Spectropolarimetric Inversion in Four Dimensions with Deep Learning (SpIN4D): Overview, MHD Modeling, and Stokes Synthesis*

* Supported by NSF award #2008344

Xudong Sun, Kai Yang, Lucas Tarr, Matthias Rempel, Curt Dodds, Sarah Jaeggli, Peter Sadowski, Tom Schad, Ian Cunyngham, & Jiayi Liu

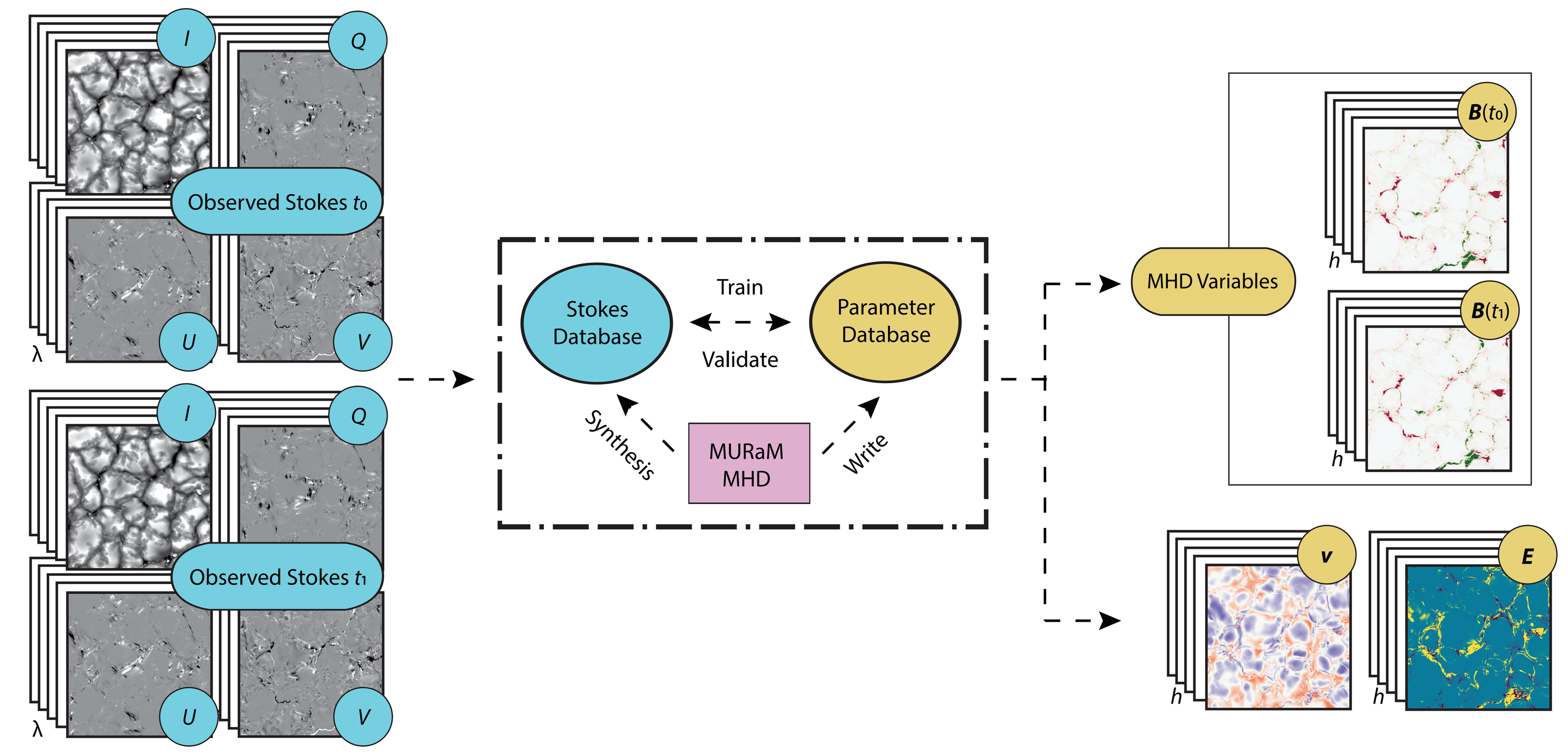

Fig. 1 | Illustration of SpIN4D model. Traditional methods fit for Stokes profiles (*I*,*Q*,*U*,*V*) at individual pixels. Additional steps are required to derive other parameters (e.g., velocity ***v*** and Poynting flux ***E***). Our new model, trained on a large library of MHD simulations, will take a temporal sequence of Stokes so as to utilize the coherent spatial/temporal structures. Higher-level parameters in 4D may be directly estimated.

Background

- Solar photosphere are well described by *MHD state variables*: magnetic field ***B***, temperature *T*, ρ, etc.
- Emergent polarized spectra, known as the *Stokes* profiles, can be used to infer the state variables.
- This *inversion* process requires radiative transfer modeling and can be computationally expensive.

Motivation

- NSF's *Inouye Solar Telescope* (*DKIST*) will provide high-cadence, high-resolution, multi-line Stokes data with revolutionary diagnostic potential.
- Owing to *DKIST*'s large data rate, new computational methods are needed to meet the demands of the "big-data" solar physics.
- Advances in deep learning (DL) and MHD simulations allows for faster and more accurate Stokes inversion algorithm, as demonstrated in [1].

Objectives

A set of DL models will be trained/tested on MURaM MHD simulations [2] of solar plages (Fig. 1, 2). The SIR code [3] will be used for Stokes synthesis/inversion.

- We will use MURaM simulations to create publicly available Stokes data sets that mimic Fe I 630 nm & 1.56 μm observations from *DKIST*/DL-NIRSP [4].
- We will use these data to develop open-source, deep convolutional neural networks that rapidly invert Stokes profiles.
- We will compare our DL models to SIR inversions to benchmark the performance of each.
- We will explore *domain adaptation* methods to reduce potential differences between simulation and observation domains.

Highlights

- SpIN4D will exploit spatial/temporal (4D) *coherence properties* in observations (Fig. 1), as well as the implicit physical constraints in MHD simulation.
- SpIN4D will address the 180° azimuthal ambiguity resolution *during* DL inversion.
- SpIN4D will provide the uncertainty over the inferred MHD states using the latest DL methods.

Progress

- We finished six MURaM runs (Fig. 2) for a total of 36 solar hr, totaling 85 TB output.
- We finished the Stokes synthesis for Fe I lines using SIR (LTE) and DeSIRe (NLTE), totaling 10 TB output.
- We finished SIR inversion from the synthetic Stokes profiles that will be used for benchmarking.
- Overview paper & data release are planned for later this year.
- Initial DL model training for individual snapshots is in progress.
- DKIST observation has been carried out during Cycle 2. Data analysis is underway.

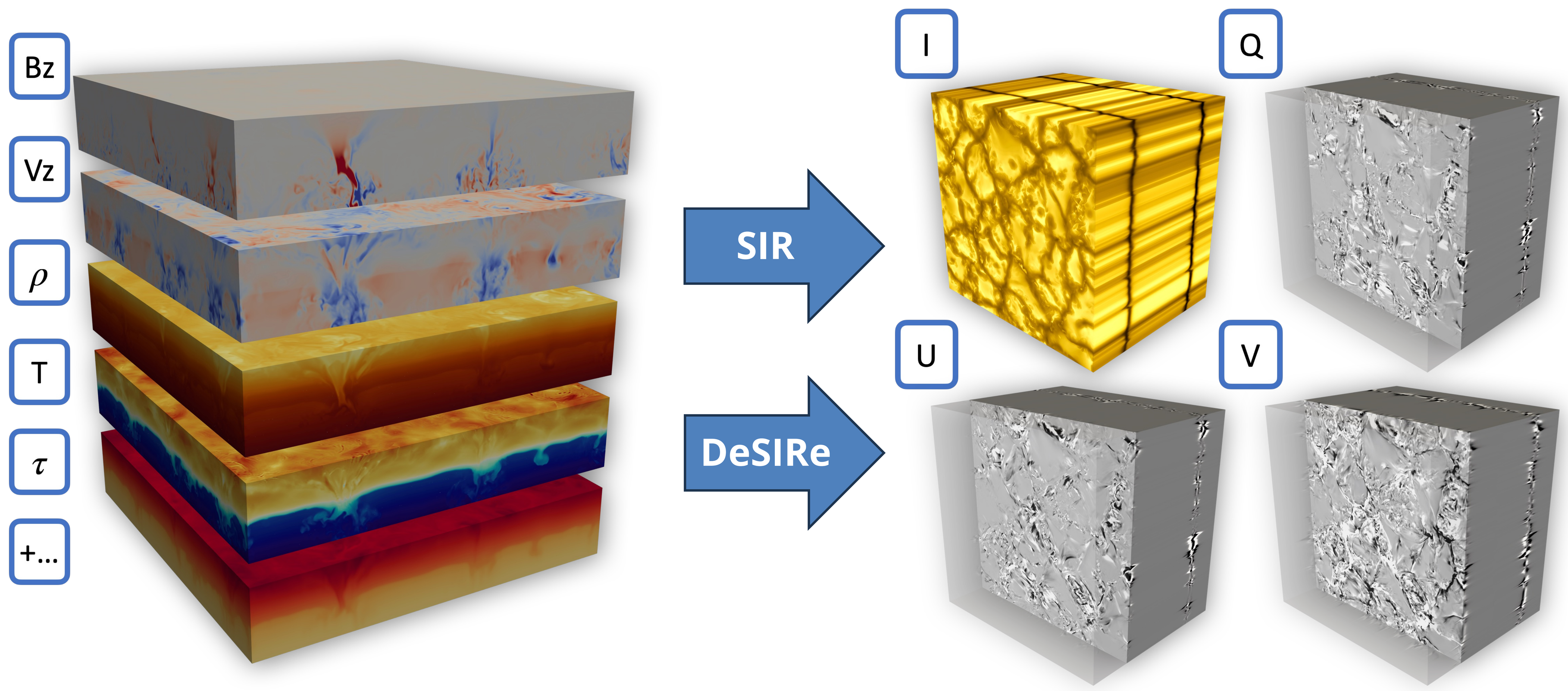

Fig. 2 | Illustration of MHD modeling and Stokes synthesis. Left: snapshot of MURaM simulation for plage region, for vertical field (*Bz*), vertical velocity (*Vz*), density (ρ), temperature (*T*), optical depth (τ), etc. The domain size is 25 × 25 × 8.2 Mm. The spatial resolution is 16 (12) km in horizontal (vertical) direction. The cadence is 40 s. We have run six cases: small-scale dynamo (SSD), SSD with 50 G, 100 G, and 200 G initial vertical field, SSD with 50 G initial field in all directions, and a larger FOV view with a mixture of four different initial mean fields. Right: illustration of wavelength dependent, synthetic Stokes profiles (*I*, *Q*, *U*, *V*). The spectral sampling is 0.89 pm (3.13 pm) for the 630 nm (1.56 μm) lines.

References

[1] Asensio Ramos, A., & Díaz Baso, C. J. 2019, *A&A*, **626**, A102
[2] Rempel, M. 2014, *ApJ*, **789**, 132
[3] Ruiz Cobo, B., & del Toro Iniesta, J. C. 1992, *ApJ*, **398**, 375
[4] Jaeggli, S. A., Lin, H., Onaka, P., et al. 2022, *SoPh*, **297**, 137