# Predicting IMF $B_z$ at 1 AU
## -The past, present, and future

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Space Weather Operations and Research Infrastructure: Workshop Part I

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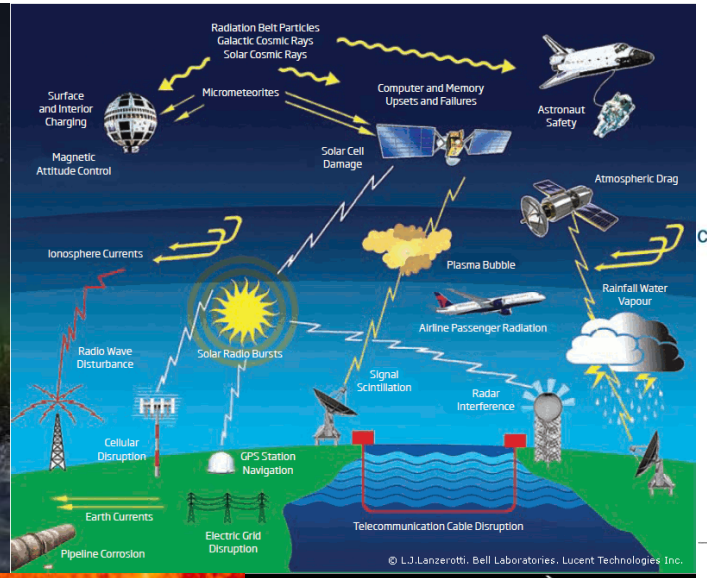
# BLUF

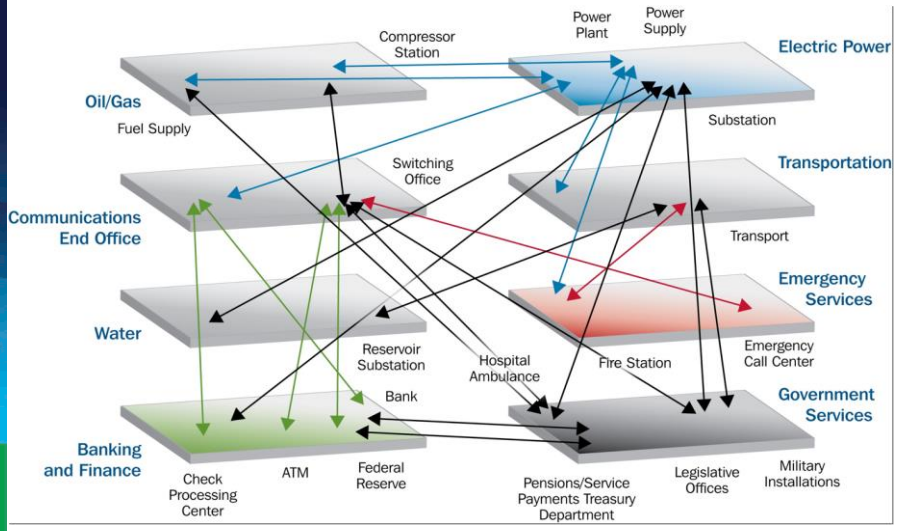
- We can't predict IMF $B_z$ (well)
- Anyone who tries to convince you otherwise is misinformed, deluded, or lying
- Reproducing 1 AU observations is not the same as forecasting/predicting
- Being able to make useful forecasts of $B_z$ is going to be more difficult than we (or at least I) thought
- If forecasting is the goal, we have to be goal-orientated, not theory-orientated
- If $B_z$ prediction is really a priority, it will require significant investment

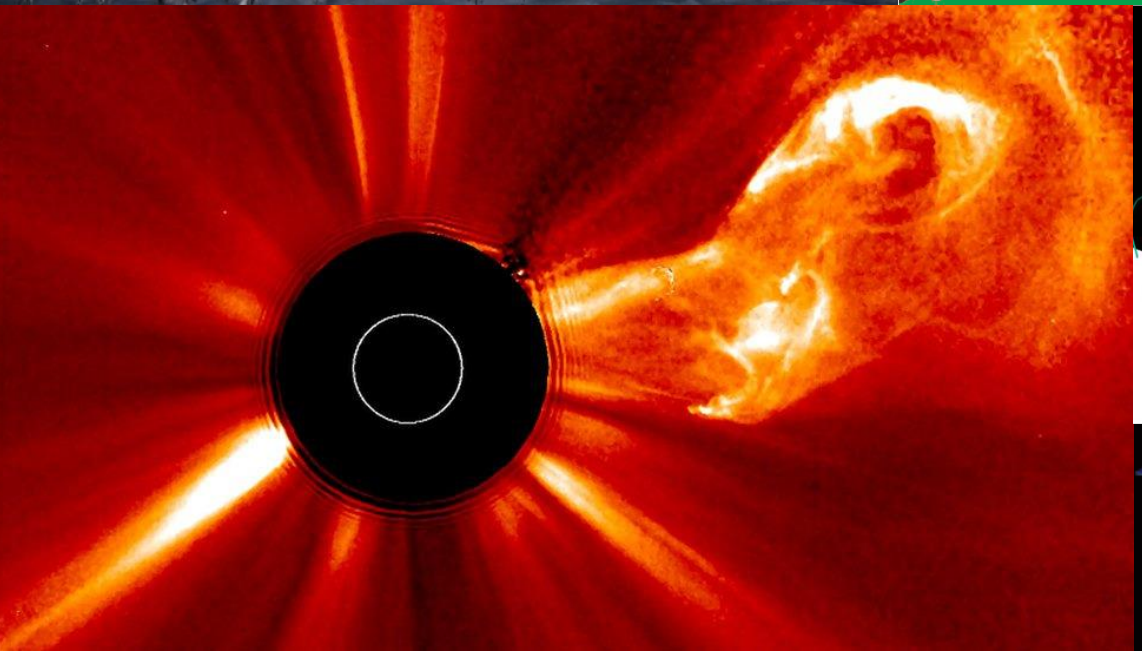
# Overview

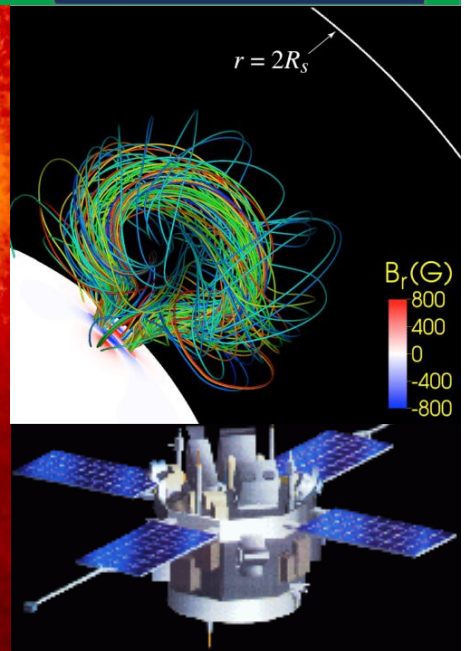
- Why do we care?
- What physical processes produce $B_z$?
- How can we predict non-zero $B_z$?
- Past and current status of $B_z$ predictions
- Basic uncertainties that need to be resolved
- Conclusions
- Future Opportunities

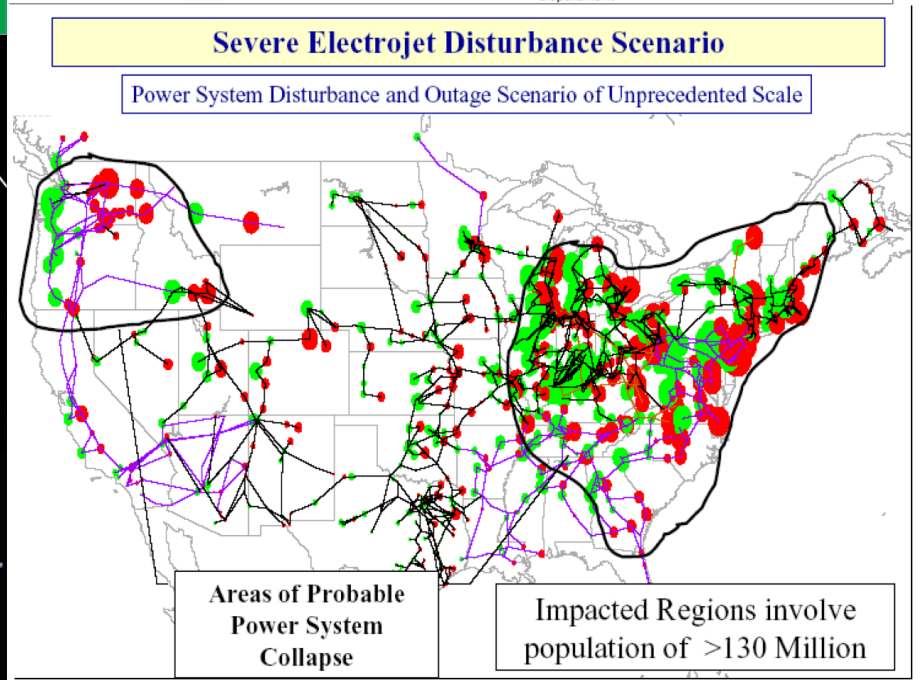
# Why do we care about $B_z$?
# -Science and Society

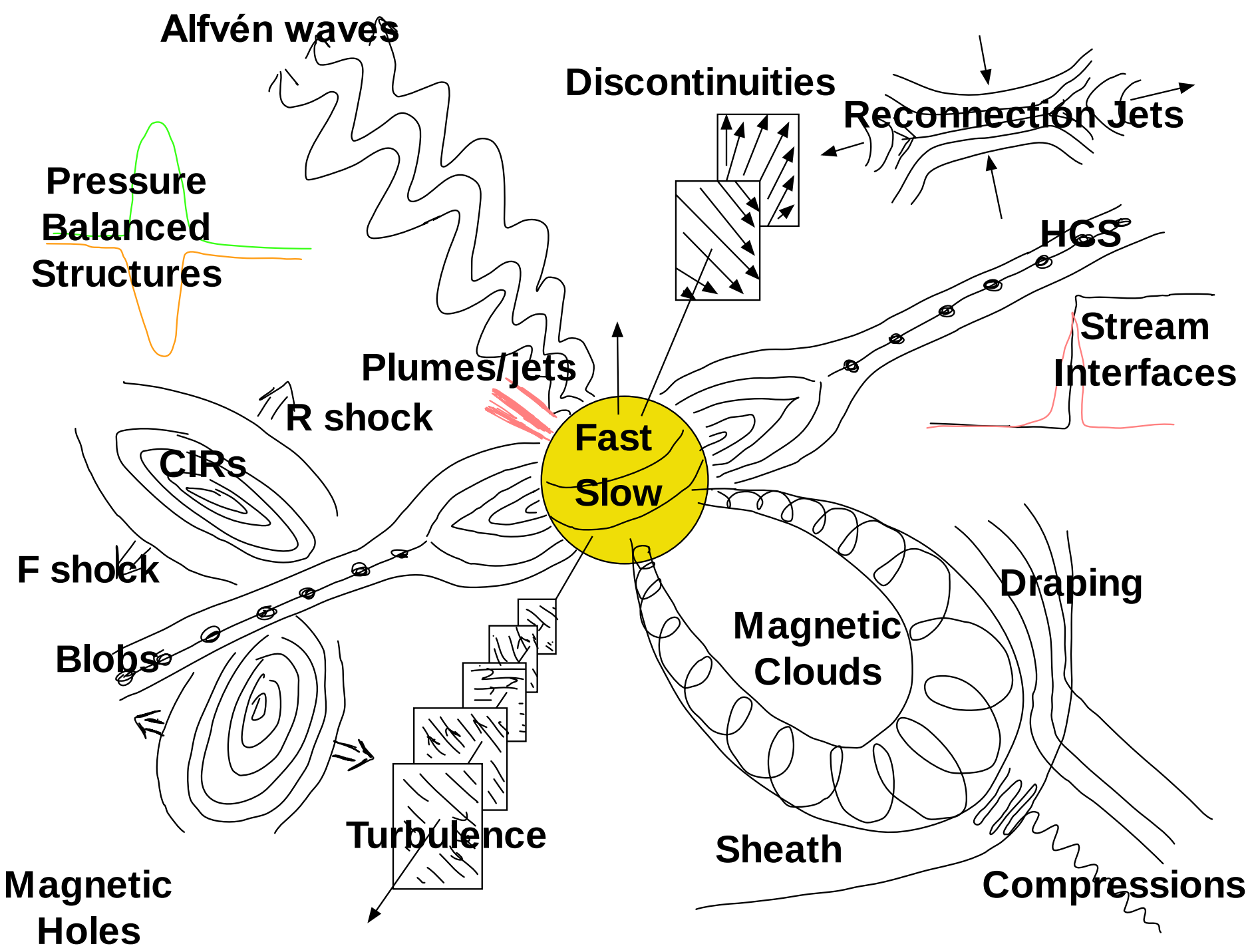


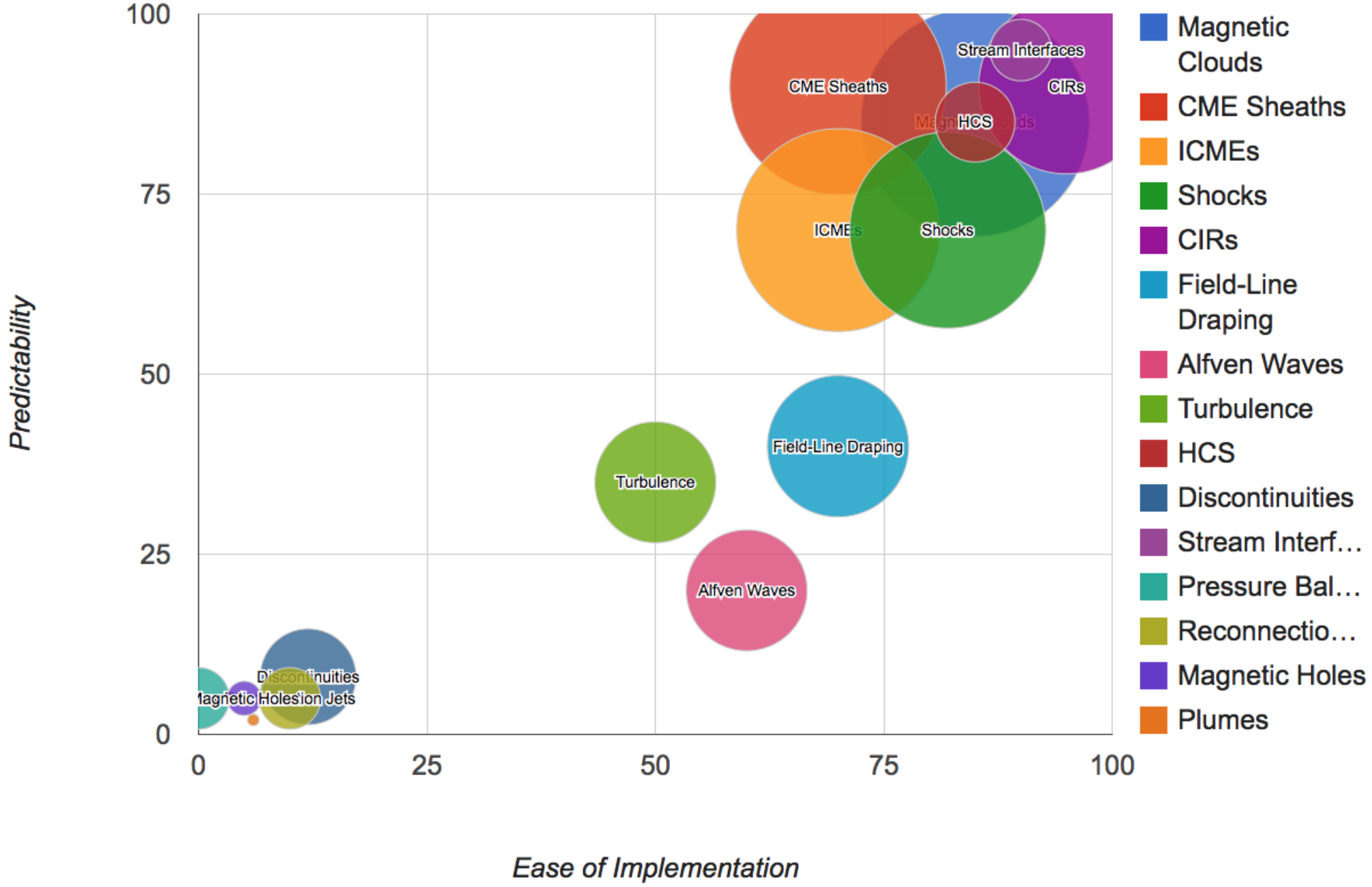





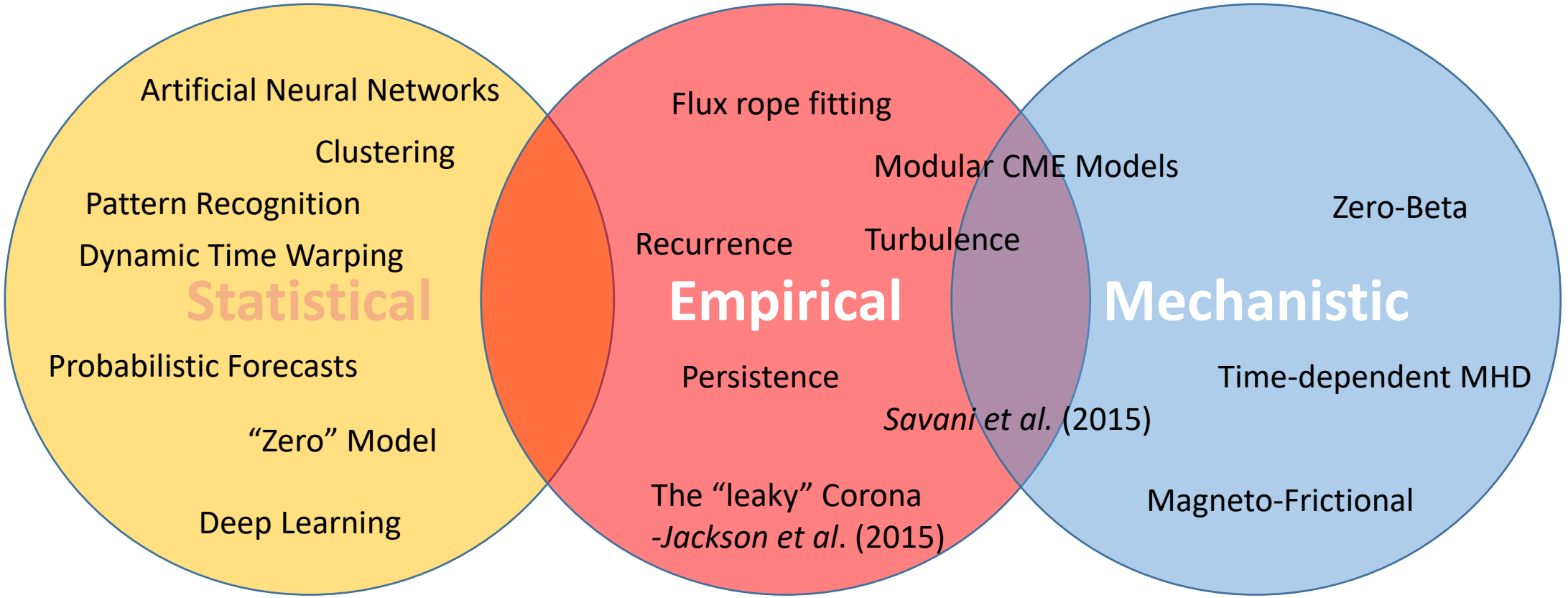




Alfvén waves
Discontinuities
Reconnection Jets
Pressure
Balanced
Structures
HCS
Stream
Interfaces
Plumes/jets
R shock
Fast
Slow
CIRs
F shock
Draping
Magnetic
Clouds
Blobs
Turbulence
Sheath
Compressions
Magnetic
Holes

# How do we Prioritize these Processes?



# Techniques for predicting non-zero $B_z$



# Bz ‘prediction’ studies…

- Search based on:
  - (interplanetary | "solar wind") AND (southward | Bz | "z component" | "z-component” | “magnetic vectors” | “magnetic field vectors") AND (prediction | predicting | forecast | forecasting)

- Resulted in ~20 relevant papers
  - Chen, James, Peter J. Cargill, and Peter J. Palmadesso. "Real-time identification and prediction of geoeffective solar wind structures." *Geophysical research letters* 23, no. 6 (1996): 625-628.
  - Riley, Pete, Michal Ben-Nun, Jon A. Linker, Mathew J. Owens, and T. S. Horbury. "Forecasting the properties of the solar wind using simple pattern recognition." *Space Weather* 15, no. 3 (2017): 526-540.
  - Jackson, B. V., H-S. Yu, A. Buffington, P. P. Hick, M. Tokumaru, K. Fujiki, J. Kim, and J. Yun. "A daily determination of BZ using the Russell-McPherron effect to forecast geomagnetic activity." *Space Weather* 17, no. 4 (2019): 639-652.
  - Sarkar, Ranadeep, Nat Gopalswamy, and Nandita Srivastava. "An Observationally Constrained Analytical Model for Predicting the Magnetic Field Vectors of Interplanetary Coronal Mass Ejections at 1 au." *The Astrophysical Journal* 888, no. 2 (2020): 121.
  - Savani, N. P., A. Vourlidas, A. Szabo, M. L. Mays, I. G. Richardson, B. J. Thompson, A. Pulkkinen, R. Evans, and T. Nieves-Chinchilla. "Predicting the magnetic vectors within coronal mass ejections arriving at Earth: 1. Initial architecture." *Space Weather* 13, no. 6 (2015): 374-385.
  - Möstl, Christian, Tanja Amerstorfer, Erika Palmerio, Alexey Isavnin, Charles J. Farrugia, Chris Lowder, Reka M. Winslow, Julia M. Donnerer, Emilia KJ Kilpua, and Peter D. Boakes. "Forward modeling of coronal mass ejection flux ropes in the inner heliosphere with 3DCORE." *Space Weather* 16, no. 3 (2018): 216-229.
  - Kay, C., and N. Gopalswamy. "Using the coronal evolution to successfully forward model CMEs' in situ magnetic profiles." *Journal of Geophysical Research: Space Physics* 122, no. 12 (2017): 11-810.

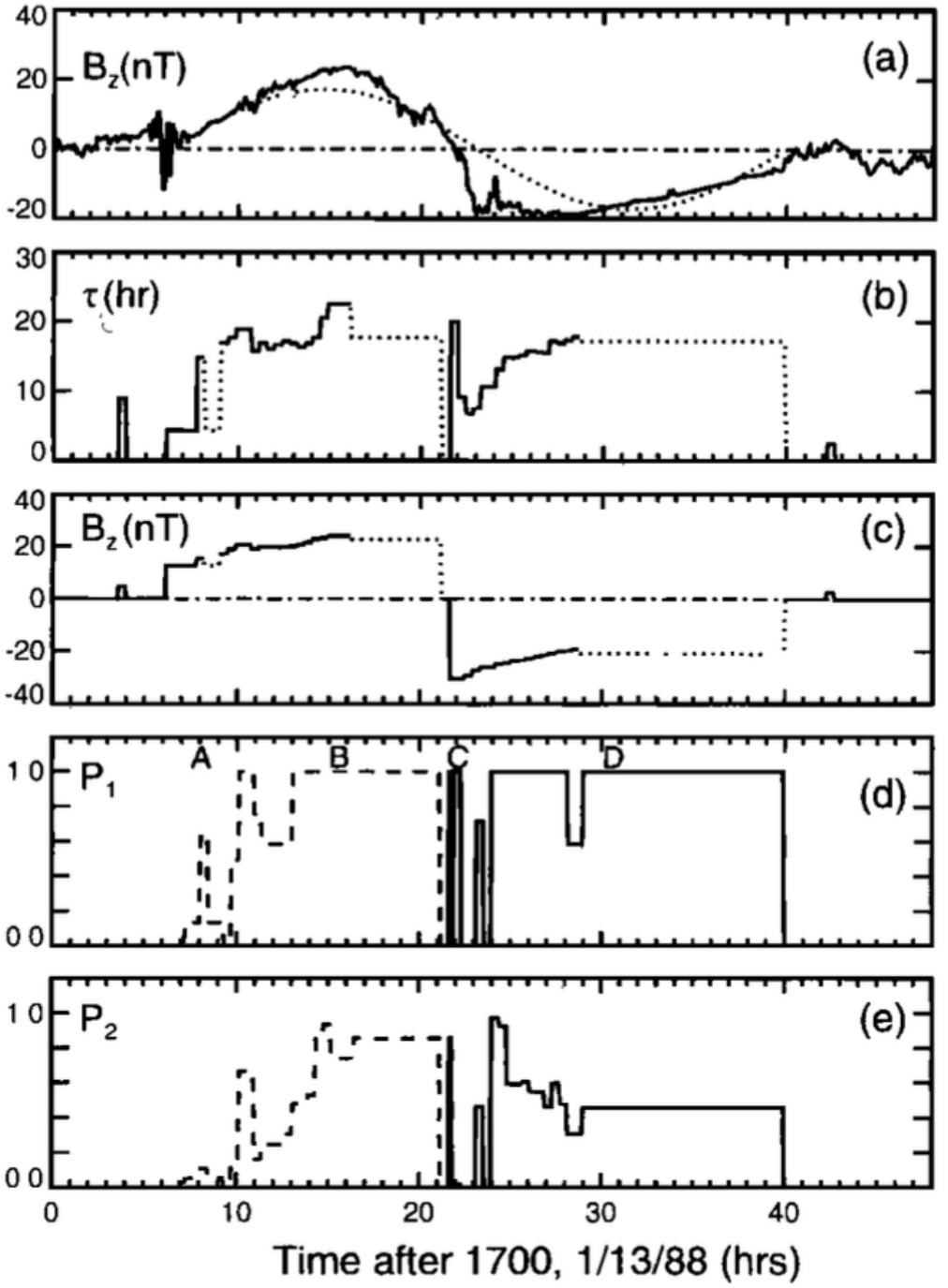
# “Historical” attempts to predict $B_z$ …

GEOPHYSICAL RESEARCH LETTERS, VOL. 23, NO. 6, PAGES 625-628, MARCH 15, 1996

**Real-time identification and prediction of geoeffective solar wind structures**

James Chen, Peter J. Cargill, Peter J. Palmadesso
Plasma Physics Division, Naval Research Laboratory

- Feature-based classification technique
- Extrapolation of coherent signal
- Precursor to flux-rope fitting and/or pattern recognition
- Focuses on sinusoidal variation of Bz
  - If Bz < 1 during first-half => limited prediction
  - If Bz > 0 during first-half => longer prediction
- Danger of false positives
- Only demonstrated for a few case studies



http://www.predsci.com/project-zed/

# Predictive Science - Project Zed

Choose a date, time (in hours), forecasting time window, and some combination of models

## Date

2020-06-13

**Hour:**

19

**Window (hours or days):**

24 hours

## Models to include

- [x] Baseline
- [ ] Persistence
- [ ] Recurrence
- [x] Pattern Recognition
- [ ] Turbulence

## Coordinate System

- (•) RTN
- ( ) GSE
- ( ) GSM

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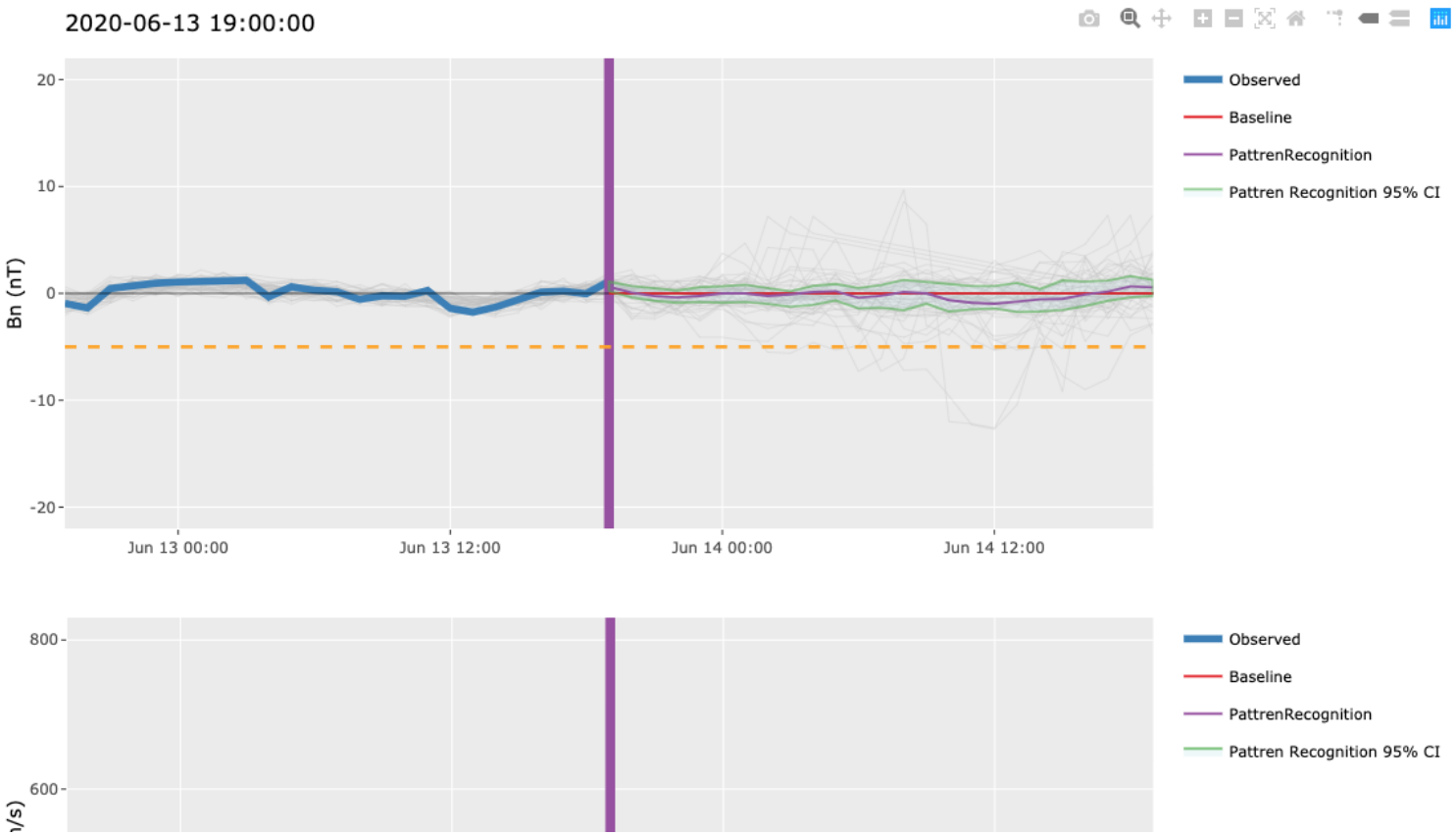
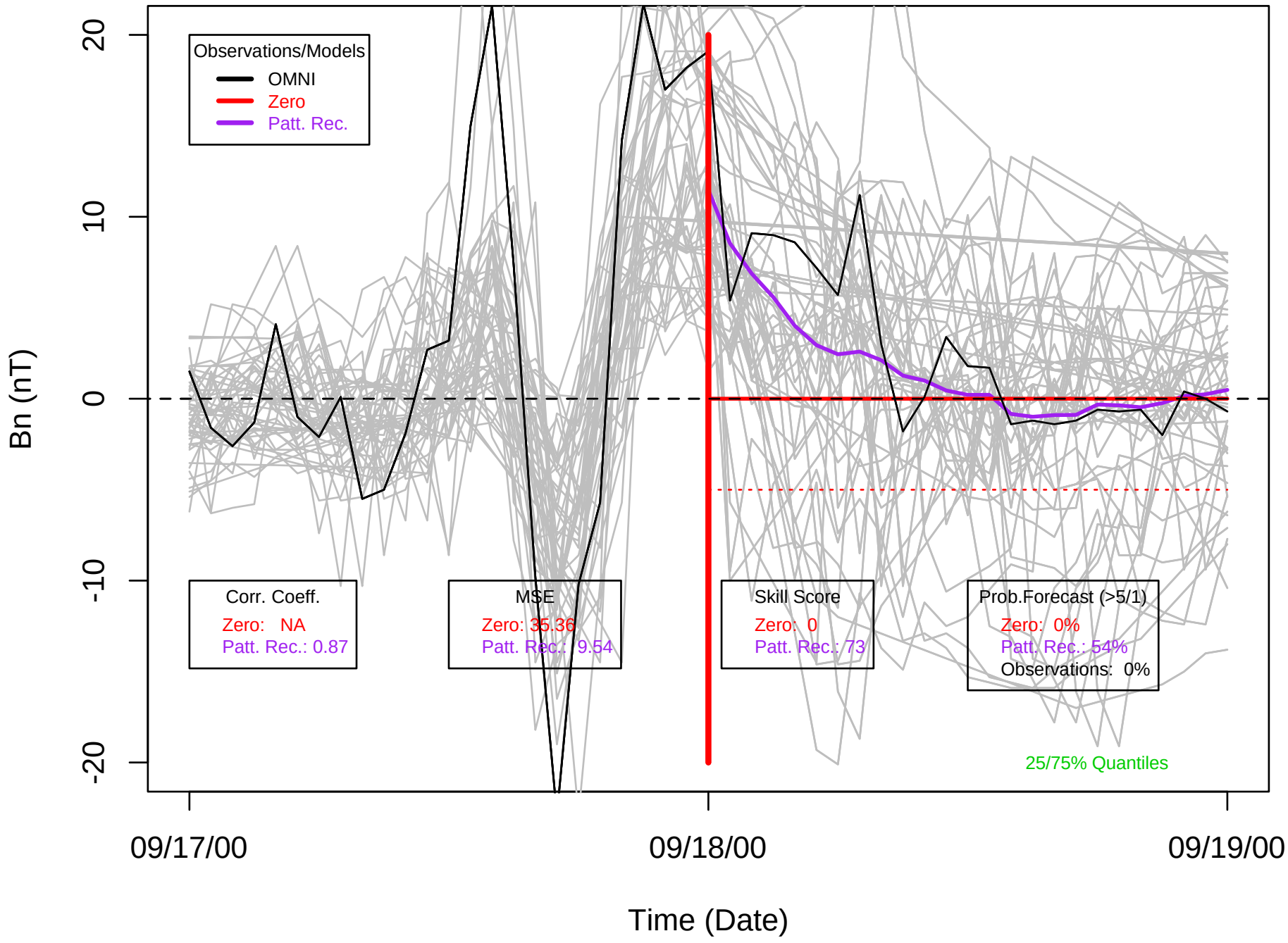
## Solar Wind Data and Forecast




*Riley et al.* (2017)

# Pattern Recognition *Riley et al.* (2017)



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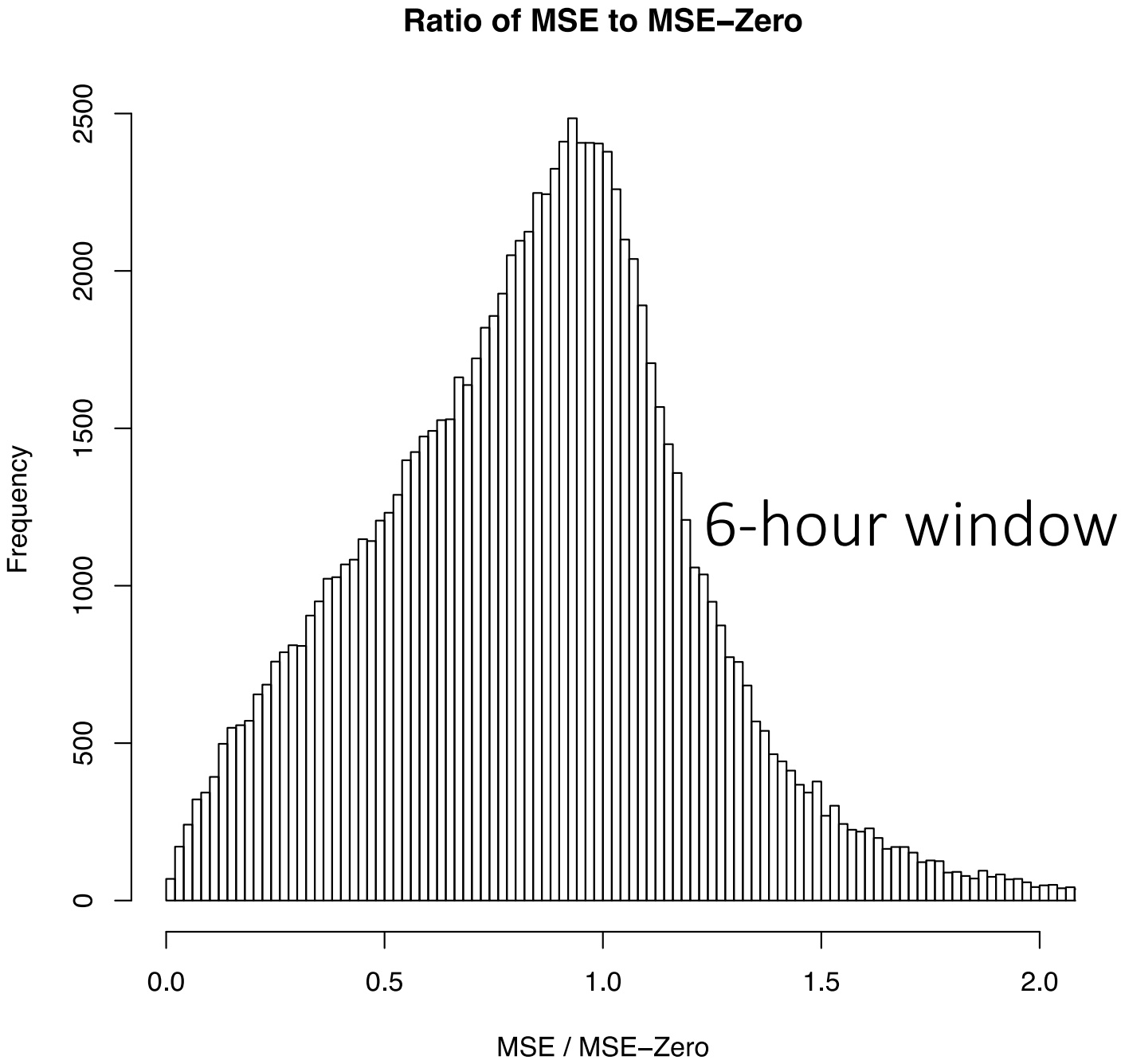
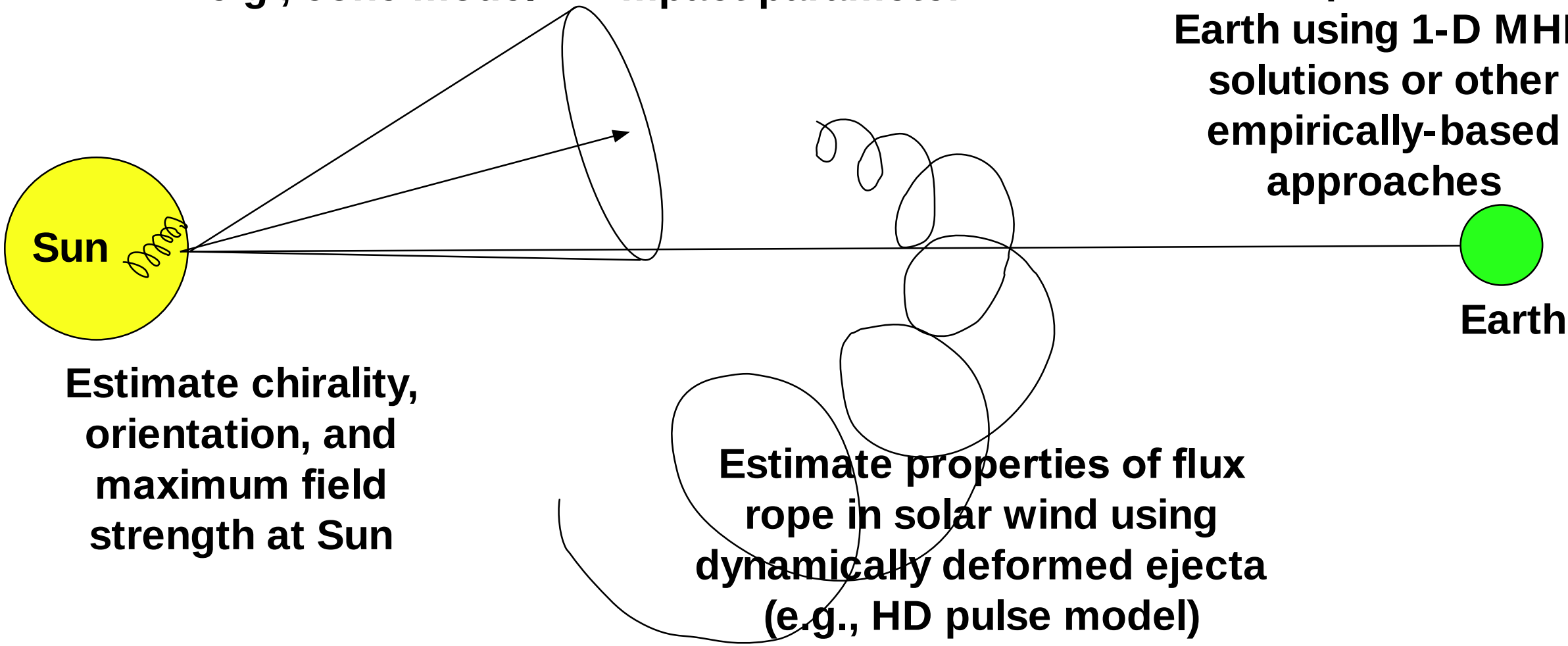


# Empirical Modular CME (EMC) Models

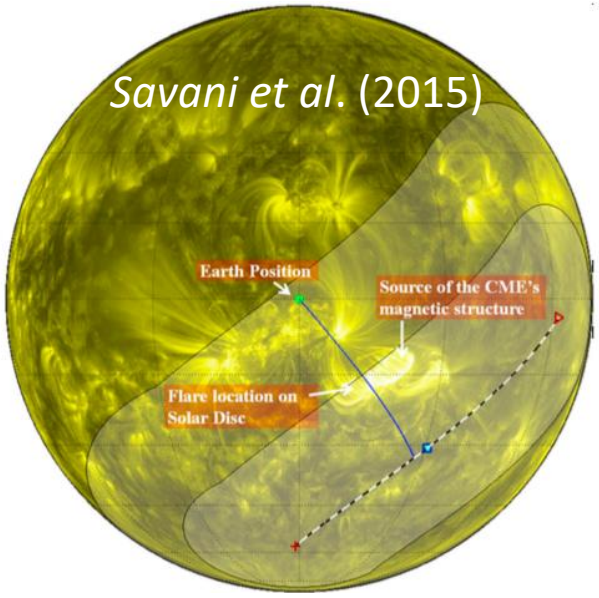
**Estimate kinematic/geometric properties of ejecta near Sun e.g., cone model => Impact parameter**

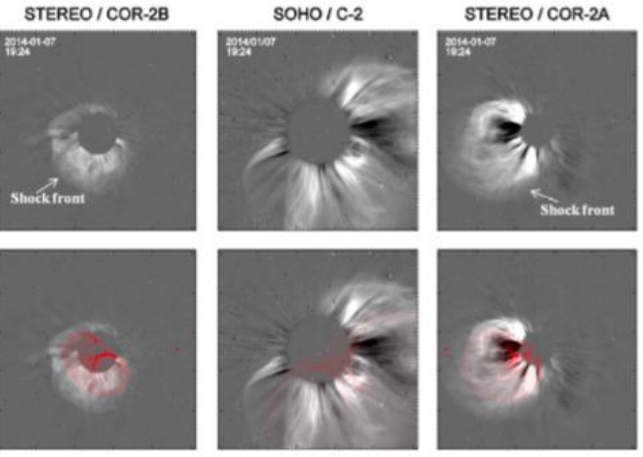
**Estimate transit time (τ) of flux rope from Sun to Earth using 1-D MHD solutions or other empirically-based approaches**

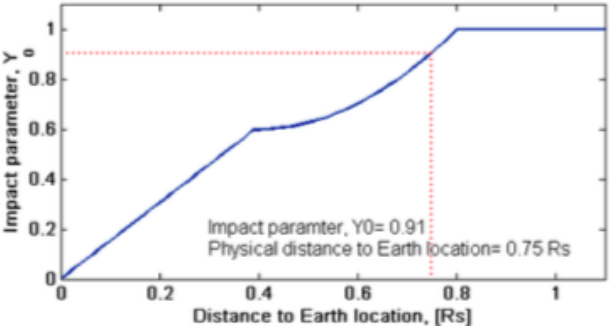



**Estimate chirality, orientation, and maximum field strength at Sun**

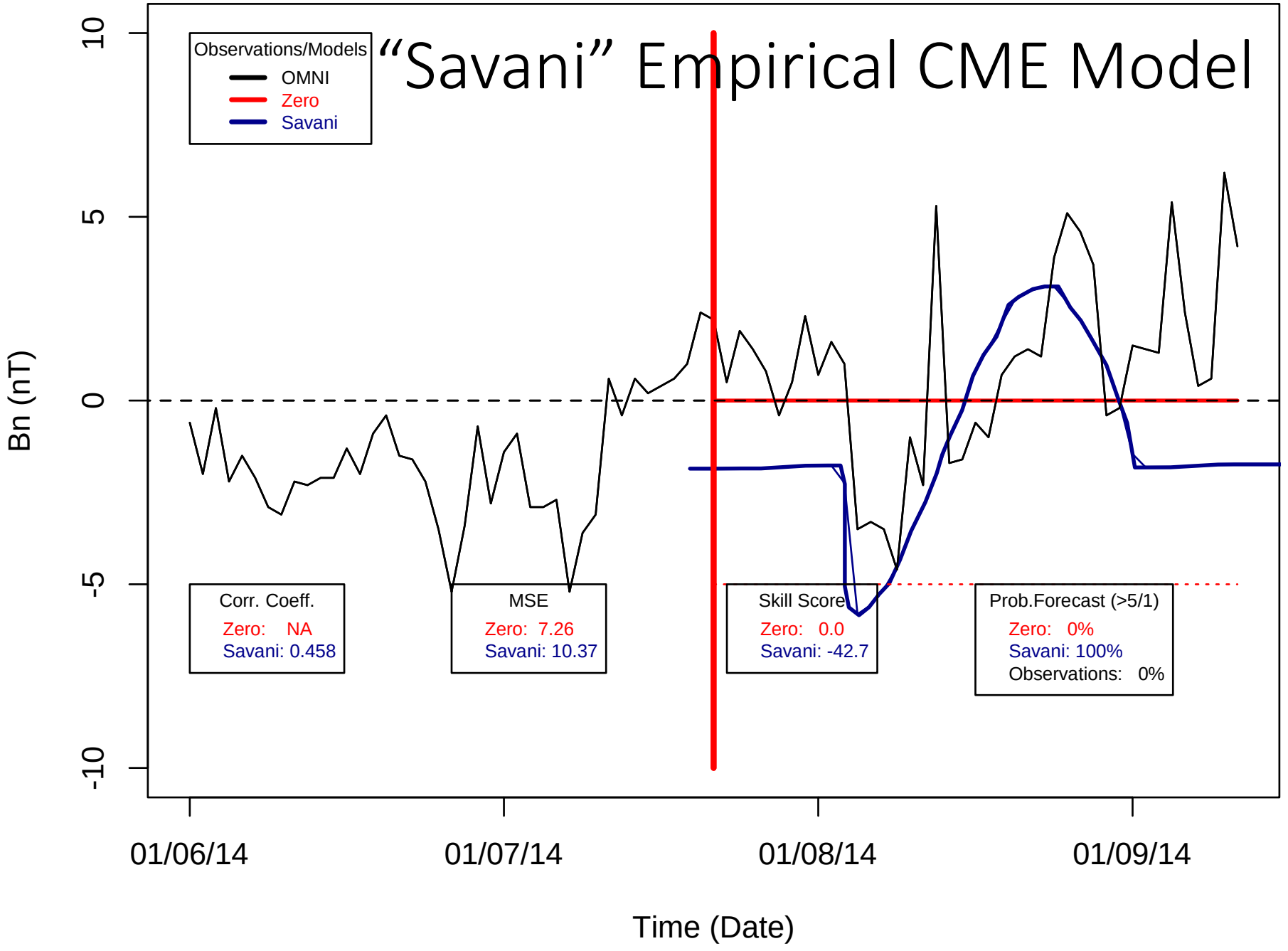
**Estimate properties of flux rope in solar wind using dynamically deformed ejecta (e.g., HD pulse model)**




# "Savani" Empirical CME Model



# $B_z$ Prediction: A Comedy of Errors

- Initial helicity (accuracy ~0.75)
- Photospheric FR axial orientation ($\theta \pm 5^o$, $\phi \pm 5^o$)
- Flux rope rotation (~ $\theta \pm 20^o$, $\phi \pm 20^o$)
- Ejecta speed (~±100 km/s)
- Ejecta mass (~$\pm 1 \times 10^{12}$ kg)
- Ejecta propagation direction ($\theta \pm 15^o$, $\phi \pm 15^o$).

# $B_z$ Prediction: CME/ICME relationships

- 46% of ICMEs have no obvious solar event associated with them (*Richardson et al.* (2010))
  - But, many slow, weak events that are convected out with the solar wind.
- 10% of the ICMEs driving “Dst <-100 nT” storms had no clear associated solar event (*Zhang et al.,* 2007)
- Only ~56% of halo CMEs produce MC at 1 AU

# Conclusions

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# Suggestions for Future Paths for Forecasting $B_z$?

- Invest time/money specifically into forecasting, not coopting research studies
- Work on specific components of the Sun-Earth chain to reduce uncertainties
- Investigate statistical approaches more carefully (c.f. weather forecasting)
- Optimize NASA/ESA/NOAA mission designs to measure critical inputs
- Start with simpler objectives: Predict speed (time of arrival), $B$, $B_r$, and $B_t$
- Identify and focus on “lowest hanging fruit”: CME sheaths, ultra-fast events, etc.