

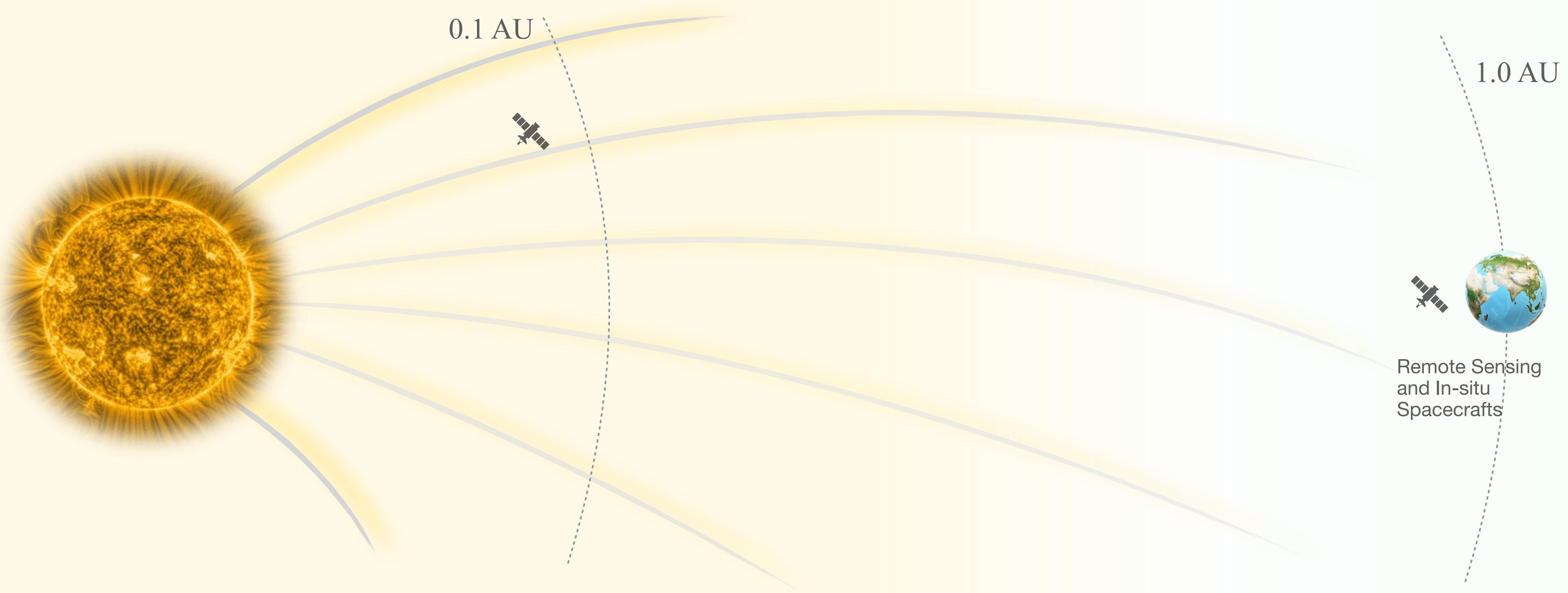
Next-Generation MHD Modeling of Solar Wind Plasma Using Neural Operators

Prateek Mayank

NASA Jack Eddy Postdoctoral Fellow



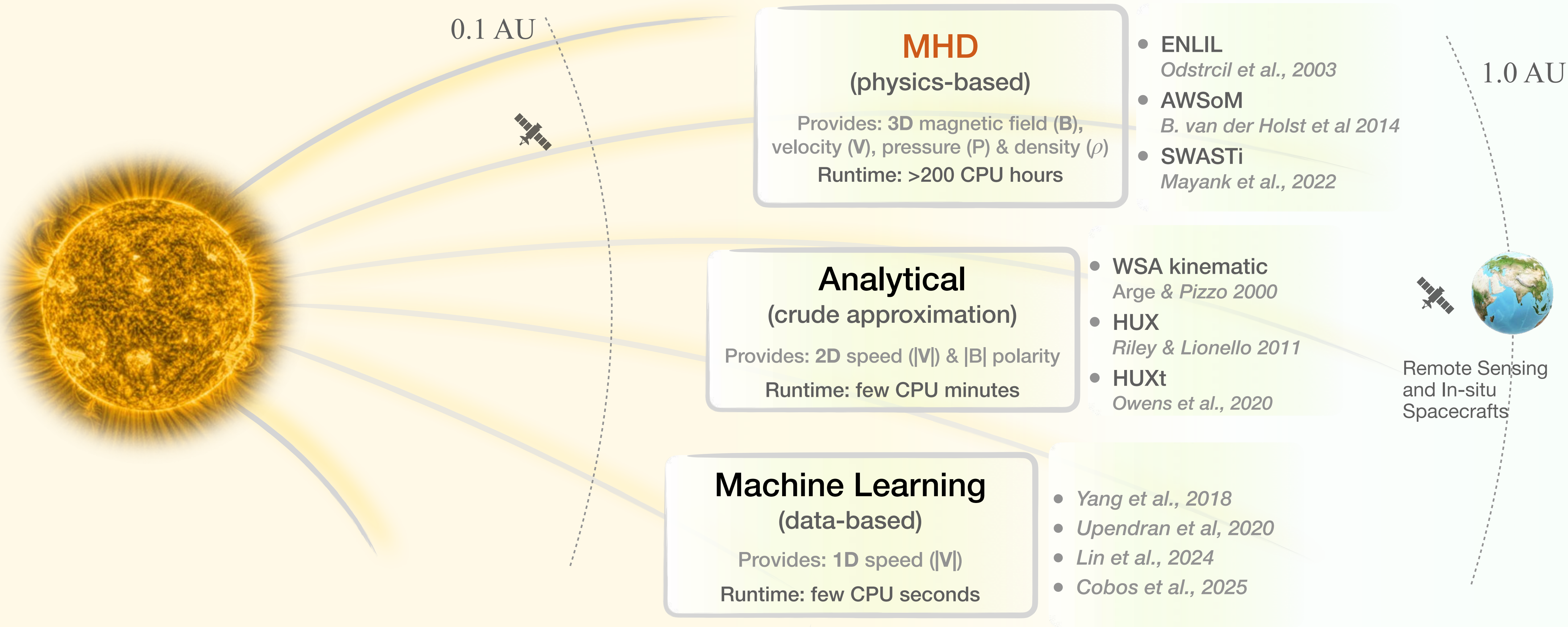
Current Modeling Approaches



Solar Corona

Inner Heliosphere

Current Modeling Approaches

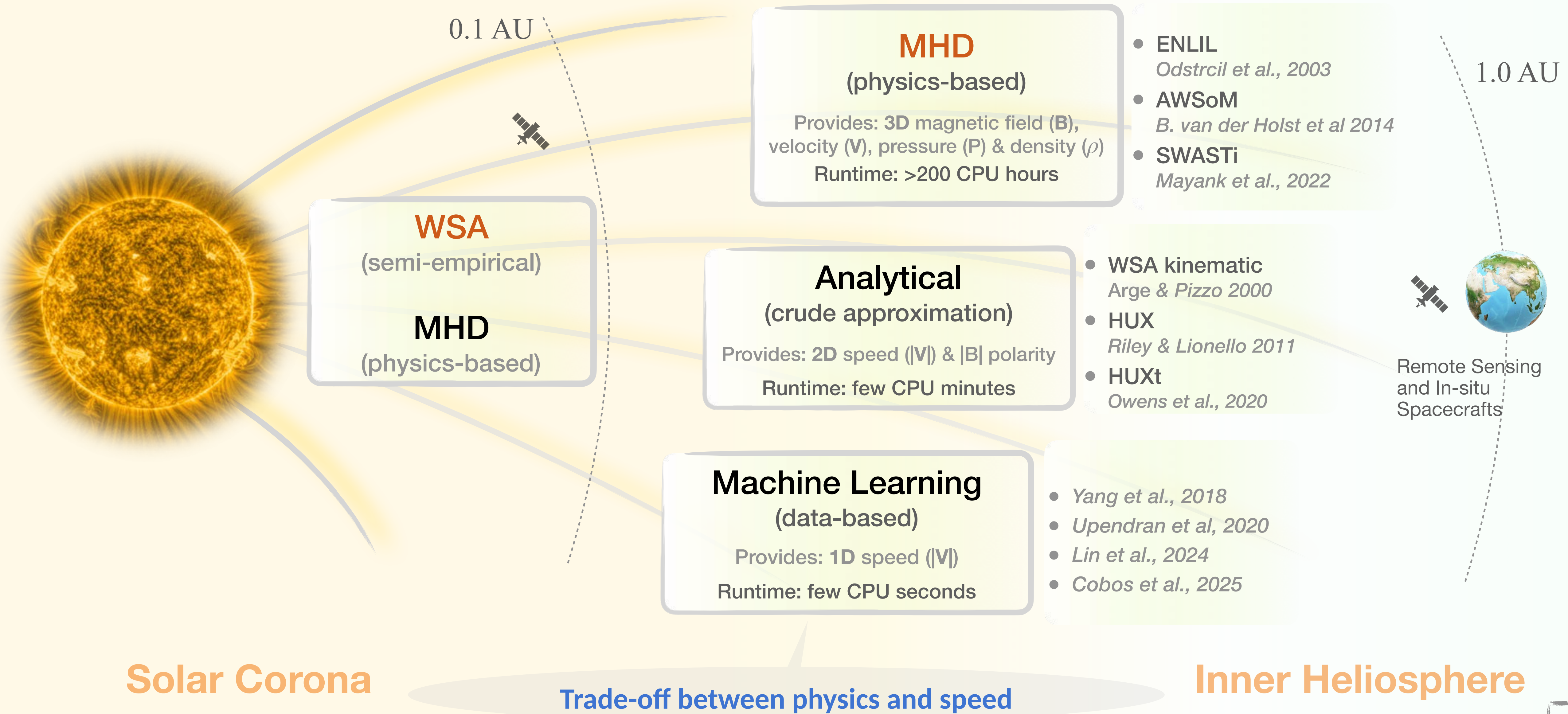


Solar Corona

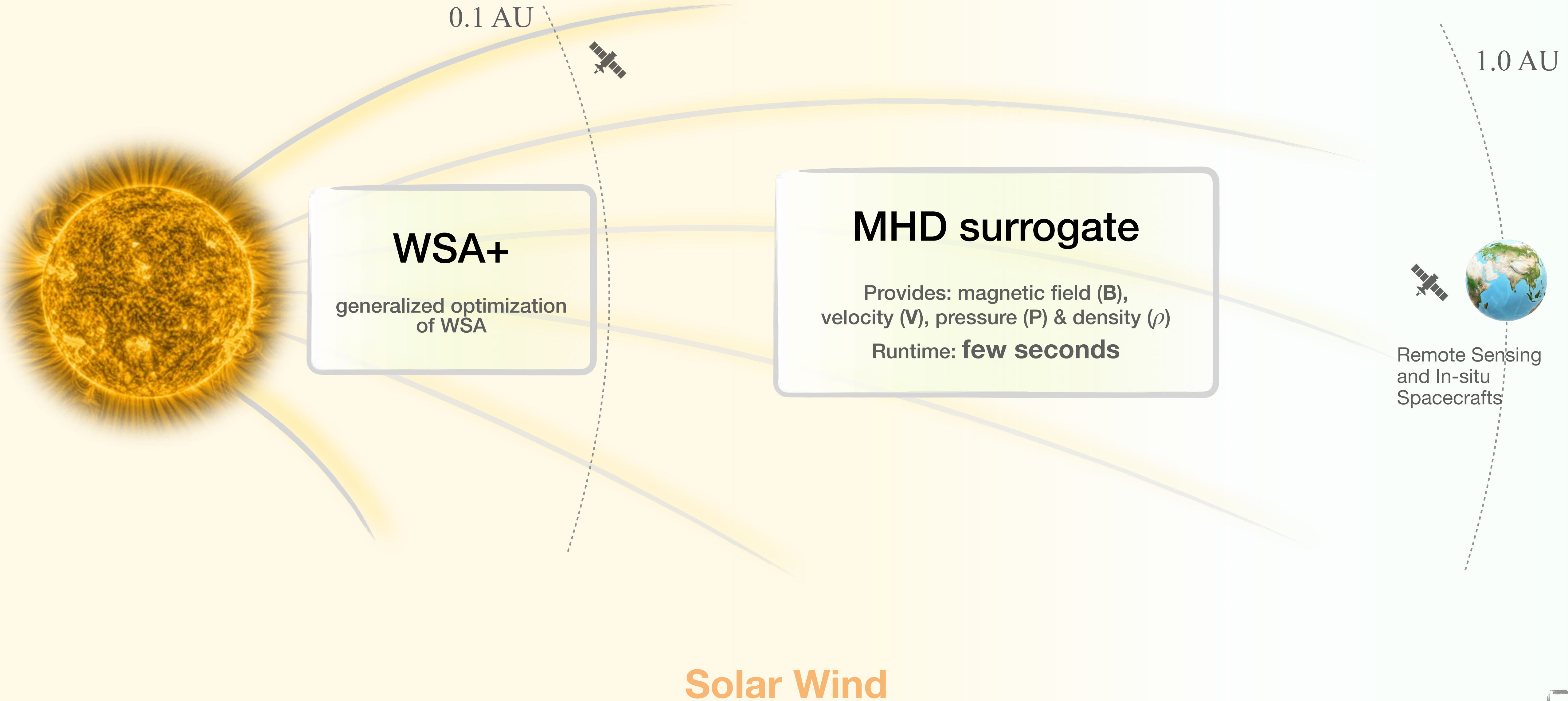
Trade-off between physics and speed

Inner Heliosphere

Current Modeling Approaches



Next-Generation Approach



WSA+

Neural enhancement of the Wang–Sheeley–Arge solar wind model

Smarter. More accurate. Ready to forecast.



ENHANCED ACCURACY

Neural optimization of WSA parameters for best match to in-situ observations



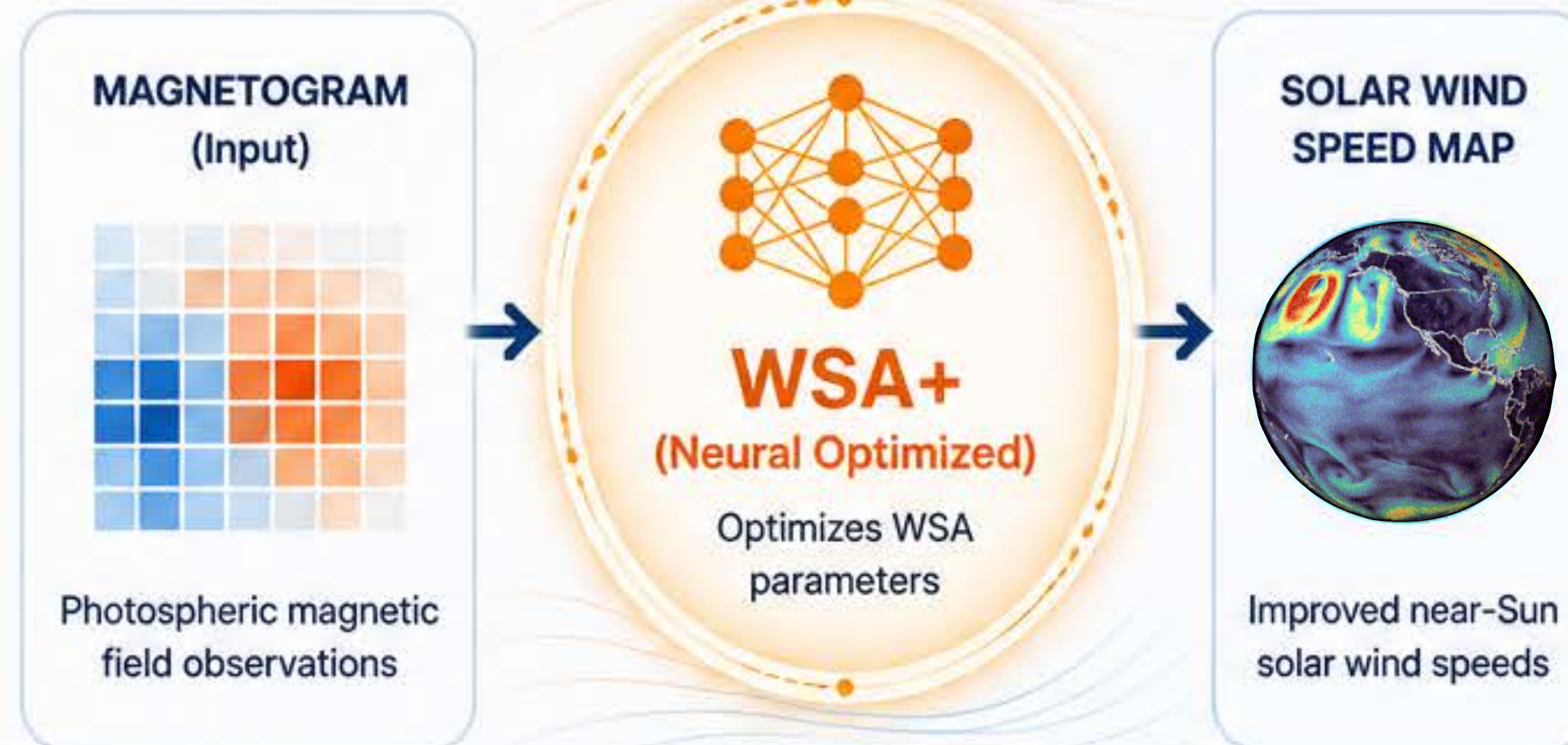
DIFFERENTIABLE

End-to-end differentiable and physics-constrained pipeline



READY FOR OPERATIONS

Generalizes across solar conditions and enables real-time forecasting



Higher correlation with in-situ data



Lower errors across multiple metrics



Robust across solar cycles



Mayank et al. 2025

ApJ Lett., 994, L5



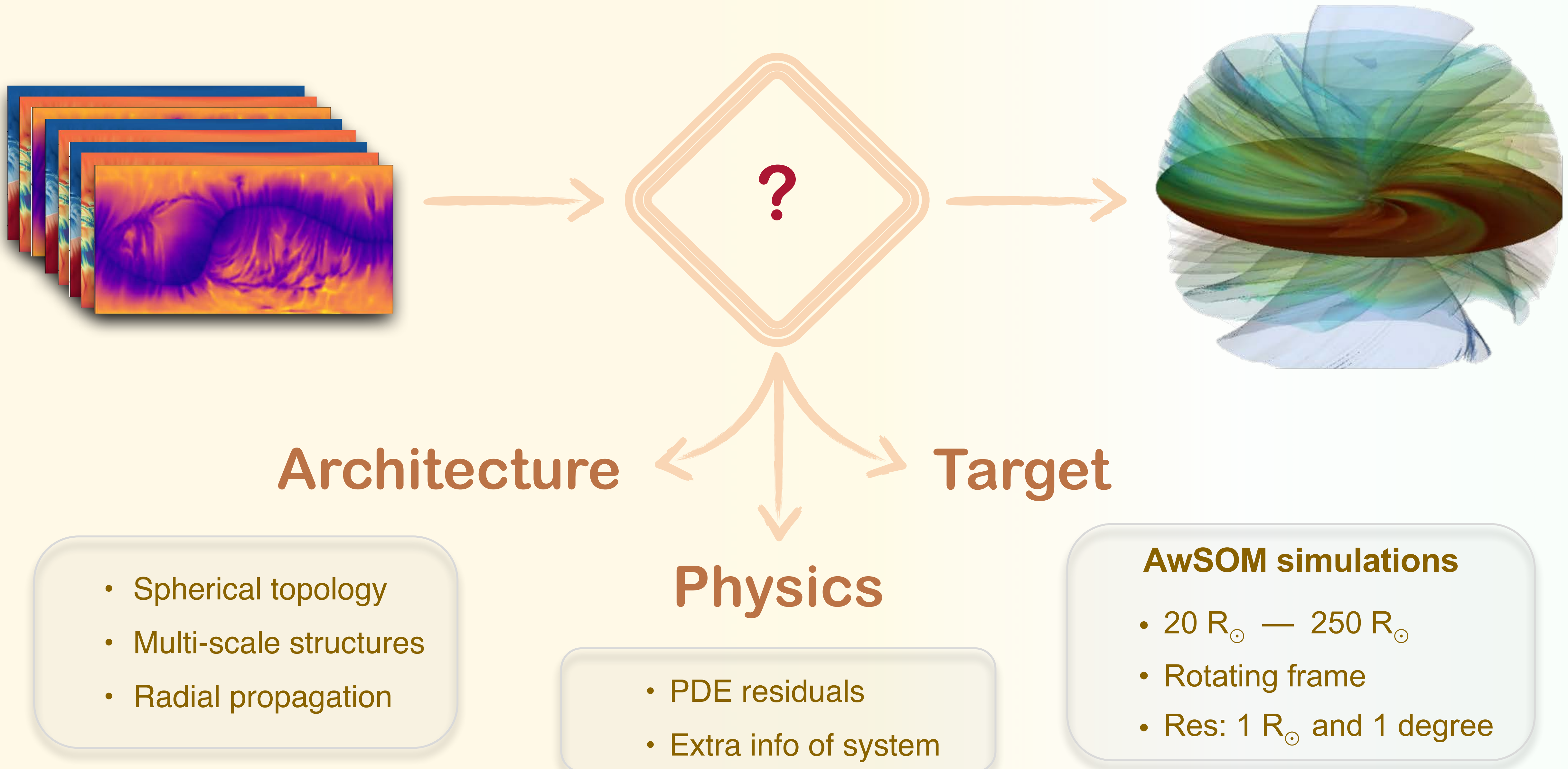
PROVEN & VALIDATED

- ✓ Significant improvement over traditional WSA across multiple metrics
- ✓ ~40% average improvement
- ✓ Validated on multiple solar cycles and independent datasets

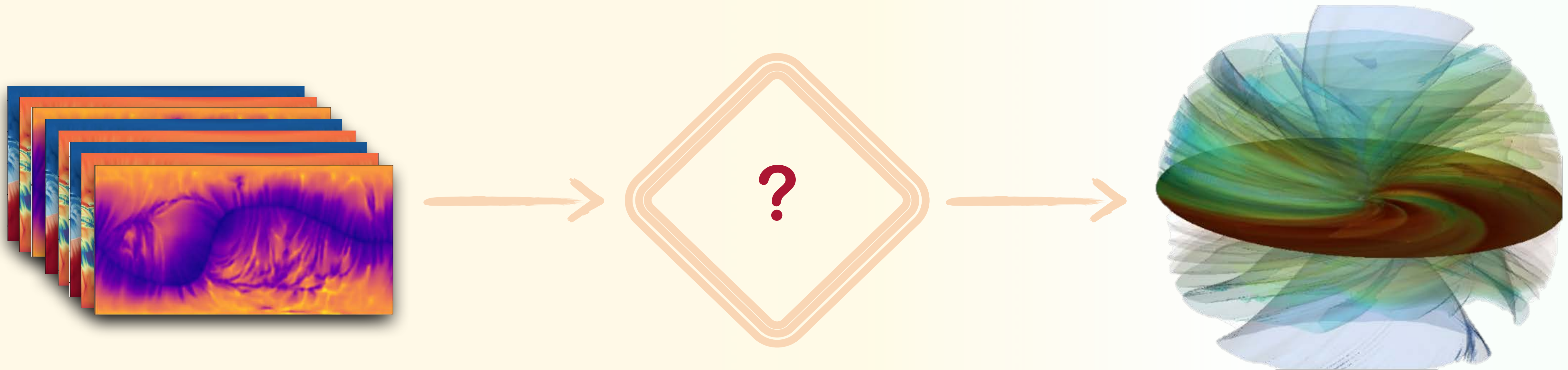


PIP INSTALL: WSAPLUS
`pip install wsaplus`

MHD Surrogate Approach



MHD Surrogate Approach



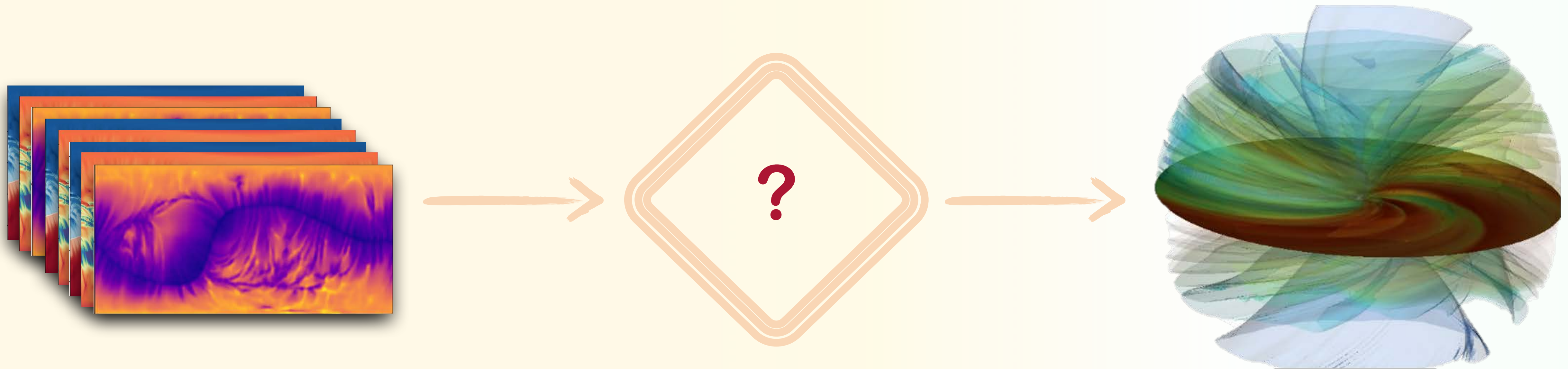
Neural Network

- Vector mapping
- Fixed Grid
- Classification & regression

Neural Operator

- Function mapping
- Resolution Independent
- PDE surrogates

MHD Surrogate Approach



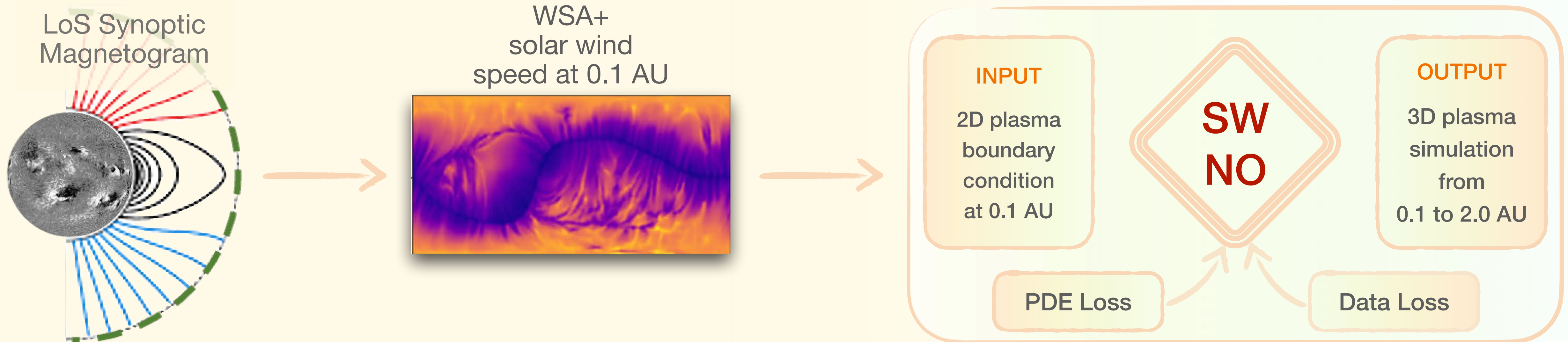
3D Fourier

- Fourier in r, θ, ϕ
- Not suitable for poles
- Requires higher computation

Spherical Harmonics

- Fourier in ϕ , Legendre in θ
- Suitable for spherical geometry
- Affordable computation budget

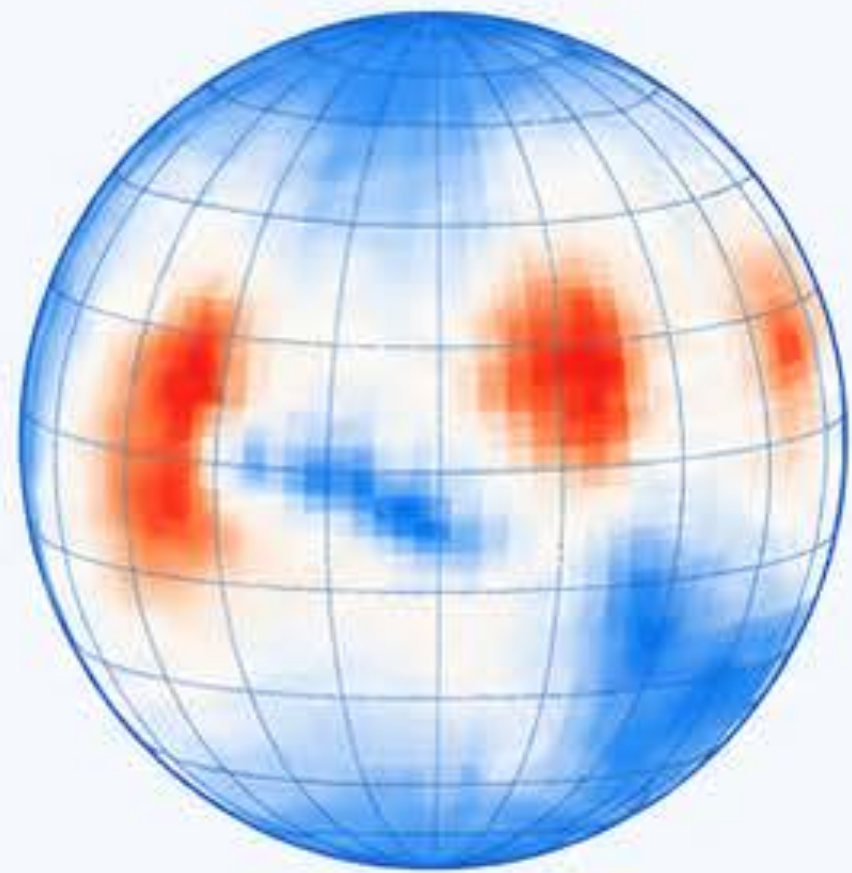
Solar Wind Neural Operator



Flow of Model Architecture

1. Input

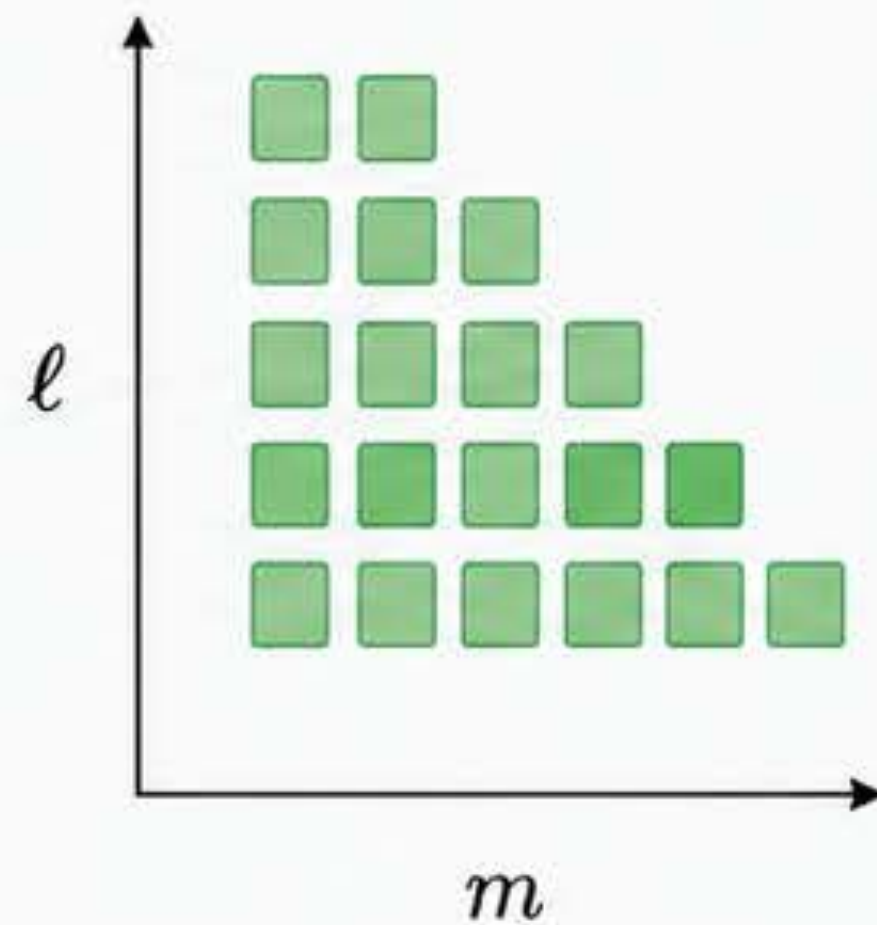
MHD state on sphere
at r_i



8 MHD variables
(e.g., ρ , v_r , v_θ , v_ϕ ,
 B_r , B_θ , B_ϕ , p)

2. Spherical Harmonic Encoding

Transform to SH coefficients



3. Spherical Harmonics Operator (Surrogate)

Input coeffs
at r_i



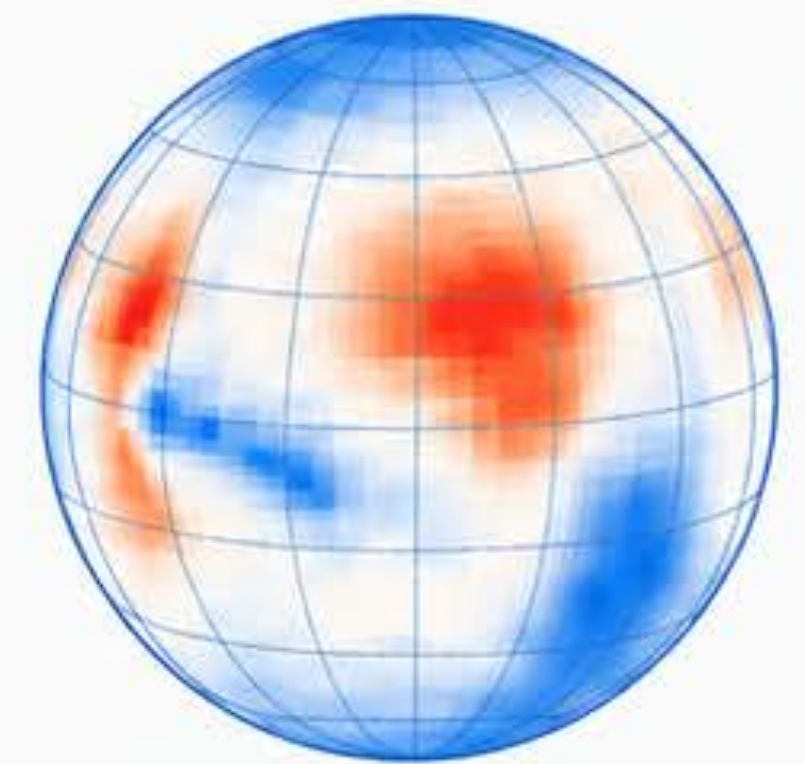
Spectral mixing
($l-m$ coupling)

Output coeffs
at r_{i+1}



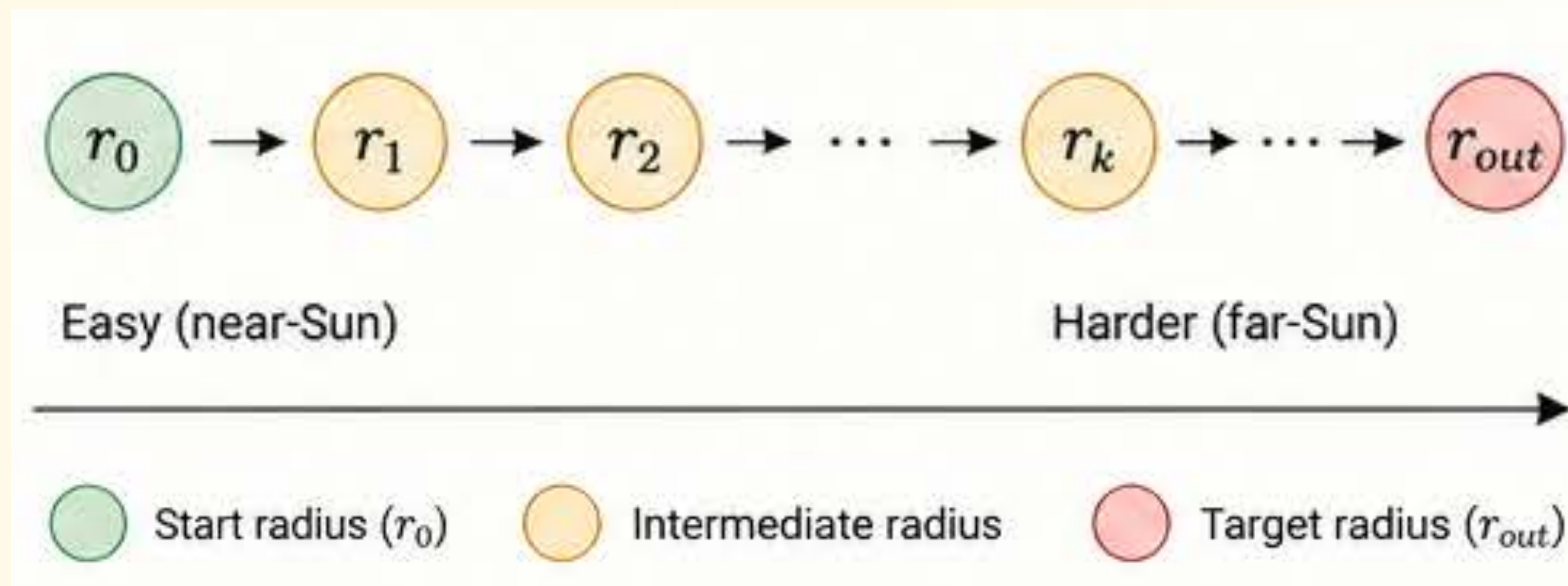
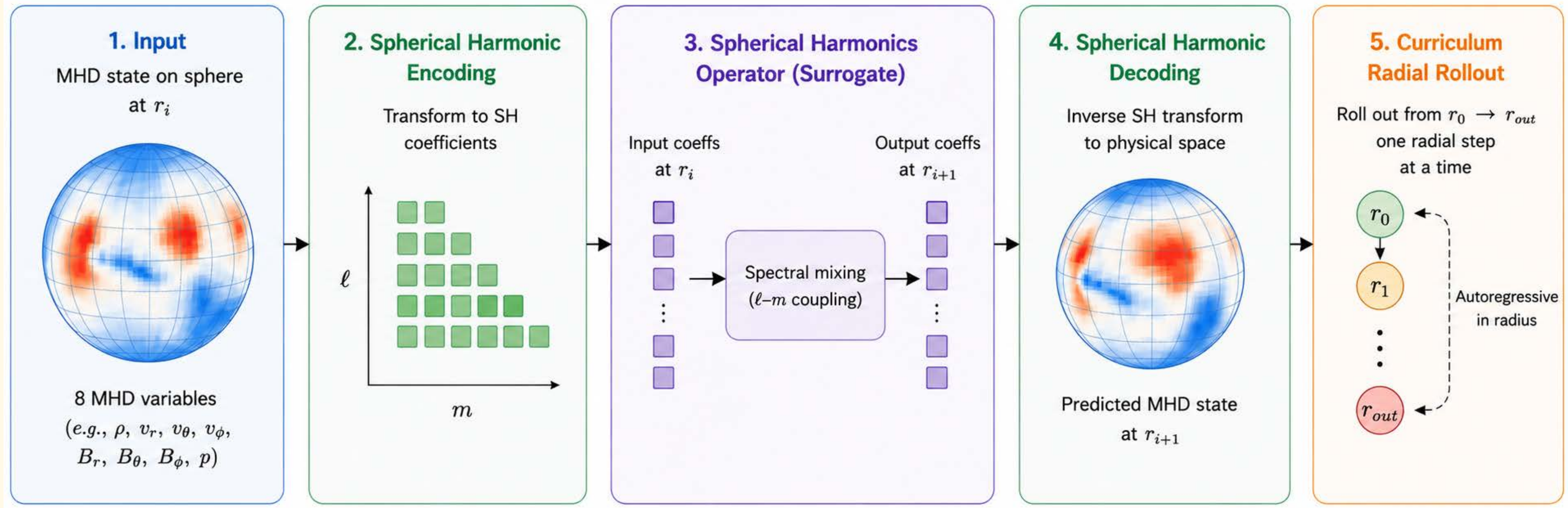
4. Spherical Harmonic Decoding

Inverse SH transform
to physical space

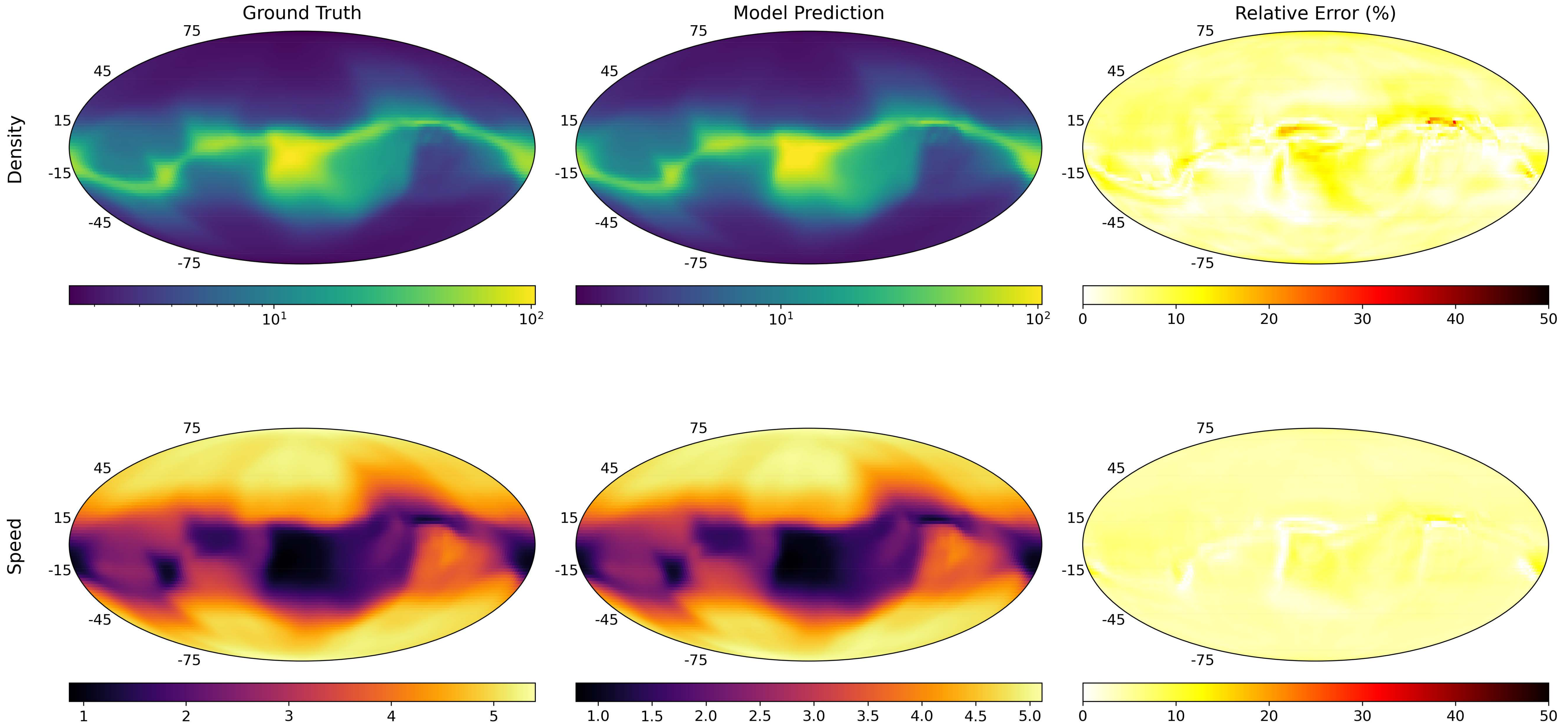


Predicted MHD state
at r_{i+1}

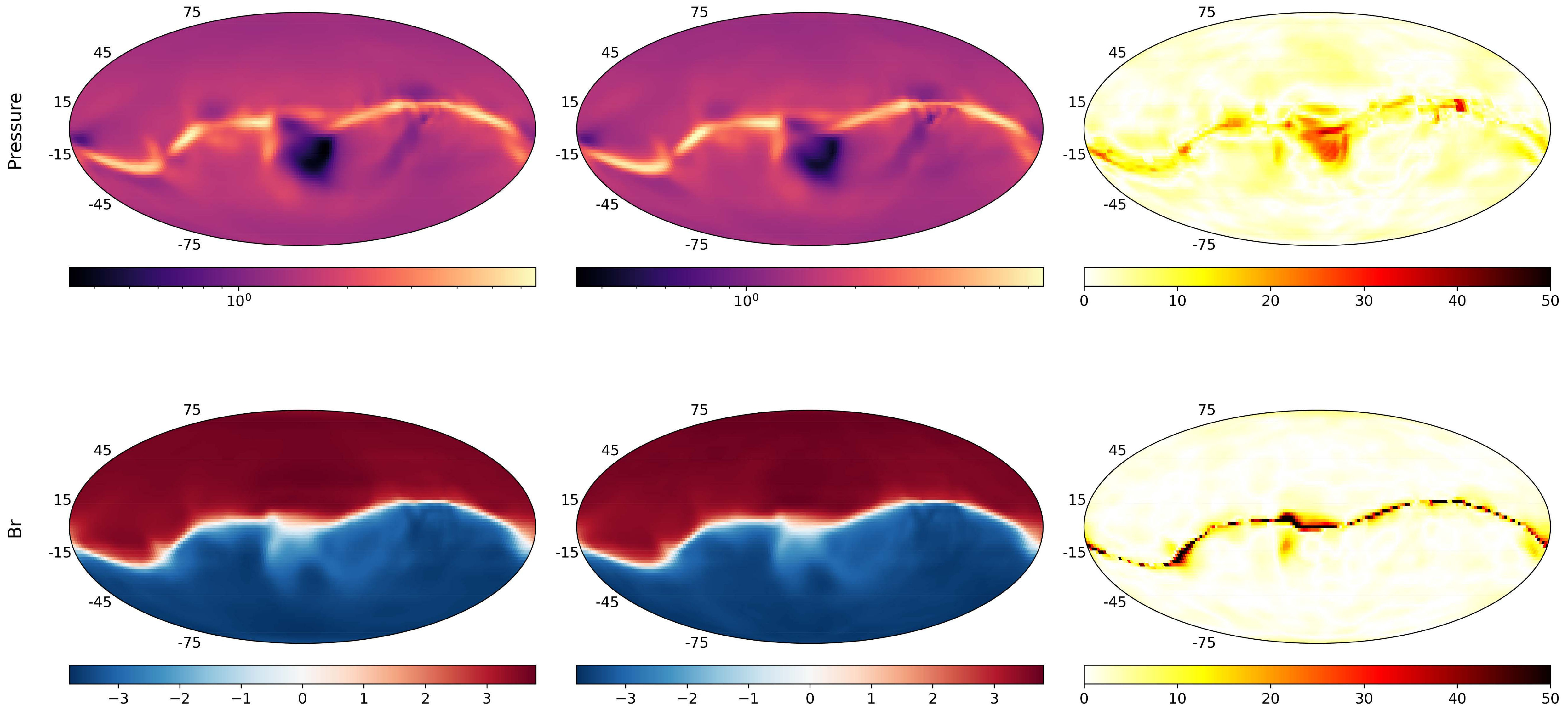
Curriculum Radial Rollout



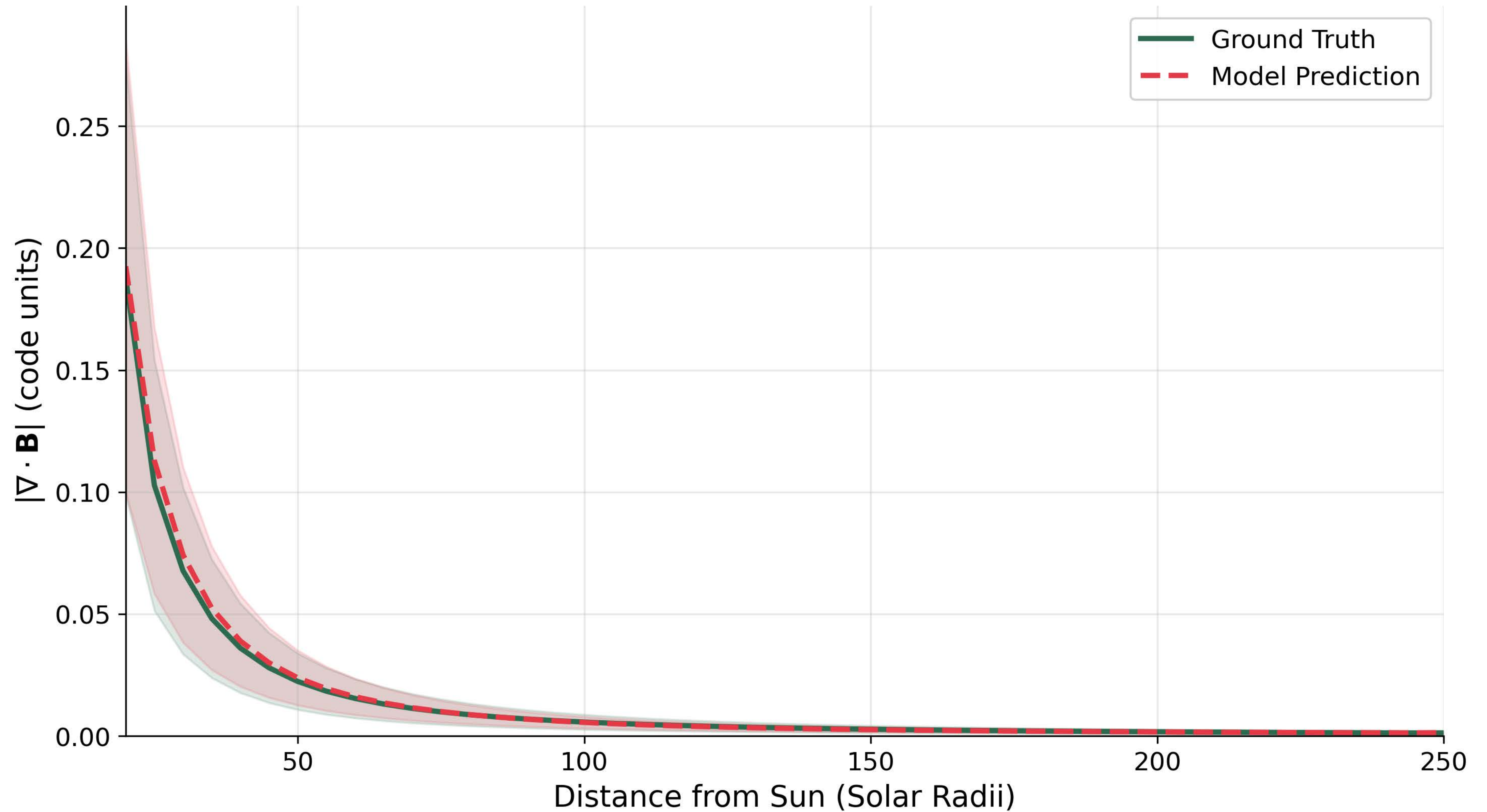
Spherical Learning is Awesome



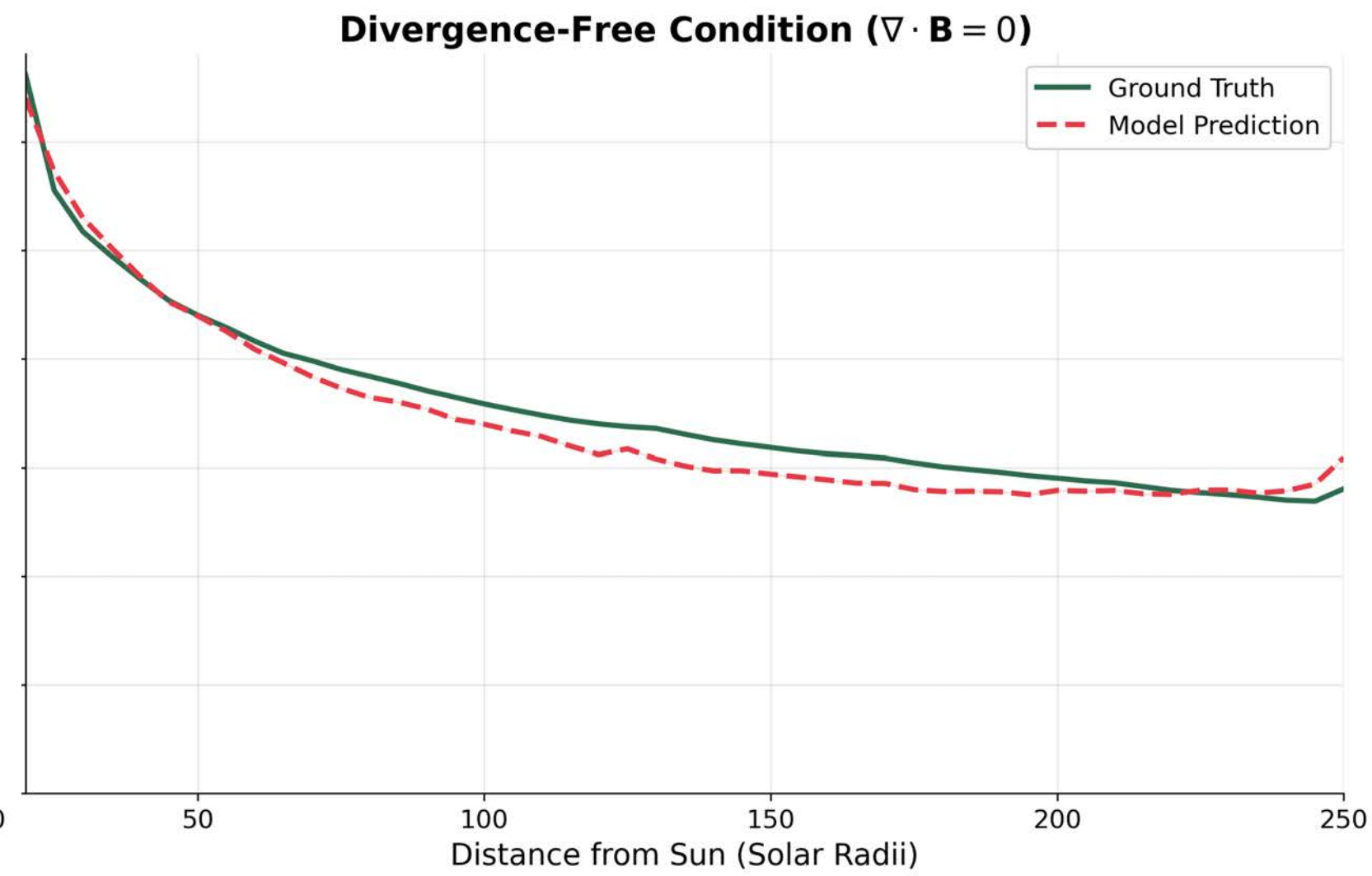
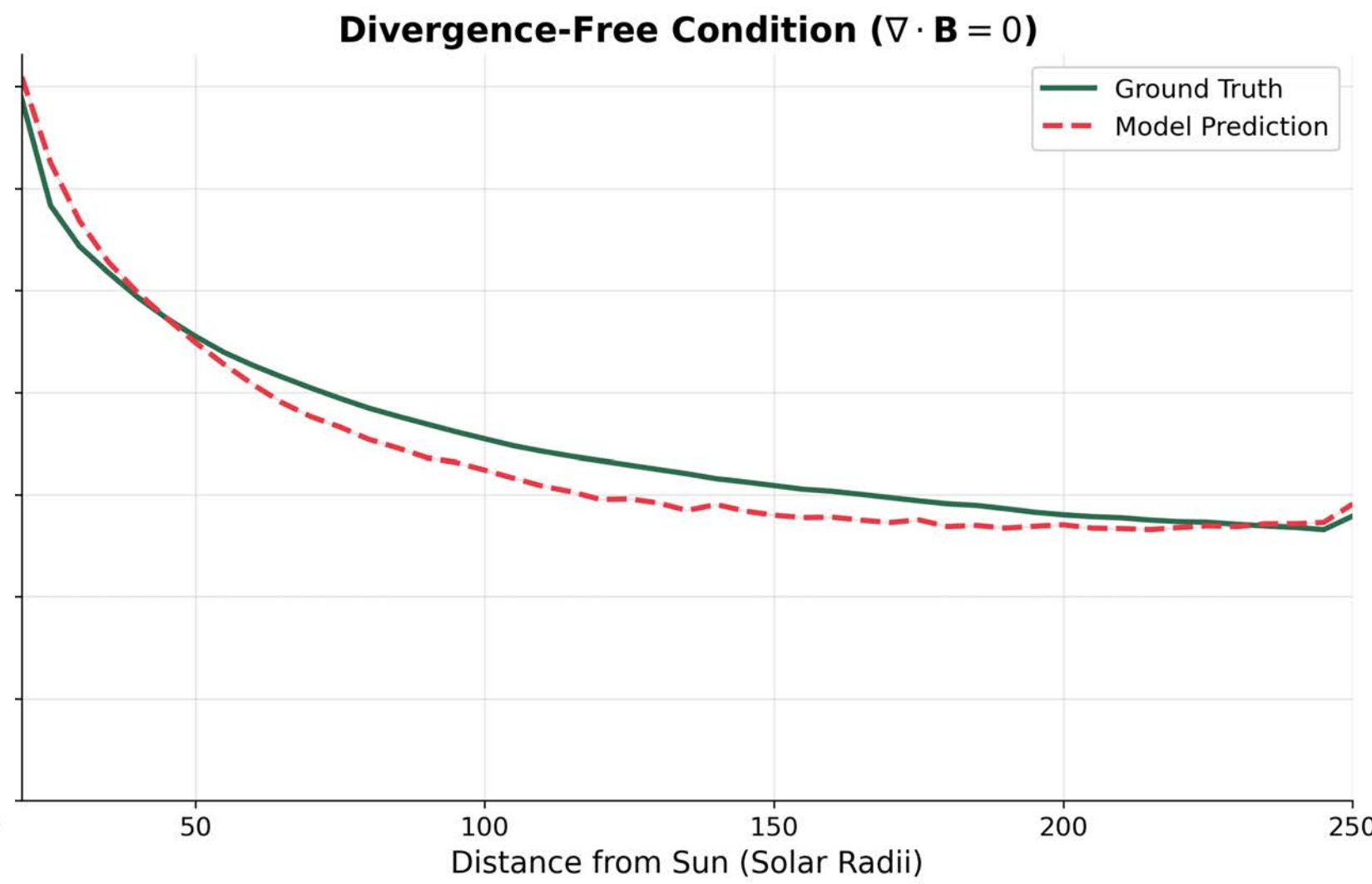
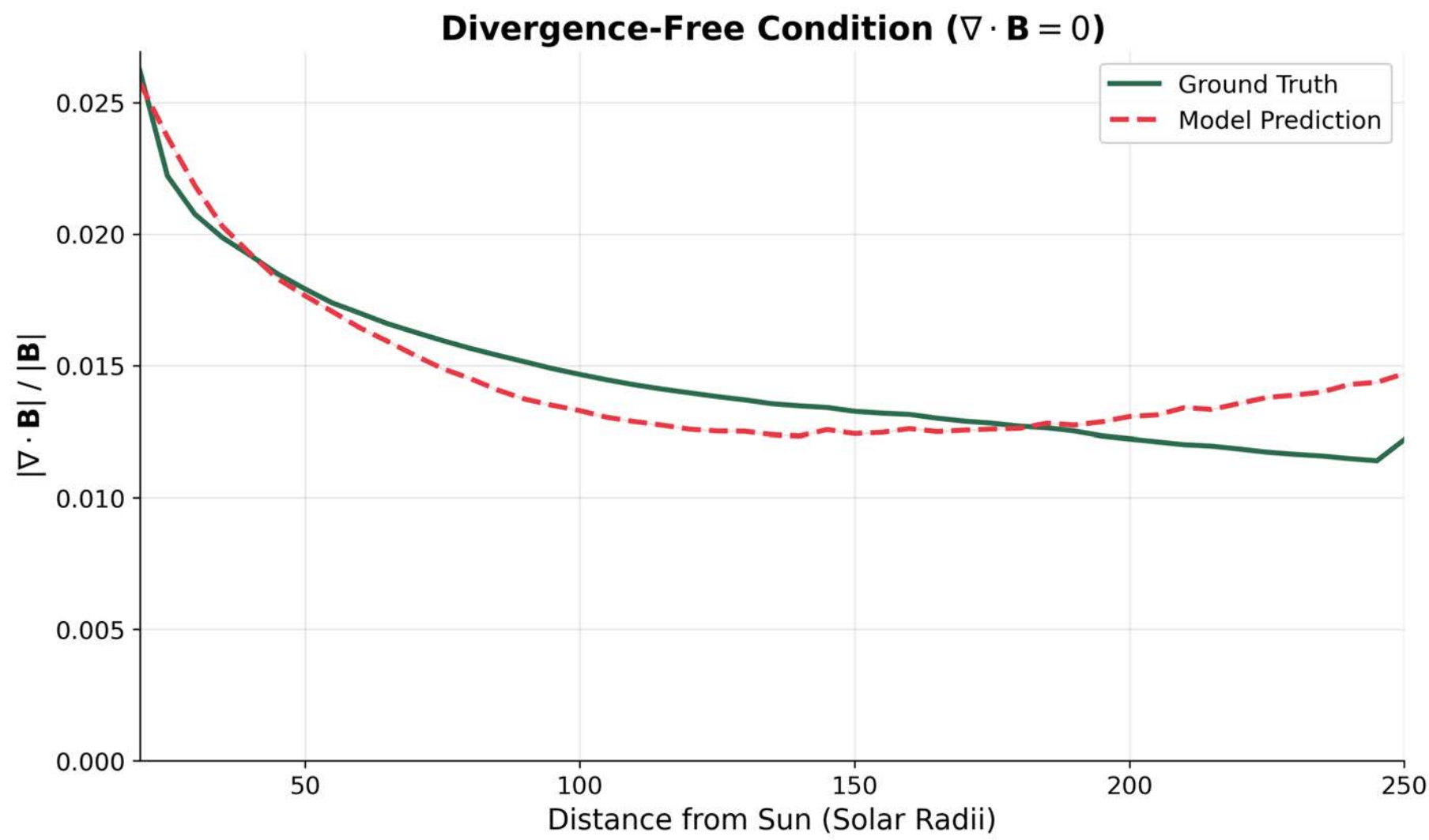
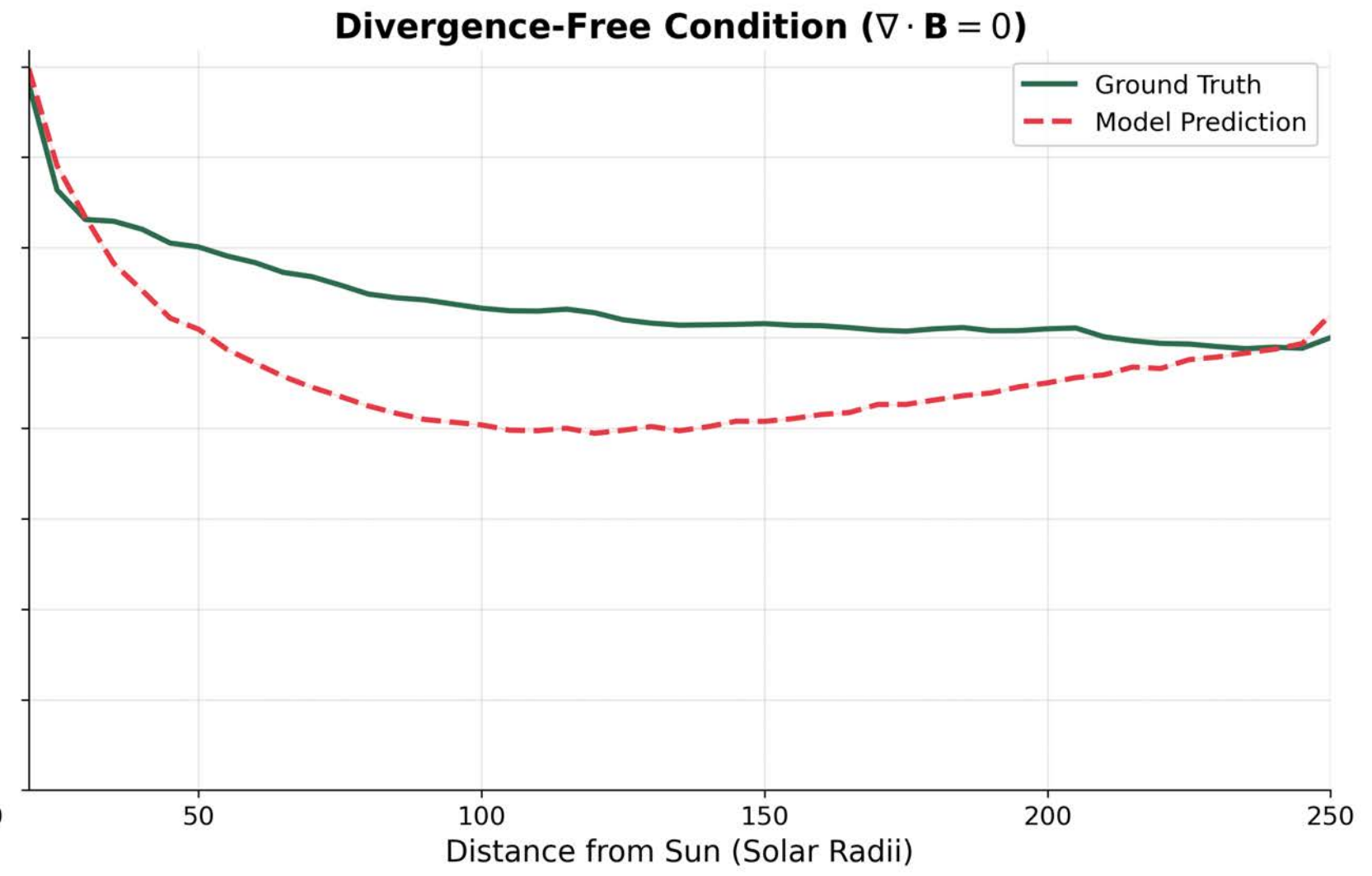
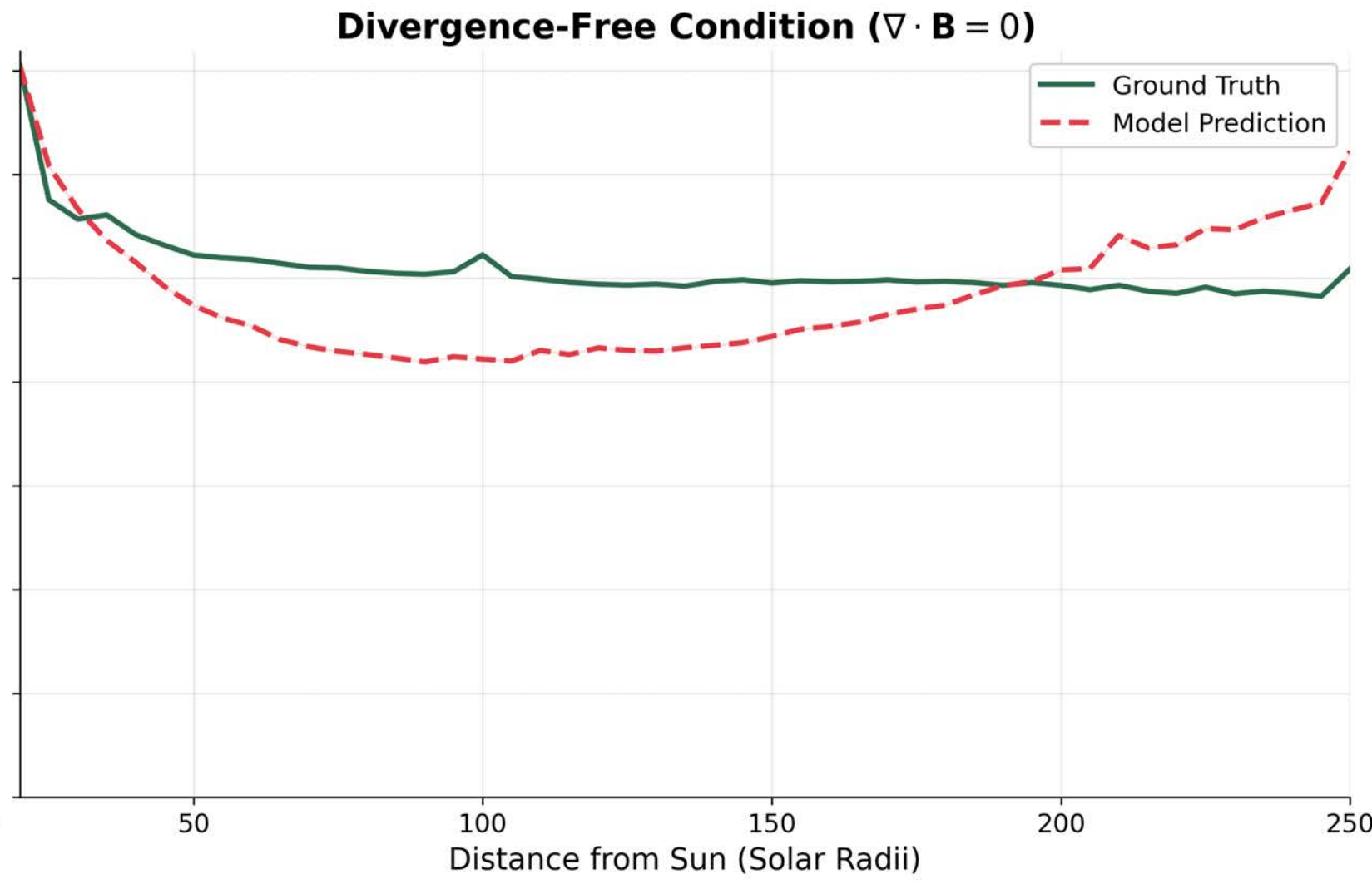
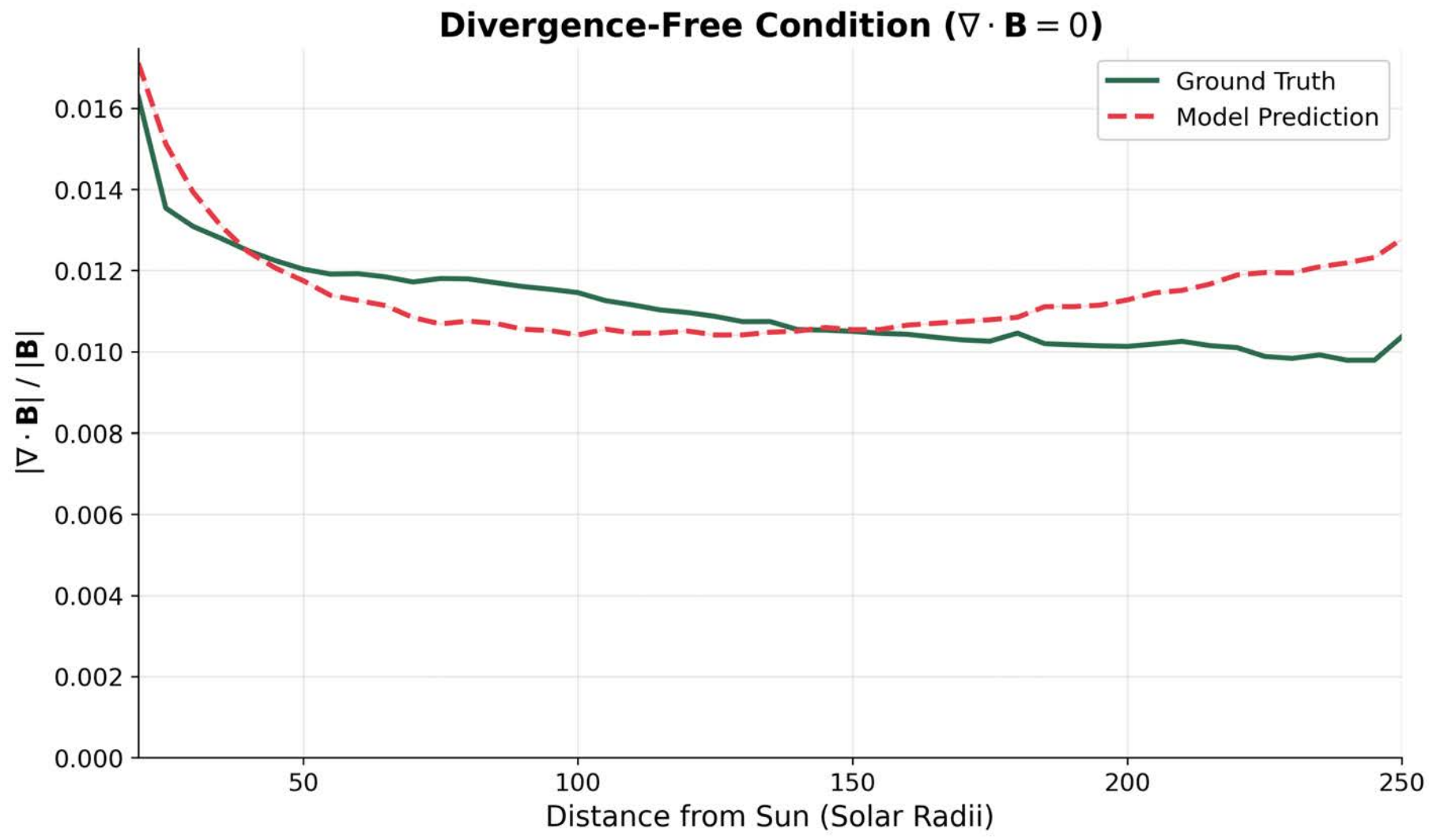
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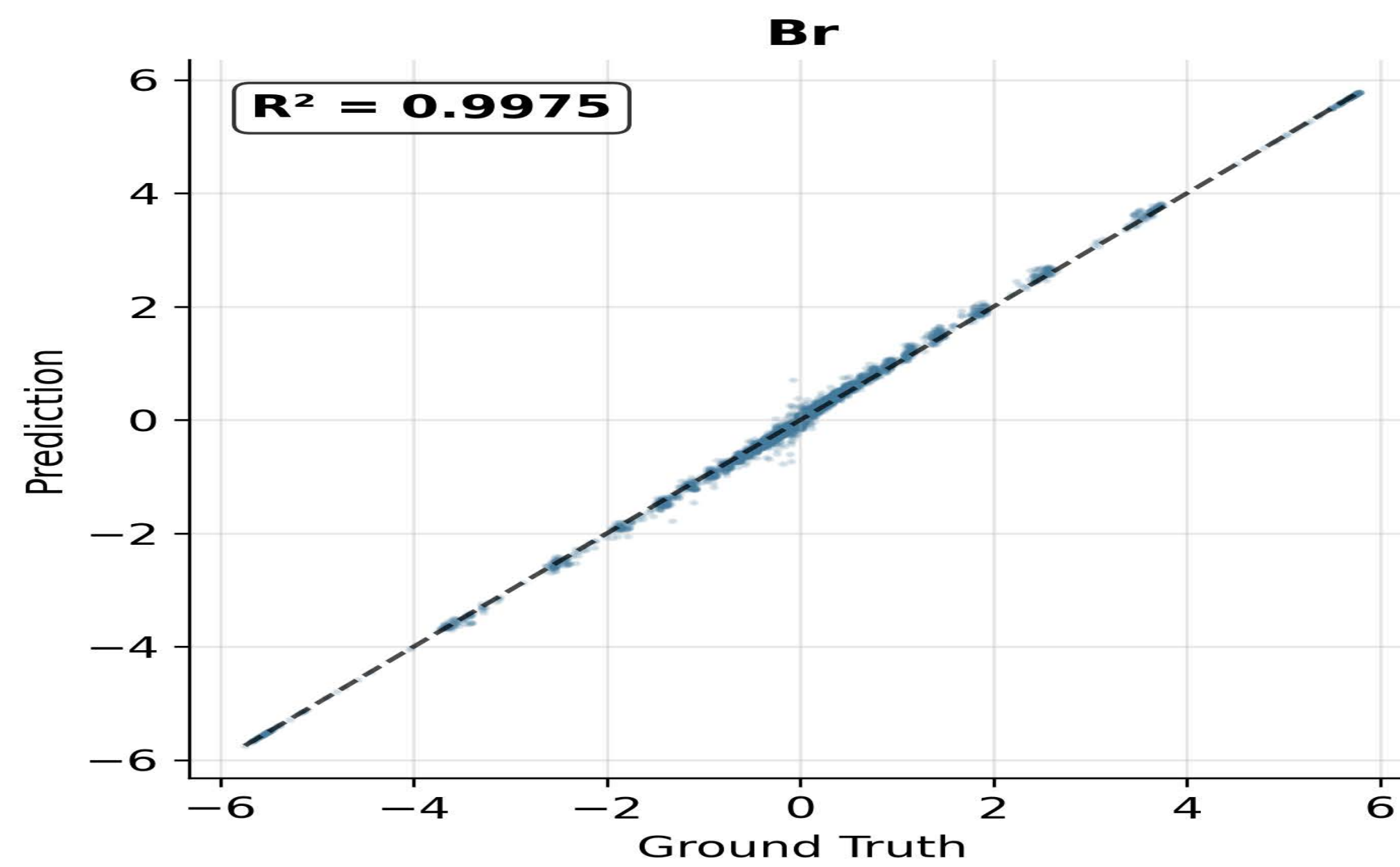
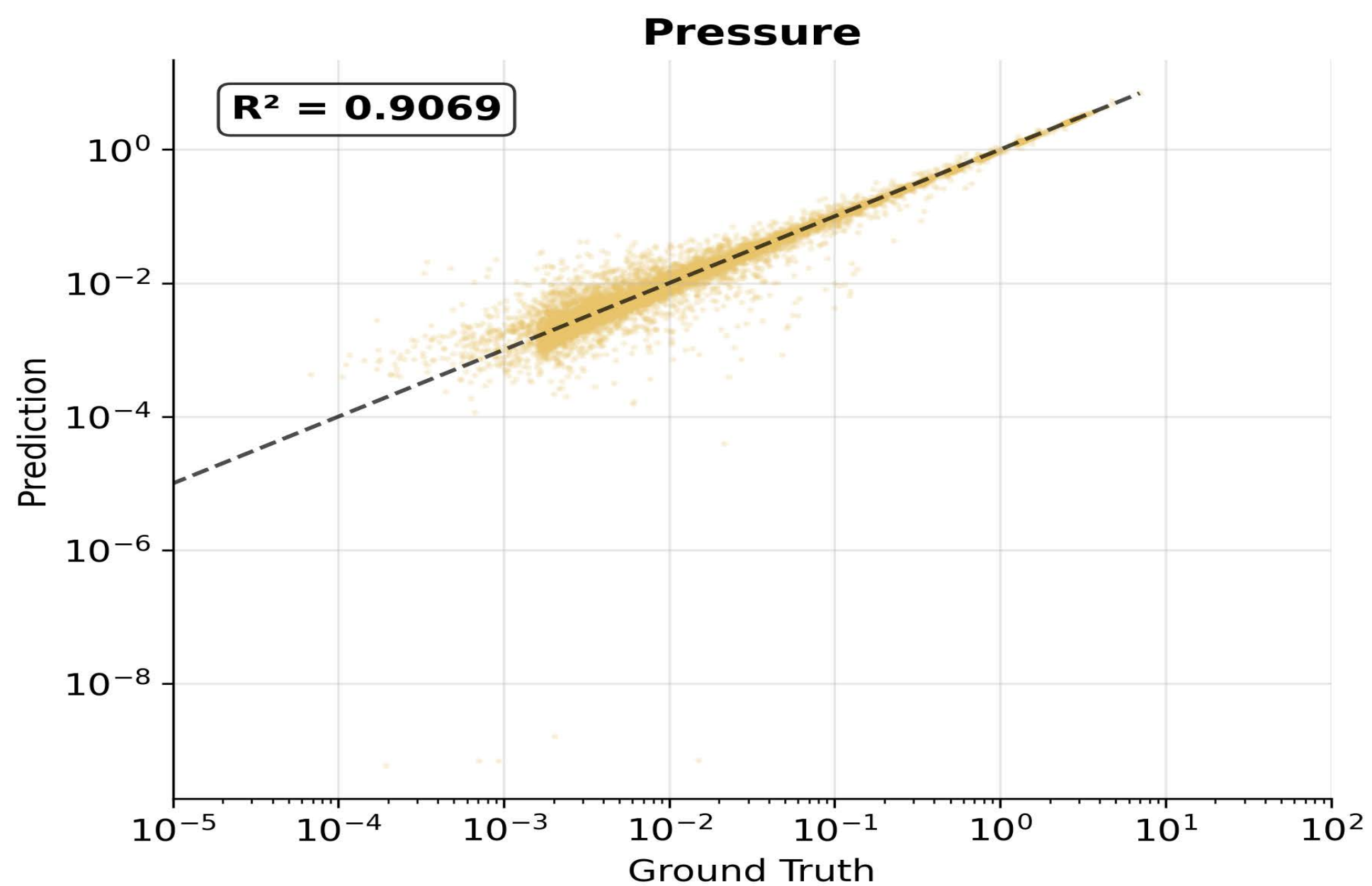
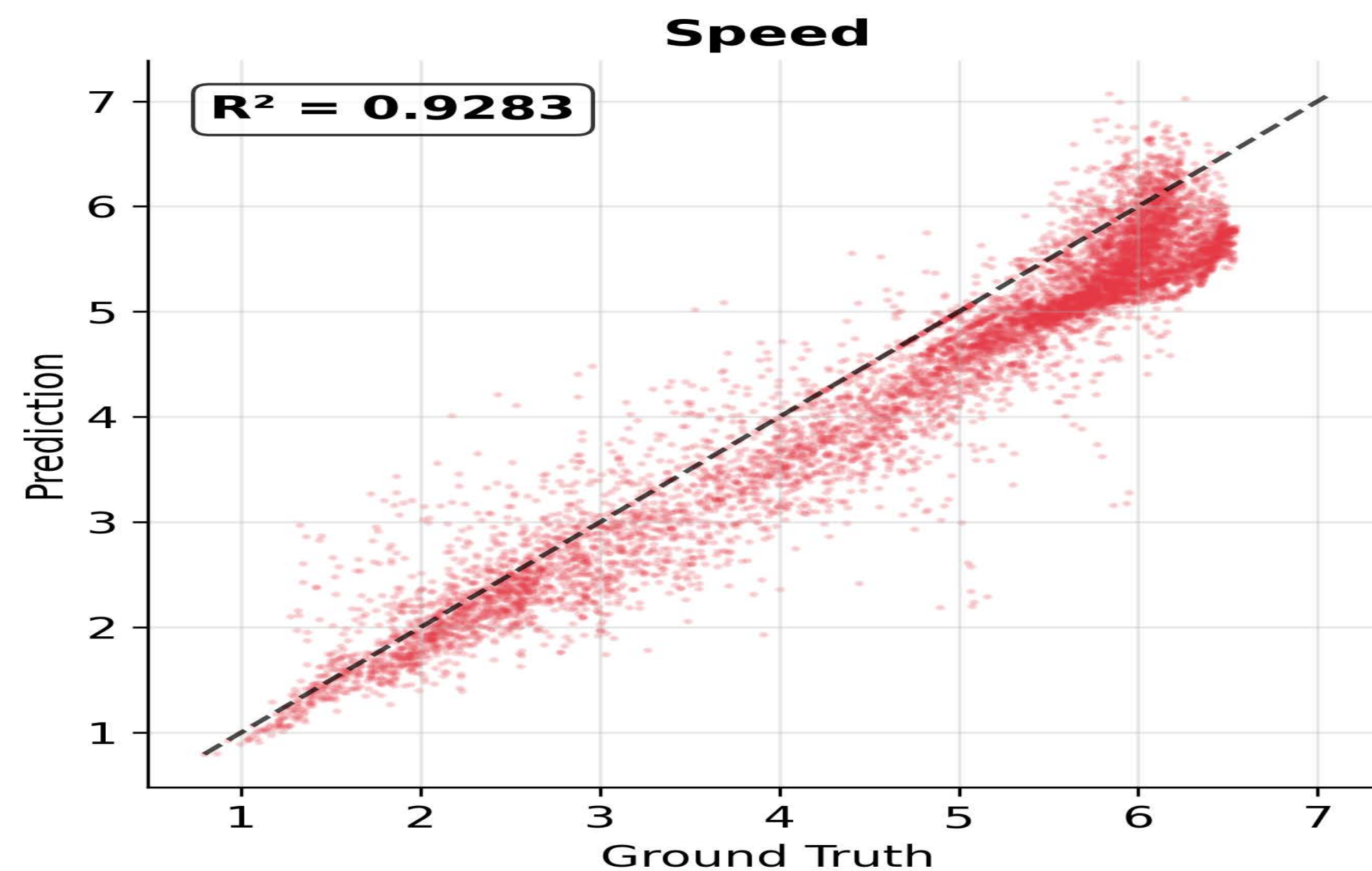
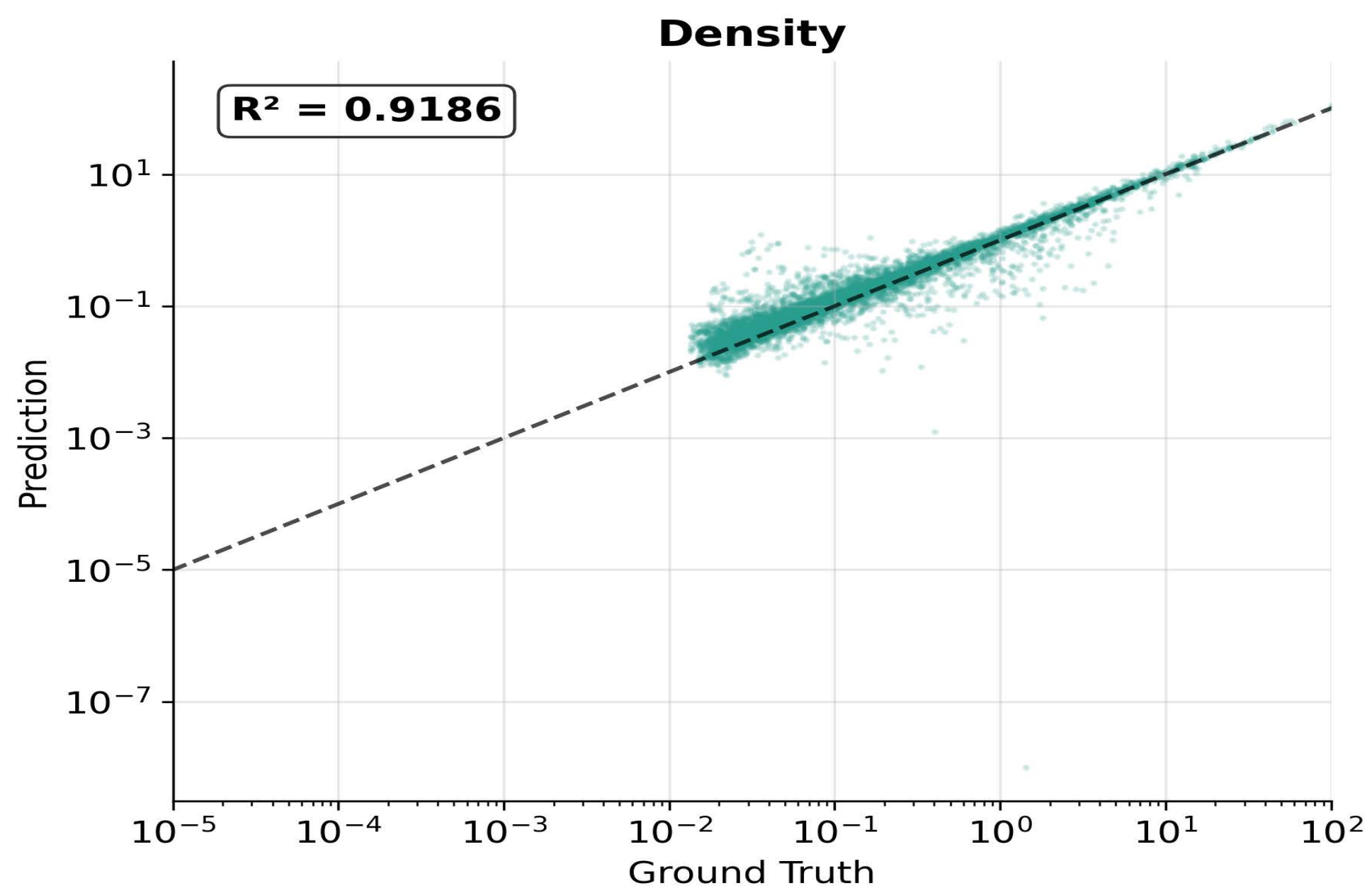
Divergence of B



Divergence of B

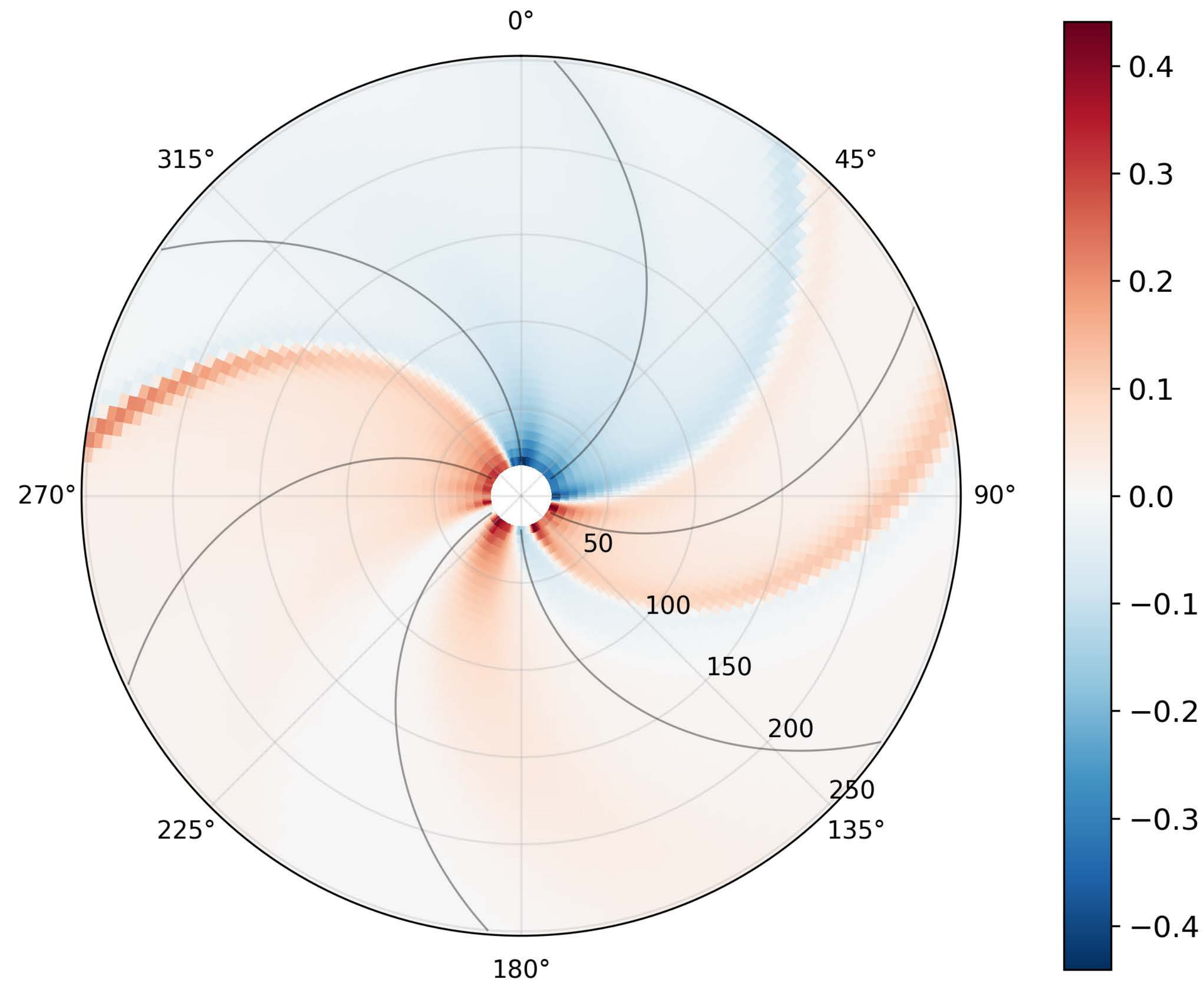


Far from Perfect

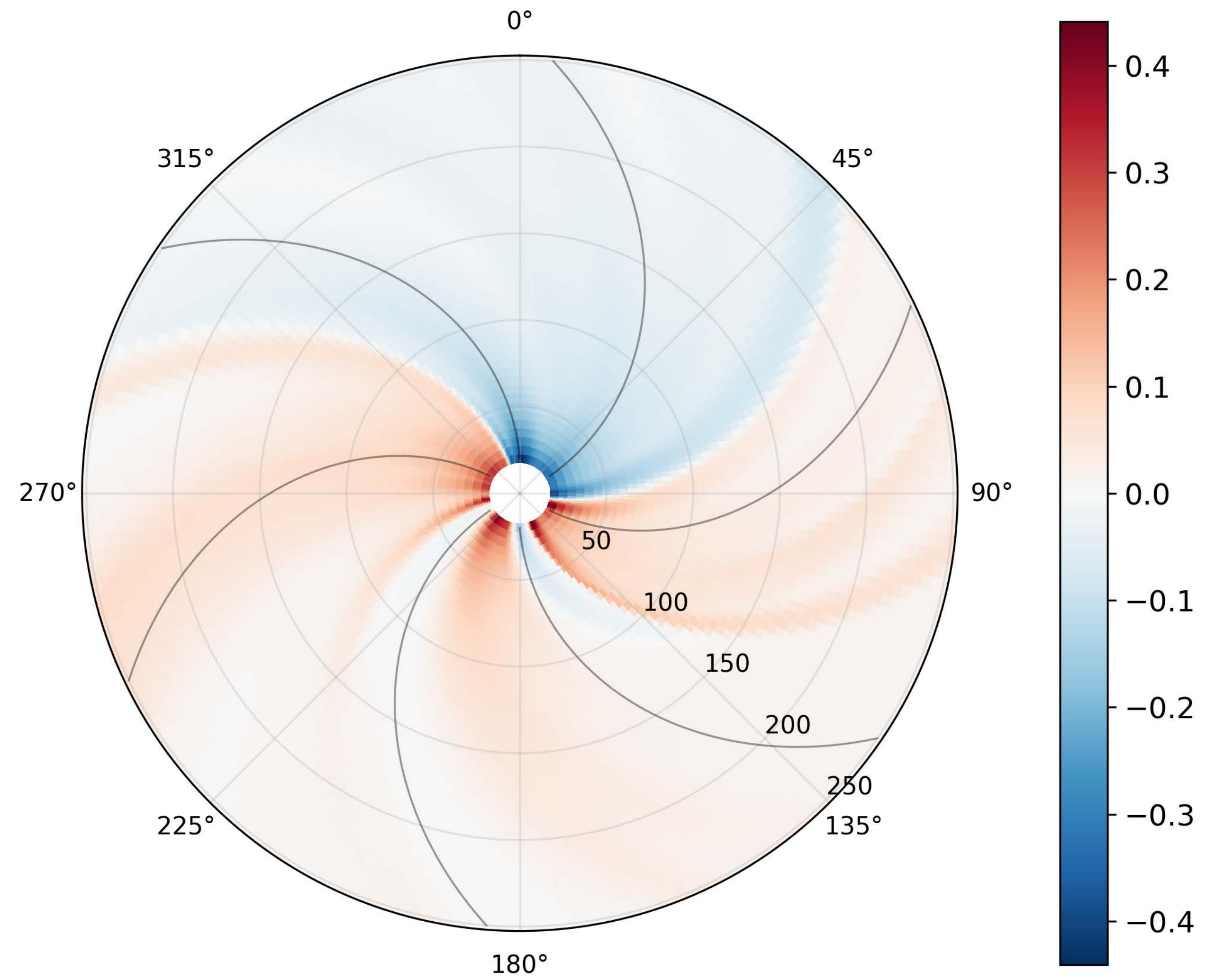


Challenges ...

Ground Truth



Model Prediction

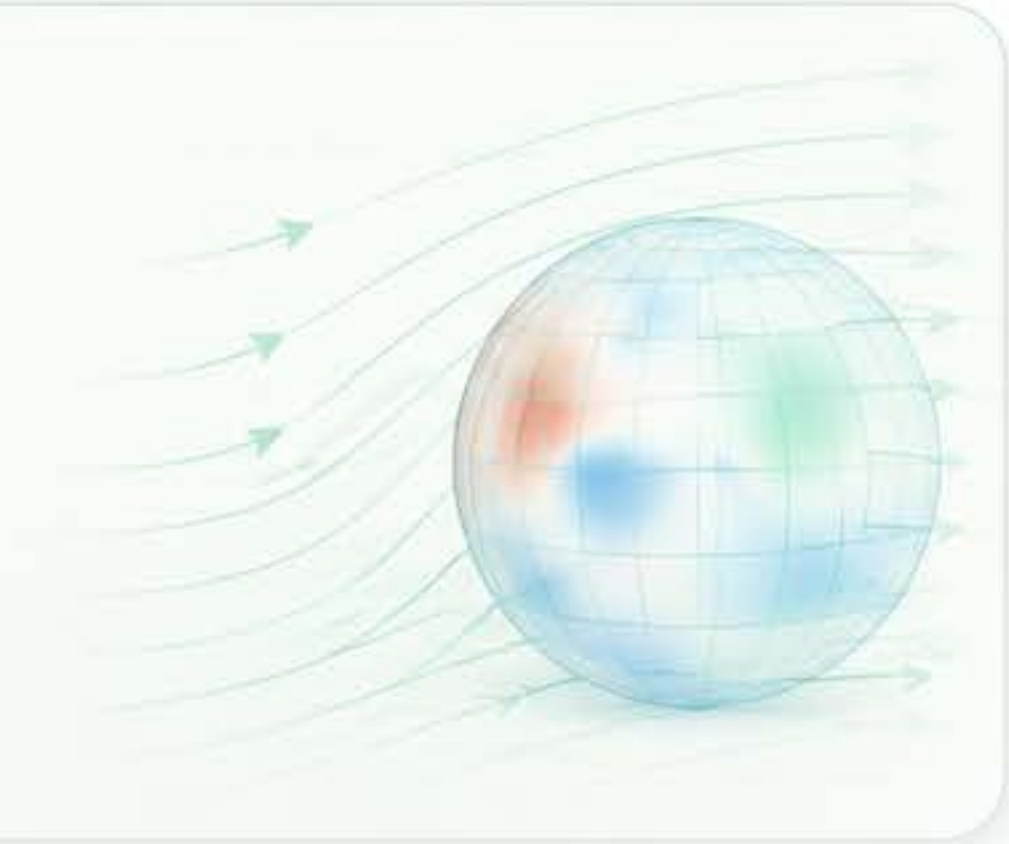


Take Away ...



Orders of Magnitude Faster:

- ✓ from ~100 CPU hrs to mere few seconds on one GPU
- ✓ capable of real-time operational forecasting

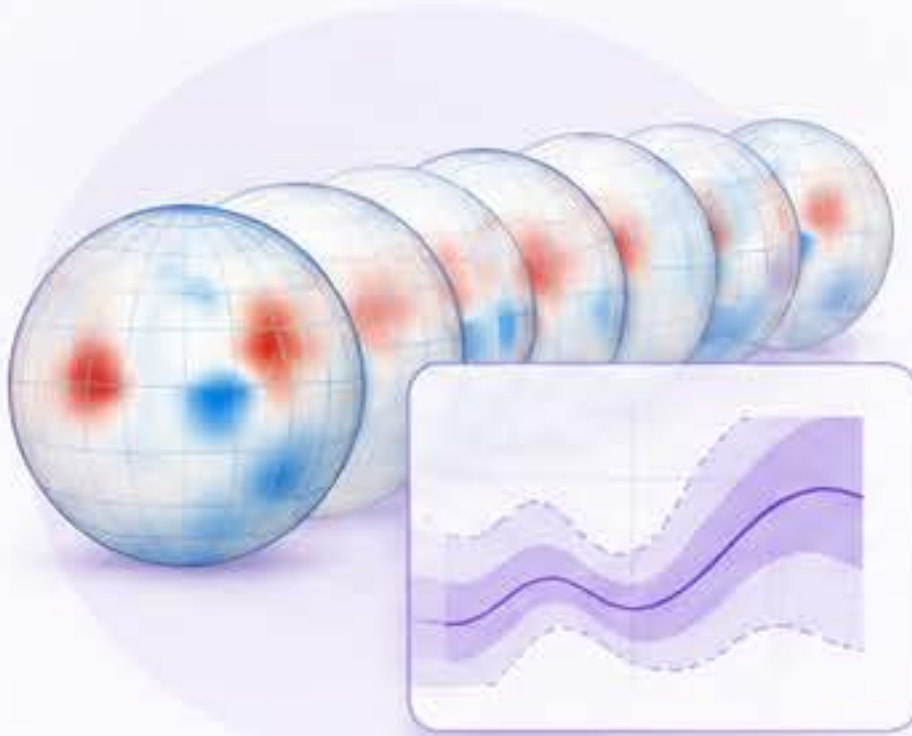
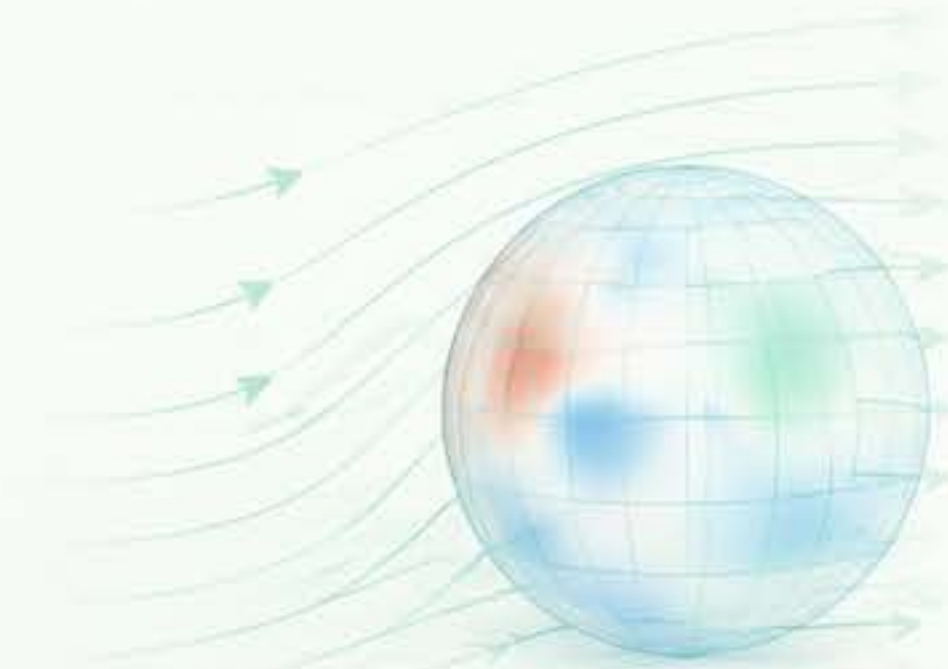


SO WHAT ?



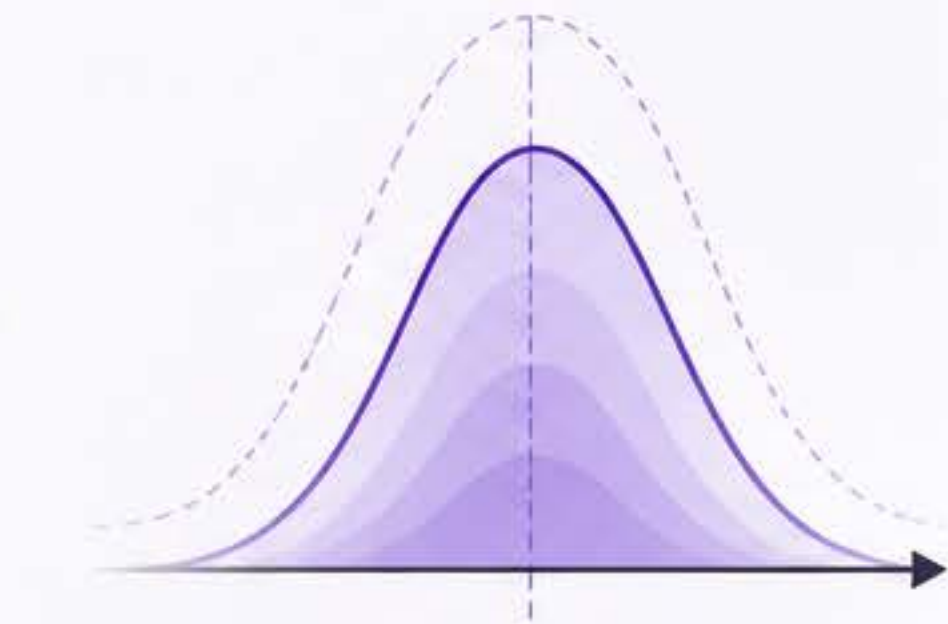
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Uncertainty Quantification:

- ✓ large ensembles to generate confidence bounds
- ✓ capable of incorporating other approaches (e.g., Bayesian, HNN, CF)

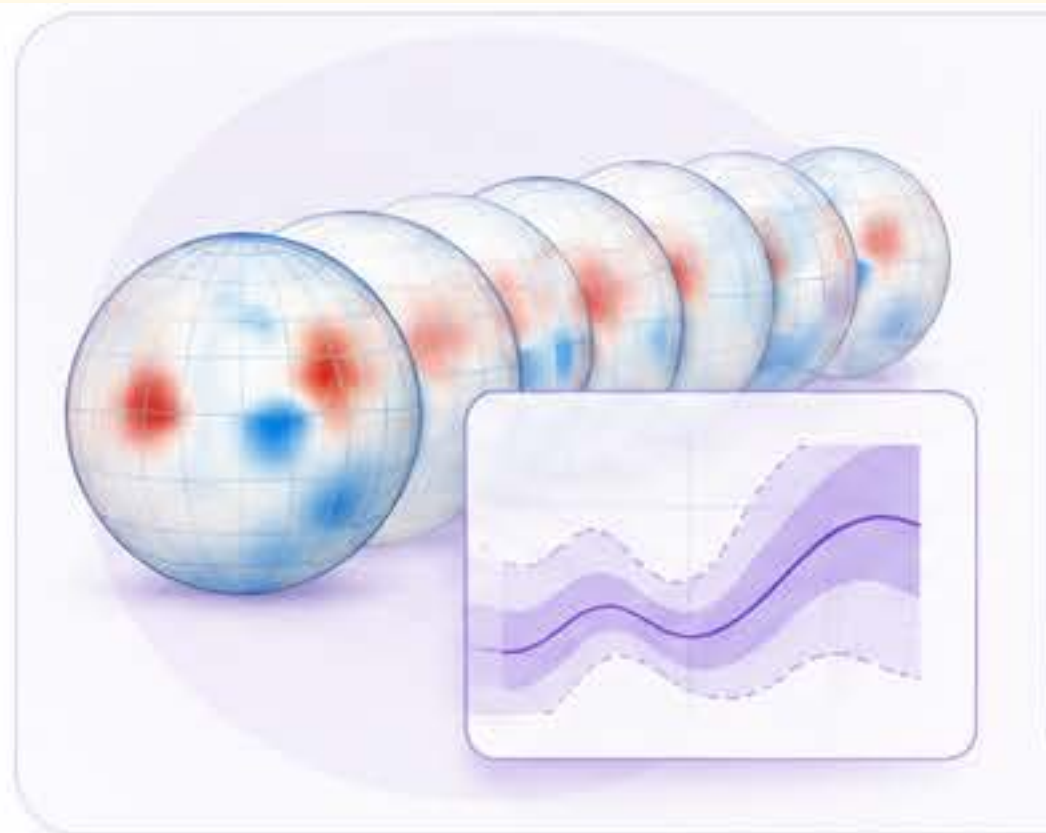
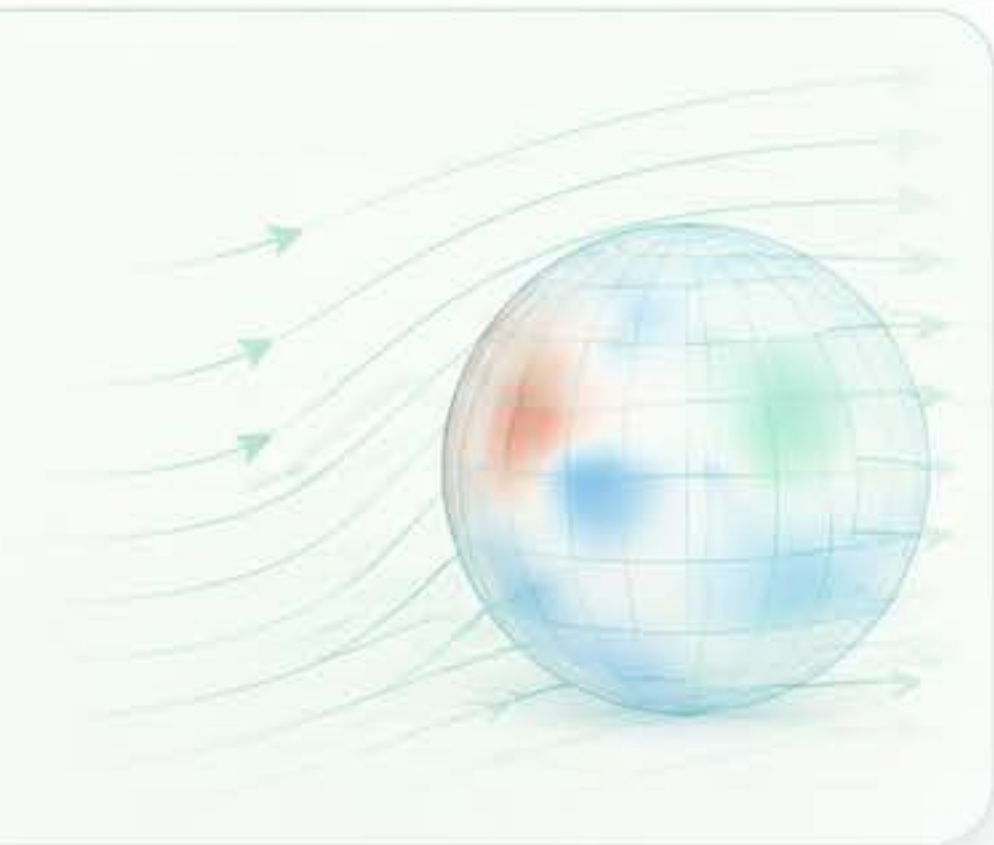


SO WHAT ?



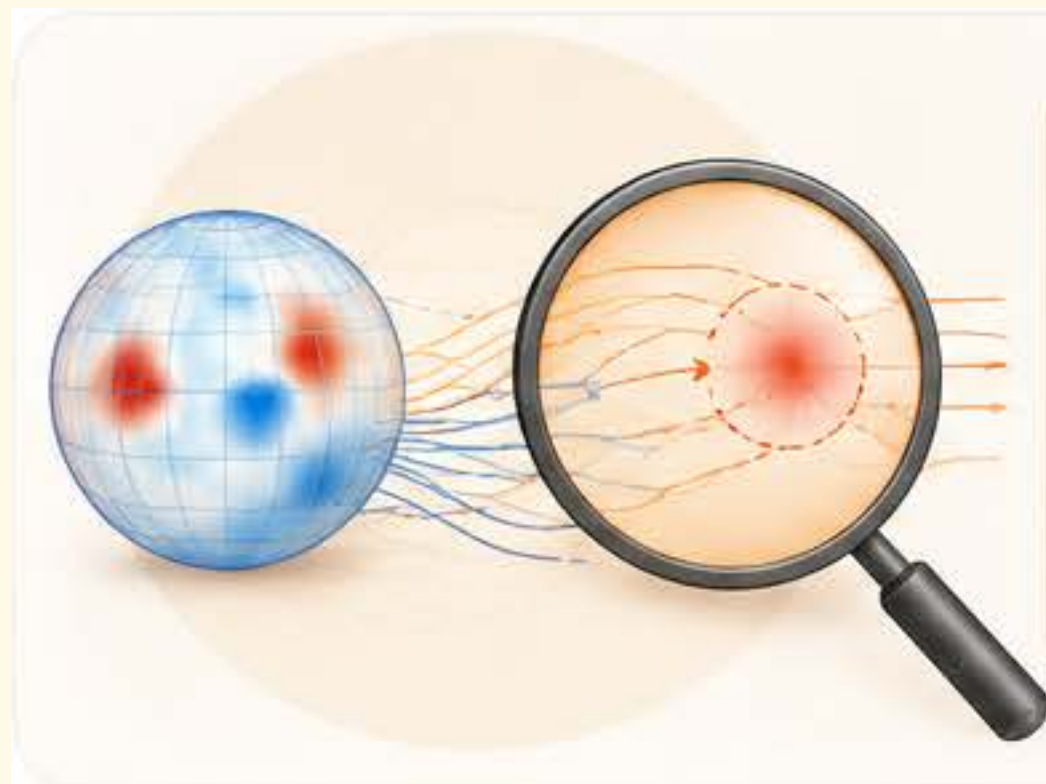
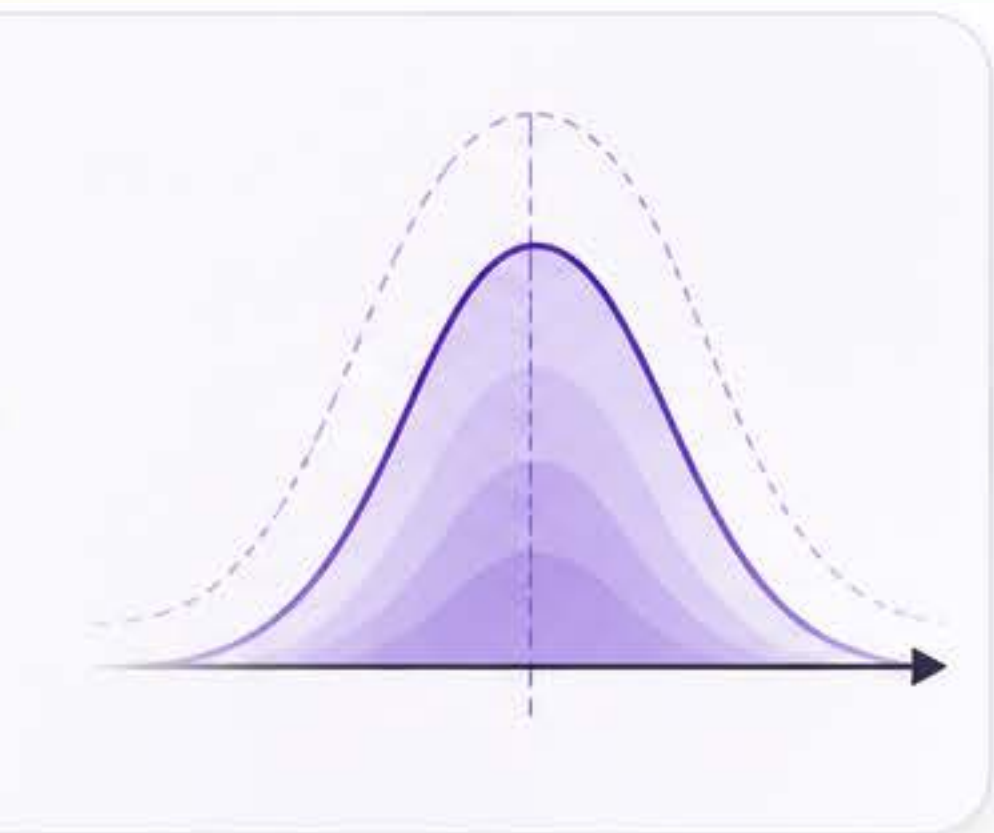
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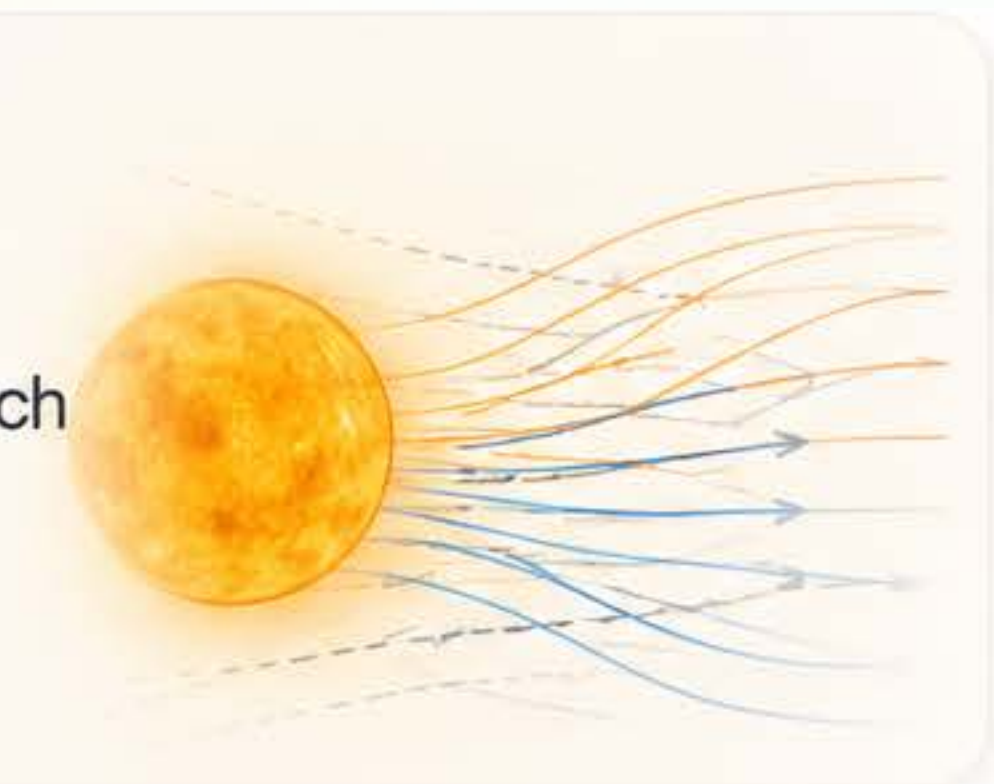
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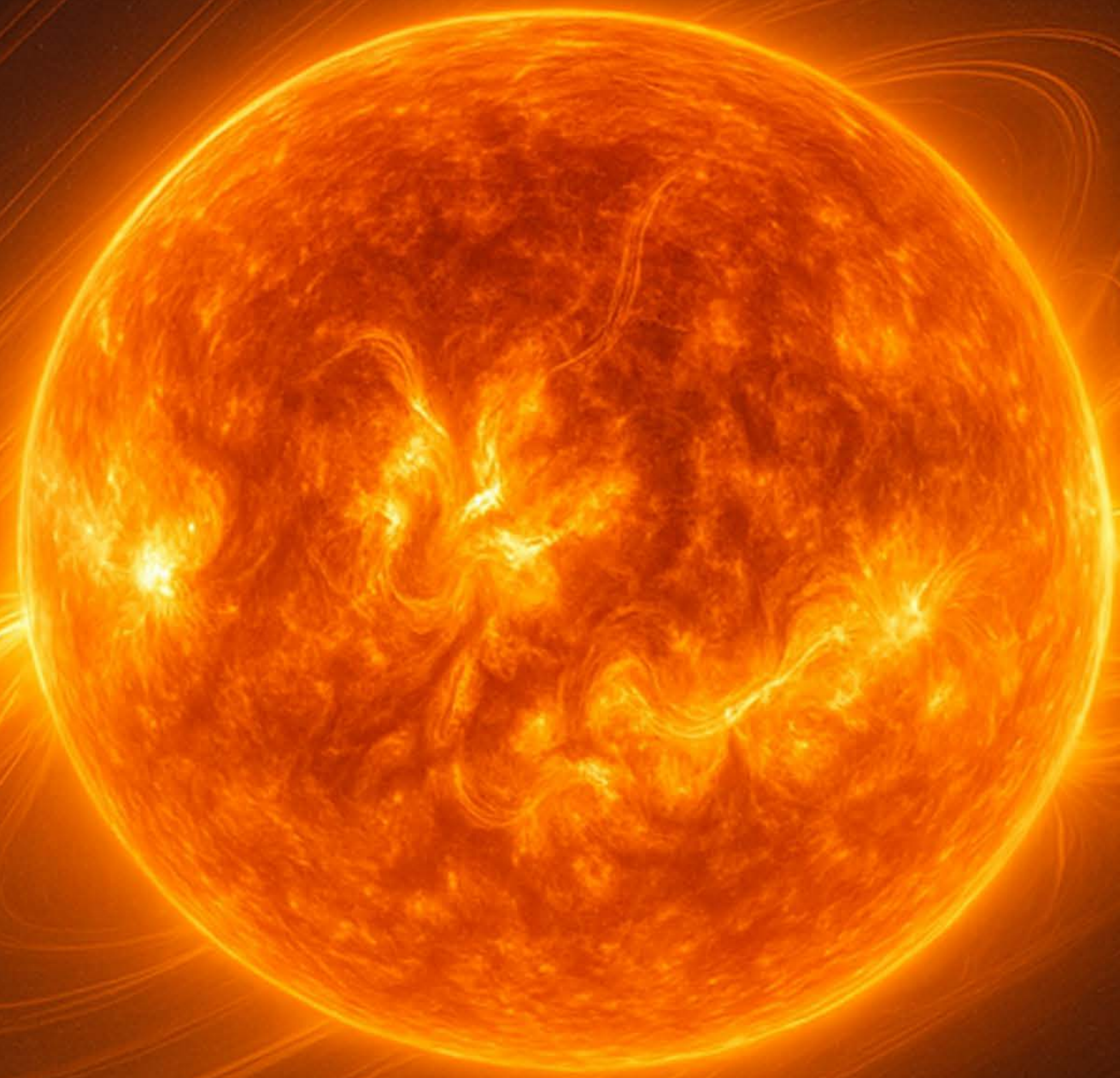


A Differentiable Diagnostic Lens:

- ✓ source discovery of model and observation mismatch
- ✓ *reverse-engineer* to correct near Sun solar wind conditions



**Thank
You!**



Curriculum Radial Rollout

