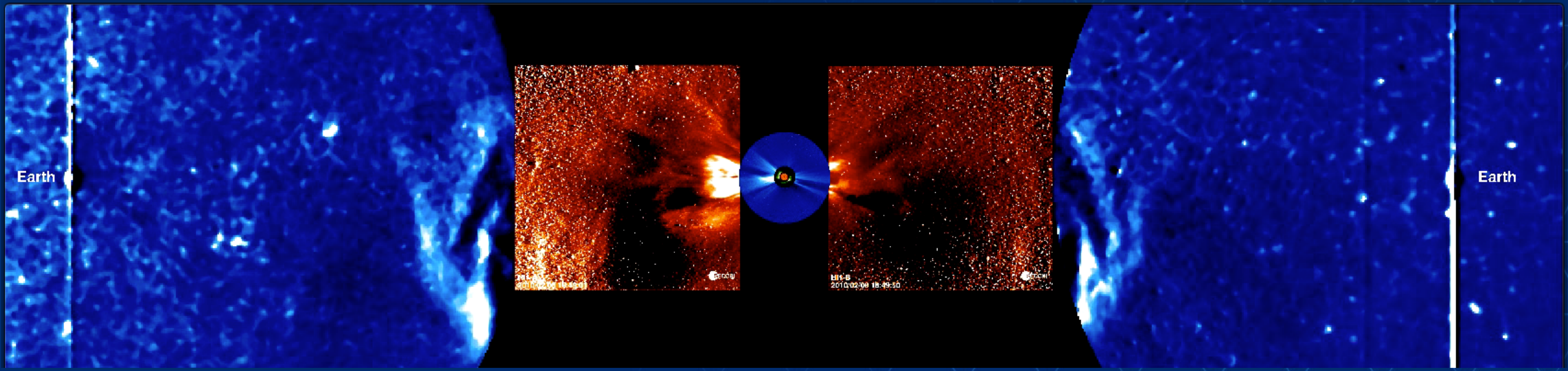

The State of CME Research

Where do we stand and how could PUNCH help

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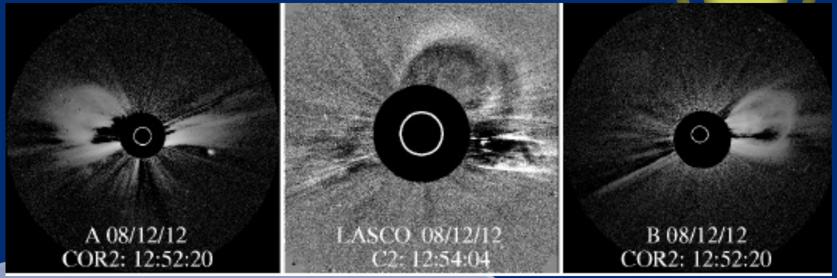
Covered Topics

- **The State of CME Research**
  - ‘paradigm’ shifts in understanding CMEs
- **What is still missing?**
  - Key knowledge gaps
- **Where do we go next?**
  - Where PUNCH can help and…
  - where it cannot

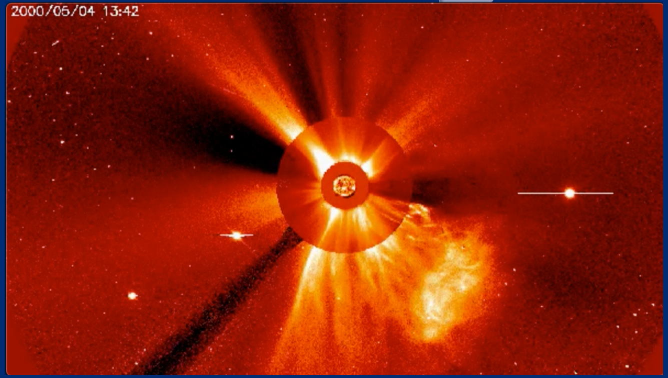
‘Paradigm Shift’: Coronal Mass Ejections

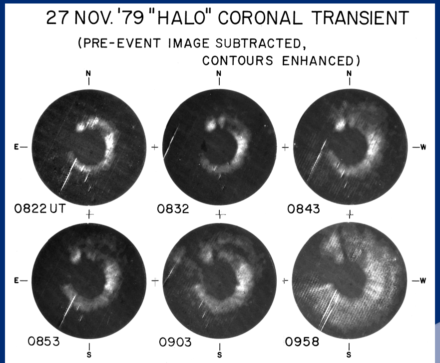
Fifty years of CME observations



2007- : CMEs in 3D

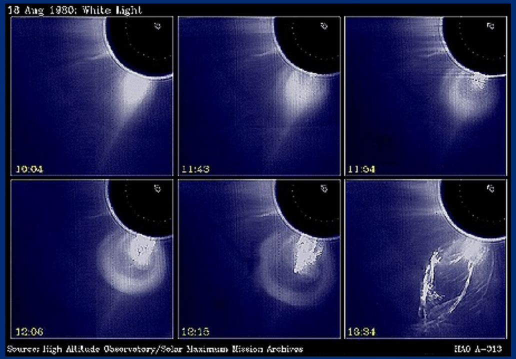
1996- : CMEs across 2 cycles & over the full corona

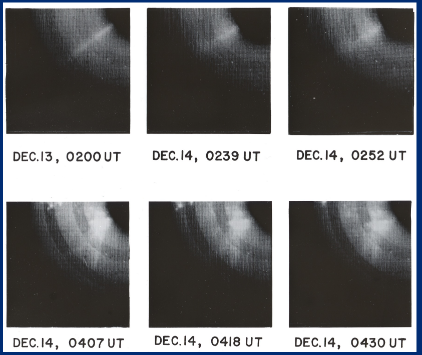




1980s: Halo CMEs

1980s: CMEs in the inner corona

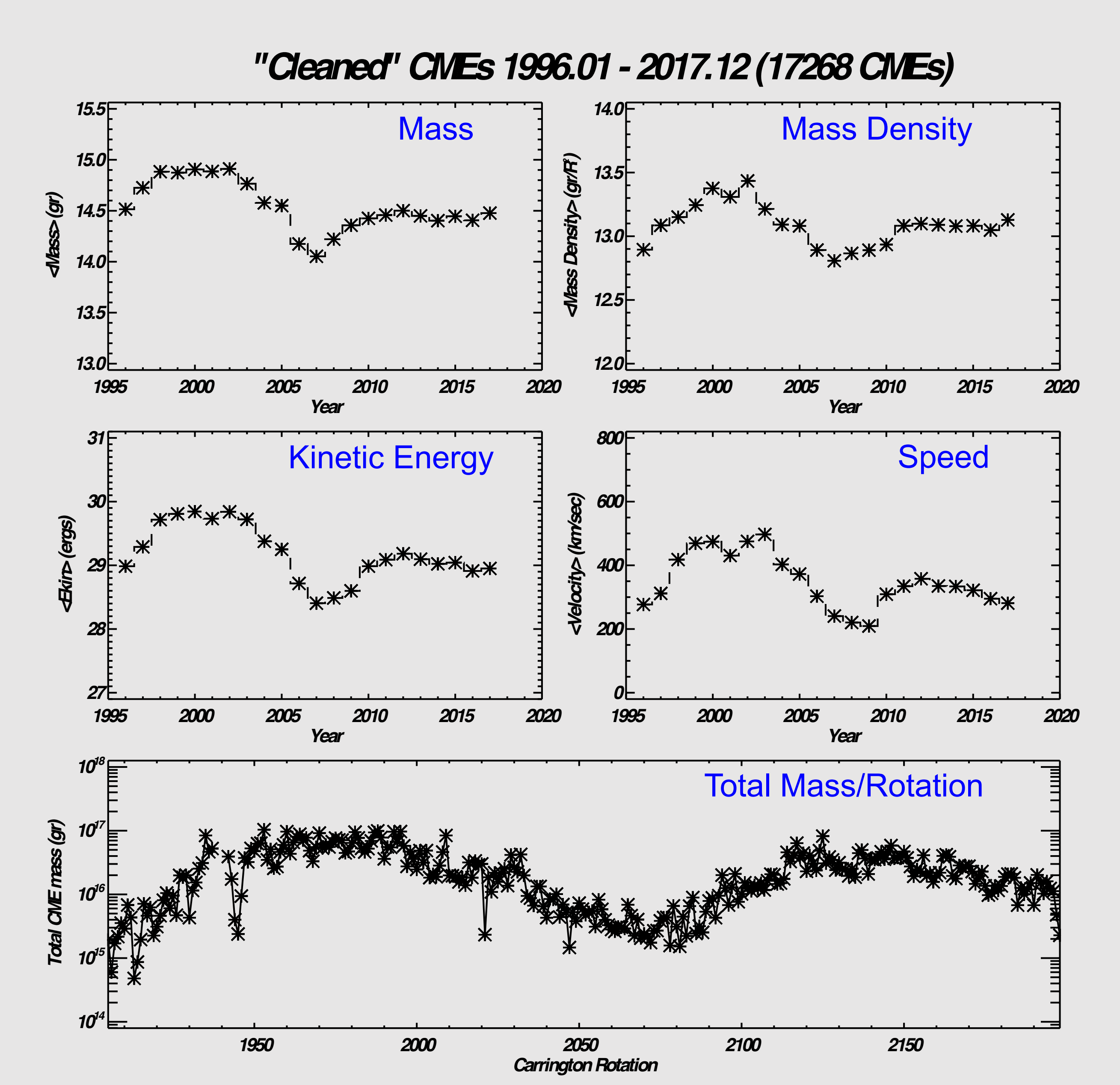




1971: Discovery!

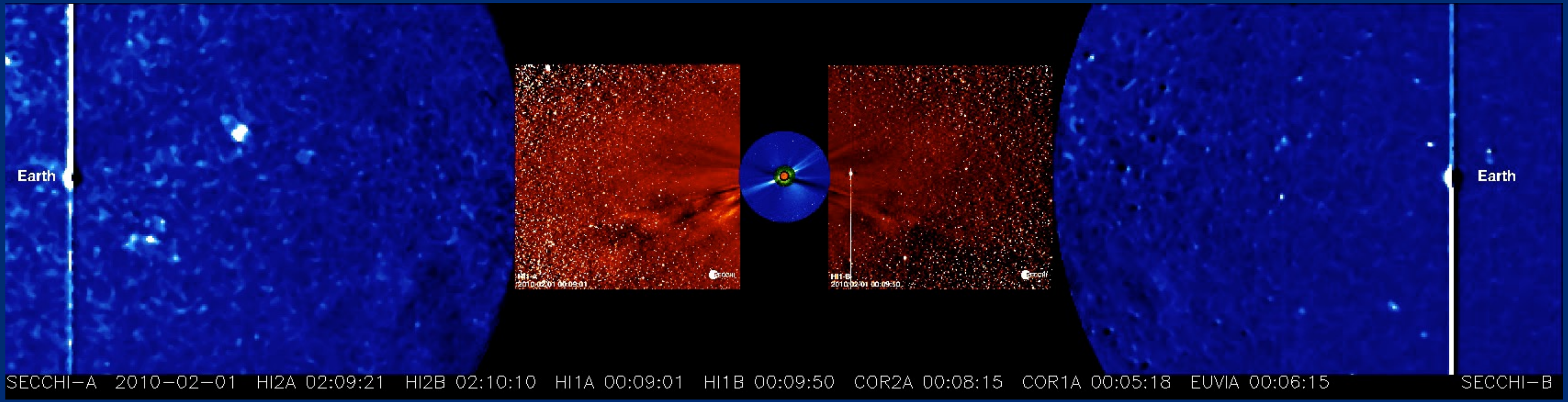
CME Properties

Population physical properties are well understood



CME Research in the STEREO Era (2007-)

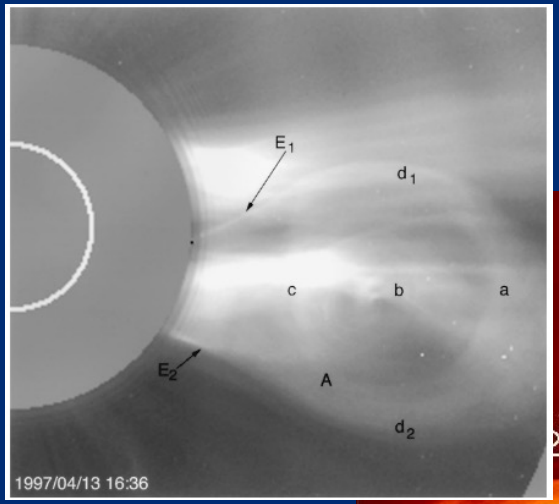
Major Breakthroughs



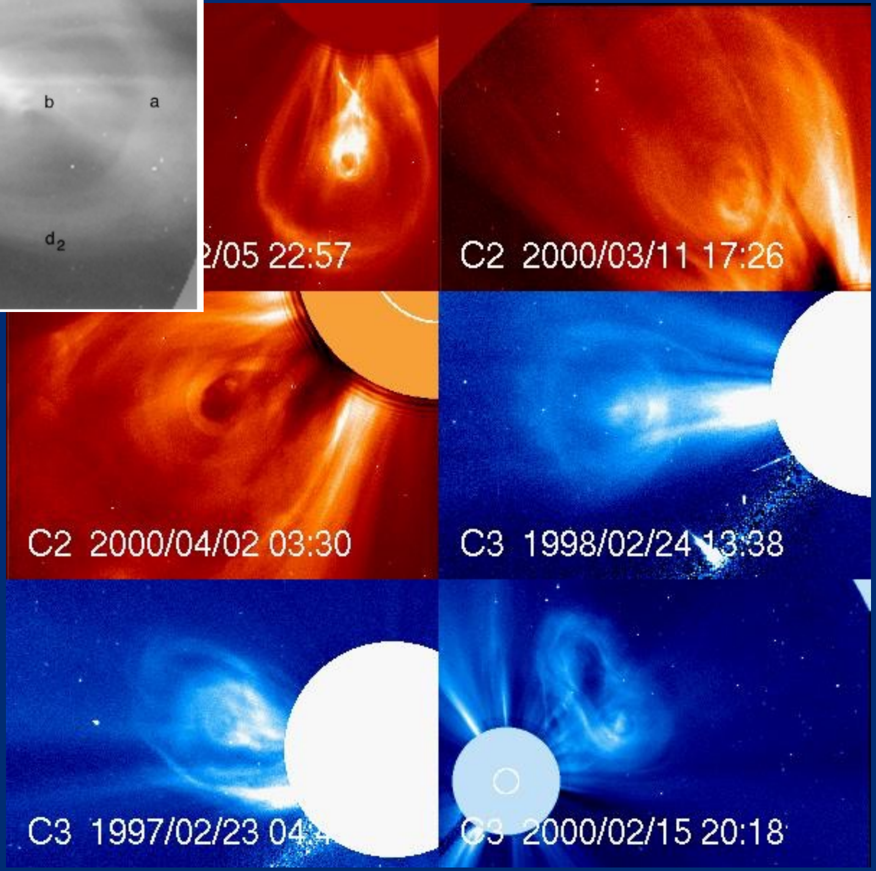
- 3D Reconstructions of CMEs, shocks, and their directions
- Imaging of CMEs and CIRs in the IP.
- CMEs are Magnetic Flux Ropes
- Direct comparison of imaging (CMEs) and in-situ (ICMEs).
- Discovery of rotations, deflections, both in low corona and IP
- Clarification of shock-SEP relation, EVEN in low corona.
- Discovery of the hot flux-rope core of CMEs.

‘Paradigm Shift’: CME Structure

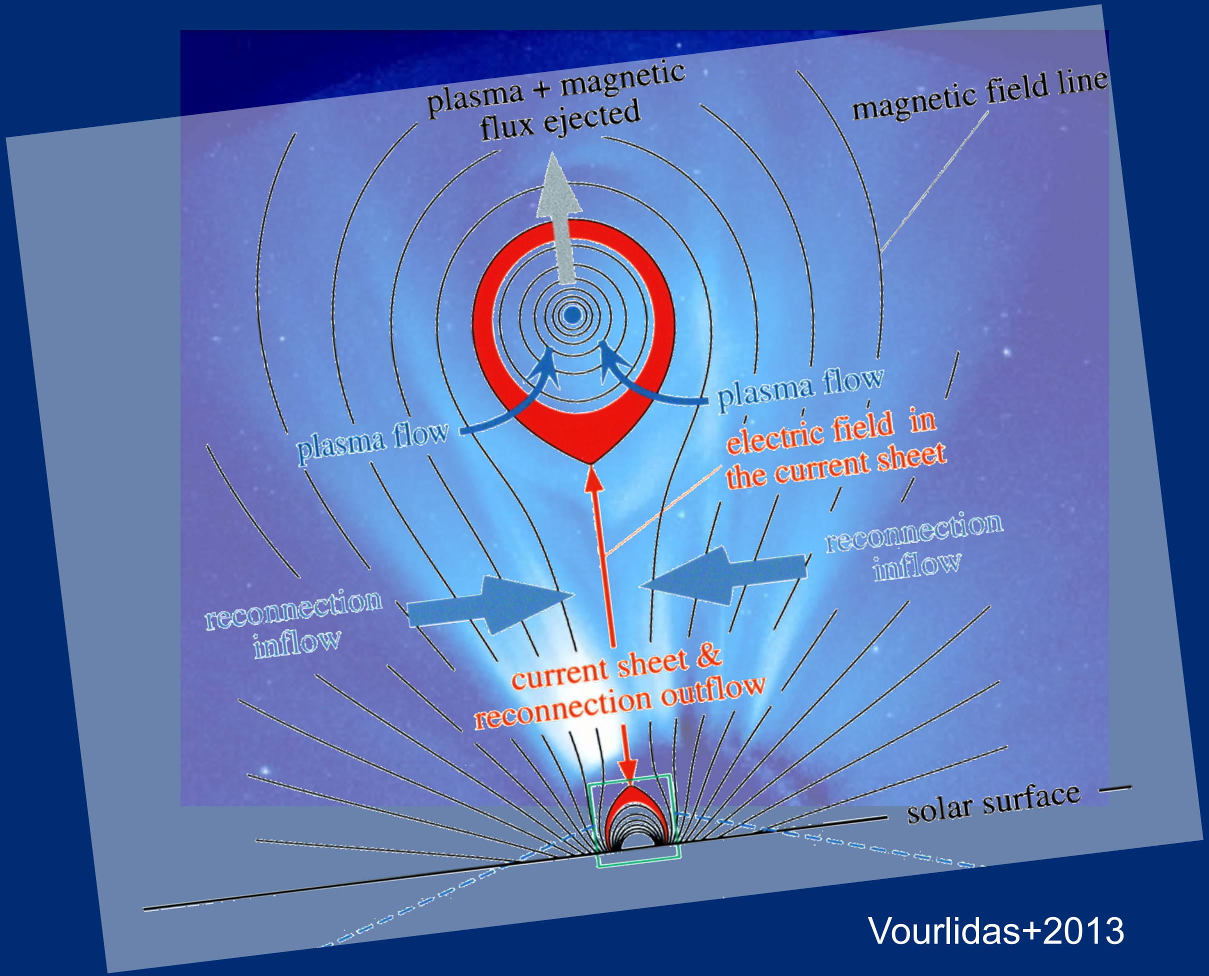
CMEs contain Magnetic Flux Ropes (as theory predicts)



Chen+1997



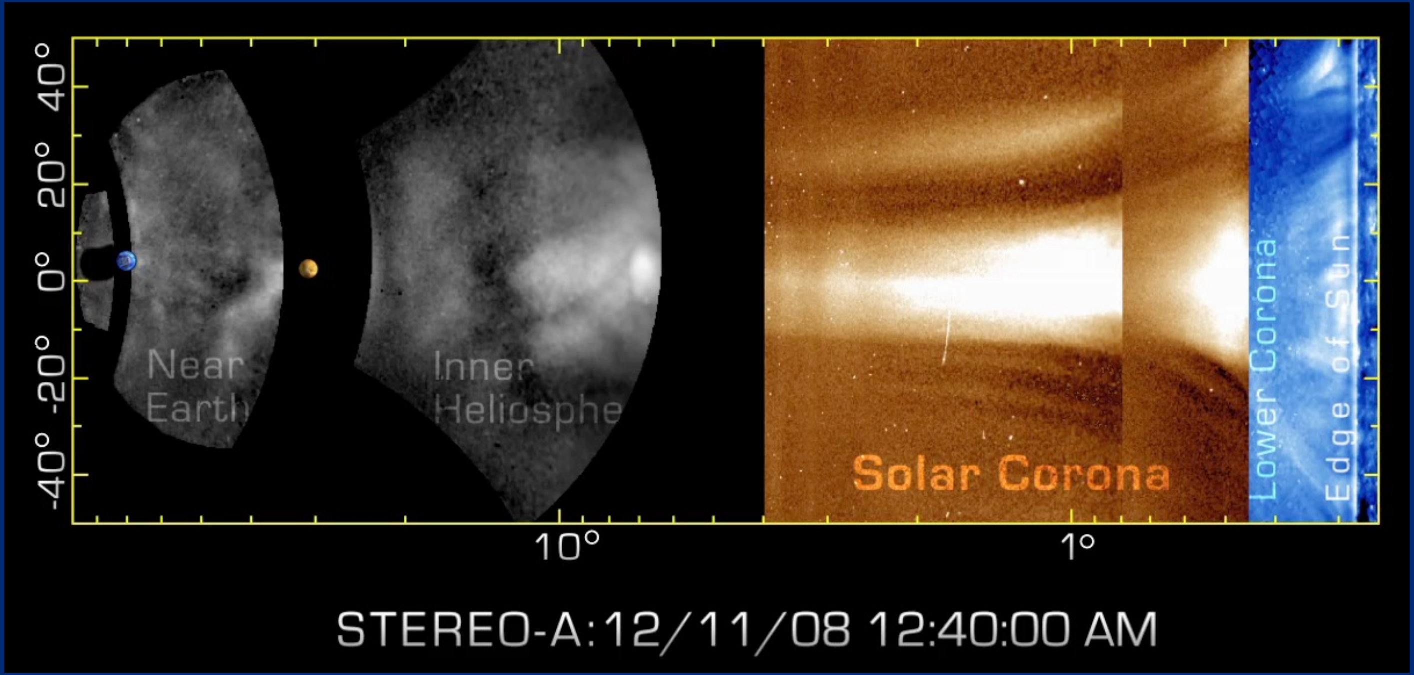
Vourlidas+2000



Vourlidas+2013

‘Paradigm Shift’: Imaging the Solar Wind

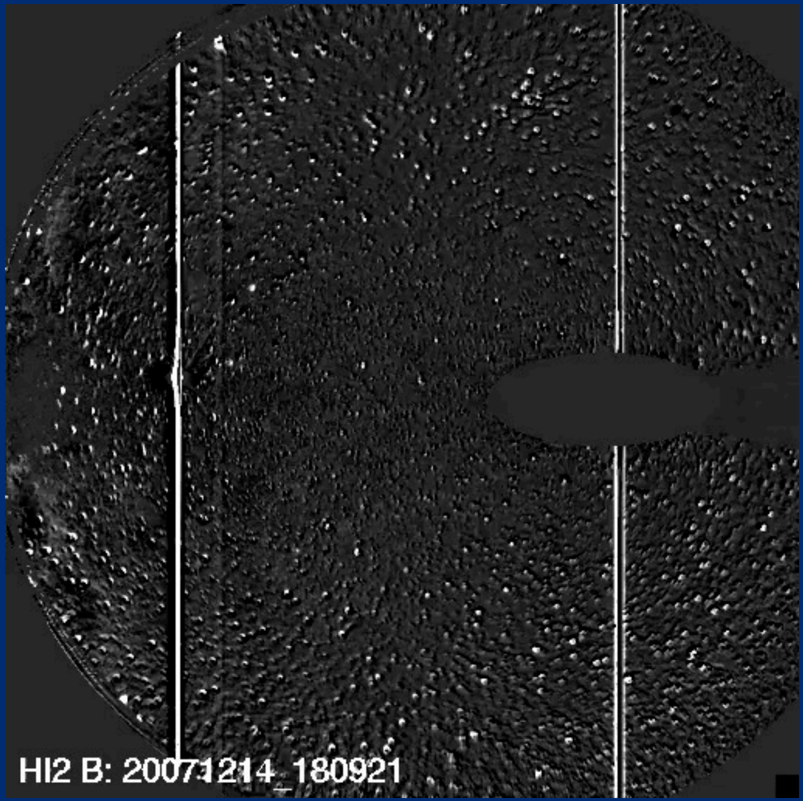
Heliospheric imaging offers a new way to study the inner heliosphere



Tracking solar wind from Sun to 1 AU

DeForest+ 2012

Imaging of SIRs



Sheeley+ 2008

Solar Driver Forecasting Status

A way to identify gaps in our understanding of CMEs

TABLE 1 | Forecasting status of key quantities used to assess the Geo-effectiveness of the main solar drivers of space weather.

Quantity	Observational inputs	Forecasting status	Choke points
CME/shock			
Direction (Hit/Miss)	Source region / flare location, 3D CME reconstruction	85%*	Deflection in low corona, IP evolution
Time-of-arrival	Speed in corona or inner heliosphere	9.8 ± 2 h[a]	IP propagation, CME/shock front shape at 1 AU
Speed-on-arrival	Speed in corona or inner heliosphere	±200 km/s*	Same as above
Density	CME mass	Unknown	IP propagation, small-scale structure of CME/shock sheath
Magnetic configuration	Radio emission, 3D CME reconstruction, coronal magn. field extrapolations	~ 30 min (L1 *in-situ* meas.)	Coronal origin, evolution (< 3 Rs), IP propagation

Vourlidas 2020,
Vourlidas+ 2019

CME Structure

Remote Sensing and In Situ Comparisons

Table 5.1: EFR Model Parameters

CME	Lon ϕ (deg)	Lat θ (deg)	Rot ξ (deg)	Major (AU)	Minor (AU)	Y_o (AU)
1	206	-44	108	0.35	0.33	0.34
2	119	-66	12	0.30	0.29	0.23
3	358	-5	28	0.02	0.01	0.02
4	**41**	**-14**	**174**	**0.10**	**0.09**	**0.05**
5	19	-31	16	0.36	0.08	-0.27
6	179	-69	145	0.20	0.14	0.03
7	63	-61	384	0.37	0.36	0.14
8	**1**	**7**	**89**	**0.04**	**0.01**	**0.01**
9	**273**	**-18**	**0**	**0.09**	**0.08**	**-0.08**

Table 5.2: GCS Model Parameters

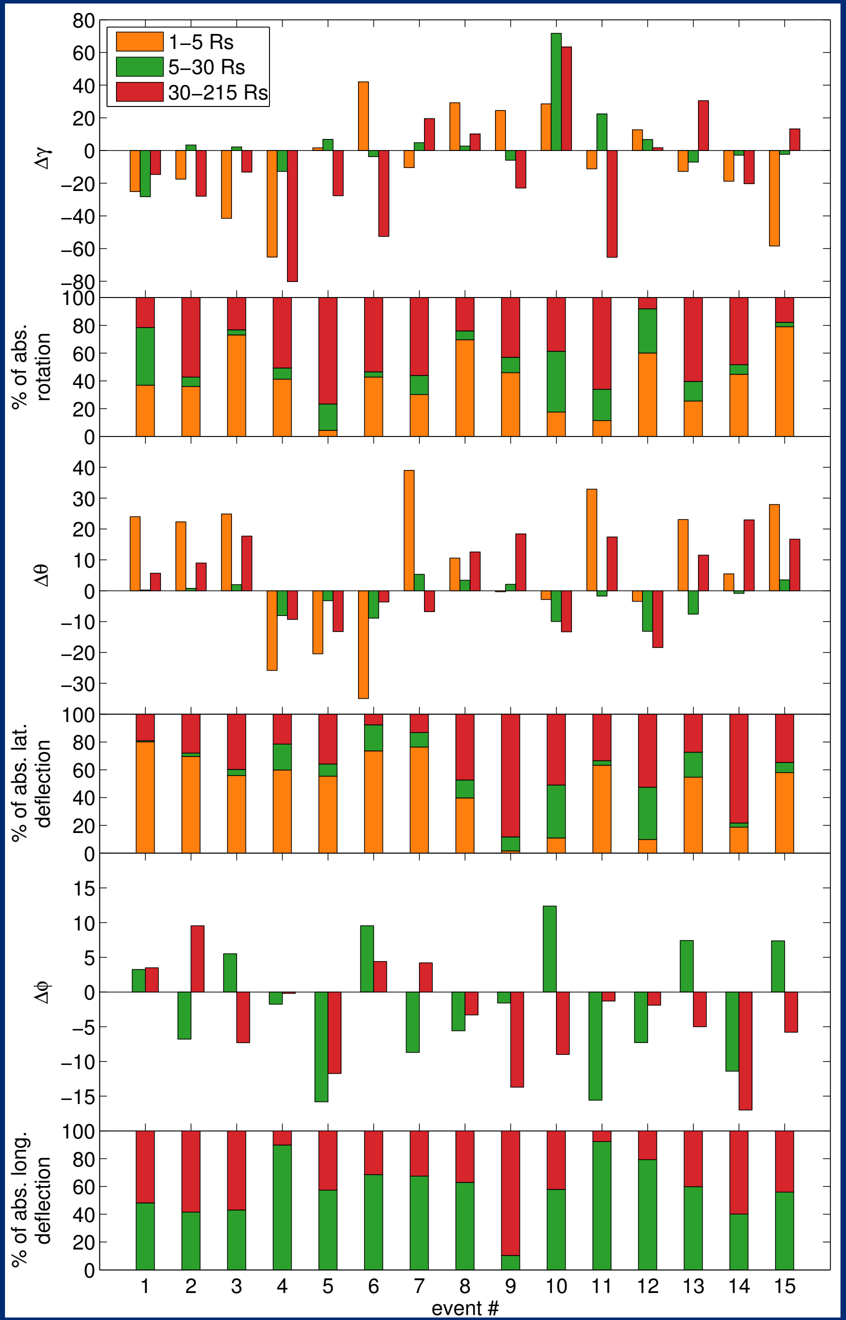
CME	H ($R_\odot$)	Lon (deg)	Lat (deg)	Rot (deg)	Radius (AU)	Width (AU)
1	1.66	26	-3	-35	0.41	0.60
2	1.01	8	-2	12	0.32	0.50
3	1.10	-10	8	-50	0.28	0.49
4	1.22	-17	6	-33	0.32	0.41
5	1.31	-21	17	-43	0.46	0.59
6	1.33	13	-29	-55	0.42	0.62
7	1.00	2	3	26	0.36	0.51
8	1.06	-20	3	-11	0.40	0.59
9	1.12	-21	-3	-16	0.29	0.50

Colaninno (2012) PhD Thesis
also Nieves-Chinchilla+ 2012,2013; Wood+ 2017

ICME Rotations and Deflections

- 3D height-time & orientation measurements.
- In COR2 and in-situ reconstructions.
- Source region geometry from EUV.
- Deflection based on upstream solar wind structure (from MHD sims).

$$\Delta\phi = \Omega\left(\frac{1}{V_{\mathrm{FR}}} - \frac{1}{V_{\mathrm{SW}}}\right)\cdot 1\mathrm{AU}$$

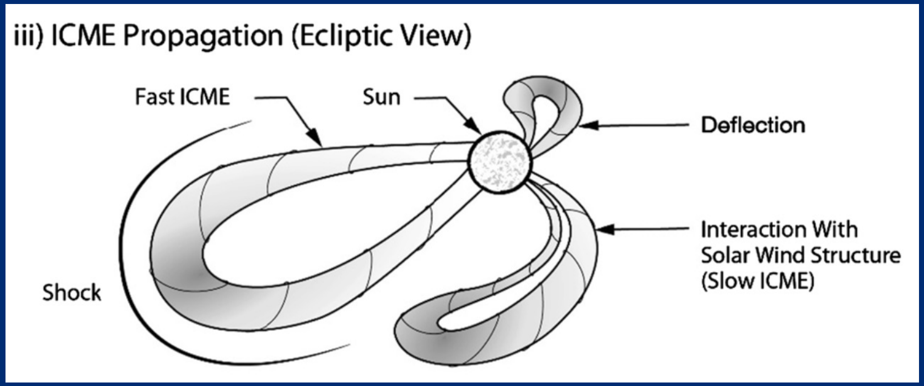


Isavnin+ 2014

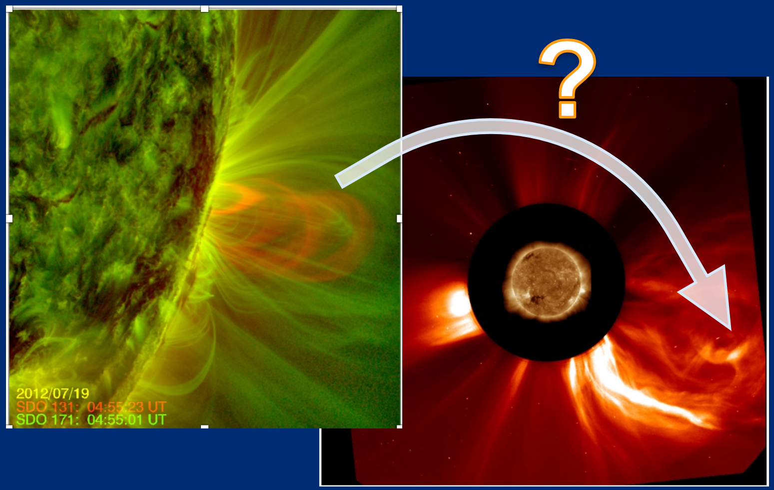
What are we missing?

Top-level knowledge gaps in 2020

Luhmann+2020

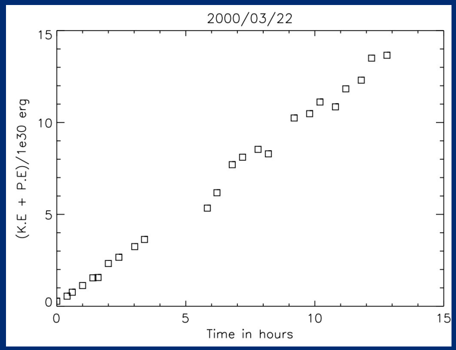


- **The interaction challenge**
  - CME-CME
  - CME-Solar Wind
  - CME-Magnetic Field



- ~~**The inner corona challenge**~~
  - ~~What really happens between ~1.3 and 3-4 Rs?~~

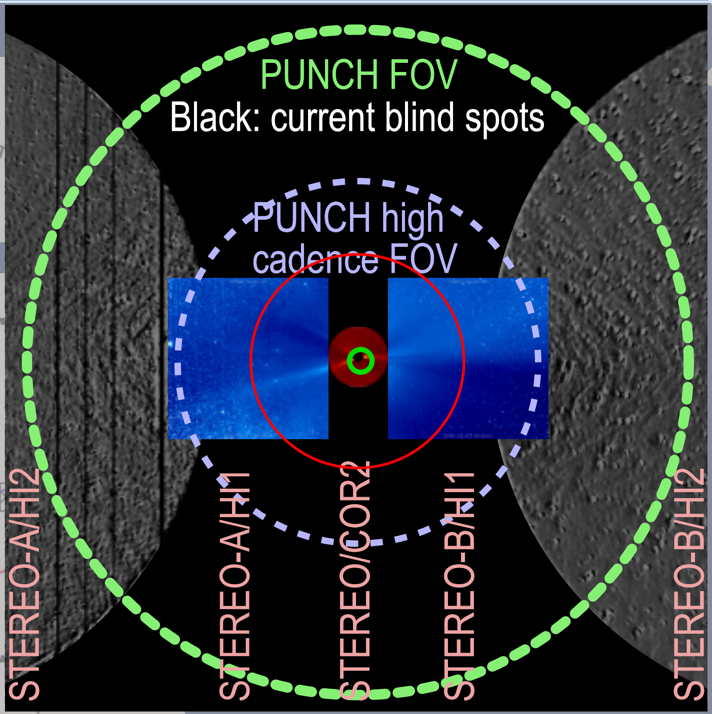
- **The physics challenge**
  - Energy budgets and force-balance

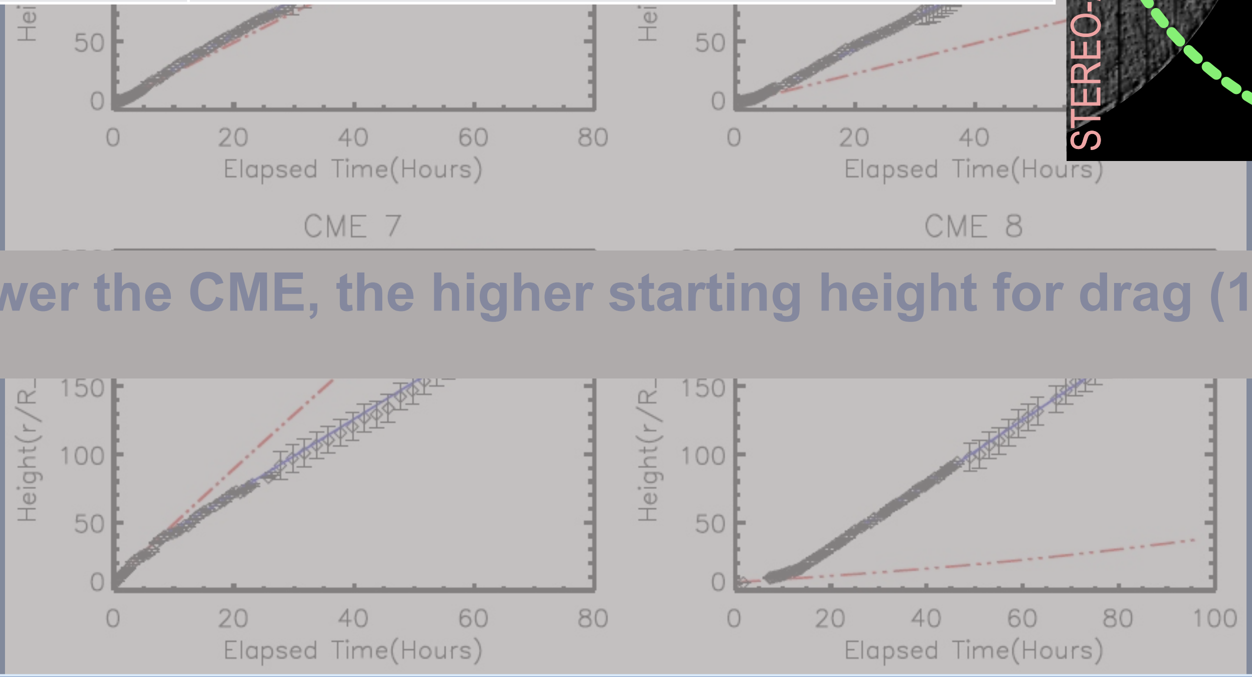


Subramanian & Vourlidas 2007

Force Balance

Pros	Cons
Continuous imaging < 80 Rs	Single viewpoint
Large NFI/WFI overlap	Less sensitive to earth-directed structures
Higher sensitivity than HI-1	High-latitude aurora interference
Full 360º coverage < 80 Rs	Unknown F-corona polarization
Polarization information	Science phase during sc25 solar max
High & consistent cadence	**No assets off the Sun-Earth line**





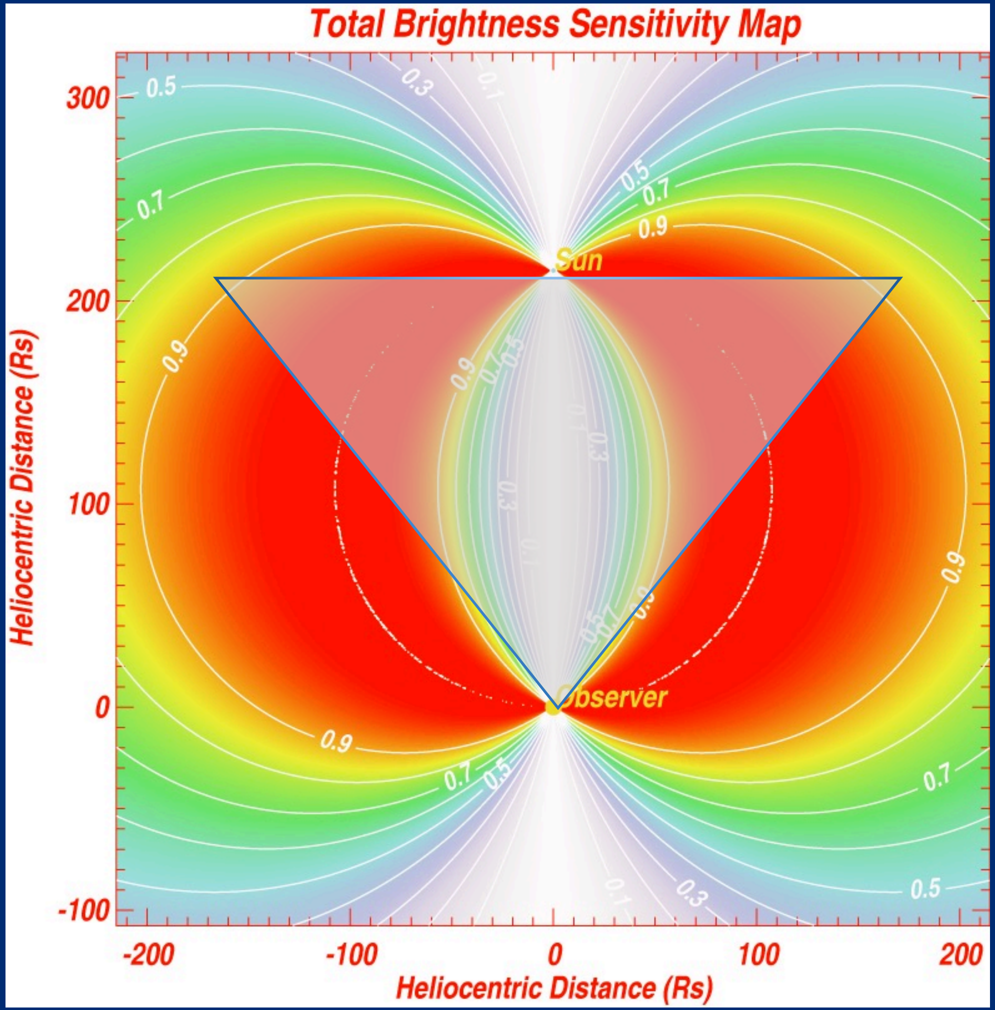
The slower the CME, the higher starting height for drag (15-50 Rs)

Sachdeva et al (2015)

CME IP Propagation

Possible PUNCH contributions

Research Issue	How
CME-CME interactions	Detailed kinematics (high cadence); structure disambiguation (polarization); 360º FOV
CME Kinematics > 50 Rs	High SNR; 360º FOV
CME Sub-structure	High SNR; polarization; +WISPR/SoloHI
non-'self-similar' expansion	Polarization; high SNR; 360º FOV; +WISPR/SoloHI
Pileup effects	WFI/NFI FOV overlap; high SNR
(Estimate) of CME B-field	High SNR; polarization; +Forward models



e.g. Vourlidas & Howard (2006)

Conclusion/Discussion

PUNCH's impact on CME research

- PUNCH could lead to important insights into
  - CME kinematics, morphology, interactions with ambient structures

- PUNCH could provide important constraints/inputs for
  - CME propagation and inner heliosphere models,
  - data assimilation & ensemble modeling development
  - Space weather forecasting improvements

- But…attention is needed for
  - Dealing with the effects of F-corona polarization and high-lat aurora on data quality
  - Dealing with the limitations of the single (along the Sun-Earth line) viewpoint (primarily for SWx studies).
  - Developing/optimizing CME models (e.g. FIDO, 3DCORE, etc.) for the PUNCH data
  - Accounting for the wide inner field cutoff (ie. In mass and kinematic studies).
  - Establishing coordinated observing plans with PSP and Solo (and hopefully, Proba-3).

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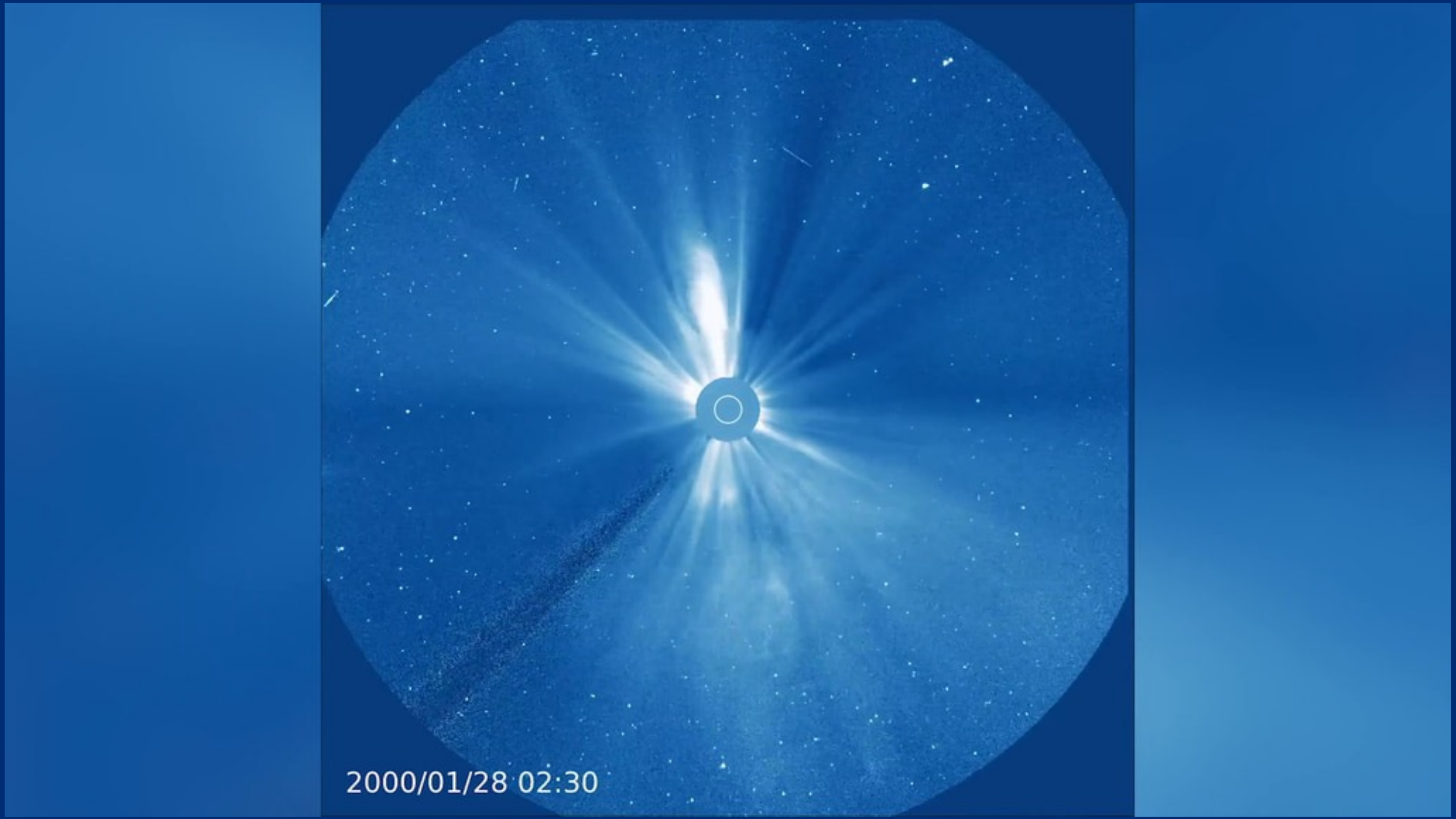
The Corona 24x7!

Recognition of CMEs as the main SWx driver
Recognition of the minute-hour-daily coronal variability



25 years of SOHO Coronagraph Observations