From Observations Toward Prediction of the Downstream Properties of CME-Driven Shocks

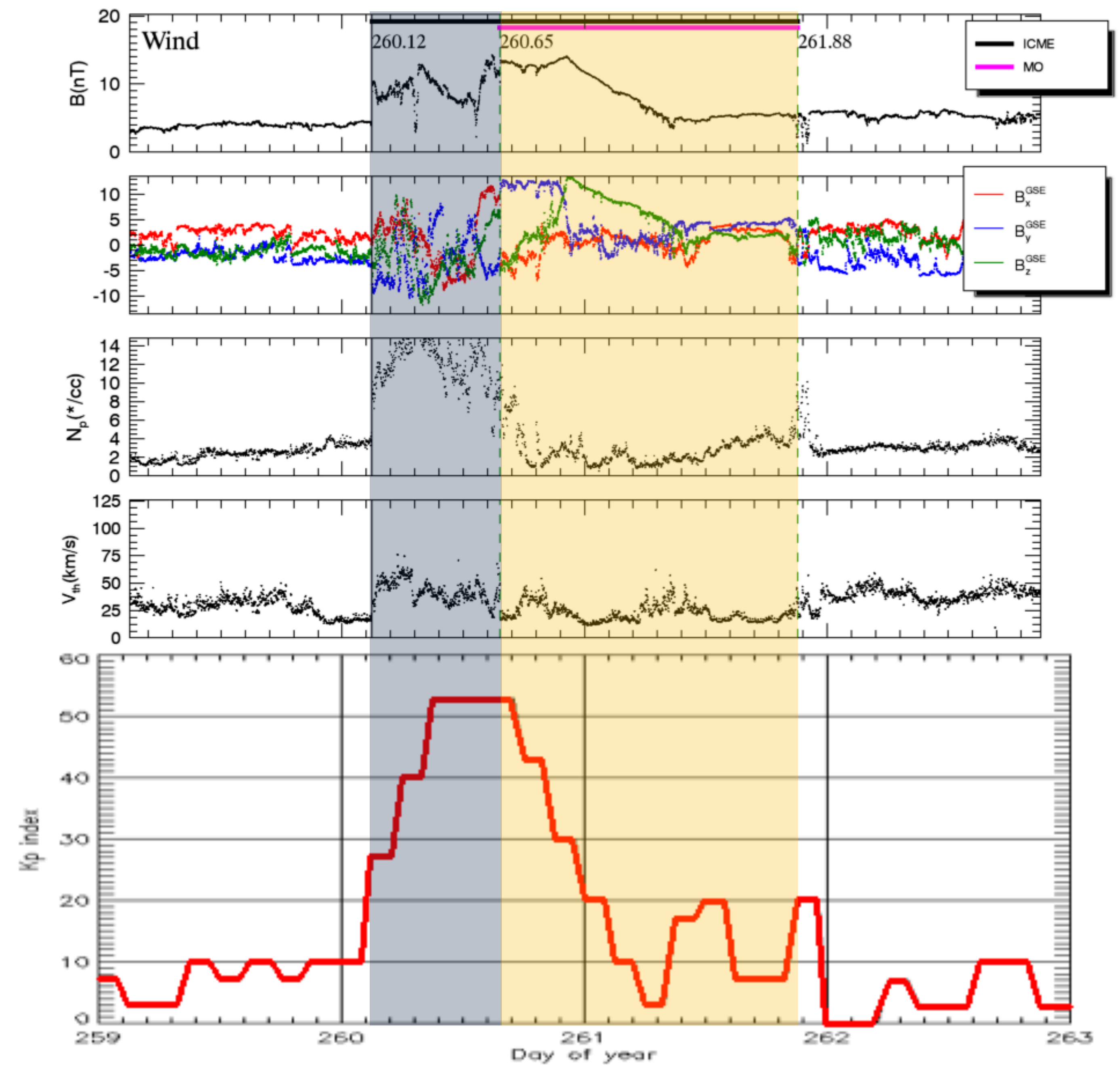
Christina Kay (NASA GSFC/CUA)

Kay, Nieves-Chinchilla, & Jian, JGR Space Physics (under revision)

Why Sheaths?

- Roughly a quarter of large geomagnetic storms (Dst < -100 nT) are driven by the sheath as opposed to the CME flux rope (*Zhang+ 2008*, *Guo+ 2011*)
    - Often strongest storms are mix of transients
- Start focusing on isolated sheath/shock close to Earth here
    - Intrinsically related to interacting cases and near-Sun behavior affects SEP production

17 September 2011 CME



FIDO

- The ForeCAT In Situ Data Observer (FIDO, *Kay et al. 2017*) reproduces the in situ magnetic field of CME flux ropes using a physics-driven approach

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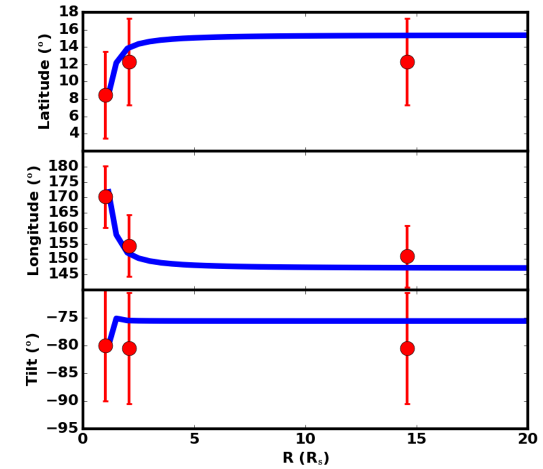

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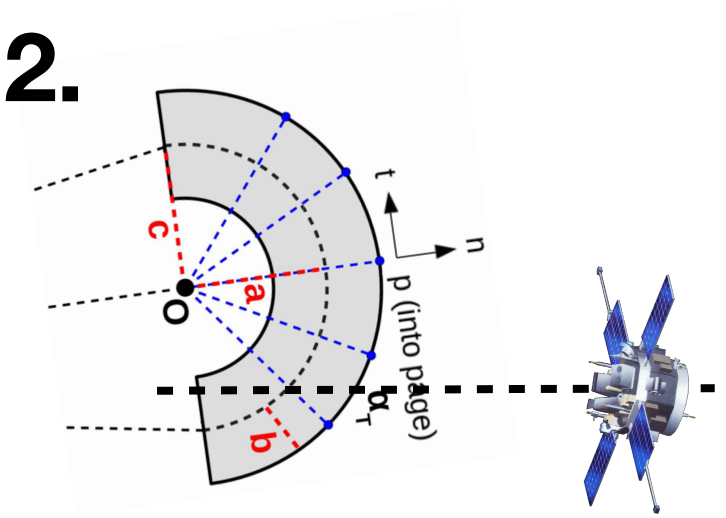

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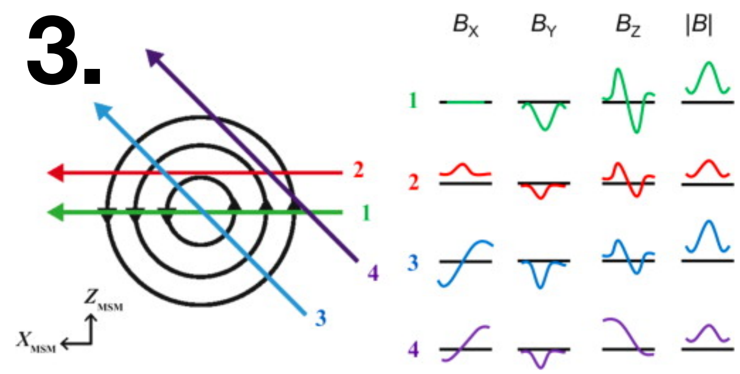
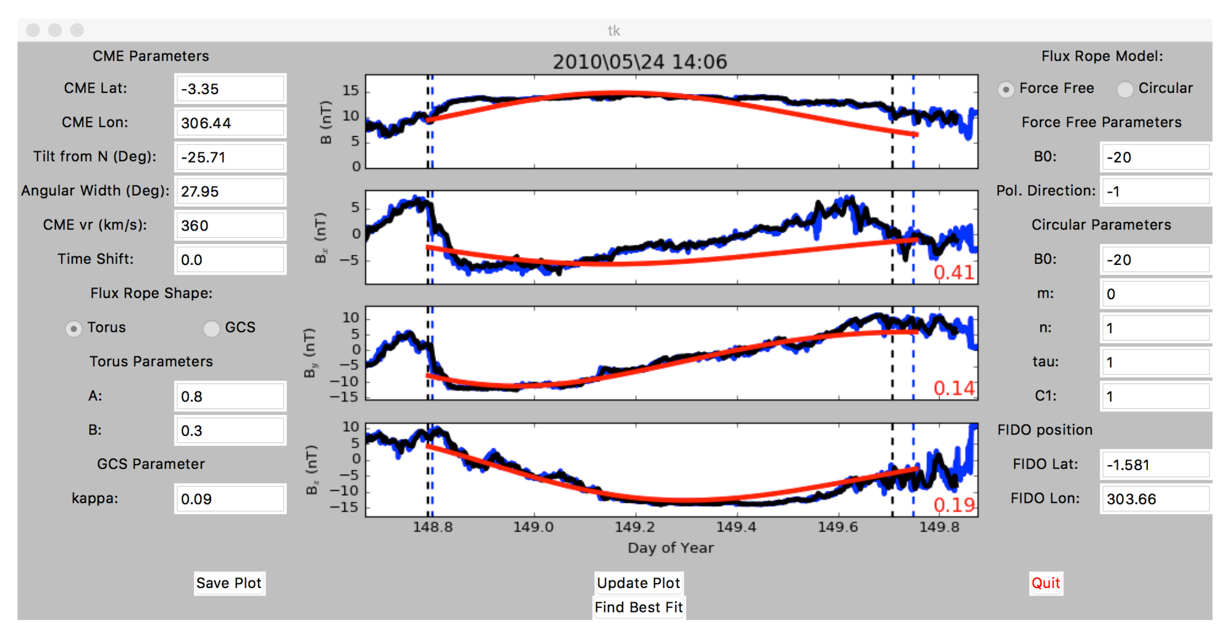


$$B_t = B_0 J_0 \left(\frac{2.4 d_t}{R_{CME}}\right)$$

$$B_p = B_0 H J_1 \left(\frac{2.4 d_t}{R_{CME}}\right)$$

Image from DiBraccio+ 2015

- Simple flux rope model propagated past synthetic spacecraft

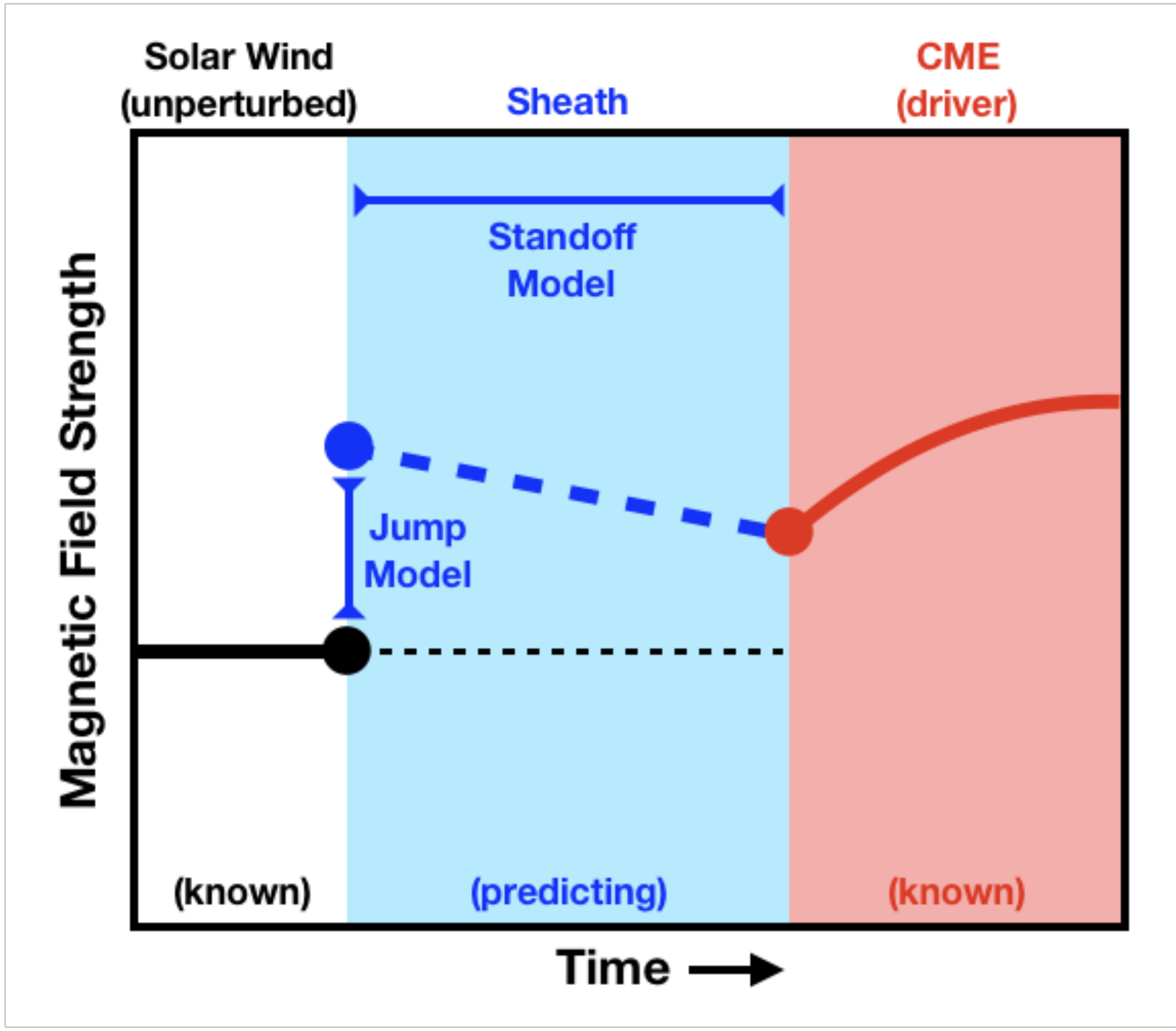


→ Can we do something similar for sheaths?

FIDO-SIT

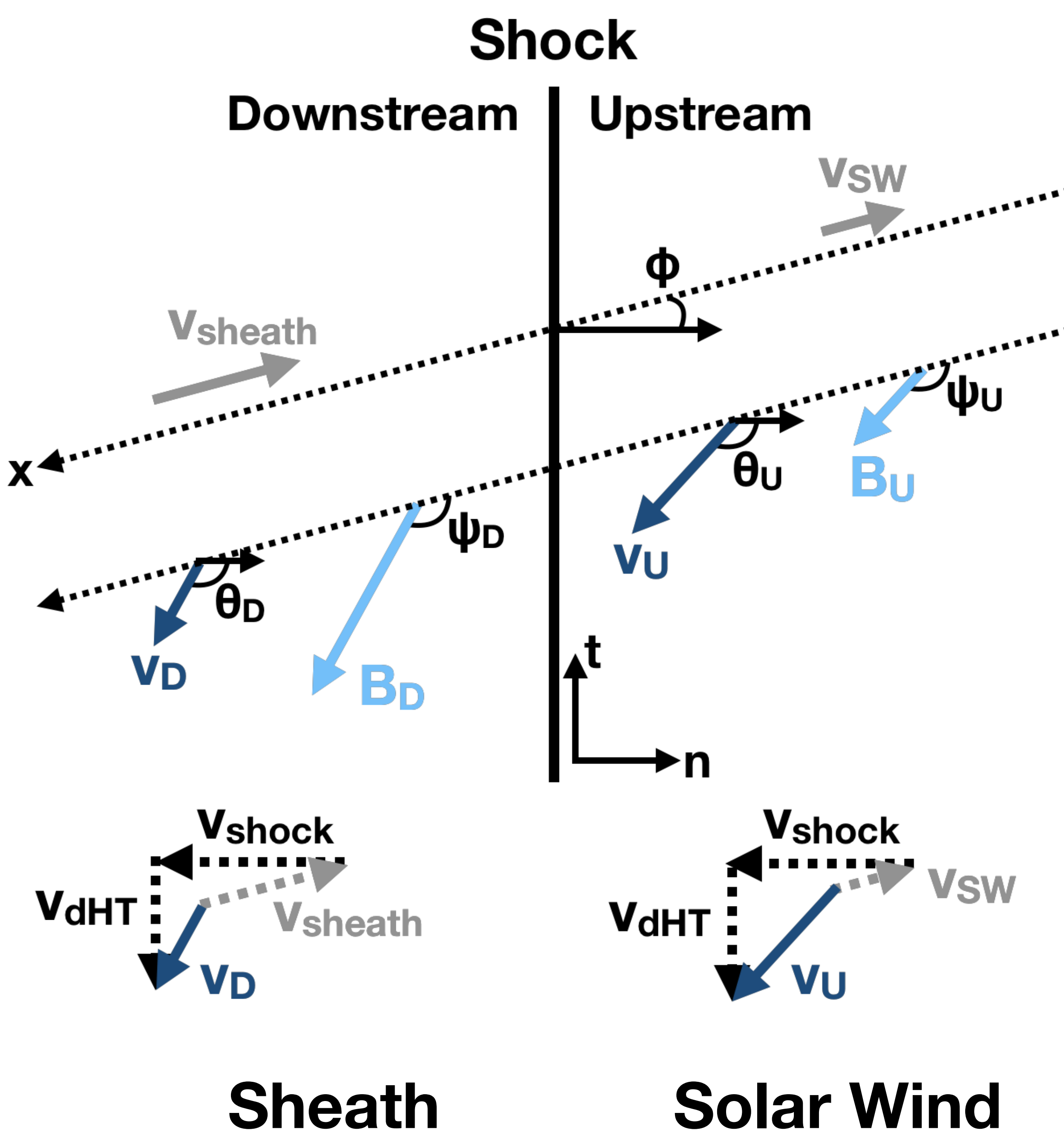
- Can we use a simplified physics-driven approach for a CME sheath?

- Add Sheath Induced by Transient into FIDO model
  - Compression model determines jump at shock
  - Standoff determines sheath width
  - Force transition to follow smooth rotation



Compression Model = Shock Physics

- Rankine-Hugoniot jump conditions relate upstream and downstream properties
  - Only show perpendicular shock results here
  - Oblique shock (in paper) is less successful due to oversimplifying assumptions and/or difficulty determining inputs?
- Given all upstream conditions and downstream velocity, we can solve for the remaining downstream parameters



Data Set

- Develop set of well-observed CME-driven shocks/sheaths from online catalogs

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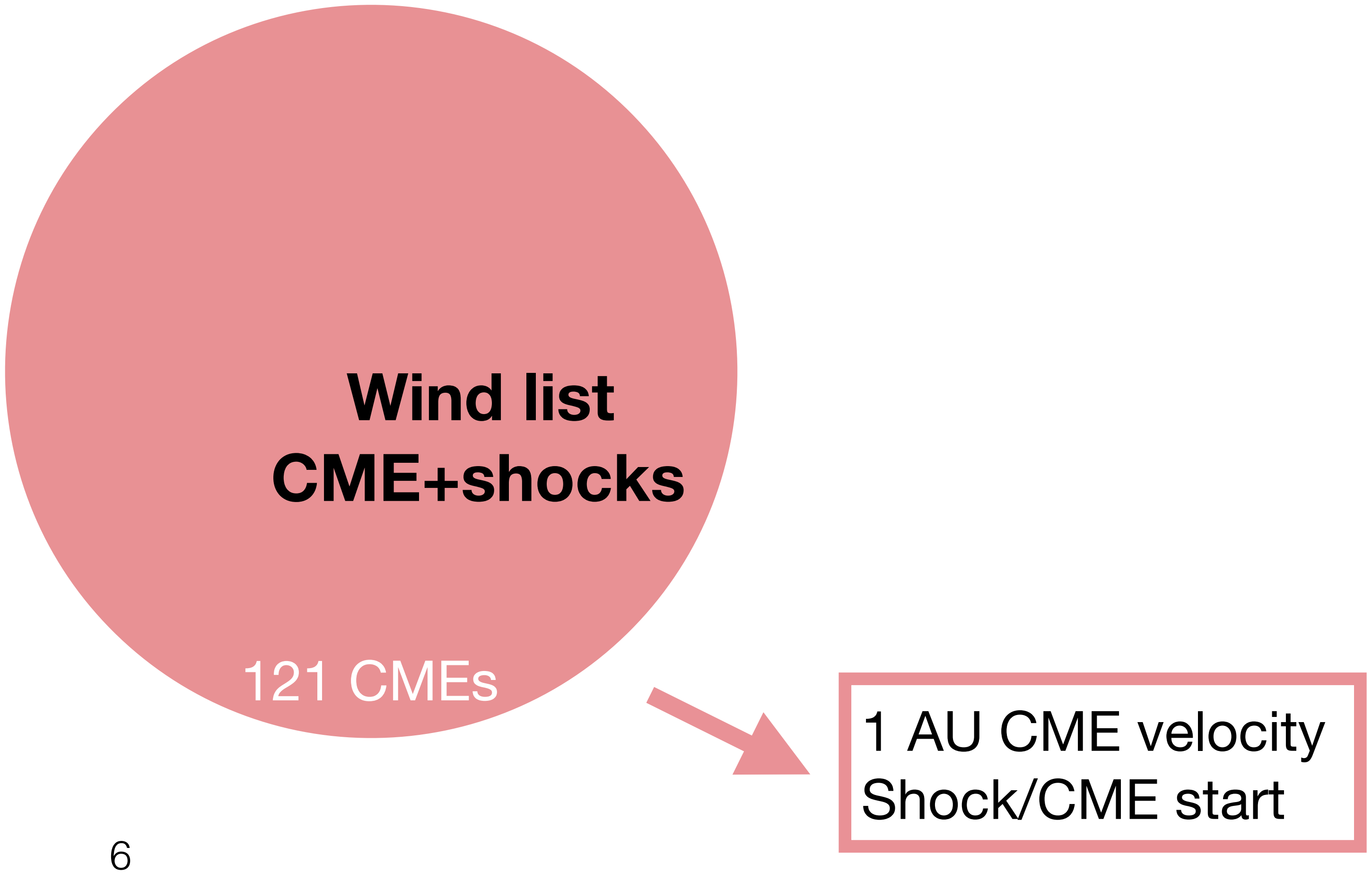

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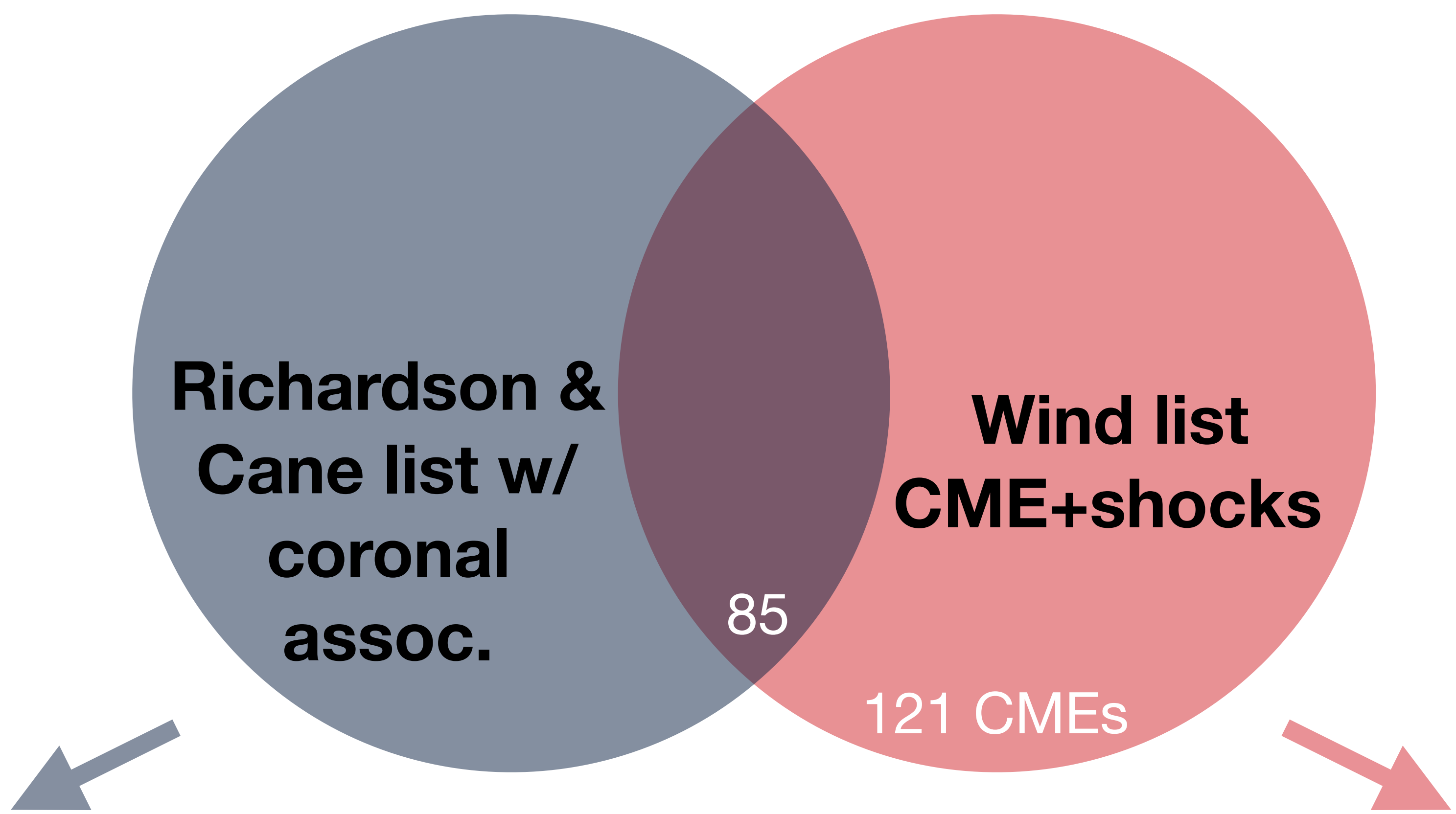
Transit velocity
1 AU CME velocity
Shock/CME start



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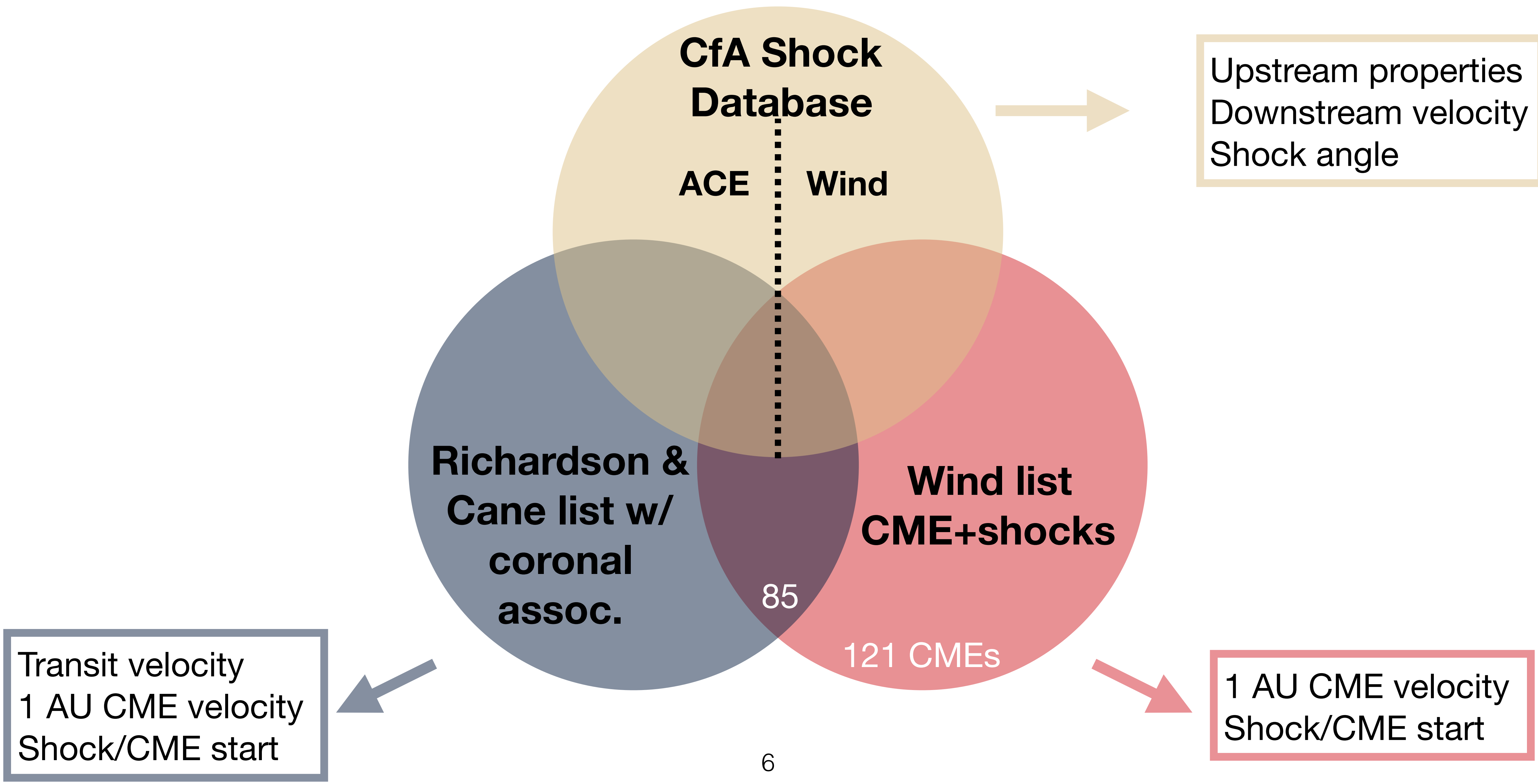

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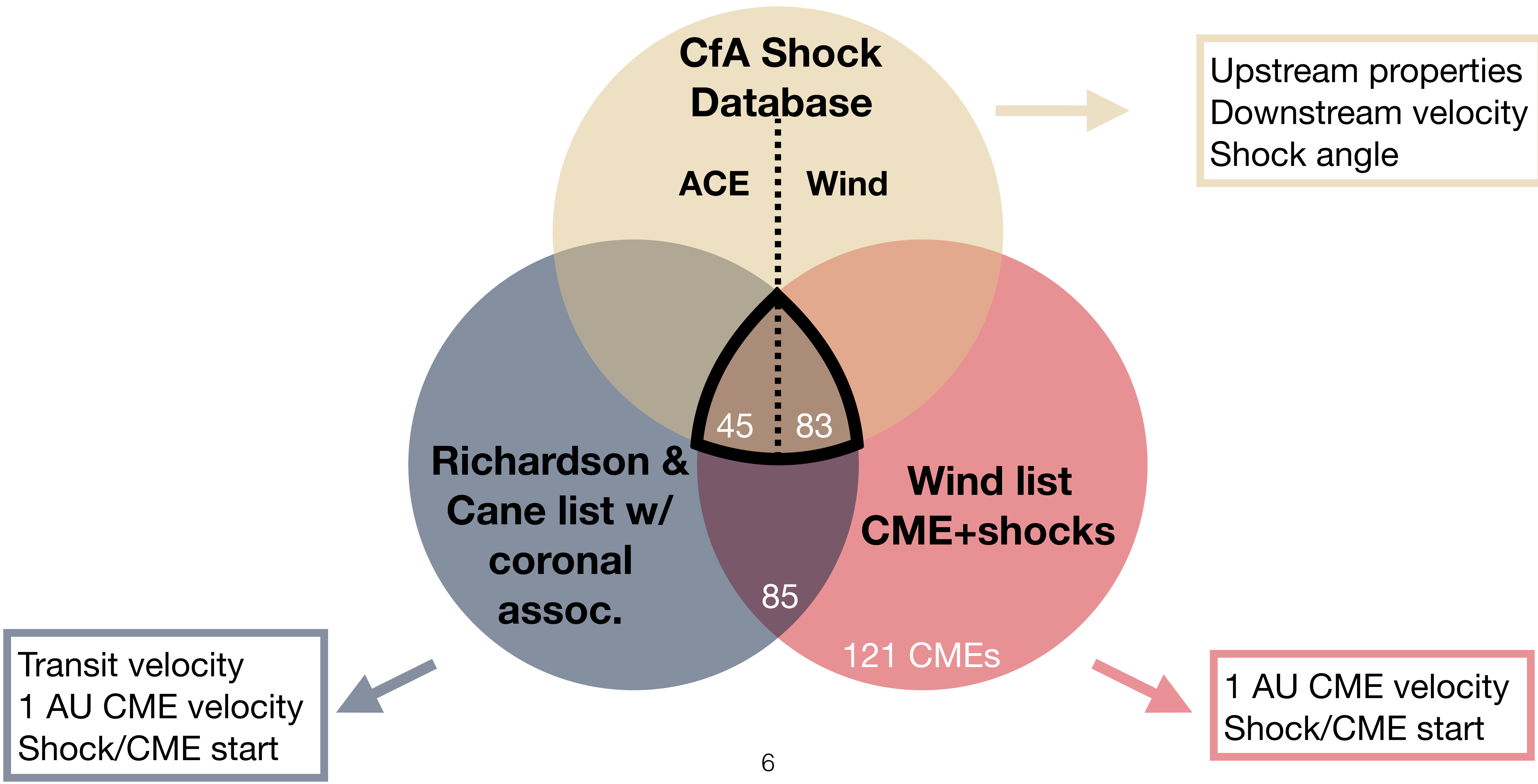
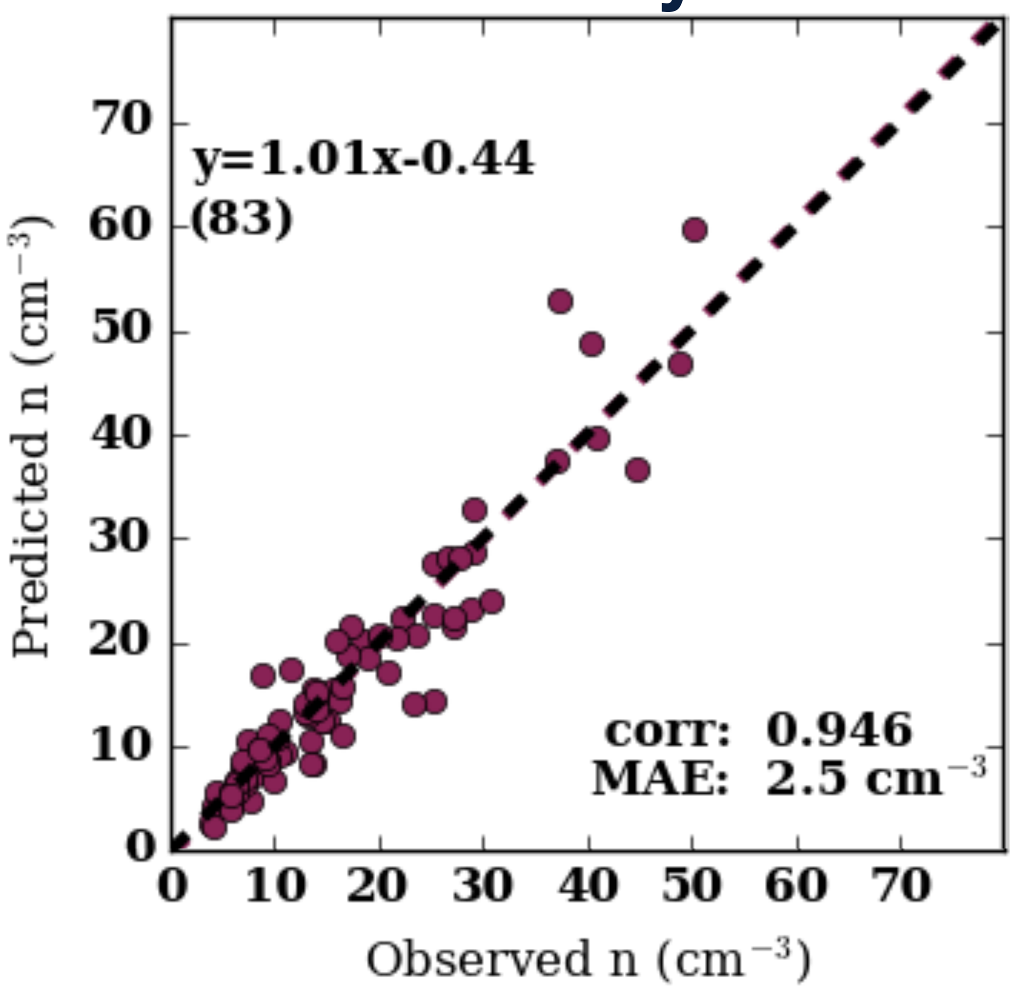


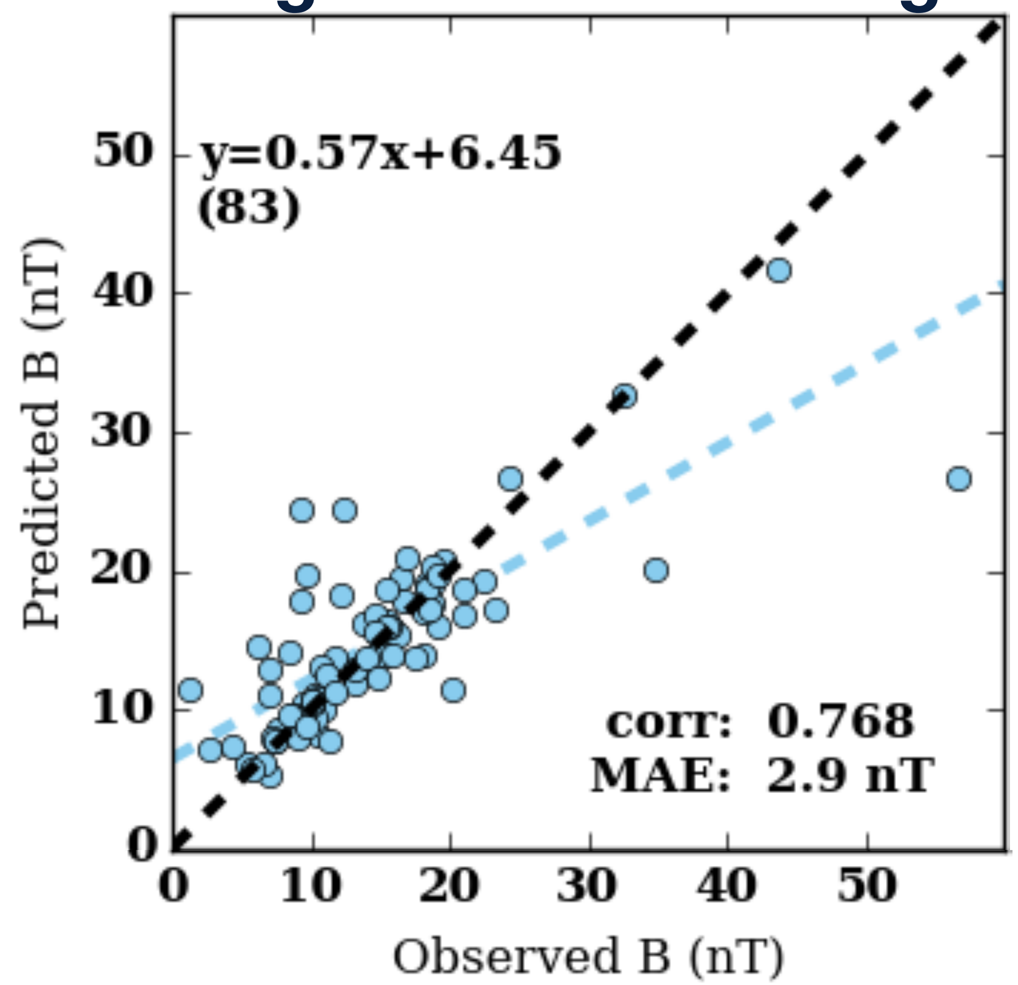
Predicting Compression 1

- Use observed downstream velocity to establish model baseline before testing our ability to determine inputs
- Mean average error (MAE) of 2.5 cm^{-3} for density and 2.9 nT for magnetic field strength

Density



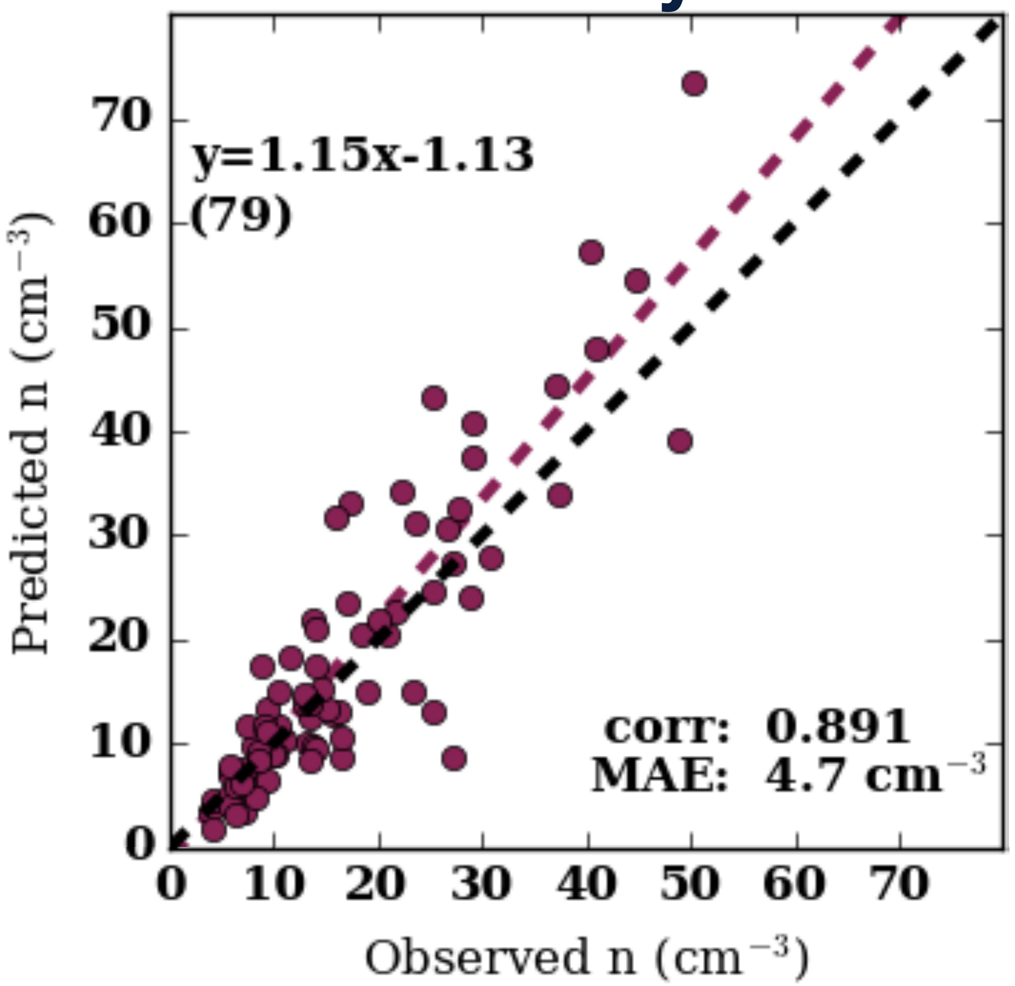
Magnetic Field Strength



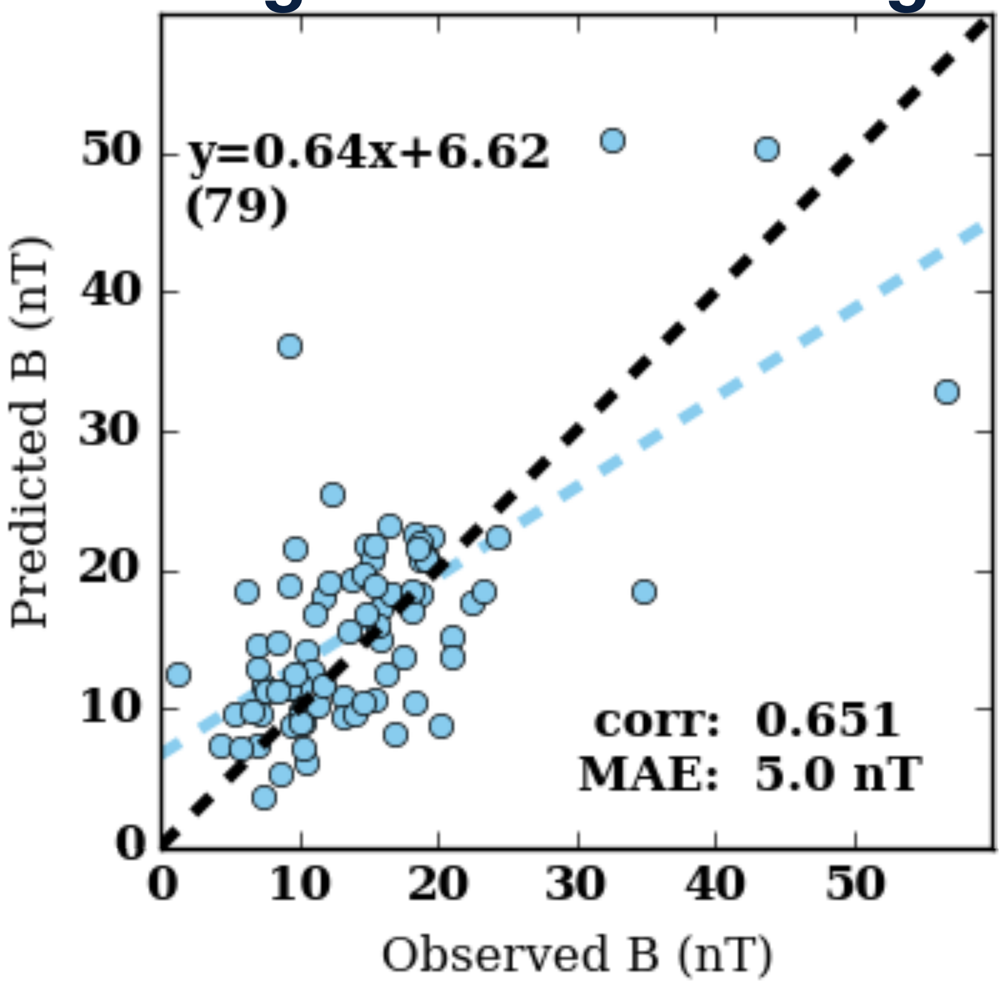
Predicting Compression 2

- Set downstream velocity equals to CME front edge velocity (average + expansion)
- MAEs roughly double → need better approximation for downstream velocity

Density

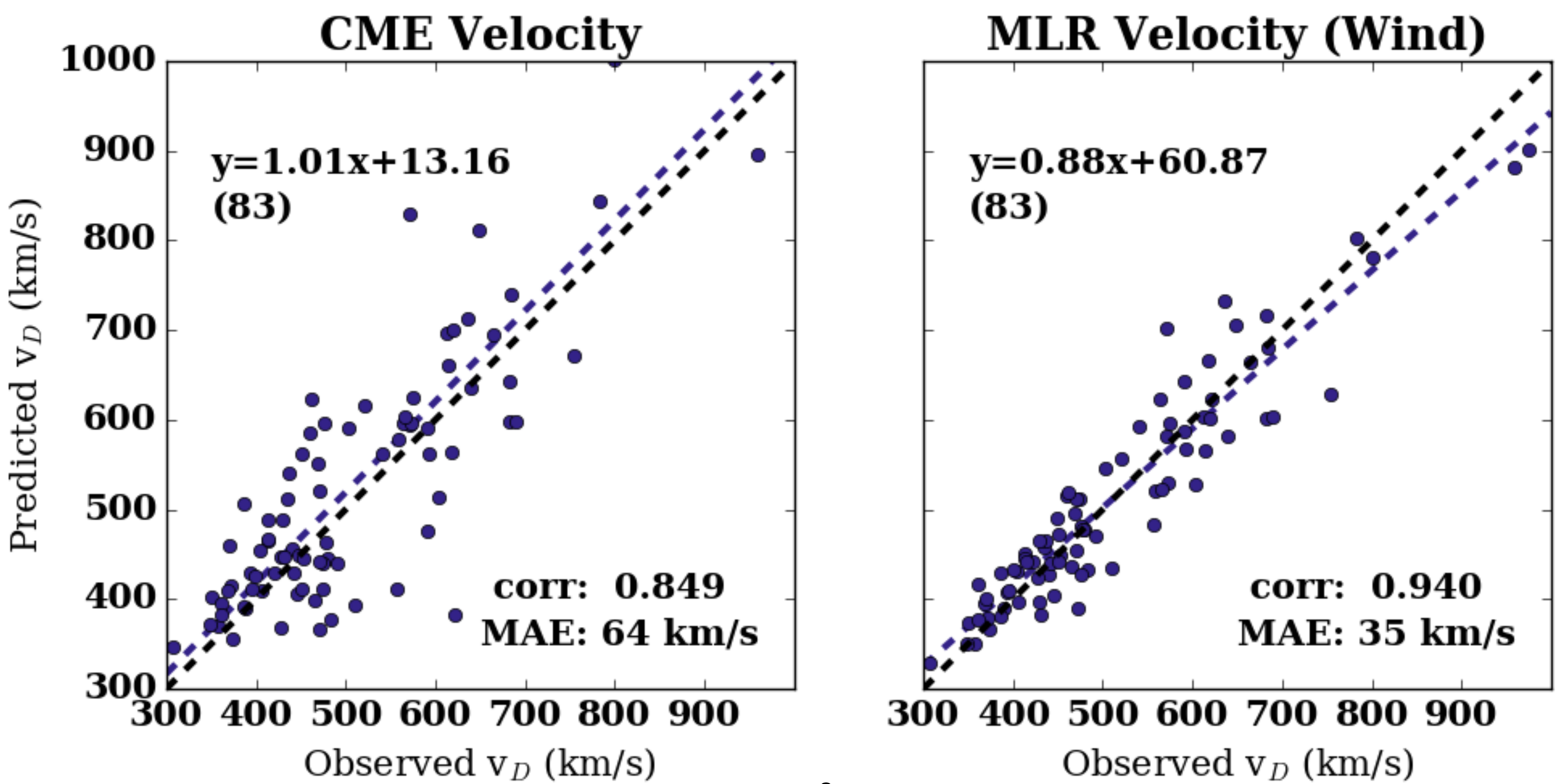


Magnetic Field Strength



Predicting Downstream Velocity

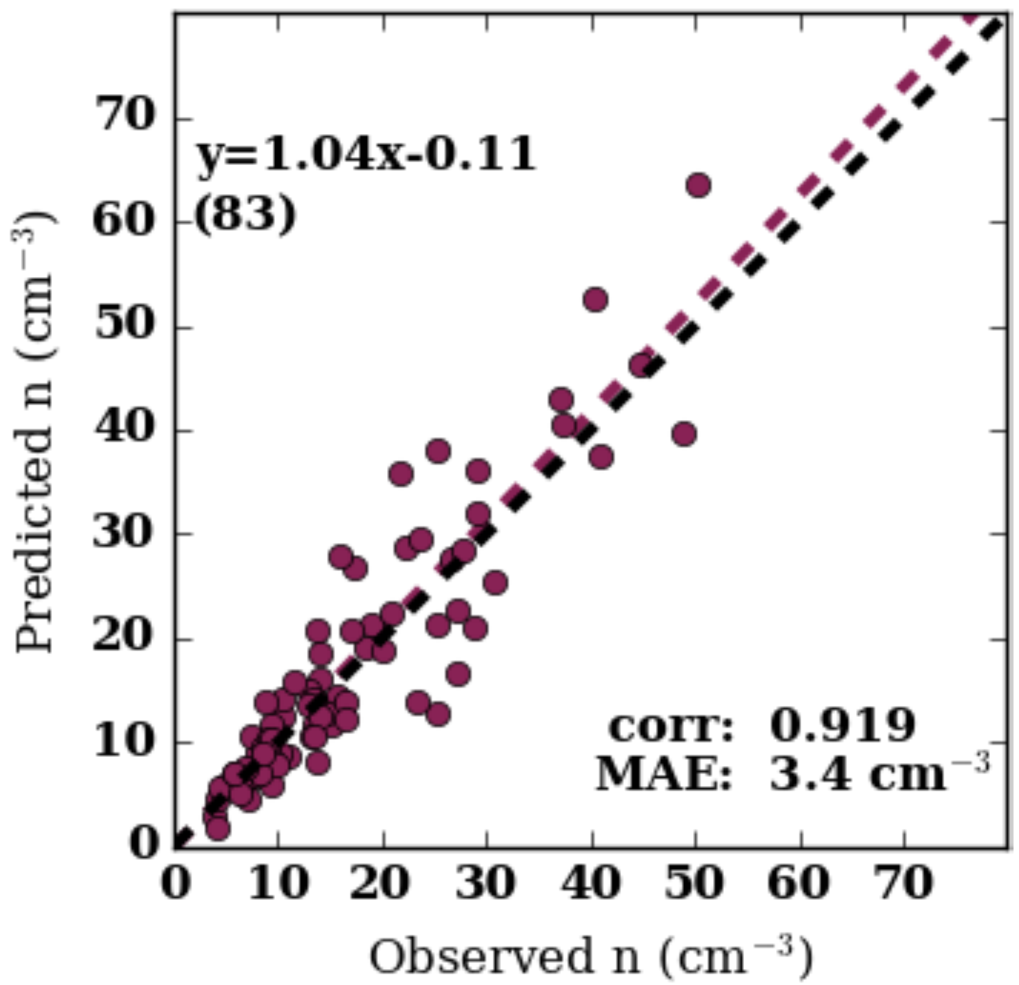
- Compare CME velocity with downstream velocity → clearly correlated but much scatter
- Use Multiple Linear Regression (MLR) to relate CME velocity, transit velocity, and upstream solar wind velocity to downstream velocity



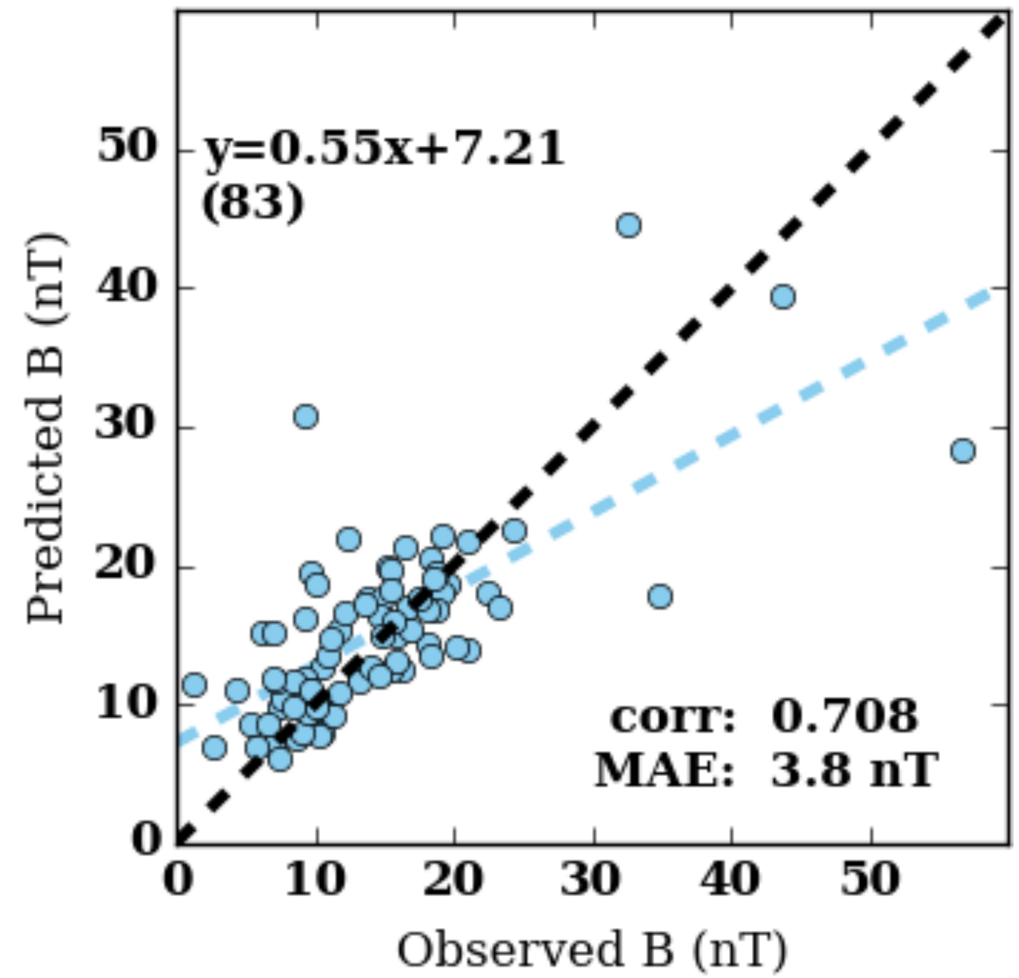
Predicting Compression 3

- Use downstream velocity predicted from MLR model
- MAEs improve from using CME velocity, but still slightly worse than baseline

Density



Magnetic Field Strength



Standoff Duration Models

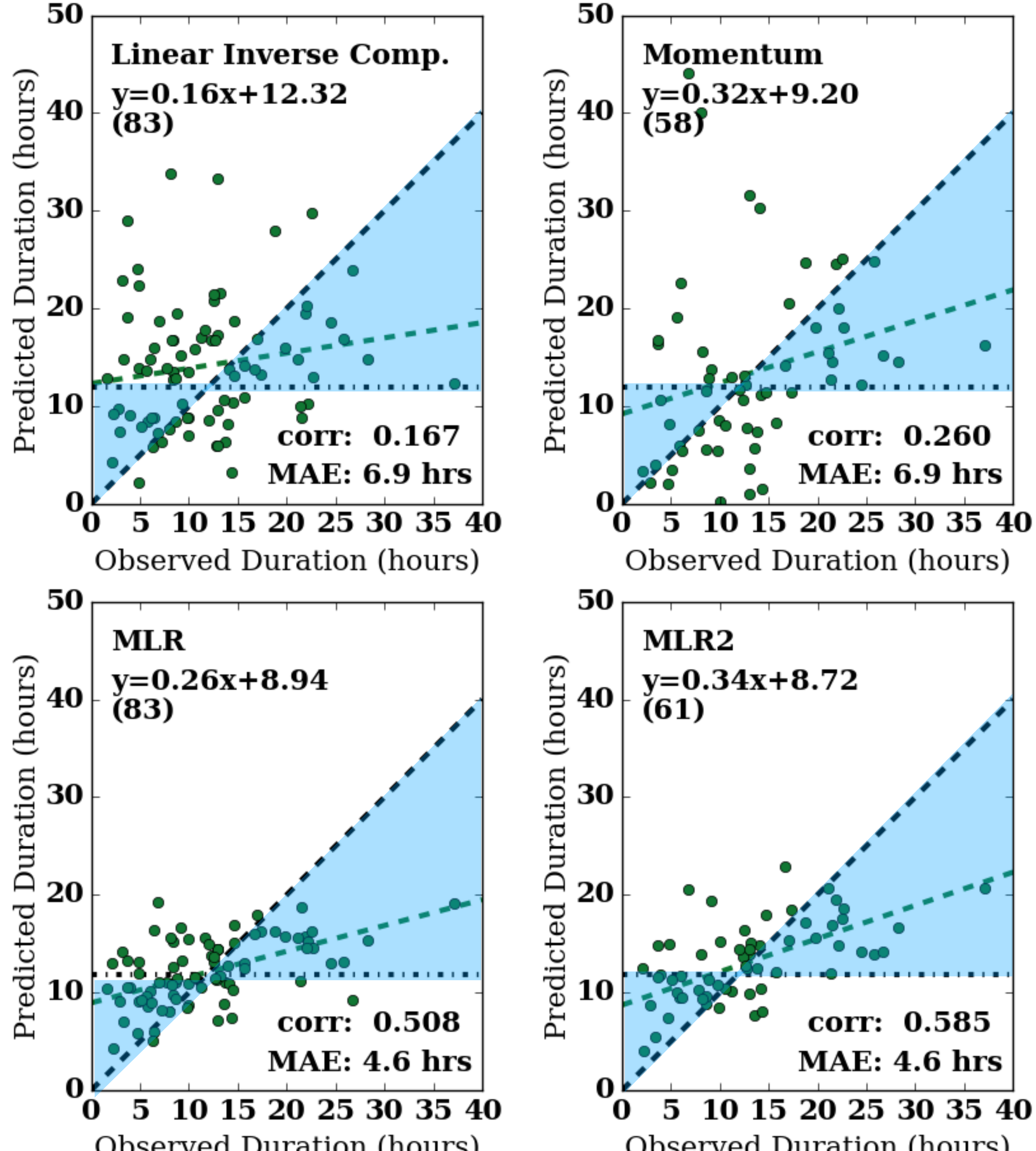
- Inverse Compression - most commonly used method, standoff linearly related to inverse compression ratio

- Conservation of Momentum - momentum lost by CME goes into accelerating sheath (similar to *Tappin 2006*, *Takahashi & Shibata 2017*)

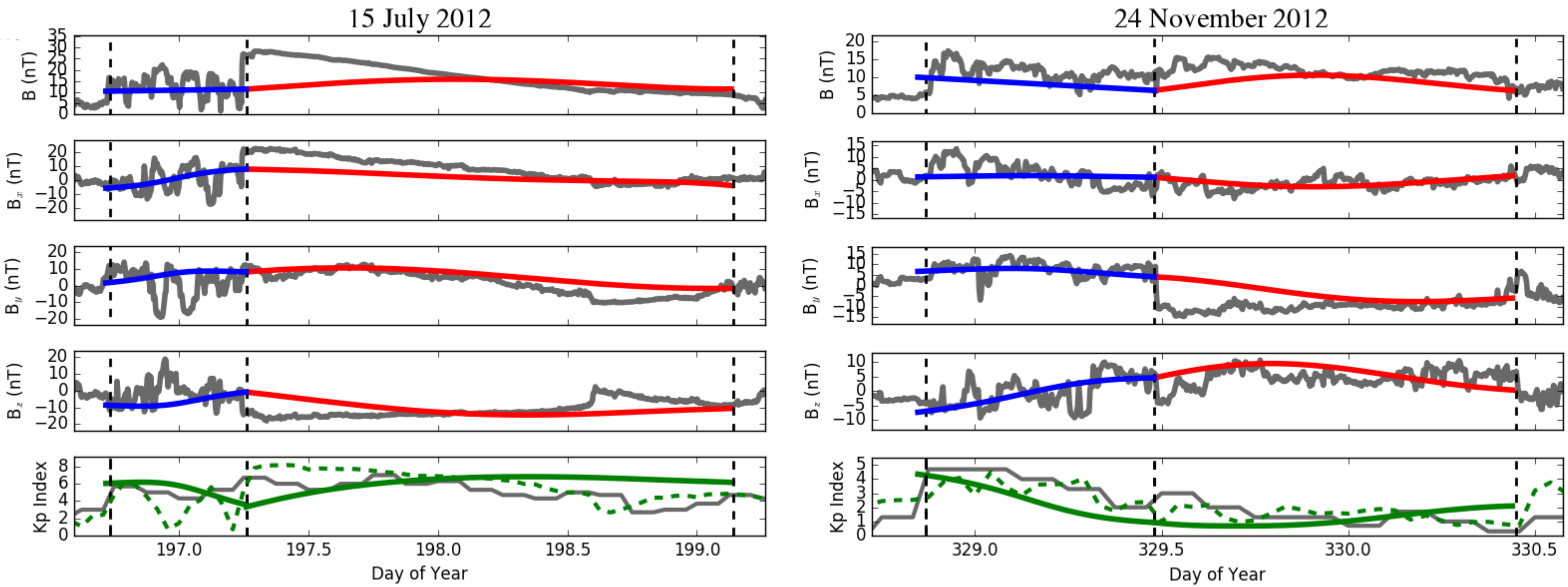
- MLR - determine best relation with CME observables, find same velocities as before work best
  - Try using approximate distance of impact from CME nose as sheath width expected to increase toward flanks (*Kilpua+ 2017*)

Predicting Standoff Duration

- Compare inverse compression, momentum, and MLR with and without angular distance from nose
- Horizontal dot dashed line is avg. standoff duration of all cases → MAE of 5.5 hrs
- MLR model performs the best but angular distance doesn't help
  - Plenty of room to improve model

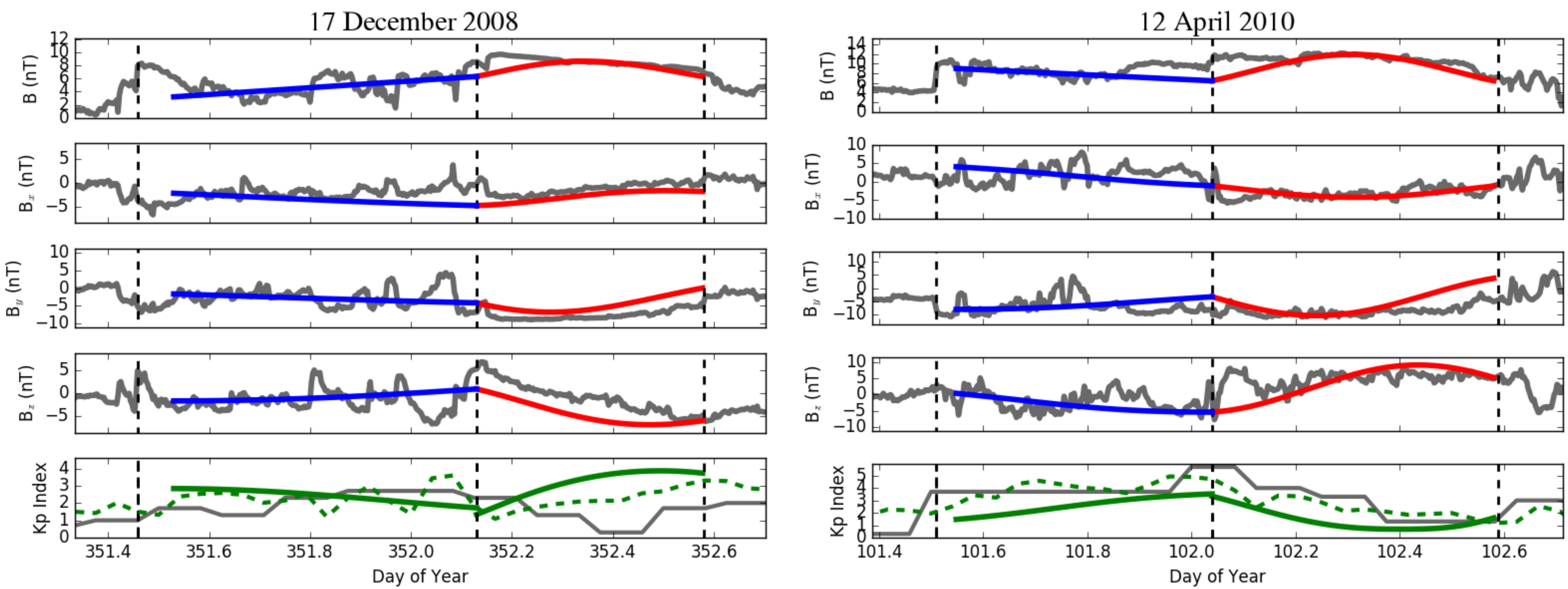


FIDO-SIT Cases 1



- Results for two cases that are part of CME data set
- General sheath behavior captured
  - Error in each vector component typically about third of total B magnitude
- Kp decently reproduced using simple analytic relation to v and B_T

FIDO-SIT Cases 2



- Results for two weaker cases not included in data set
- Sheath duration slightly short but general behavior reproduced

Summary

- We have developed models for the the properties of CME-driven sheaths with the following Mean Average Errors:
  - Velocity - 35 km/s
  - Density - 3.4 cm^{-3}
  - Total Magnetic Field Strength - 3.8 nT
  - Standoff Duration - 4.6 hrs

- We have presented the initial coupling of these models to the in situ magnetic field model FIDO and can reproduce the individual vector components of the sheath with an error each of roughly one-third of the total magnitude

Coming Soon…

- Used our arrival time model ANTEATR to determine sensitivity of drag-models to input parameters
  - Kay, Mays, & Verbeke, *Space Weather* (under revision)

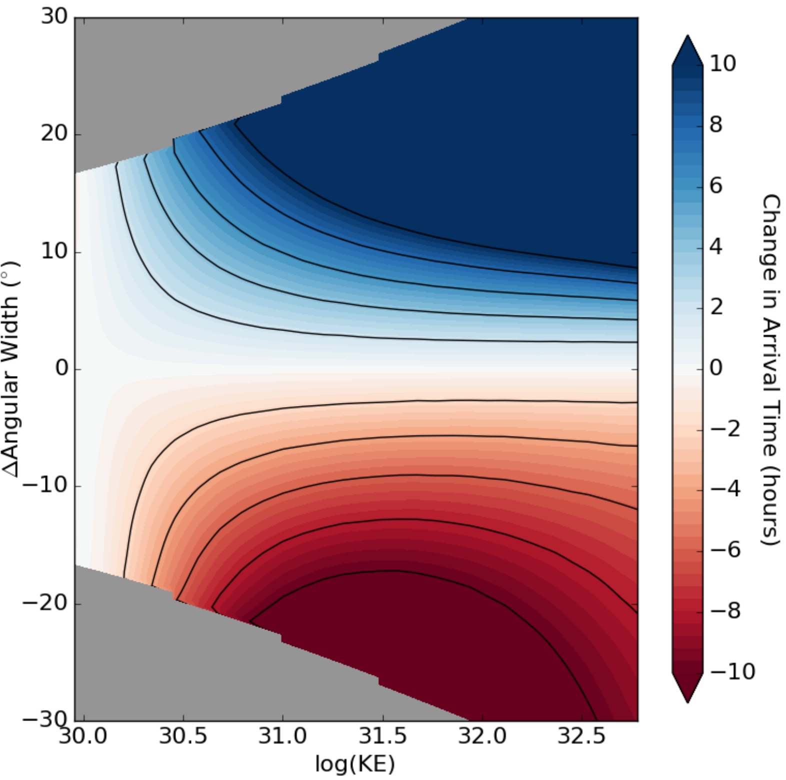


Table 2. Minimum Accuracy Needed for 5 Hour Arrival Time Accuracy

CME Size	Pol. Pos. (°)	Tor. Pos (°)	v_{CME} (km/s)	M_{CME} (10^{15} g)	AW (°)	v_{SW} (km/s)	n_{SW} (cm^{-3})	C_d	Γ ($10^{-8}km^{-1}$)
Average	24.5	15.6	29	–	–	64	–	–	–
	8.0	3.5	-36	–	–	-80	–	–	
Fast	41.5	31.5	275	7.7	-7.3	110	-2.8	-0.40	-0.8
	13.5	7.5	-198	-3.8	6.0	-80	3.6	0.52	1.04
Extreme	53.0	50.0	400	–	-9.0	–	-3.4	-0.49	-0.98
	14.0	10.5	-283	–	5.0	–	3.8	0.55	1.10

- In process of combining coronal propagation, arrival time, and in situ models into open-access, user-friendly suite
  - Minimizing number of necessary inputs (defaults), automatic coupling, standardized output/visualization
  - GitHub.com/ckay314(/OSPREI ?)