Sun-to-Earth CME Modeling with OSPREI: Using Ensembles to Explore Uncertainties

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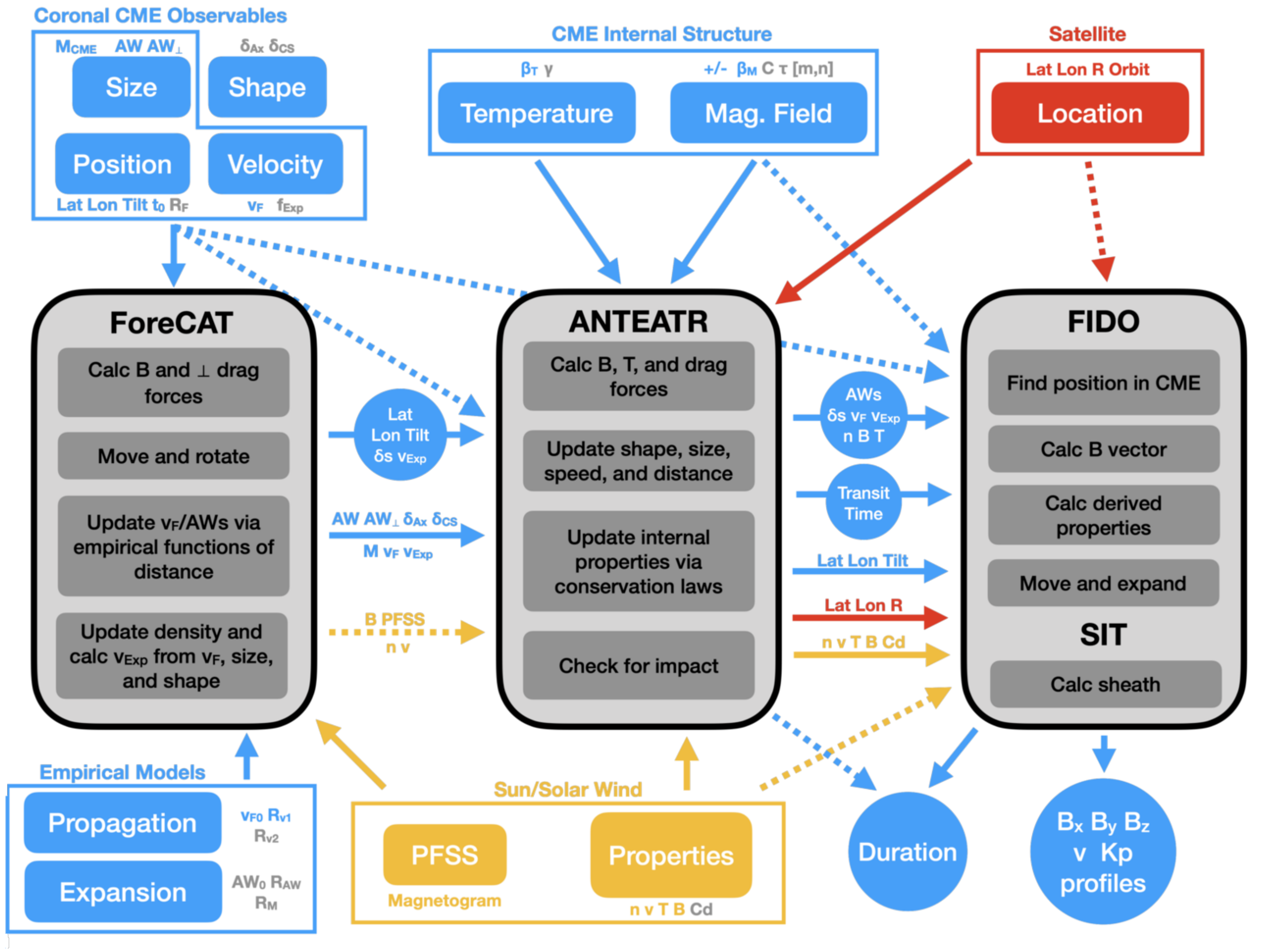
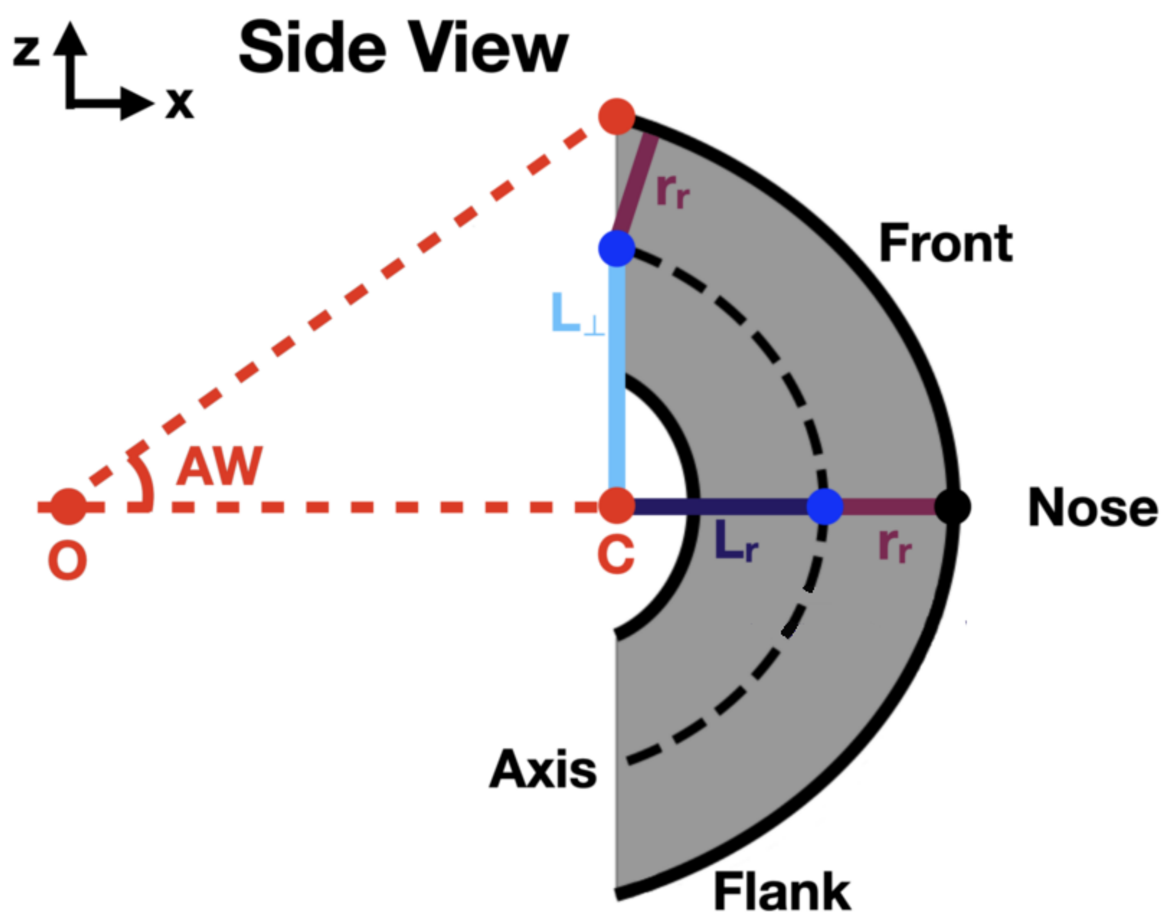
Kay, Mays, Collado-Vega (2022),
Space Weather, 20, 4, e2021SW002914

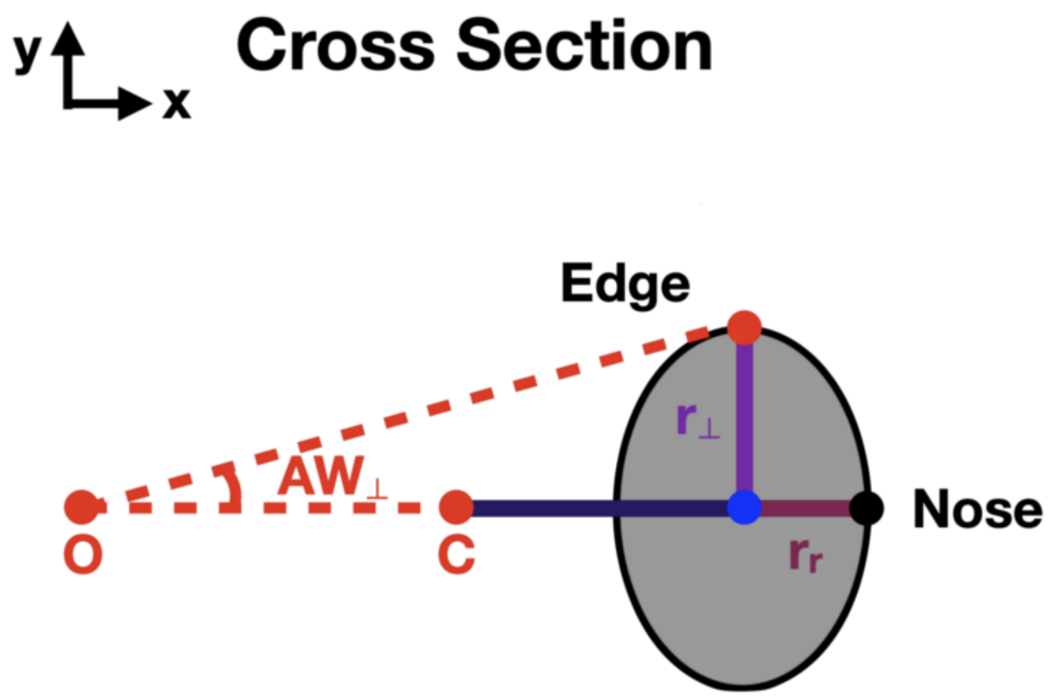
OSPREI Suite

- Set of three fully-coupled models to describe the Sun-to-Earth evolution of CMEs
- **ForeCAT** - coronal deflection and rotation of CMEs from background magnetic forces
- **ANTEATR** - interplanetary propagation including CME expansion and deformation
- **FIDO** - in situ magnetic field and velocity profiles

- Toroidal axis shape is hybrid of parabola and ellipse
- Elliptical cross section





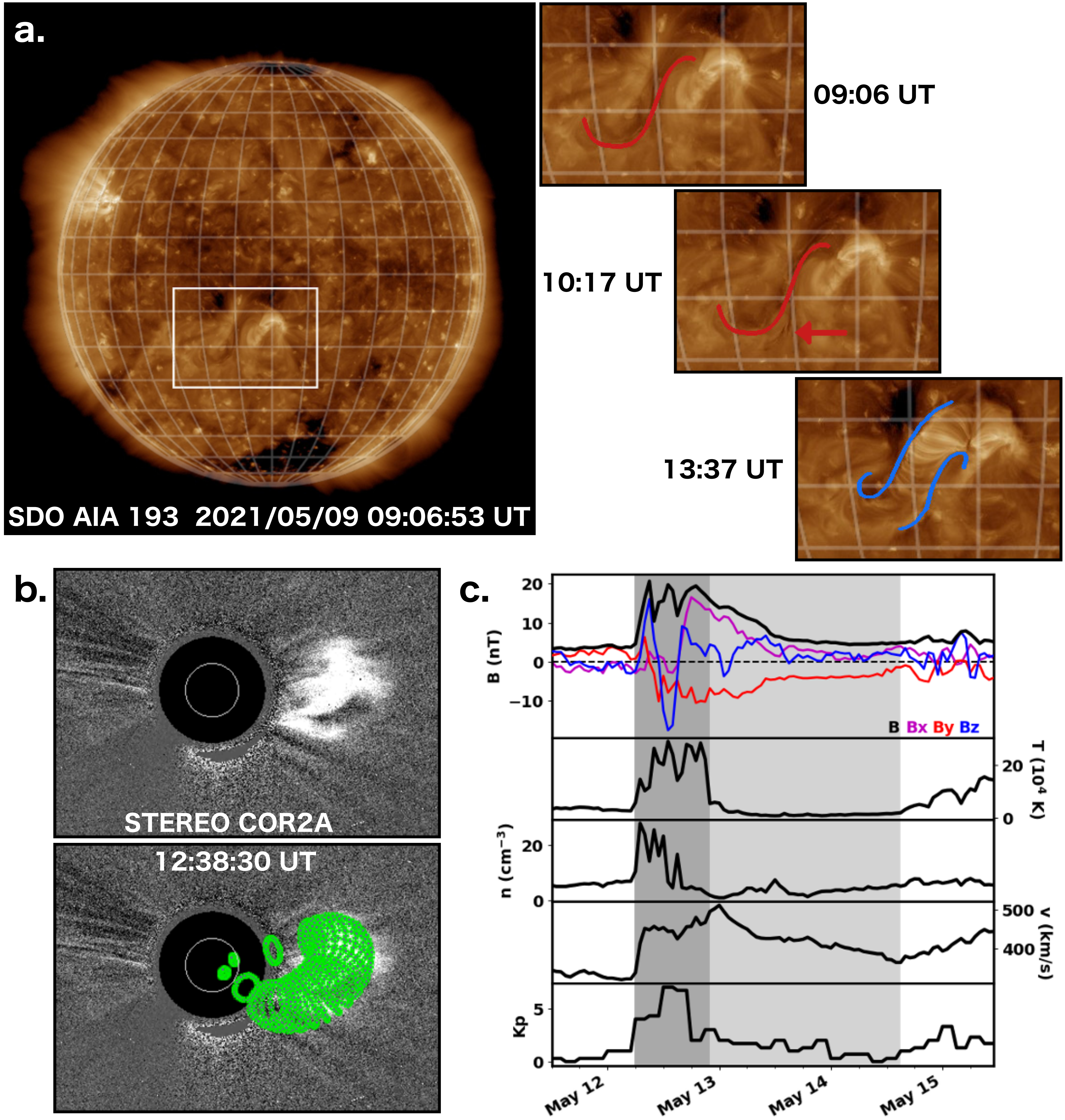


github.com/ckay314/OSPREI

bit.ly/OSPREIdemo

Test Case

- Approach test case as if we were forecasting in real time
- Eruption on 2021 May 09 at 10:06 UT around S20E10, shock arriving at 05:48 UT on May 12 (DONKI catalog)
- **EUV signatures** - earliest movement for precise timing, forward S shapes for handedness
- **GCS reconstruction** - rough constraints on position/orientation and velocity
- In situ OMNI data shown but not used in determining inputs



OSPREI Inputs

- Large number of input parameters (34) but most have **sources (17)** or can be left at **defaults (13)** but a few **hard to constrain (4)** inputs
- Use ensemble to sample uncertainty in **16 different inputs**

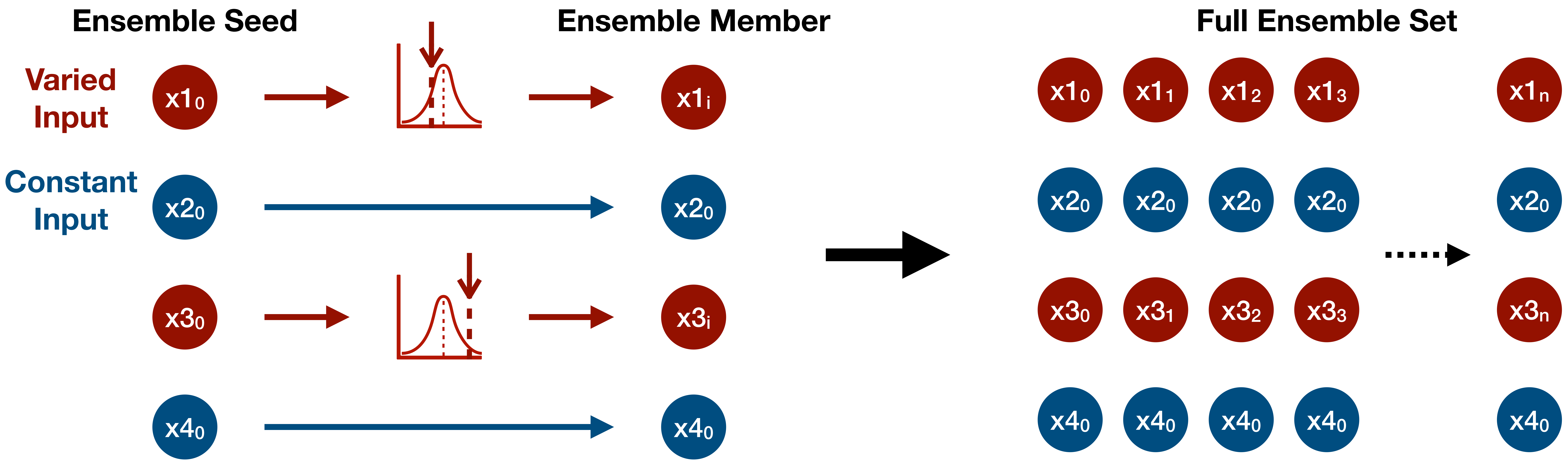
	Parameter	CME 1	Source
	ForeCAT CME Properties		
	Start time (t_0)	2021/05/09 09:00 UT	EUV
	Starting nose height (R_{F0})	1.1 R_s	*Default*
★	Initial latitude (Lat)	-12±1°	EUV/DONKI
★	Initial longitude (Lon)	-10±1°	EUV/DONKI
★	Initial tilt (Tilt)	45±5°	EUV
★	Max coronal velocity (v_F)	800±50 km/s	GCS/DONKI
★	Max coronal angular width (AW)	30±5°	GCS/DONKI
★	Max coronal perpendicular AW ($AW_\perp$)	10±1°	–
★	Maximum mass (M_{CME})	$3\pm0.5\times10^{15}$ g	–
★	Coronal axis aspect ratio (δ_{Ax})	0.75±0.1	*Default*
★	Coronal cross section aspect ratio (δ_{CS})	1±0.1	*Default*
	ForeCAT empirical models		
	Initial slow rise velocity (v_{F0})	40 km/s	EUV/GCS*
	Start of rapid acceleration (R_{v1})	1.5 R_s	EUV/GCS*
	Height of max coronal velocity (R_{v2})	10 R_s	*Default*
	Expansion model initial AW (AW_0)	5°	*Default*
	Expansion model length scale (R_{AW})	1 R_s	*Default*
	Height of max mass (R_M)	10 R_s	*Default*

Parameter	CME 1	Source	
ANTEATR CME Properties			
Flux rope magnetic scaling (β_M)	4±0.25	–	★
Elliptical flux rope model powers ([m,n])	[0,1]	*Default*	
Elliptical flux rope model twist (τ)	1	*Default*	
Elliptical flux rope model tor/pol ratio (C)	1.927	*Default*	
Flux rope temperature scaling (β_T)	4±0.25	–	★
Adiabatic index (γ)	1.33±0.1	*Default*	★
Interplanetary expansion factor (f_{Exp})	0.5±0.1	*Default*	★
FIDO CME Properties			
Flux rope handedness (+/-)	Right	EUV	
Solar Wind Properties			
Solar wind 1 AU velocity	350±25 km/s	OMNI	★
Solar wind 1 AU density	5±1 cm^{-3}	OMNI	★
Solar wind 1 AU magnetic field	5±1 nT	OMNI	★
Solar wind 1 AU temperature	4×10^4 K	OMNI	
Drag coefficient	1	*Default*	
Satellite Parameters			
Latitude	-3.3°	Earth location	
Longitude	0° (27.6°)	Earth location	
Distance	213 R_s	L1	
Orbital Speed	2.8×10^{-6} rad/s	Earth's orbit	

All longitudes in Stonyhurst coordinates at the start time

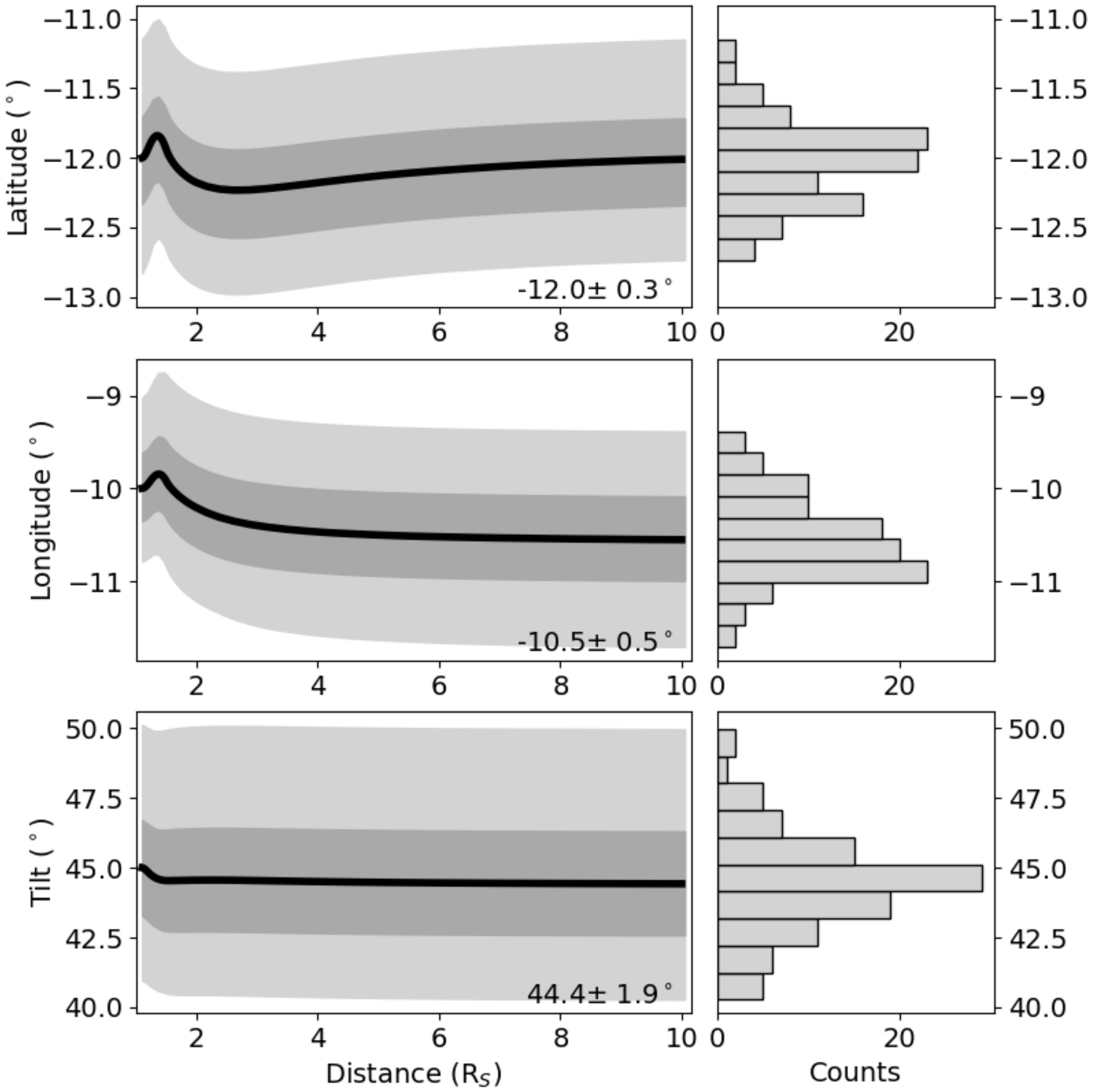
OSPREI Ensembles

- Individual components very efficient (~min/simulation) allowing for ensemble simulations on prediction timescales
- Use ensembles to explore sensitivity to uncertain input parameters
- Pick certain inputs to vary, simultaneously vary them randomly while holding all other parameters constant

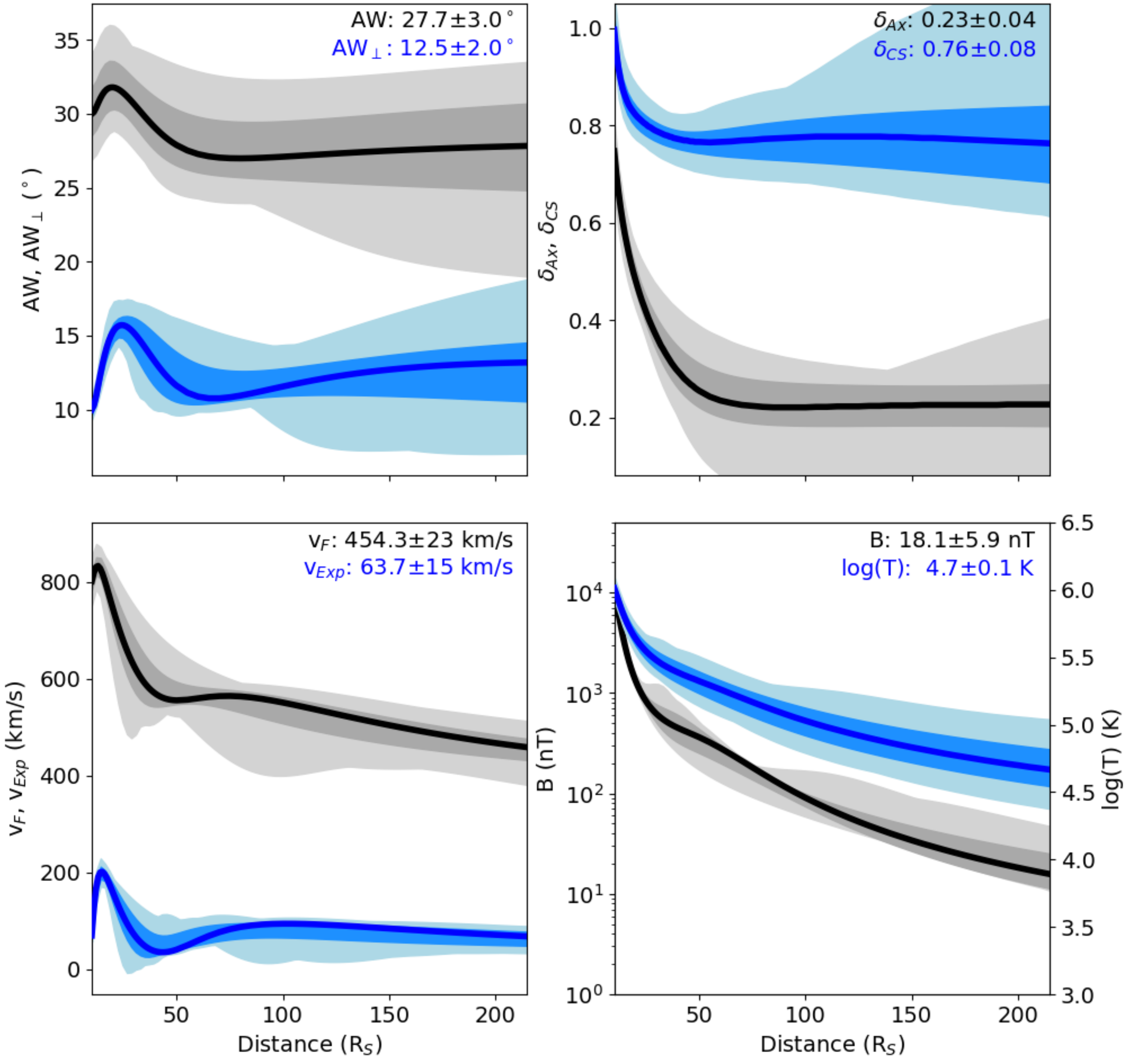


Coronal Results

- ForeCAT results for the coronal deflection and rotation versus distance
    - Black line shows ensemble seed, dark gray region is core of ensemble, light gray is full extent
- OSPREI varies inputs normal distribution with σ set to 1/3 of provided uncertainty (99.7% of random values within given range)
- ***Negligible deflection or rotation for this case → spread in each output is essentially the same the corresponding spread in that input***



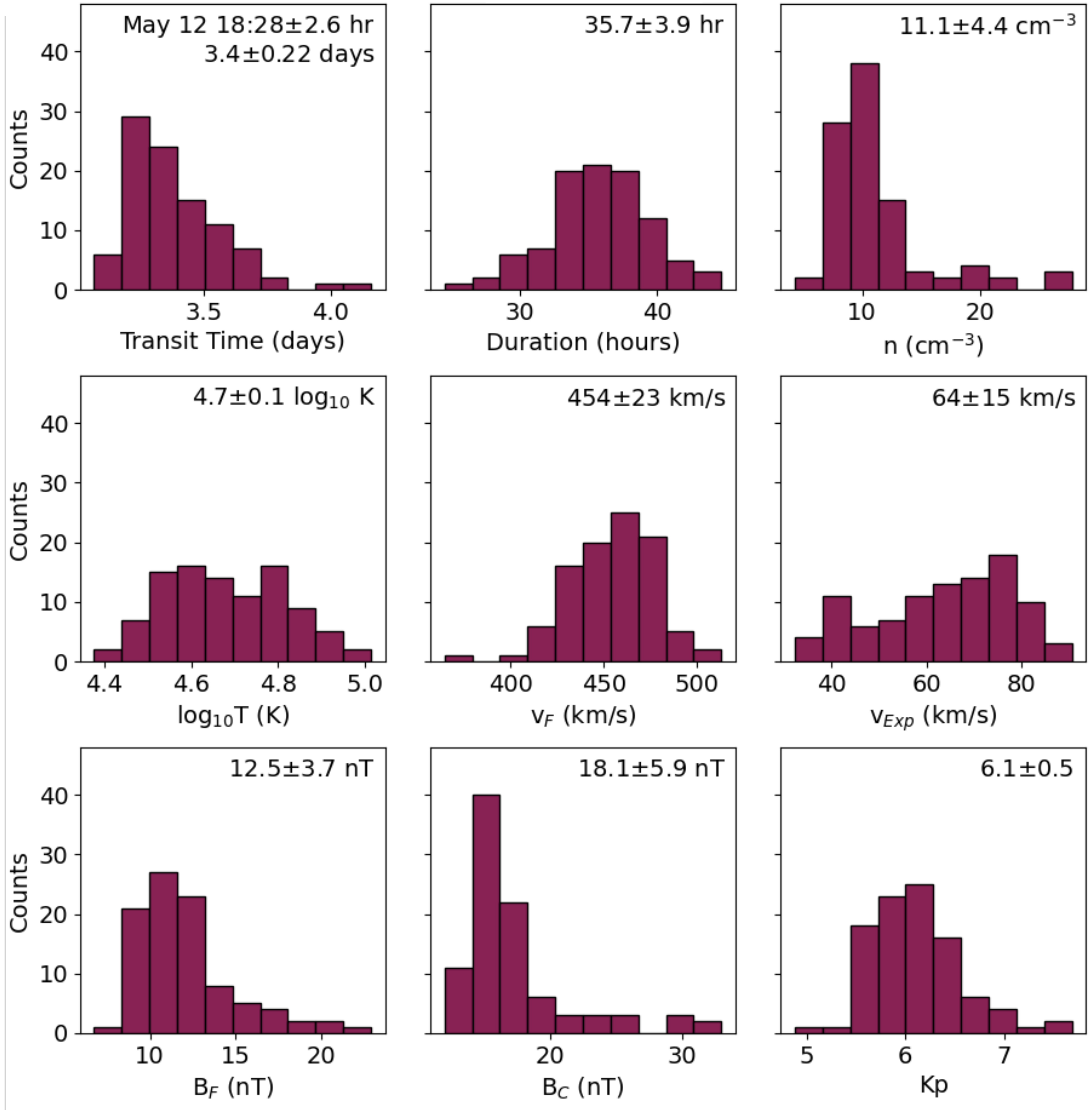
Interplanetary Results



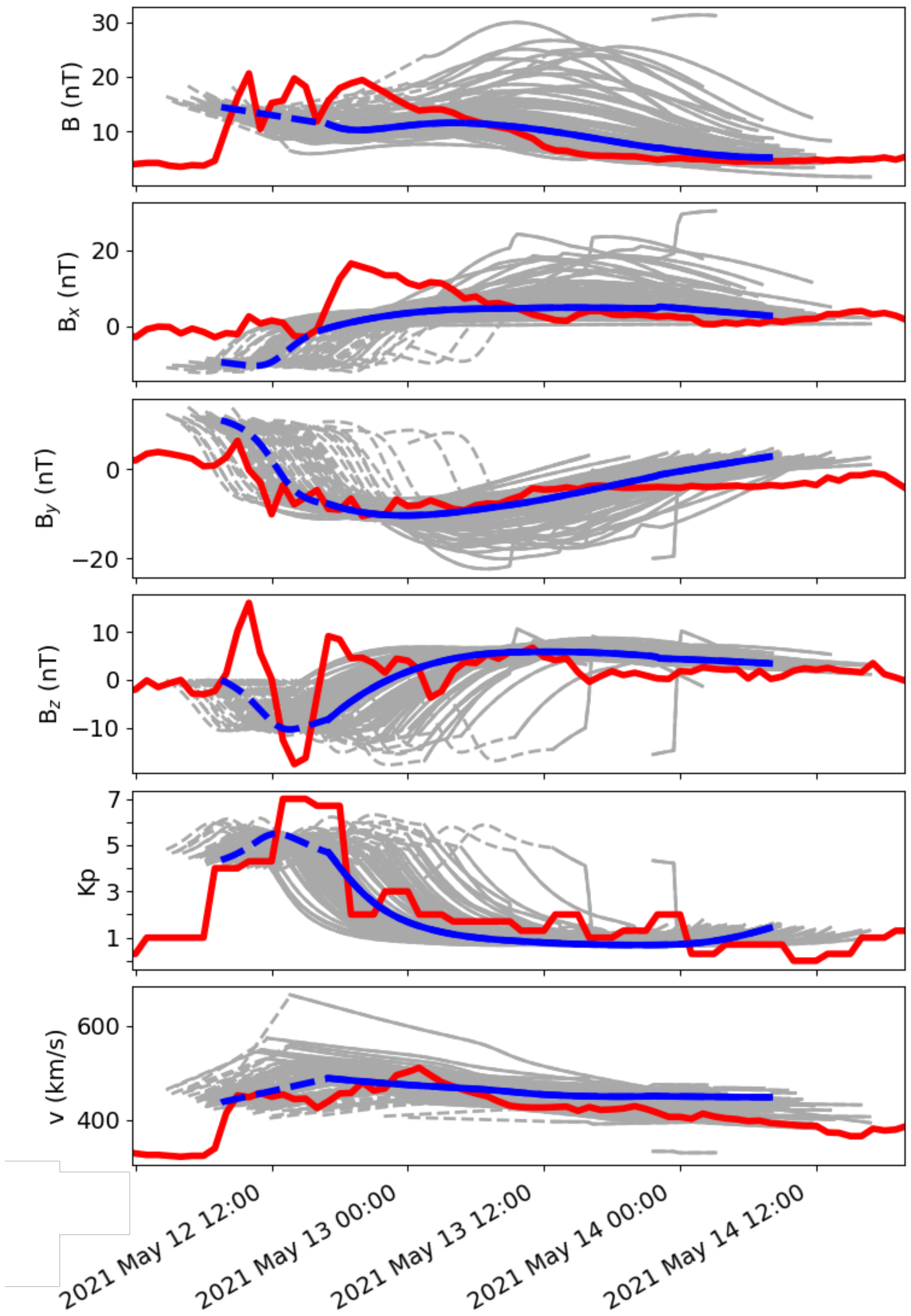
- IP model simulates deceleration, expansion, and deformation
- ***IP evolution affected by CME geometry, speed, internal properties and solar wind properties → direct relationship between inputs/outputs less obvious than in coronal model***
- Most cases behave similarly with subtle changes in exact value but see some extreme outliers
  - Synergistic variation in multiple inputs leads to greater output variation
  - More on diagnosing these cases later

Interplanetary Results

- For forecasting purposes, the full IP evolution is likely unnecessary
- Produce histograms of parameters important for prediction
  - Transit time, duration, internal properties, estimated Kp
- ***Have measure of most probable values and the spread in each one***
  - Some distributions highly peaked, others are flatter



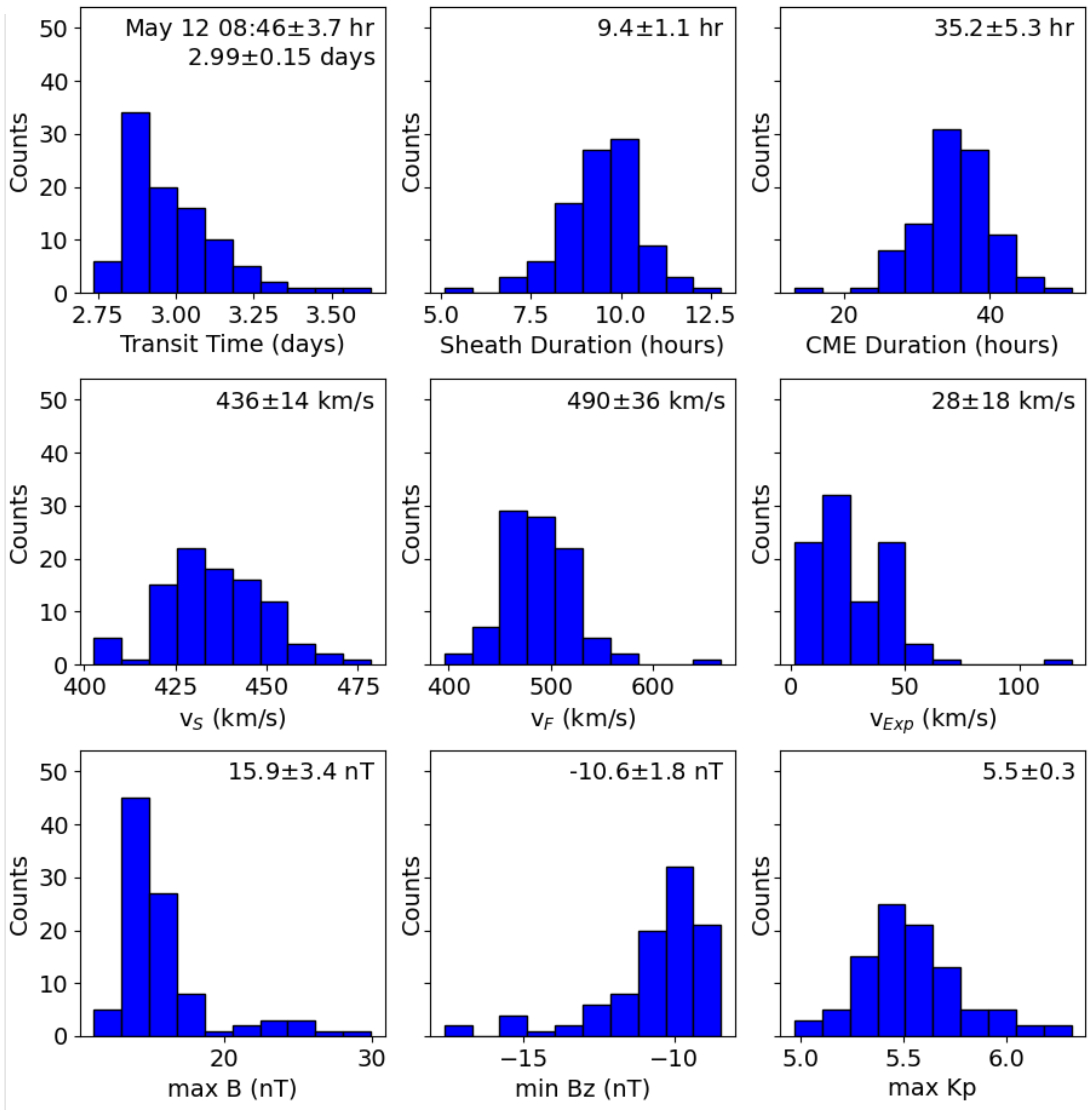
In Situ Results



- In situ model uses modeled arrival time and evolved CME parameters to create profile for CME-driven sheath (dashed) and flux rope (solid)
- Wide range in arrival times, profiles mostly similar but vary in magnitude, some extreme outliers
- Standard/obvious way of visualizing results but somewhat hard to derive meaning from overlapping cases
- Pile of spaghetti rather than useful probabilities

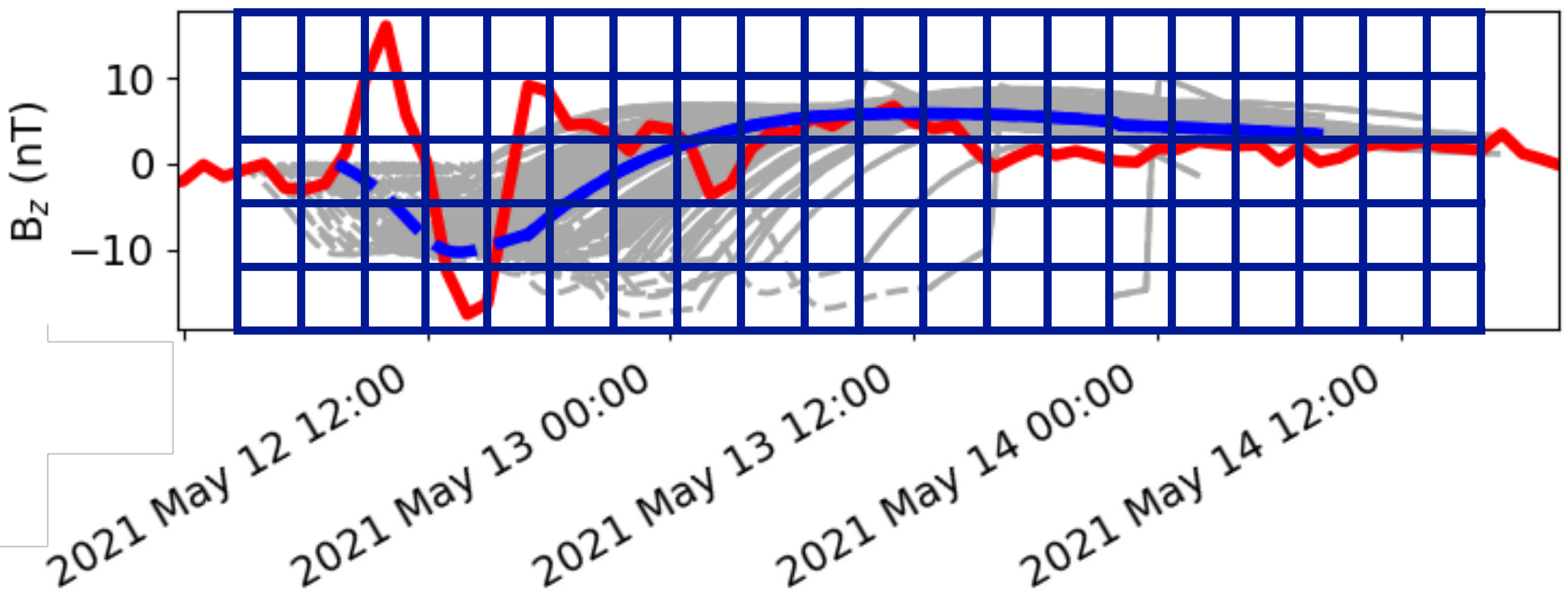
In Situ Results

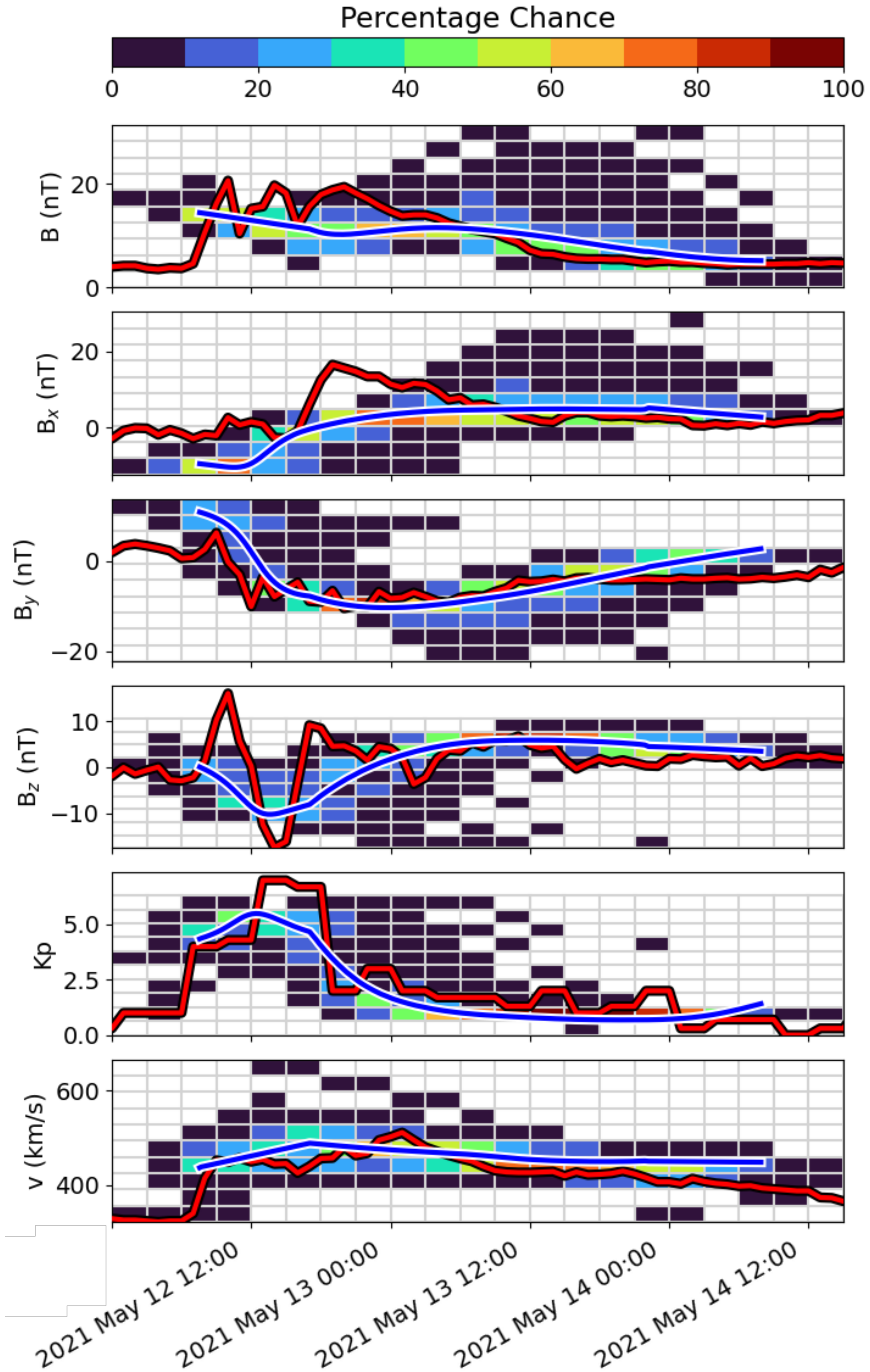
- Histograms for forecasting-relevant outputs
- Some duplicated parameters between in situ and IP histogram
    - IP model makes approximation of the exact geometry of the spacecraft/CME interaction, in situ model does not
- *Somewhat useful, but loses all information about where most neg Bz occurs, how long it stays southward…*



Novel Visualization 1

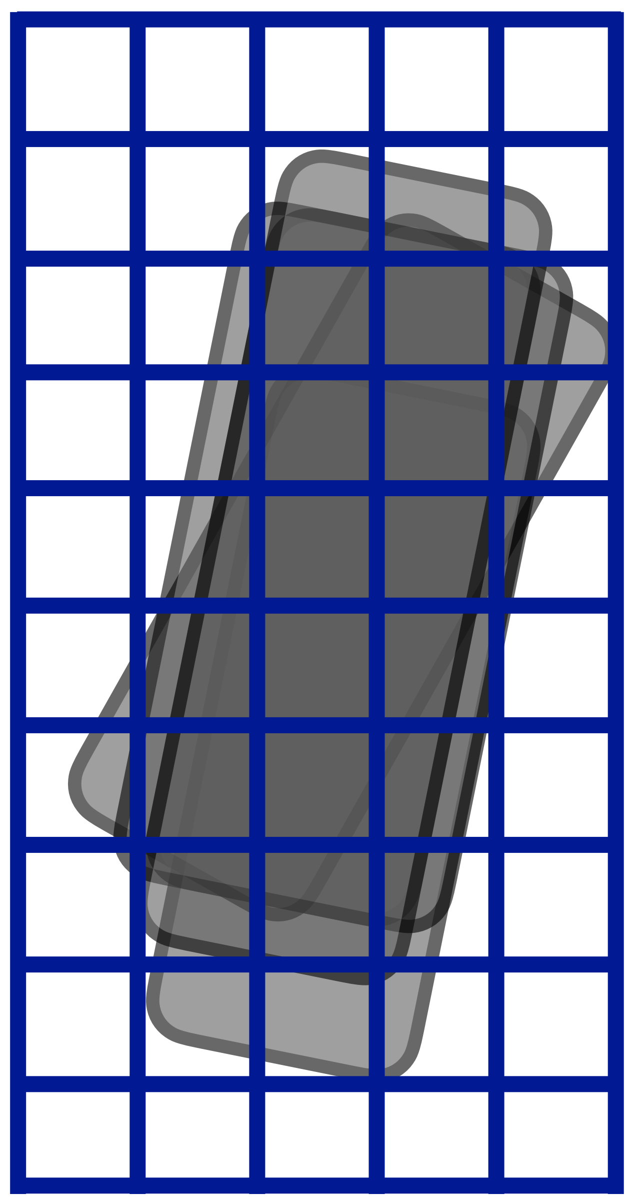
- Develop new visualization that retains the time dependence of the full in situ profiles, but allows for quick identification of the most probable values and their range

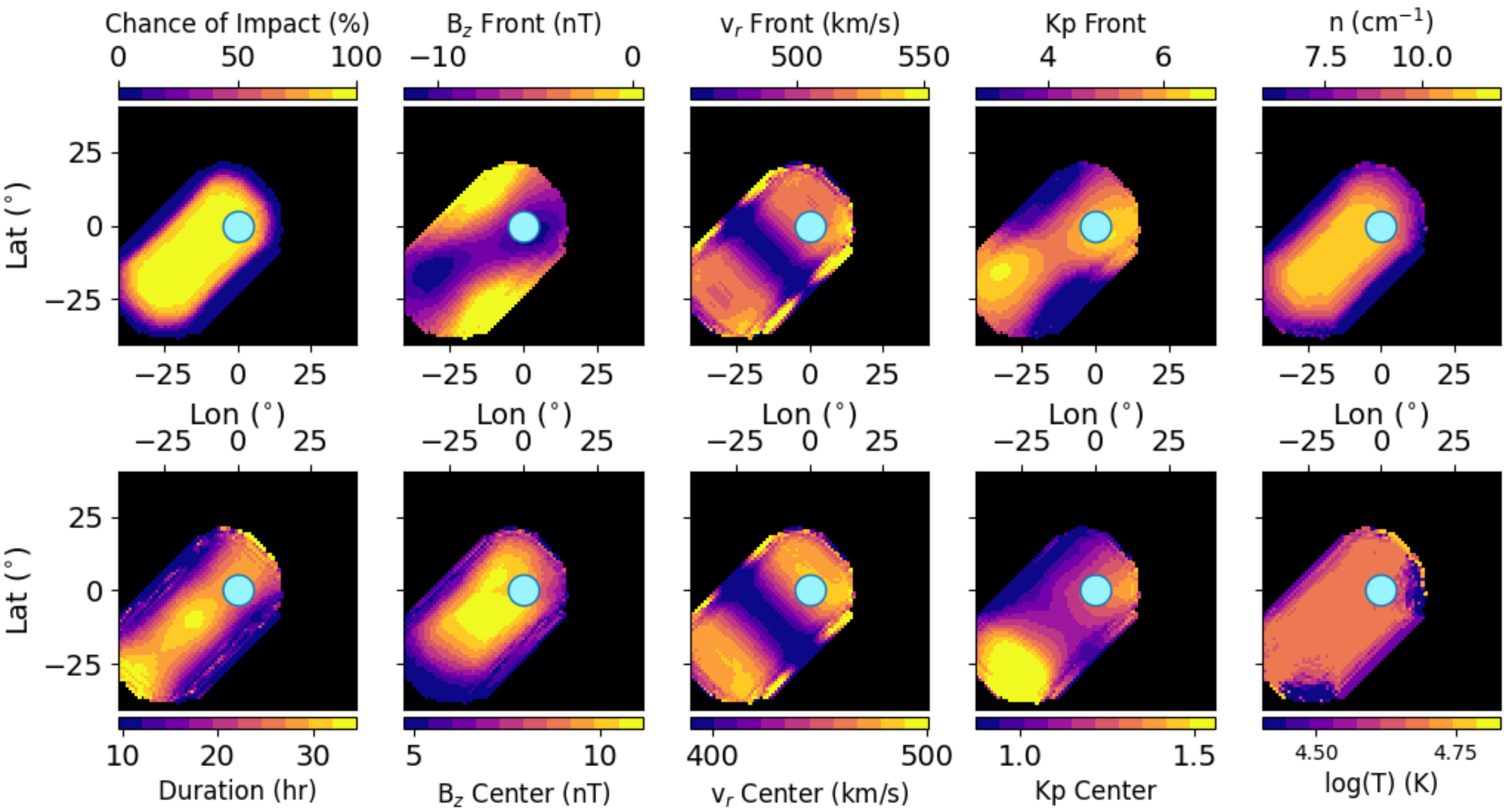




Novel Visualization 2

- Similar approach for spatial variations in critical forecasting outputs



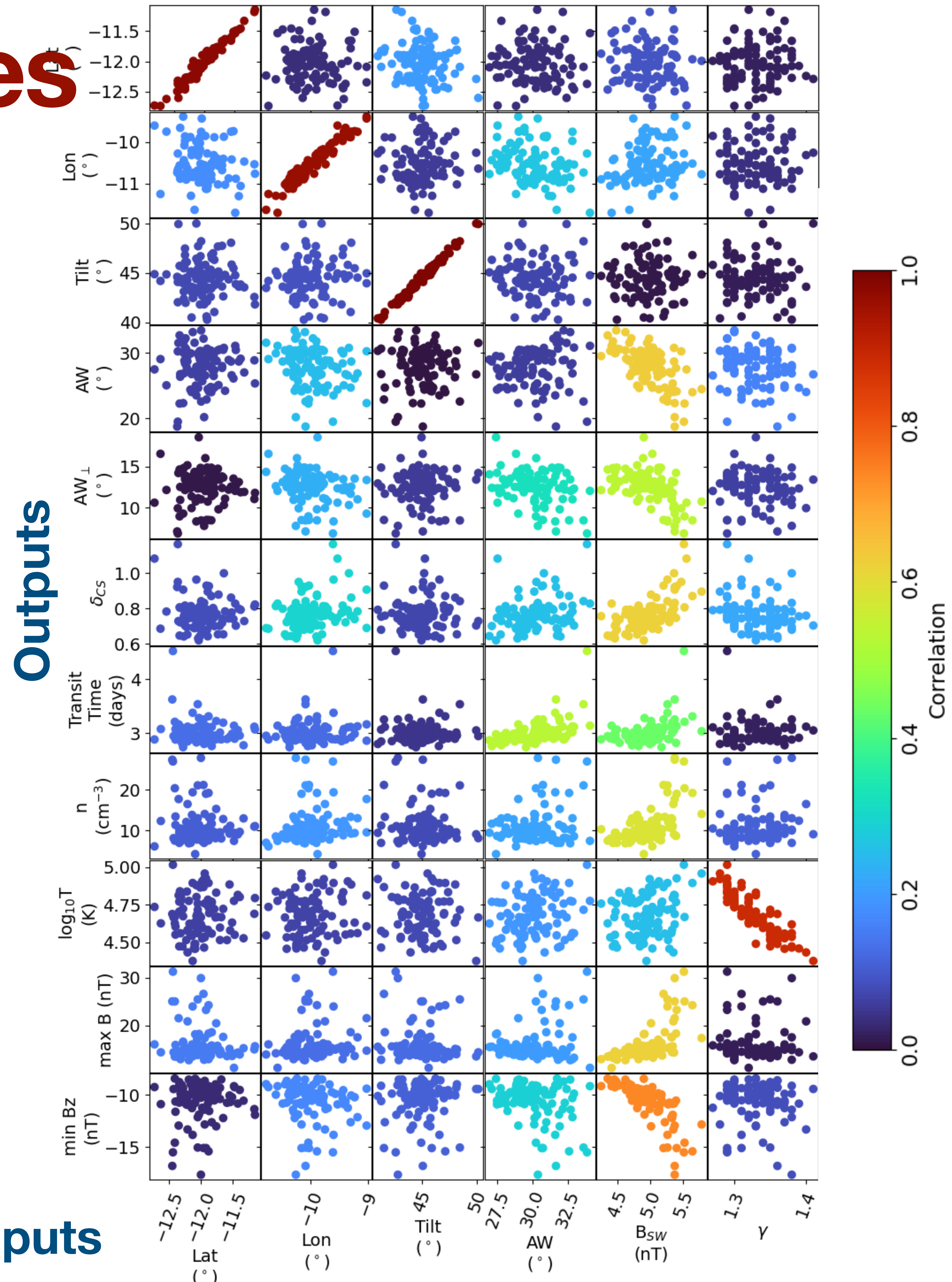


Direct Relations between Inputs and Outputs

- For this case, for the coronal portion we could easily track the correlation between certain inputs and outputs
- As we couple models, effects begin to compound and it may not be obvious how uncertainty in an input translates into uncertainty in an output
  - e.g. uncertainty in the initial AW
    - Larger size means less dense
    - More deflection and rotation → could move toward or away from satellite depending on geometry of situation
    - Stronger interplanetary forces → typically more expansion closer to Sun, potentially contraction farther out if it overexpands early on?
    - Cannot say, in general, whether increasing AW leads to a more “direct” hit or changes the CME properties to create a more severe impact
- ***Need a way of quickly visualizing the relation between inputs and outputs for each case***

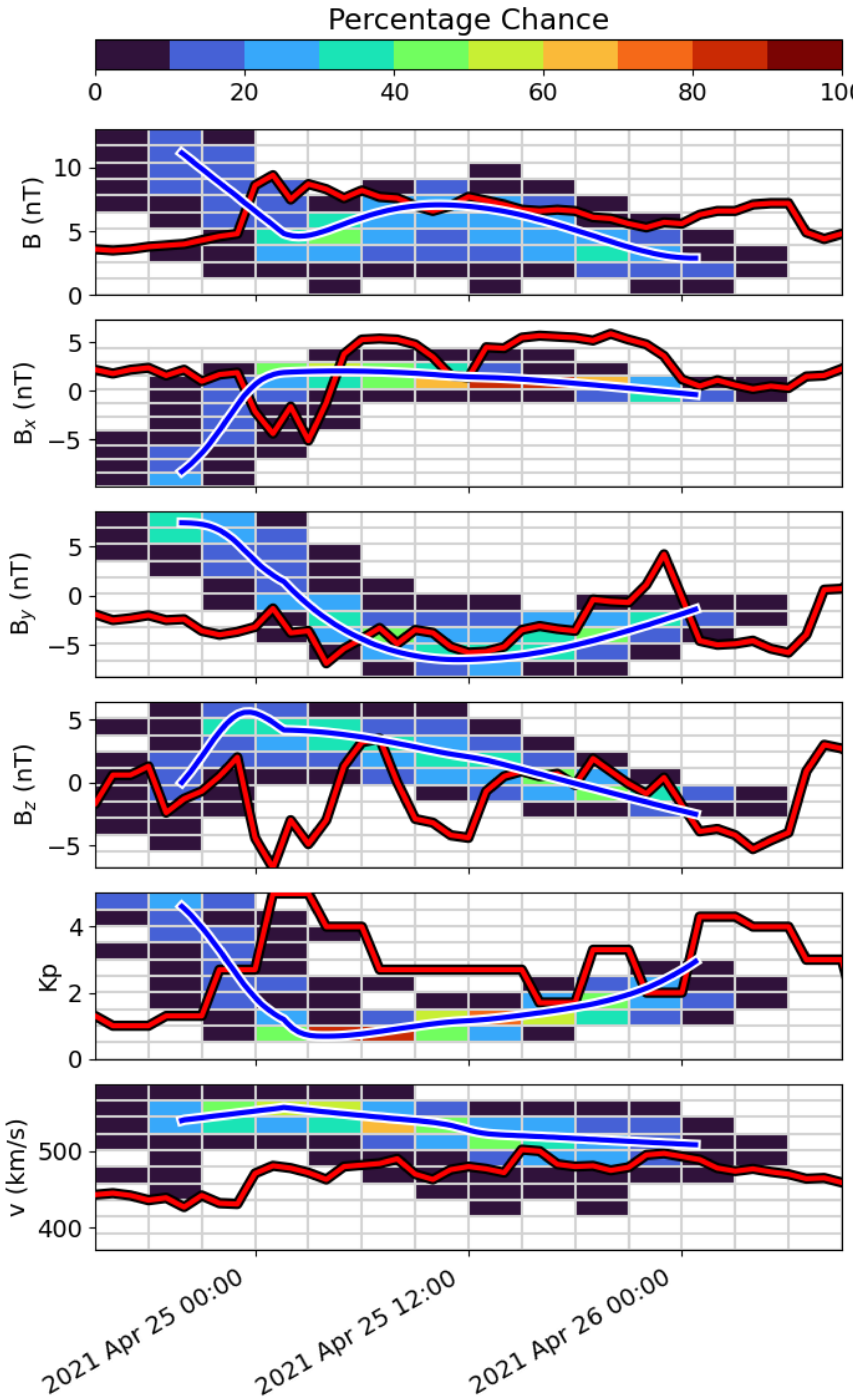
Diving Deeper into Ensembles

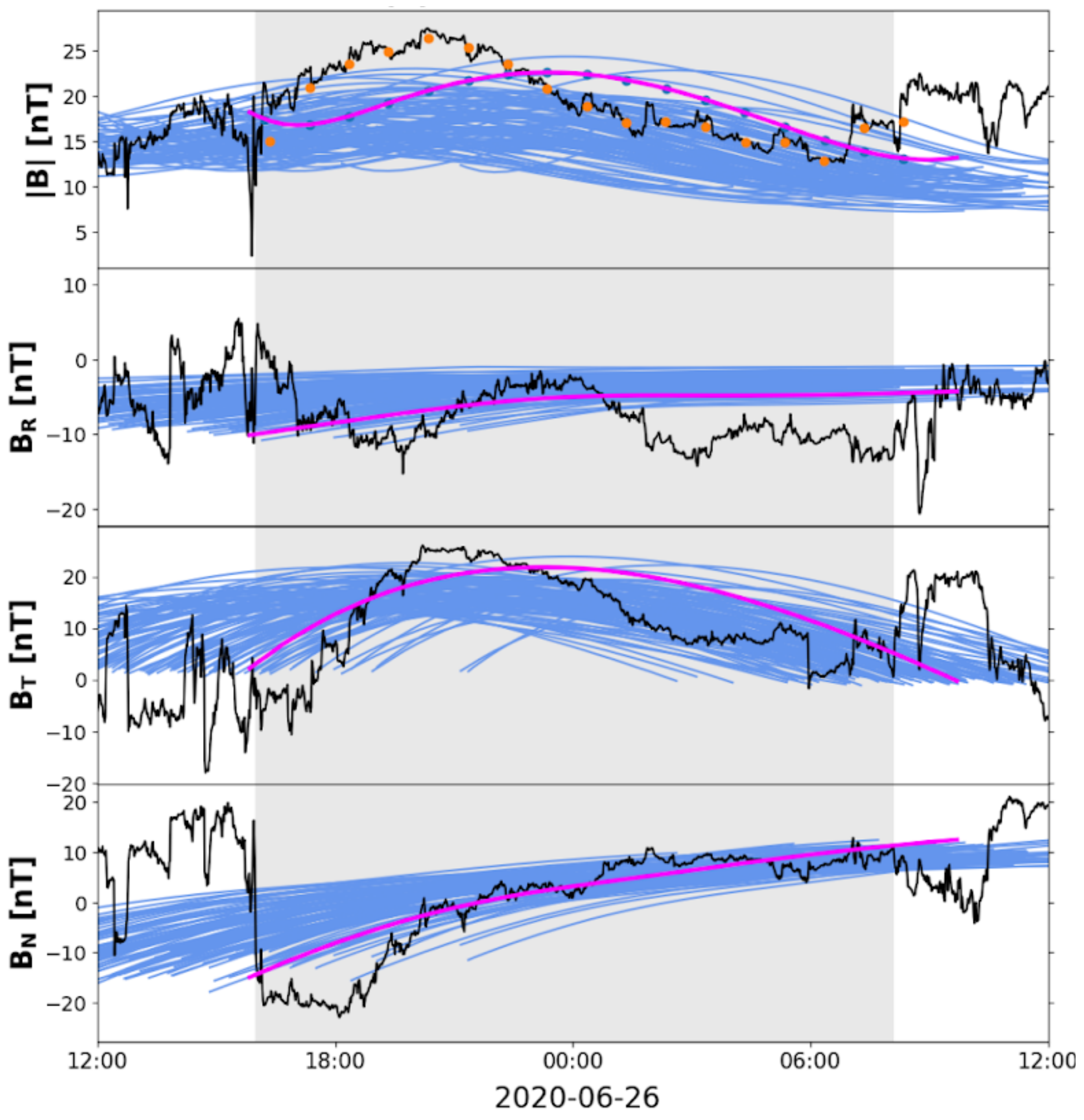
- Algorithm automatically pulls out any combination of input and output that have a “meaningful” combination
- Many of the strongest correlations are the obvious ones
    - Initial/final position, adiabatic index and final temperature
- Less obvious correlations become apparent
    - Solar wind B and final cross section aspect ratio
- AW has slight correlation with transit time (~0.5) but weak correlation with other outputs, highlight the compounding of different effects from different input parameters
- Outlier cases become apparent



OSPREI in Action

Second case from OSPREI paper





CME observed by PSP (Palmerio et al. 2021)

Summary

- OSPREI combines existing CME models into a new, fully-coupled, highly efficient suite. It generates systematic outputs that are automatically processed into creative visualizations designed to facilitate space weather forecasting.

- ***By running ensembles, OSPREI provides information on the most probable Sun-to-Earth behavior, as well as the range of possibilities. Sometimes there is an obvious link between uncertainty in inputs and uncertainties in outputs. Other times there is not a direct relation as the effects from multiple inputs and/or multiple models couple together in nonlinear fashions***

- We have begun the onboarding process with NASA's Community Coordinated Modeling Center so that OSPREI runs will be available upon request and forecasts can be generated using the real-time CME analysis from the newly formed Moon to Mars Space Weather Office

Questions? Comments? contact C. Kay at kayc@cua.edu

Ask for an OSPREI sticker!