

# NAS Space Weather workshop

## Session 3 - SUN;

### Observation and model needs

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Cooper Downs



# What is missing from our coronal models? (and why?)

Due to the Sun's proximity, our remote sensing diagnostics reveal incredible diversity and complexity.

**Models are essential laboratories for developing theory & understanding:**

**Flares/Eruptions:**

*Energization & Destabilization*

**Solar Wind:**

*Connectivity & Dynamics*

**Coronal Heating:**

*Mechanism(s), Space & Time Stratification*

**Physics:**

*Non-thermal & Collisionless Processes*

**High Resolution**

*Current Sheets, Nanoflares, Turbulence*

**Global Topology:**

*Influence & Implications*

**Q: What will it take for a generational improvement in coronal modeling?**

## Inputs

Magnetic BCs are essential but have inherent limitations.

**What is the most important input to target for the future?**

- Global B Photo
- Polar Fields
- 3D Coronal B
- Vector B Chromo

## Time Dependence

Global/Local B is constantly evolving, which is key for energization and relaxation processes. Yet PFSS and steady-state MHD models completely ignore it.

*Major Challenge:* Deriving E-field and implementing BCs to apply it.

**What observational, theoretical, and technical challenges can we target to make this a routine aspect coronal**

## Constraint

Complementary observables are available, but they are rarely used all together.

Even so comparisons are easy to cherry pick & actionable metrics are dubious (poor inputs or physics?).

**Can we build an unified framework for model benchmarking?**

**Is true “data-assimilation” a future we can build towards?**

## Resolution

The corona we observe has high-resolution structure.

High-k time & space complexity links the surface to coronal dynamics & the solar wind.

**What are we missing when we smooth this away in low-resolution, steady state models?**

**This is important but technically challenging. Do we need a new paradigm for modeling support & infrastructure?**

## Physics

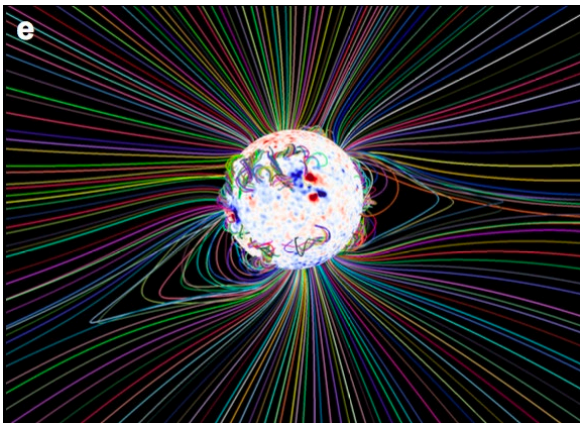
Corona is not fully MHD (sure), but it is certainly not potential or always low  $\beta$  & force free.

We use PFSS, NLFF, & magnetofrictional because it is easy & fast!

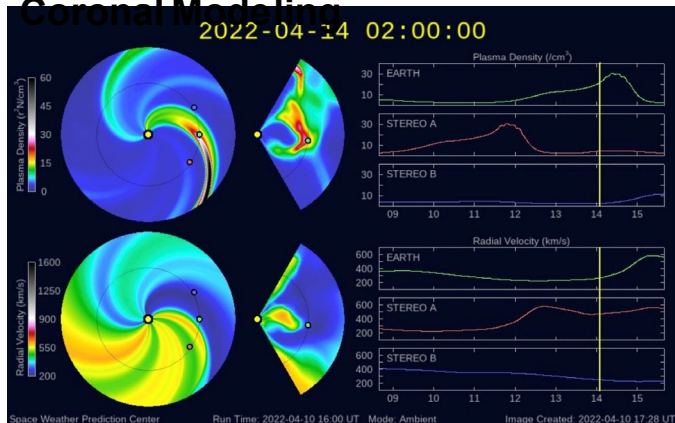
**Can easy & fast be achieved with MHD+ models? Algorithms? Ease of use? Open source? Community Infrastructure?**

**Do we need new physics? What and why? (multi-fluid, hybrid, PIC)**

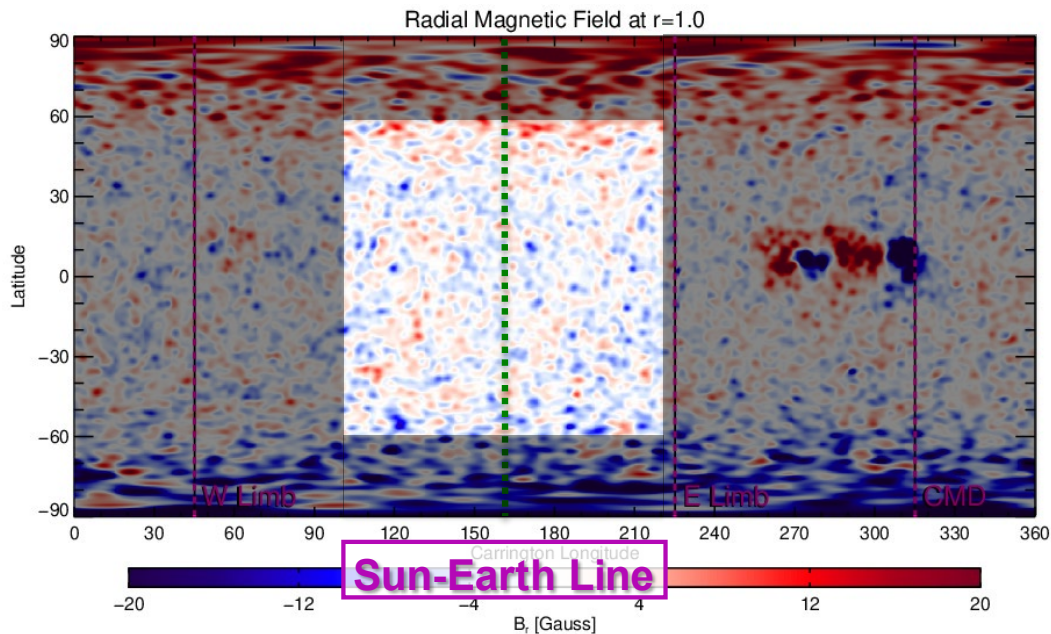
# Key Input: Full-Sun $B_r$



## Research Example: Global Coronal Modeling



## Space Weather Example: WSA/ENLIL



The **single most important** input to a coronal model is the magnetic boundary conditions. The physics, assumptions, and everything else is secondary.

For global coronal models and/or heliospheric space weather models, the input is ultimately a full-sun magnetic map (WSA uses PFSS).

However we only observe  $B_r$  reasonably well around  $\pm 60$  of the Sun-Earth line.

# A Visual Example

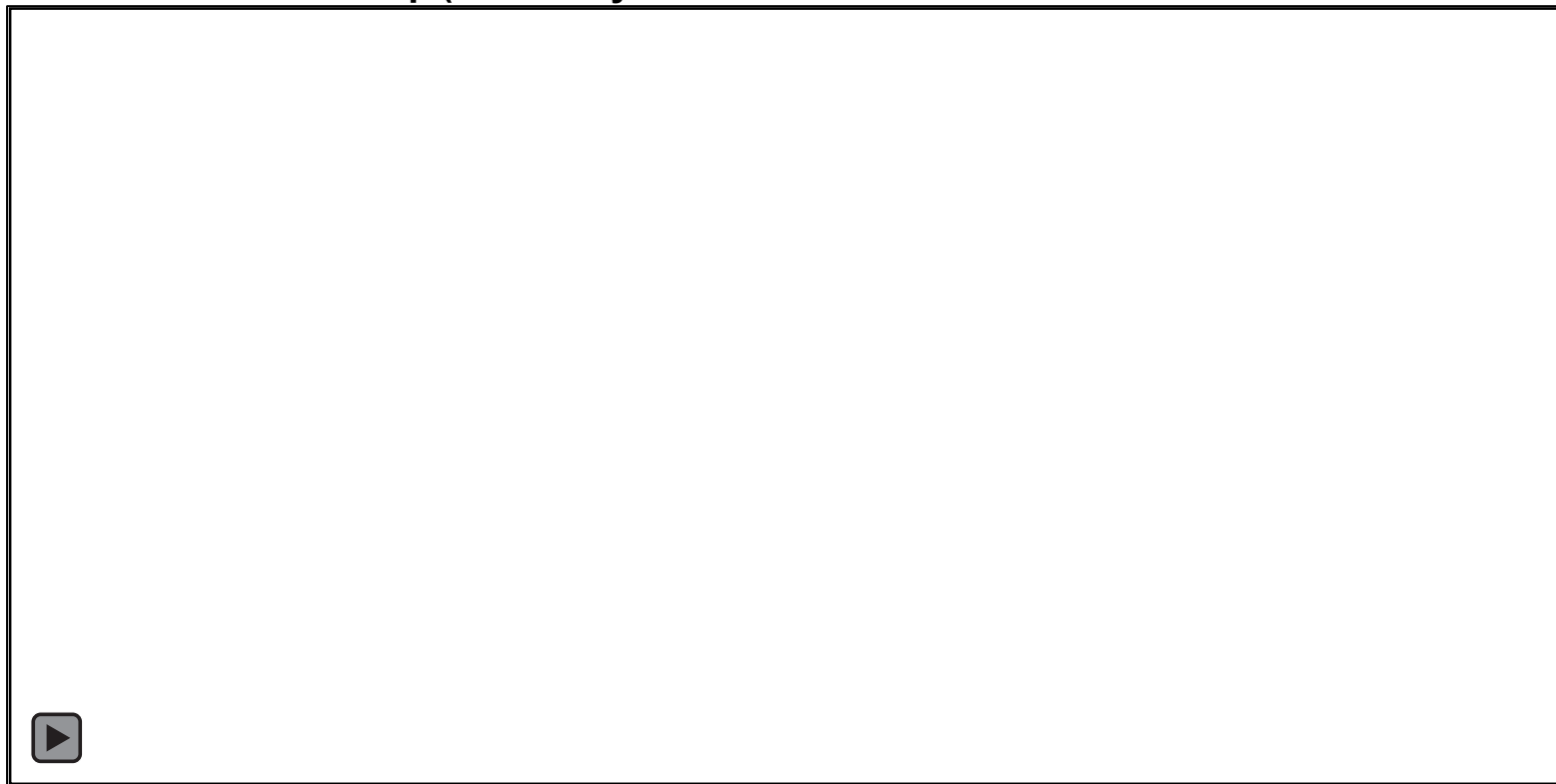
2017

HMI Daily PFSS + Q  
Maps

<http://hmi.stanford.edu/QMa>

Full-Sun Br Map (Boundary

Open Flux: (i.e. Coronal



Signed  $\text{Log}_{10}$  Q at  $r=1.1$  (low  
down)

Signed  $\text{Log}_{10}$  Q at  $r=2.5$   
(HCS + SWEB)

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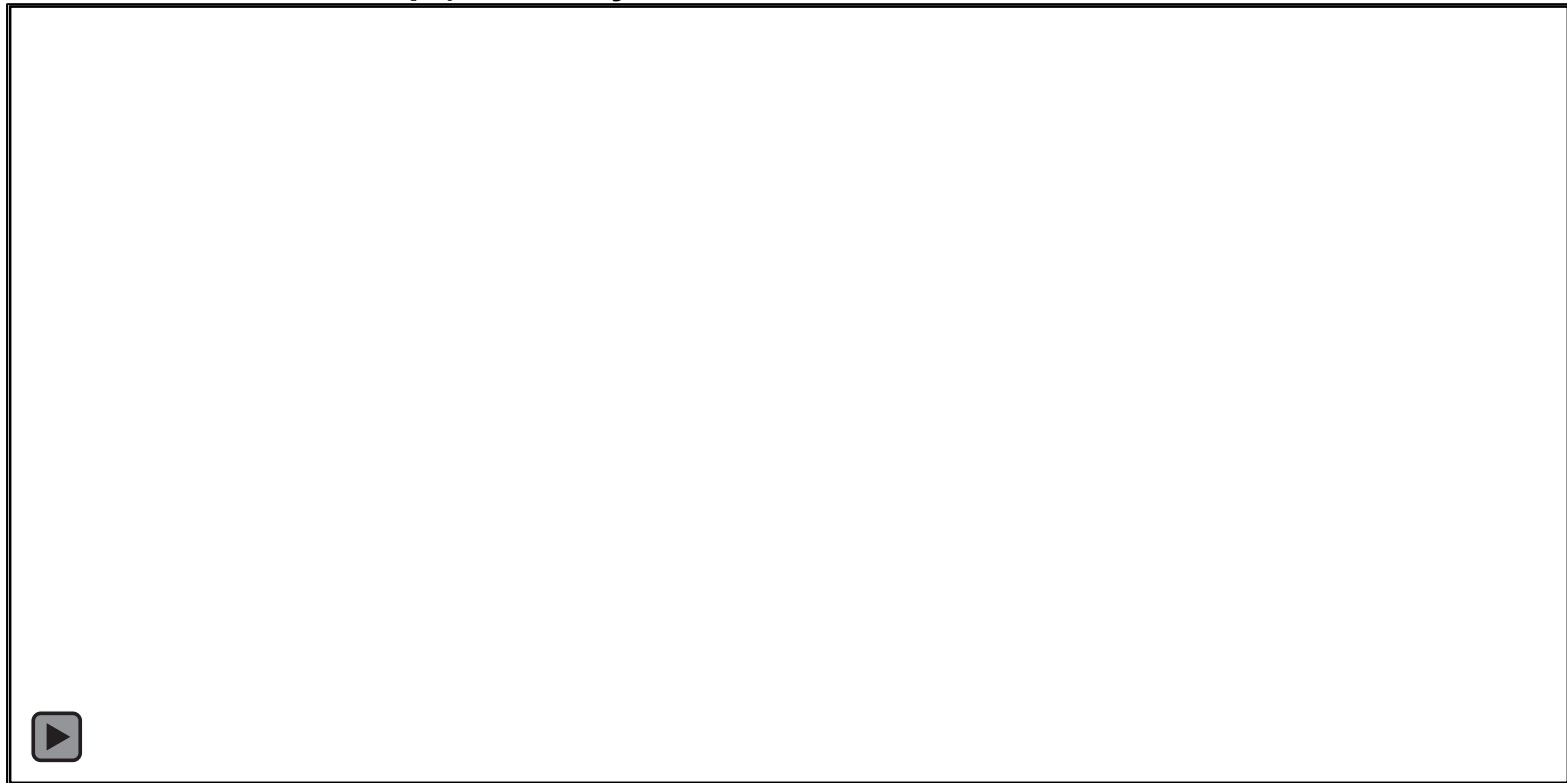
2014

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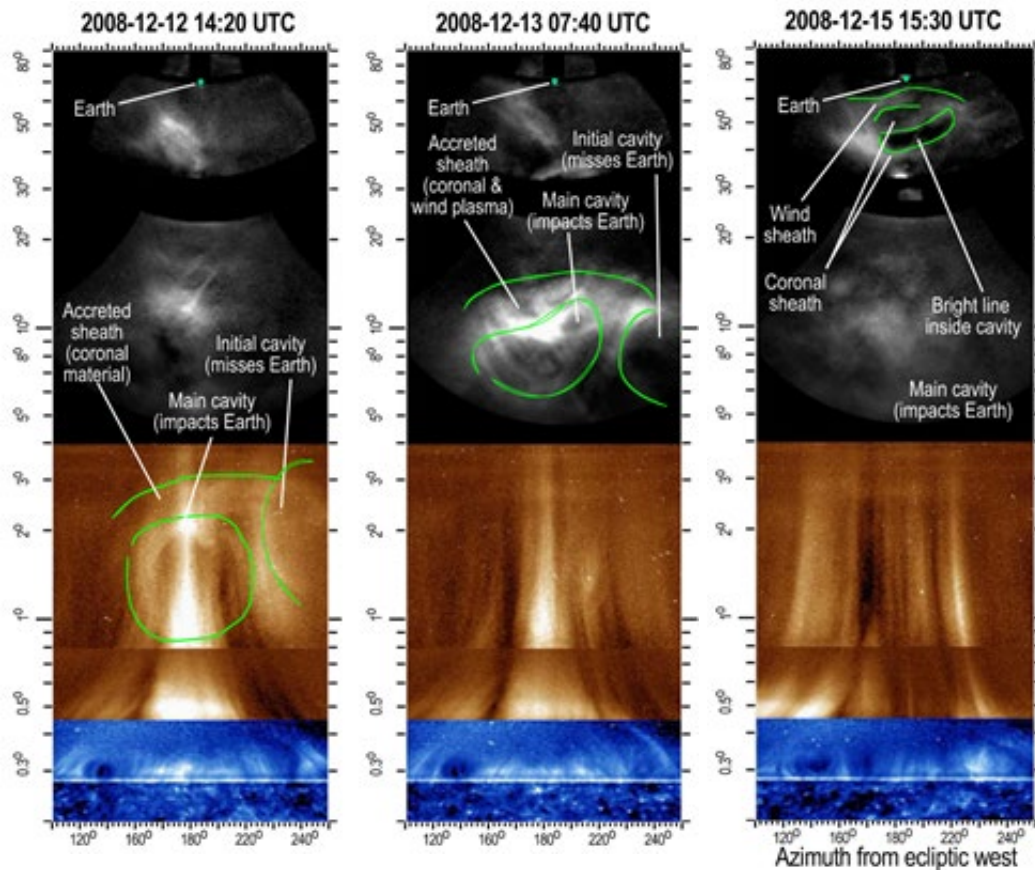
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Craig DeForest



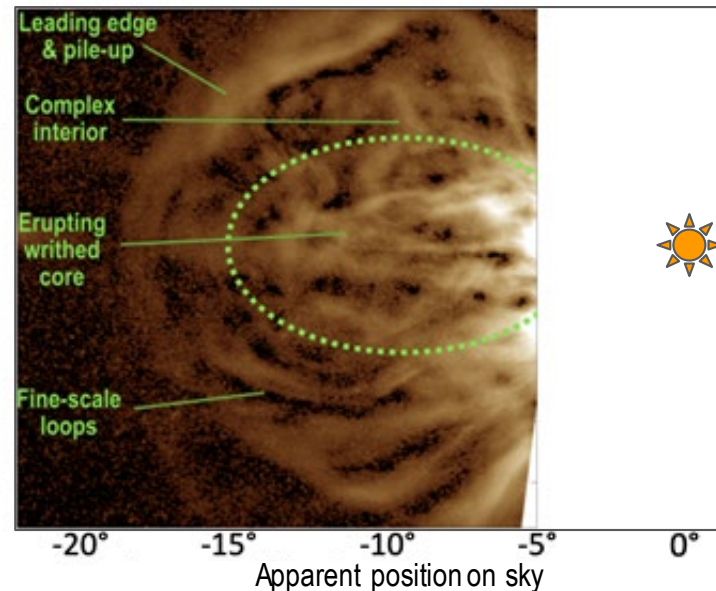
# Space weather systems evolve between Sun and Earth.

*Direct measurement is required to improve forecasting.*



*Left: a CME changes shape and direction as it interacts with the solar wind between Sun and Earth.*

*Below: a typical CME (Sun for scale) has very complex anatomy that evolves as the CME propagates.*



Blue: low corona (EUV); orange: middle corona (white light coronagraph); grey: solar wind (white light heliospheric imagers). Source: DeForest, Howard & McComas 2013.

*Unsharp-masked CME seen with STEREO/HI-1 in 2013.*

# Track Space Weather Transients in 3D

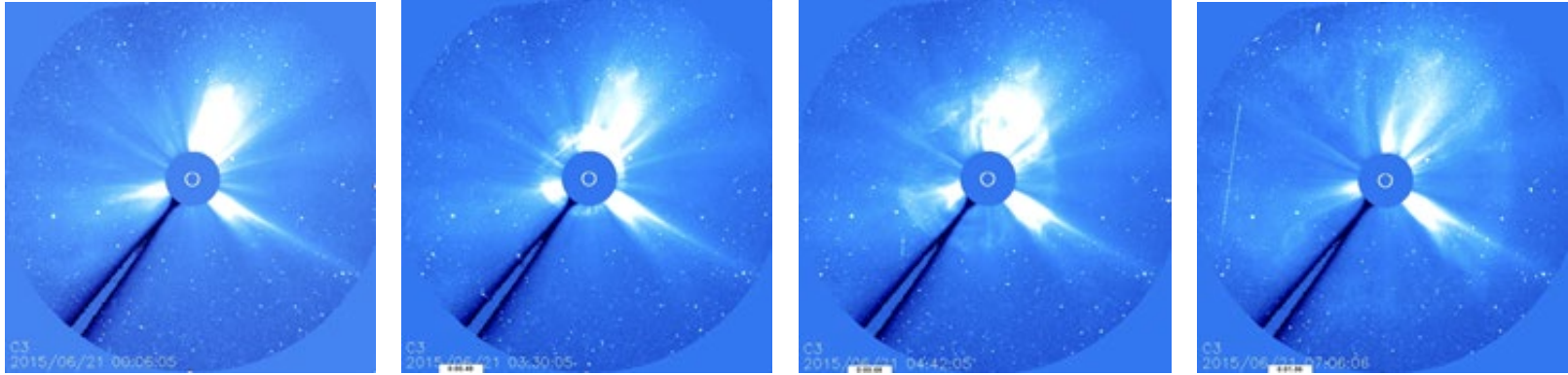
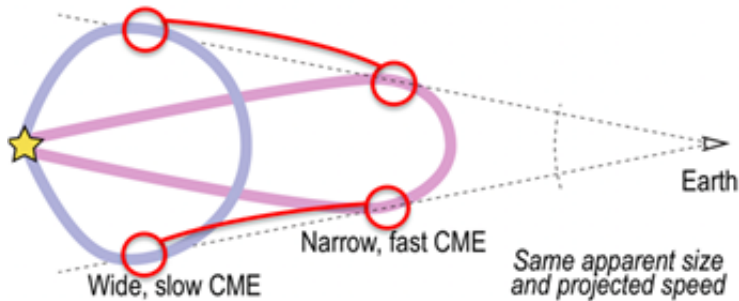


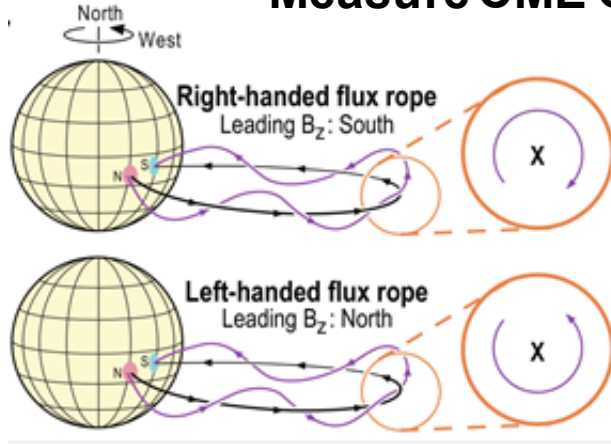
Image sequence: LASCO C-3 data of a “halo CME” launched directly at Earth, 2015 June 21



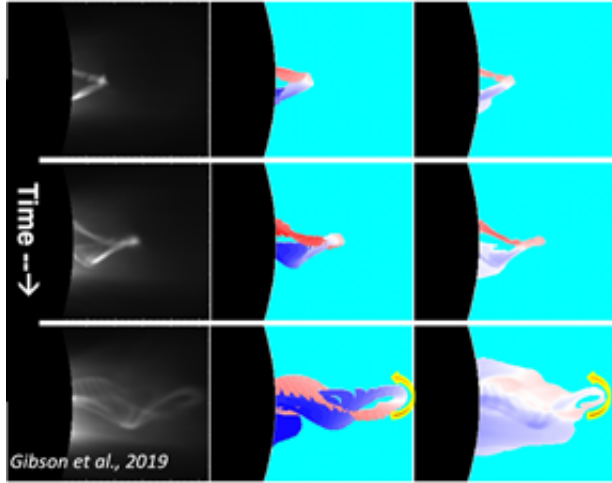
- **Tracking CMEs in 3D is necessary** to eliminate the “plane-of-sky” ambiguity between narrow, fast CMEs and wide, slow CMEs.
  - Large-scale morphology can be tracked via stereoscopy (e.g. from L4 or L5)
  - Polarization measurement is an inexpensive and more effective way to get 3D information.
- **Wide-field 3D tracking replaces models with direct physical evidence.**
  - Analogous to satellite tracking of hurricanes
  - Enables accurate forecasting of “landfall” timing & severity
- *NASA’S PUNCH mission will demonstrate this technology.*



# Measure CME Chirality to Forecast Geoeffectiveness



Above: twist direction (currently not measured) relates the Solar-surface magnetic field to leading-edge B<sub>z</sub> in a CME



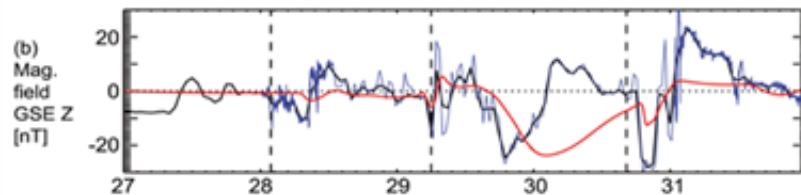
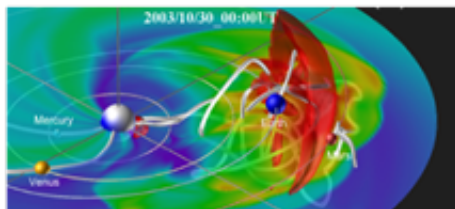
Left: 3D determination with polarized light permits direct detection of CME chirality (simulation: Gibson et al. 2019)

- **3D imaging/measurement enables forecasting geoeffectiveness:**
  - B<sub>z</sub> (N/S) direction determines geoeffectiveness of a particular CME when it impacts Earth.
  - Current magnetograms measure the mainly-E/W core field direction in the CME.
  - Chirality (twist direction) determines how currently-measured surface field relates to leading-edge field direction in a CME.
  - No existing measurements capture the direction of twist; 3D measurement via polarization is required to do so.
- *NASA's PUNCH mission will demonstrate this technology.*

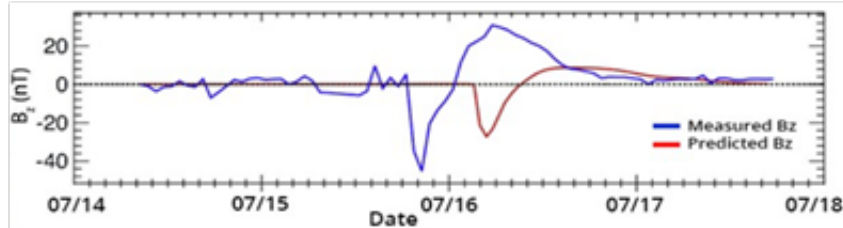
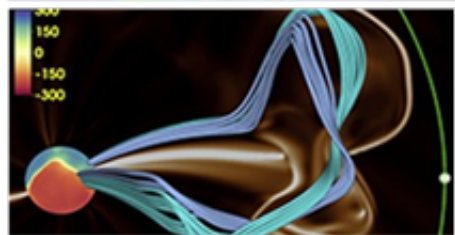
Valentin M Pillet

# Filaments, CMEs & Bz

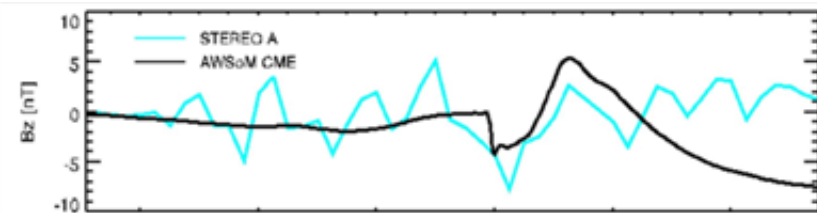
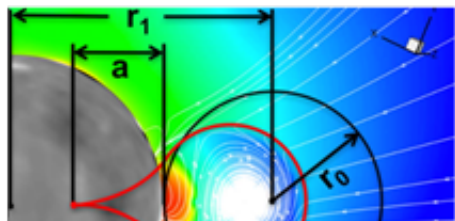
SUSANOO-CME  
(Shiota et al, 2016)



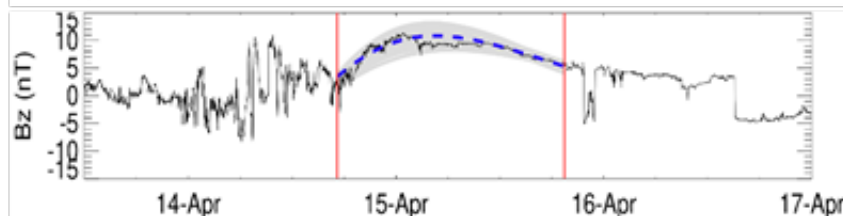
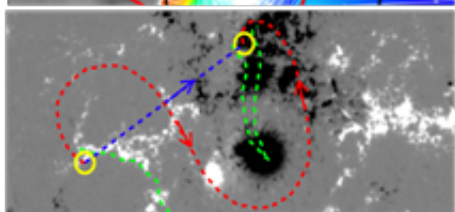
MAS  
(Torok et al, 2018)



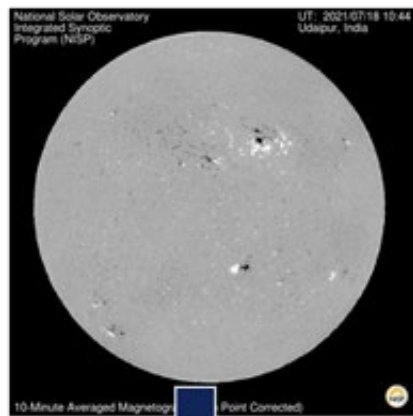
AWSoM-SWMF  
(Jin et al, 2017)



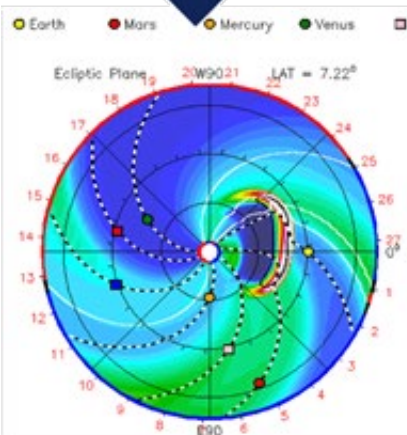
INFROS  
(Sarkar et al, 2020)



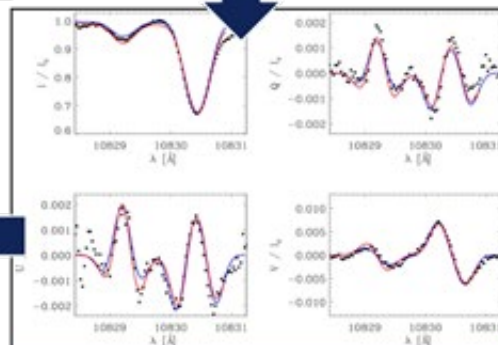
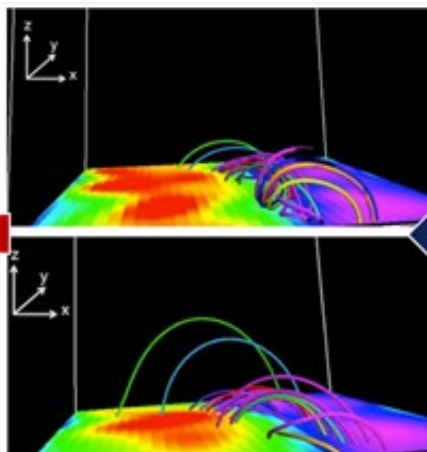
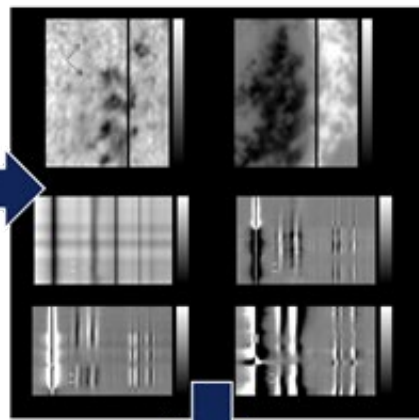
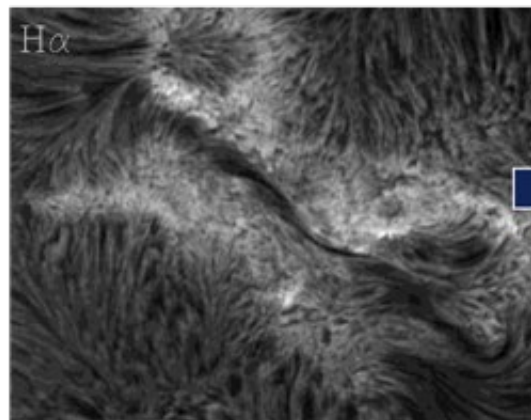
# Propagate Magnetized CMEs



Magnetographs  
from NSO's  
GONG network  
used as input to  
WSA ENLIL at  
SWPC

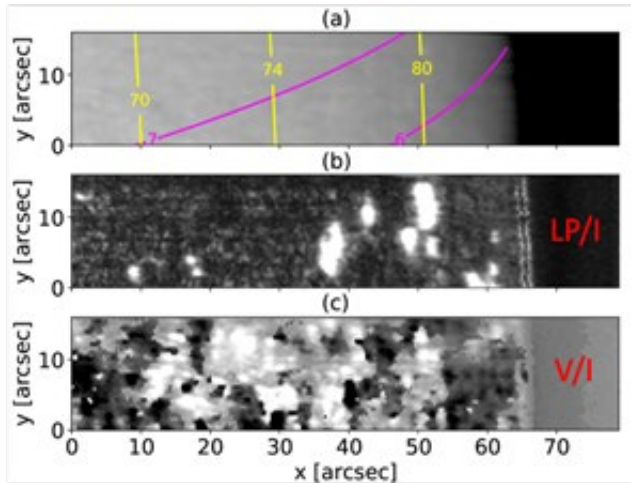
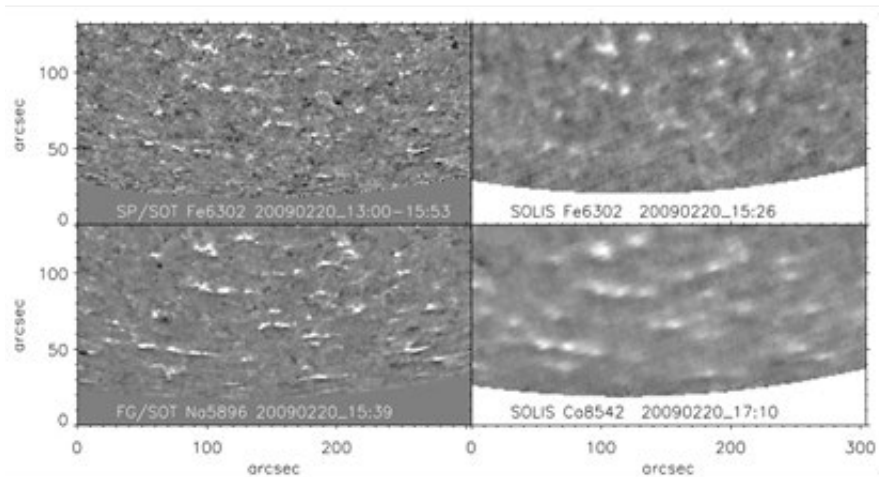


CME propagation  
does not use  
magnetic  
boundary data



No synoptic program  
tracking filaments

# Boundary data: the solar poles



Earth is magnetically connected to the poles a majority of the time

- From the Earth poles are hard to see. Hinode maps are the best data available so far
- Field lines at the poles are mostly transverse  $\rightarrow$  increase sensitivity to  $B_T$
- From the Earth  $\rightarrow$  Increase spatial resolution (AO) & sensitivity to  $B_T$  (IR)
- From orbit  $\rightarrow$  if a sufficiently large number of vantage points ( $4\pi$ ), might only need  $B_L$ !

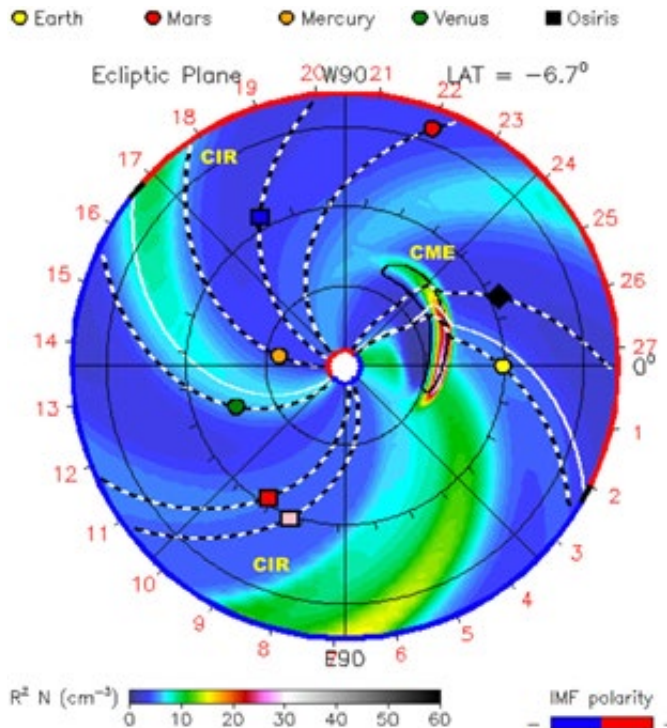
Sarah Gibson



# Space weather from the poles

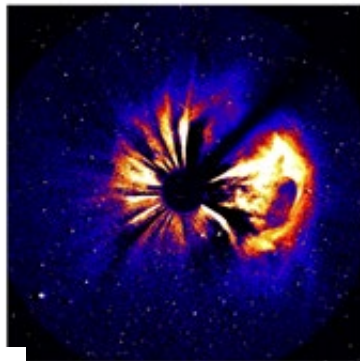
Polar view reveals longitudinal structure and trajectory of CMEs, CIRs, and shocks

Enlil model: polar view



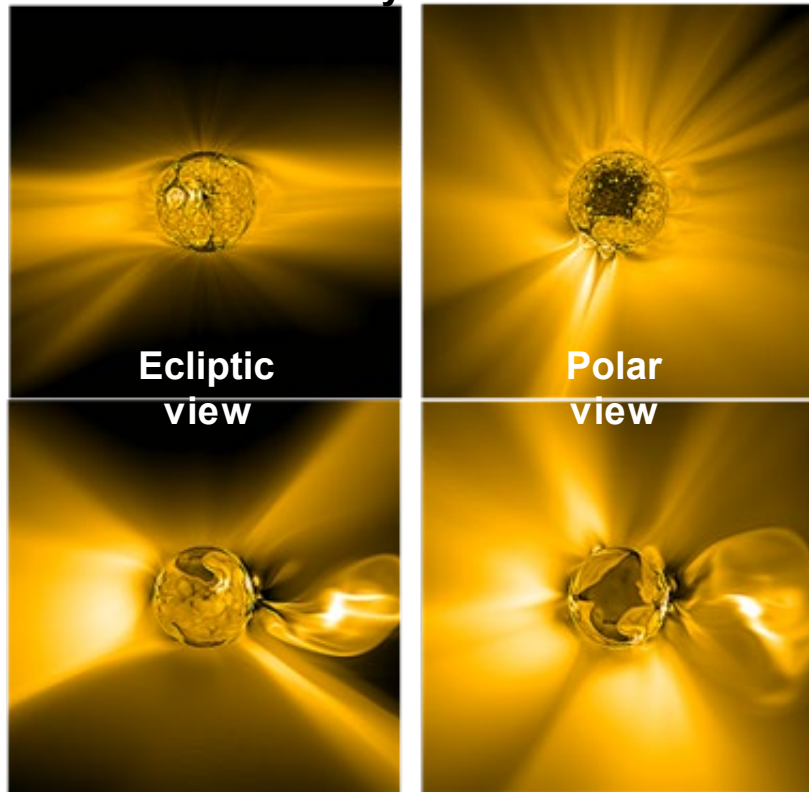
Coronal “head fake”

20111126 SOHO FD Image, 1154 UT



Courtesy V. Pizzo

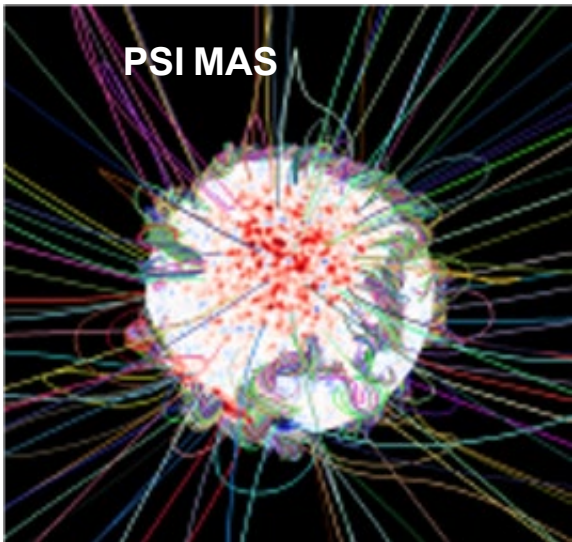
PSI MAS synthetic EUV



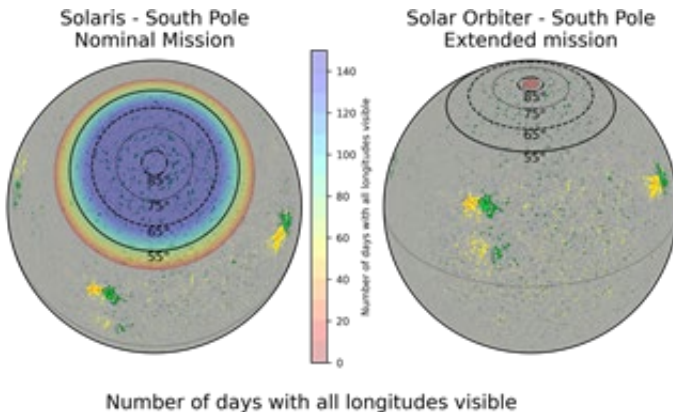


# Boundary on the heliosphere

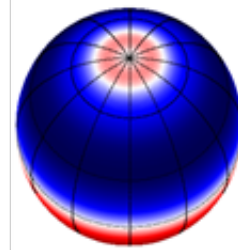
PSI MAS



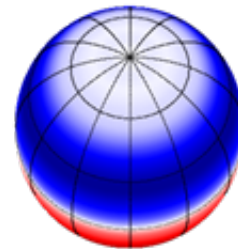
Usable observations:  
within 60° disk center



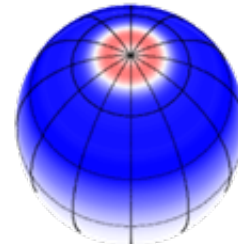
Seasons of Space Weather:  
Measuring High-latitude  
Meridional Circulation



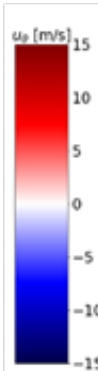
**Ground Truth:**  
Synthetic Solar  
Meridional Circulation  
Model with Counter-Cell  
(Surface Flows)



**Reconstruct from  
ecliptic:**  
– Misses the  
Counter-cell

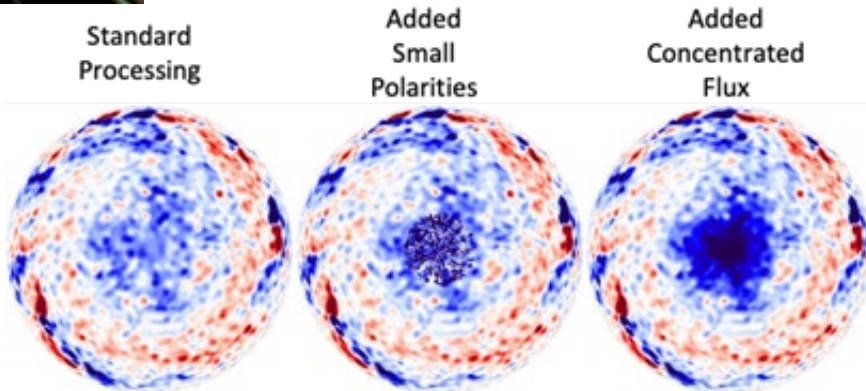


**Reconstruct  
from  
Solaris:**  
– Recovers  
Counter-cell



Courtesy D. Fournier (MPS)

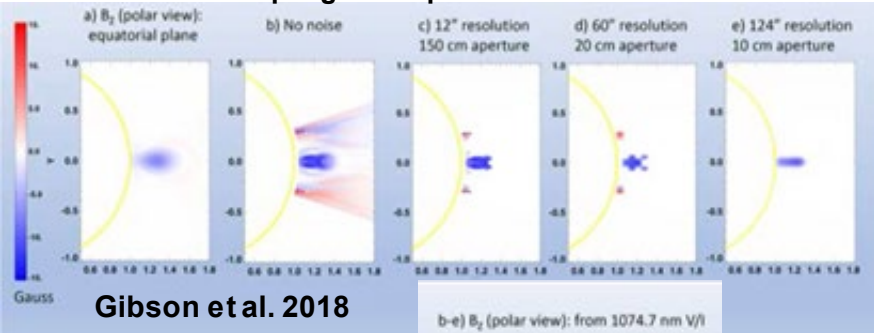
**Which one of these modeled  
polar fields is correct?** These  
three polar photospheric magnetic  
field distributions are all consistent  
with ecliptic observations but result in  
dramatically different heliospheres.  
Adapted from Riley et al. (2019);  
red/blue pos/neg. Middle and right  
match *in situ* observations.



# Ingesting coronal observations into models

**Space-based:** short wavelength; heliographic imagers; out of the ecliptic; instrument miniaturization/ disaggregated approach →  $4\pi$  multiwavelength

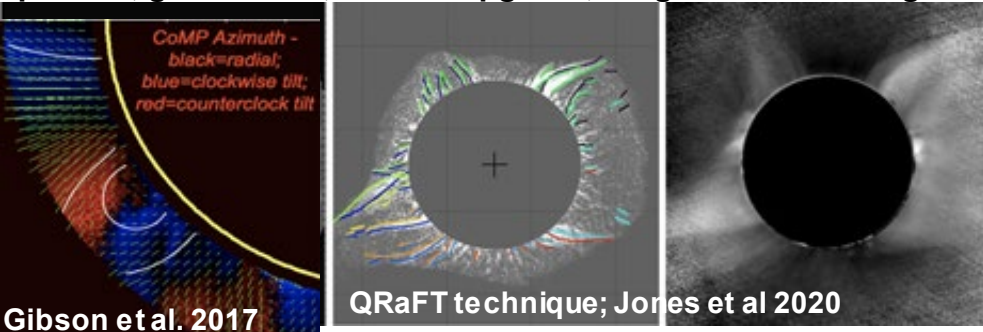
Forward modeled erupting flux-rope CME: direct measurement of  $B_z$ !



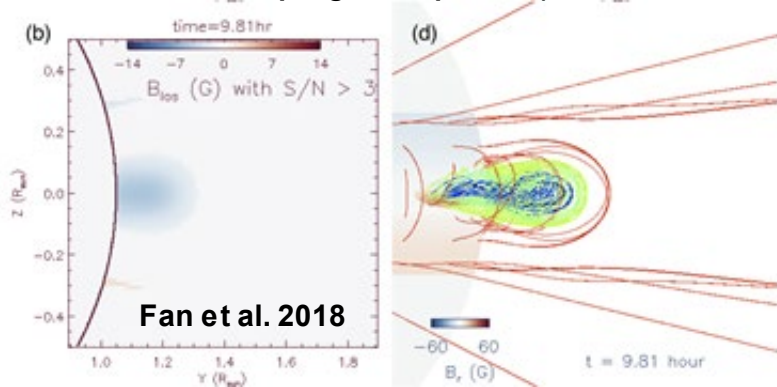
**Forward modeling: sensitivity study** → requirements on coronal observations → constrain coronal magnetic field

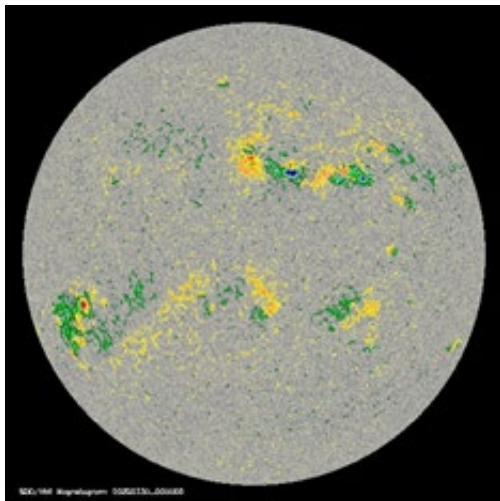
| Process                            | Physical-state dependency                                       | Observation                                                                     | Magnetic quantity probed                                                           |
|------------------------------------|-----------------------------------------------------------------|---------------------------------------------------------------------------------|------------------------------------------------------------------------------------|
| Thomson scattering                 | Electron density                                                | White-light pB, TB                                                              | Plasma structured by field (e.g., closed vs. open field boundaries, flux surfaces) |
| Collisional excitation             | Electron density, temperature                                   | IR/Visible/EUV/SXR emission                                                     | Plasma structured by field (incl. loops, closed/open boundaries, flux surfaces)    |
| Continuum absorption               | Chromospheric population density, electron density, temperature | EUV absorption features                                                         | Can indicate magnetic geometry suitable for prominence formation                   |
| Resonance scattering: polarization | Electron density, temperature, vector magnetic field            | Visible/IR spectra<br>UV (Raouafi et al. 2016; Zhao et al. 2019)                | $B_{los}$ from Stokes V, Magnetic field direction from Stokes Q, U                 |
| Doppler shift                      | Electron density, temperature, velocity                         | Visible/IR spectra                                                              | $B_{pos}$ and field line direction from waves; flux surfaces from bulk flow        |
| Thermal bremsstrahlung             | Electron density, temperature, vector magnetic field            | Radio emission (intensity and circular polarization) as a function of frequency | $B_{los}$ from Stokes V                                                            |
| Gyroresonance                      | Electron density, temperature, vector magnetic field            | Radio emission (intensity and circular polarization) as a function of frequency | Surfaces of constant magnetic field strength at each frequency                     |
| Faraday rotation                   | Electron density, temperature, vector magnetic field            | Rotation of plane of polarization                                               | $B_{los}$ from rotation measure                                                    |

**Ground based:** V/IR/radio wavelengths (spectropolarimetry); large aperture; global view; ease of upgrade; longitudinal coverage

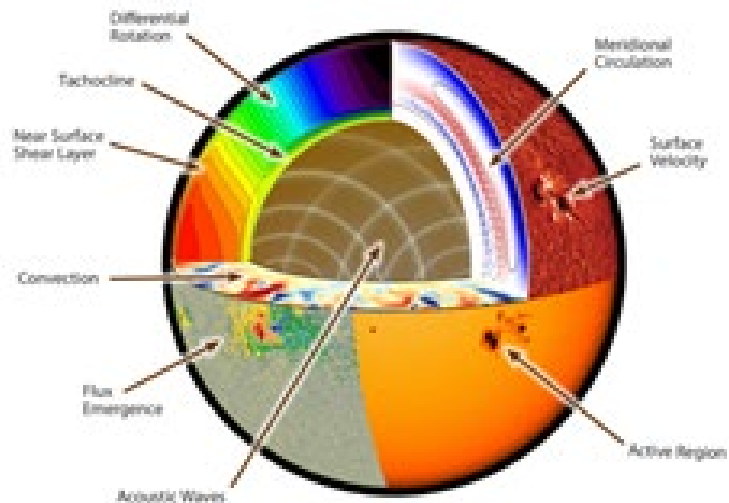


Forward modeled erupting flux-rope CME (10747\_A; COSMO-LC)





Todd Hoeksema  
Stanford University



## Observing and Modeling Needs

**Limitations apply to both space weather and space climate, i.e., short and long term variability.**

- How active will the next solar cycle be? What influences the large-scale dynamo?
- When and where are active nests likely to occur? How long will a nest continue to develop?
- How much flux will appear in an emerging region? Where and when? How complex will the structure be? How will emerging flux interact with existing flux patterns?
- How much energy is stored in a magnetic structure? Will a region flare? Will it successfully erupt? What, if anything, will trigger energy release?
- What is the initial field configuration of an eruptive event? How will it evolve as it moves through the corona and beyond?
- What determines how an event propagates from the Sun to the observer?
- Which events will accelerate particles that reach 1 AU, and the Earth?
- How does photospheric flux reach the corona and beyond really?

## Observing and Modeling Needs

**Important limitations to predictive skill are driven by locations and time-scales for which we do not have reliable or complete observations.**

- Expensive vantage points:  $4\pi$ ,  $4\pi \cdot t$ ,  $4\pi \cdot R \cdot t$ : the poles, the far side, L5 & L4, the inner heliosphere, other planets, sparse data/satellite constellations
- Inaccessible regions: The solar interior: the tachocline, the near surface shear layer, flux emergence through the convection zone. Time dependent flow patterns – convective, meridional, zonal and other flows in 3D.
- Detectible, but hard to measure: the coronal field (1D & 3D); flux, energy and helicity build-up; time evolution, subsurface flux concentrations, solar-cycle comparisons

**Important limitations to predictive skill are driven by inadequate modeling and data analysis techniques**

- Solar dynamo: flux generation, triggers for emergence; implications of flow and convection patterns
- Detection and characterization of emerging magnetic flux through the convection zone
- Modeling of energy build-up in the atmosphere and triggers for energy release and particle acceleration
- Modeling of field evolution after energy release begins in an existing environment
- Propagation of eruptions and particles through the heliosphere

# Phillip Chamberlin

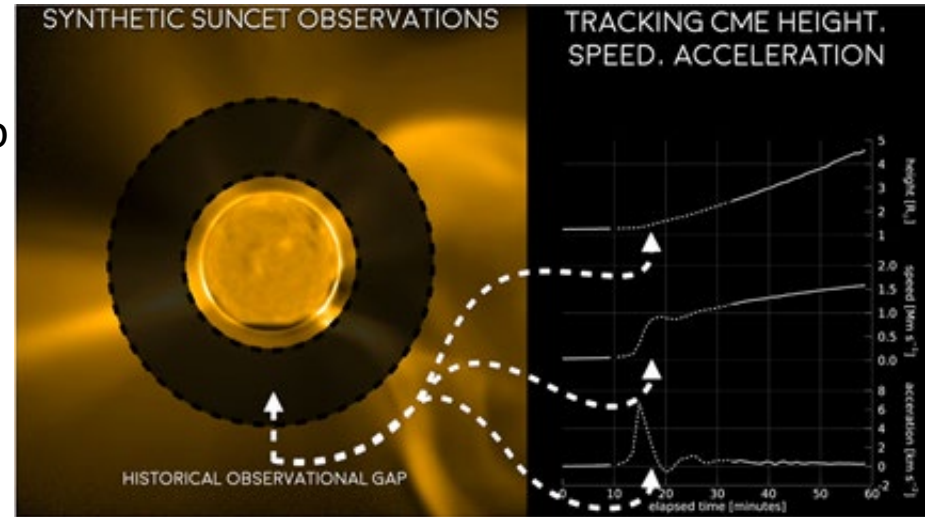
U. of Colorado, Laboratory for Atmospheric and Space Physics



# Solar Measurements: Spatial Coverage

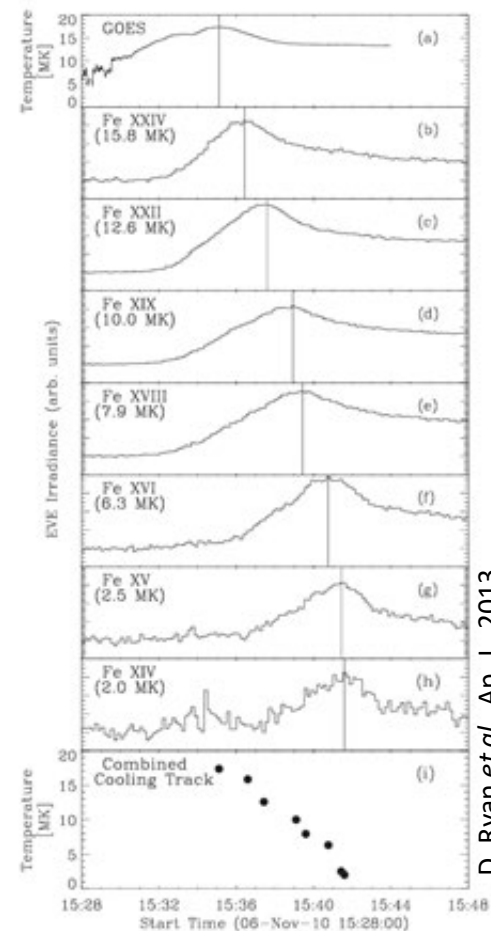
- Along with the  $4\pi$  coverage, **future imaging measurements of the Sun need to ensure there is overlap** between instrument fields-of-view (FOV), so there are no gaps.
- Current gaps exist between EUV solar imagers and white-light coronagraphs; therefore, we do not measure the critical region where Coronal Mass Ejections (CMEs) are accelerated.
- This leave numerous physical models of CME initiation and acceleration all stating they are correct, despite very different physics, as they are severely unconstrained by the measurements.
- Need to increase the FOV of EUV imagers ( $\geq 4R_{\odot}$ ) and bring the lower bound of white-light coronagraph down close to the solar surface.

J. Mason *et al.*, JSWSC, 11 (2021)



# Future Measurements: Solar Irradiance (1)

- **Solar EUV irradiance is the primary energy input into Earth/planetary upper atmospheres**
- Proxy models (e.g. based on XRS/EXIS) will never be as accurate as measuring the full spectrum, but can get full temporal and spectral coverage.
  - One example (right): Solar flare emission timing as flares cool through the contribution functions – all emissions don't peak at the GOES XRS peak!
- Physics models (e.g. CHIANTI) still don't have all the necessary physics and are computationally expensive to run for all times, and still rely on measurements to constrain/drive them
  - Radiative Hydrodynamics, Differential Emission Measures, Optical Thickness, Flare Cooling vs Continued Heating
- Solar eruptive event (SEE) case studies will rely on accurate quantification of the full solar irradiance spectrum.
  - Both dynamics and energetics of the solar plasma itself as well as the impact on planetary thermosphere and ionospheres.
- Solar flares and EUV irradiance have critical Space Weather impacts.
  - Immediate impact, no warning
  - Impact the lower latitudes where most of the impacted technology resides



# Future Measurements: Solar Irradiance (2)

- Irradiance dimming can tell us a lot about the early stages of the CME mass/irradiance.
  - There are no GOES/EUVS lines measured that are sensitive to coronal dimming.
- Still haven't had spectral irradiance measurements in the soft X-rays (2-6nm).
  - Currently only have been broad-band (5-7nm) measurements, need 0.1 nm resolution.
  - Huge impact on energy distribution in planetary ionospheres (see Fig lower right, red/green have same total energy 0-7nm).
- Doppler shifts and thermal broadening in irradiance measurements have potential to have a much more complete temperature and spatial coverage.
- Getting multi-vantage point and full 4pi (full Sun) coverage will help with Space Weather prediction (1-7 days) and UV input to all planetary systems.
- Solar/Stellar connections
  - Solar Irradiance is Sun as a star!
- **Every flare is different.**

