An Ensemble Modeling Framework for Propagating Solar Wind Conditions to Jupiter

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April 26, 2024

Abstract

The important question of how the solar wind influences Jupiter's magnetosphere is difficult to answer due to the lack of consistent up-stream monitoring of the interplanetary medium (IPM) and the large-scale dynamics internal to the magnetosphere. To compensate for the relative lack of in-situ data, solar wind propagation models are often used to estimate the ambient IPM conditions near Jupiter for comparison to remote observations or in-situ measurements. A statistical analysis of the timescales over which Jupiter's magnetosphere reacts to changes in the IPM would allow the solar wind interaction to be better decoupled from internal dynamics; however, solar wind propagation from near-Earth measurements out to Jupiter introduces uncertainties in both the timing and magnitude of changes in the IPM which are themselves difficult to assess. Here, we present an ensemble modeling framework for the solar wind at Jupiter. A variety of existing solar wind models were compared to in-situ measurements from near-Jupiter spacecraft spanning diverse spacecraft-Sun-Earth alignments and phases of the solar cycle, amounting to more than 23,000 hours over four decades. Typical errors in prediction timing and magnitude, as well as conditions under which the different input models performed better than average, were then characterized as part of this framework. The resulting ensemble model produces the most-probable near-Jupiter IPM conditions for times within the tested epoch and provides the estimated variance in these conditions, allowing for a statistical analysis of the relationship between Jupiter's magnetosphere and the solar wind. In addition to remote sensing studies, the robust modeling of solar wind conditions near Jupiter is crucial to ongoing and future in-situ studies using *Galileo*, *Juno*, JUICE, and *Europa Clipper* measurements; the compression or expansion of the magnetosphere is crucial to interpreting in-situ measurements of Jupiter's middle and outer magnetosphere. Finally, we will discuss how the work presented here can be extended towards more robust characterization of solar wind parameters and time-dependent propagation of solar wind conditions at other planetary magnetospheres.


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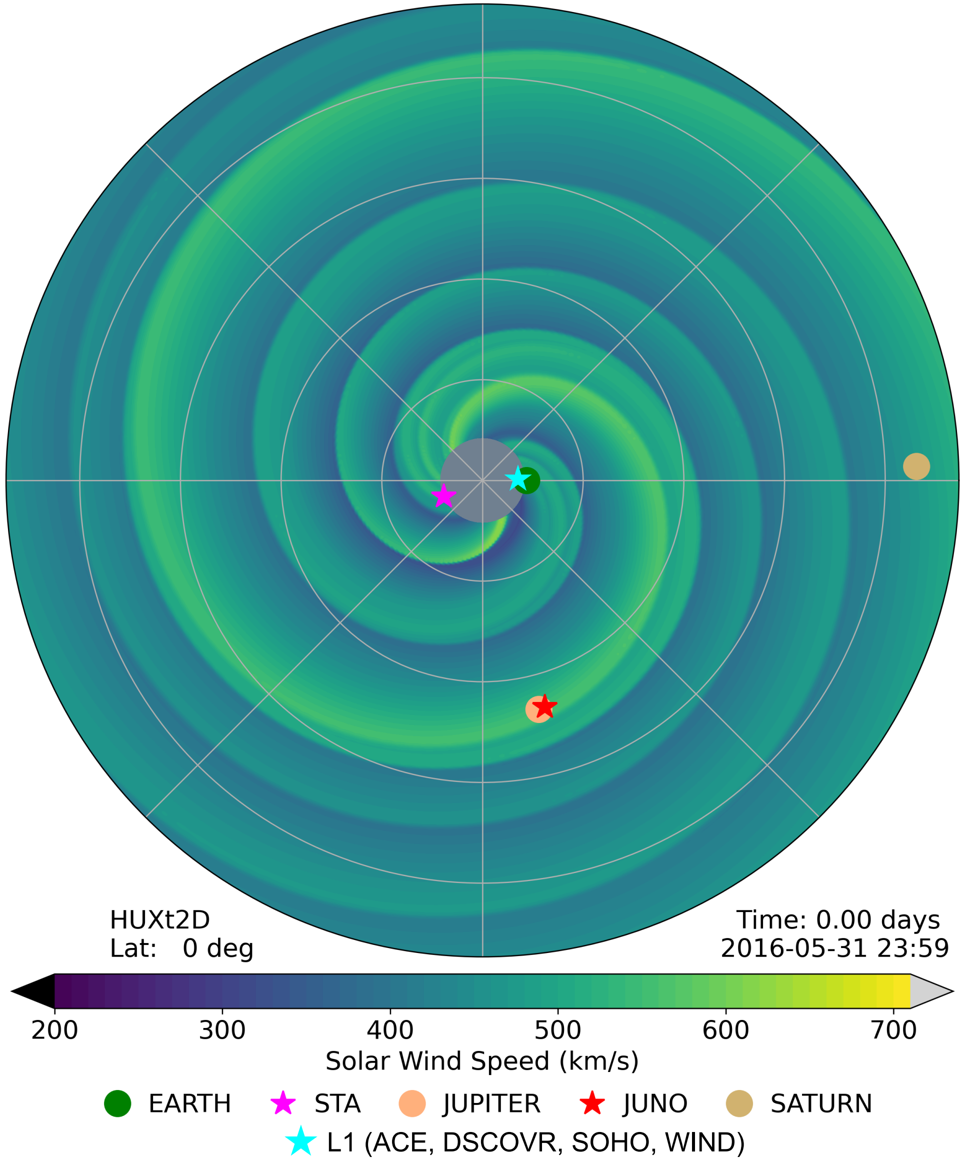
SOLAR WIND UNCERTAINTIES: JOVIAN PERSPECTIVE

- Sources of solar wind information
  - Upstream monitors: outer heliosphere spacecraft
    - 6 in-situ monitors, 33 months of hourly coverage over last 50 years (~5%) at Jupiter
  - Upstream monitor proxies: solar wind models
    - Propagation of near-Earth or Solar data over large physical domain

    ➡ Significant timing uncertainties (≤4+ days) (e.g. Tao+ 2005, Zieger+ 2008)

➡ Difficulty in establishing causality, interaction timescales



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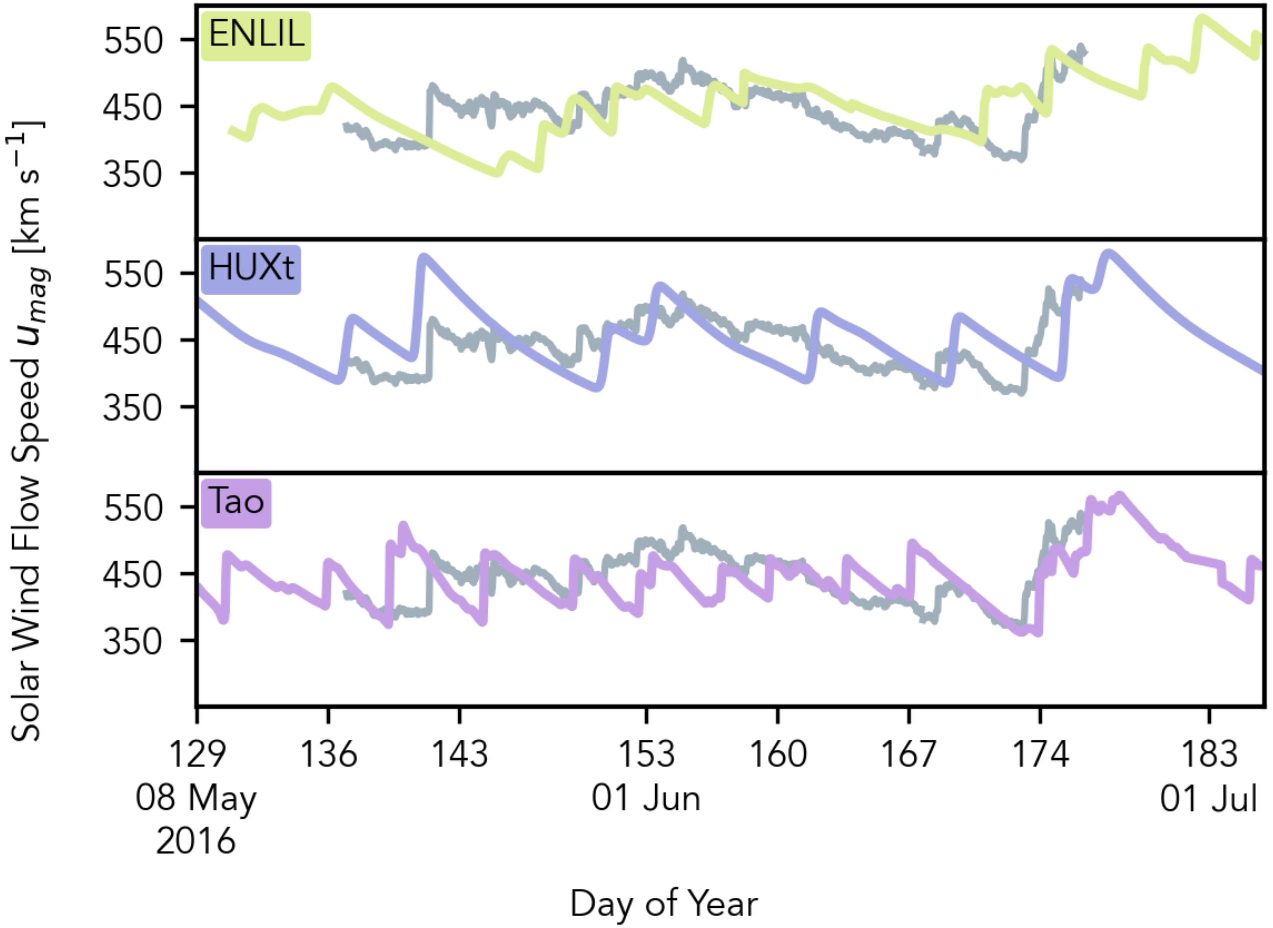
MULTI-MODEL ENSEMBLE SYSTEM FOR THE (OUTER) HELIOSPHERE (**MMESH**): OBJECTIVES

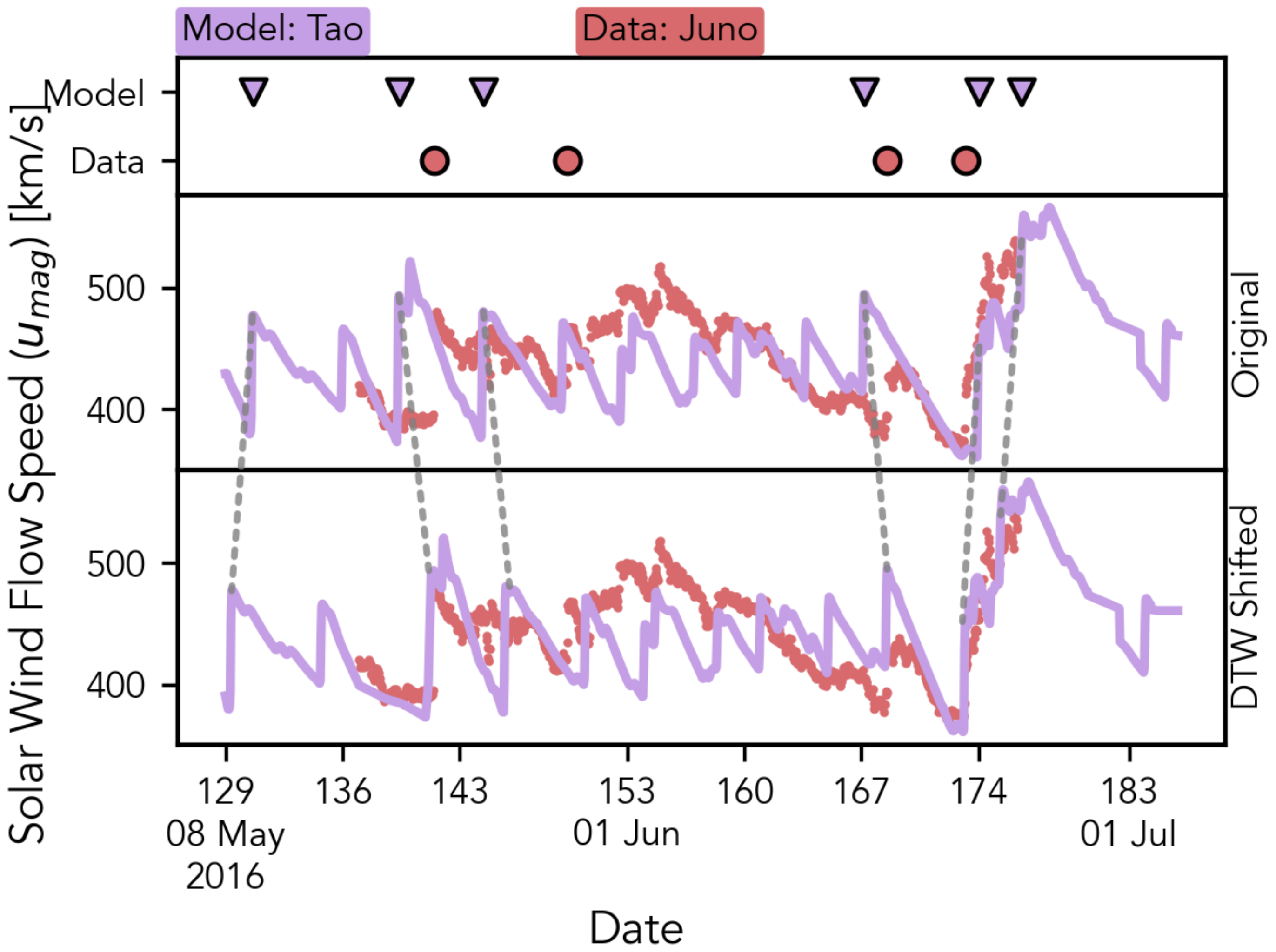
1. Characterize uncertainties
2. Identify causes of biases
3. Mitigate impacts of biases and uncertainties
   - Through multi-model ensembling

- Here, consider three models: ENLIL (Odstrcil 2003), HUXt (Owens+ 2020, Barnard+ 2022), and Tao (Tao+ 2005)



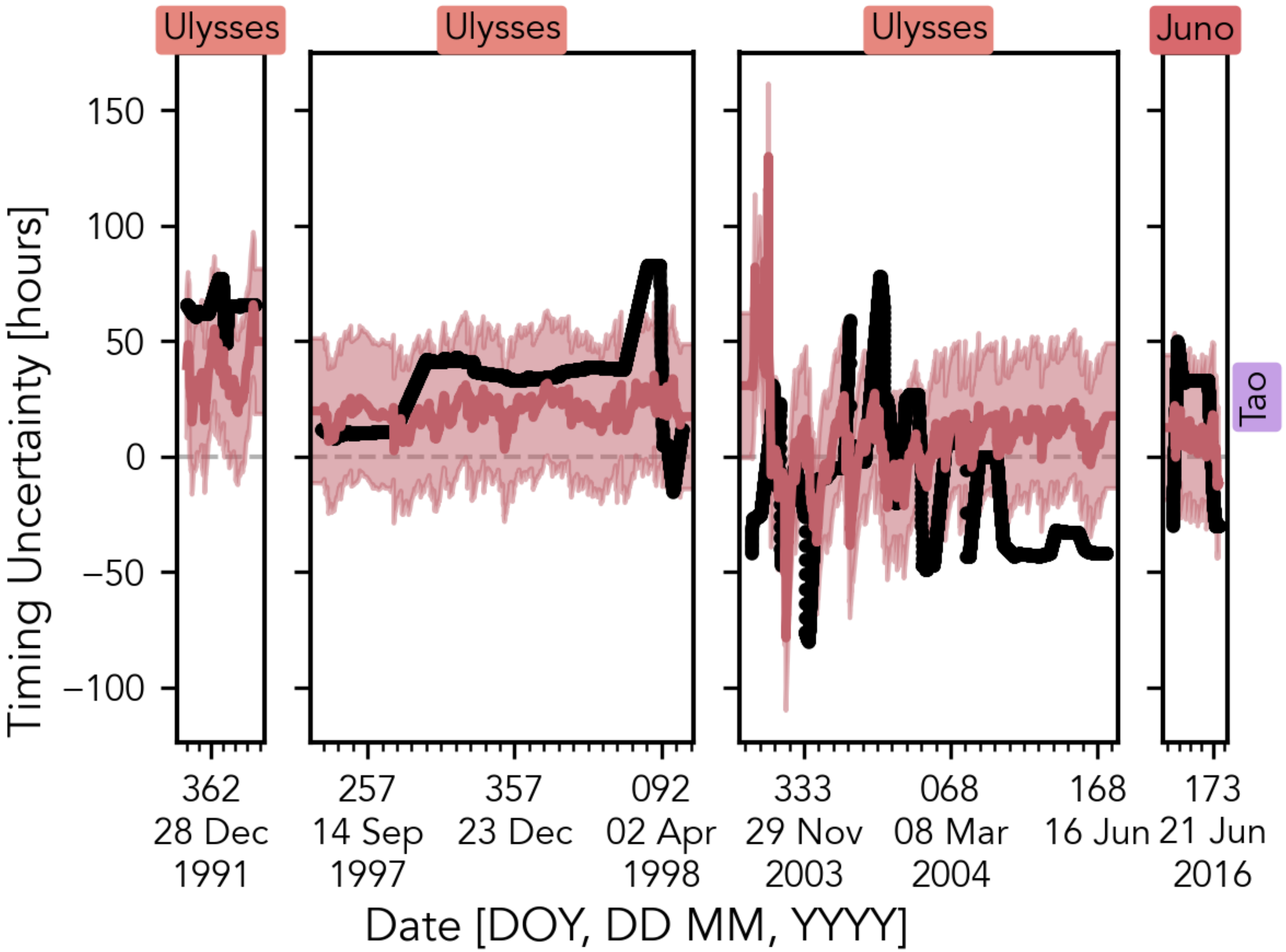
CHARACTERIZING UNCERTAINTIES: ARRIVAL TIMES

- Automatic ‘feature’ identification
  - Based on normalized time-derivative of solar wind flow speed (u_{SW})
- Model-data comparison over any timescale
  - Dynamic time warping (e.g. Giorgino 2009, Samara+ 2022)
    - Aligns model with data
    - Provides timing offsets (uncertainties)



IDENTIFYING CAUSES OF SYSTEMATIC UNCERTAINTIES

- Multiple linear regression (MLR) analysis
  - Correlate timing biases with parameters known to affect propagation models
    - Solar cycle phase (F10.7 flux)
    - Separation in heliolon., heliolat.
    - Modeled u_{SW}
- Consider multiple spacecraft epochs
  - Robust fitting between epochs
  - Prevent overfitting



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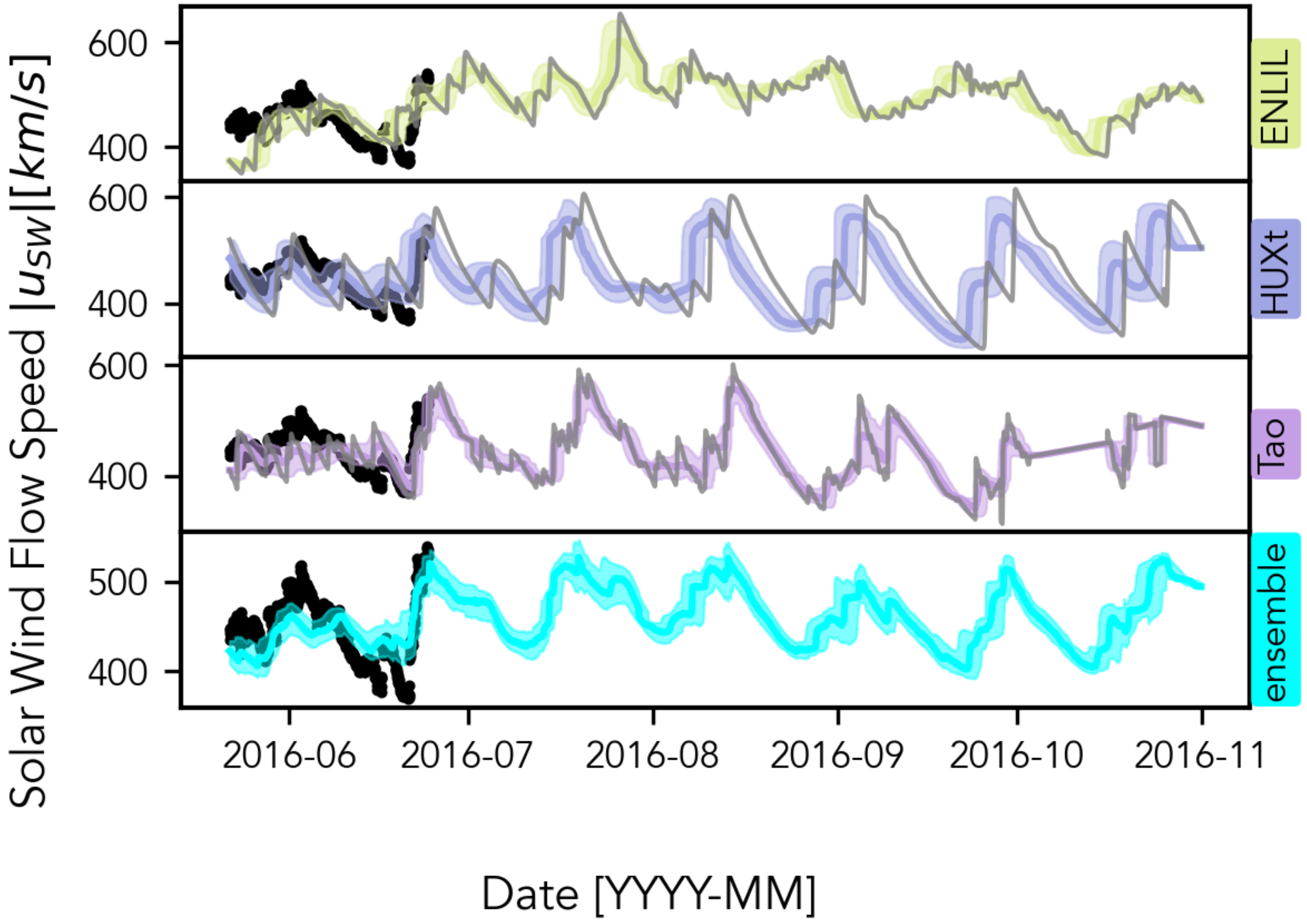
MITIGATING IMPACTS USING MMESH

- Combine de-trended (shifted) models
  - Equal weighting (Guerra+ 2020)
  - Propagated timing uncertainties
- Compared to input models (vs. *Juno* in-situ data):
  - 80%-105% better in *r*
  - 25%-37% better in RMSE



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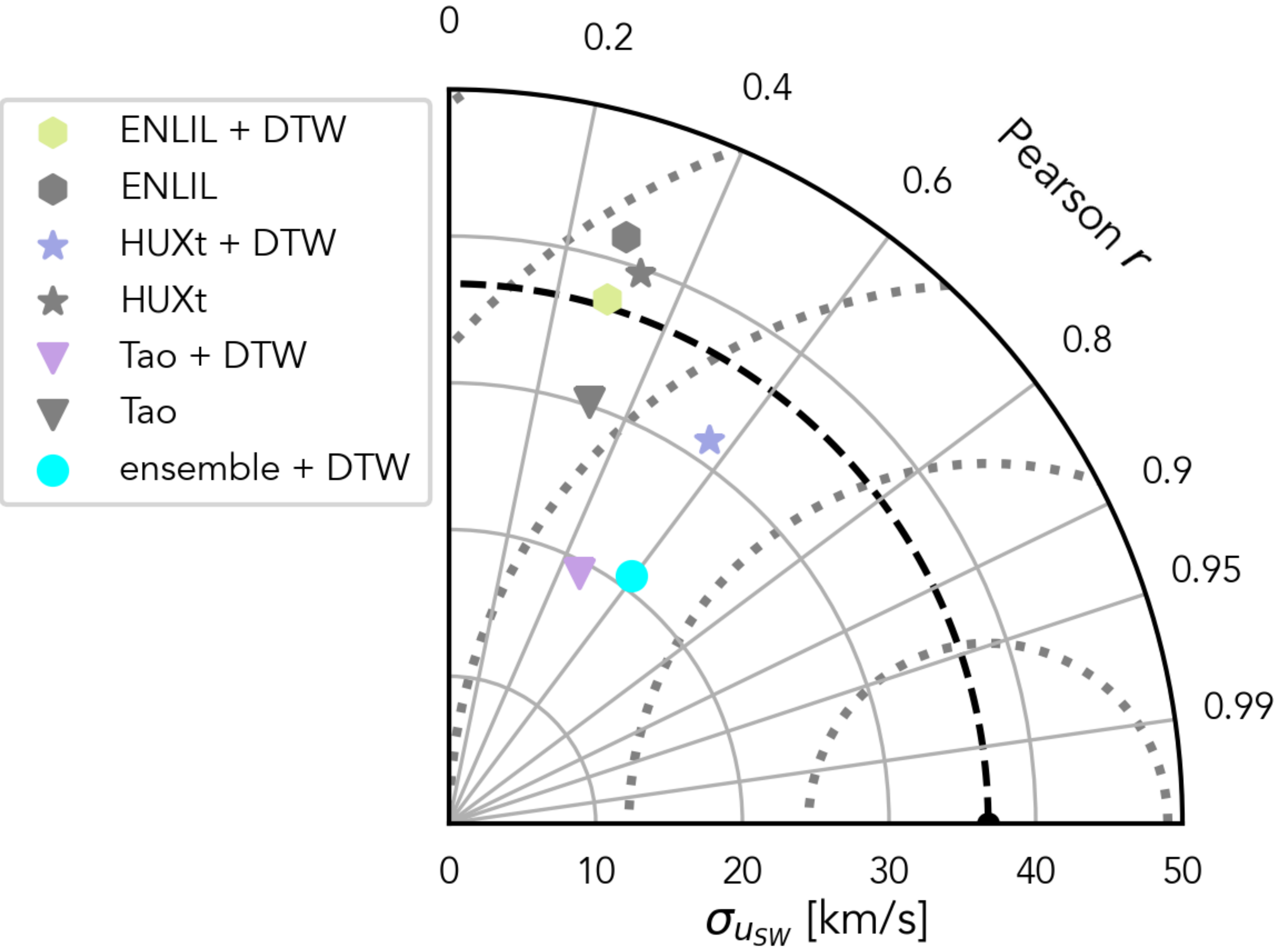
SUMMARY

- **MMESH** aligns, ensembles models:
  - 80%-105% better in *r*
  - 25%-37% better in RMSE
- **MMESH** code, *Juno*-epoch dataset to be released with Rutala+ 2023 (*in prep.)*
  - ➡ Deeper statistical analyses of solar wind-magnetosphere interactions in data-poor regions
- Timing bias MLR analysis accounts for less than 36% of variation
  - Some causes of uncertainty addressed
  - Additional significant, unmodeled causes still to be found



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