Developing the Michigan Sun-to-Earth Model

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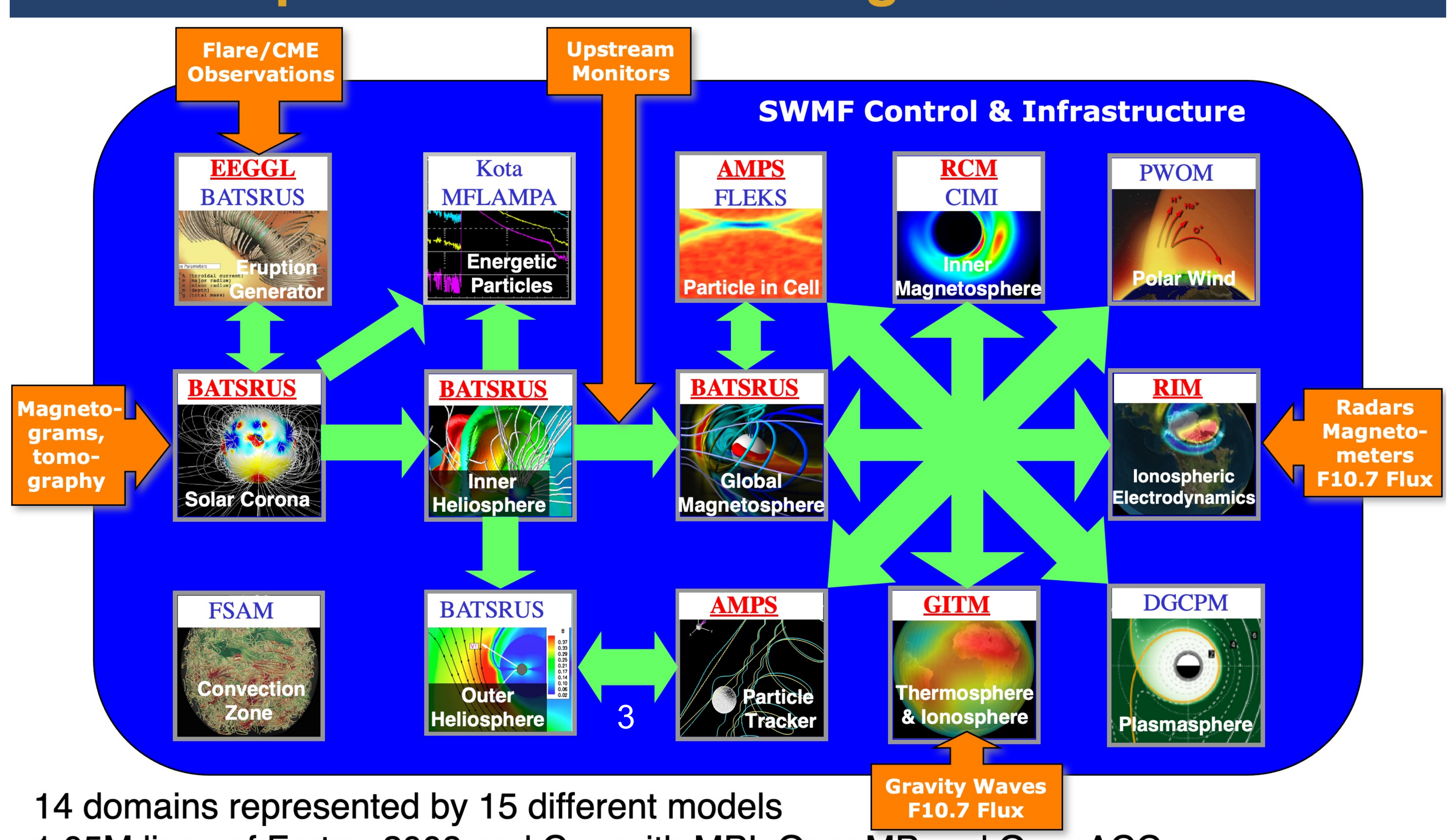
Michigan Sun-to-Earth Model with Quantified Uncertainties and Data Assimilation: MSTEM-QUDA

- **MSTEM-QUDA is based on the Space Weather Modeling Framework (SWMF)**
- **It employs First-principles models from the surface of the Sun to the surface of Earth in combination with data assimilation and uncertainty quantification to provide optimal and quantified probabilistic space weather forecasting.**
- **The model will run efficiently on multiple GPUs to achieve faster than real time performance and provide high-fidelity & high-skill prediction with a practically useful forecast window.**
- **Open-source software: https://github.com/MSTEM-QUDA**
- **Funded by the NSF SWQU program**

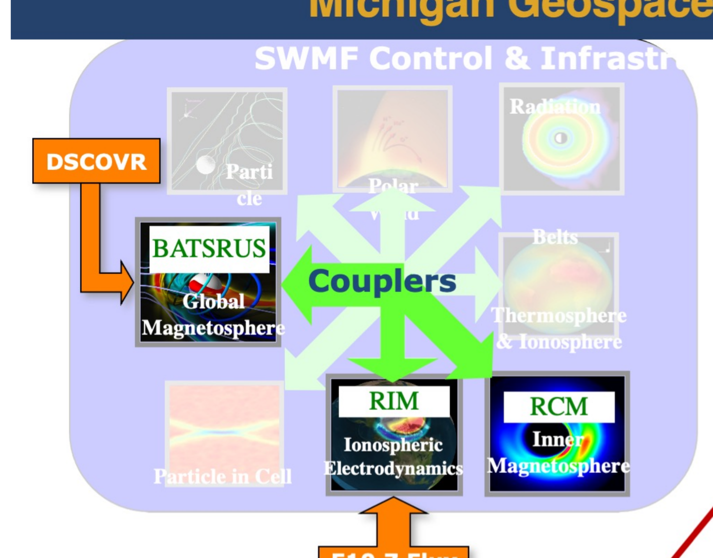
Name	Dept.	Task	Name	Dept.	Task
Gabor Toth PI	CLASP	Sim. GPU	Yifu An (GT)	CLASP	GPU
Shasha Zou CoPI	CLASP	Geosp, DA	Timothy Keebler (GT)	CLASP	Sim.
Yang Chen CoPI	Stat.	DA	Jiaen Ren (SZ)	CLASP	Sim.
Xun Huan CoPI	ME	UQ	Daniel Iong (YC)	Stat.	DA
Bart van der Holst CoP	CLASP	Solar	Hongfan Chen (YC)	Stat.	DA
Ward Manchester	CLASP	Solar	Aniket Jivani (XH)	ME	UQ
Michael Liemohn	CLASP	Geosp			
Nishtha Sachdeva	CLASP	Solar, DA			
Zhenguang Huang	CLASP	Sim., DA			
Alexander Gaenko	CSCAR	GPU			

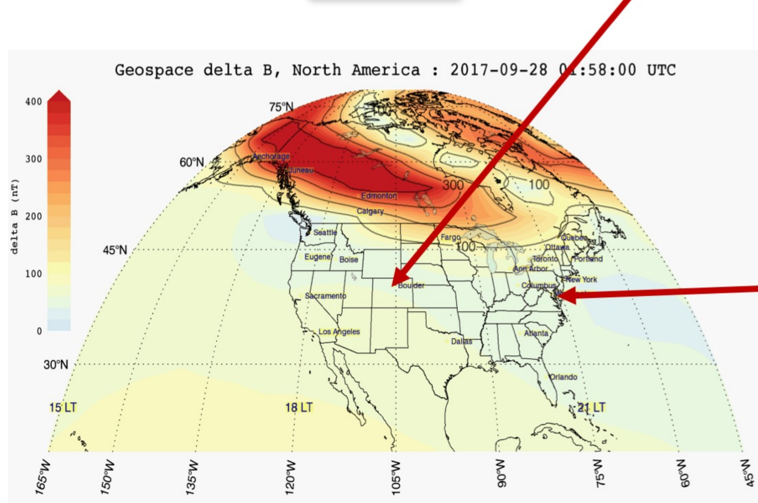
Space Weather Modeling Framework



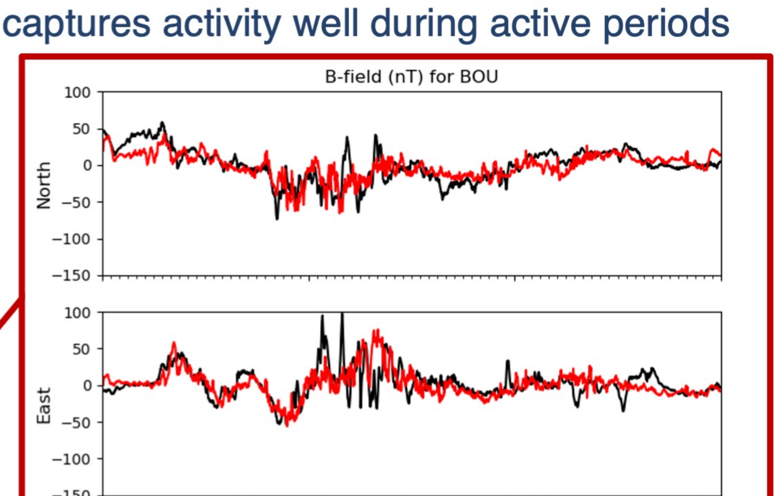
14 domains represented by 15 different models
1.05M lines of Fortran2008 and C++ with MPI, OpenMP and OpenACC
Scripts, Makefiles, visualization macros, documentation, nightly tests.
SWMF is freely available: http://csem.engin.umich.edu/swmf. Runs-on-request: CCMC.
Open-source part: https://github.com/MSTEM-QUDA, AMPS and GITM

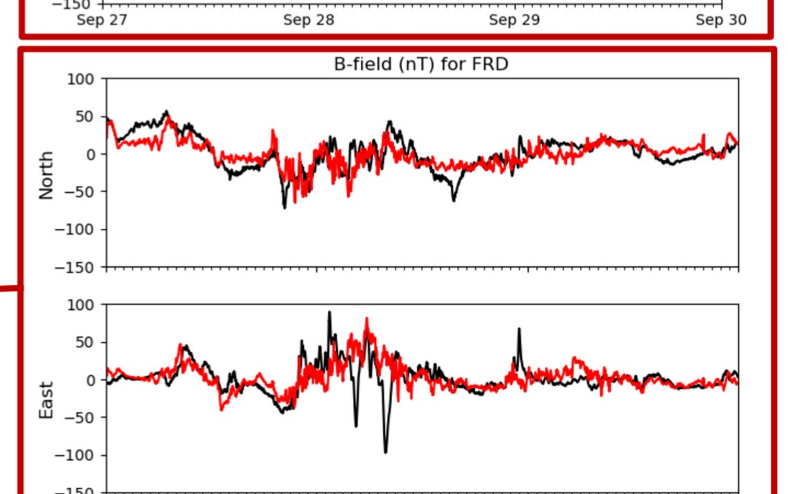
Michigan Geospace Model at SWPC since 2016



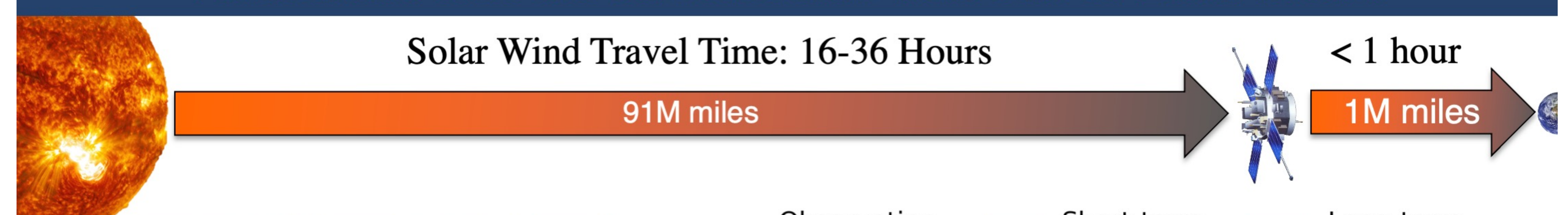


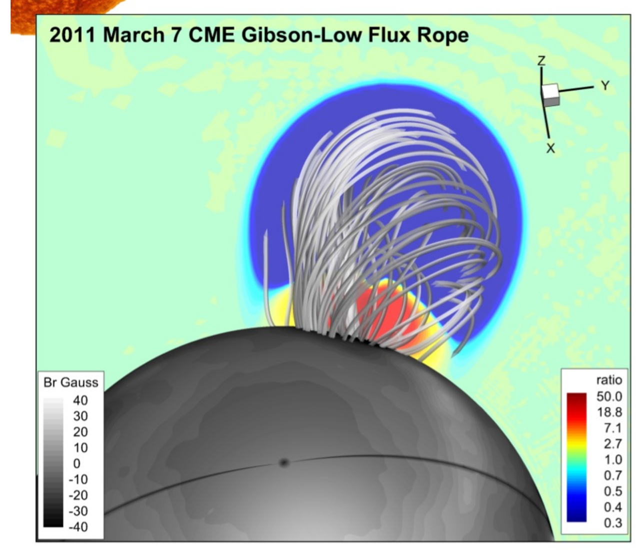
- Global and regional forecast: captures activity well during active periods

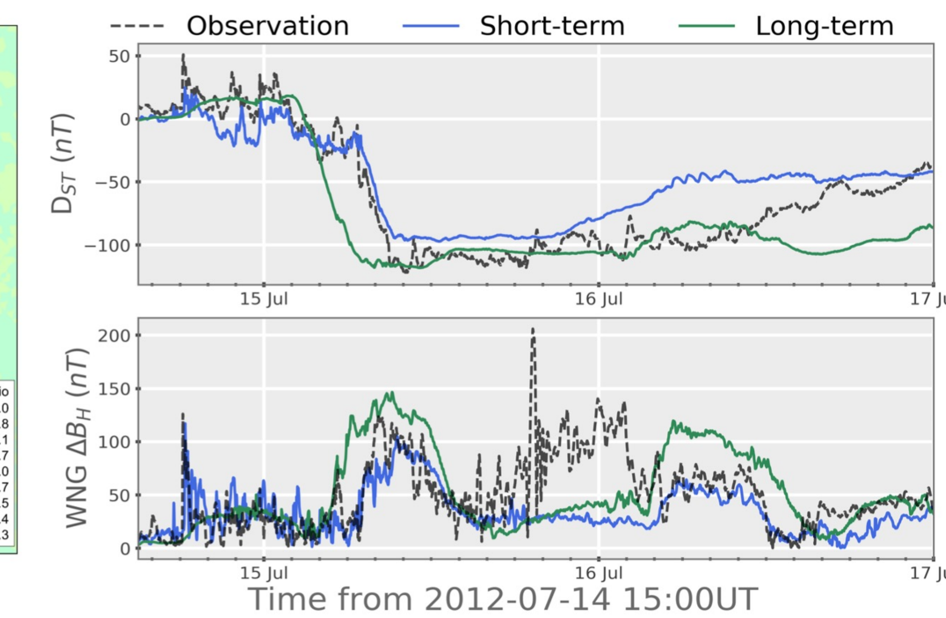




Future: Increase the forecast time with Sun-to-Earth model





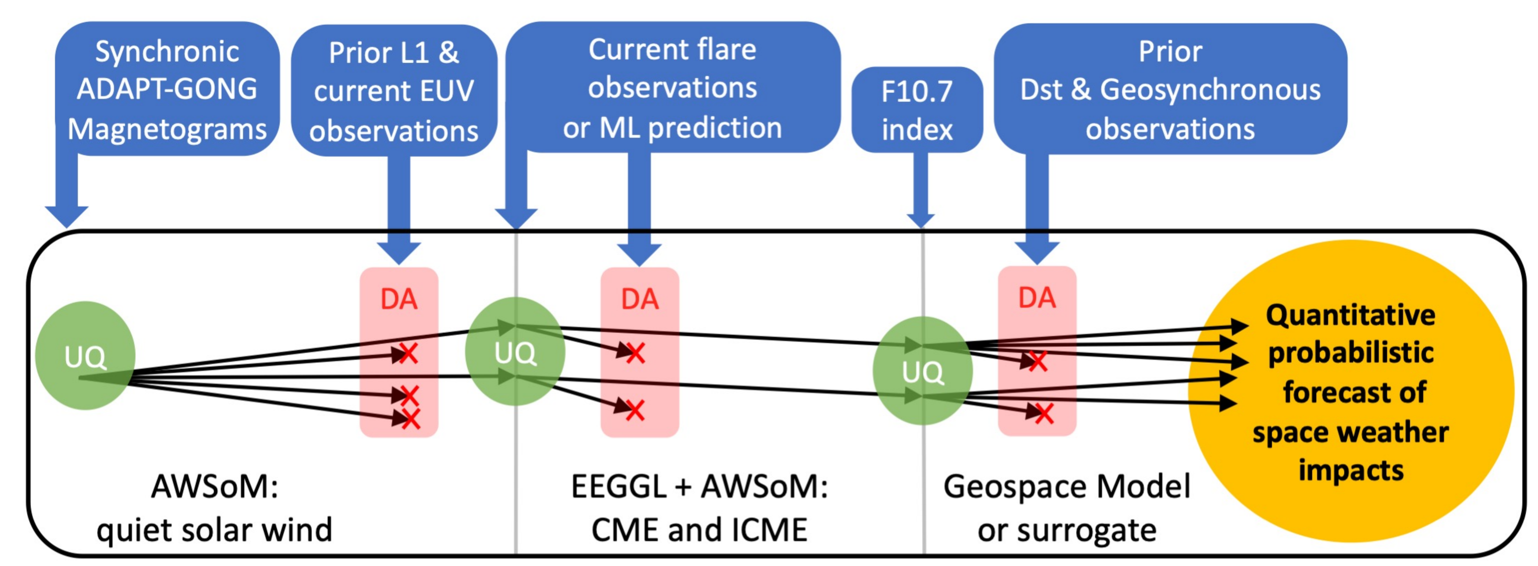


AWSoM-EEGGL prediction of Dst and ΔB_H

- Amplitudes are good
- Too smooth variation
- **Still good skills**

	ΔB_H (100 nT Threshold)		
	PoD	PoF	Heidke
L1 Obs. + Geospace	0.5760	0.0211	0.5871
EEGL-AWSOM + Geospace	0.5732	0.0564	0.5431

Michigan Sun-To-Earth Model with Quantified Uncertainty and Data Assimilation: MSTEM-QUDA

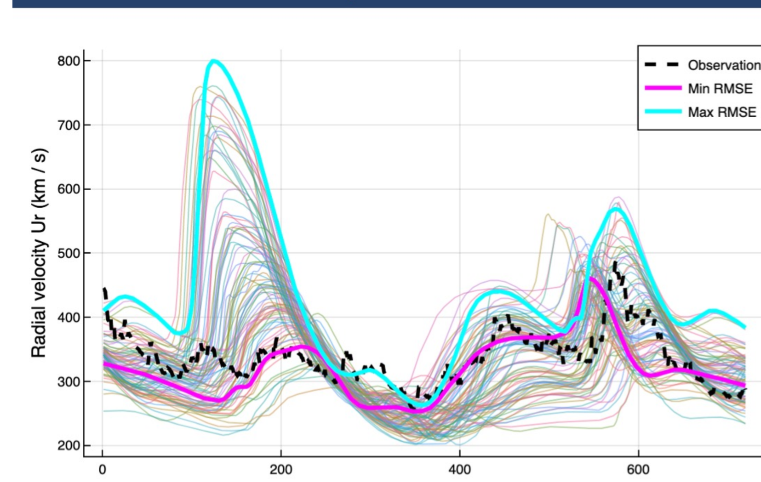


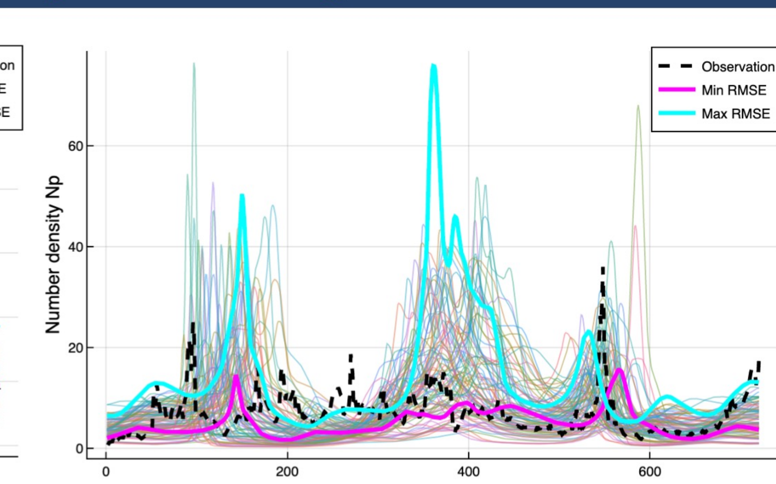
SWMF + Data Assimilation + UQ

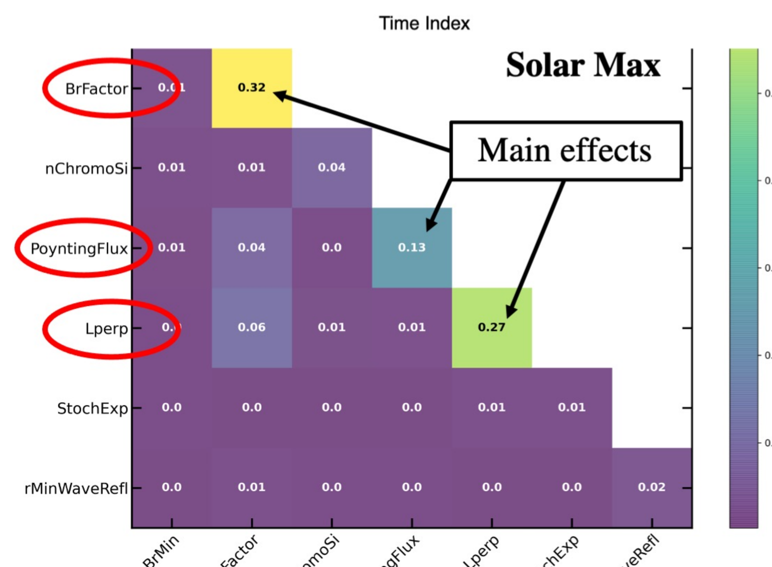
- UQ provides possible parameter values
- Computer experimental design constructs ensemble of simulations
- Data Assimilation constrains plausible model parameters to a smaller, more "confident" range using observations: selects best-performing subset of ensemble
- Approximate Bayesian Computation (ABC) based particle filter: **repeat process**

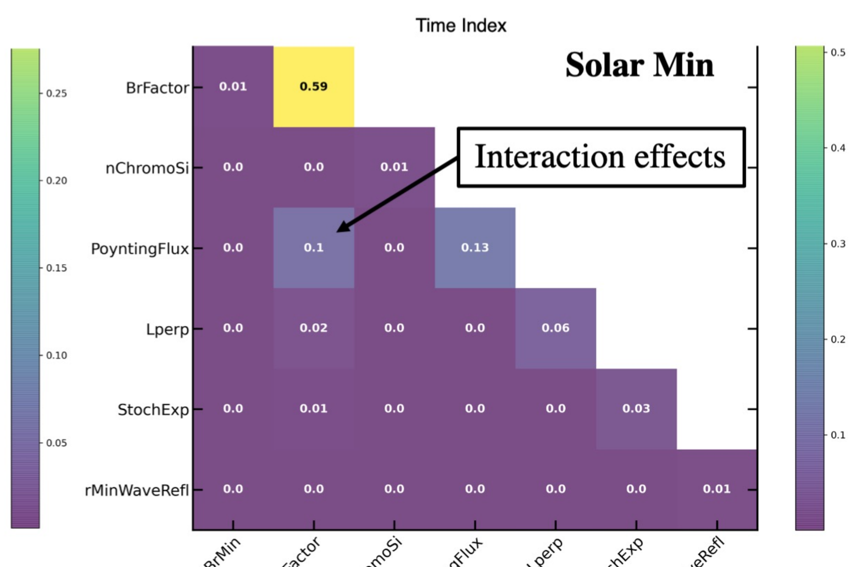
Available as open source at https://github.com/MSTEM-QUDA

Uncertainty Quantification analysis for background solar wind



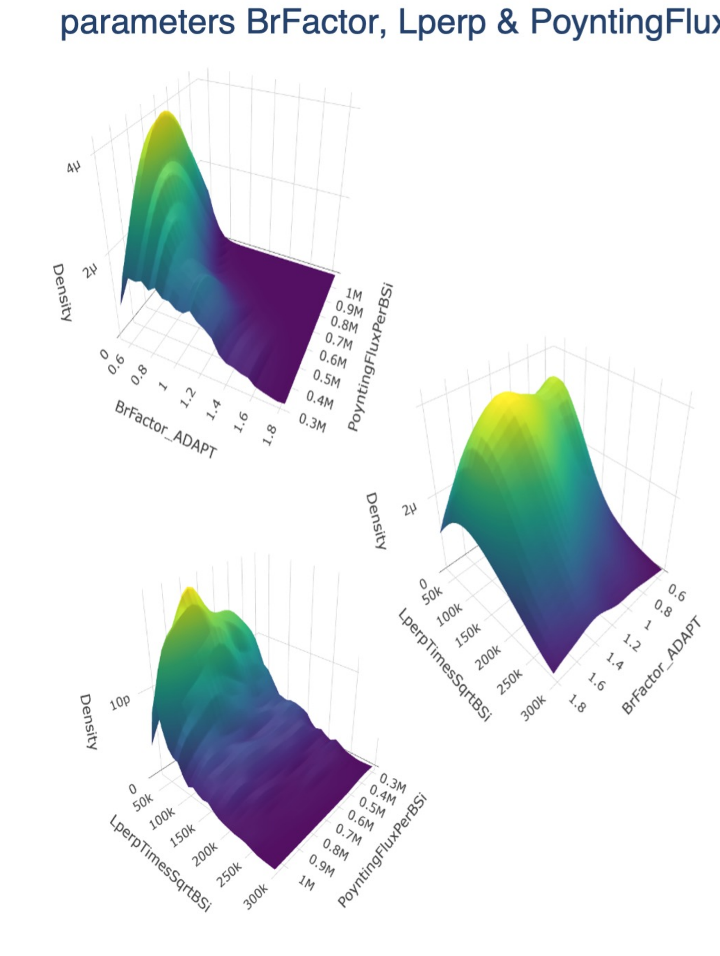


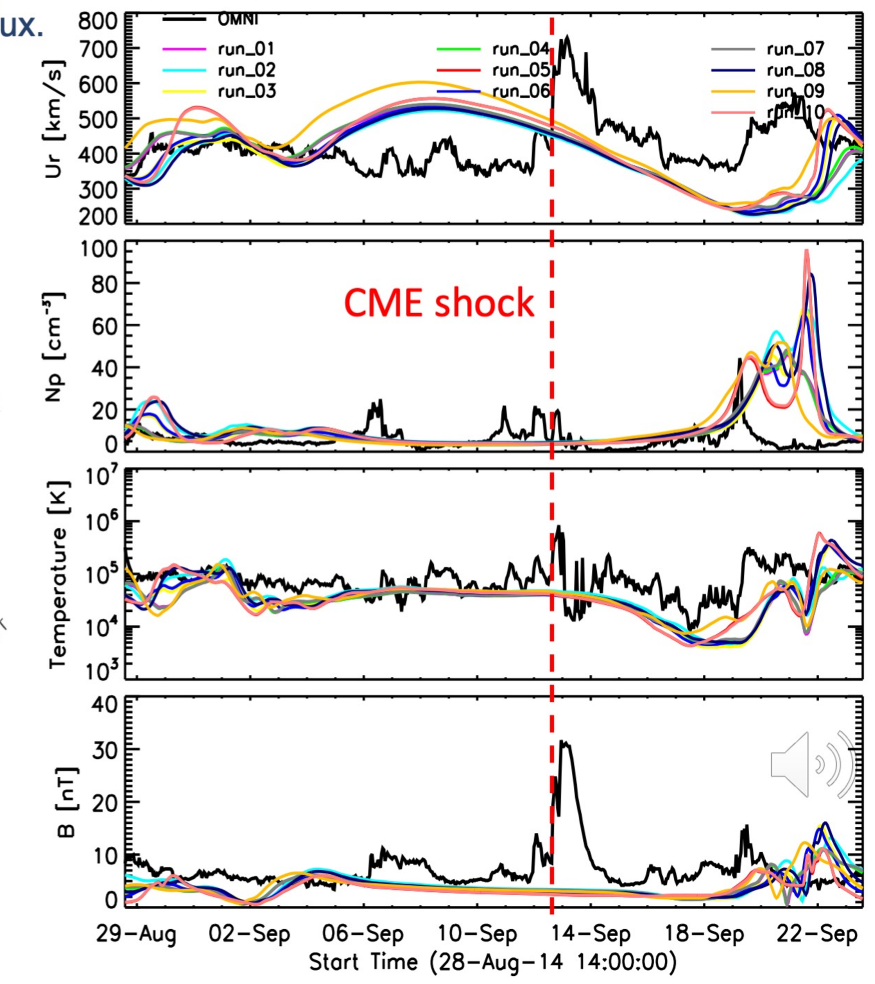




Data Assimilation for background solar wind

- Smoothed posterior distribution obtained from Bayesian analysis for the key parameters BrFactor, Lperp & PoyntingFlux.
- These distributions can be used to generate optimal parameters for ensemble runs.

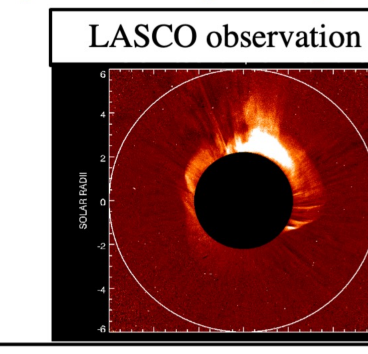




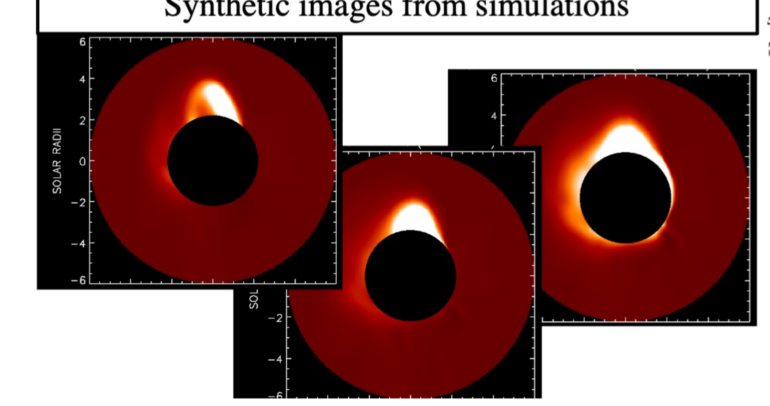
UQ and Data Assimilation for CMEs

- Select clean CME events
- Catalogue CME model parameters (fluxrope size, orientation, field strength…)
- MaxPro design for 100s of Sun-to-Earth simulations.
- UQ for coronal white light images and 1 AU observations. Dominant parameter: flux rope energy.
- DA: compare white light image with observations to predict success at 1AU (work in progress)

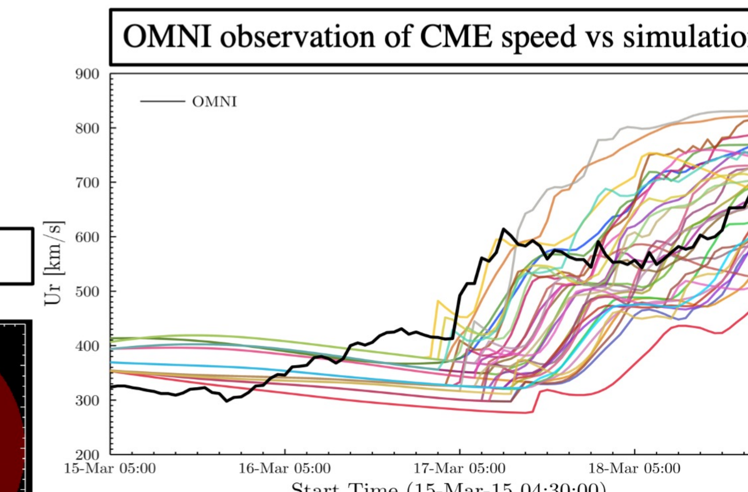
LASCO observation



Synthetic images from simulations



OMNI observation of CME speed vs simulations



SUMMARY

The Space Weather Modeling Framework (SWMF) is a mature first-principles model. It contains the Michigan Geospace model that provides short-term forecast of global and local magnetic perturbations at NOAA's Space Weather Prediction Center. With the support of the NSF SWQU grant PHY-2027555, we are developing the next generation SWMF that uses first-principles models from the Sun to Earth in combination with uncertainty quantification (UQ) and data assimilation (DA) to provide long term (1 day or longer) probabilistic forecast of space weather impacts. The Michigan Sun-to-Earth Model (MSTEM) consists of an ensemble of about 20 simulations with varied parameters using an experimental design based on UQ and DA analysis of many hundreds of simulations of past events. The best performing ensemble members are selected based on comparison with available data, including in-situ observations of the background solar wind and coronal white light images of the coronal mass ejection (CME). After pruning, the ensemble is replenished with new members using varied parameters of the CME model and the Geospace model. The final ensemble will provide a probabilistic forecast of geospace impacts. To make this approach more feasible, we are porting the computationally most expensive BATSRUS model to GPUs. The Geospace model runs about 100-150 times faster on single V100 GPU than on a state-of-the-art intel CPU core. We are currently porting the Alfven Wave Solar atmosphere Model (AWSoM) to multiple GPUs.

REFERENCES

- G. Toth et al., Adaptive Numerical Algorithms in Space Weather Modeling, 2012, Journal of Computational Physics, 231, 870, doi:10.1016/j.jcp.2011.02.006
- N. Sachdeva et al., Simulating Solar Maximum Conditions Using the Alfven Wave Solar Atmosphere Model (AWSoM), 2021, Astrophysical Journal, 923, 176, doi:10.3847/1538-4357/ac307c
- A. Jivani et al., Solar Model Uncertainty Quantification, 2022, to be submitted to Space Weather, in preparation