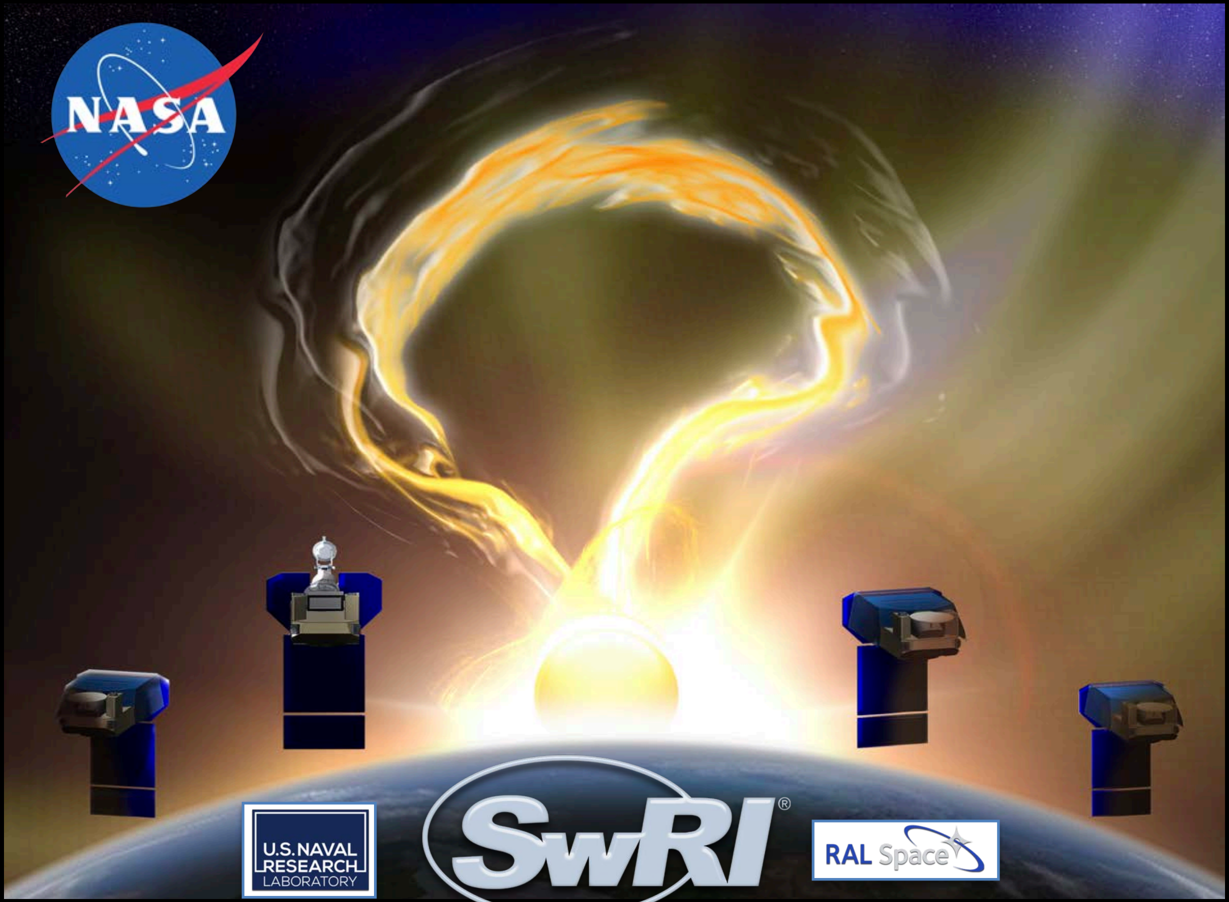
Polarimeter to UNify the Corona and Heliosphere

PUNCH, Space Weather, and You

Craig DeForest, PUNCH PI
Southwest Research Institute



NOAA/SWPC Seminar
Skaggs Research Center
October 10, 2019

What is PUNCH?

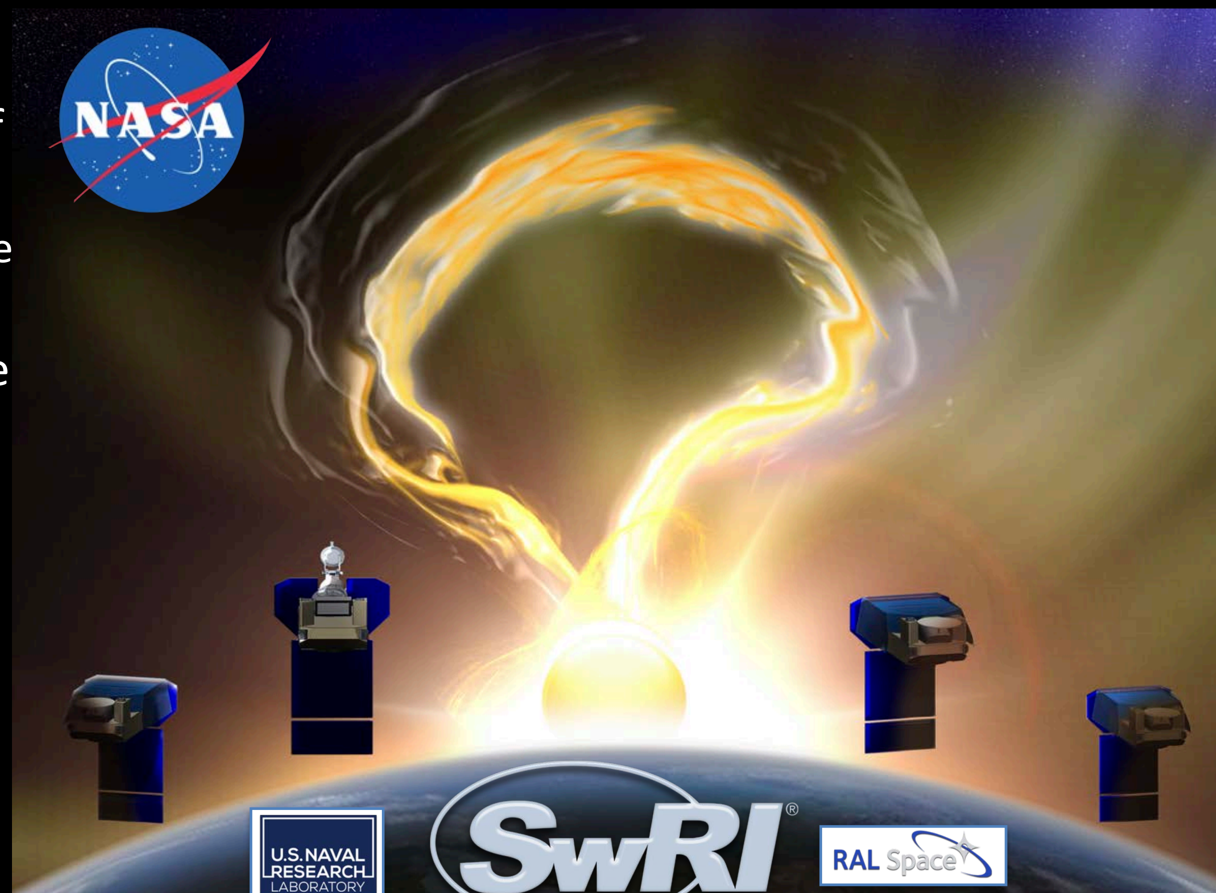
Scientific Driver: Understanding how the corona gives rise to the heliosphere and solar wind

Approach: direct 3D imaging of the entire outer corona and inner heliosphere (4 min cadence

Measurement: polarized image of Thomson-scattered light

Mission structure:
- four synchronous smallsats
- 570km sun-synch LEO
- two year duration
- Launch: Q1 2023

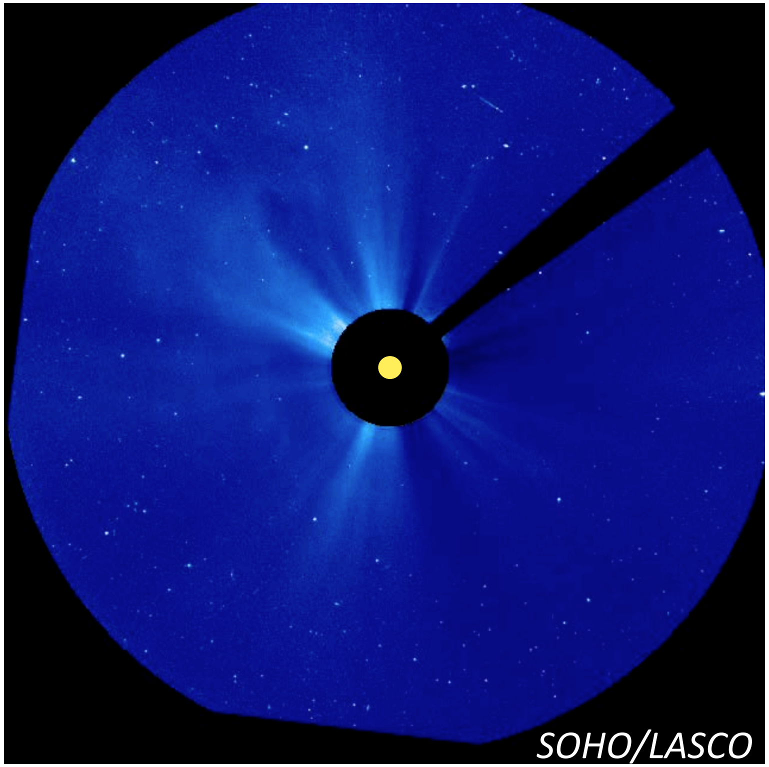
NASA's latest Small Explorer mission

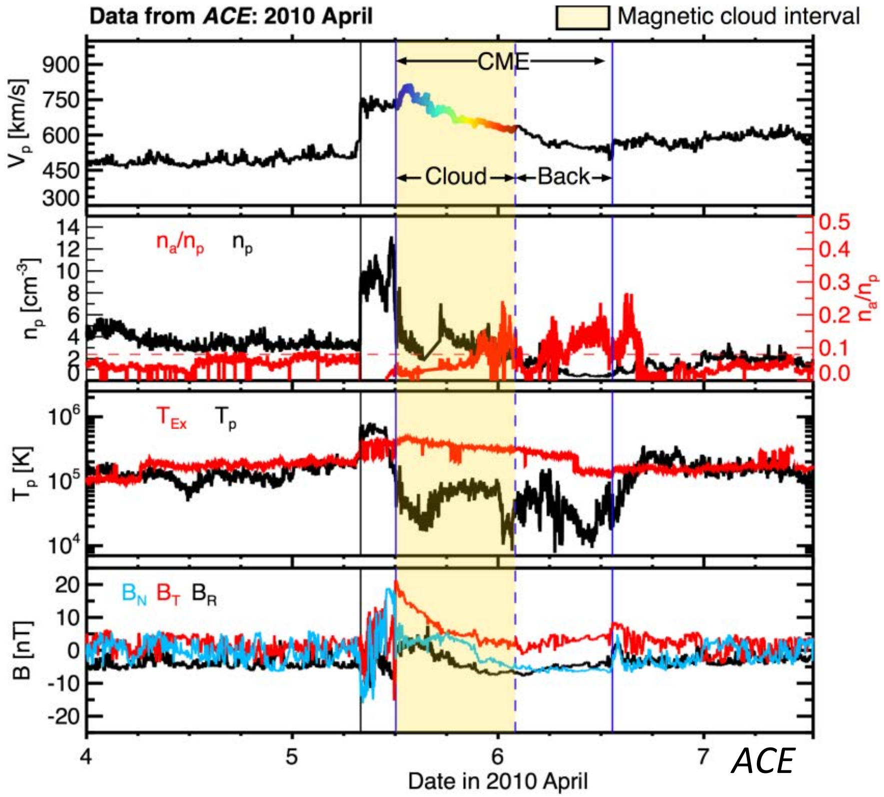


Why PUNCH?
Unify solar physics & heliospheric physics

Solar physics studies the Sun and solar corona, primarily through remote sensing and spectral analysis.

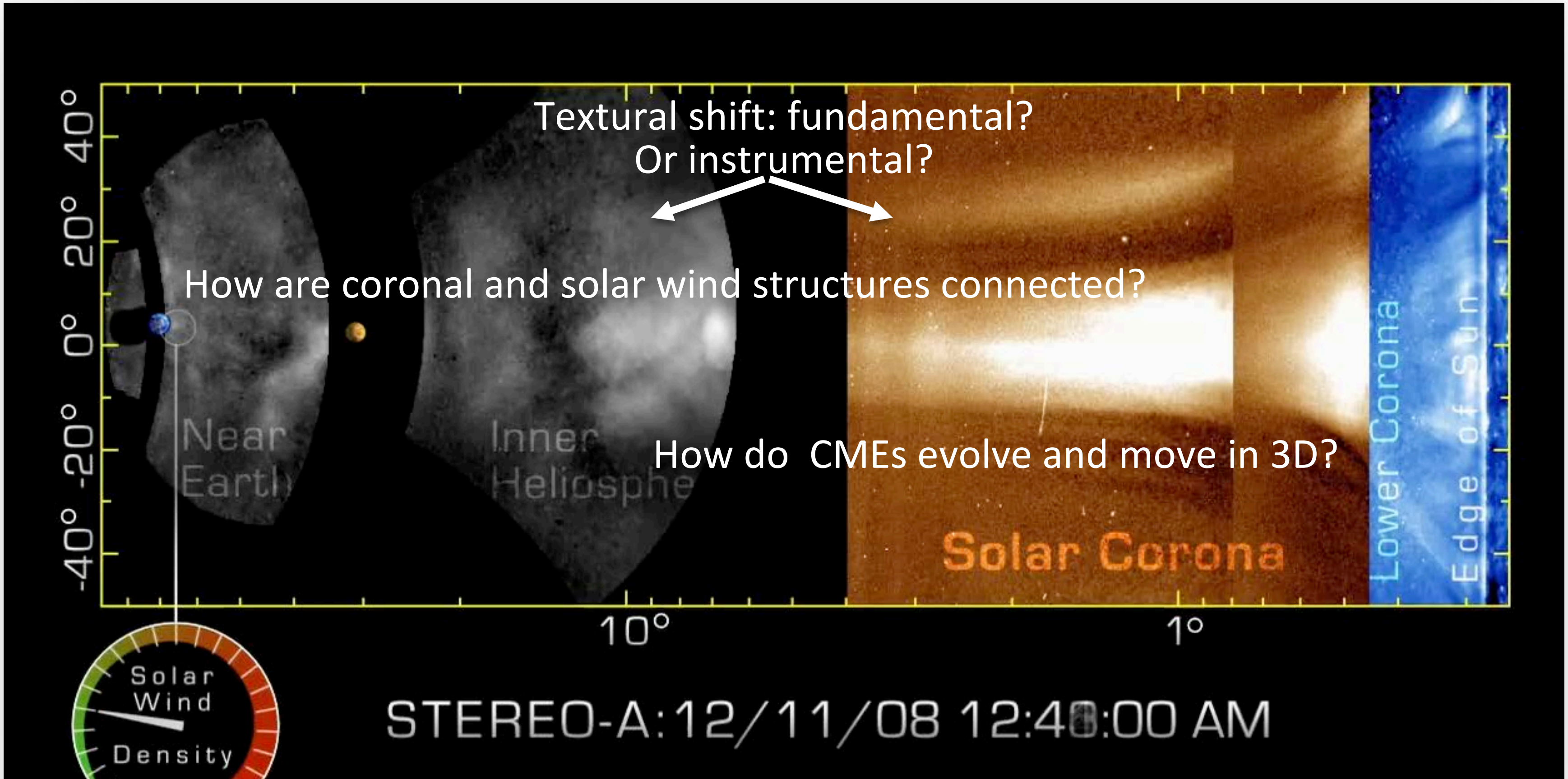
Heliospheric physics studies the solar wind in interplanetary space, primarily through in-situ sampling.





Revealing the Sun – Heliosphere Connection

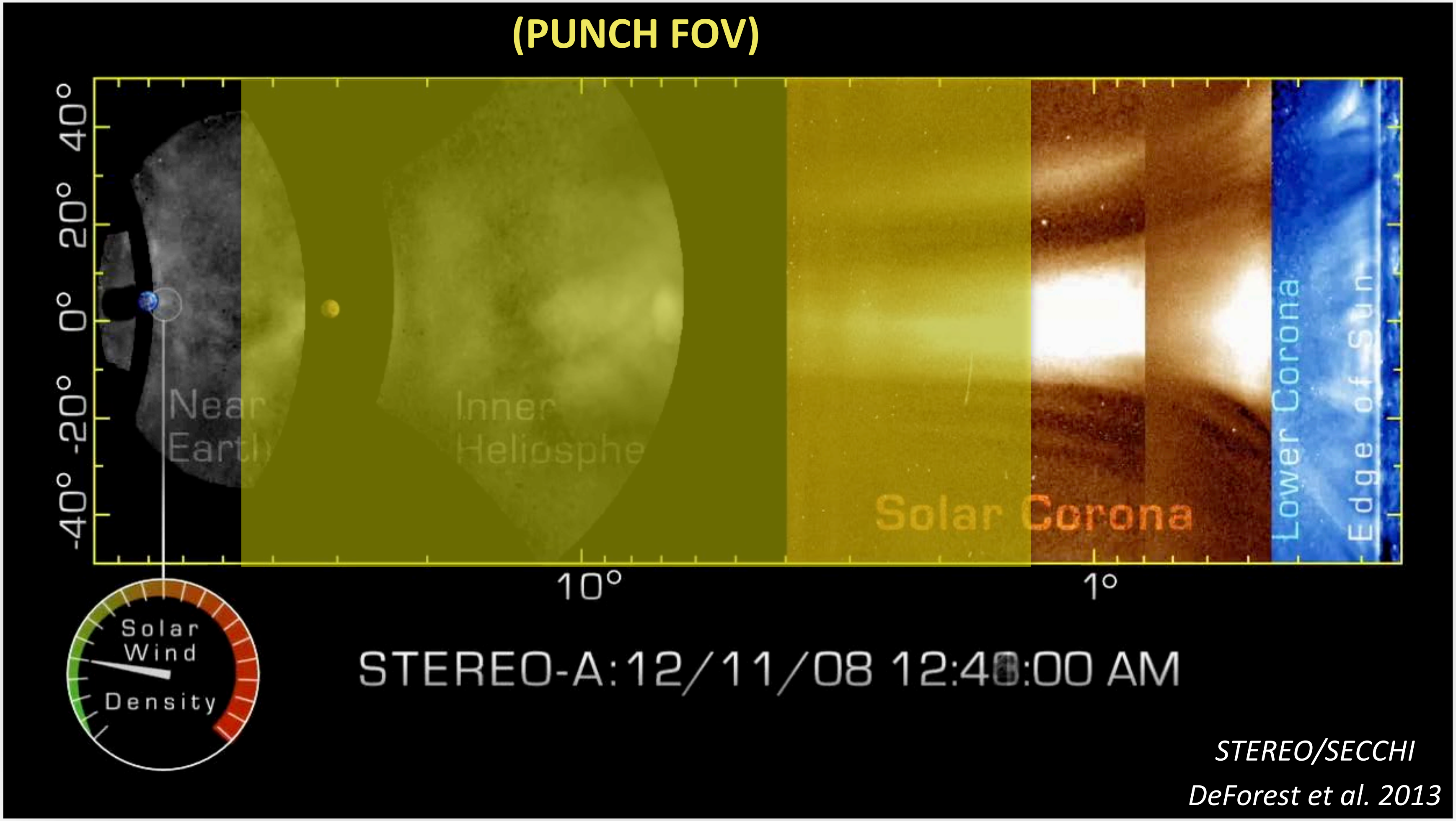
The Sun and Earth are connected … but major questions remain



STEREO/SECCHI
DeForest et al. 2013

PUNCH links the Sun and Heliosphere

What STEREO glimpsed, PUNCH reveals… in three dimensions

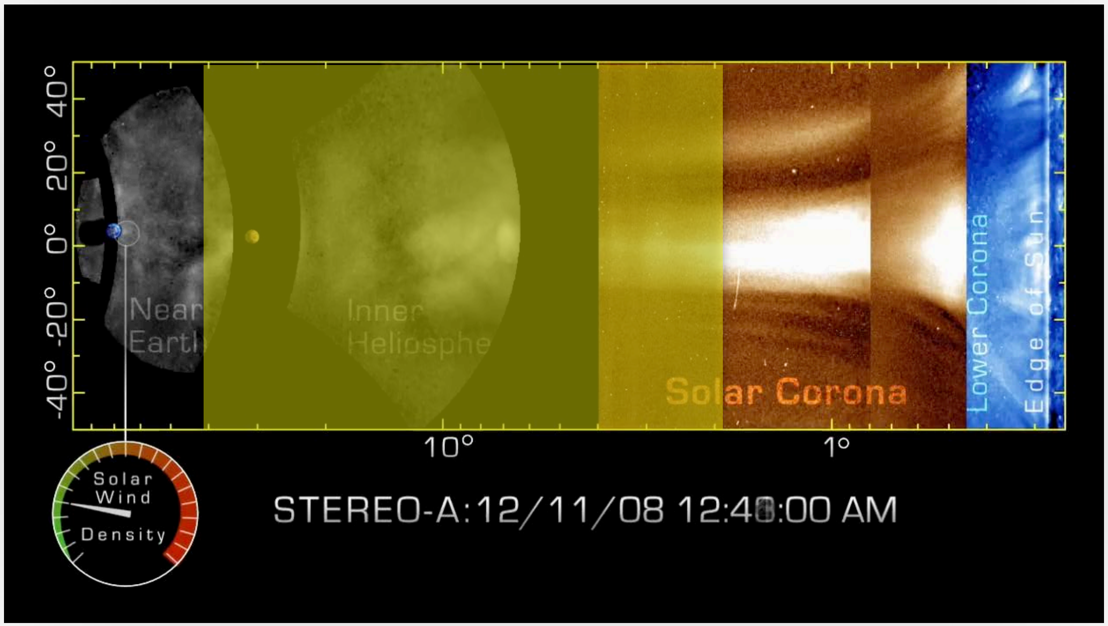


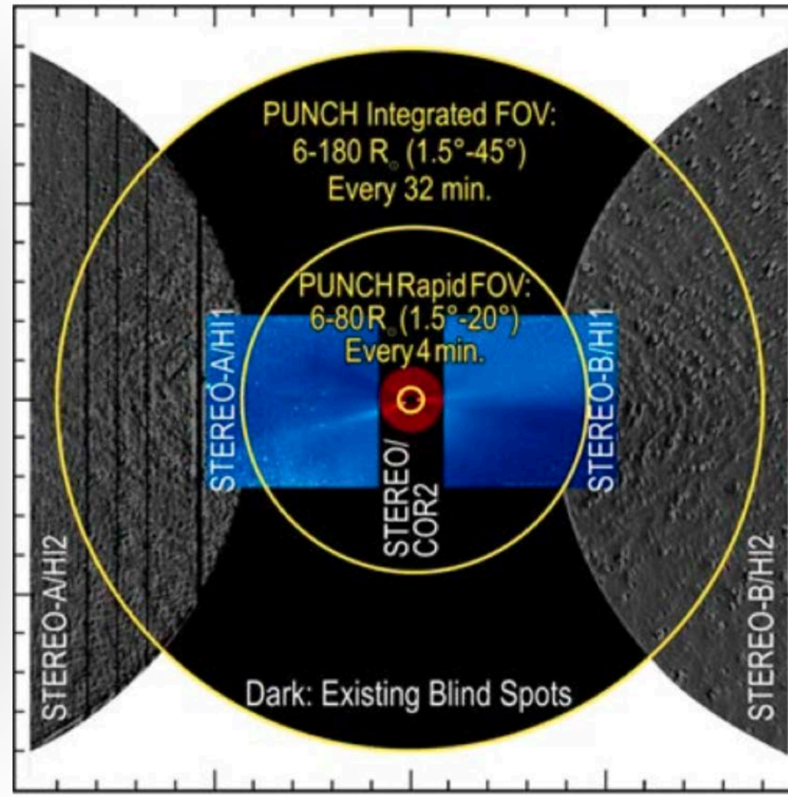
STEREO/SECCHI

DeForest et al. 2013

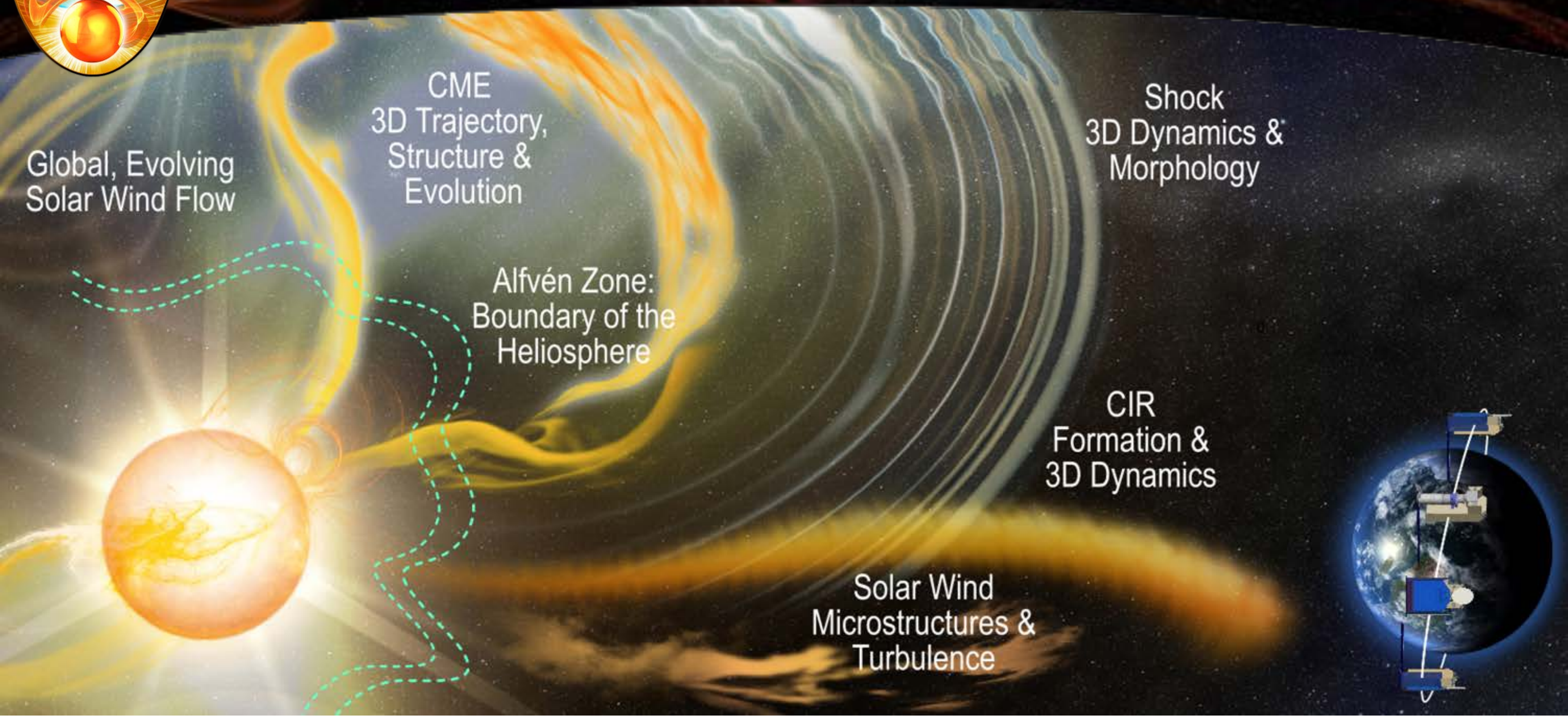
Exploring the unknown polar solar wind

What STEREO glimpsed, PUNCH reveals… in three dimensions …and from pole to pole of the Sun.





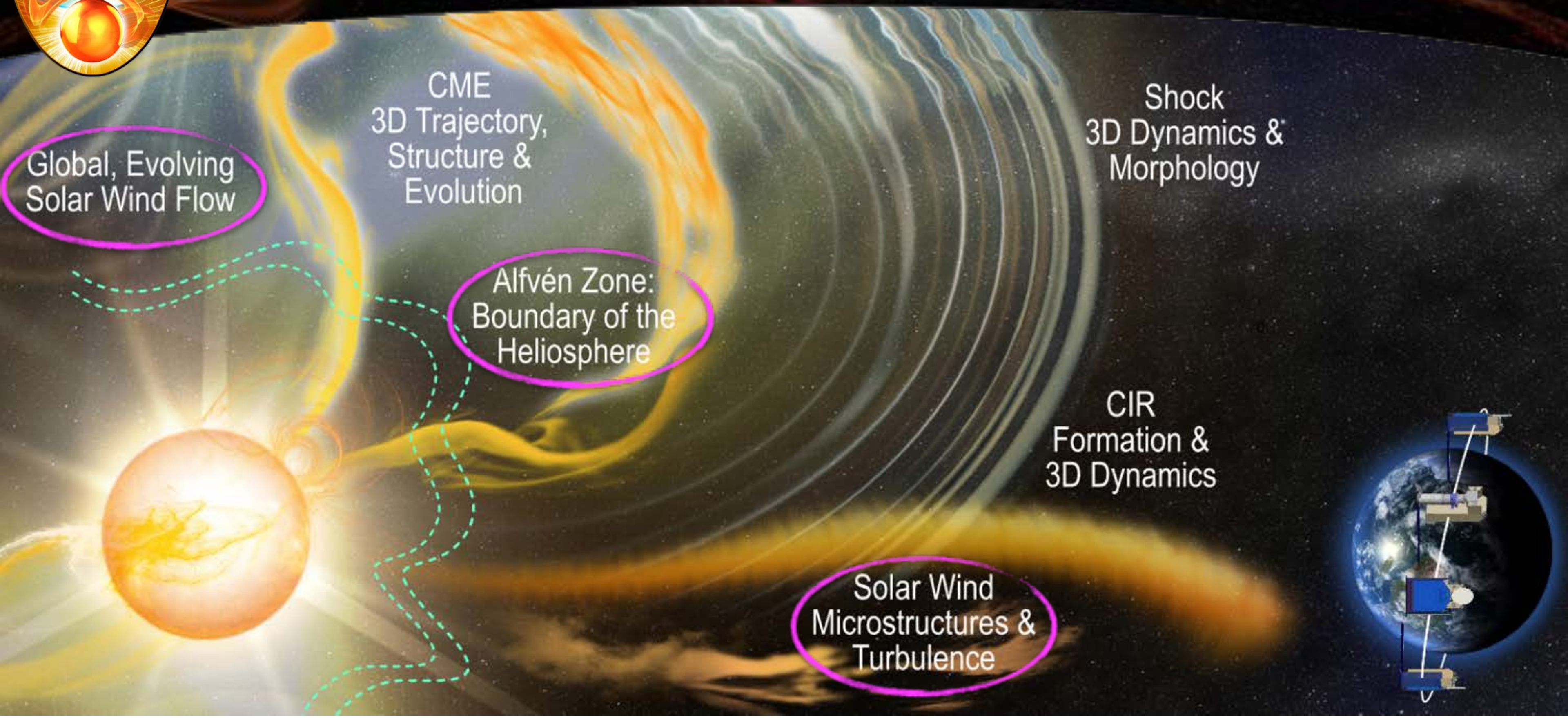
PUNCH science is central to heliophysics



PUNCH's **science goal:** comprehend the *cross-scale* physical processes – from microscale turbulence to the evolution of global-scale structures – that **unify the solar corona and heliosphere**.

1. **Understand how coronal structures become the ambient solar wind.**
2. **Understand the dynamic evolution of transient structures in the young solar wind.**

Understanding the ambient solar wind



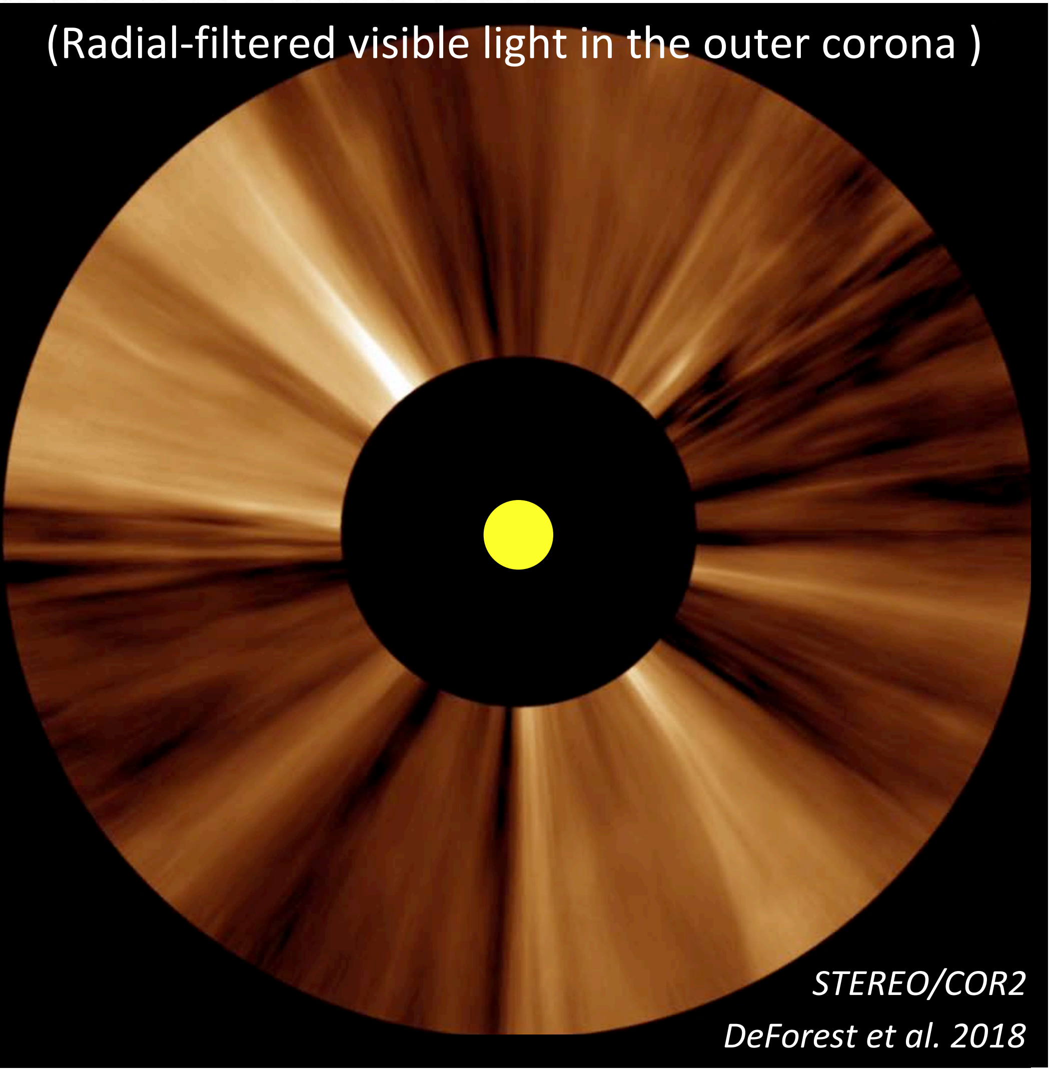
1. Understand how coronal structures become the ambient solar wind.

1A: How does the young solar wind **flow and evolve** on global scales?

1B: Where and how do **microstructures and turbulence** form in the solar wind?

1C: What are the evolving physical properties of the **Alfvén Zone**

Resolving coronal and solar wind structure

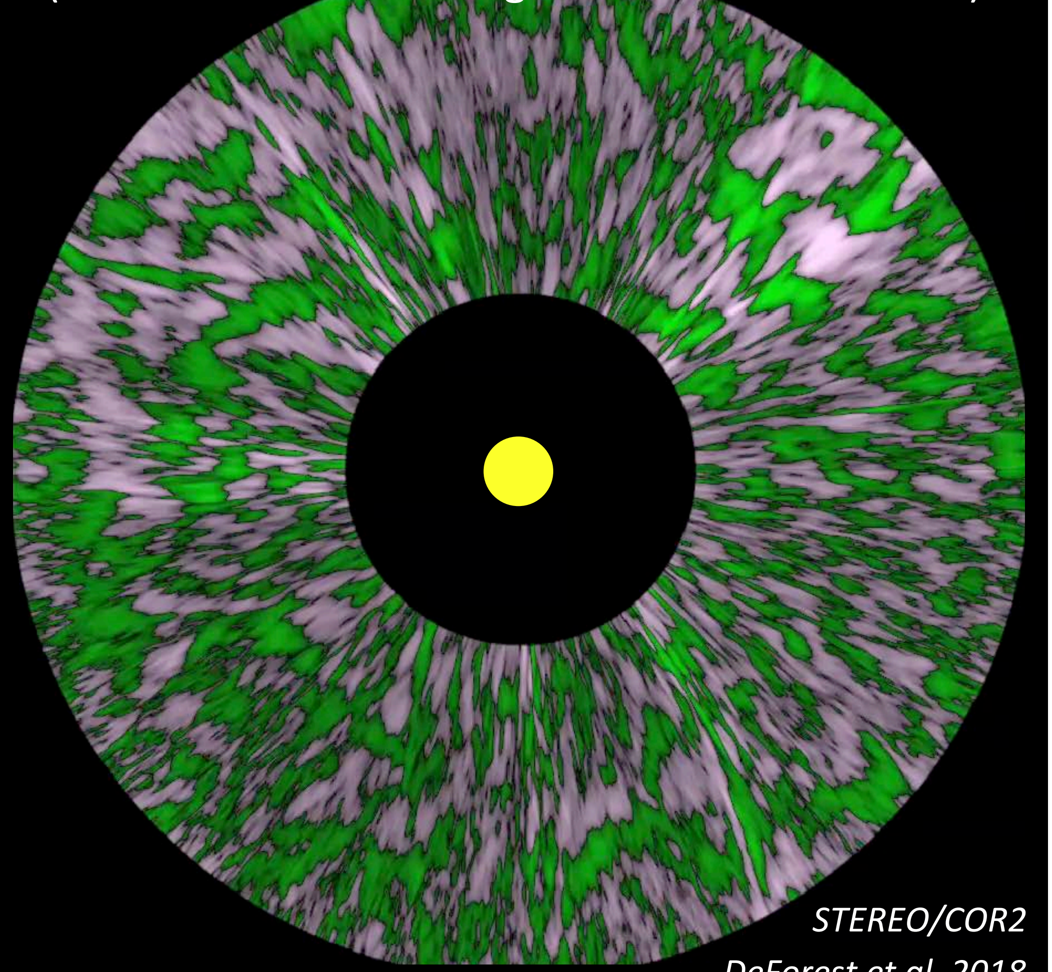


- The outer corona is highly structured.
- The importance of this complexity to the solar wind remains unknown.
- PUNCH provides the first routine global images of how this structure evolves.

…out to >10x farther from the Sun.

Revealing flow in the young solar wind

(Radial-filtered visible light in the outer corona)



STEREO/COR2
DeForest et al. 2018

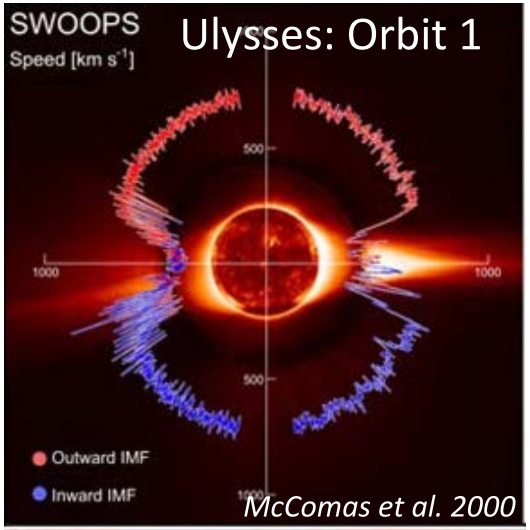
PUNCH quantifies gloal solar wind flow, every 6 hours, using the observed riotous torrent of ejecta.

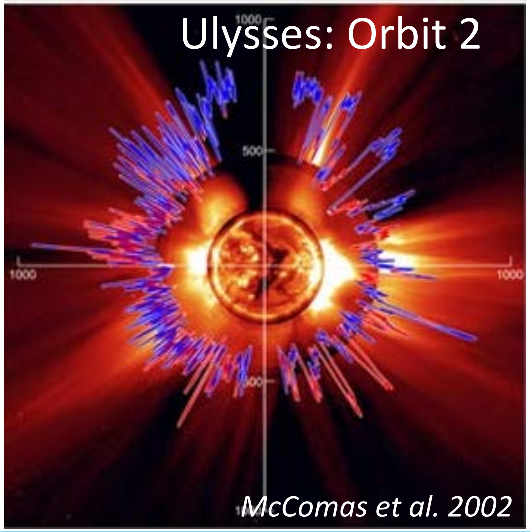
- Solar wind global flow has *never* been routinely imaged.
- What causes solar wind late-phase acceleration (DeForest et al. 2018)?
- What fraction of the solar wind is intermittent ejecta (Viall et al. 2011, 2018)?

Revealing flow in the young solar wind

Ulysses/SWOOPS
wind mapping:
Cadence: 6 years
Single track, >1AU

PUNCH
wind mapping:
Cadence: 6 hours
Range: 20-120 Rs





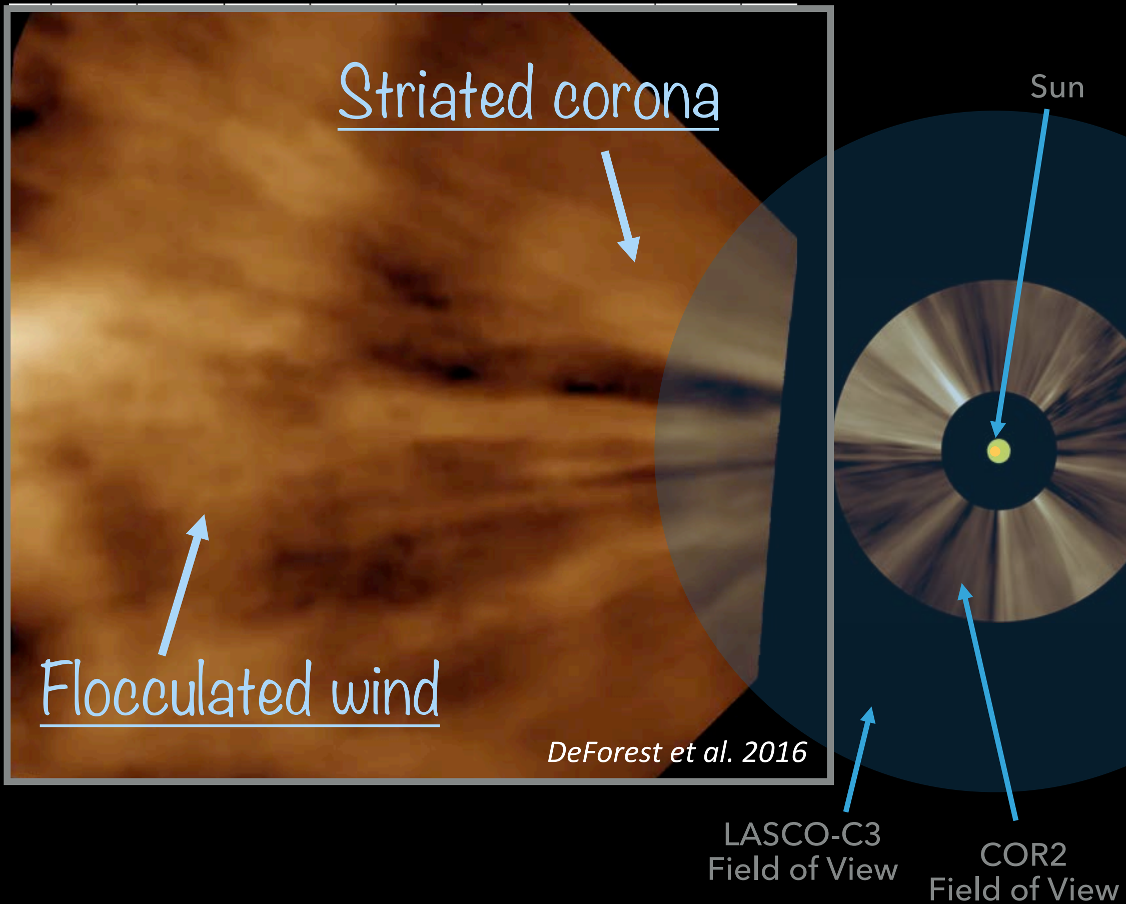
PUNCH quantifies global solar wind flow, every 6 hours, using the observed riotous torrent of ejecta.

- Solar wind global flow has *never* been routinely imaged.
- What causes solar wind late-phase acceleration (DeForest et al. 2018)?
- What fraction of the solar wind is intermittent ejecta (Viall et al. 2011, 2018)?

PUNCH determines, for the first time, the *global, evolving* flow of the young solar wind.

Understanding the transition to solar wind flow

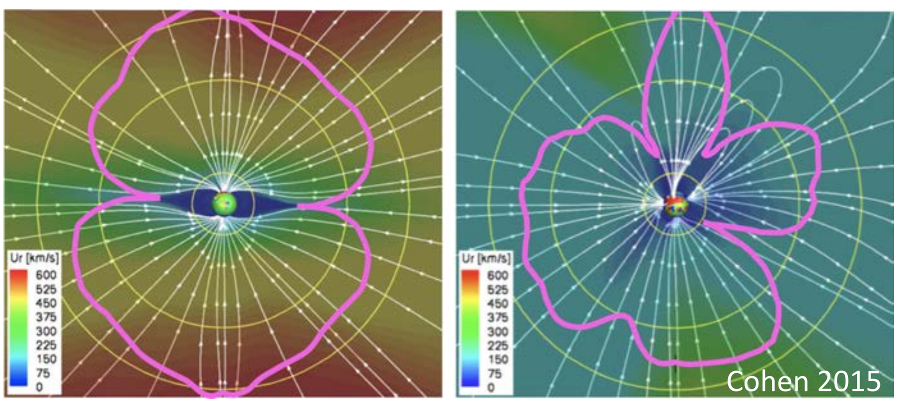
- The solar wind is turbulent.
- STEREO detected the transition from coronal striae to flocculated (puffy) solar wind.
- PUNCH reveals the nature of this transition, and the onset of solar wind turbulence.



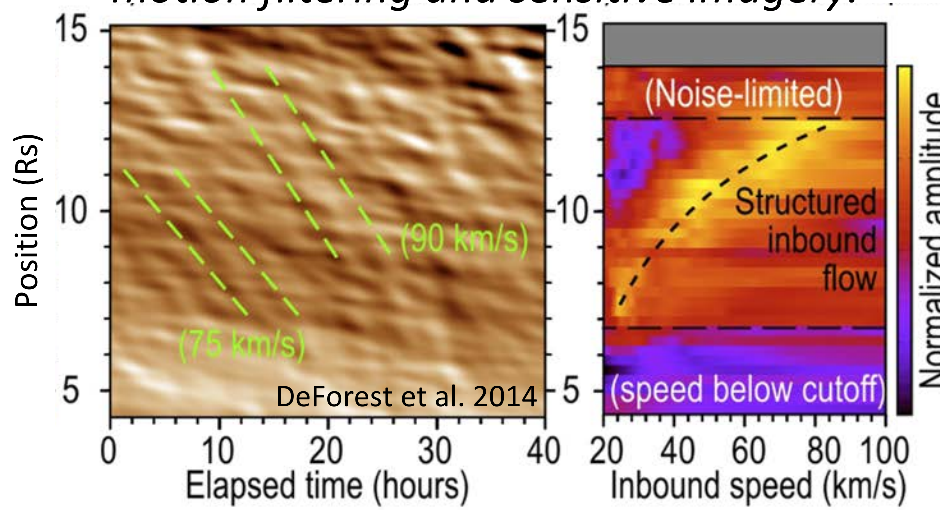
Exploring the mysterious Alfvén zone

- The Alfvén zone (DeForest et al. 2018) is the dynamical outer boundary of the corona, where the wind speed exceeds the wave speed.
- Physics of the Alfvén zone control the IMF strength and the solar wind.
- The region has never been located and models are nearly unconstrained.
- PUNCH is specifically designed to map the global structure of the Alfvén zone.

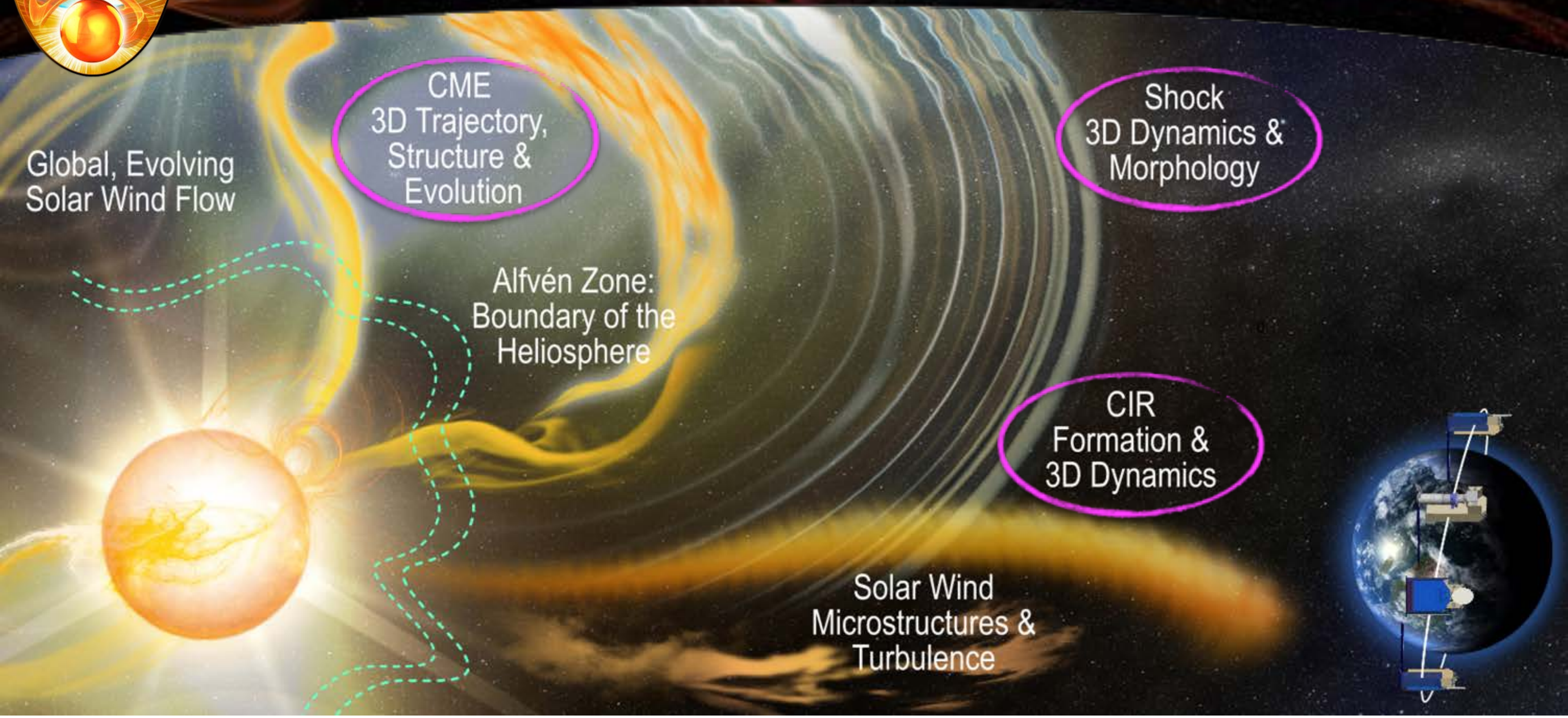
Alfvén zone models are currently nearly unconstrained.



PUNCH maps the Alfvén zone with proven motion filtering and sensitive imagery.



Understanding the transient structures that cause space weather

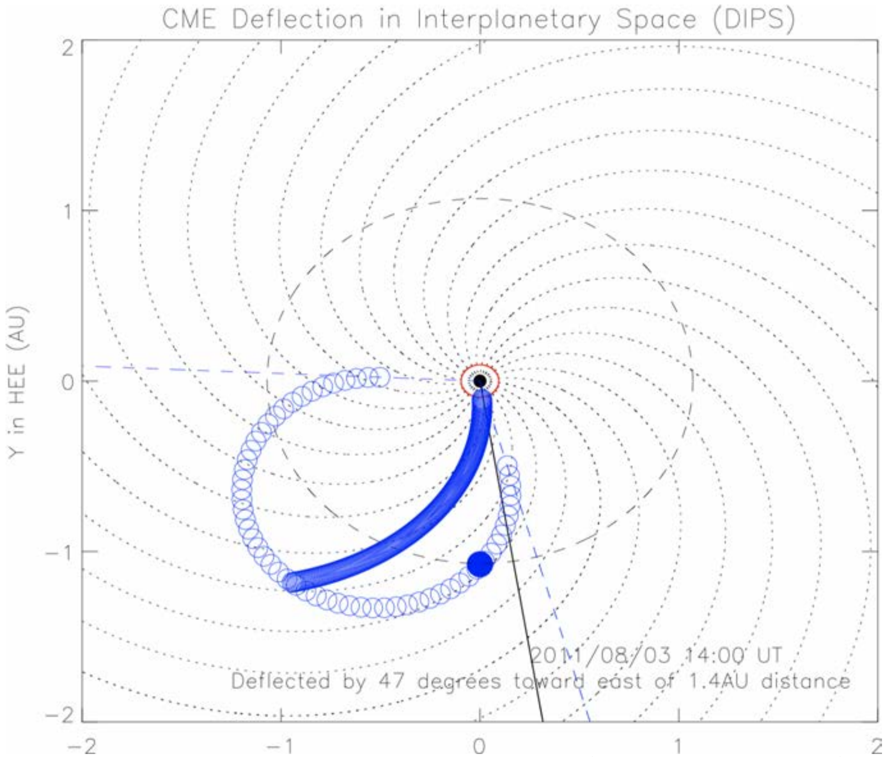


2. Understand the dynamic evolution of transient structures in the young solar wind.

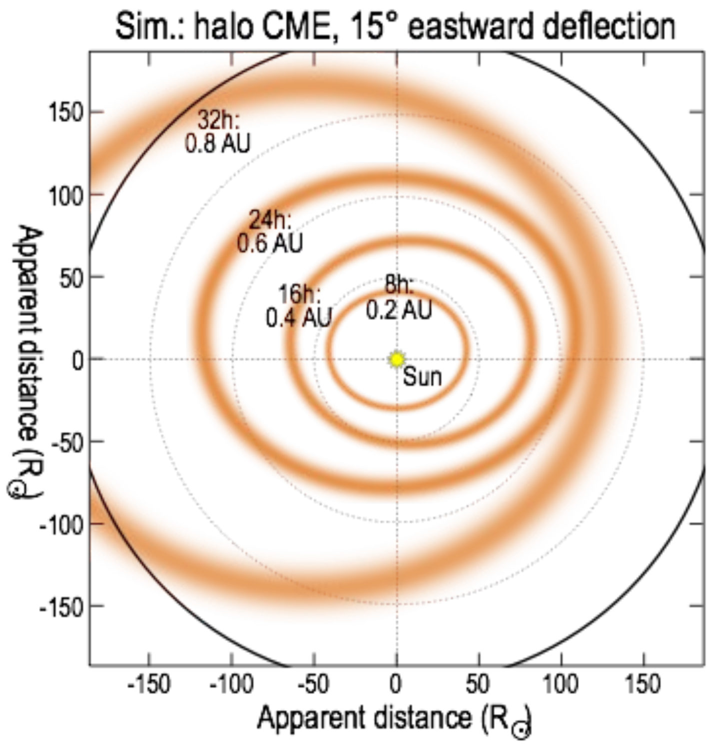
- 2A: How do **coronal mass ejections** (CMEs) propagate and evolve in the solar wind in 3D?
- 2B: How do quasi-stationary **corotating interaction regions** (CIRs) form and evolve?
- 2C: How do **shocks** form and interact with the solar wind across spatial scales?

Tracking CMEs and their Structure in 3D

- CME 3D trajectory tracking yields understanding of their interaction with the solar wind – currently inaccessible by any other measurement.

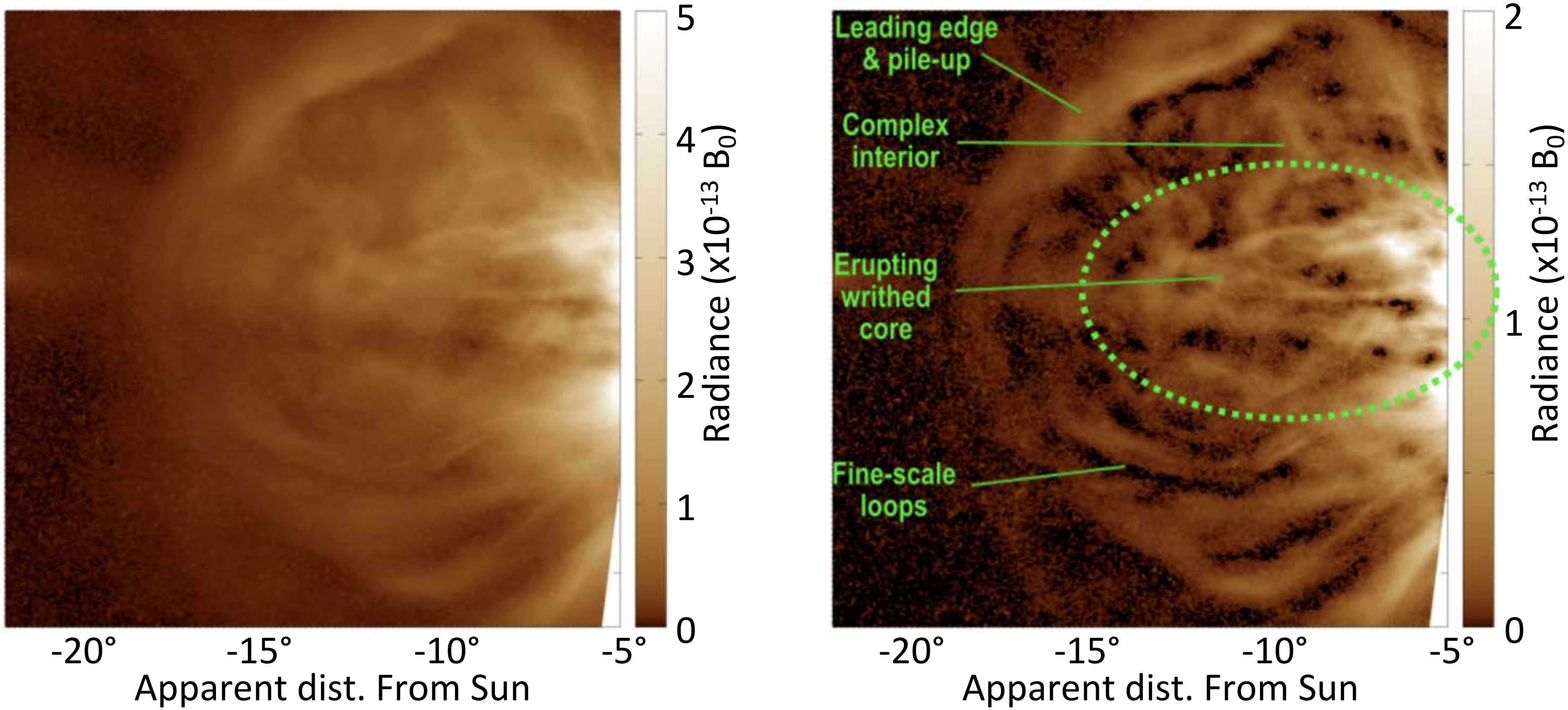


(Zhuang et al. 2017)



Tracking CMEs' Evolving Structure in 3D

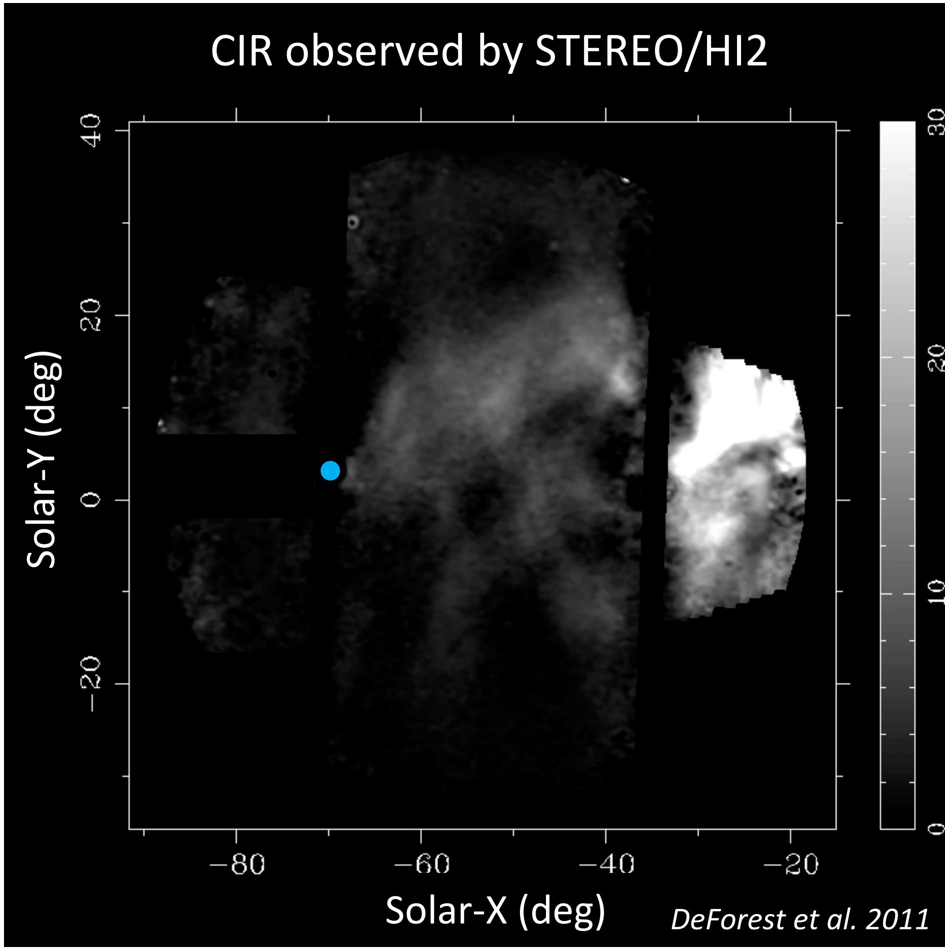
CME: STEREO-A/HI-1, 2012-09-03 04:09 UTC



Probing CIRs and Shocks

Corotating Interaction Regions (CIRs)

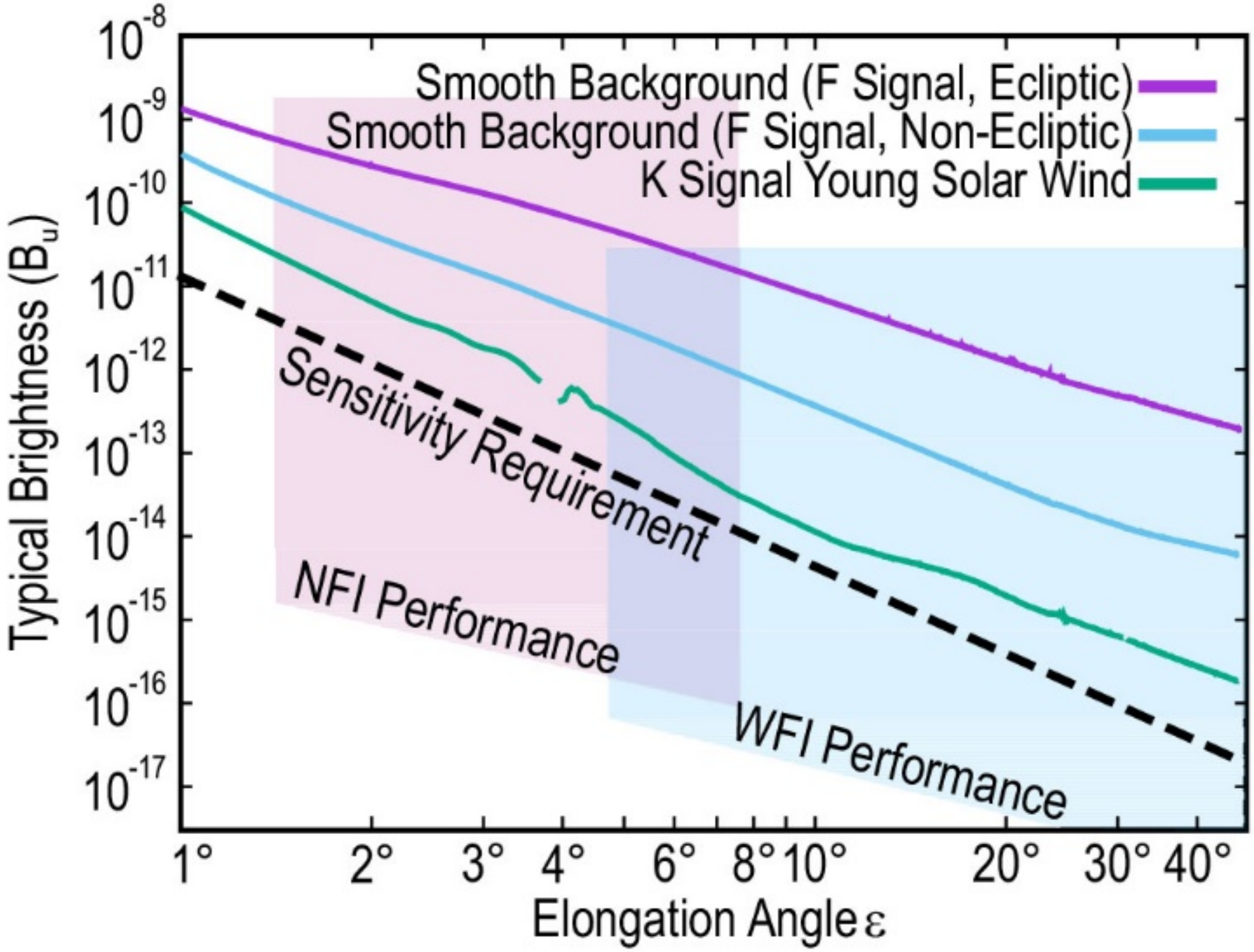
- CIR impact is the most common form of space weather at Earth.
- CIRs are poorly explored but are valuable probes of the solar wind.
- Why are CIR fronts scalloped?
  (solar wind variability, turbulence, waves?)
- How do CIR shocks form at 20-40 $R_\odot$?
- How do CIR and CME shocks evolve in 3D?



PUNCH 3D imaging explores now-inaccessible CIR and shock physics.

Instruments: Two Imager Types

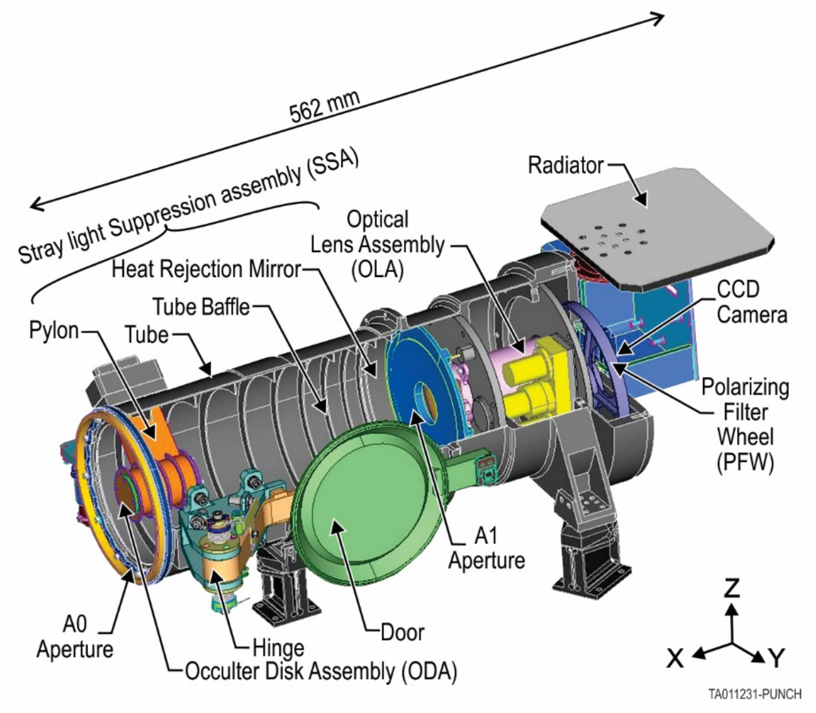
Brightness gradient drives two imager types



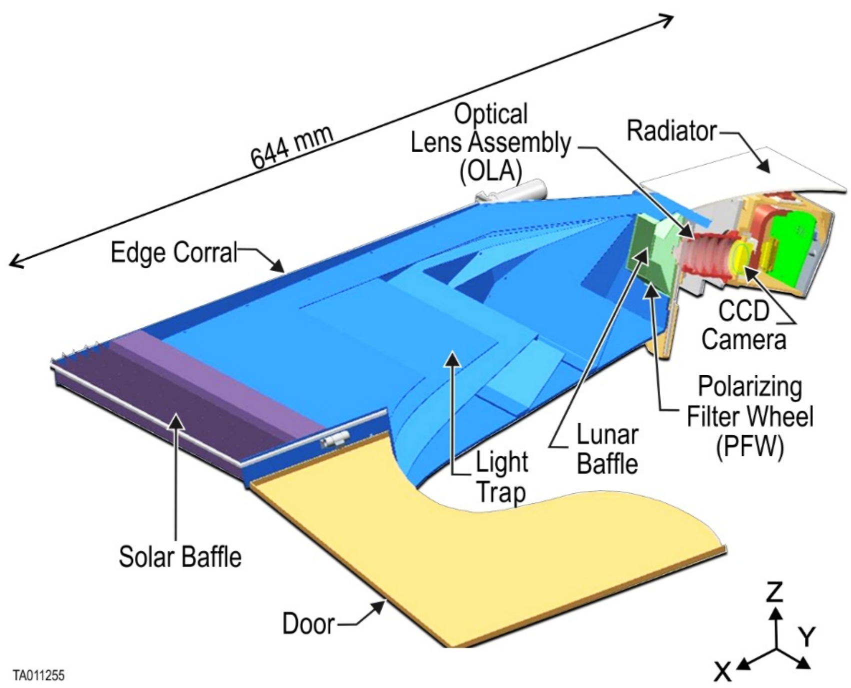
Instruments

- Instruments are matched for joint observation.
- High heritage, simple designs share common subsystems.
- Interfaces are interchangeable for resilience.

NFI: Compact Coronagraph design
Naval Research Laboratory



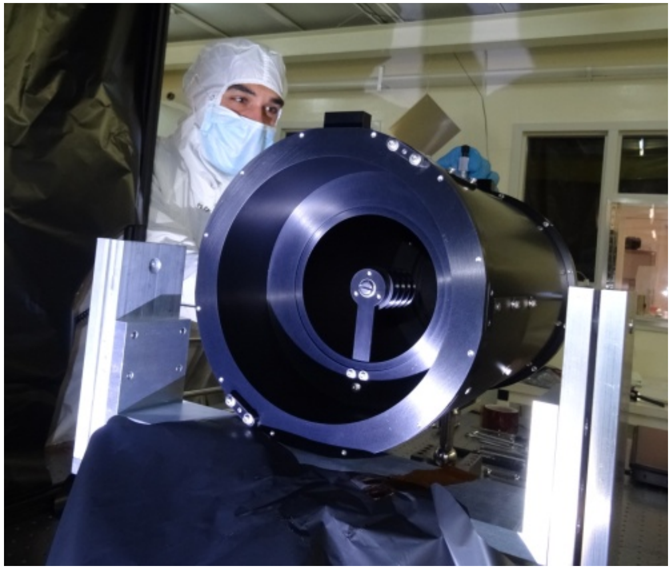
WFI: Heliospheric Imager design
Southwest Research Institute



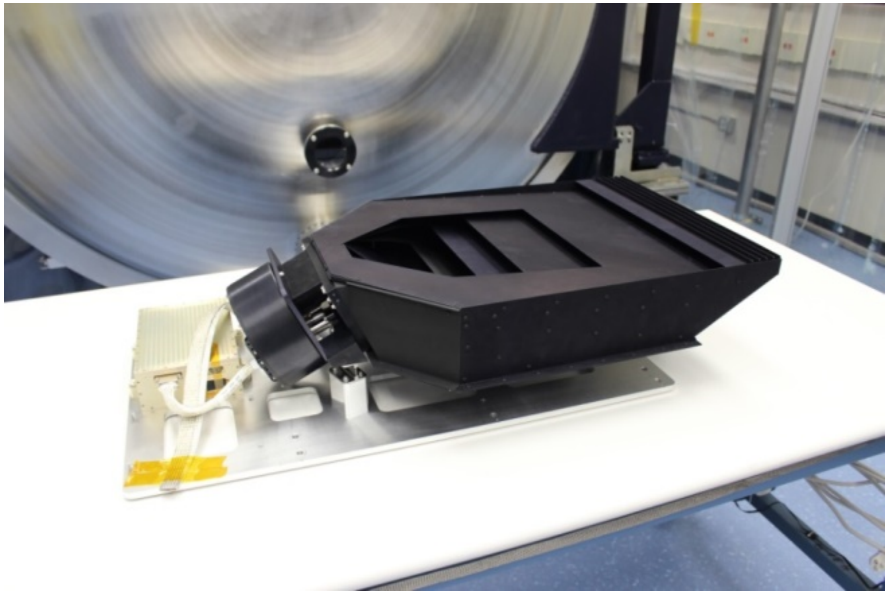
Instruments

- Both instruments were prototyped, tested, and qualified in Phase A.

NFI prototype
Naval Research Laboratory



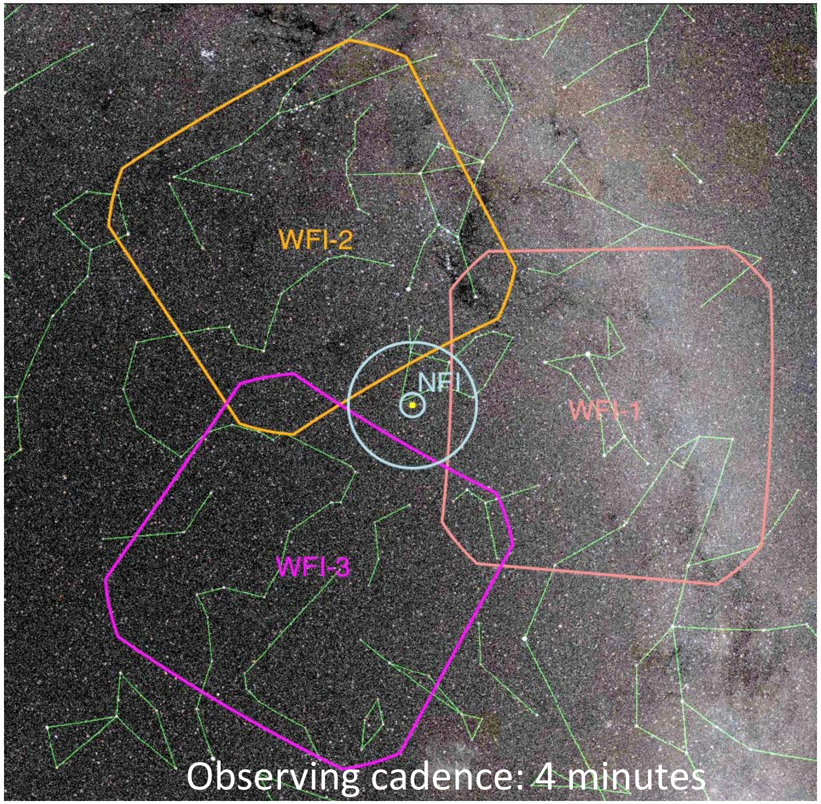
WFI prototype
Southwest Research Institute



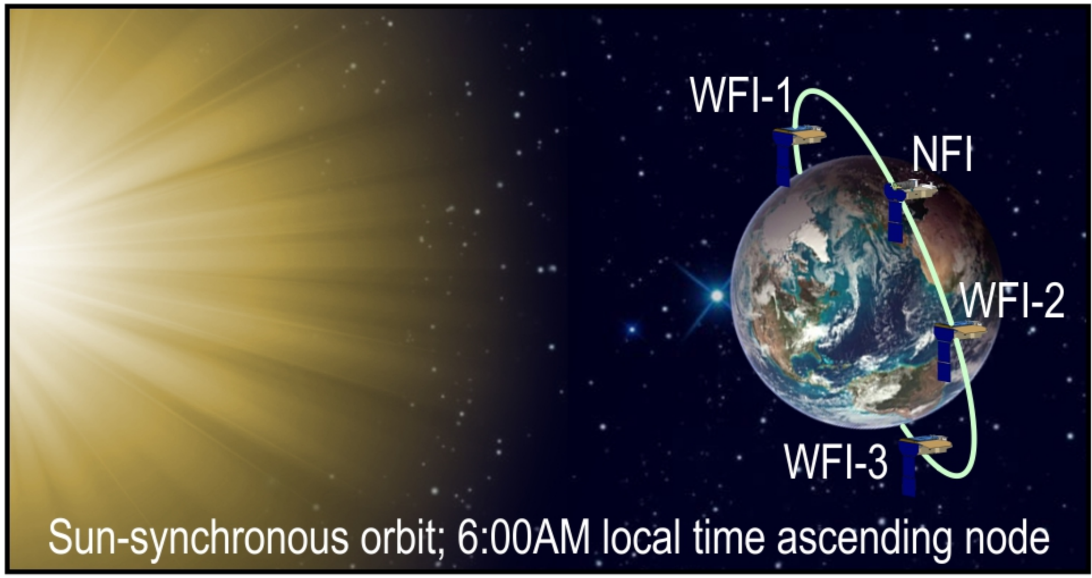
Implementation: 1+3 Constellation

LEO orbit and cadence requirements drive a constellation solution.

PUNCH sweeps its full FOV 3x per orbit

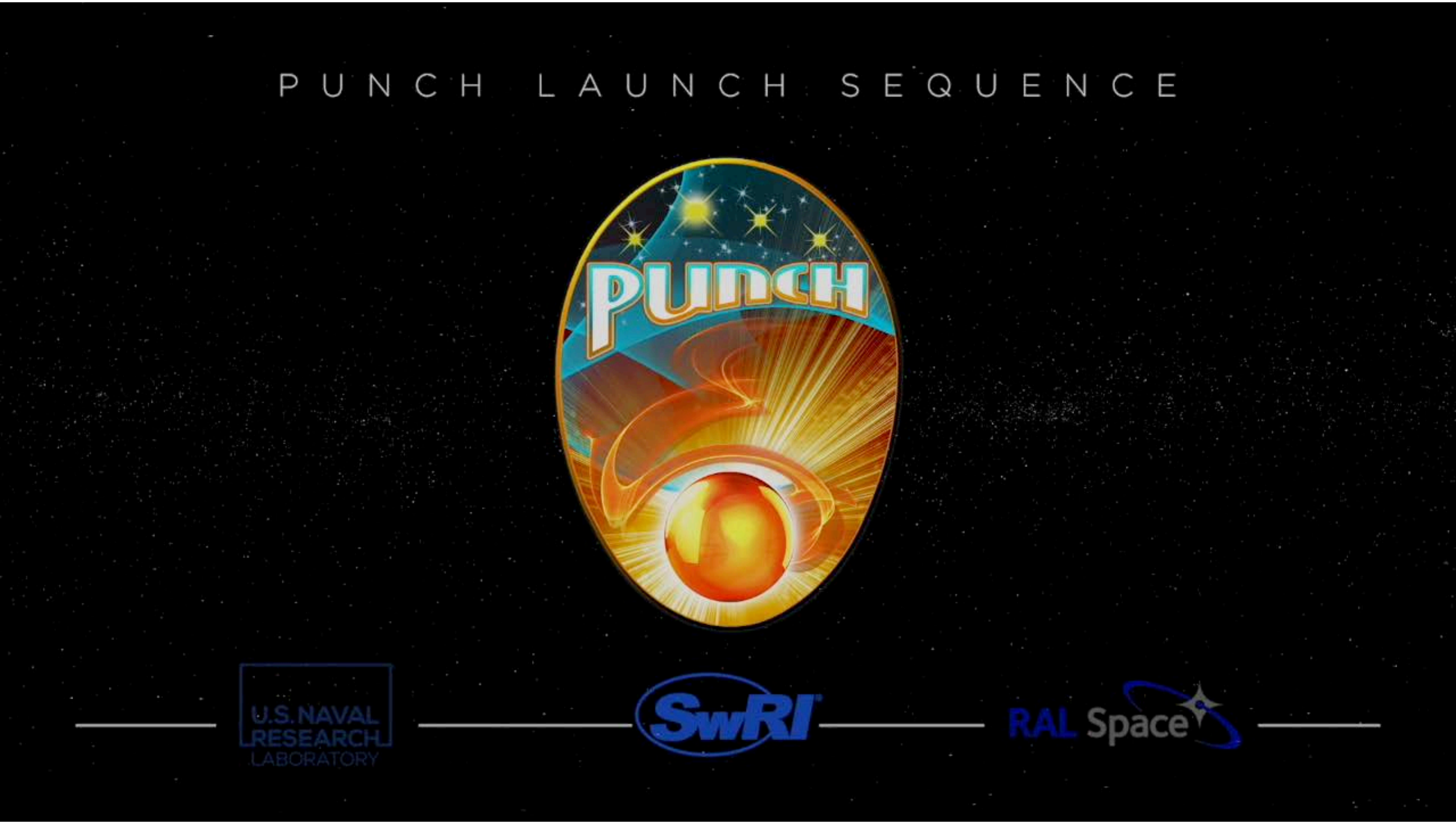


Three WFIs are 120° apart; NFI is unconstrained



(Four cameras act as a single distributed "virtual instrument")

NASA-LSP Launch and PUNCH operations



Science "Dream Team"

- The PUNCH Science Team spans the nation and the globe.
- All-star cast unites multiple fields of heliophysics.
- International contributions (not required for closure) add resilience, breadth.

- Aberystwyth University
- Johns Hopkins University Applied Physics Lab
- Boston College
- Cooperative Institute for Research in the Environmental Sciences
- European Space Agency
- George Mason University
- High Altitude Observatory
- Imperial College London
- Indian Institute of Astrophysics
- Institut de Recherche en Astrophysique et Planétologie
- National Aeronautics and Space Administration
- National Oceanic and Atmospheric Administration
- Naval Research Laboratory
- Princeton Plasma Physics Laboratory
- Rutherford Appleton Laboratories
- Southwest Research Institute
- University of CA, Berkeley: Space Space Sciences Lab
- University of CA, SD: Center for Astrophysics & Space Science
- University of Delaware
- University of Sydney

International Institution

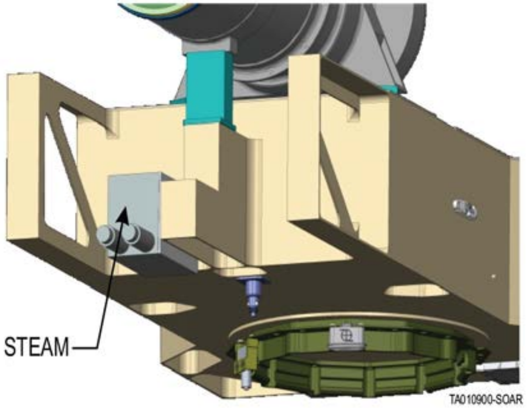
The PUNCH Science team are Young Solar Wind pioneers, spanning heliophysics and the globe.

Outreach via Student Collaboration (STEAM)

- Full-Sun, time-resolved SXR & HXR spectrometer

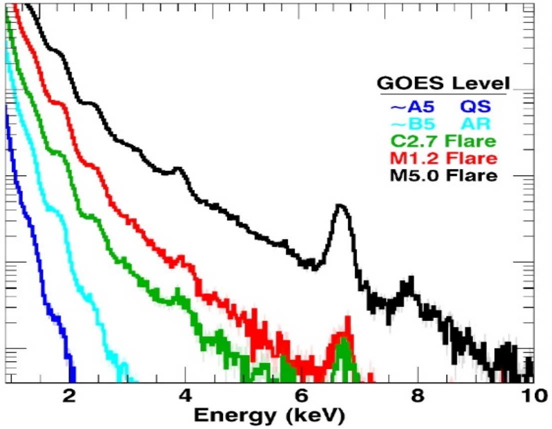
- Led by Colorado Space Grant Consortium
- Science Mentor at CU Boulder
- Engineering Mentorship at SwRI
- Students participate in 7120.5E reviews
- Scientifically relevant project

STEAM rides with NFI

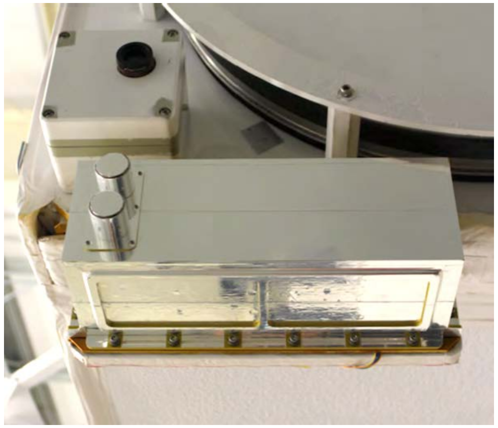


Direct Hands-On Experience

Scientifically Useful Data

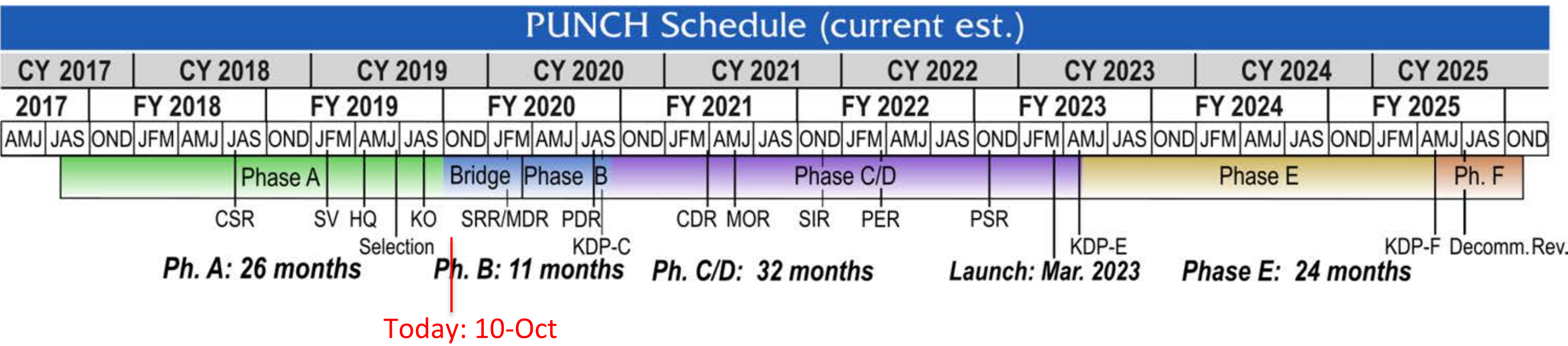


SwRI heritage



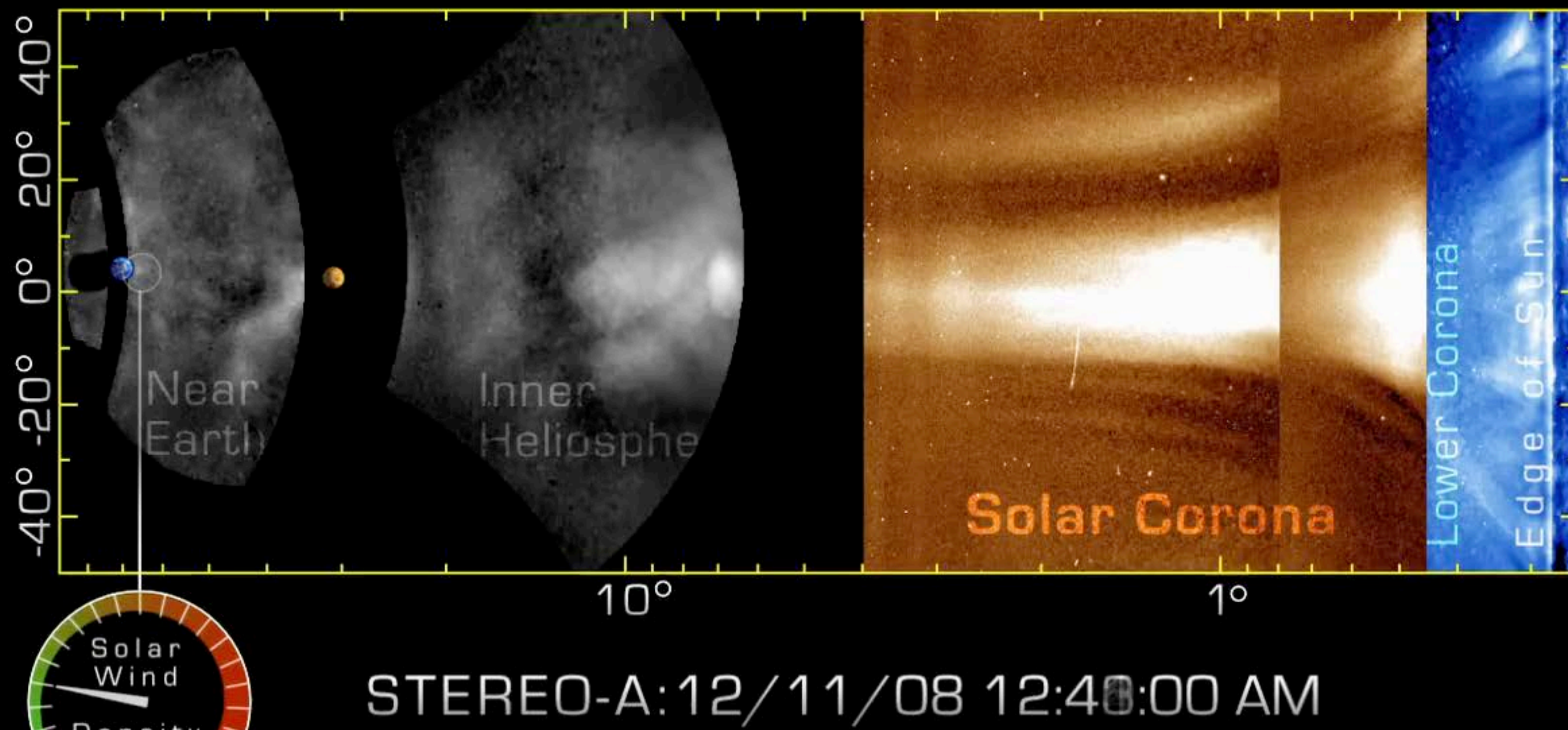
STEAM delivers meaningful, scientifically relevant engineering & space experience

PUNCH Schedule



Why 3D Imaging?

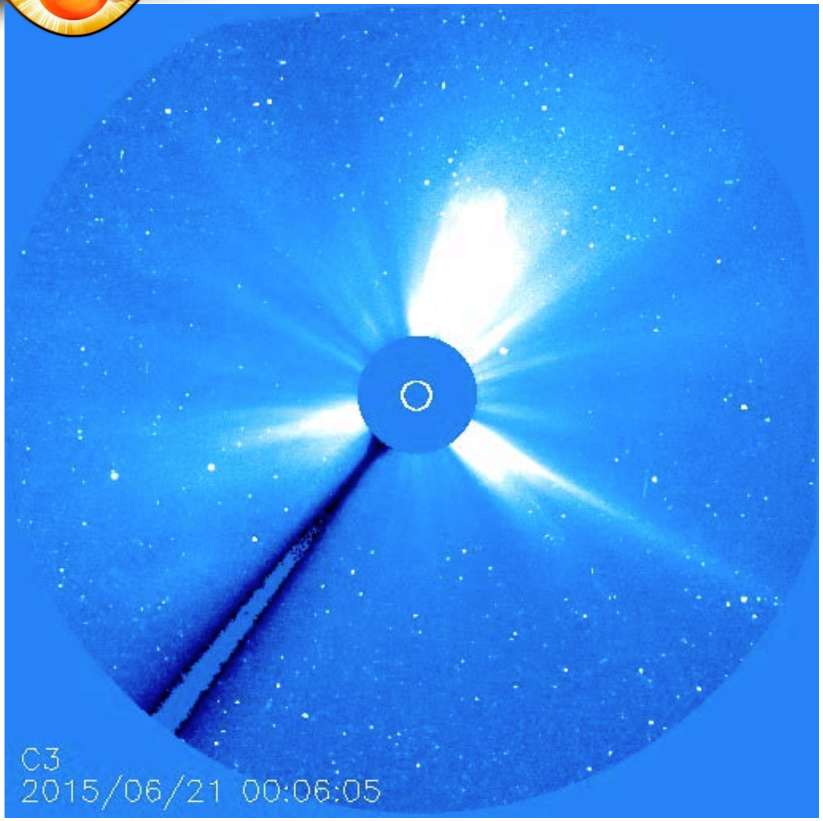
2D CME tracking is great … when it works.



- Off-axis (deep space) viewpoint is required.
- Front/back alignment is hard to determine.
- Shape and chirality are uncertain.

Why 3D Imaging?

2D CME tracking fails in the cases that matter most.



Halo CME seen from SOHO/LASCO:

Earthbound … but how fast?

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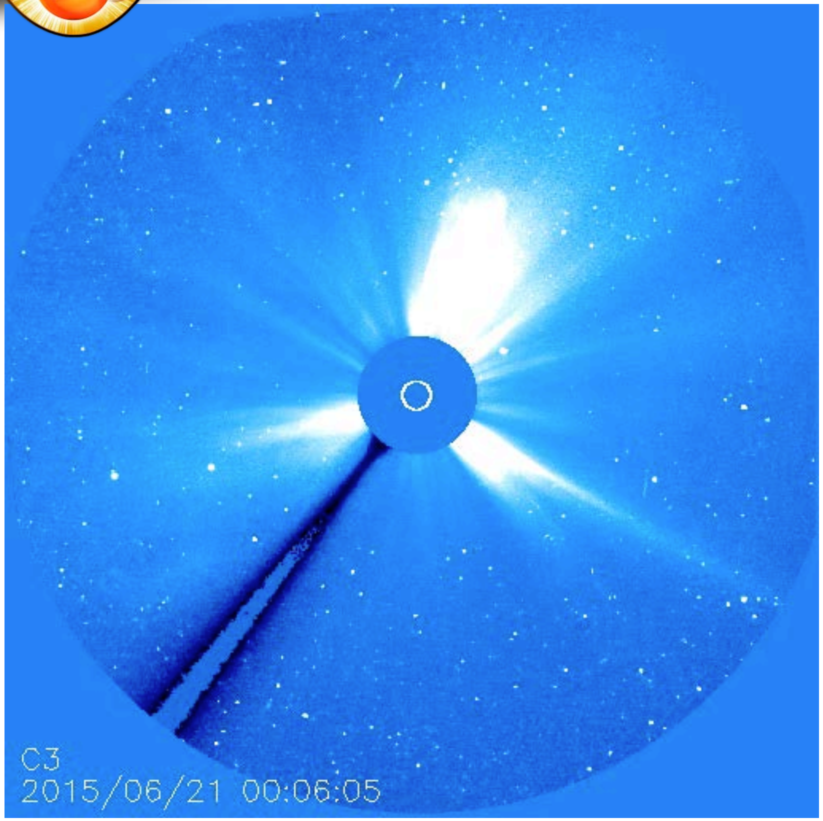

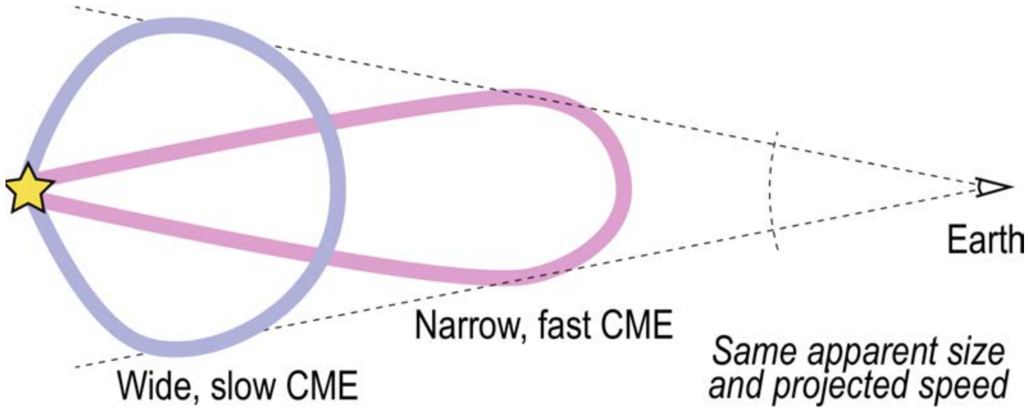

Halo CME seen from SOHO/LASCO:

Earthbound … but how fast?

The speed/size ambiguity:
Fast, narrow halo CMEs look the same as slow, wide CMEs (in 2D).

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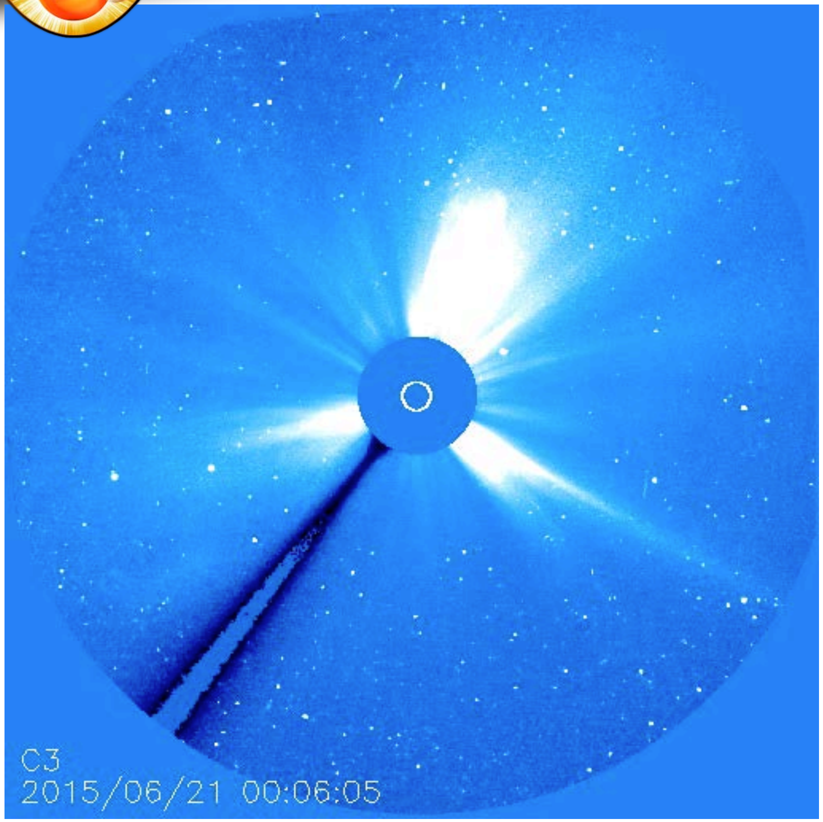
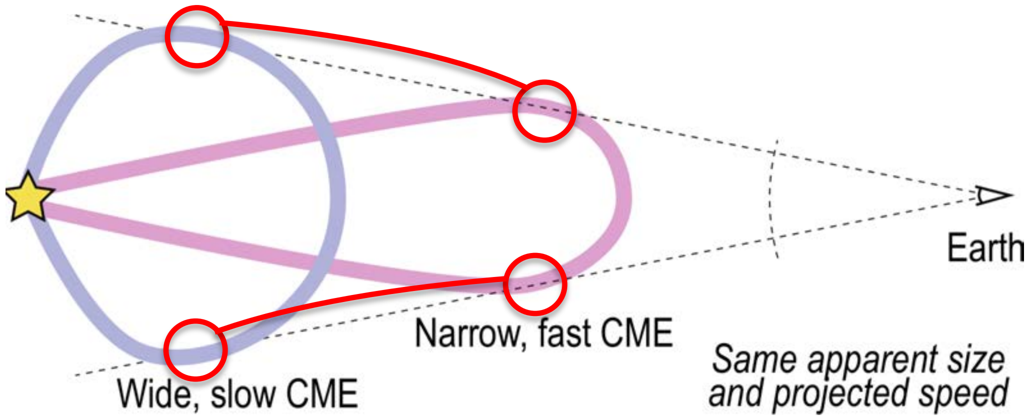




Halo CME seen from SOHO/LASCO:

Earthbound … but how fast?

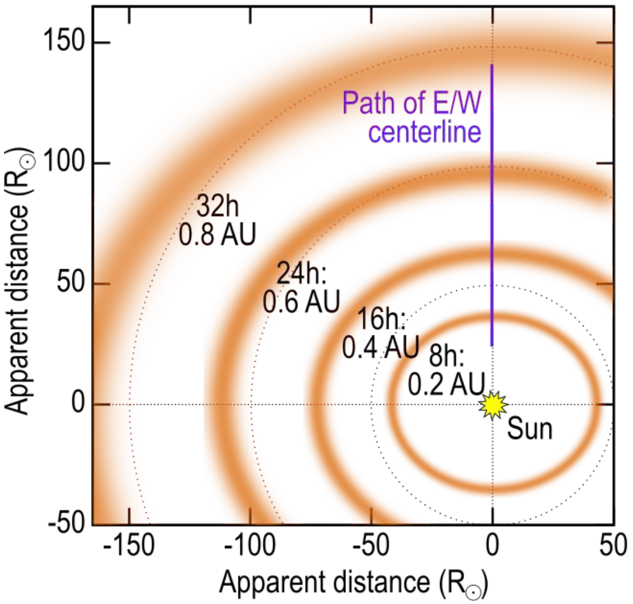
The speed/size ambiguity: ***Fast, narrow halo CMEs look the same as slow, wide CMEs (in 2D).***

Why 3D Imaging?

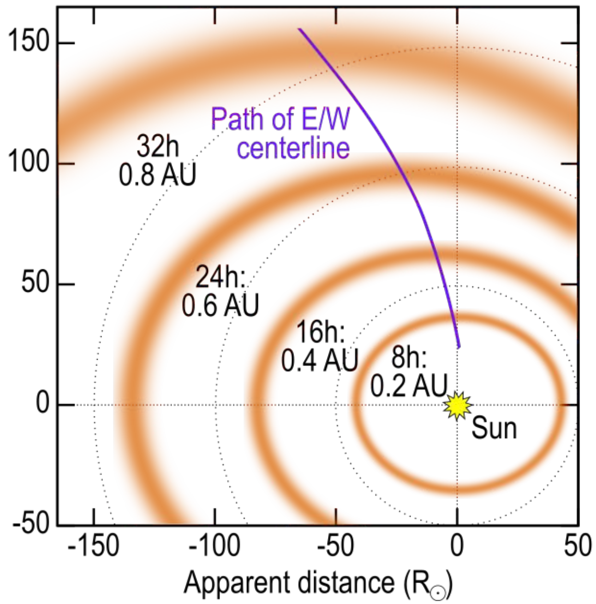
*PUNCH, **Space Weather**, and You*

3D tracking of halo CMEs: what will it look like?

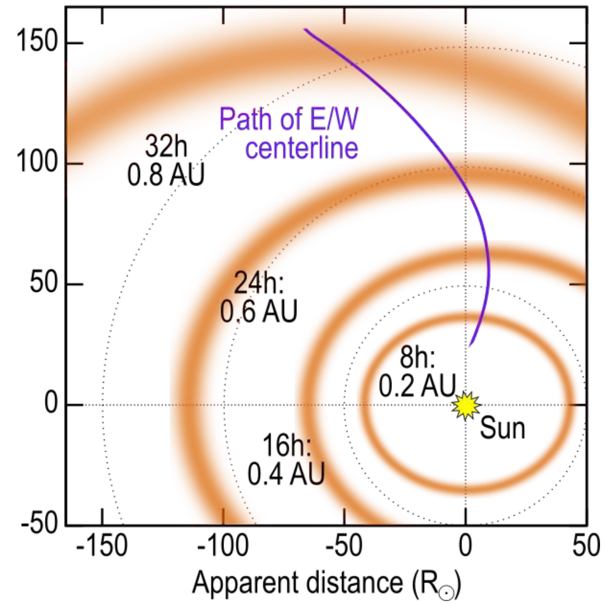
Direct hit: centerlines propagate straight



Glancing hit: E/W centerline evolves



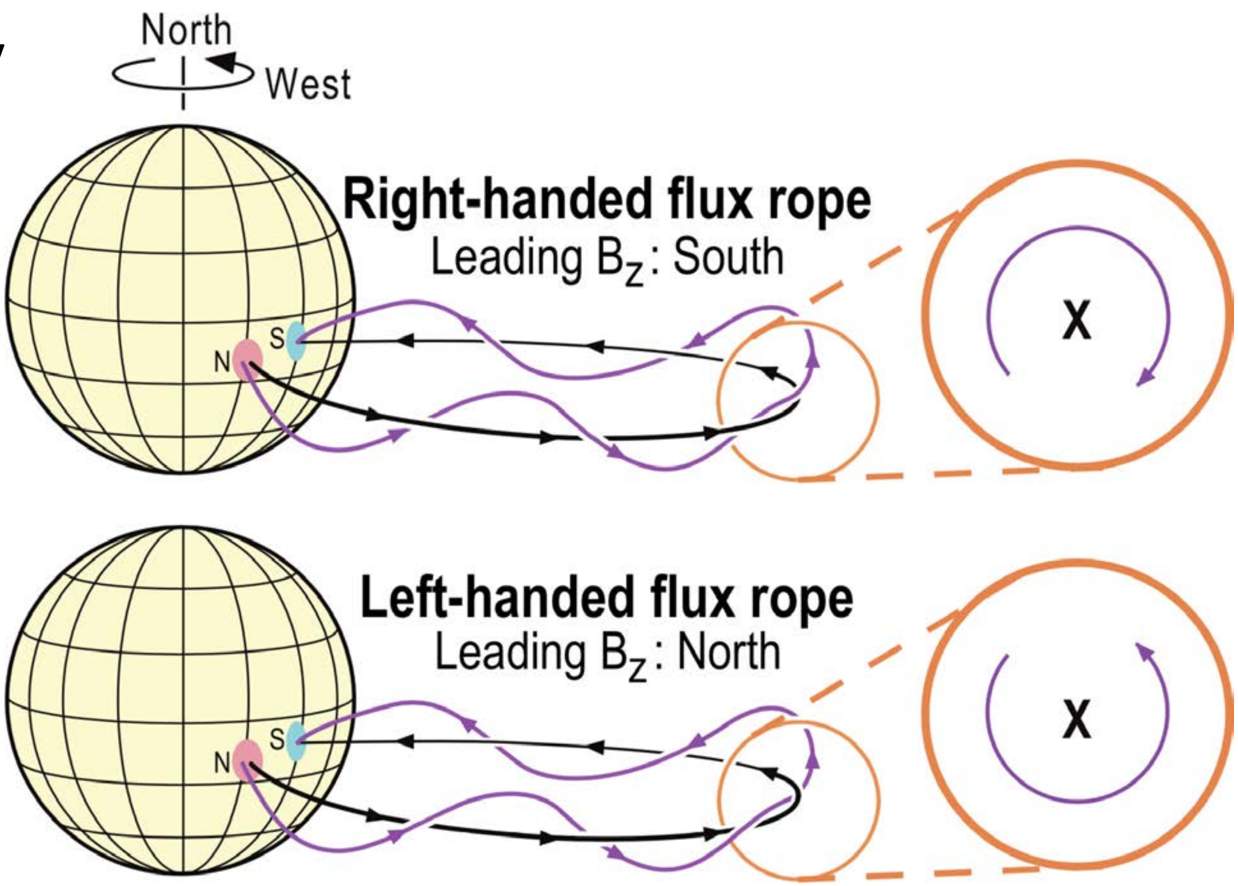
Deflection: E/W centerline is anomalous



Why 3D Imaging?

Chirality determines leading-edge B_z!

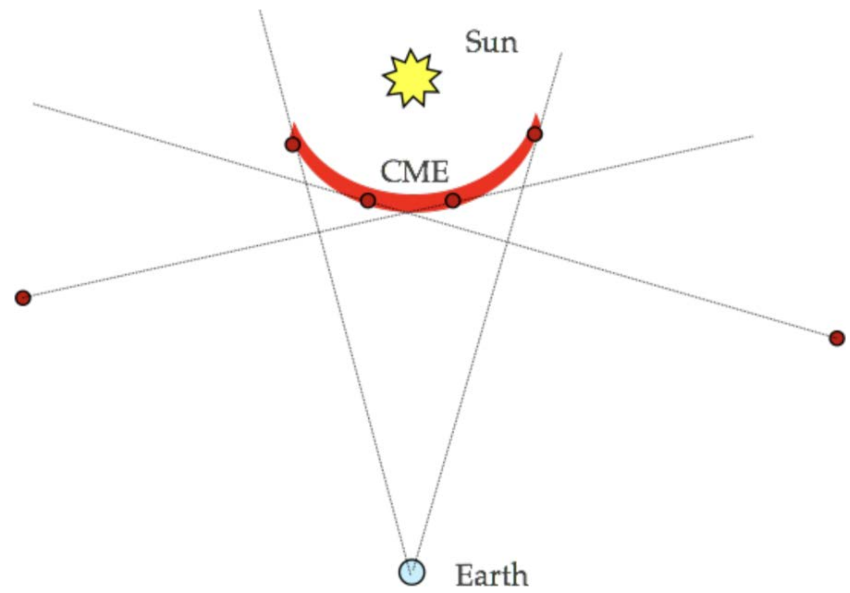
- Leading-edge B_z is set by CME core field and twist direction ("chirality").
- Core field direction is known from magnetograms.
- 3D imaging reveals chirality, bridging the photosphere to leading-edge B_z prediction.



Why polarized imaging?

Stereoscopy is flawed for CME tracking.

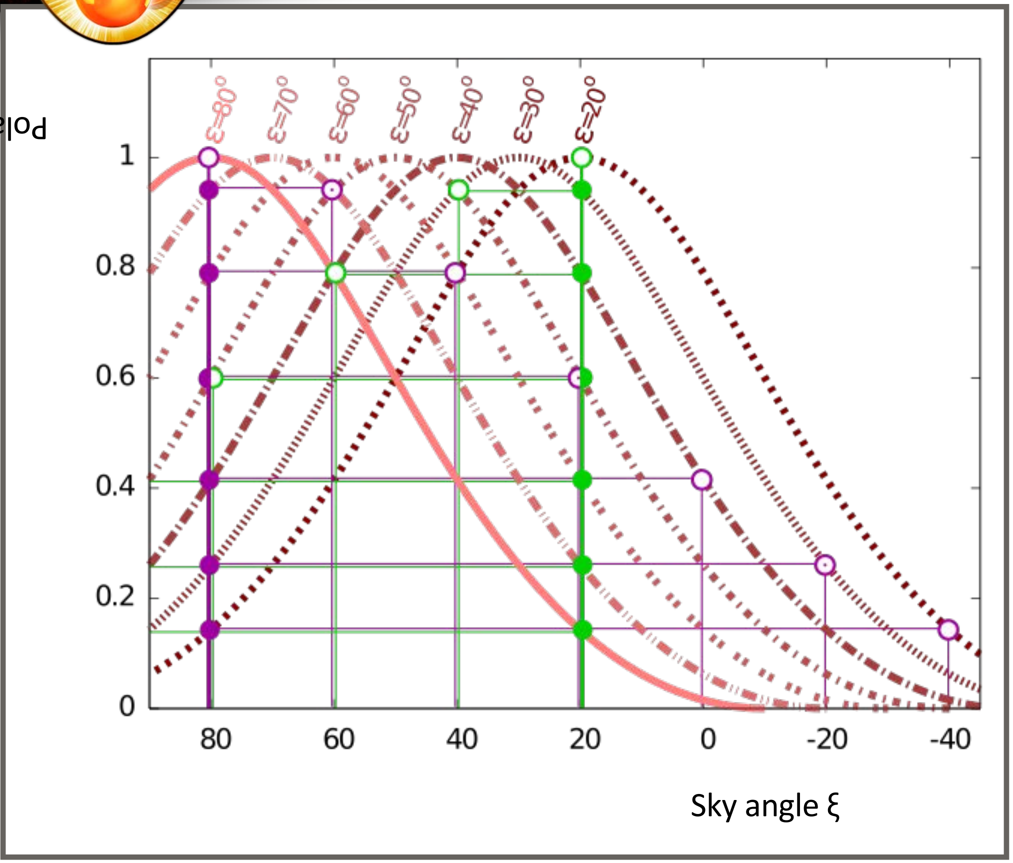
- Stereoscopy suffers from a line-of-sight confusion problem.
- CME detailed features are extended manifolds and do not generally work properly in perspective.
- Polarization affords single-line-of-sight 3D location.

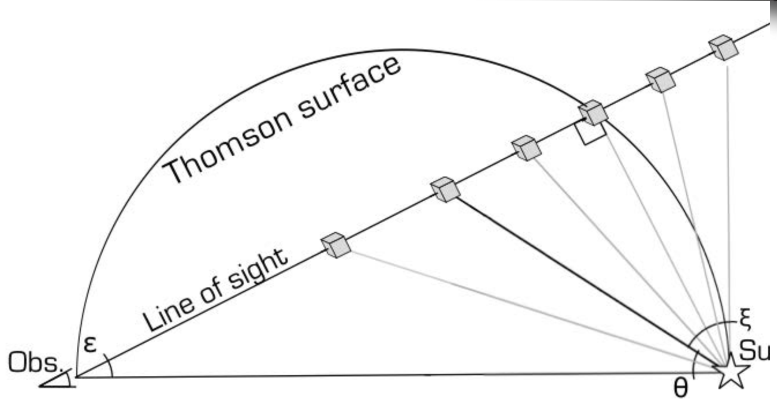


L4, L5, and terrestrial viewpoints see different parts of a halo CME.

Why polarized imaging?

Location determines features' polarization fraction.



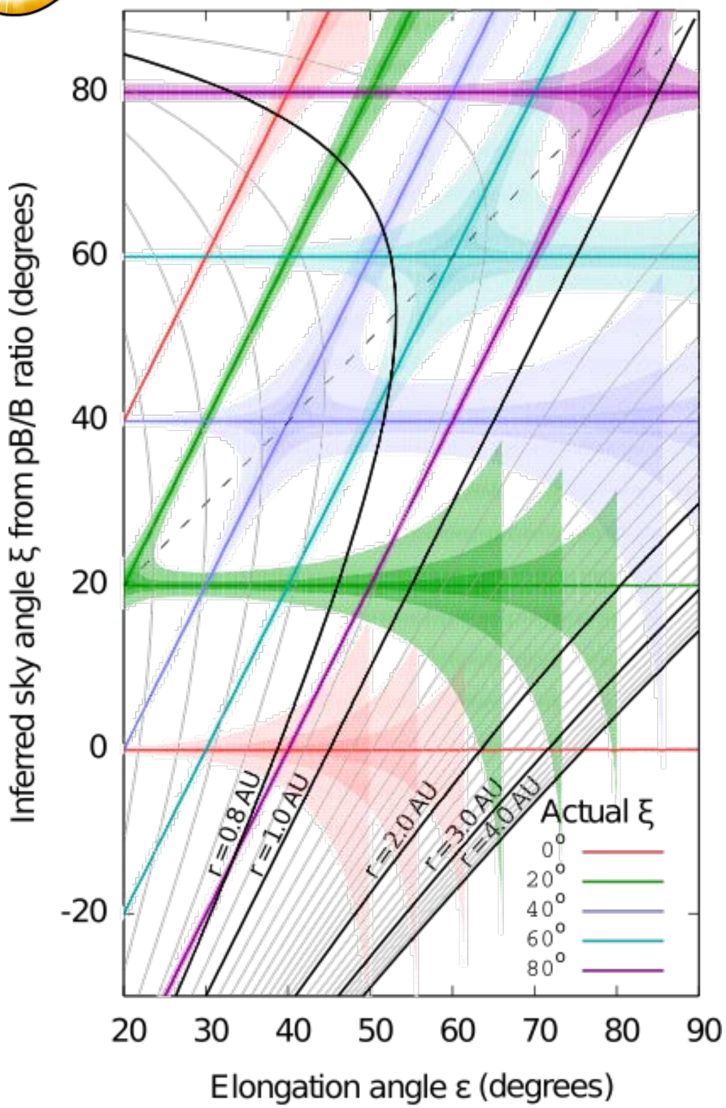


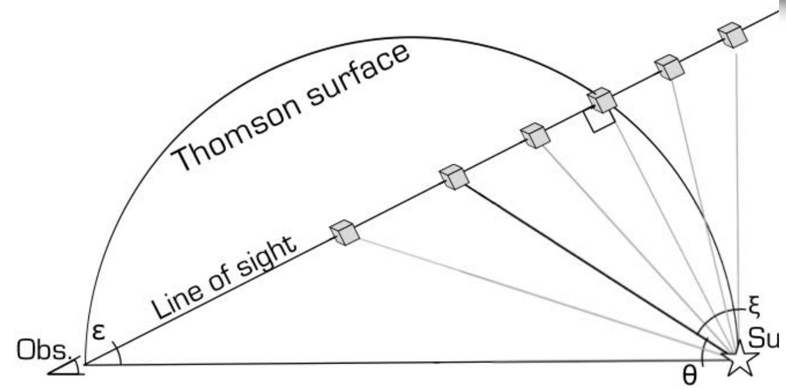
- Thomson scattering polarizes light.
- The degree of polarization depends on scattering angle.
- Scattering angle determines 3D position (basic trigonometry).
- Position is *most* accurate for Earth-directed events.

3D location from one position "only" requires polarized photometry in white light.

Why polarized imaging?

Polarization fraction reveals features' location.





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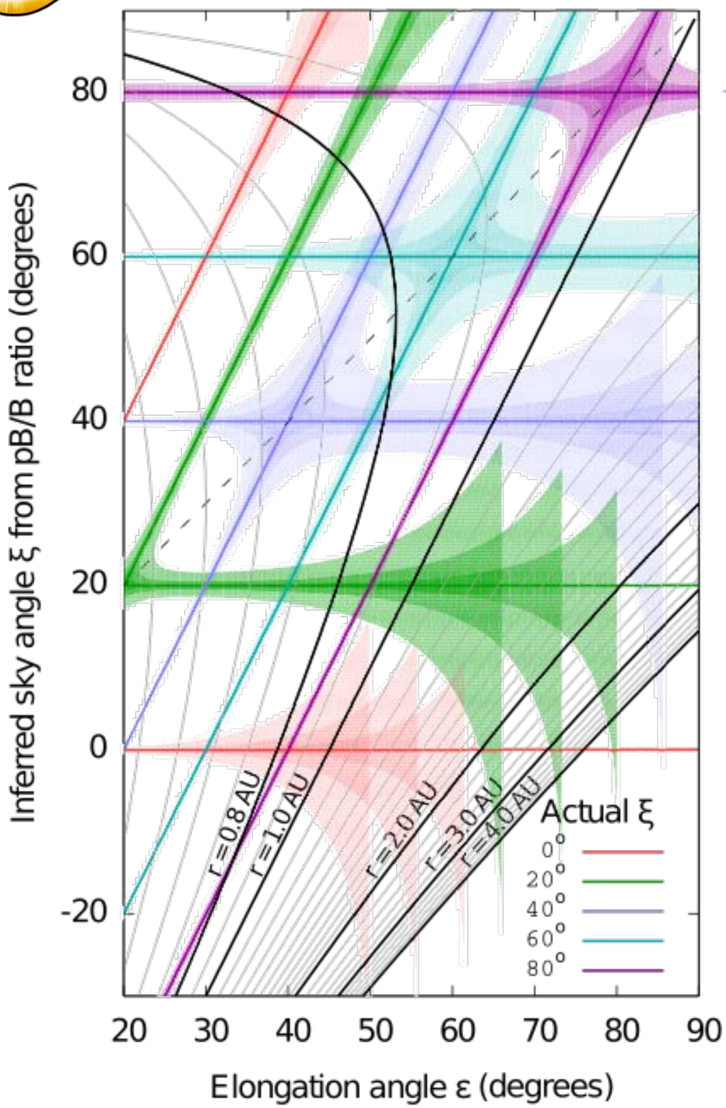

Smallest error bars are for Earth-directed events (space weather relevant)

- Thomson scattering polarizes light.
- The degree of polarization depends on scattering angle.
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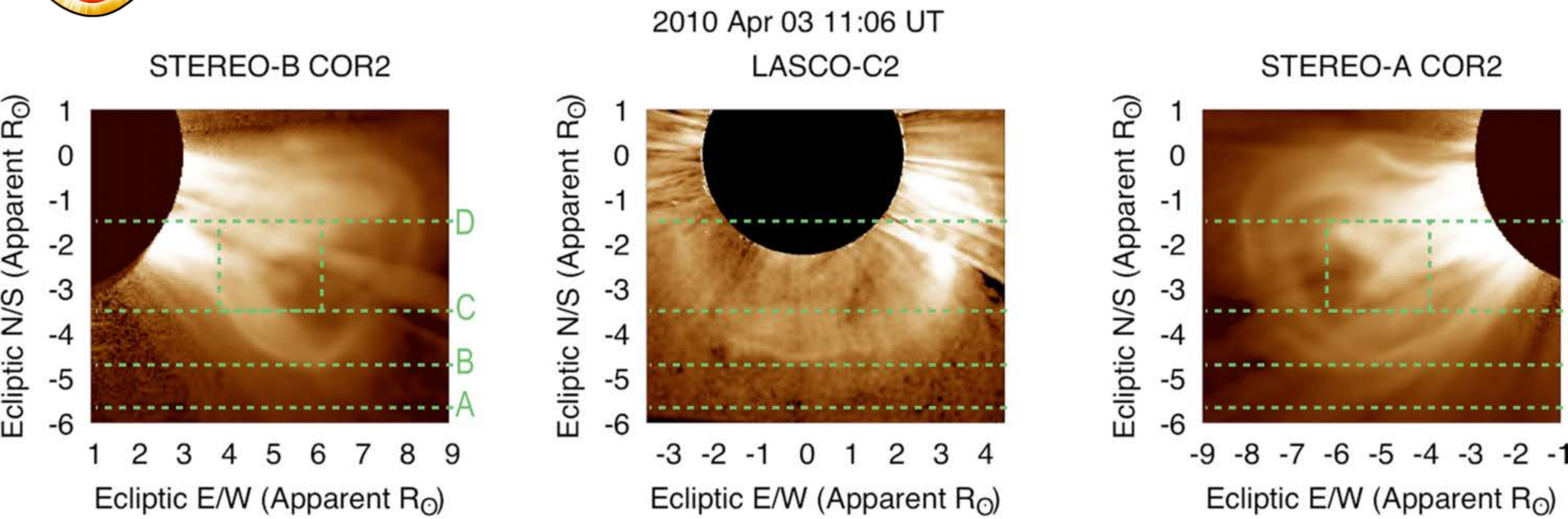
An example measurement

A well-observed halo CME (2010)



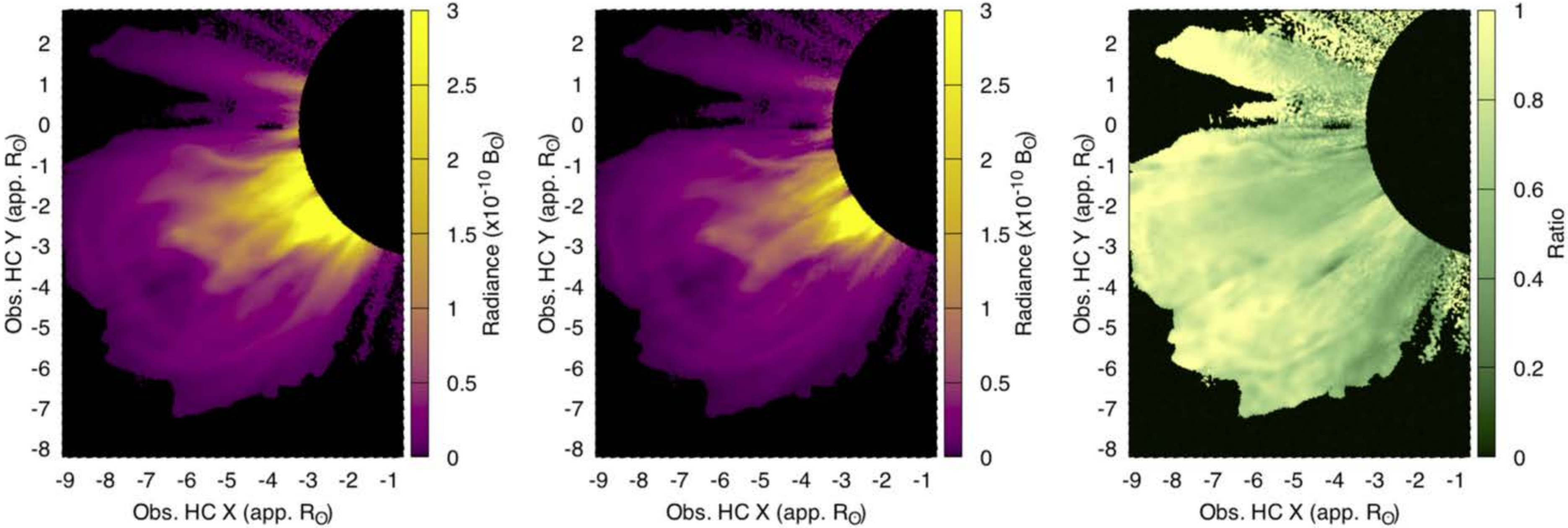
- Halo CME was seen by SOHO, STEREO-A, and STEREO-B
- STEREO: ~70° ahead/behind in orbit
- Good validation event: corroborate detection with stereoscopy

Ref: DeForest, de Koning & Elliott 2017

An example measurement

COR2 polarization

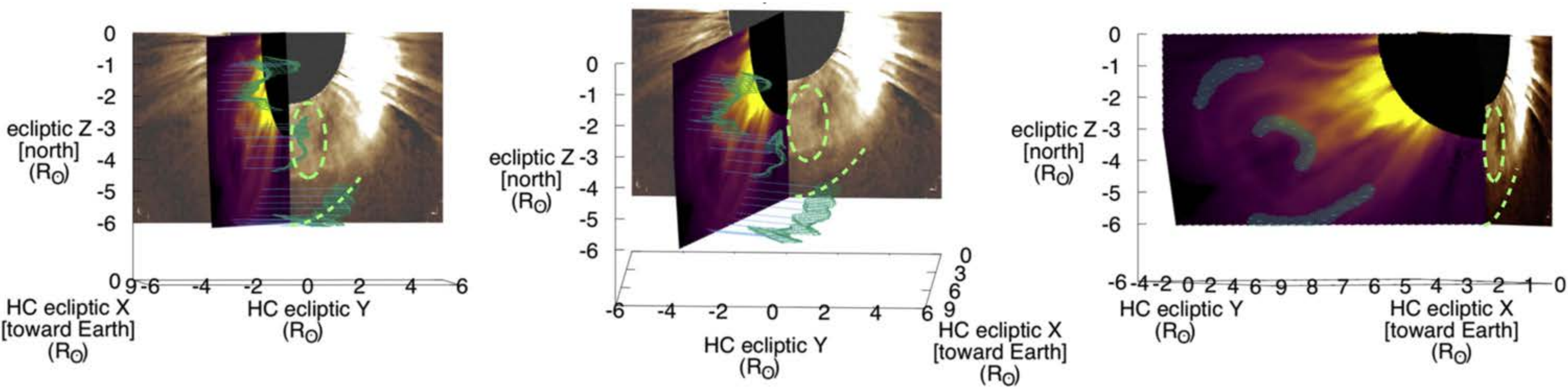
CME in unpolarized light | **CME in "excess polarized" (pB) light** | **Polarization ratio**



- COR2 synoptic data after background subtraction
- Images are noise-gated to improve photometry
- 3D structure is directly visible in the pB/B ratio.

Ref: DeForest, de Koning & Elliott 2017

SOHO view **Oblique view** **STEREO-A view**

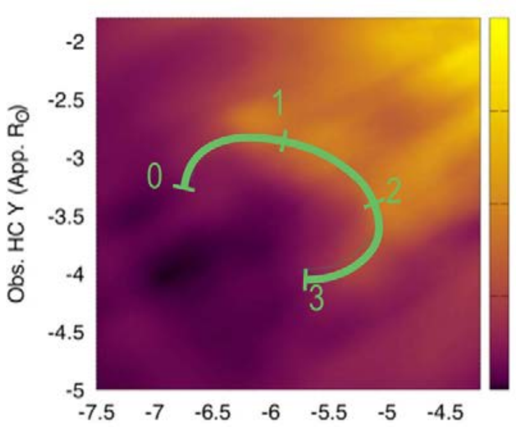


- STEREO-A and SOHO projected in perspective
- Green features highlight the leading edge and core of the CME.
- Green feature location is plotted using pB/B ratio.

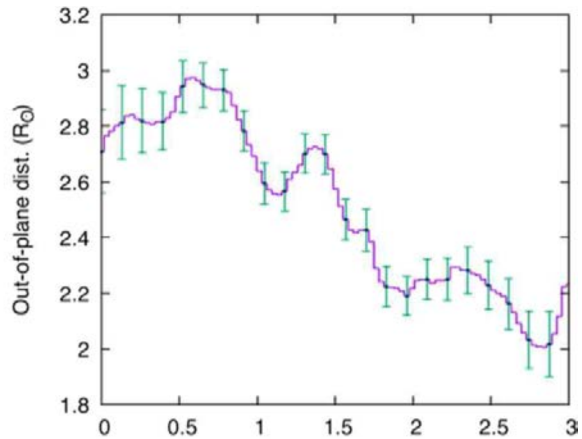
- Leading edge matches SOHO leading edge (green dashed line).
- Core location matches SOHO core (green dashed ellipse).

Ref: DeForest, de Koning & Elliott 2017

Close-up of CME core



Out-of-plane distance vs. distance along curve

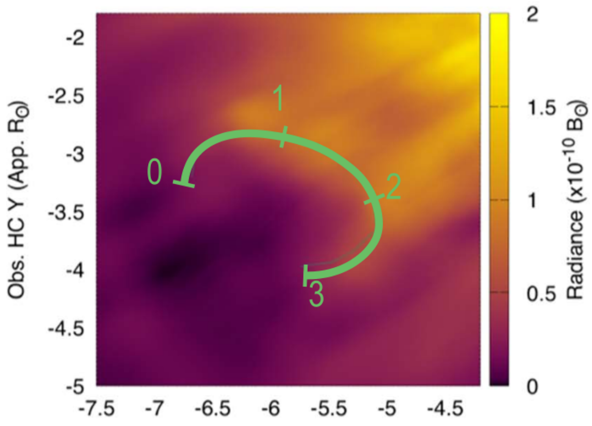


- Traversing the curve clockwise yields motion into the page.
- **Helix was right-handed.**

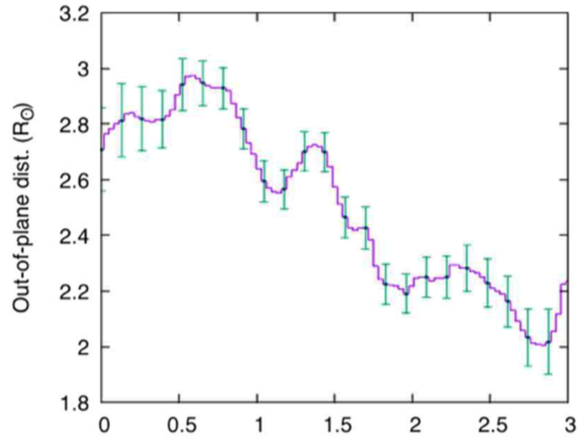
An example measurement

Chirality: polarization matches the ACE measurement

Close-up of CME core



Out-of-plane distance vs. distance along curve



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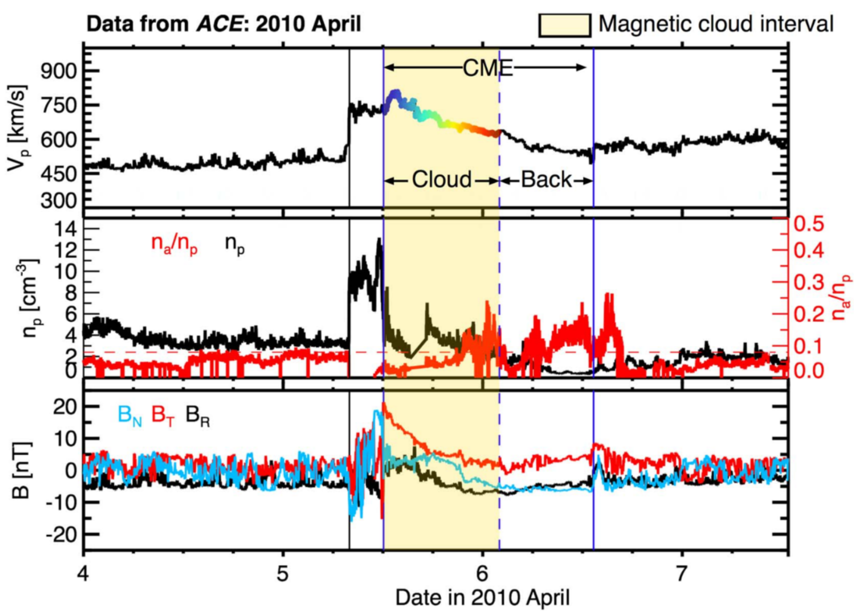
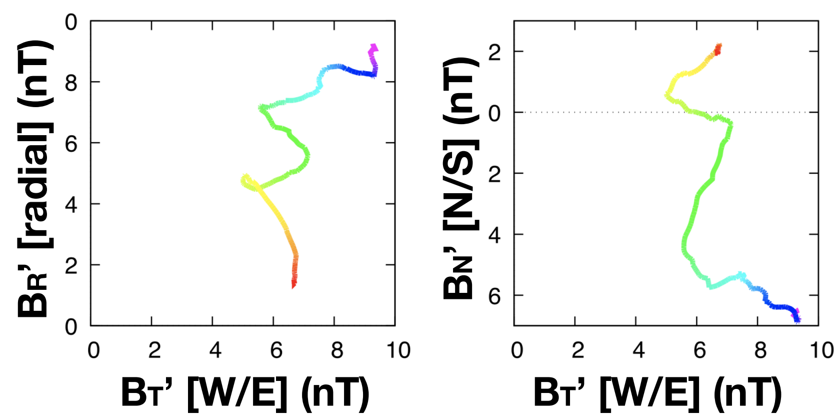
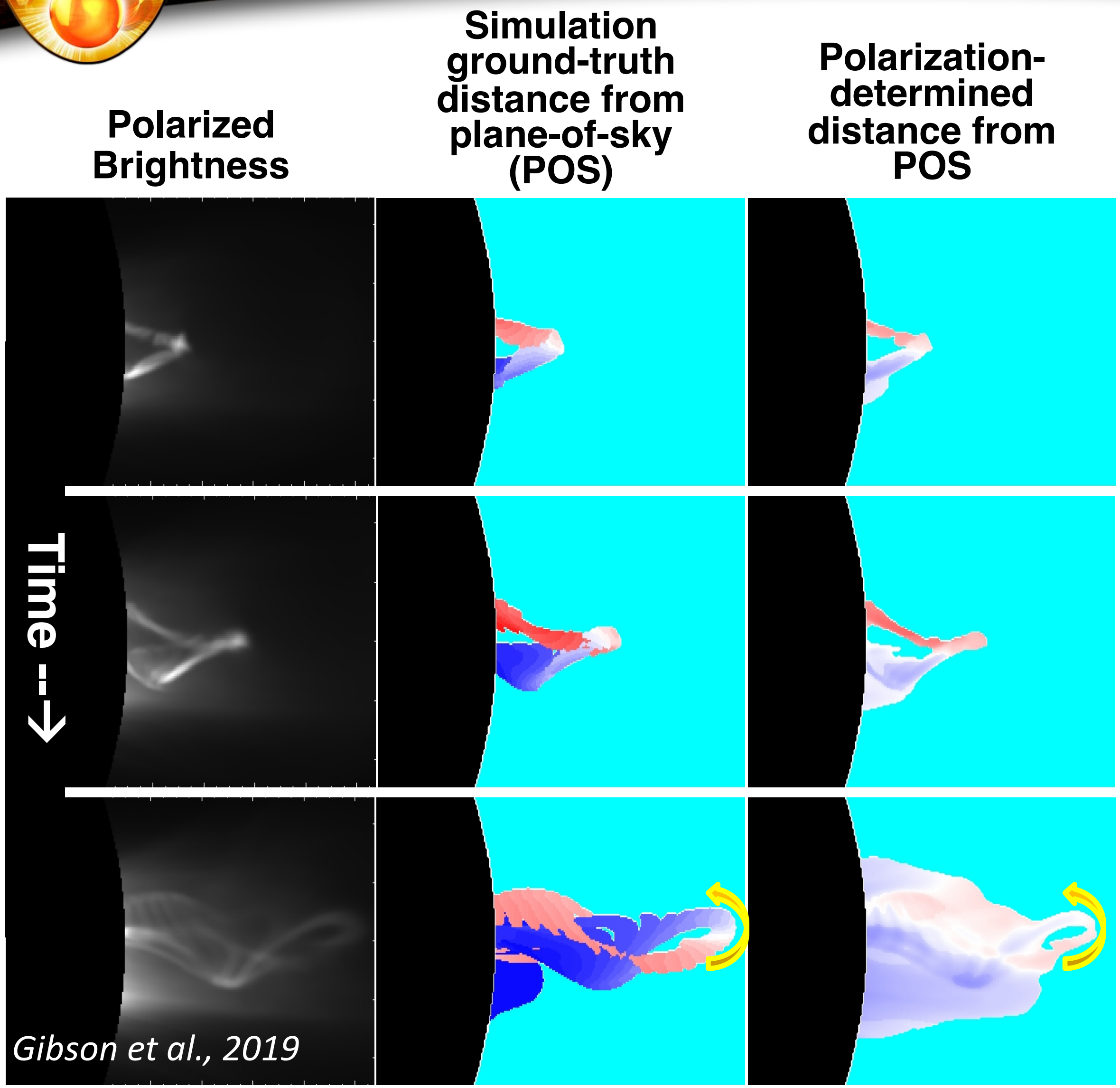


- **Flux rope was right-handed.**



Chirality from complex structure

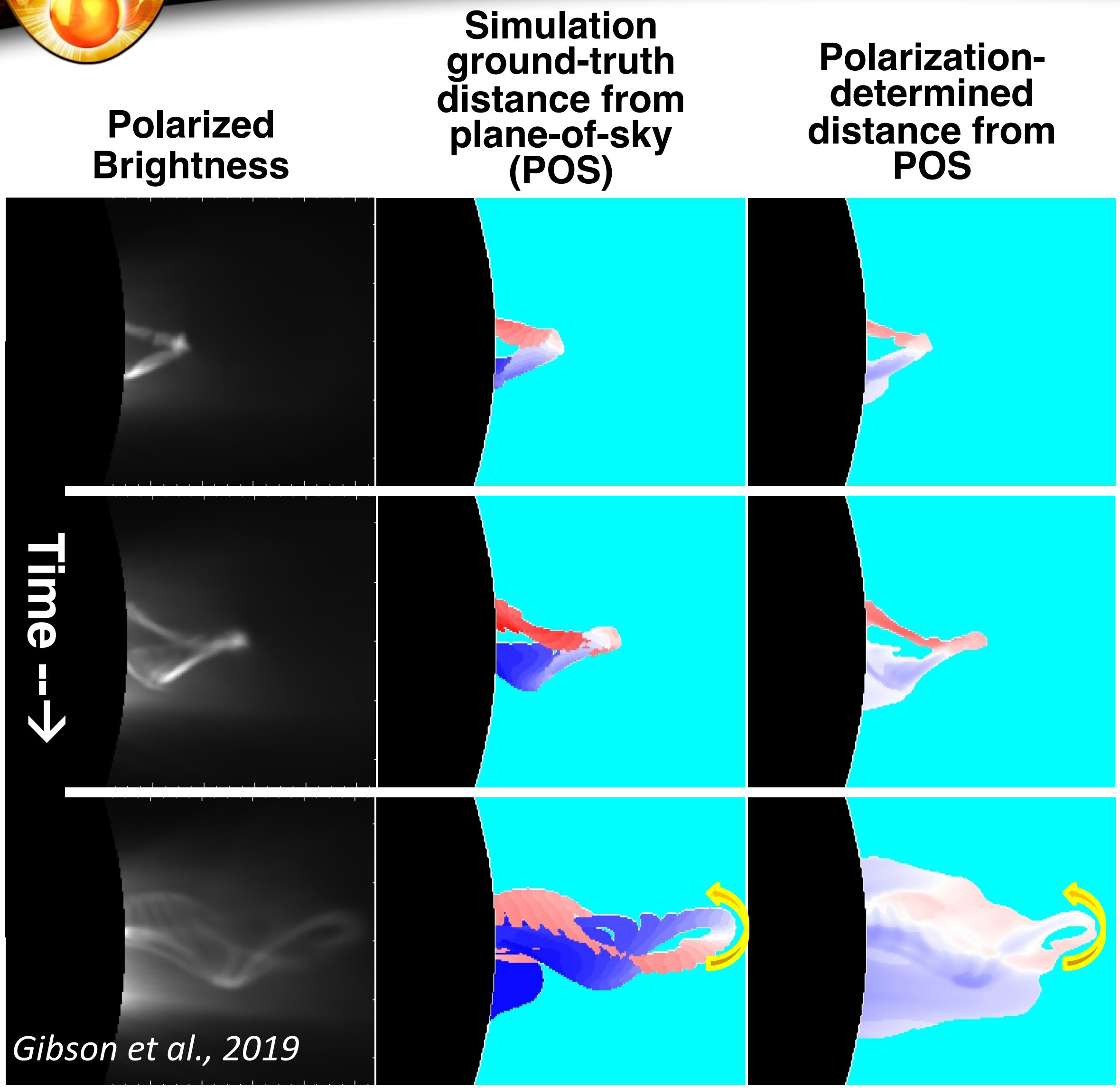


Test chirality technique with MHD erupting-flux-rope model (Fan 2018)

Front (red) vs. back (blue) is clear.

Circulation about axis correctly identifies a left-handed flux rope.

Chirality from complex structure



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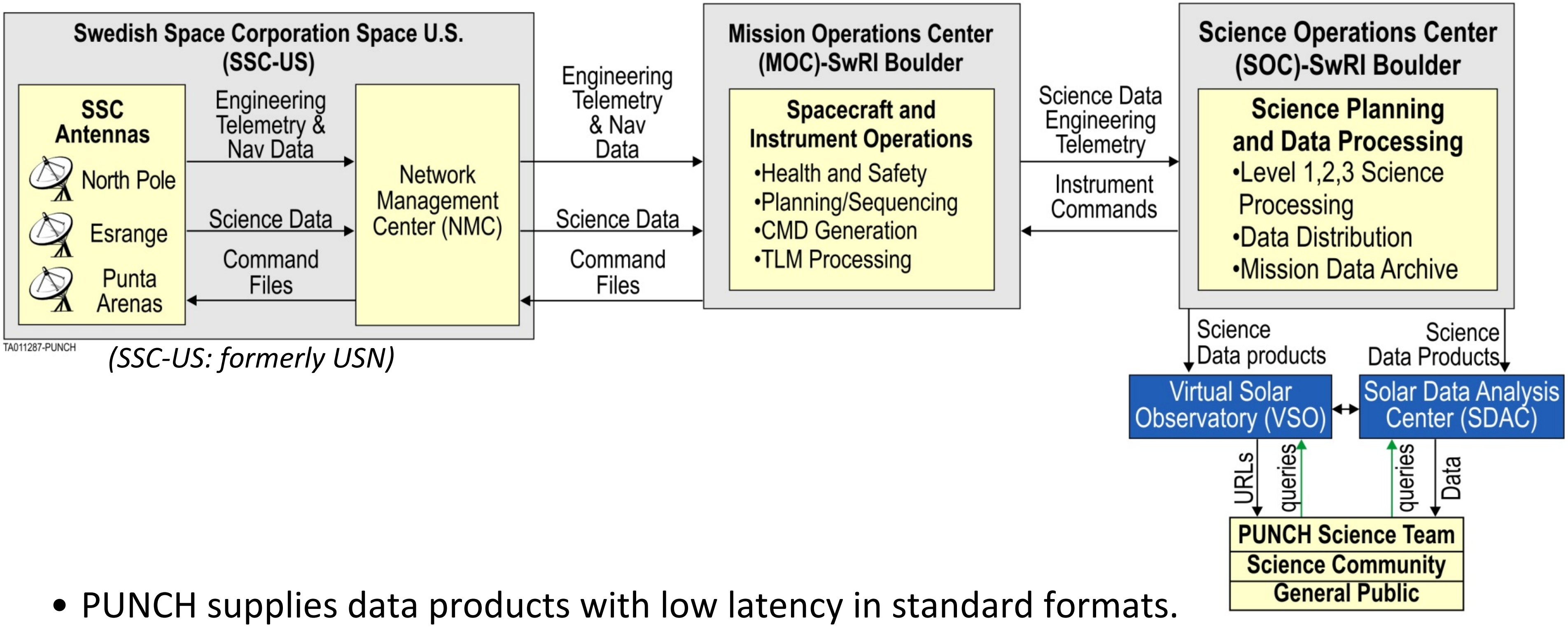
PUNCH and Space Weather

- PUNCH cadence is 4 minutes.
- Latency is driven by ground contact frequency: ~1/day/spacecraft (nominal).
- Mission design permits additional contacts.
- As low as 45 minutes latency from spacecraft to ground is possible (with dedicated antennas at both poles).
  - Overall latency: ~60-90 minutes for quick look background-subtracted polarimetric data

- PUNCH SEO #3 covers space weather low-latency data
- NASA/NOAA collaboration?

Data flow: rapid and open

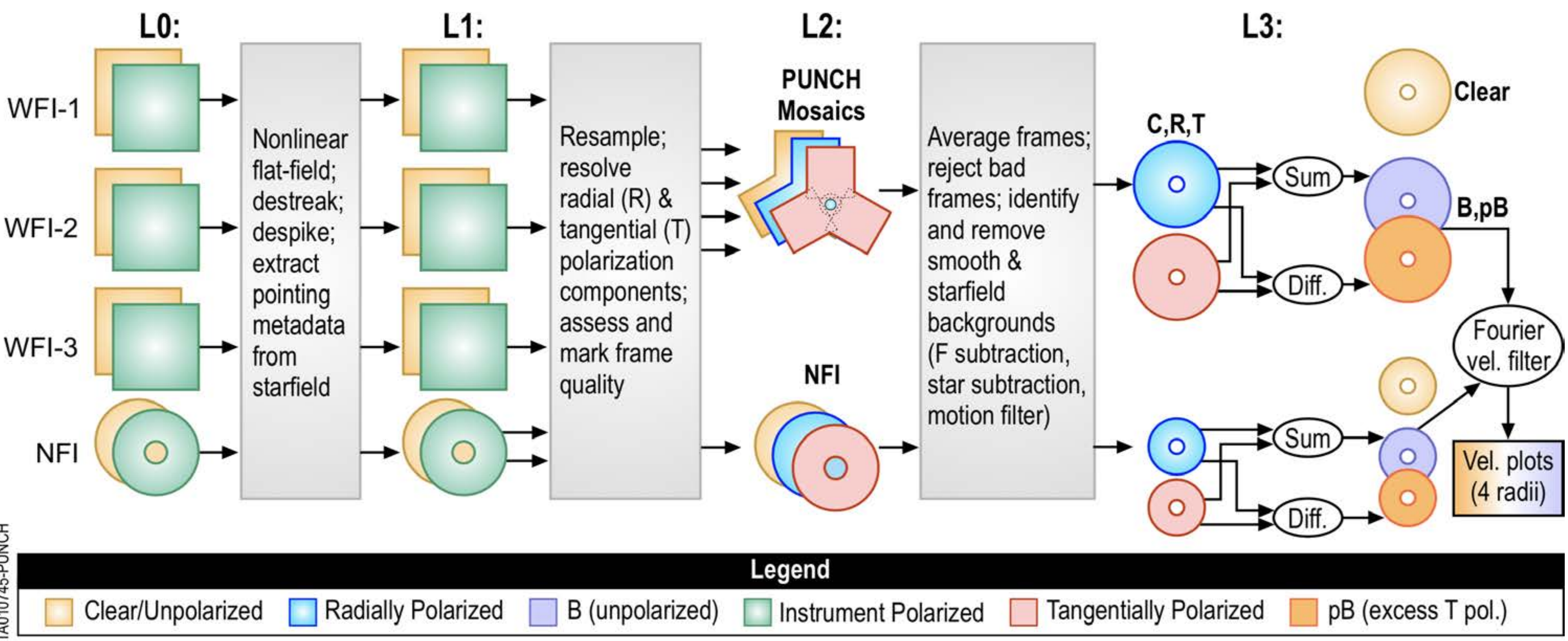


(SSC-US: formerly USN)

- PUNCH supplies data products with low latency in standard formats.
- Calibration adapts existing modules to heritage SOC infrastructure.
- PUNCH has an open data policy.

PUNCH has an open data policy with no proprietary period and rapid dissemination.

Polarimetric, background-subtracted data



PUNCH data products include background-subtracted coronagraph & wide-field images

Getting involved with PUNCH

- PUNCH science team meetings: first is late spring 2020 (date TBD)
- Use PUNCH data (when available): VSO & PUNCH website
- PUNCH SEO for Space Weather: TBD
- PUNCH GI Program(s): planned but details TBD from NASA.

Summary

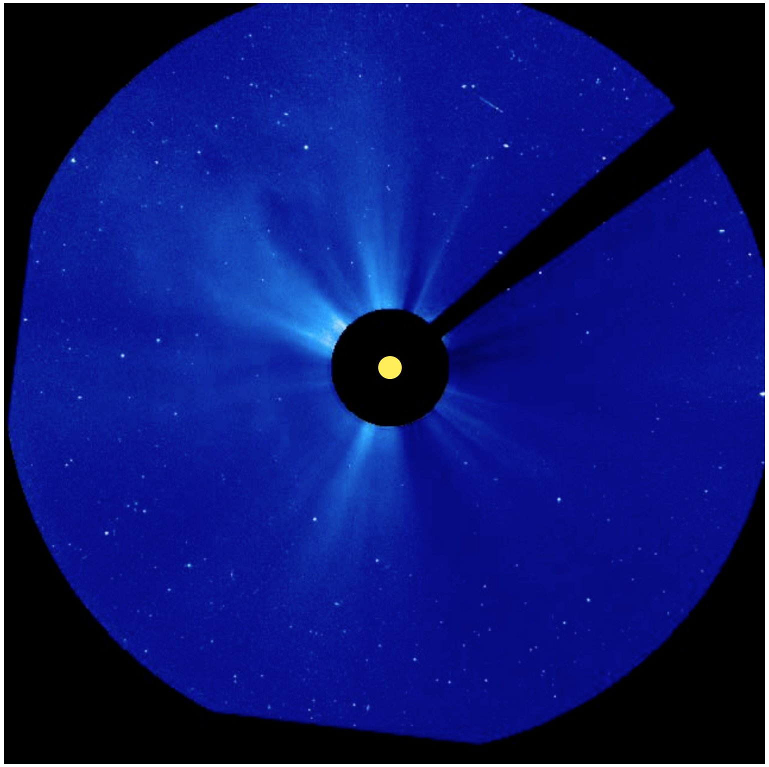
- PUNCH will provide routine, low-noise, global images of the corona and “young solar wind” to understand how the corona gives rise to the heliosphere.
    - Cadence: 4 minutes
    - FOV: 5 Rs – 180 Rs
- PUNCH images will include 3D information via polarimetry
- PUNCH will provide solar wind speed maps 4x daily.
- PUNCH status: Now in Phase B (“preliminary” design)

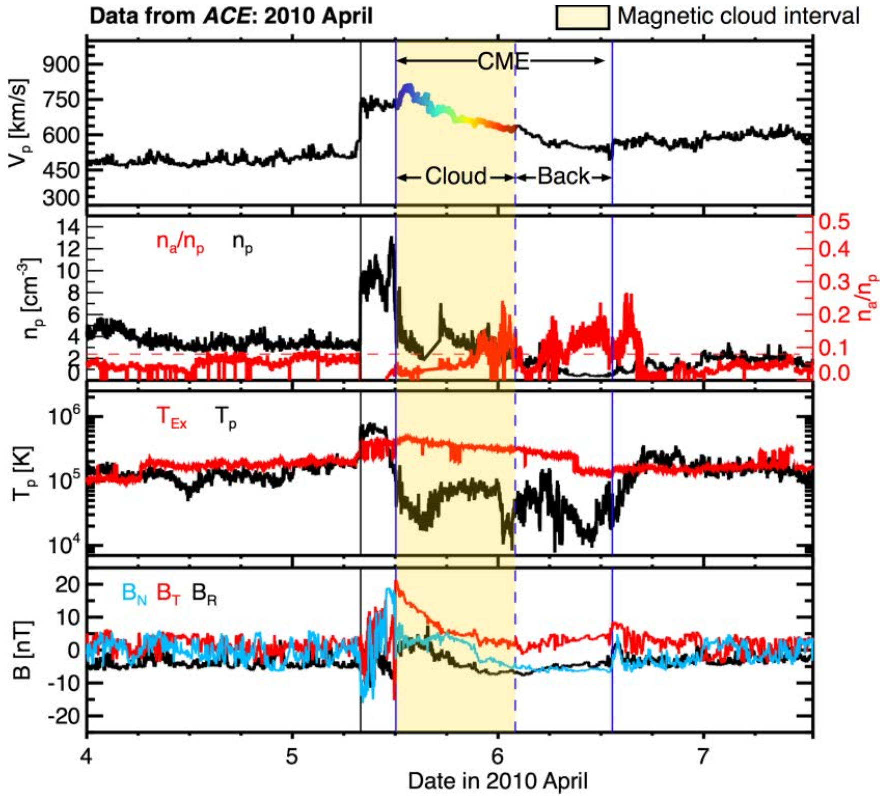
- Use PUNCH data (when available): VSO & PUNCH website
- PUNCH SEO for Space Weather: TBD
- PUNCH GI Program(s): planned but details TBD from NASA.

PUNCH Unifies the Corona and Heliosphere

Solar physics studies the Sun and solar corona, primarily through remote sensing and spectral analysis.

Heliospheric physics studies the solar wind in interplanetary space, primarily through in-situ sampling.





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