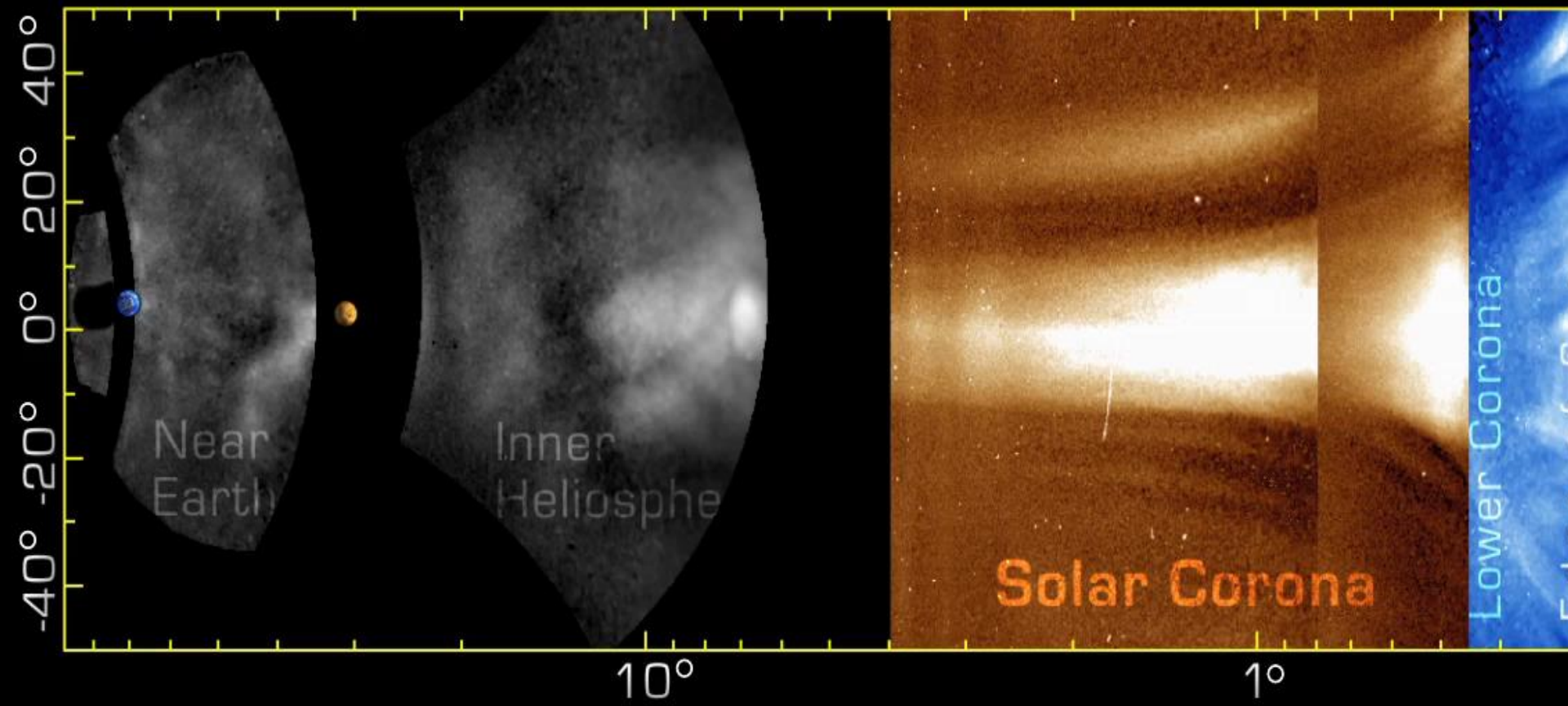
Peter Gallagher, Pietro Zucca, Eoin Carley

School of Physics
Trinity College Dublin
Ireland

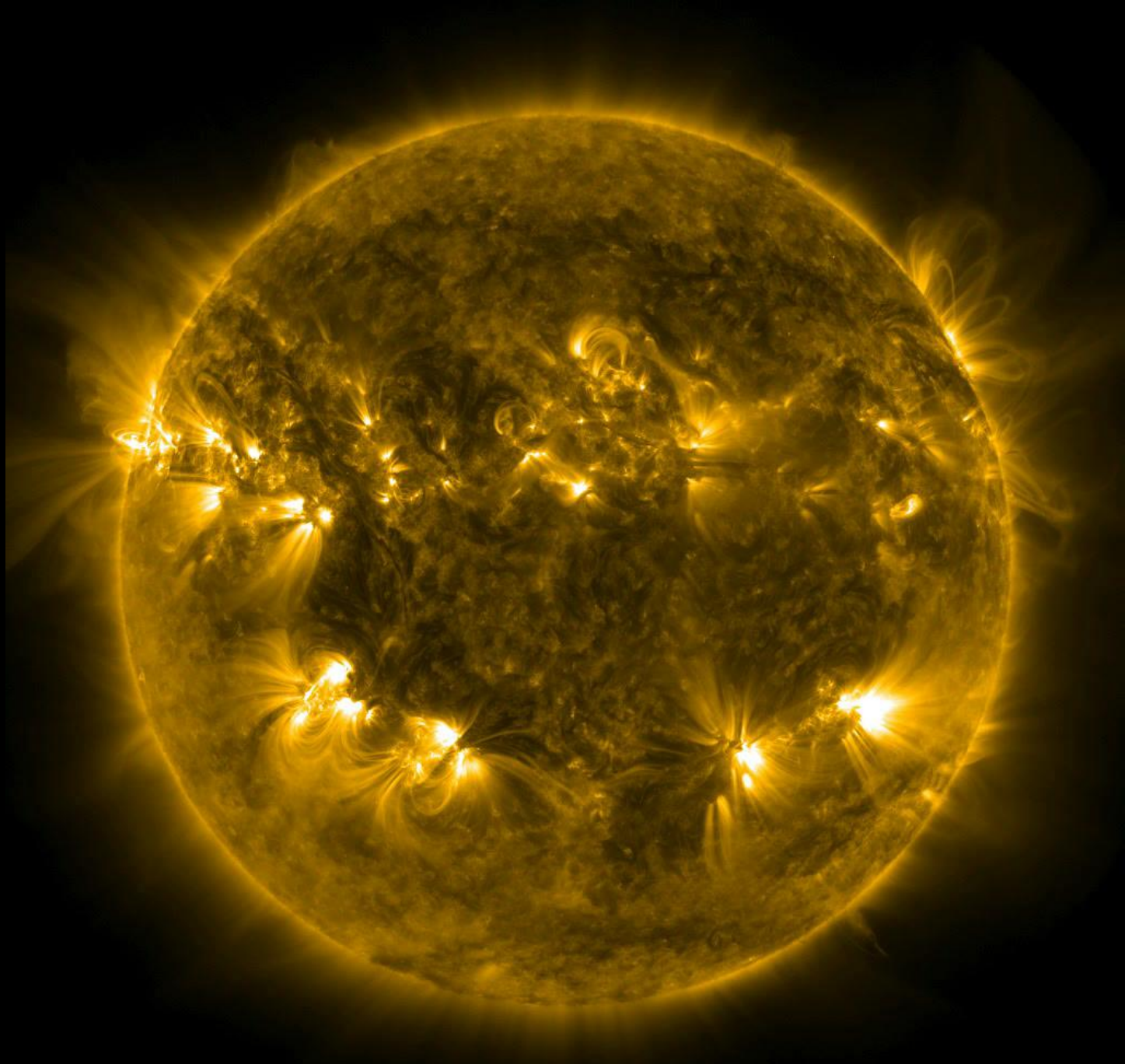
Göttingen Magnetischer Verein

- Trinity College Dublin was a site of Gottingen Magnetic Union (1836-1841).
- Magnetic measurements up to every 5 mins.
- Led to magnetic crusades by Edward Sabine and Humphrey Lloyd.
- Sabine (1852): Sunspot cycle identical to geomagnetic cycle.



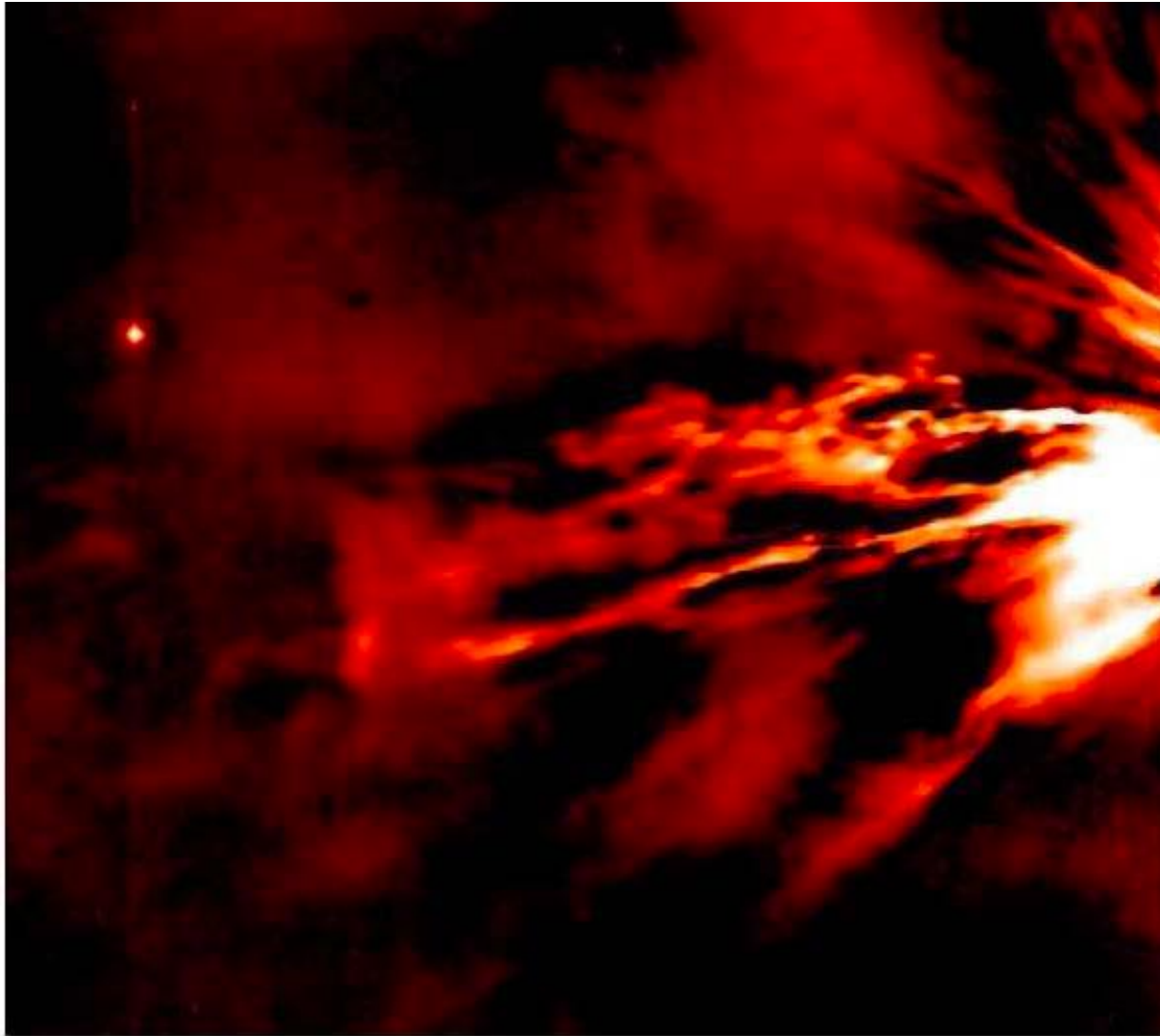


STEREO-A:12/11/08 12:40:00 AM

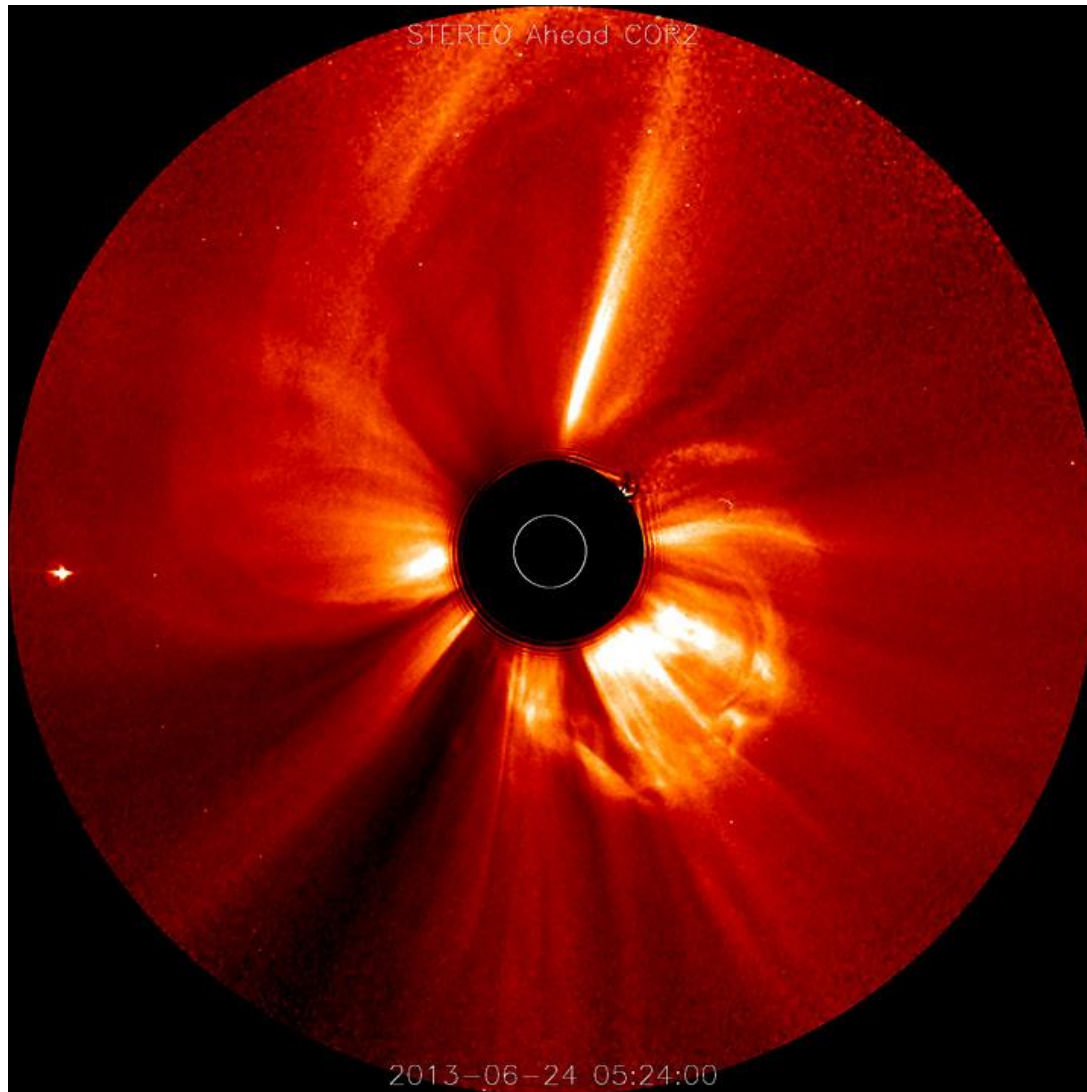


SDO/AIA 171 2011-11-20 21:28:13 UT

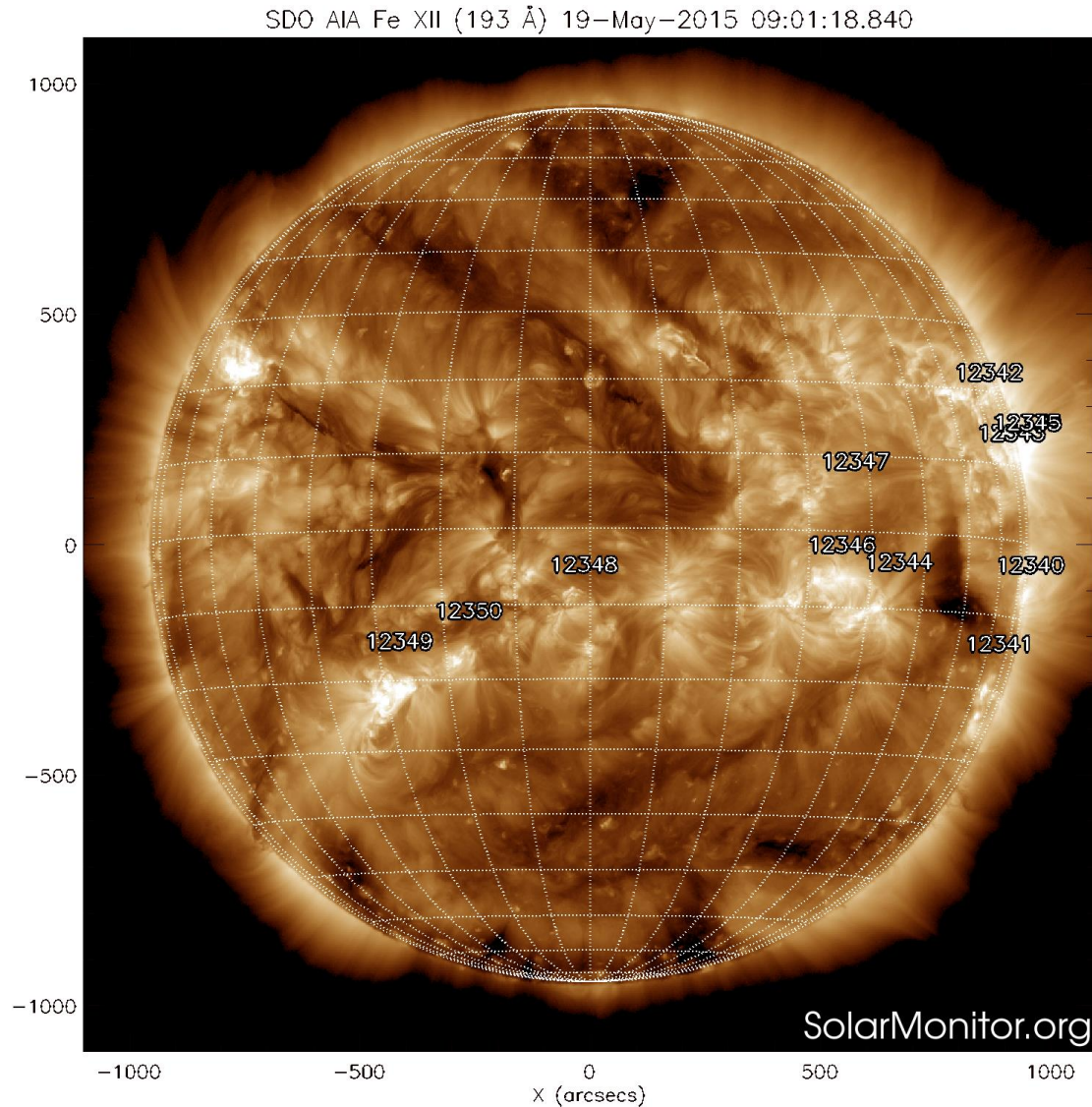
The Problem: Linking ICMEs to CMEs to Flares to Active Regions



The Problem: Linking ICMEs to CMEs to Flares to Active Regions

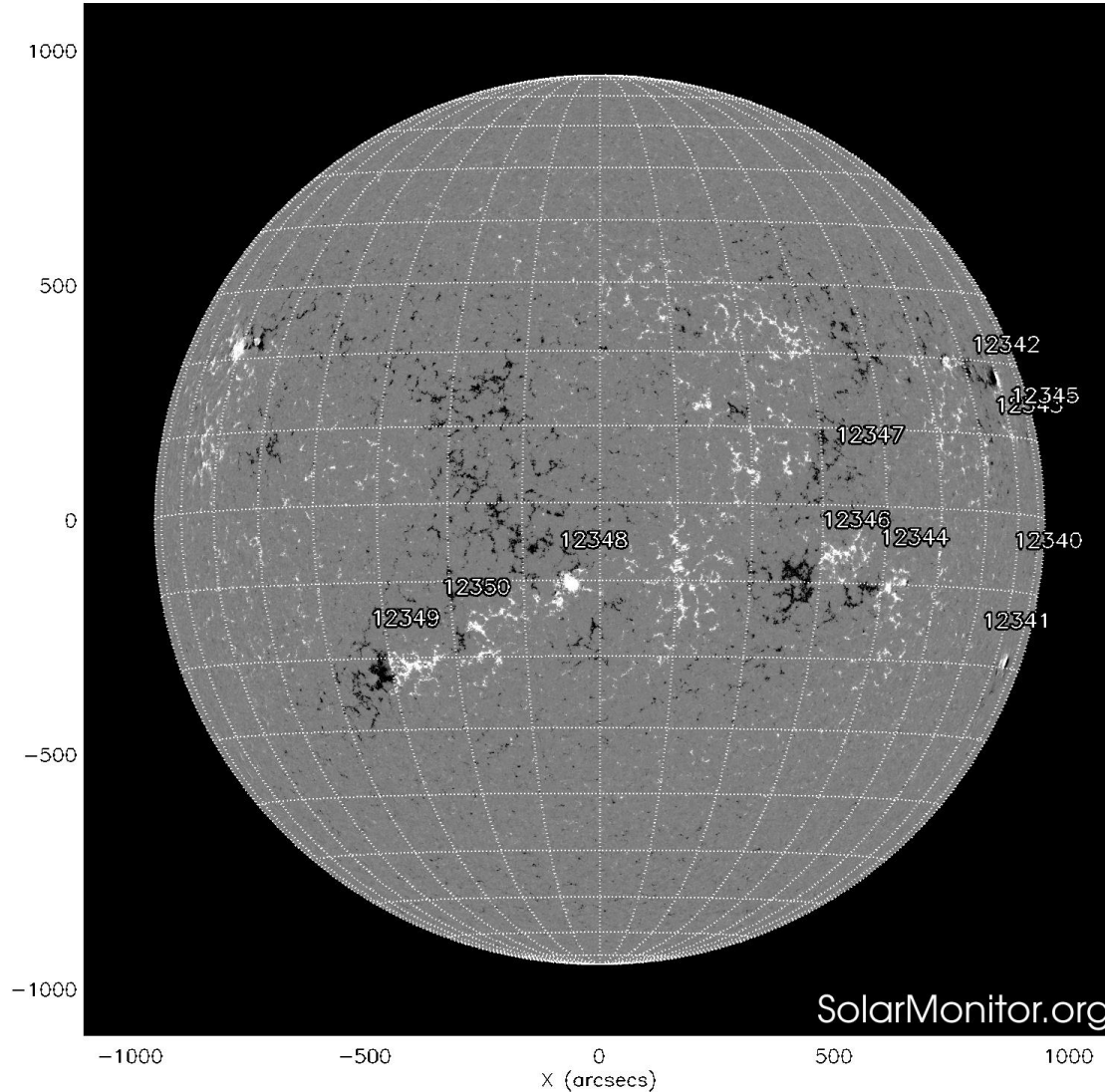


The Problem: Linking ICMEs to CMEs to Flares to Active Regions

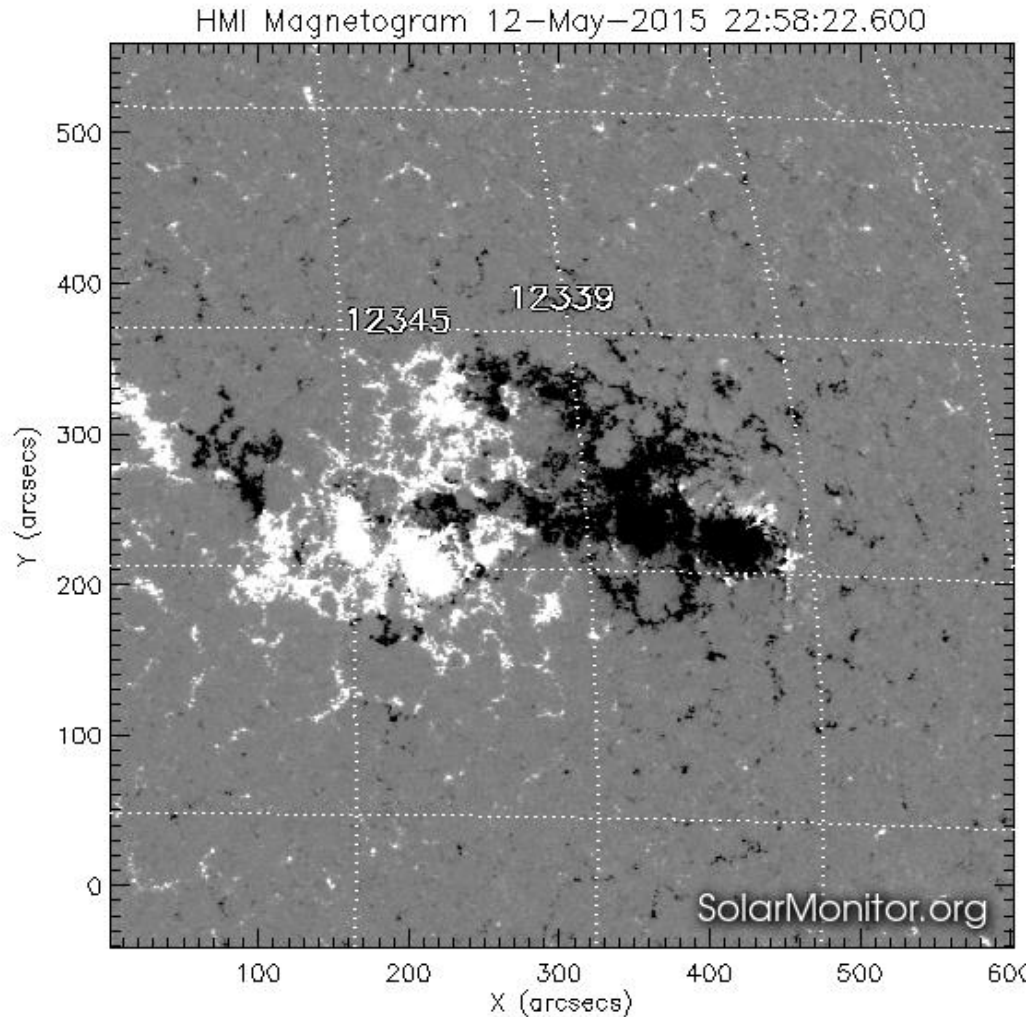


The Problem: Linking ICMEs to CMEs to Flares to Active Regions

SDO HMI Magnetogram 19-May-2015 08:22:23.400



The Problem: Linking ICMEs to CMEs to Flares to Active Regions



HELIO Propagation Model

HELIO Front End - Mozilla Firefox
Fichier Édition Affichage Historique Marque-pages Outils ?
msslr.phys.ucl.ac.uk/Helio/
HELIO
Windows Live Hotmail GRL Editor IRAP Webmail
HELIO Front End

HELIO
HELIOPHYSICS INTEGRATED OBSERVATORY
7
CAPSULES

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Data Cart

CME Forward Propagation Model (from Sun to Earth)

Parameters

Select Dates

1 2011-02-14T00:00:00

Select

Select Parameters

Select

Submit

Select Parameter

Parameter	Value	Description
Longitude	0	Heliographic longitude in degrees (e.g., the position of a flare)
Width	45.0	Longitudinal width of the CME in degrees
Speed	800	CME speed in km/s
SpeedError ±	0	Error in the speed in km/s

Diagram illustrating CME propagation from the Sun towards Earth. The Sun is shown on the left, emitting a CME (Coronal Mass Ejection) represented by a red cone. The CME's velocity, width, and longitude are labeled. The Earth is shown on the right, with the CME's path and position relative to the Earth's surface (latitude and longitude) indicated.

Help Cancel Ok

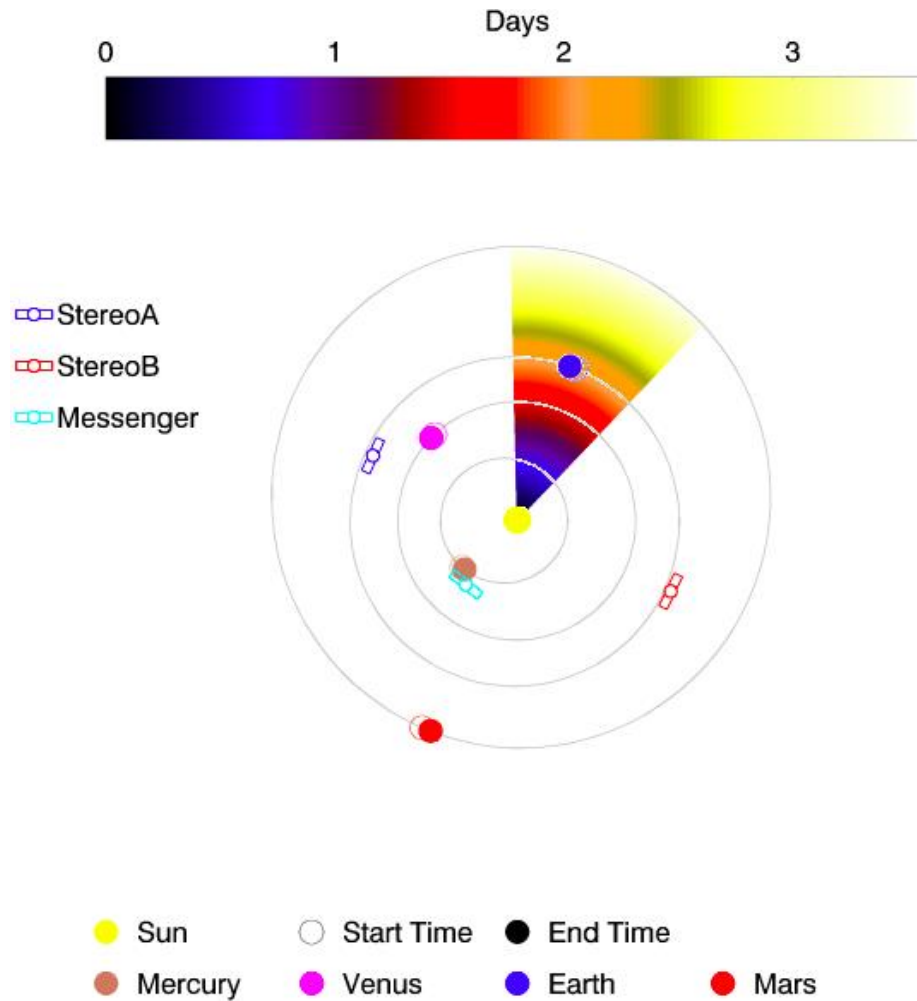
Step 1: Click 'Submit' to send the query to the server and retrieve the result. Depending on the query this may take a while.

Step 2: Define additional task specific parameters.

Step 3: Click 'Submit' to send the query to the server and retrieve the result. Depending on the query this may take a while.

FR 08:39 20/11/2012

HELIO Propagation Model



Ballistic Propagation Model

Input Property	Input Parameter
Initial time	τ_i
Initial distance	R_i
Final distance	R_f
Velocity range	$v \pm \Delta v$
Position angle	PA
Width	$(PA_N - PA_S) / 2$

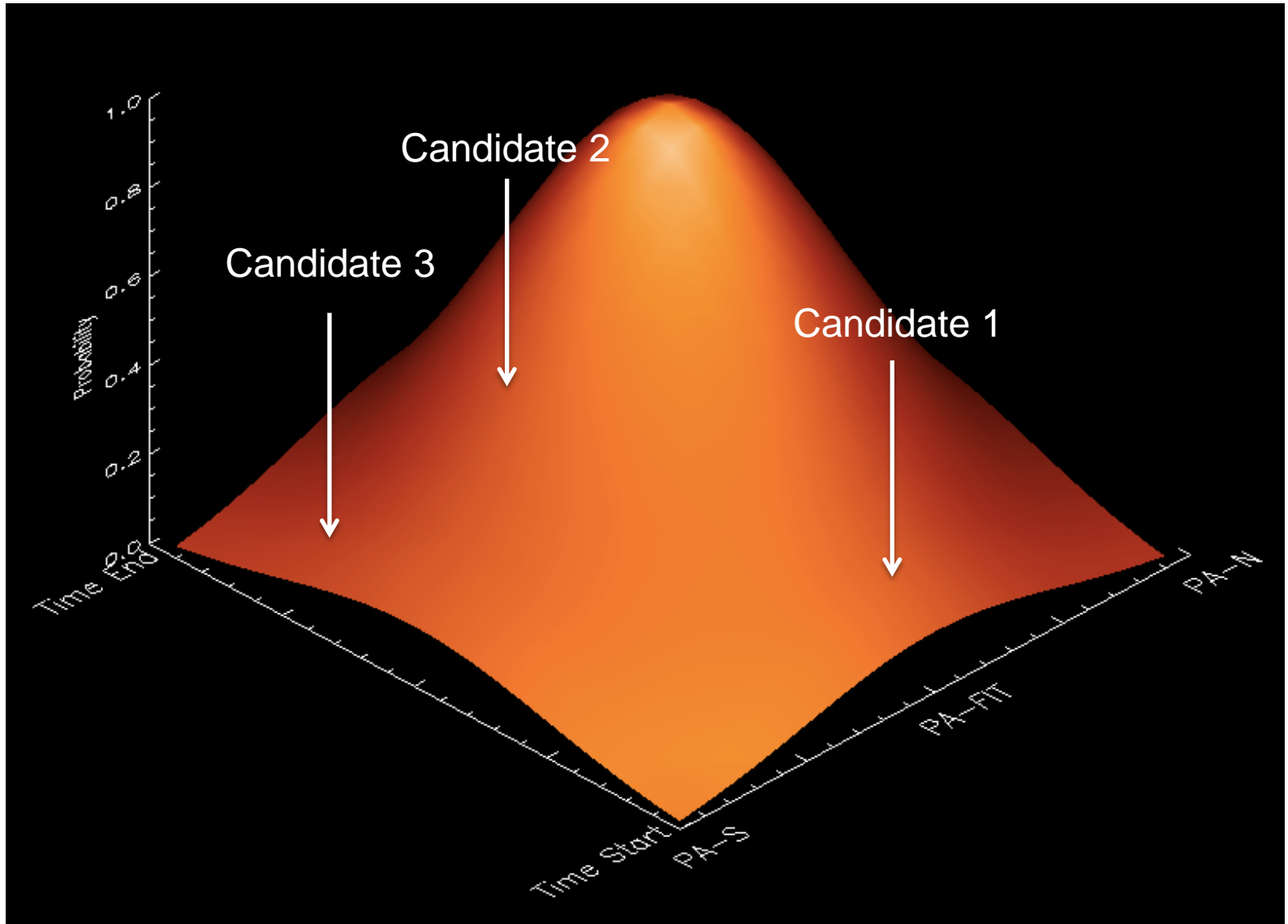
- Search time window: $t_f \pm D t_f = t_i - \frac{R_i - R_f}{v \pm Dv}$
- Search PA window: $PA \pm \Delta PA$

HI1 -> COR2

Input Property	Input Parameter
Initial time	τ_i
Initial distance	$12 R_S$
Final distance	$2 R_S$
Velocity range	200-600 km/s
Position angle	PA_{fit}
Width	$(PA_N - PA_S) / 2$

- Search time window: $t_{COR2} \pm D t_{COR2} = t_{HI1} - \frac{R_{HI1} - R_{COR2}}{v_{SW} \pm D v_{SW}}$
- Search PA window: $PA_{\text{fit}} \pm \Delta P$

Candidate Probability Space



HELCATS HI CME List



HELCATS

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WP2 Catalogue

HELIOSPHERIC IMAGER CME CATALOGUE

The CME catalogue identified from the STEREO-HI instruments is shown below

This is version: TBD of the catalogue, released yyyy-mm-dd

[f](#) [t](#) [y](#) [p](#) [Project Wiki](#) | [Contact Us](#)

Date range

PA mid: 0 to 360 degrees

PA width: 15 to 180 degrees

From to



Show entries

Search: [Show / hide columns](#)

ID	Date [UTC]	SC	PA-N [deg]	PA-S [deg]	Quality	PA fit [deg]
HCME_A__20070419_01	2007-04-19 13:30	A	40	140	Good	105
HCME_A__20070502_01	2007-05-02 00:50	A	65	100	Fair	90
HCME_A__20070506_01	2007-05-06 06:50	A	85	120	Fair	100
HCME_A__20070509_01	2007-05-09 13:30	A	50	125	Fair	90
HCME_A__20070516_01	2007-05-16 01:30	A	30	120	Good	80
HCME_A__20070518_01	2007-05-18 00:10	A	95	115	Fair	110
.....

Case Study



Low Coronal Event Catalogue

Catalogue of events occurring the low corona which were associated with CMEs detected with the Heliospheric Imagers on board the STEREO spacecraft.

<1> No.	<2> Spacecraft (Stereo A/B)	<3> HI Date and Time (UT)	<4> HI PA North (degrees)	<5> HI PA South (degrees)	<6> COR2 Date and Time search window (UT)	<7> COR2 Candidates Date and Time (UT)	<8> Flare Estimated Date and Time (UT)	<9> GOES Class	<10> NOAA Region (Location)	<11> Hale Class
29	A	29-Jul-2007 07:30	240	300						

Case Study

- ***** HI2 Parameters *****
- HI2 Start Time : 29-Jul-2007 07:30:00.000
-
- ***** COR2 Search Parameters *****
- COR2 Start Time: 28-Jul-2007 18:37:46.668
- COR2 End Time : 29-Jul-2007 05:05:12.500
- Window (hours) : 10.457176
- COR2 PA-N : 240.000
- COR2 PA-S : 300.000
-
- ***** Flare Search Parameters *****
- Flare Start Time: 28-Jul-2007 17:25:22.918
- Flare End Time : 28-Jul-2007 18:01:34.793
- Window (mins) : 36.197919

Case Study



Low Coronal Event Catalogue

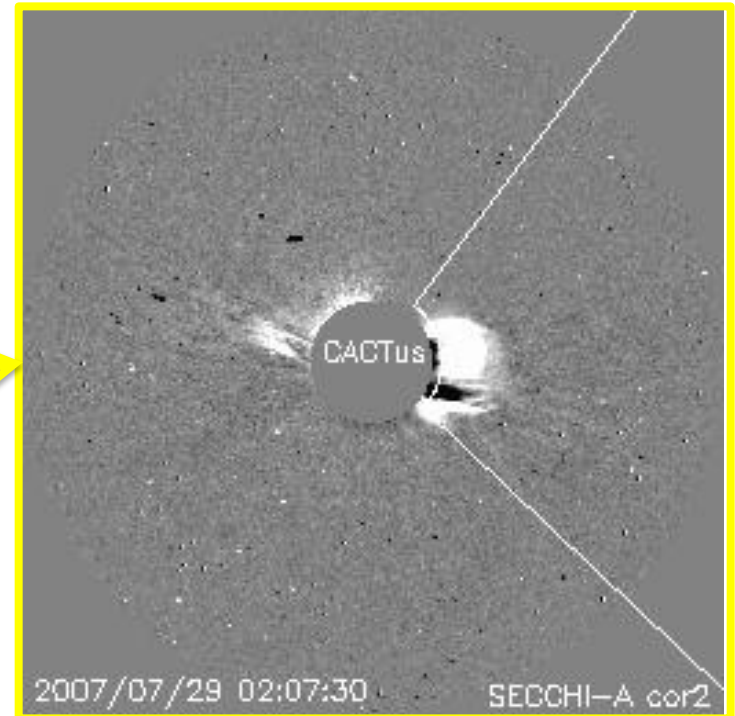
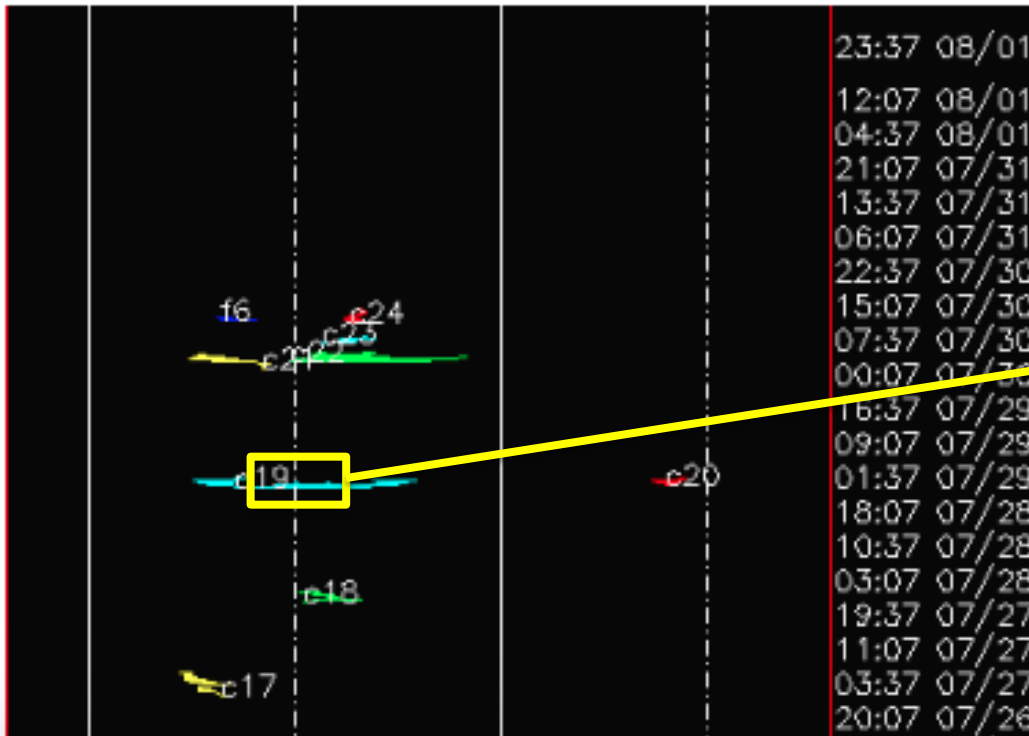
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<1> No.	<2> Spacecraft (Stereo A/B)	<3> HI Date and Time (UT)	<4> HI PA North (degrees)	<5> HI PA South (degrees)	<6> COR2 Date and Time search window (UT)	<7> COR2 Candidates Date and Time (UT)	<8> Flare Estimated Date and Time (UT)	<9> GOES Class	<10> NOAA Region (Location)	<11> Hale Class
29	A	29-Jul-2007 07:30	240	300	28-Jul-2007 18:37 29-Jul-2007 05:05		28-Jul-2007 17:25 28-Jul-2007 18:01			

Case Study

Search Times: 28-Jul-2007 18:37
29-Jul-2007 05:05

Search PAs: 240-300



S 180
W 270
N 360
E 90

CME Candidate: 29-Jul-2007 01:37 | PA 275° | Width 96° | 625 km/s

Case Study



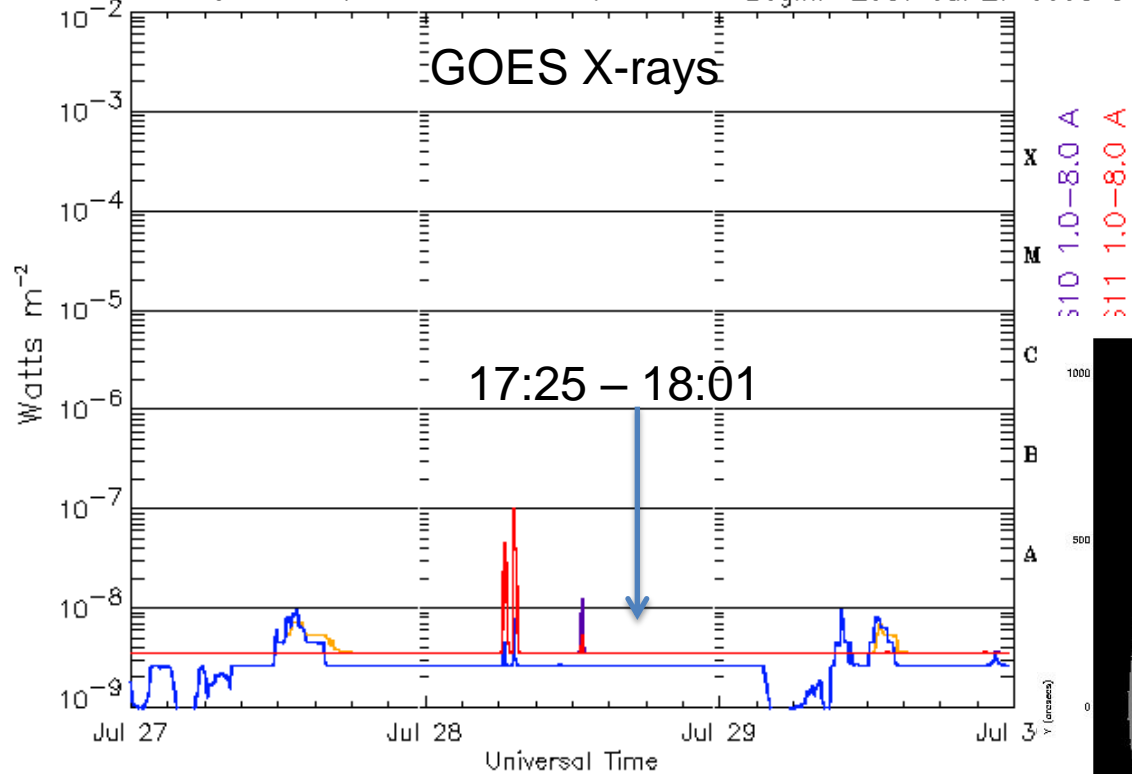
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<1> No.	<2> Spacecraft (Stereo A/B)	<3> HI Date and Time (UT)	<4> HI PA North (degrees)	<5> HI PA South (degrees)	<6> COR2 Date and Time search window (UT)	<7> COR2 Candidates Date and Time (UT)	<8> Flare Estimated Date and Time (UT)	<9> GOES Class	<10> NOAA Region (Location)	<11> Hale Class
29	A	29-Jul-2007 07:30	240	300	28-Jul-2007 18:37 29-Jul-2007 05:05	29-Jul-2007 01:37	28-Jul-2007 17:25 28-Jul-2007 18:01			

Case Study

GOES Xray Flux (5 minute data) Begin: 2007 Jul 27 0000 UTC



X
M
C
B
A

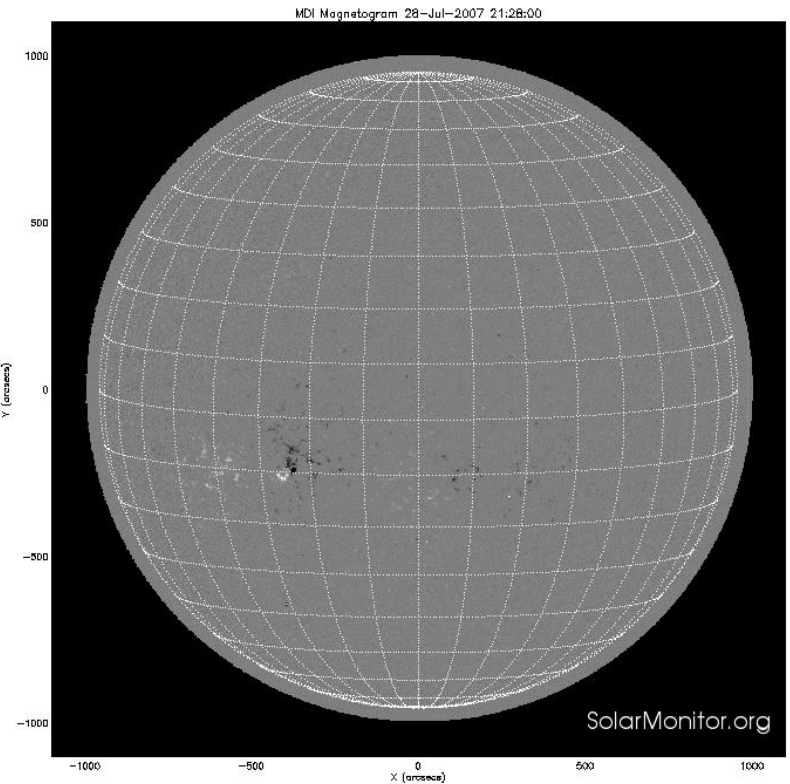
310 1.0-8.0 A
311 1.0-8.0 A

17:25 - 18:01

Updated 2007 Jul 29 23:41:04 UTC

NOAA/SEC Boulder

Active Regions



Case Study

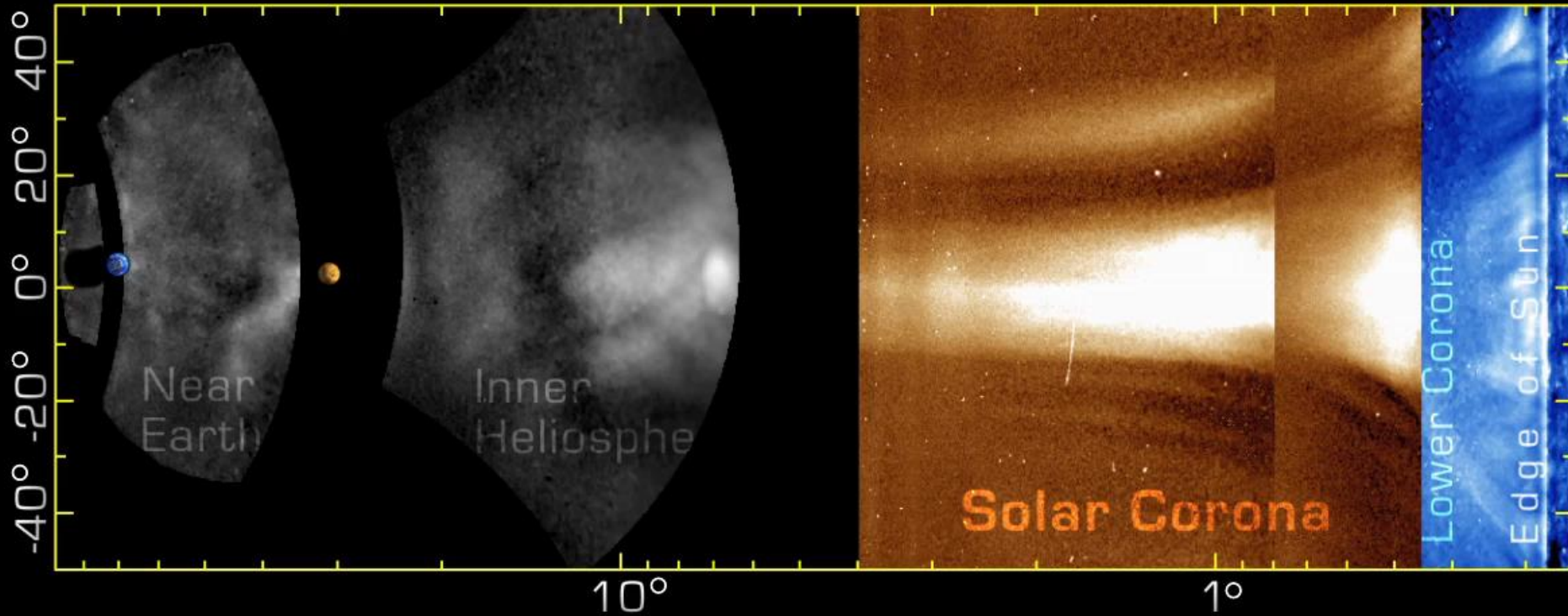


Low Coronal Event Catalogue

Catalogue of events occurring the low corona which were associated with CMEs detected with the Heliospheric Imagers on board the STEREO spacecraft.

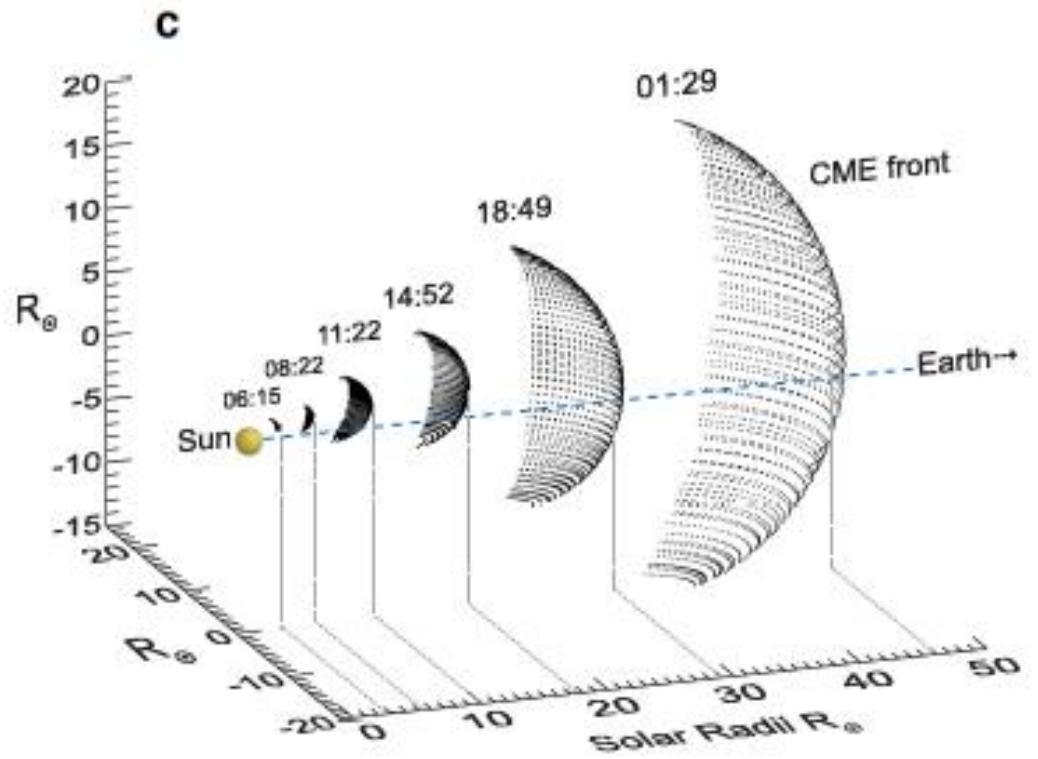
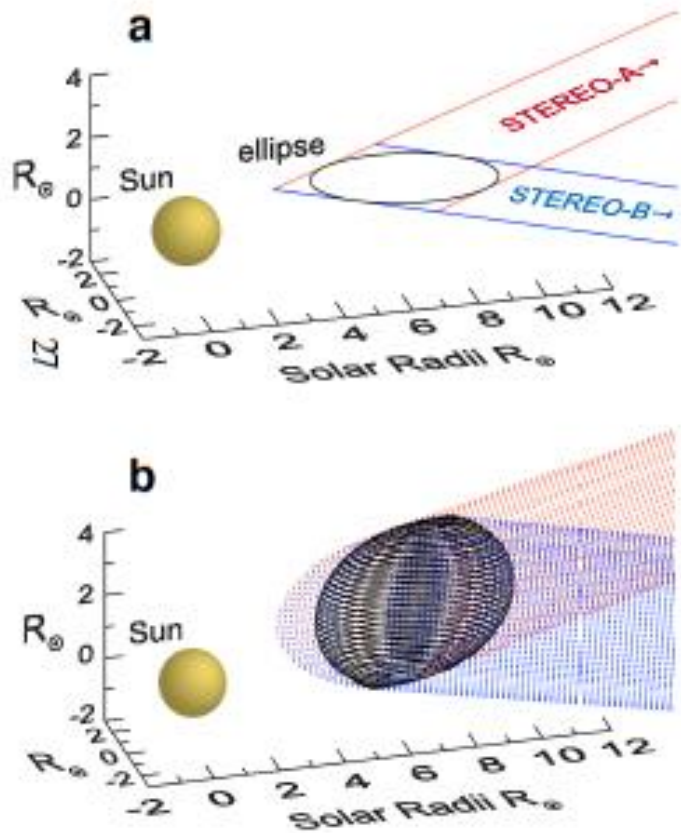
<1> No.	<2> Spacecraft (Stereo A/B)	<3> HI Date and Time (UT)	<4> HI PA North (degrees)	<5> HI PA South (degrees)	<6> COR2 Date and Time search window (UT)	<7> COR2 Candidates Date and Time (UT)	<8> Flare Estimated Date and Time (UT)	<9> GOES Class	<10> NOAA Region (Location)	<11> Hale Class
29	A	29-Jul-2007 07:30	240	300	28-Jul-2007 18:37 29-Jul-2007 05:05	29-Jul-2007 01:37	28-Jul-2007 17:25 28-Jul-2007 18:01	None	None	NA

Position Angle Variation with Distance

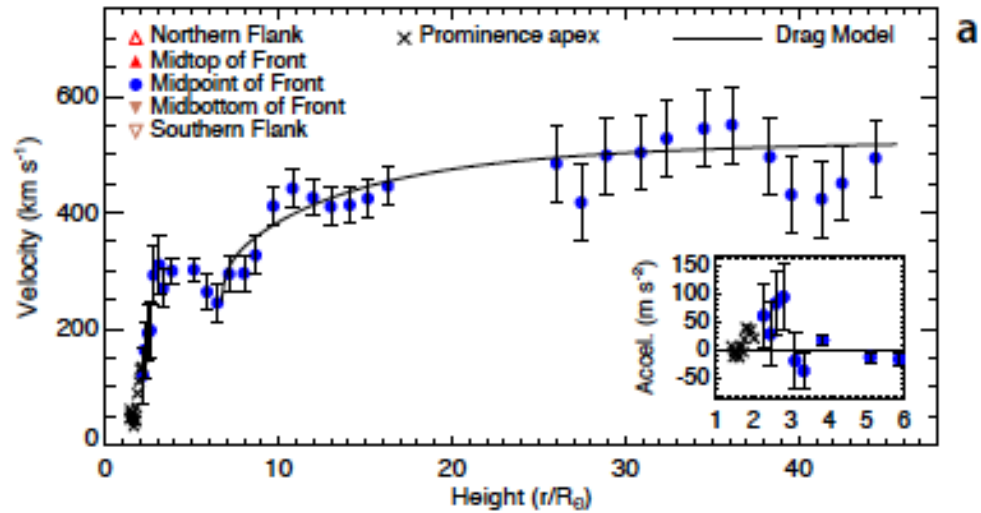


STEREO-A: 12/11/08 12:40:00 AM

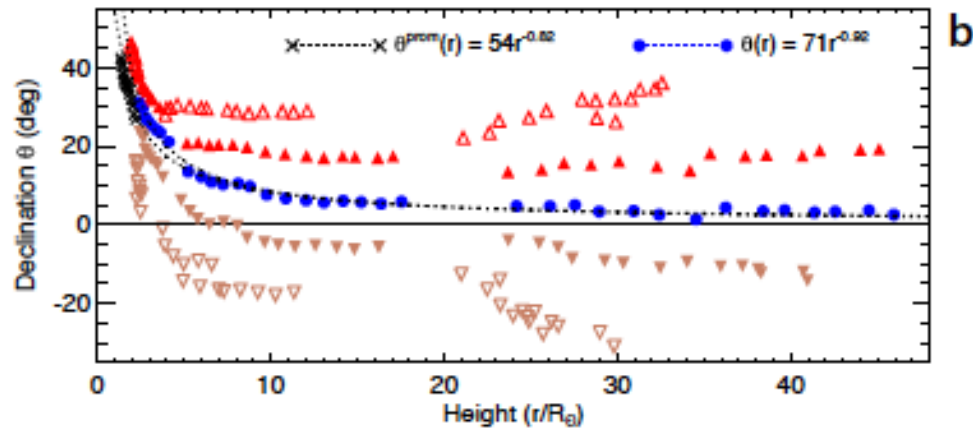
CME Deflection



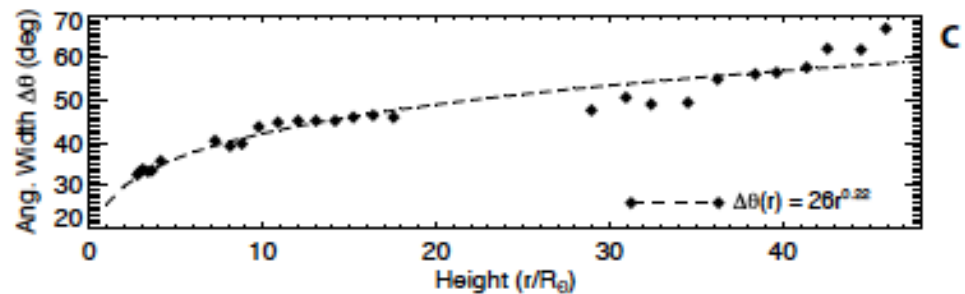
Velocity



Declination



Width



Improved Inverse Tracking

- Use variable velocity profile

$$t_f = t_i - \int_{R_i}^{R_f} \frac{1}{v(R)} dR$$

- Drag-based propagation model to obtain $v(R)$

- SOTERIA Drag-Based Model

<http://oh.geof.unizg.hr/DBM/dbm.php>

- E.g Vršnak et al. (2010)

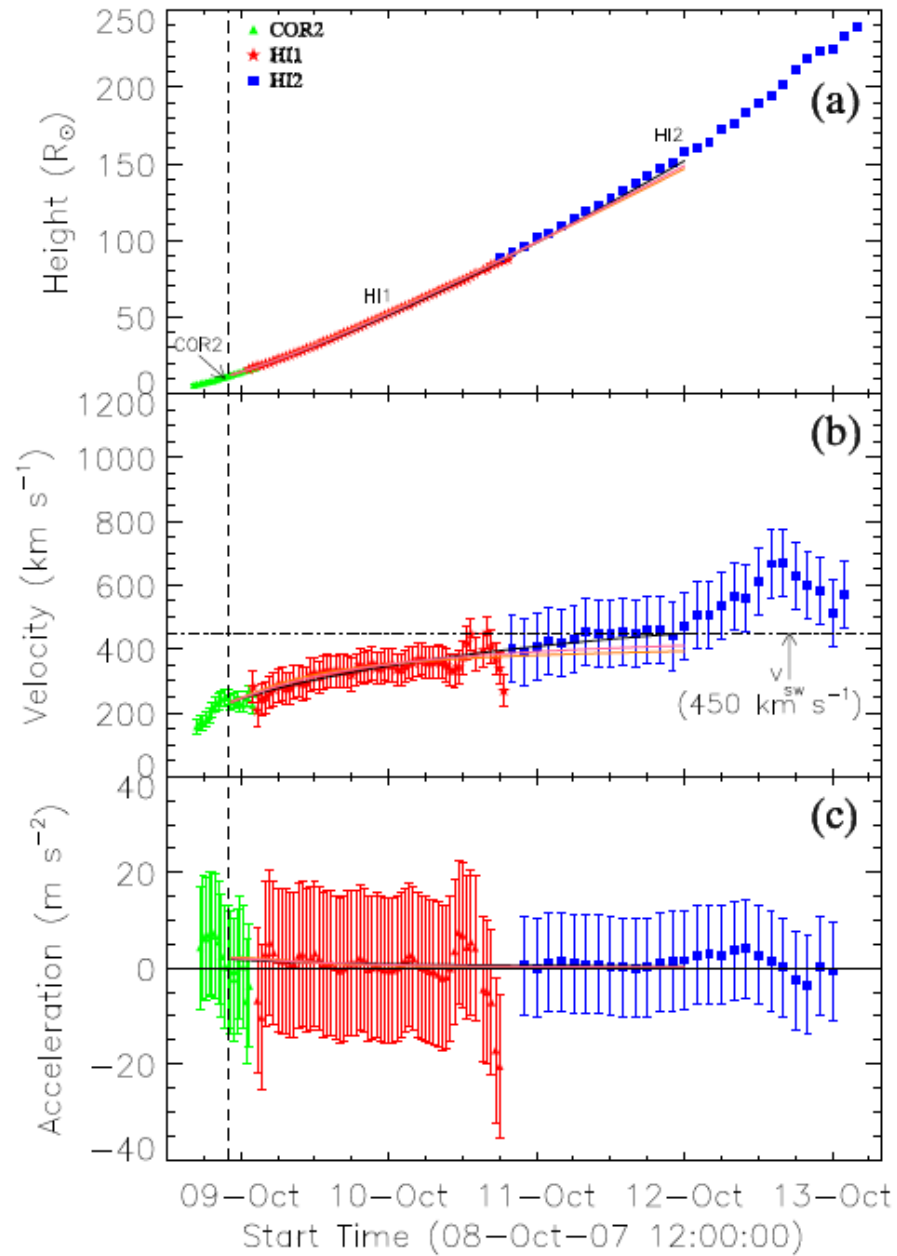
Modelling of CME Motion

- Simple model for CME propagation in heliosphere

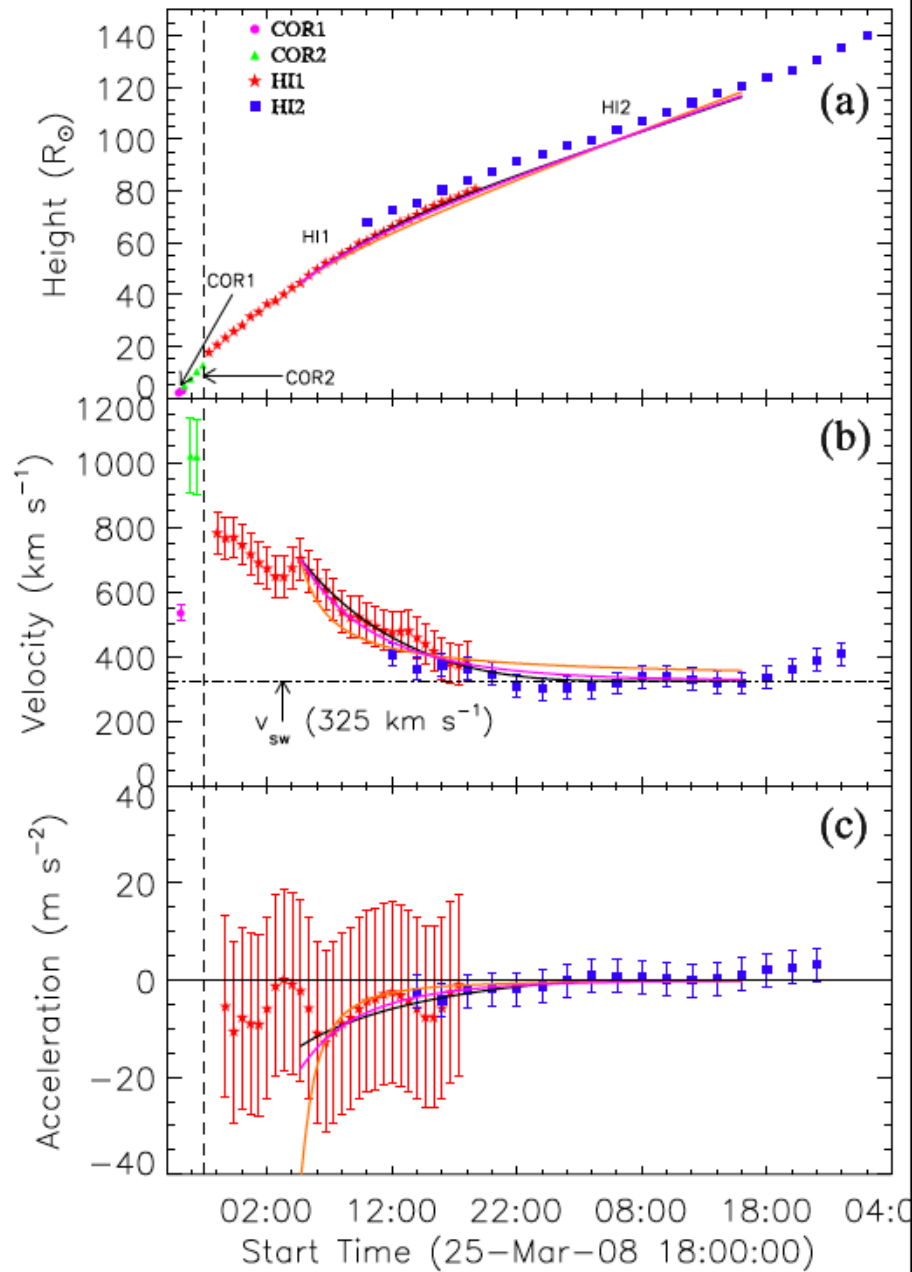
$$r \frac{dv}{dt} = -\frac{1}{2} r D v^2 A C_D$$

- Numerical integration gives $v(r)$.
- Vršnak et al. (2002), Reiner et al. (2003), Tappin (2006).

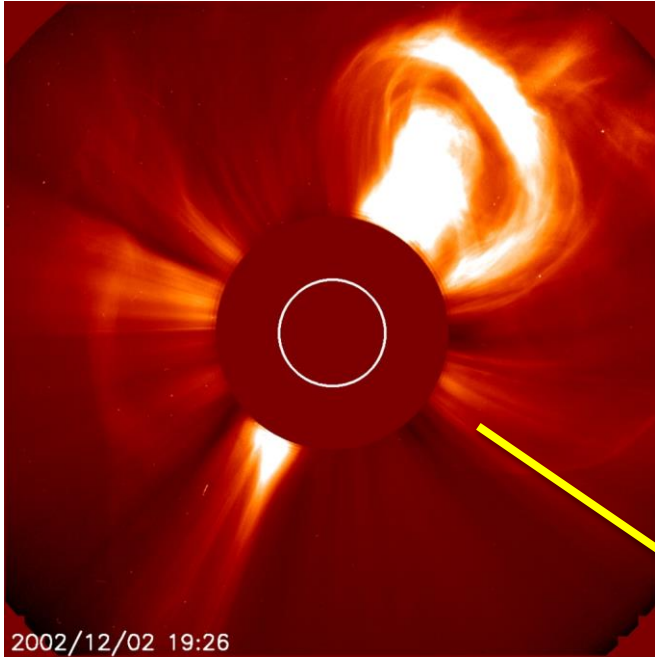
Slow CME



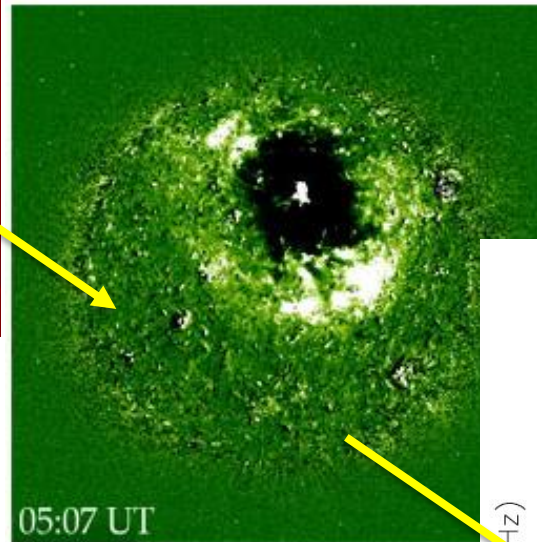
Fast CME



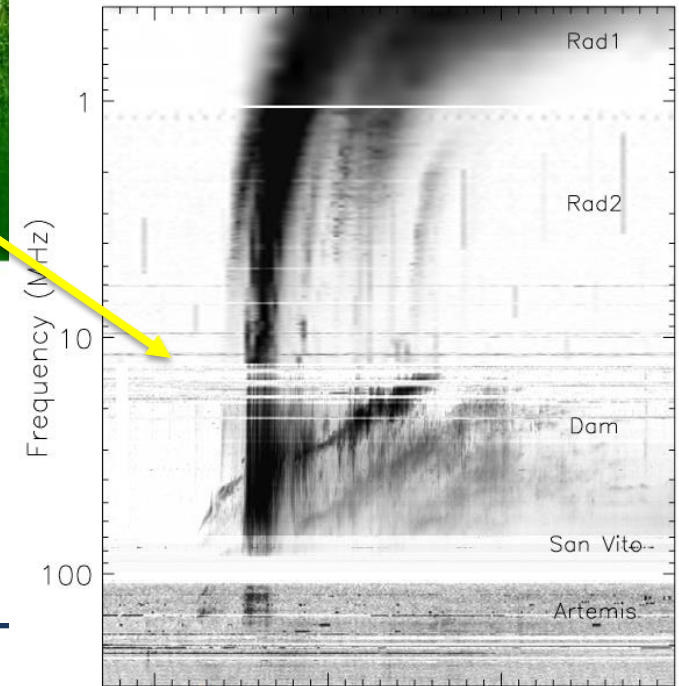
Coronal Mass Ejections



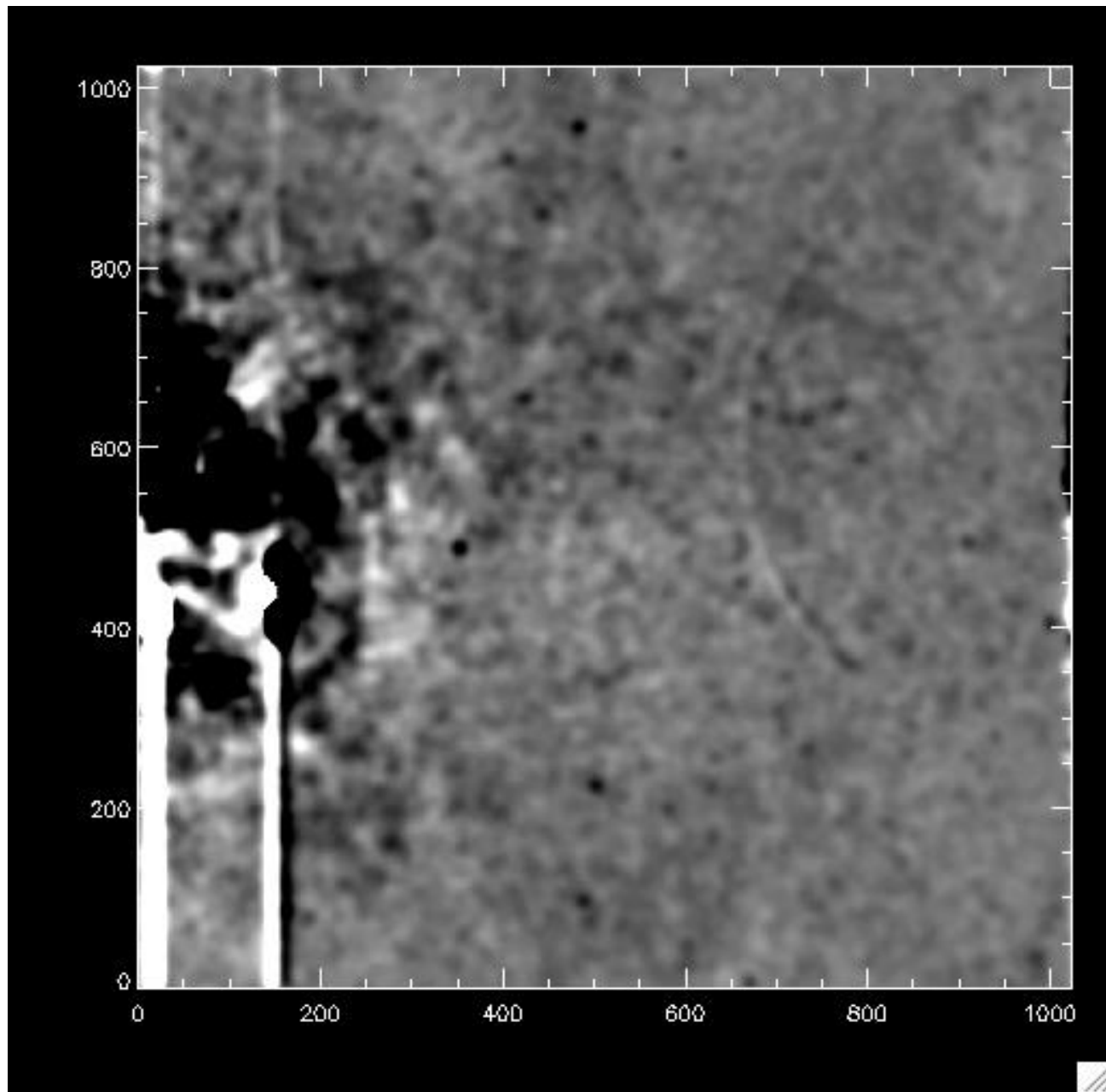
Coronal Waves



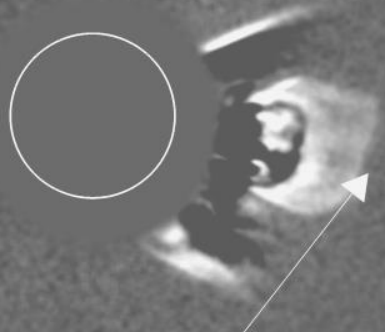
Radio Bursts



**How are these related?
How are shocks formed?**

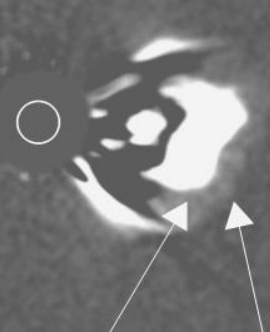


COR1 A 2008-04-05T16:15



CME

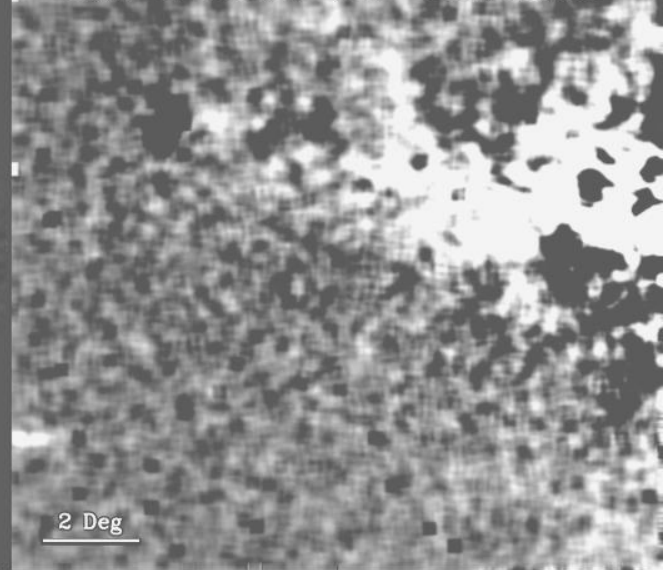
COR2 A 2008-04-05T17:22



CME

Shock

HI1 A 2008-04-06T02:09



2 Deg

COR1 B 2008-04-05T16:15



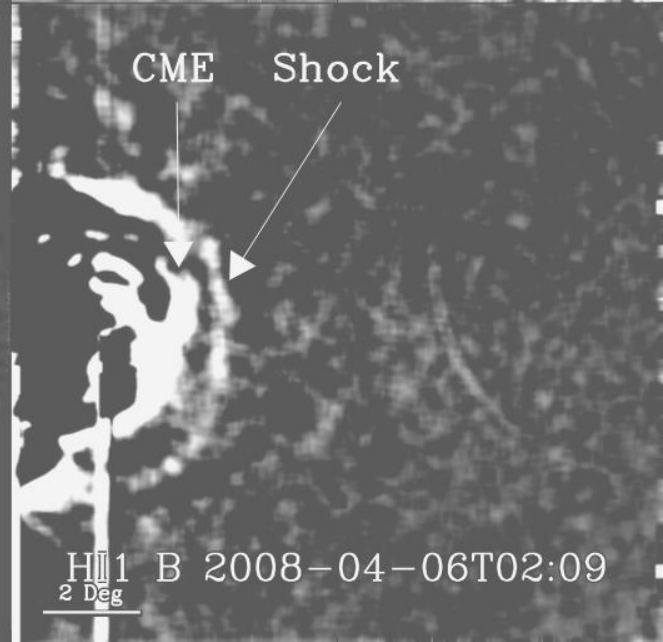
CME

COR2 B 2008-04-05T17:22



CME

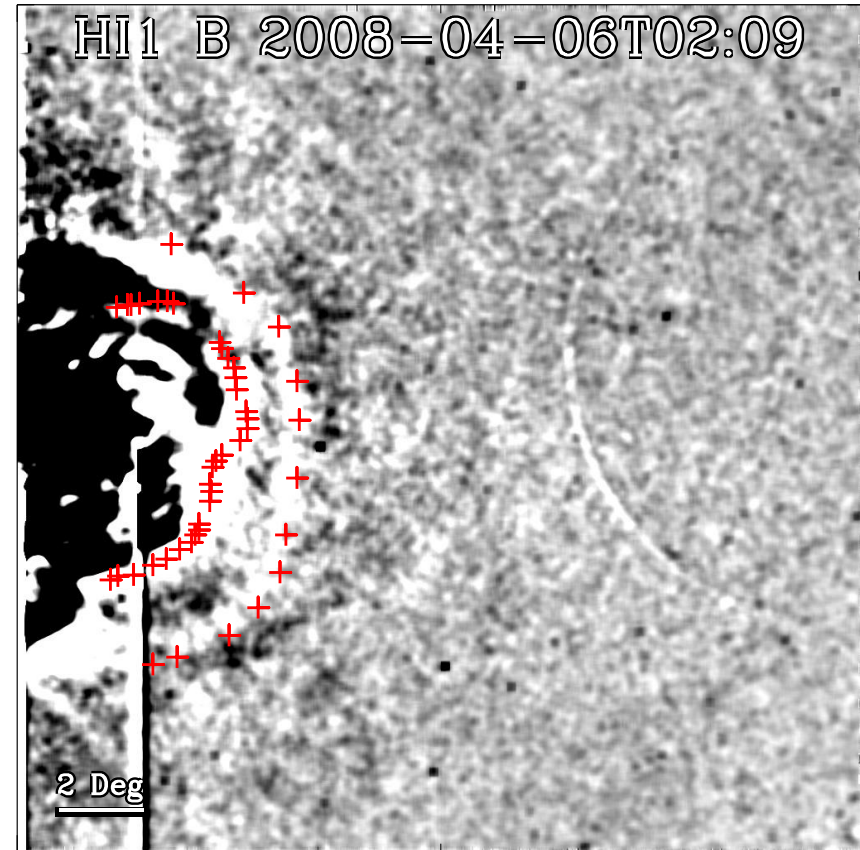
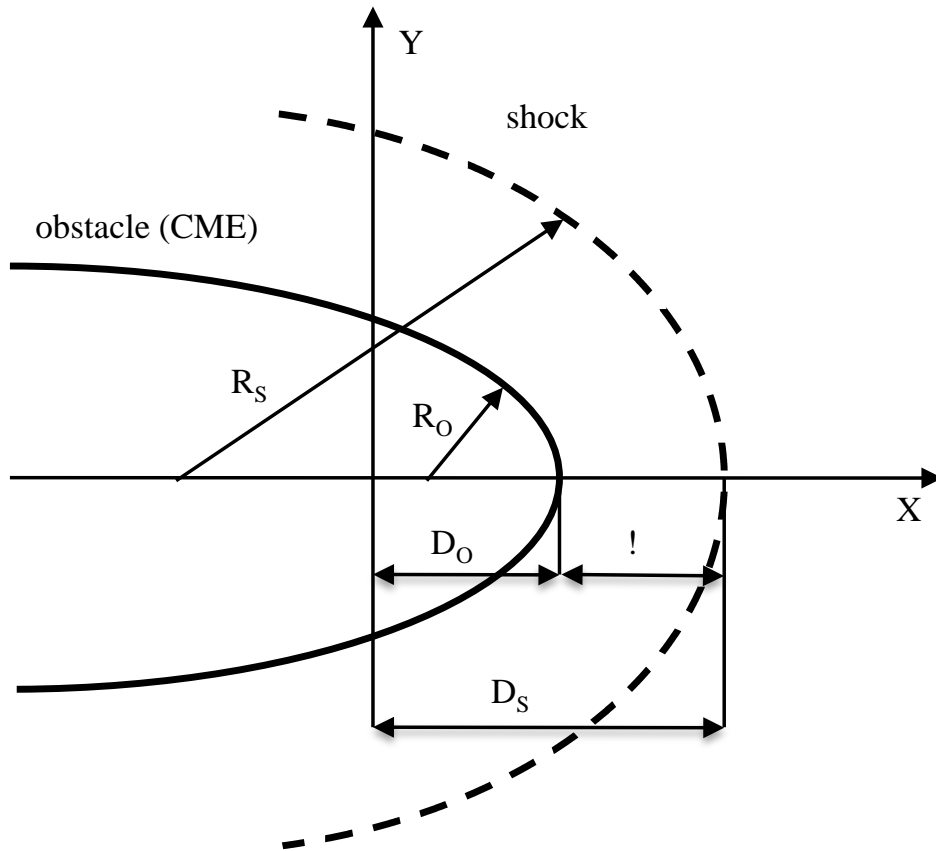
Shock



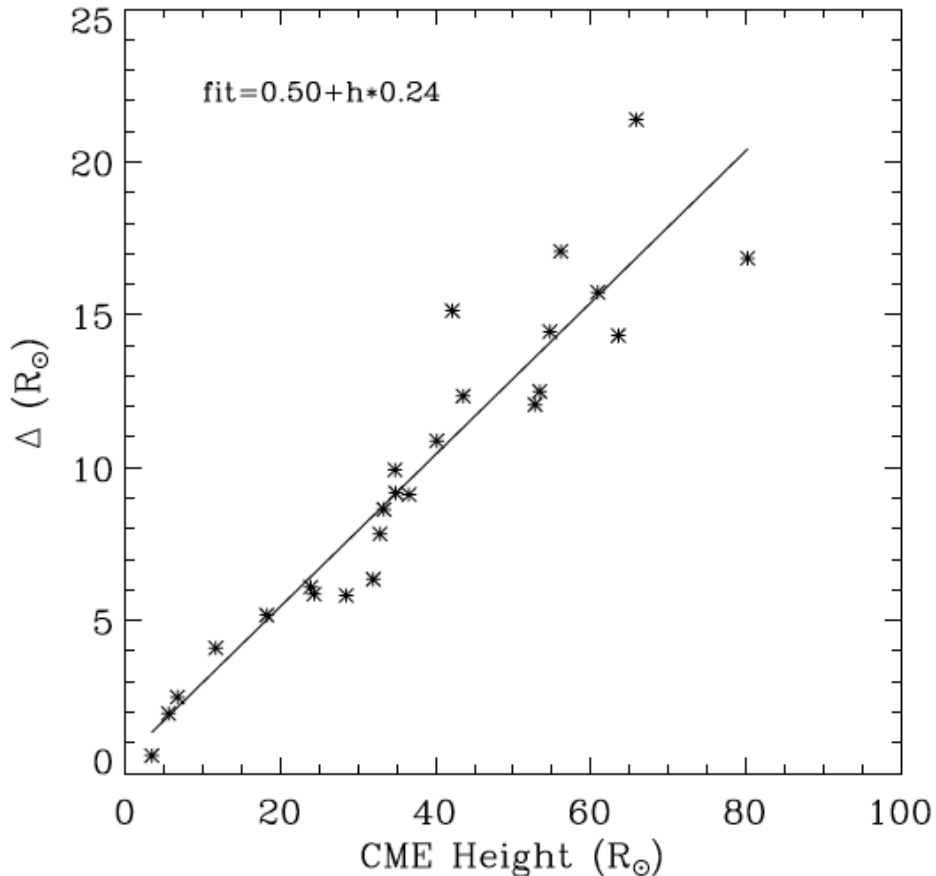
2 Deg

HI1 B 2008-04-06T02:09

CME and Shock-Front Positions



CME-Driven Shock Properties

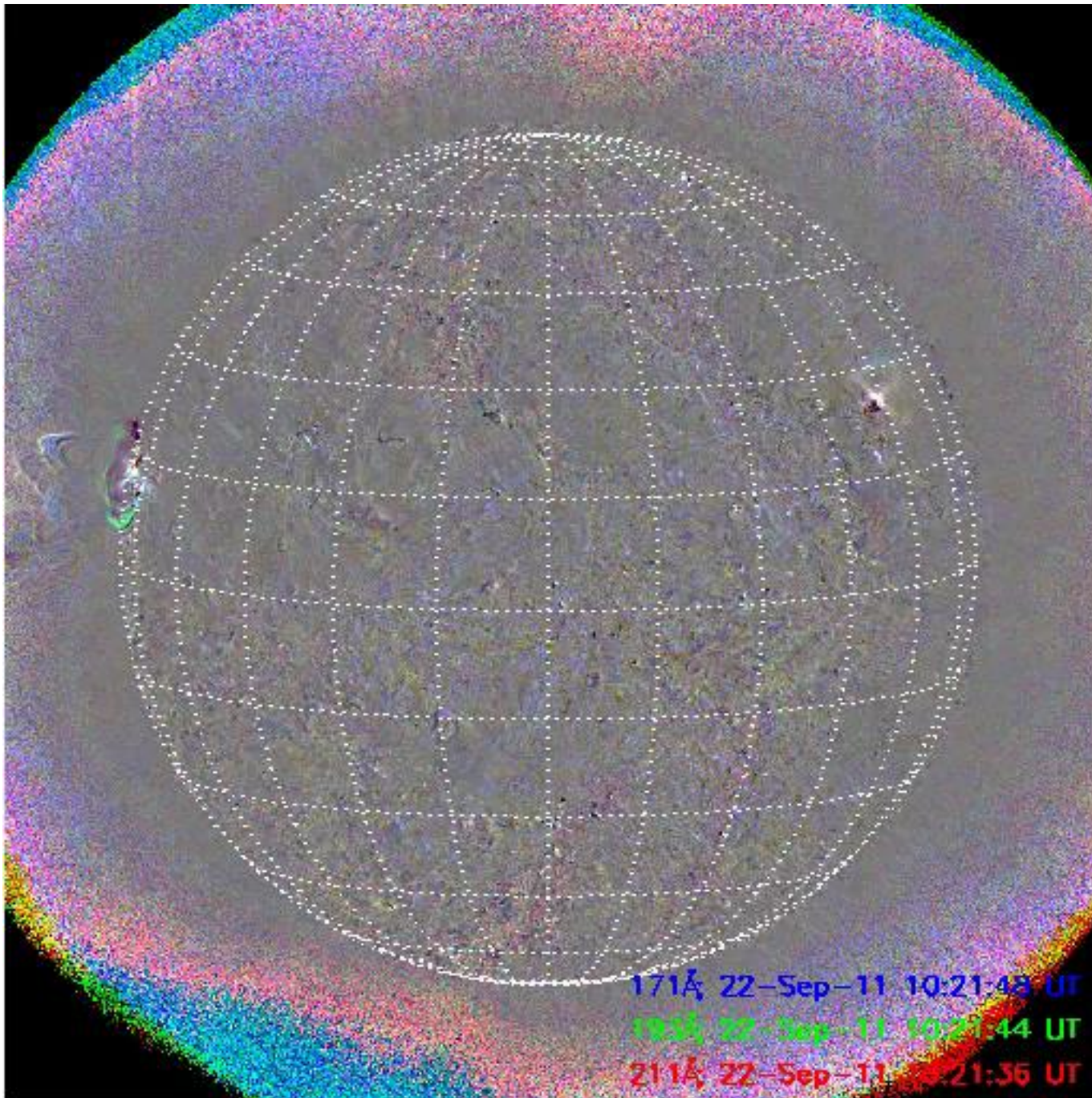


Shock standoff distance (Δ) varies linearly with height.

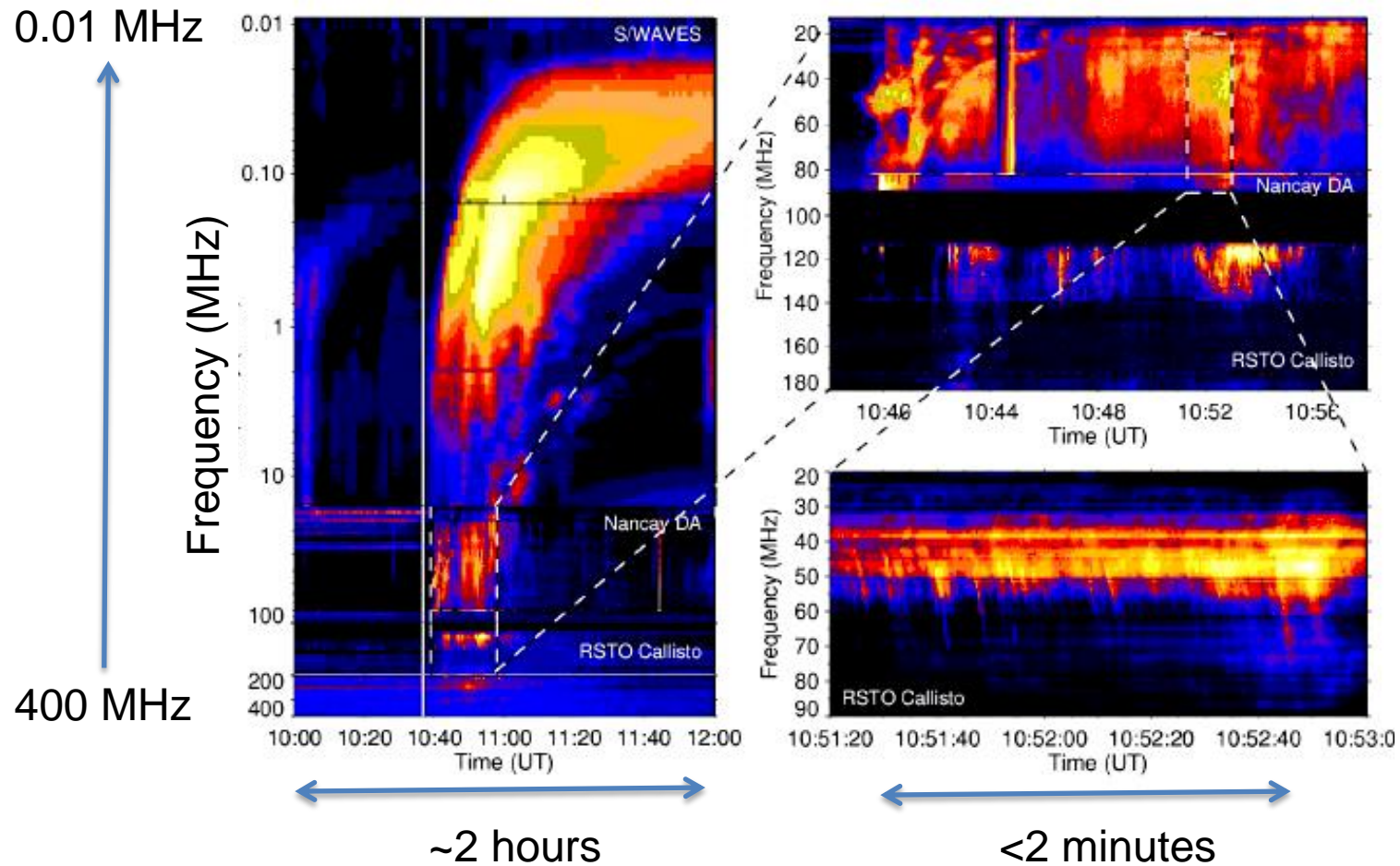
Linear extrapolation gives $\Delta \sim 40 R_{\text{sun}}$ at Earth.

Can give improved estimate of shock arrival time at Earth.

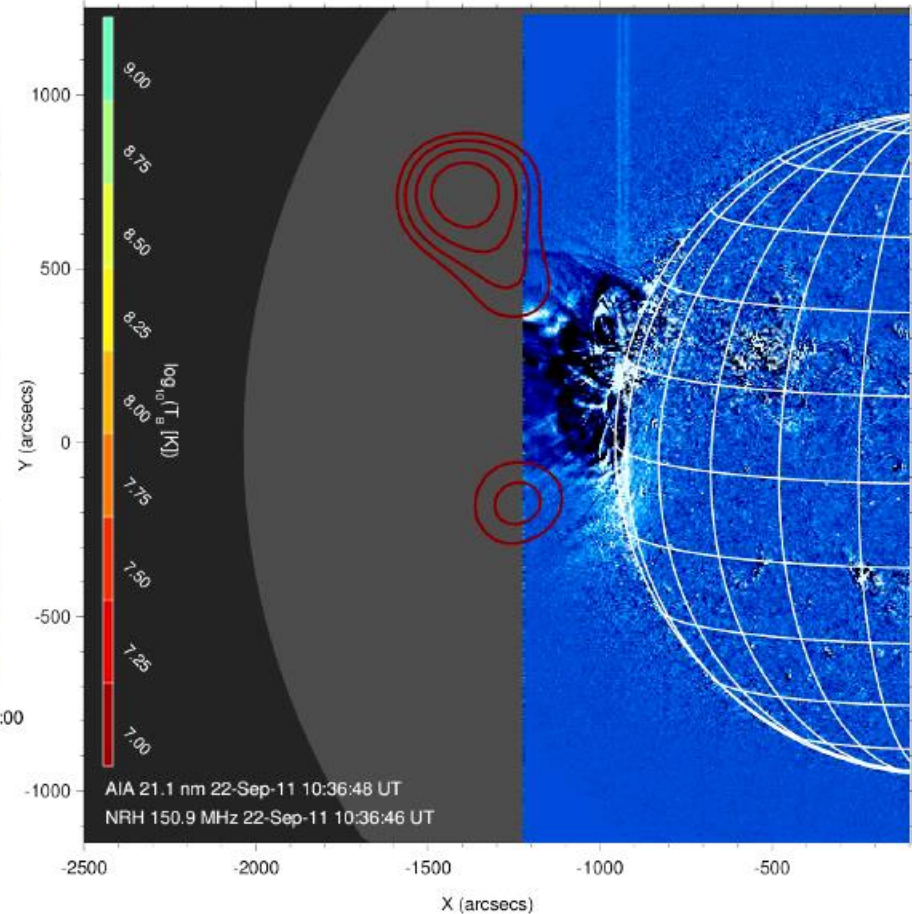
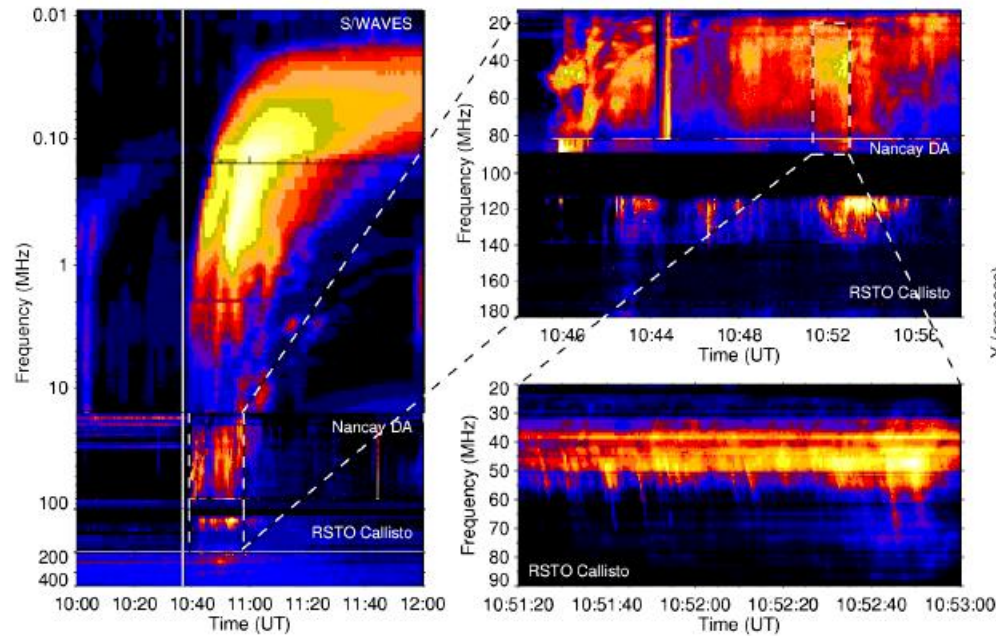
CME and EUV Wave



Birr, STEREO and Nancay Radio Spectra

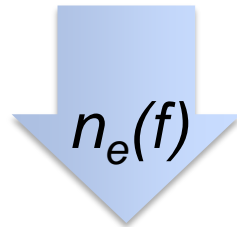


Radio Spectra & Images and EUV Wave

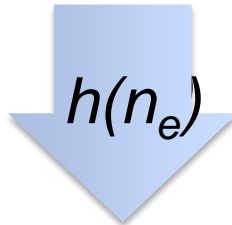


How do we find shock heights?

Frequency(t)



Density(t)



Height(t)

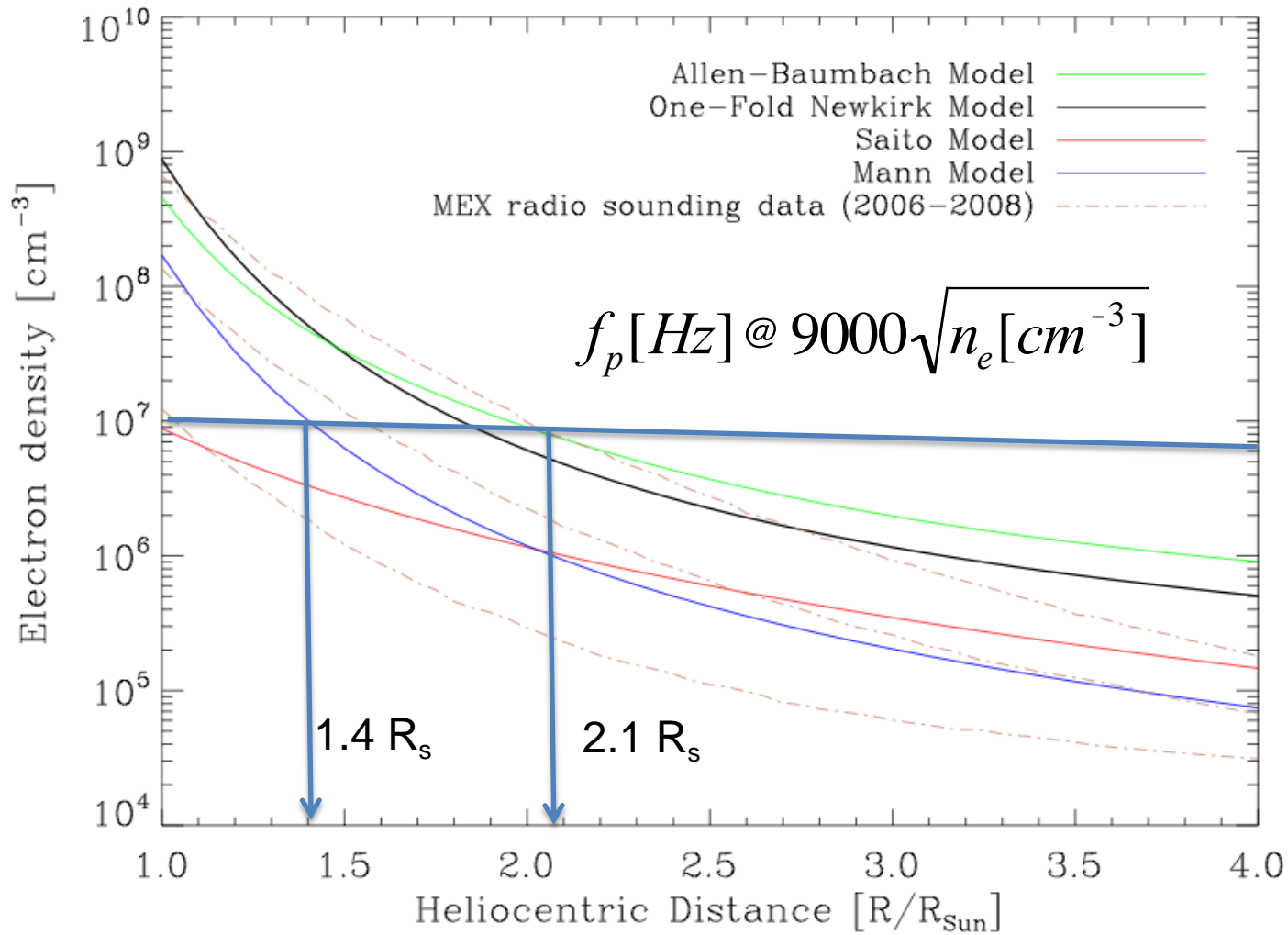
Plasma frequency:

$$f_p [Hz] @ 9000 \sqrt{n_e [cm^{-3}]}$$

Example model:

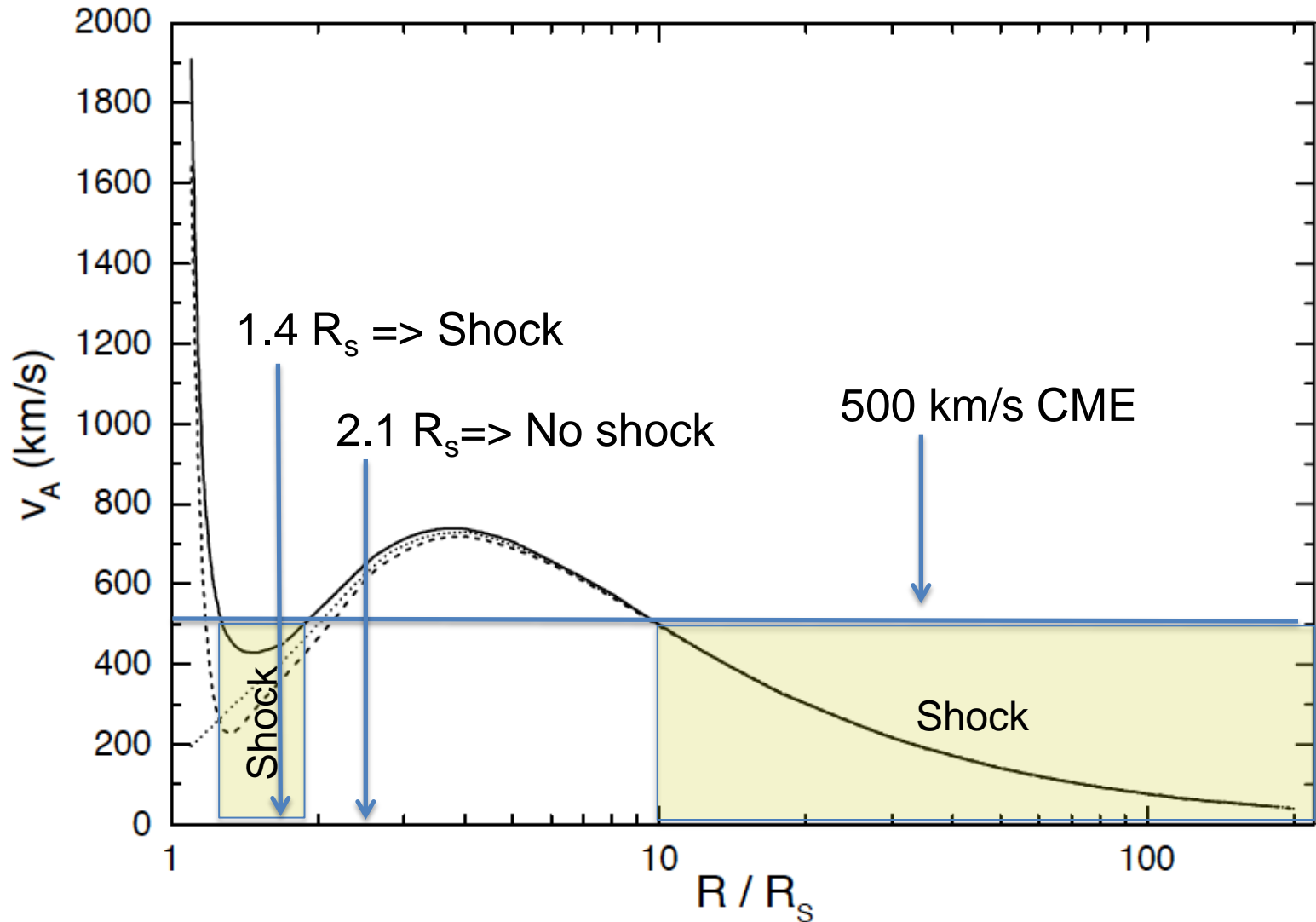
$$n_e(h) = n_0 e^{-h/H}$$

Type II Height Problem



=> Given frequency gives single density but **model dependent** heights!

Shock Height Problem



Solution: Data-constrained Alfven Maps

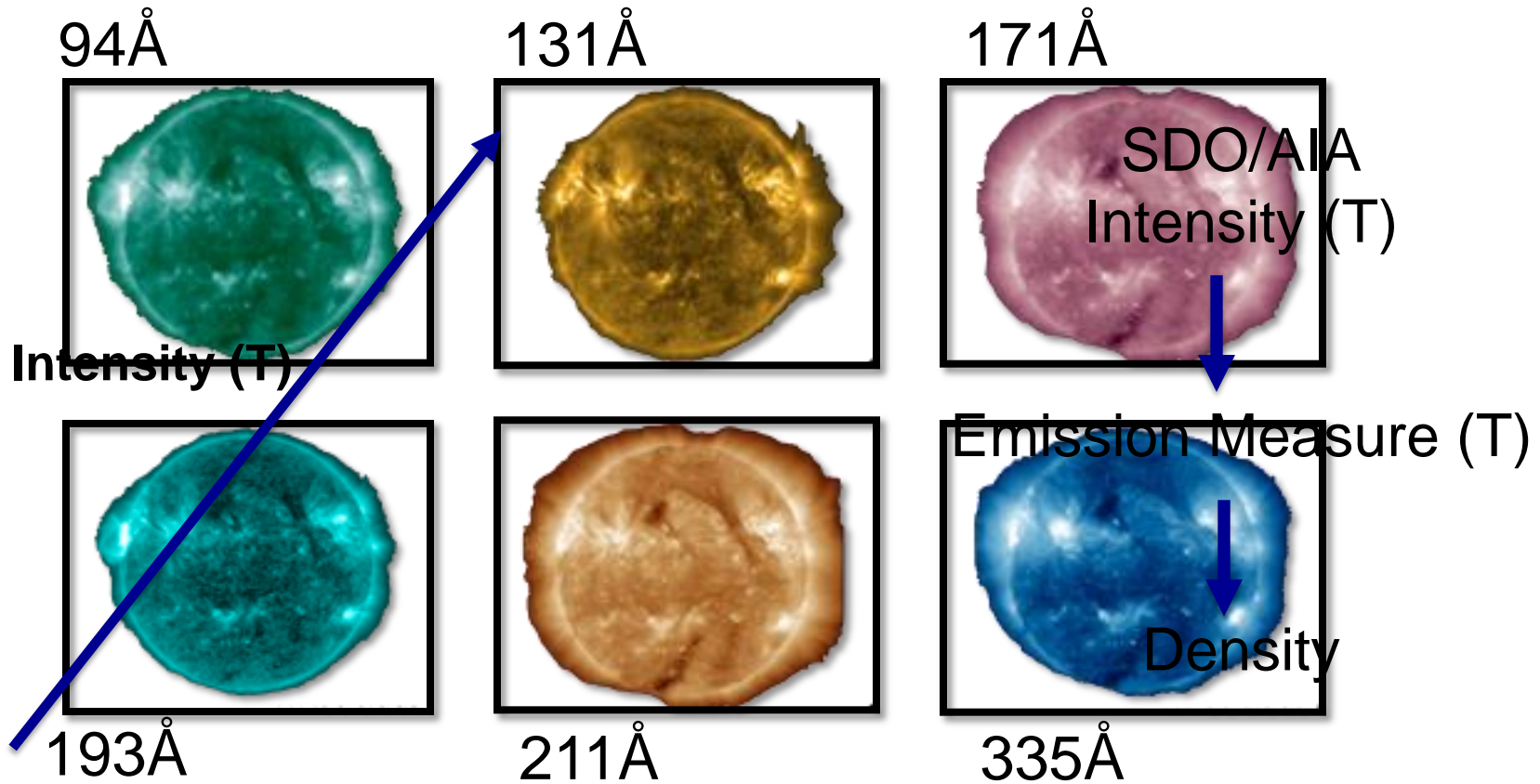
Potential magnetic field model (PFSS)

$$v_{Alfven}(x, y) = \frac{B(x, y)}{\sqrt{m m_p n_e(x, y)}}$$

Electron density maps (SDO/AIA and SOHO/LASCO)

The diagram illustrates the components of the Alfvén velocity equation. The numerator, $B(x, y)$, is circled in orange and has an orange arrow pointing to it from the text 'Potential magnetic field model (PFSS)'. The denominator, $\sqrt{m m_p n_e(x, y)}$, is also circled in orange, with an orange arrow pointing to it from the text 'Electron density maps (SDO/AIA and SOHO/LASCO)'.

Densities in low corona ($<1.3 R_S$)

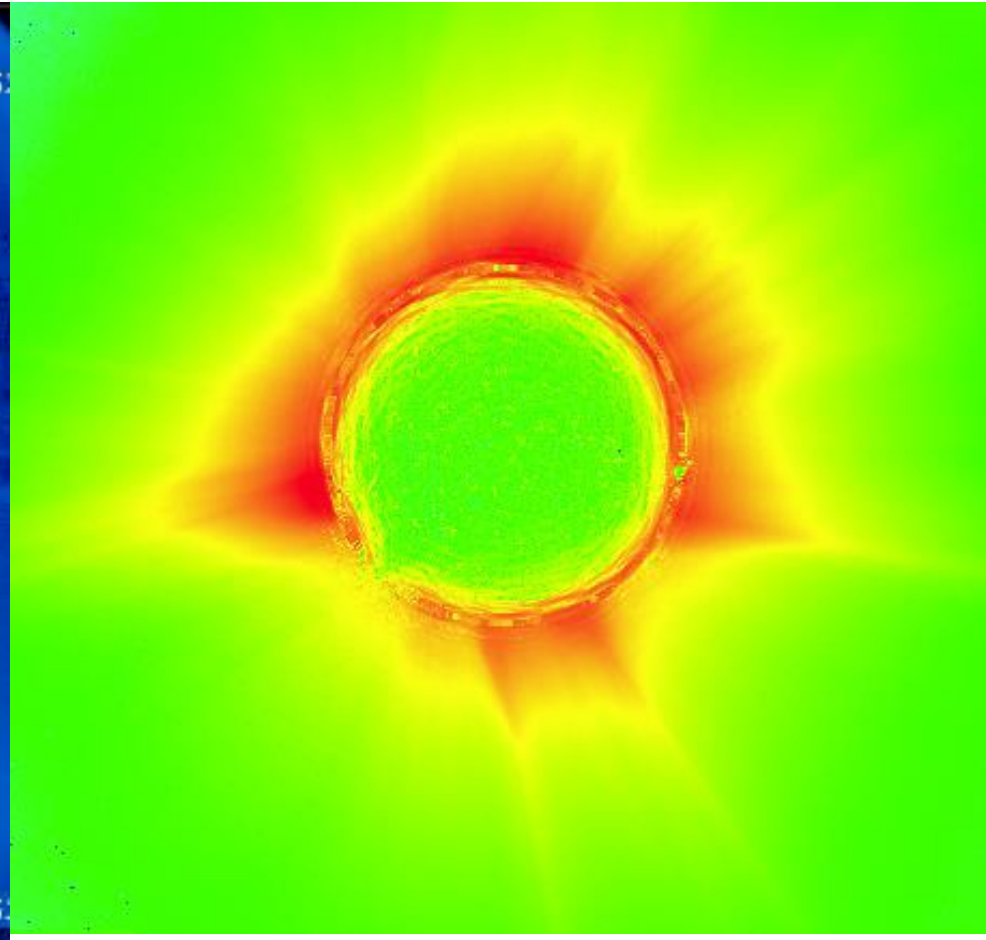
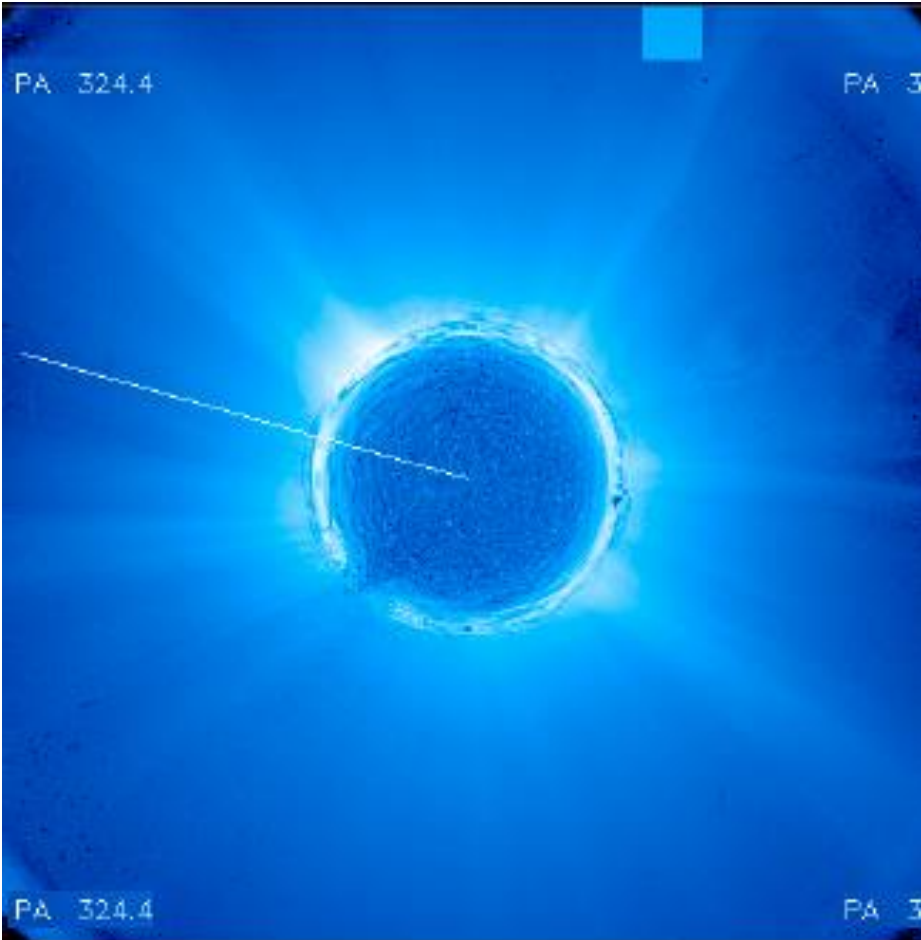


Densities in high corona ($>2.5 R_S$)

SOHO/LASCO Intensity



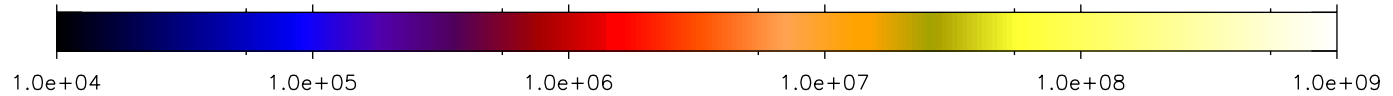
Electron Density



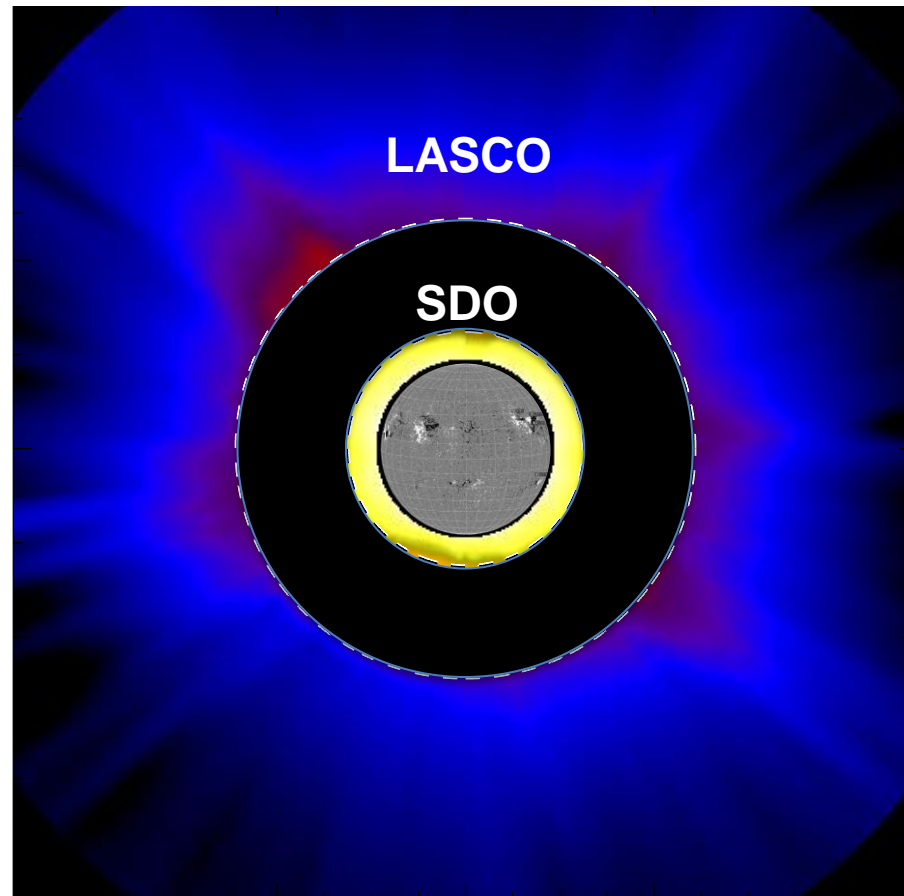
$$\text{Brightness} \propto \int_{LOS} n_e(r) G(r, s) ds$$

LOS

Electron Density Map



Electron density (cm⁻³)



Two-component Density Model

- Spherically symmetric corona in hydrostatic equilibrium:

$$n_{ss}(r) = n_{ss}(r = 1 R_{\odot}) \exp \left[-\frac{\mu m_p G M_{\odot}}{k T R_{\odot}} \left(\frac{r_0}{r} - 1 \right) \right]$$

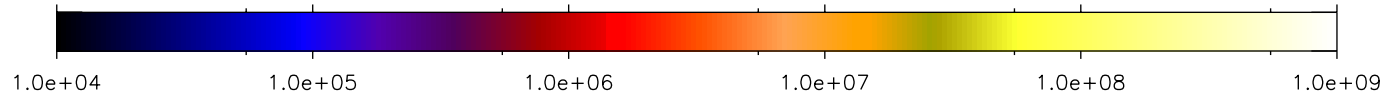
- At $r < r_0$, reduces to plane parallel solution

$$n_{pp}(r) = n_{pp}(r = 1 R_{\odot}) \exp \left[-\frac{r}{H} \right]$$

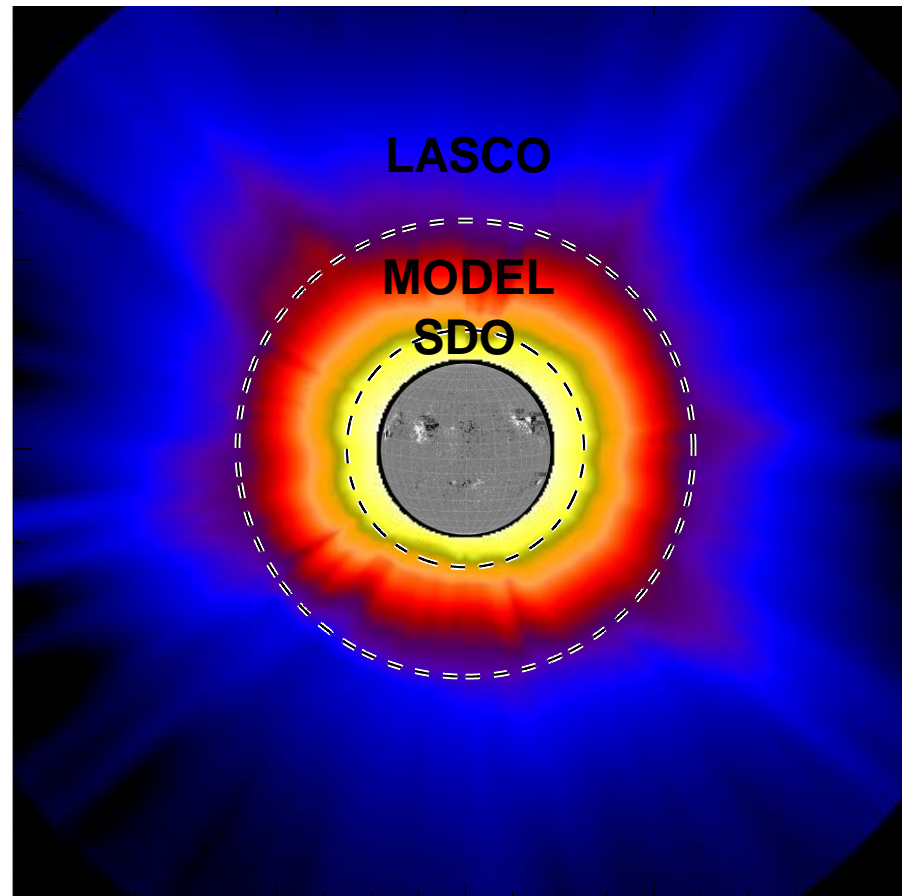
- Combine spherically symmetric and plane parallel

$$n(r) = n_{pp}(r) + n_{ss}(r)$$

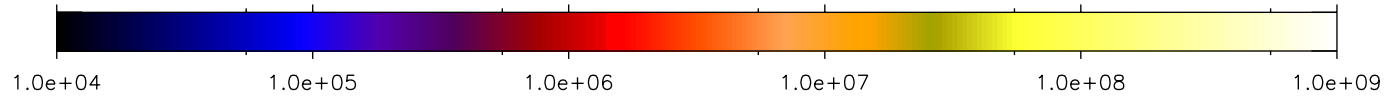
Electron Density Map



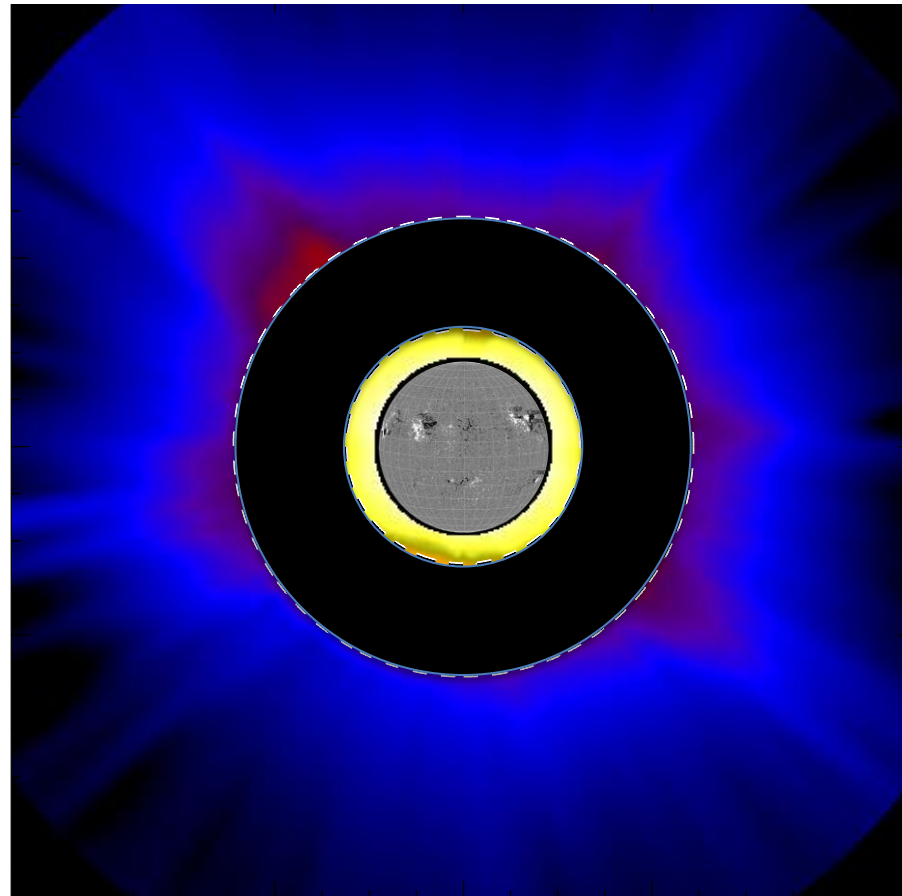
Electron density (cm⁻³)



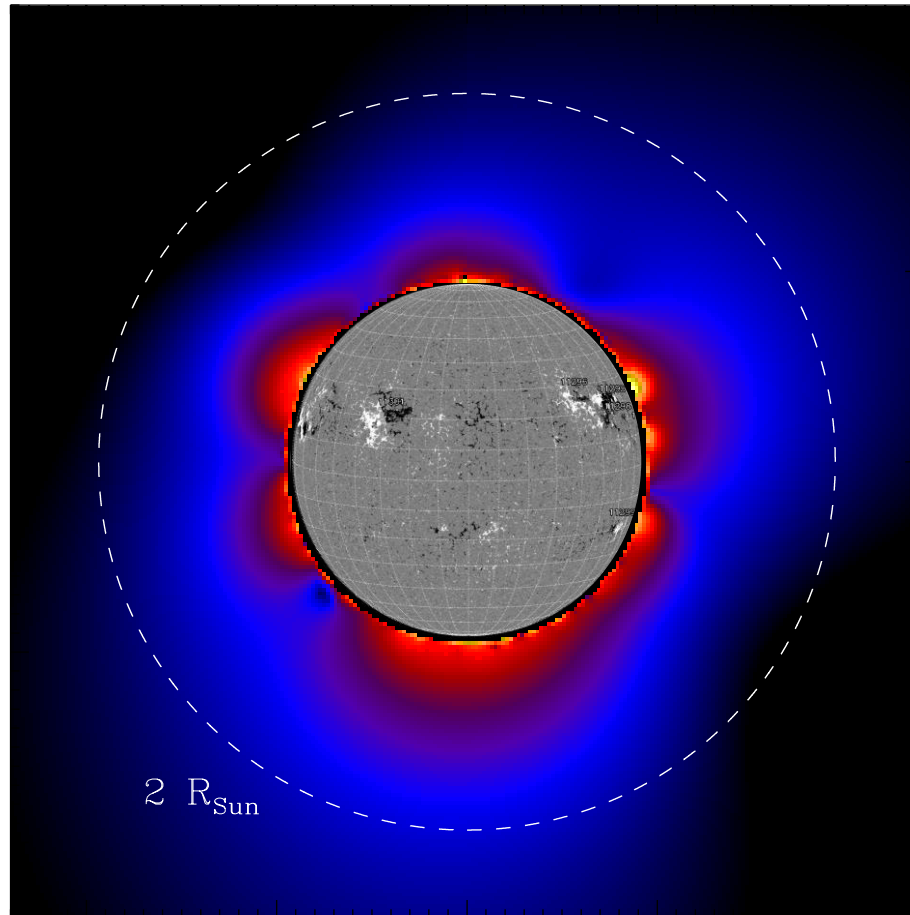
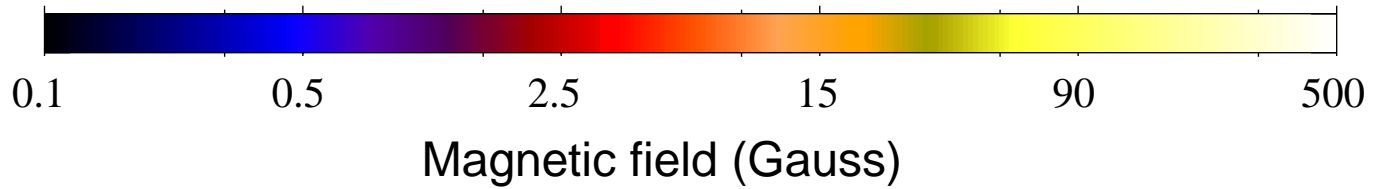
Electron Density Map



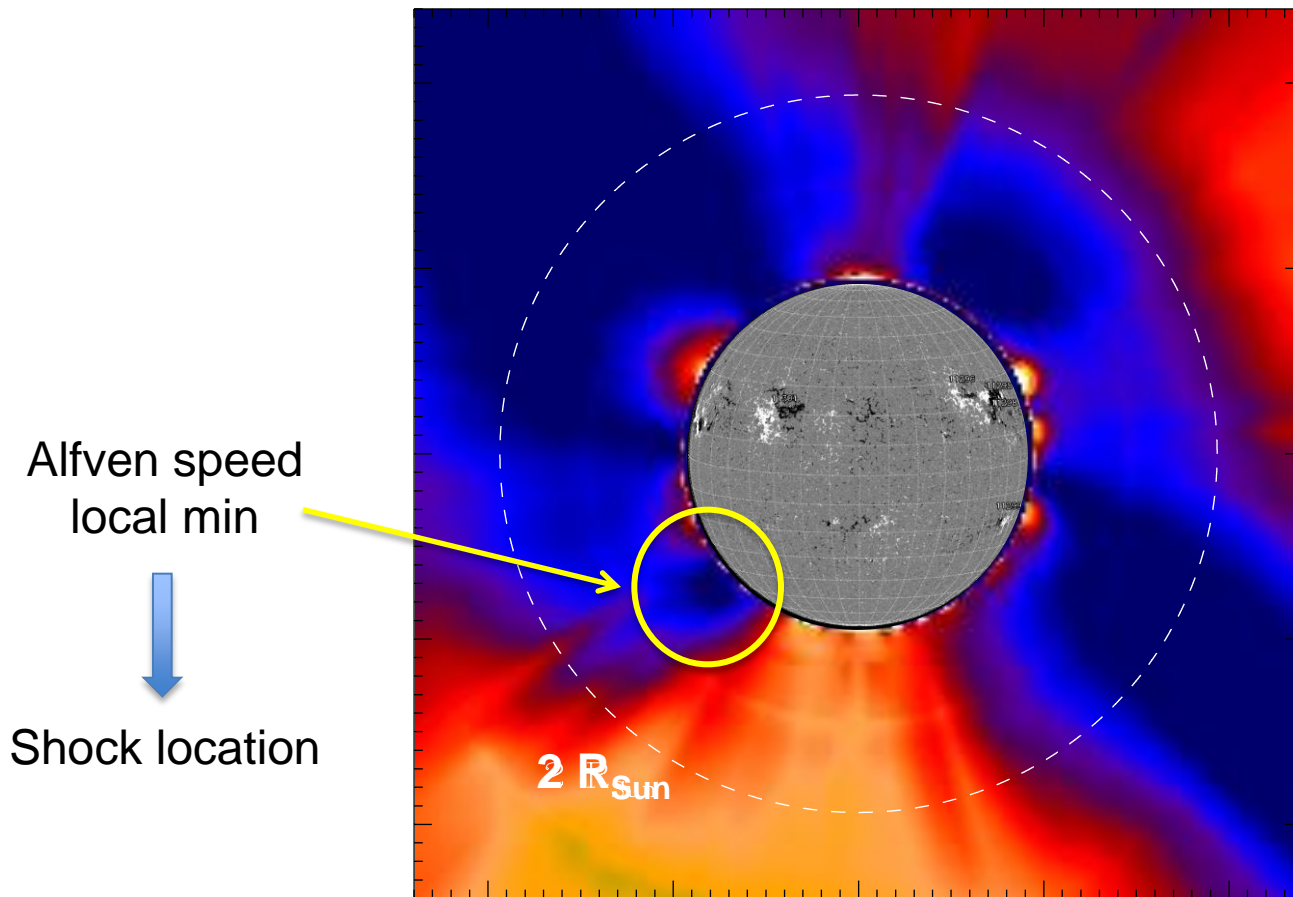
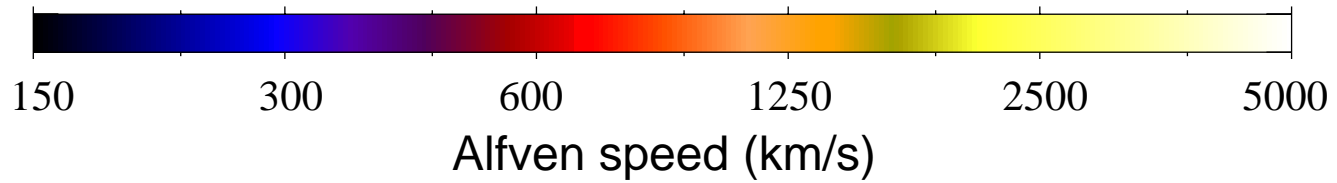
Electron density (cm^{-3})



Magnetic Field Extrapolations



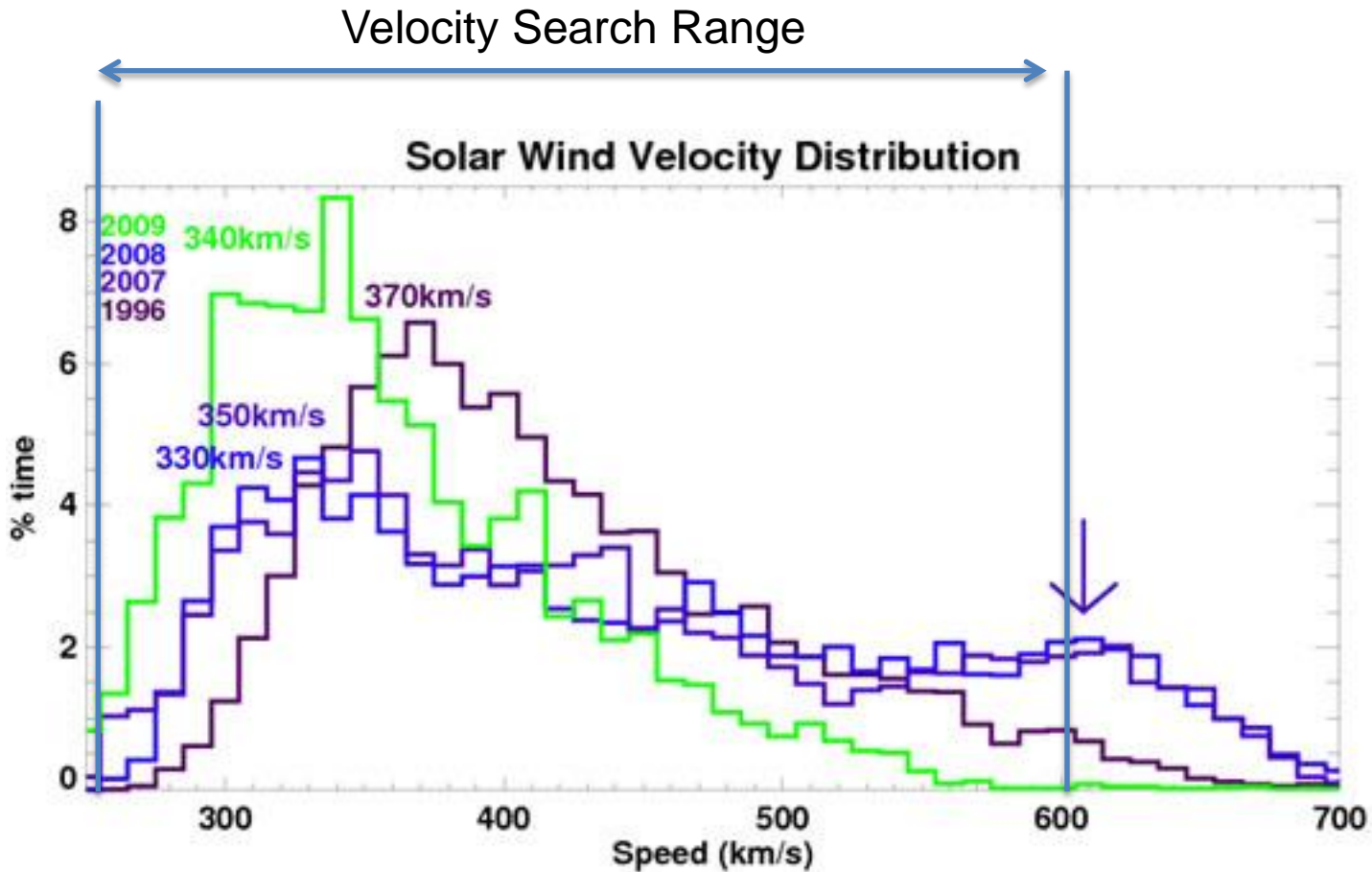
Alfvén Speed Map



Conclusions

- Linking heliospheric to coronagraph features
 - Ballistic model works well
- Linking coronagraph to low corona and surface
 - Challenging - deflection important
 - Activity in EUV images key
- Linking CMEs to IP and coronal Type II bursts
 - Difficult without radio images
 - Density and Alfvén maps key

Solar Wind Velocity Distribution



CME Velocity Distribution

Velocity Search Range

