Coronal Prediction for the 2024 Total Solar Eclipse: Boundary Conditions

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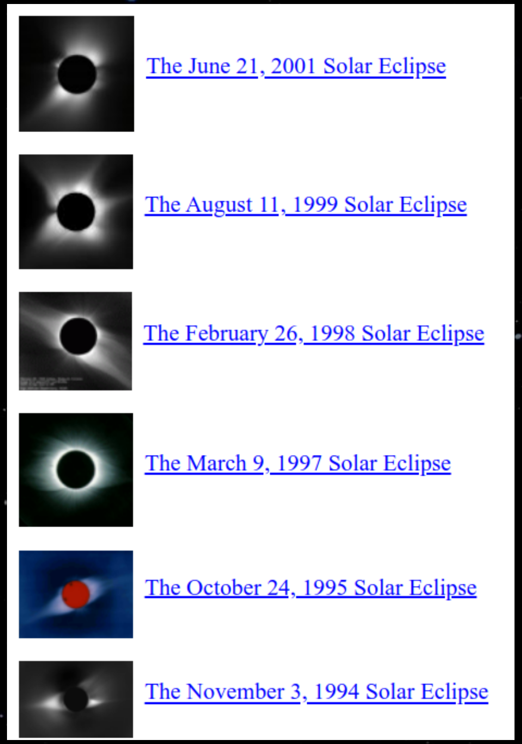
Predictive Science Inc.

NASA NSF

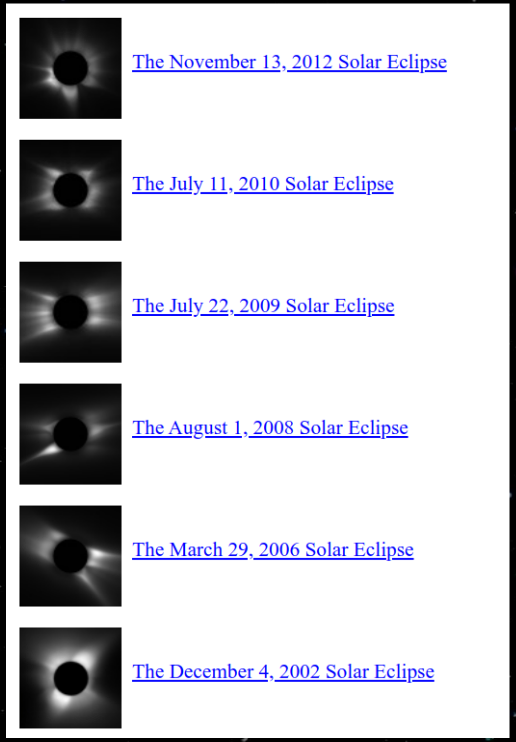
TESS

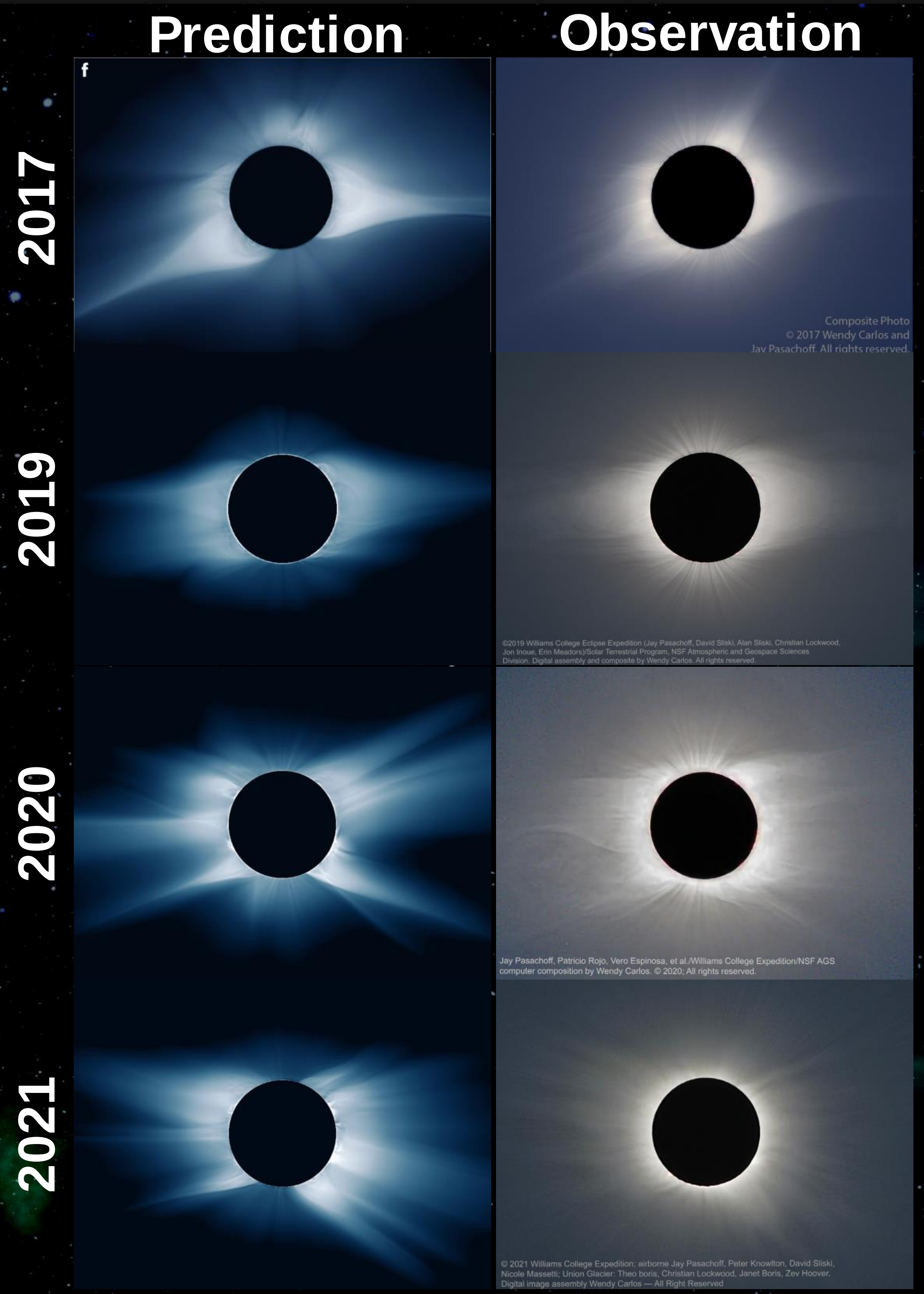
PSI and Eclipse Predictions

- The team at PSI has been posting eclipse predictions for decades
- They were made using quasi-relaxed MHD simulations of the solar corona, posted ~2 weeks before the event
- Comparing the predictions to observations helps refine the model, and can provide context for observational planning
- This year, we are using a new paradigm: a continually running, data assimilative MHD simulation in real time


The June 21, 2001 Solar Eclipse
The August 11, 1999 Solar Eclipse
The February 26, 1998 Solar Eclipse
The March 9, 1997 Solar Eclipse
The October 24, 1995 Solar Eclipse
The November 3, 1994 Solar Eclipse

predsci.com/eclipses

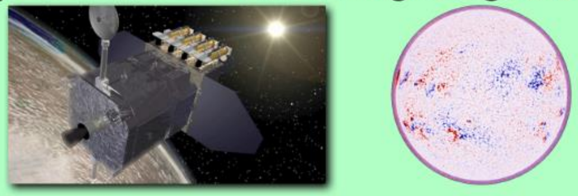

The November 13, 2012 Solar Eclipse
The July 11, 2010 Solar Eclipse
The July 22, 2009 Solar Eclipse
The August 1, 2008 Solar Eclipse
The March 29, 2006 Solar Eclipse
The December 4, 2002 Solar Eclipse



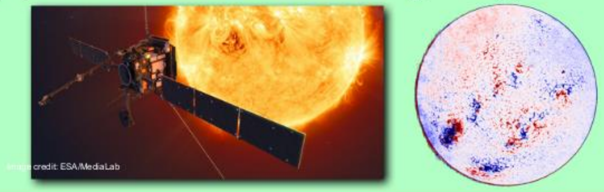
The PSI 2024 Eclipse Prediction Real-Time Pipeline

Data Acquisition

(a) SDO HMI 720s NRT Magnetograms

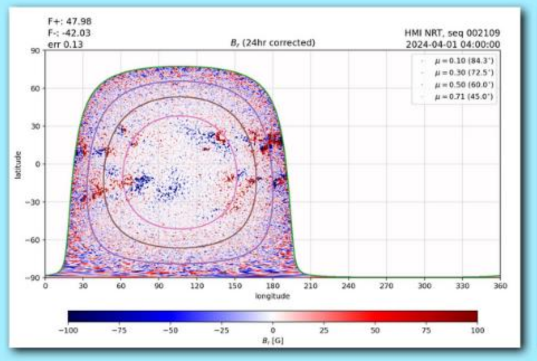


(b) SolO LL & Science Magnetograms

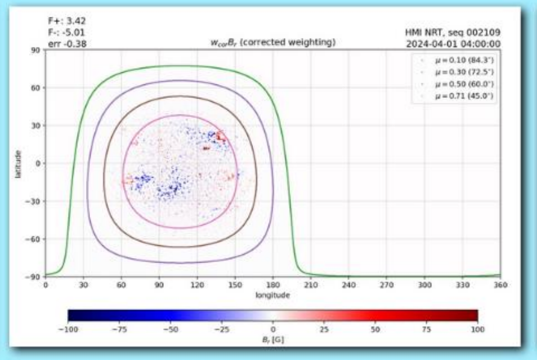


Full-Sun Magnetic Map Generation

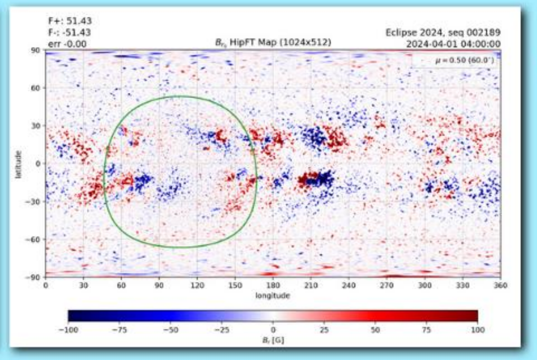
(c) Heliographic Mapping



(d) Assimilation Preparation



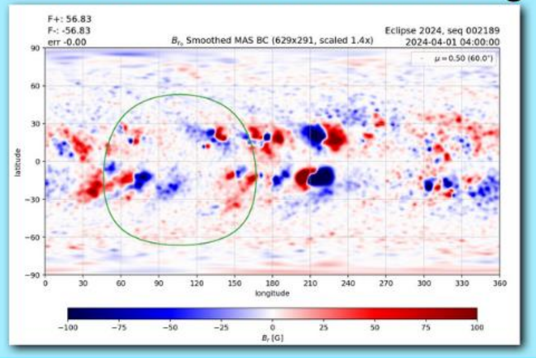
(e) Surface Flux Transport



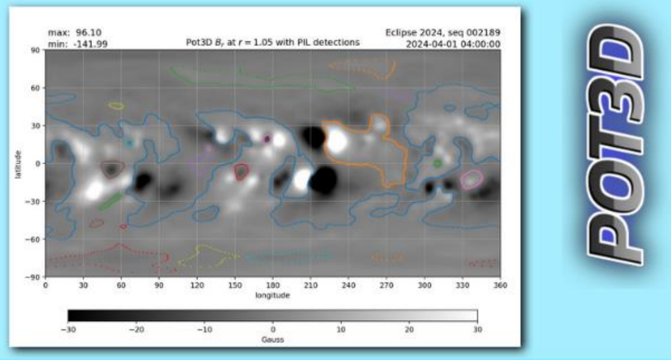
Multi-core CPU Workstation with Multiple GPUs

Model Boundary Conditions

(f) Flux-preserving re-mesh of maps and structure-aware smoothing



(g) Energization

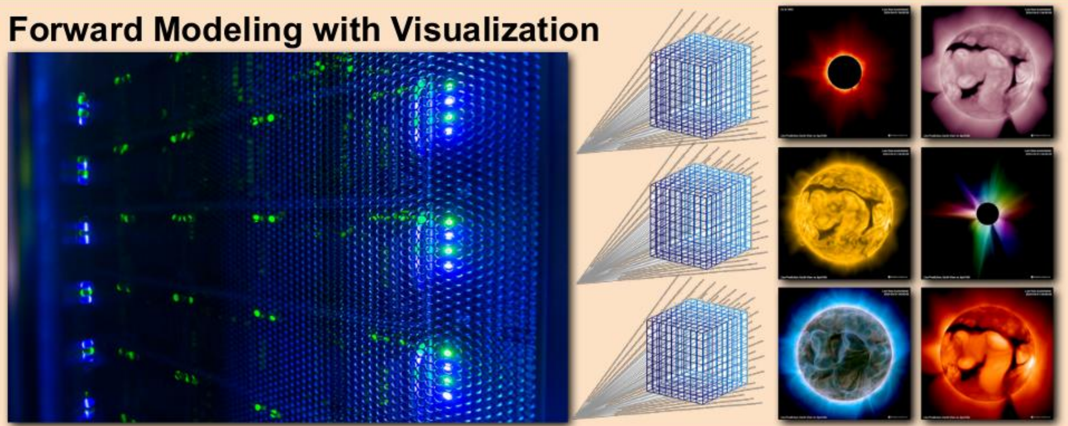


Model Simulation

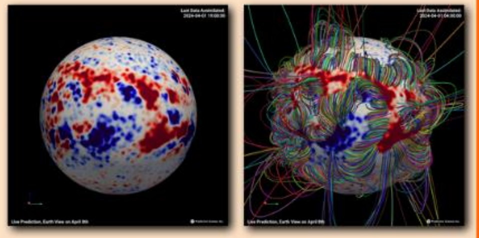
(h) Time-Evolving MHD Simulation

Post Processing Model Results

(i) Forward Modeling with Visualization



(j) Master renderer, work monitoring, additional visualizations



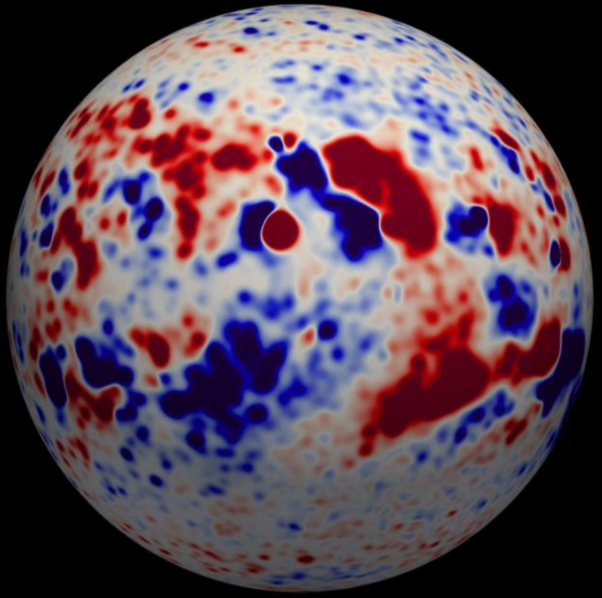
Release of Results

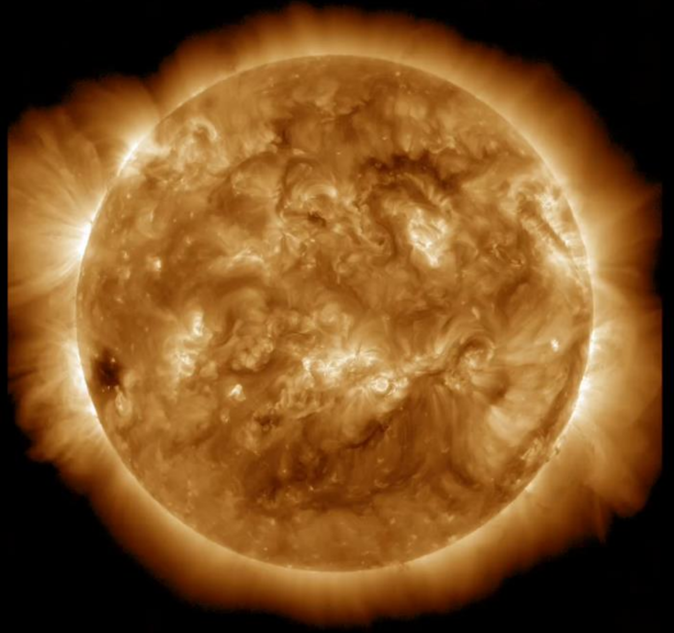
(k) PSI Live Prediction Web Site

predsci.com/eclipse2024

The Problem of Missing Magnetic Data

- MHD (and other) global models require solar surface magnetic field data as input boundary conditions
- While observed by multiple instruments, routinely only from the Sun-Earth line of sight
- In order to make a global map, old data from the Sun-Earth line can be used (e.g. Carrington/"synoptic" maps)
- The older data in the maps makes predicting the eclipse corona difficult, especially during solar maximum when the Sun is changing rapidly
- A way to mitigate this problem is to run a data-assimilative surface flux transport model (SFT) that models the Sun's surface flows to transport the field
- Although the SFT model misses new far-side flux emergence, it can accurately predict how the most recently assimilated data will change over time on the back of the Sun





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SWQU

Space Weather with Quantified Uncertainty

- Developed as part of the "Improving Space Weather Predictions with Data-Driven Models of the Solar Atmosphere and Inner Heliosphere" SWQU project

HipFT

github.com/predsci/hipft

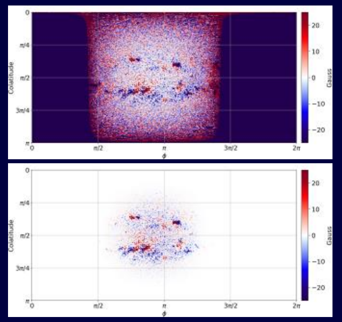
OFT

Open **S**ource **F**lux **T**ransport
A Tool for Generating Full-Sun Synchronic Magnetic Field Maps

MagMAP

Magnetic Mapping And Processing

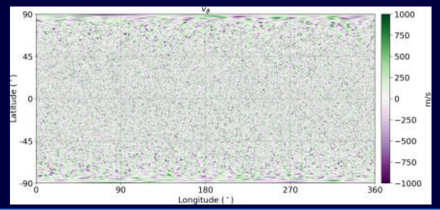
Acquire, process, map, and bin observational magnetic field data into data-assimilation database



ConFlow

Convective Flow generator

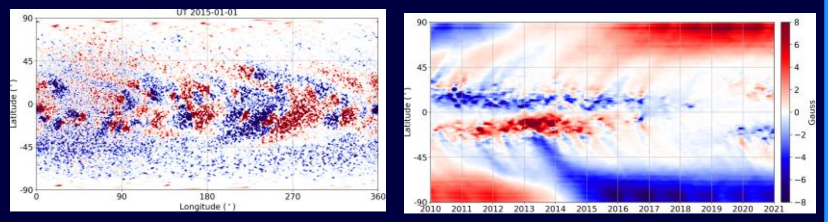
Generate sequence of supergranular flow fields



HipFT

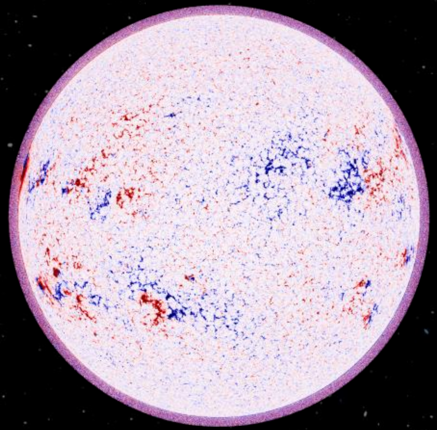
High-performance Flux Transport

Integrate surface flux transport model with differential rotation, meridional flows, diffusion, and flux sources using high-order numerical schemes and CPU/GPU parallelism over multiple realizations

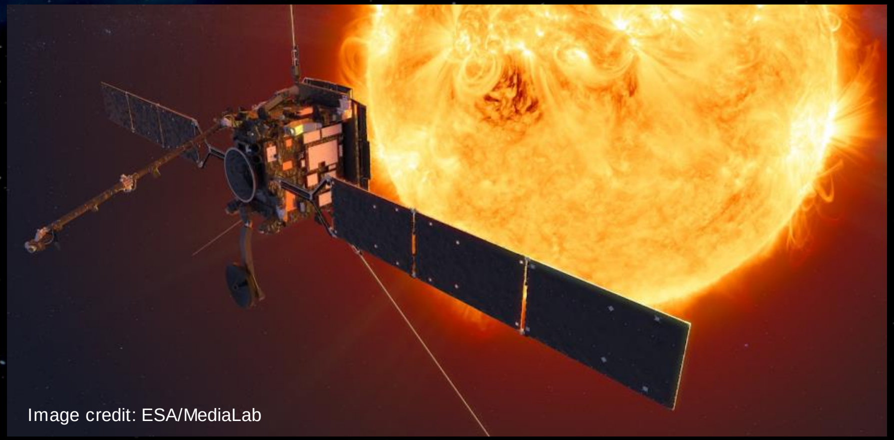


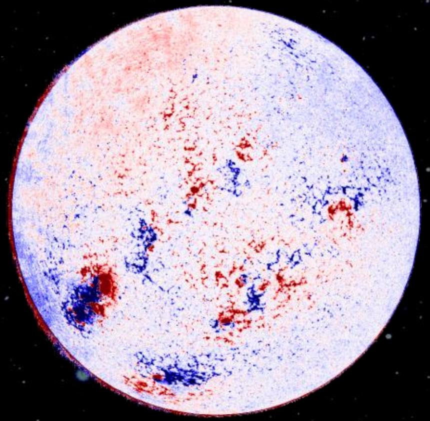
Data Acquisition and Heliographic Mapping

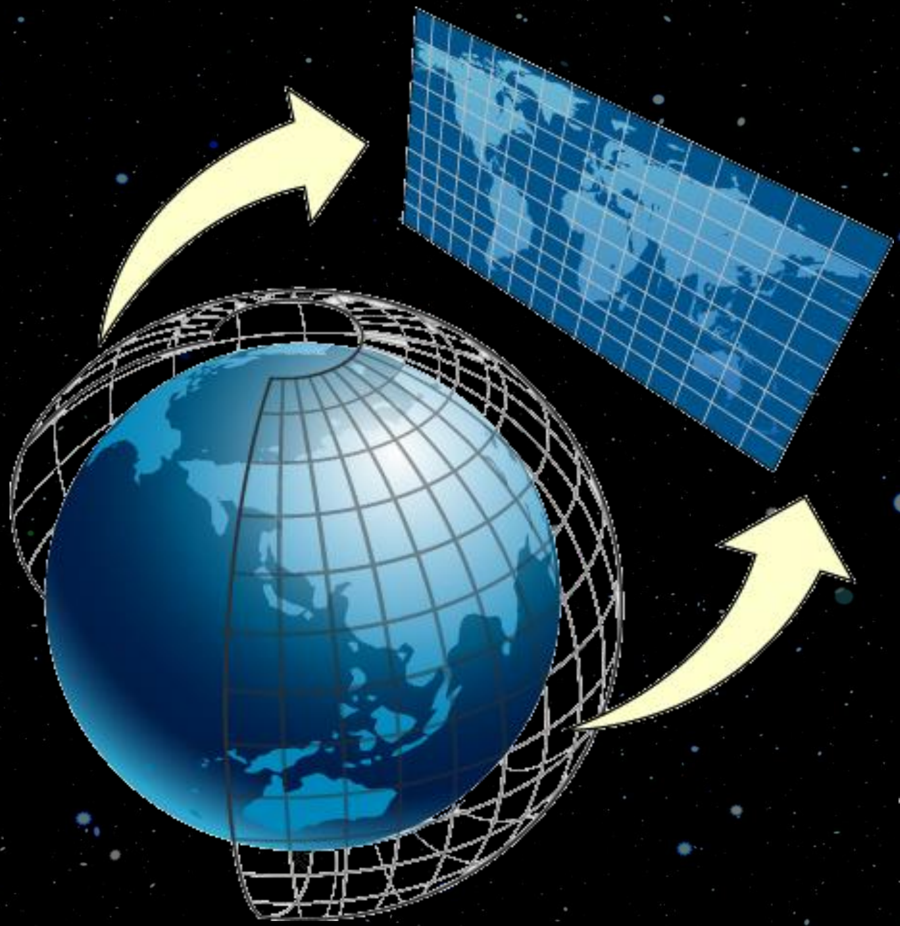
SDO HMI 720s NRT Magnetograms



SO PHI LL & Science Magnetograms

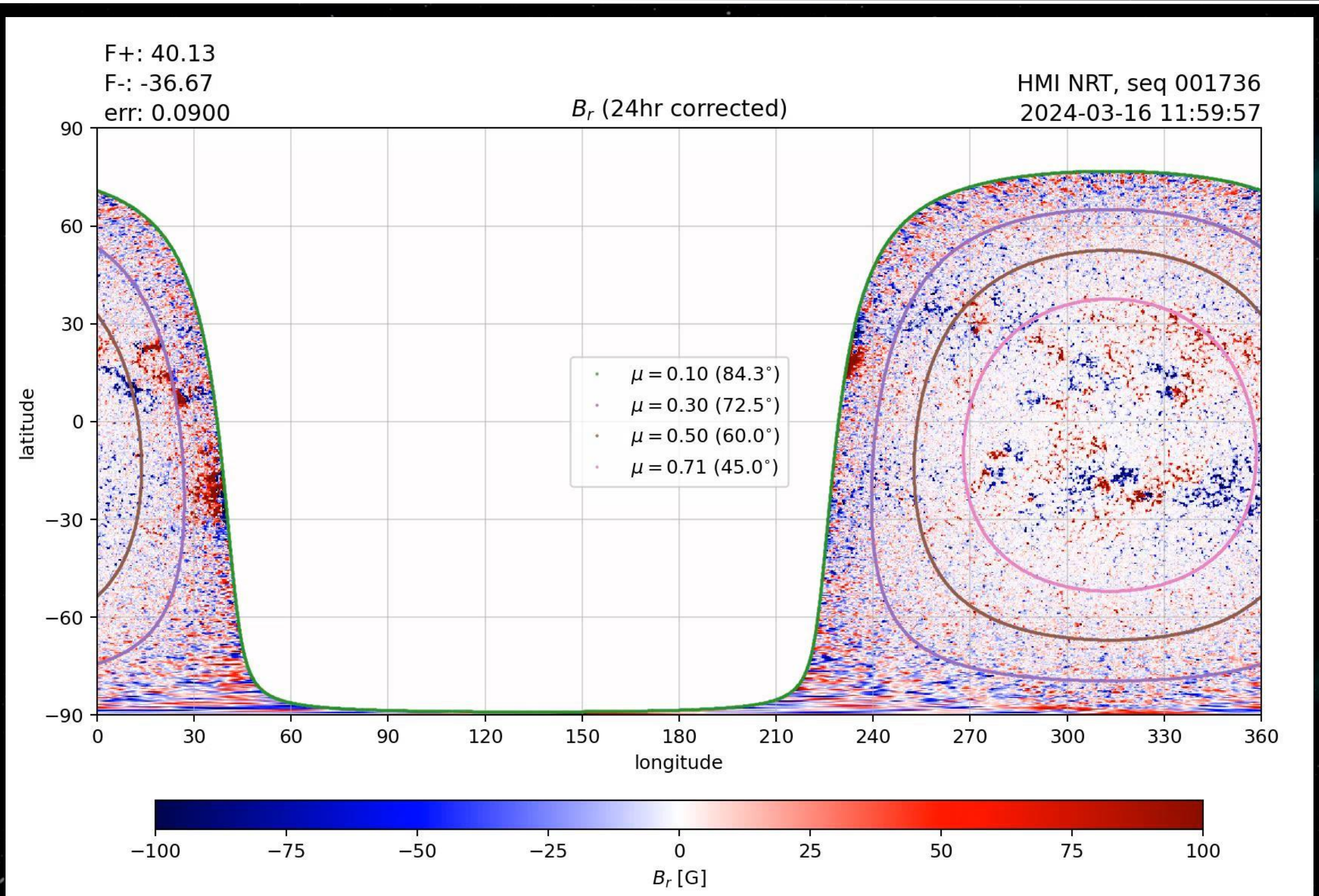






$$B_r = B_{LOS}/\mu$$

$$\mu = \cos\theta_d \in [0,1]$$



Data Assimilation

- Data is assimilated based on a weighting between the new data and the pre-existing model
- For each disk magnetogram, the center-to-limb angle is used to create the assimilation weights
- In order to avoid issues such as strong half-active regions, the weights are modified so that data entering the edge of the assimilation window takes longer to emerge
- To avoid flux imbalance, the added change in the field is flux balanced

$$B_r^{new} = F\,B_{r;data} + (1-F)\,B_r^{old}$$

$$F = \begin{cases} \mu^4, & \mu \geq 0.1 \\ 0, & \mu < 0.1 \end{cases}$$

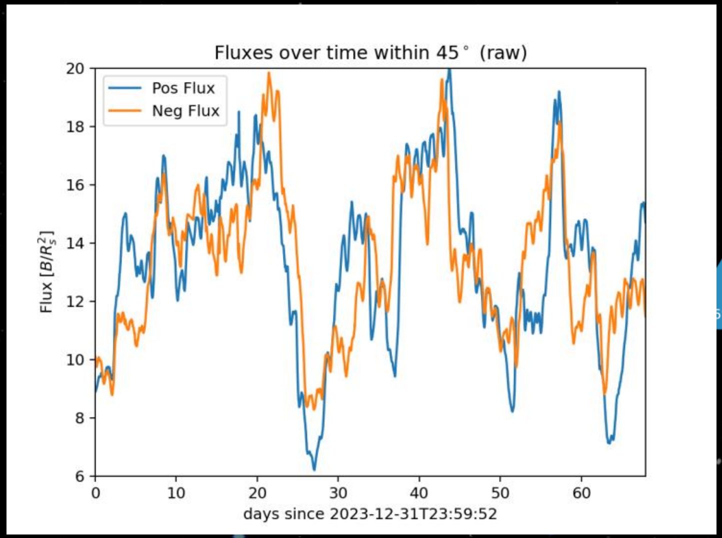
$$B_r^{new} = B_r^{old} + \Delta B_r$$

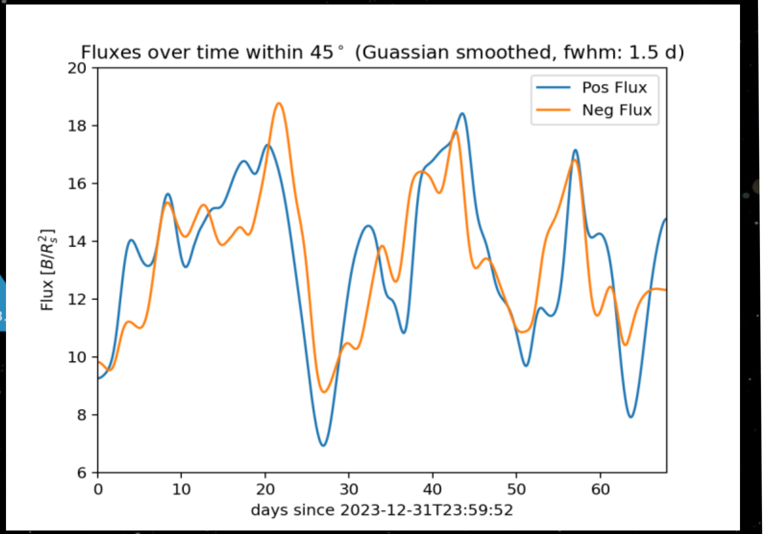
$$\Delta B_r = F\left(B_{r;data} - B_r^{old}\right)$$

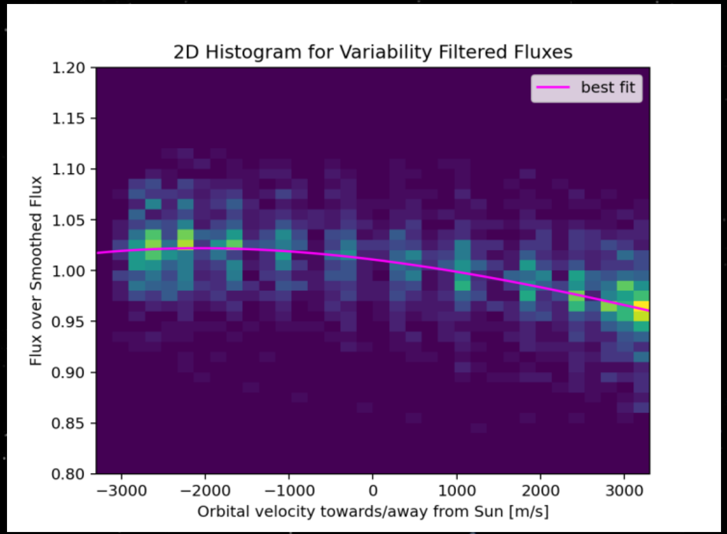
$$\Delta B_r = \begin{cases} \Delta B_r / \sqrt{|\Phi_+/\Phi_-|}, & \Delta B_r > 0 \\ \Delta B_r \sqrt{|\Phi_+/\Phi_-|}, & \Delta B_r \leq 0 \end{cases}$$

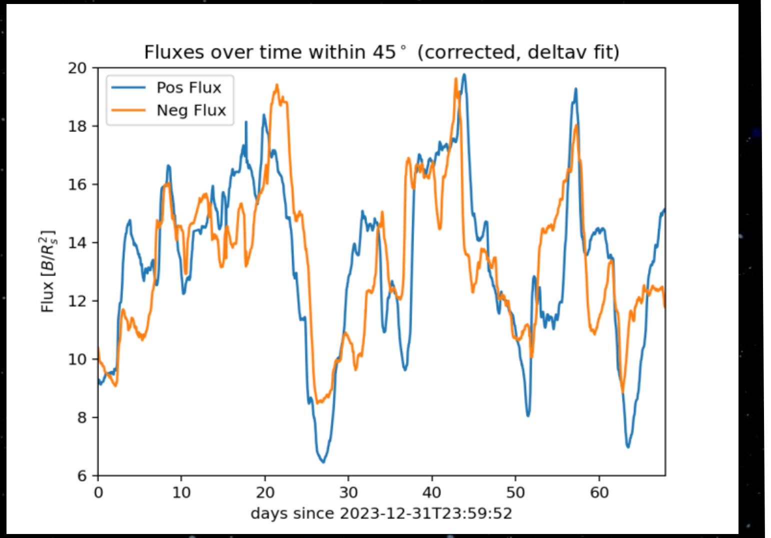
Data Assimilation Cont.

Removing Orbital Variations:



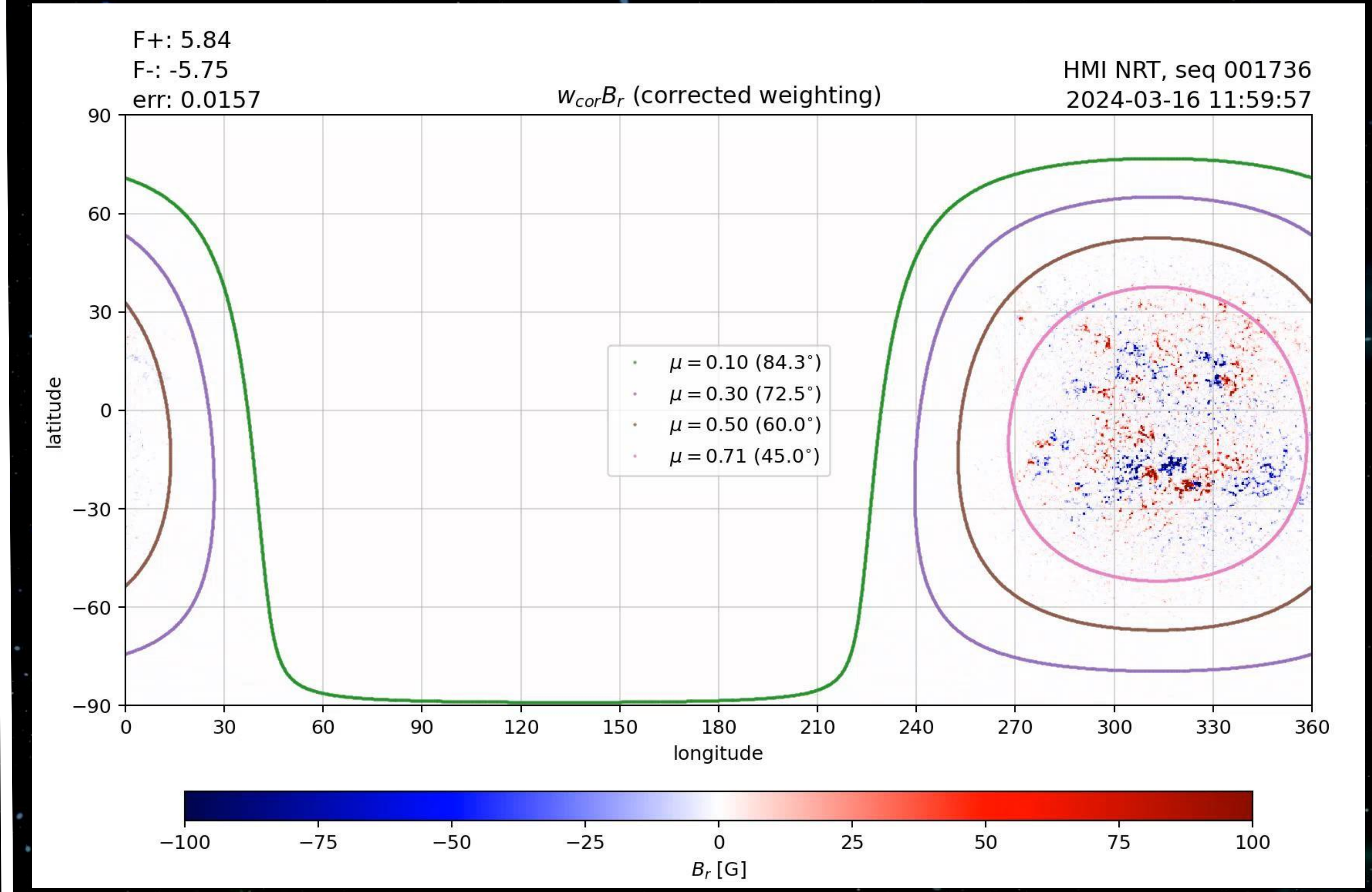






$$C_{\mathrm{OV}}(v) = 1.011 - 1.02\text{e-}5\, v - 2.02\text{e-}9\, v^2 + 1.44\text{e-}13\, v^3$$

Data and weights stored in a sequence of indexed files ready for use in the SFT model

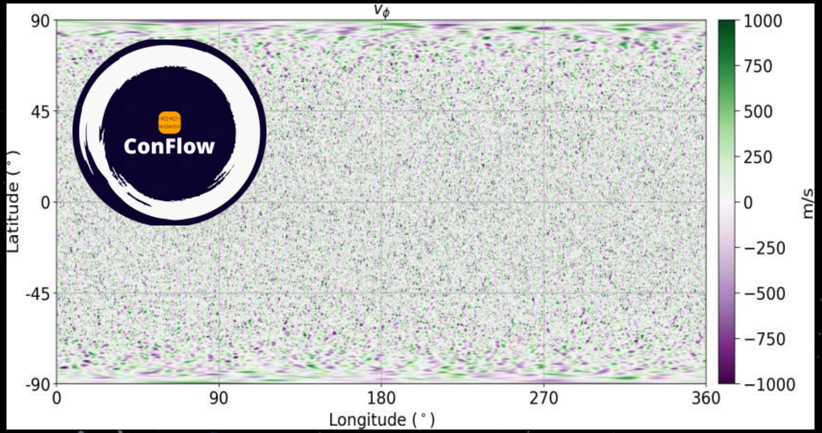


Implements advection, diffusion, data assimilation, and flux emergence over multiple realizations using high-accuracy numerical methods and CPU/GPU parallelism

github.com/predsci/hipft

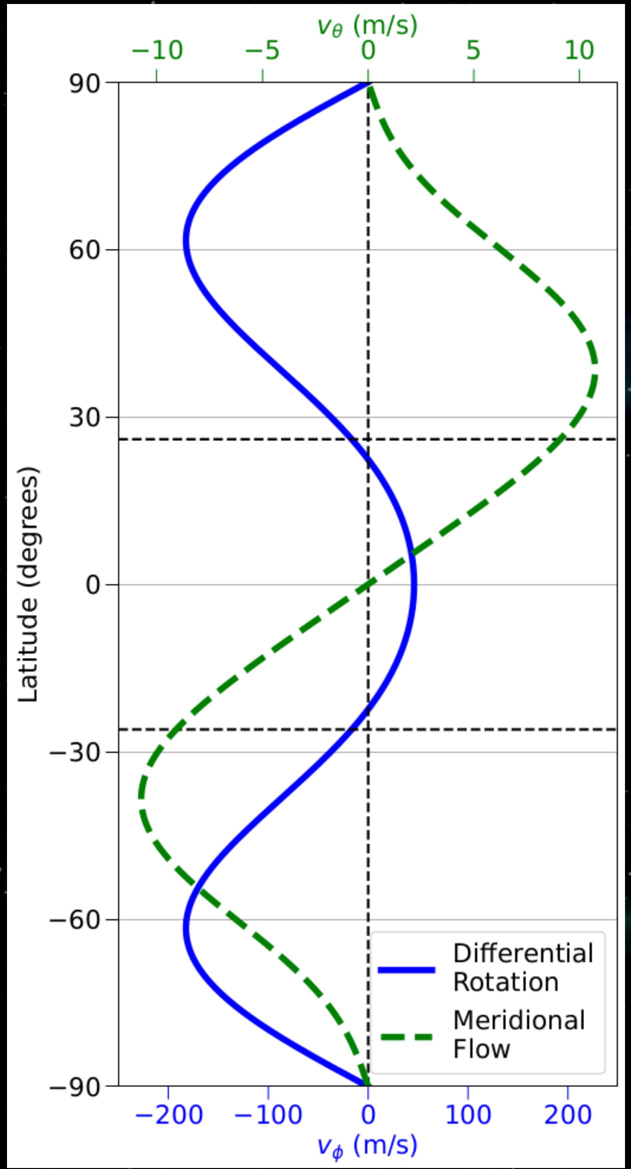
$$\frac{\partial B_r}{\partial t} = -\nabla_s \cdot (B_r \mathbf{v}) + \nabla_s \cdot (\nu \nabla_s B_r) + S,$$

- Flows
  - Analytic observationally-derived differential rotation and meridional flows
  - Time-dependent super-granular convective flows generated by ConFlow
  - Flow attenuation based on field strength
- Diffusion
  - Used to capture flux cancellations at smaller scales than the super granular flows



$$v_{\theta/\phi} \rightarrow v_{\theta/\phi} \left[1.0 - \tanh\left(\frac{|B_r|}{B_0}\right)\right]$$

$$\nu = 300\,\mathrm{km}^2/s$$

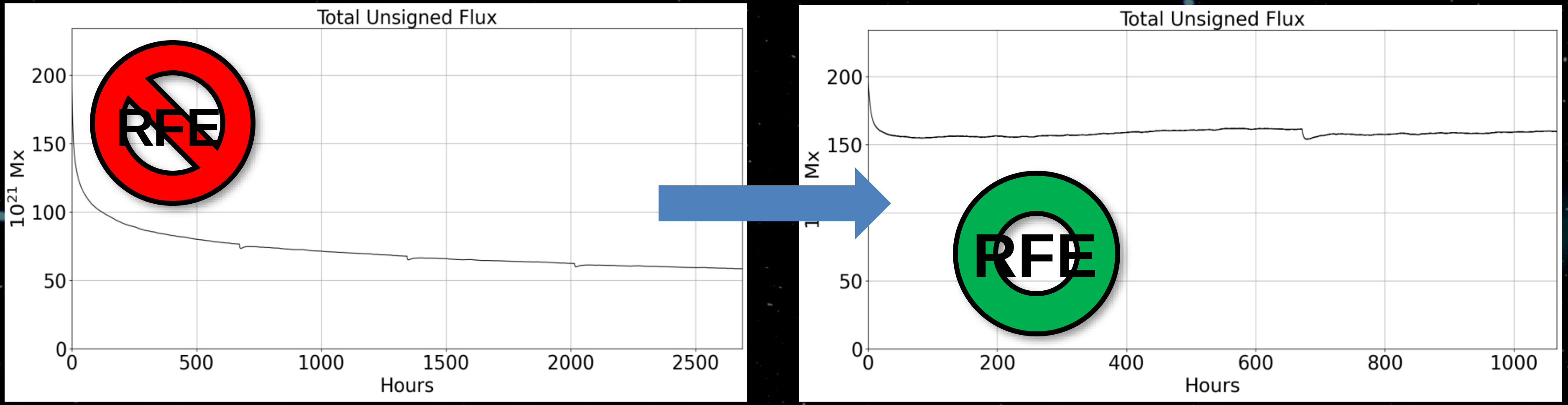


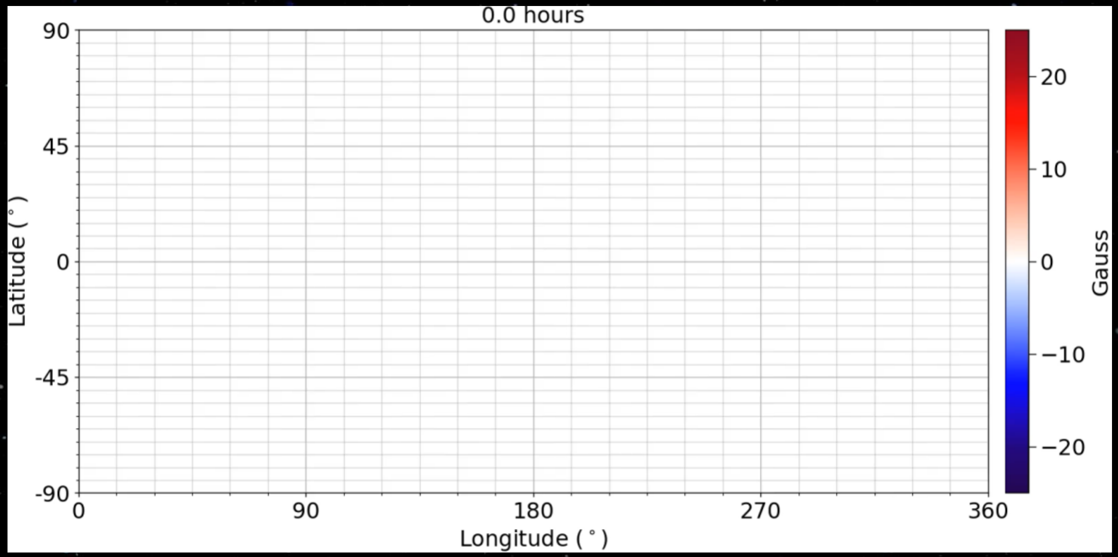
Random Flux Emergence (RFE)

- The flux-canceling processes in SFT models reduces the unsigned flux (UF) compared to that of the assimilated data
- This leads to unrealistic localized low UF regions and a variable average UF away from the assimilation region
- As our MHD model uses UF in the heating model, this can adversely affect the simulations
- We therefore add random flux emergence as a source term
- We tune the parameters to yield a constant average UF in the quiet Sun regions calibrated to the current time period and resolution of the model

$$B_{r;\mathrm{RFE}} = \frac{|\Phi_{\mathrm{RFE}}|}{N\,A_{\mathrm{cell}}}\,\frac{1}{\sigma_{\mathrm{RFE}}\sqrt{2\,\pi}}\,\mathrm{Rnd}(\sigma_{\mathrm{RFE}})$$

$$B_{r;\mathrm{RFE};1} \longleftarrow \boxed{\tau_{\mathrm{RFE}}} \longrightarrow B_{r;\mathrm{RFE};2}$$



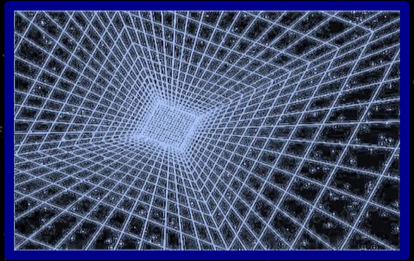


HipFT Numerical Methods

TIME

ADVECTION: 3rd-order SSPRK(4,3)
DIFFUSION: 2nd-order RKG2(3/2) + PTL

SPACE



ADVECTION: 3rd-order WENO3-CS(h)
DIFFUSION: 2nd-order CD

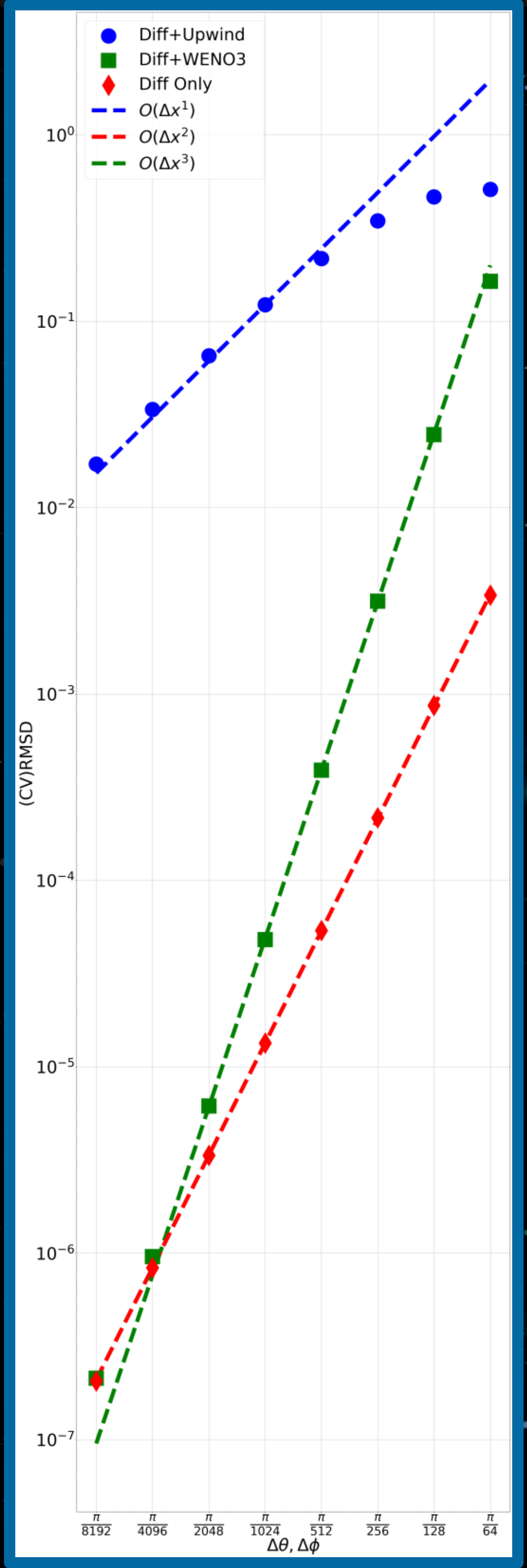
Fortran DC

```
do concurrent (i=1:N,j=1:M)
  Computation
enddo
```

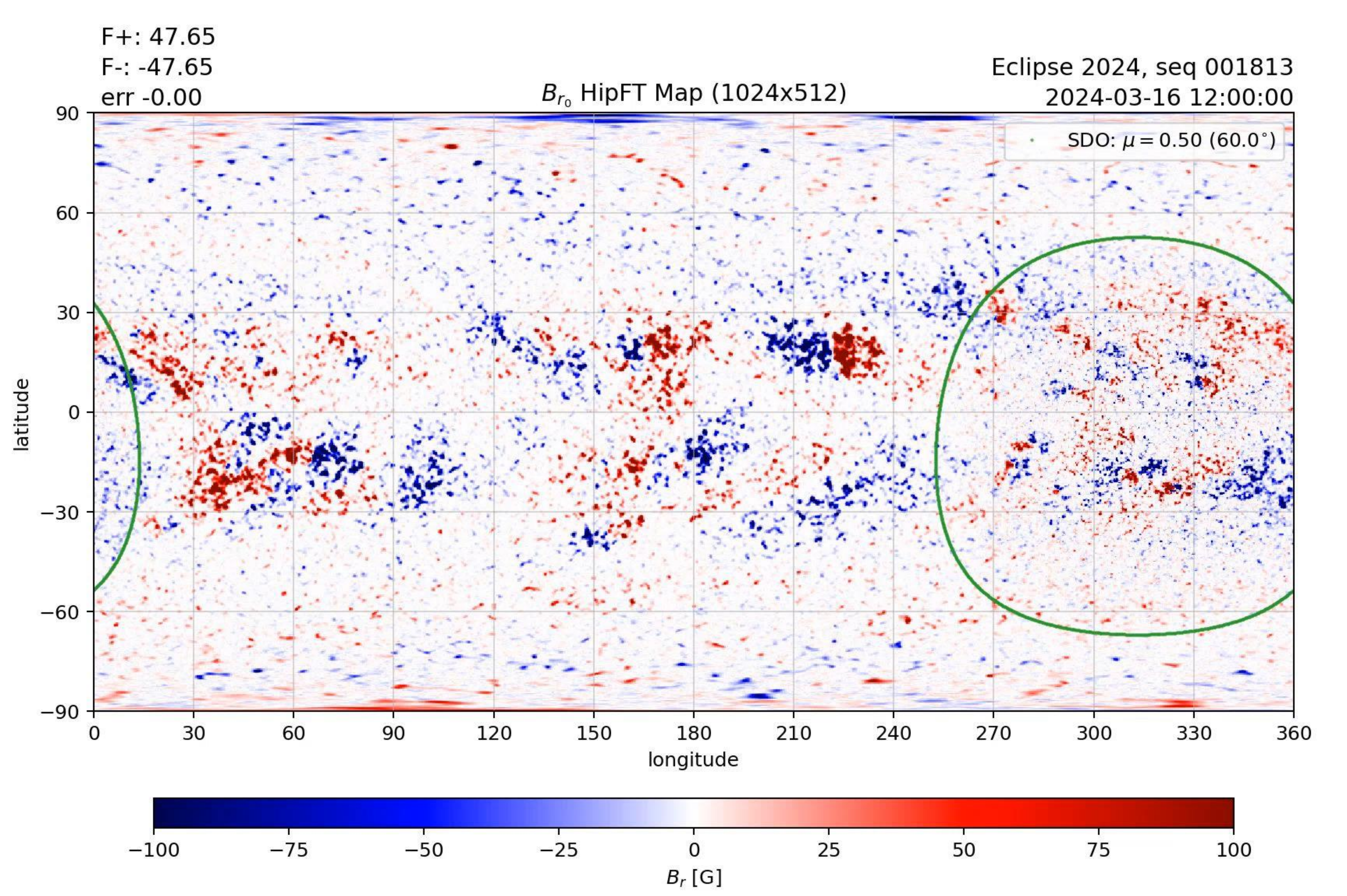
OpenMP®

```
!$omp target enter data map(to:a)
!$omp target exit data map(from:a)
```

MPI



HipFT Eclipse Run



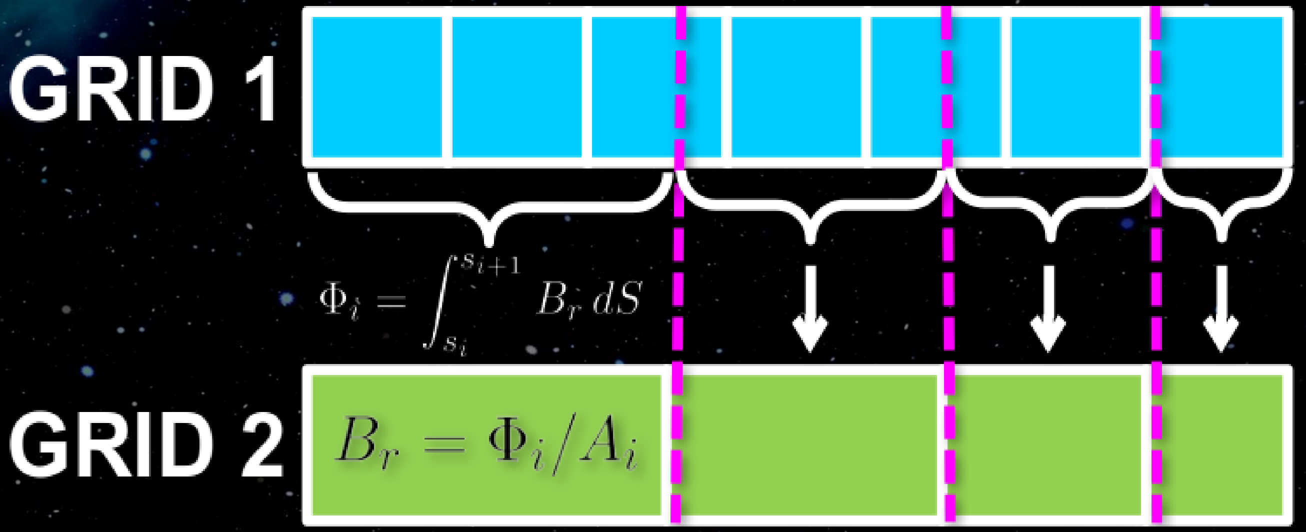
In-house workstation:

EPYC 7702P 64-core CPU

4x NVIDIA 2080Ti GPUs

Map Processing for MHD Model

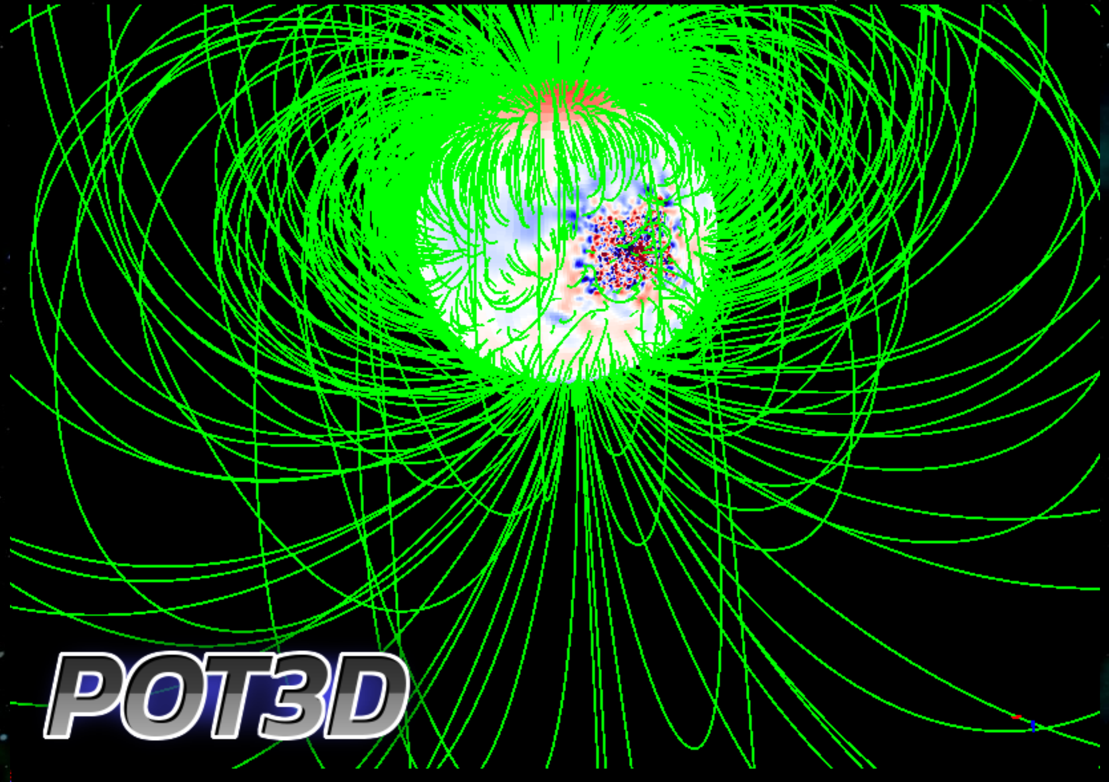
- Scale by 1.4x to make HMI similar to MDI
- Flux-preserving integral re-mesh from HipFT resolution to MHD run resolution
- Smoothing
  - Grid-based diffusivity (resolvability)
  - Very strong fields can strain model, so we also smooth such regions locally
  - The smoothing mask is made by computing a potential field solution and taking a radial slice at 1.05 Rs
  - The diffusivity is modified proportional to the magnitude of B



$$f_b = 0.5 + 7.5 \, \frac{|\vec{B}|}{200\,\mathrm{Gauss}}$$

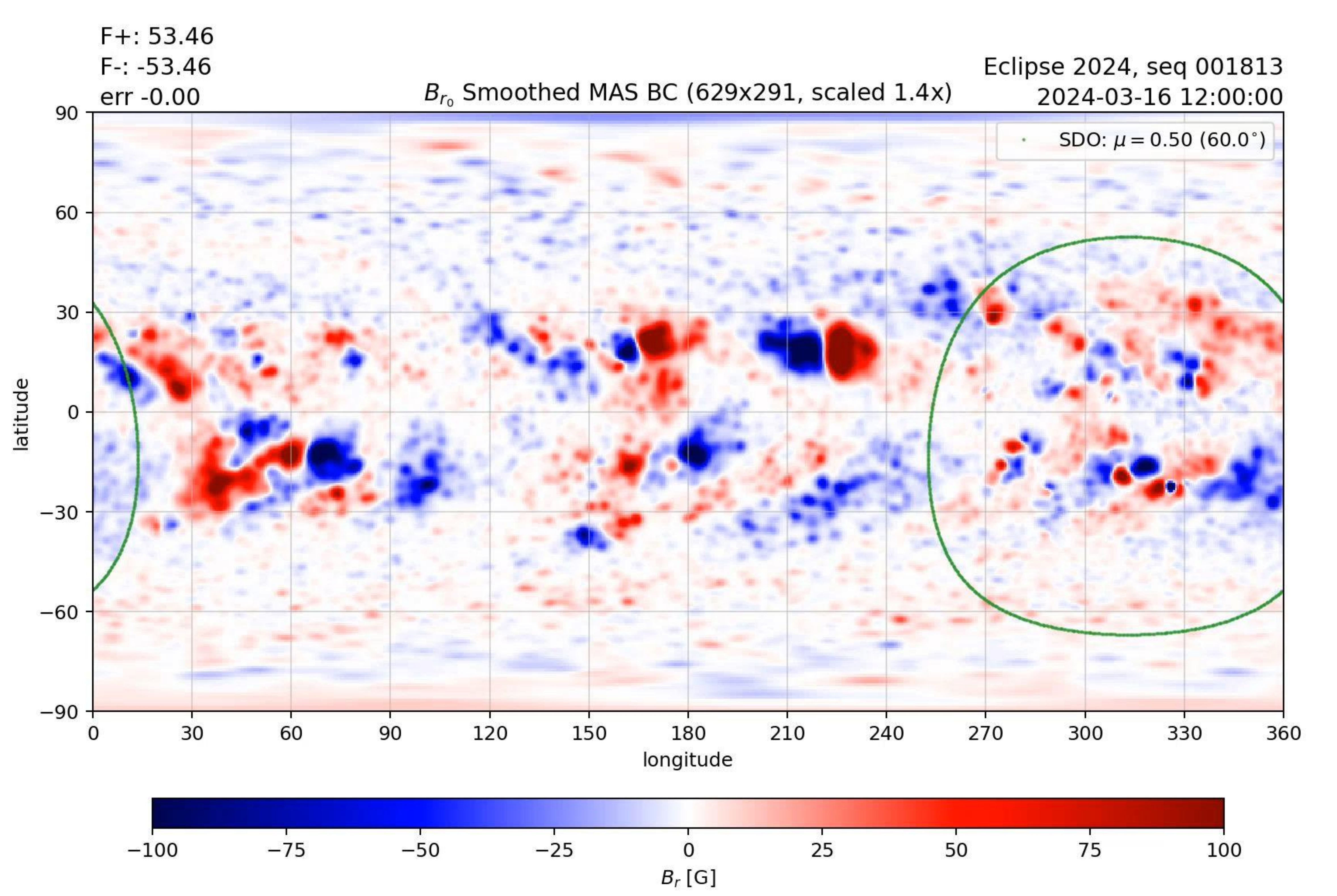
$$\nu = f_b \, \nu_{\mathrm{grid}}$$

$$\nu_{\mathrm{grid}} = (\Delta\theta)^2 + (\Delta\phi \, \sin\theta)^2$$



github.com/predsci/pot3d

Maps Ready for Time-Dependent MHD Simulation



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