Integrated Global-Sun Model of Magnetic Flux Emergence and Transport

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NASA/NSF Partnership for Collaborative Space Weather Modeling

Solar Interior
- Magnetohydrodynamics (MHD)
- Emerging magnetic flux
- Subsurface flow maps
- Far-side imaging (helioseismology)
- Magnetic flux transport

Photosphere & Chromosphere
- Magnetic field
- Solar energetic particles (SEPs)
- Flares/coronal mass ejections (CMEs)
- Coronal holes/solar wind
- Radio bursts
- X-ray/extreme ultraviolet emissions

Heliosphere
- Interplanetary magnetic field (IMF)
- Solar wind
- Shocks/SEPs
- CMEs

Magnetosphere
- IMF
- Magnetic storms/ substorms
- Auroral zones/ring currents
- Polar cap potential
- Radiation belts
- South Atlantic Anomaly

Thermosphere & Ionosphere
- Plasma bubbles/ equatorial anomalies
- Scintillation/density fluctuation
- Neutral winds
- Traveling ionospheric disturbances
- Ultraviolet heating
- Ion chemistry
- Bulk ionosphere

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The Coronal Global Evolutionary Model (CGEM)
George Fisher
University of California Berkeley

A Modular Capability for Community Modeling of Flares, CMEs and Their Interplanetary Impacts
Spiro Antiochos
NASA Goddard Space Flight Center

Integrated Real-Time Modeling System for Heliospheric Space Weather Forecasting
Dusan Odstrcil
NASA Goddard Space Flight Center

Corona-Solar Wind Energetic Particle Acceleration (C-SWEPA) Modules
Nathan Schwandron
University of New Hampshire

Integration of Extended MHD and Kinetic Effects in Global Magnetosphere Models
Amitava Bhattacharjee
Princeton University

Medium Range Thermosphere Ionosphere Storm Forecasts
Anthony Mannucci
Jet Propulsion Laboratory

A First-Principles-Based Data Assimilation System for the Global Ionosphere-Thermosphere-Electrodynamics
Robert Schunk
Utah State University

Magnetic Flux Emergence and Transport

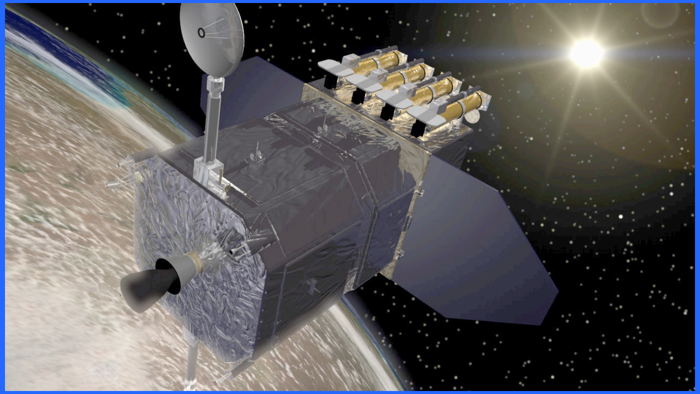
Motivation

The Sun lies at the center of space weather and is the source of its variability. The primary input to coronal and solar wind models is the activity of the magnetic field in the solar photosphere. Without focusing on and refining our understanding of the driving source of space weather, a major source of uncertainty in space weather forecast will remain.

Goal

Develop physics-based models for the dynamics of the magnetic field from the deep convection zone of the Sun to the corona with the goal of providing robust near real-time boundary conditions at the base of space weather forecast models.

What changed?



SDO

High-quality data at incredible spatial and time resolution

Pflop/s + HF physics software

Simulations previously unrealistic are now possible

Strategic Capabilities (Synopsis of the effort)

Two major elements:

1. Technology - Enhance the Air Force Data Assimilation Photospheric magnetic flux Transport model (ADAPT) by assimilating SDO-HMI data

2. Understanding (Exploratory tools)
   - ✓ SURF: from observation to modeling surface flux transport
   - ✓ Develop Coupled Models for Emerging flux:
     a) FSAM code, Fan [2008] (deep convection zone) + Realistic MHD/radiation code (subsurface to photosphere).
     b) SWMF (EEGGL+AWSoM) (subsurface to the corona).

Co-Investigators

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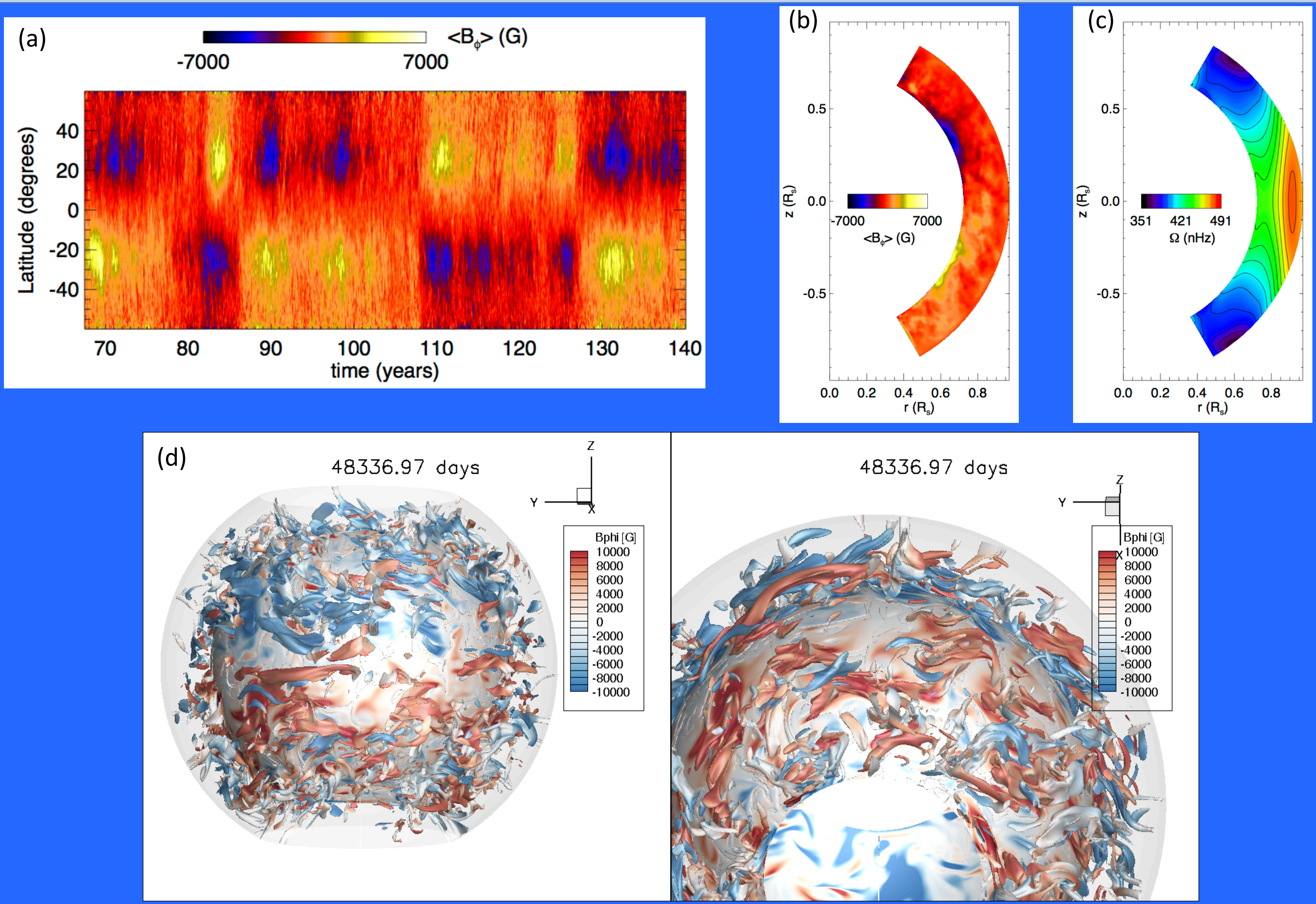
Simulations of solar convective dynamo and emerging flux with FSAM (Fan and Fong 2014, 2016)



Coupling to near surface layer radiation MHD simulations of active region formation with MURaM

Feng Chen et al. 2017 ApJ 846 149 doi:10.3847/1538-4357/aa85a0

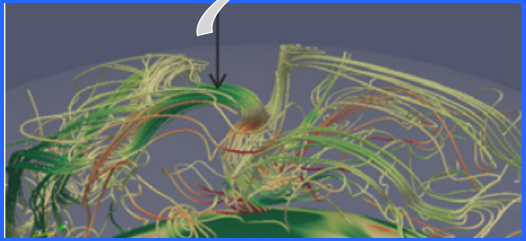
Emerging flux bundles generated by FSAM simulation of convective dynamo

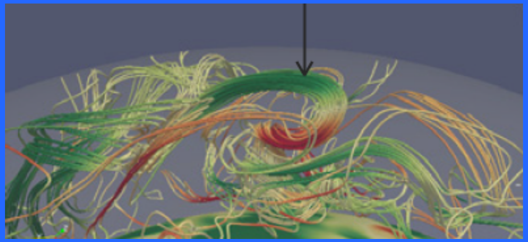
Fan & Fang, 2014

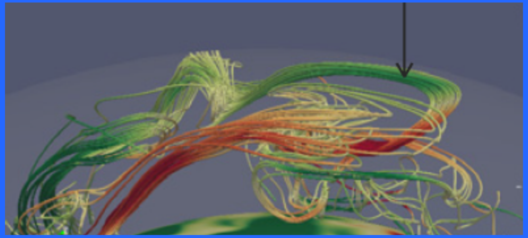
– solar-like differential rotation

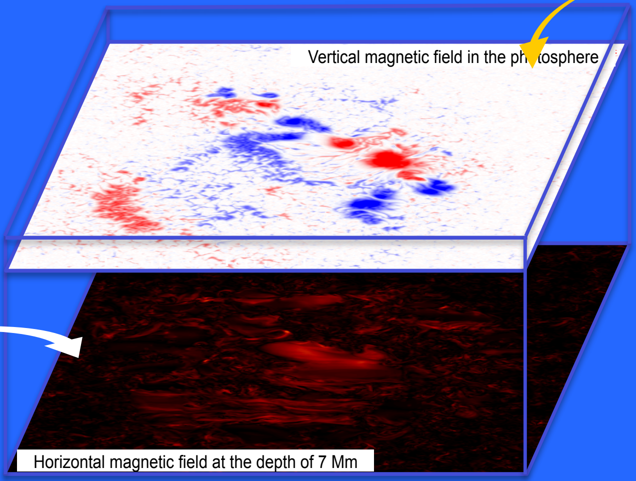
– large scale mean field exhibiting cyclic behavior

– emerging super-equipartition flux bundle:









Time-dependent lower boundary from FSAM:

– follow a region centered on the emerging flux bundle

– extract horizontal slices of **B**, **v** fields at 30 Mm depth

– vertical velocity is increased to be > rms of the convection

– Rescale the horizontal slices to fit the MURaM simulations

Emergence of the flux bundles to the photosphere

MURaM: Vögler et al. 2005 & Rempel, 2009

– realistic simulation:

– solve fully compressible MHD realistic equation of state (tabular) radiative transfer

➢ **formation of an active region in the photosphere**

The MURaM simulations

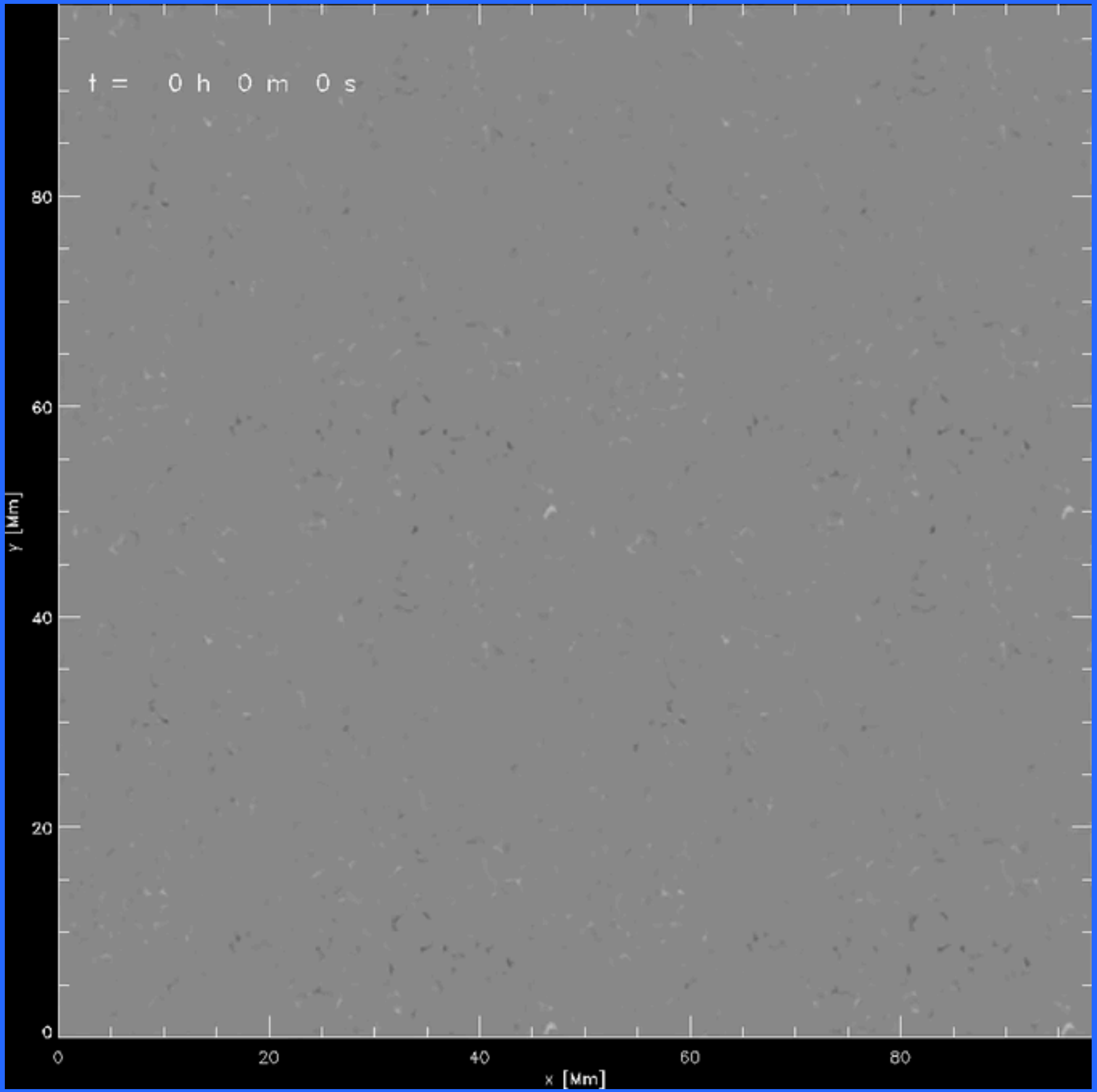
– domain sizes: depths 8, 18, 32 Mm horizontal sizes: 98, 196 Mm upper boundary: 640 km above τ=1

– horizontal resolution of 192 km: good enough to resolve the granulation

– vertical resolution of 64 km

– initial condition: relaxed magneto-convection small-scale *B* by a local dynamo

Coupling to near surface layer radiation MHD simulations of active region formation with MURaM



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SURF: Surface Flux Transport Code

T.Hartlep, D.H.Hathaway, N.N.Mansour

SURF code overview:

✓ 2D advection-diffusion equation for radial magnetic field at the solar surface (derived from the induction equation assuming flow is horizontal and does not vary with depth)

✓ Pseudo-spectral method with spherical harmonic basis functions, and 4th-order Runge-Kutta for time advancement

✓ Magnetic field is advected by a flow that consists of

1. An axisymmetric component: differential rotation and meridional flow: both derived from tracking magnetic features on the solar surface
2. Plus a cellular flow that mimics superganules which itself is advected with the axisymmetric flow

✓ Assimilate full disk HMI magnetograms using the technique of Hathaway, et al. (APJ, 2015)

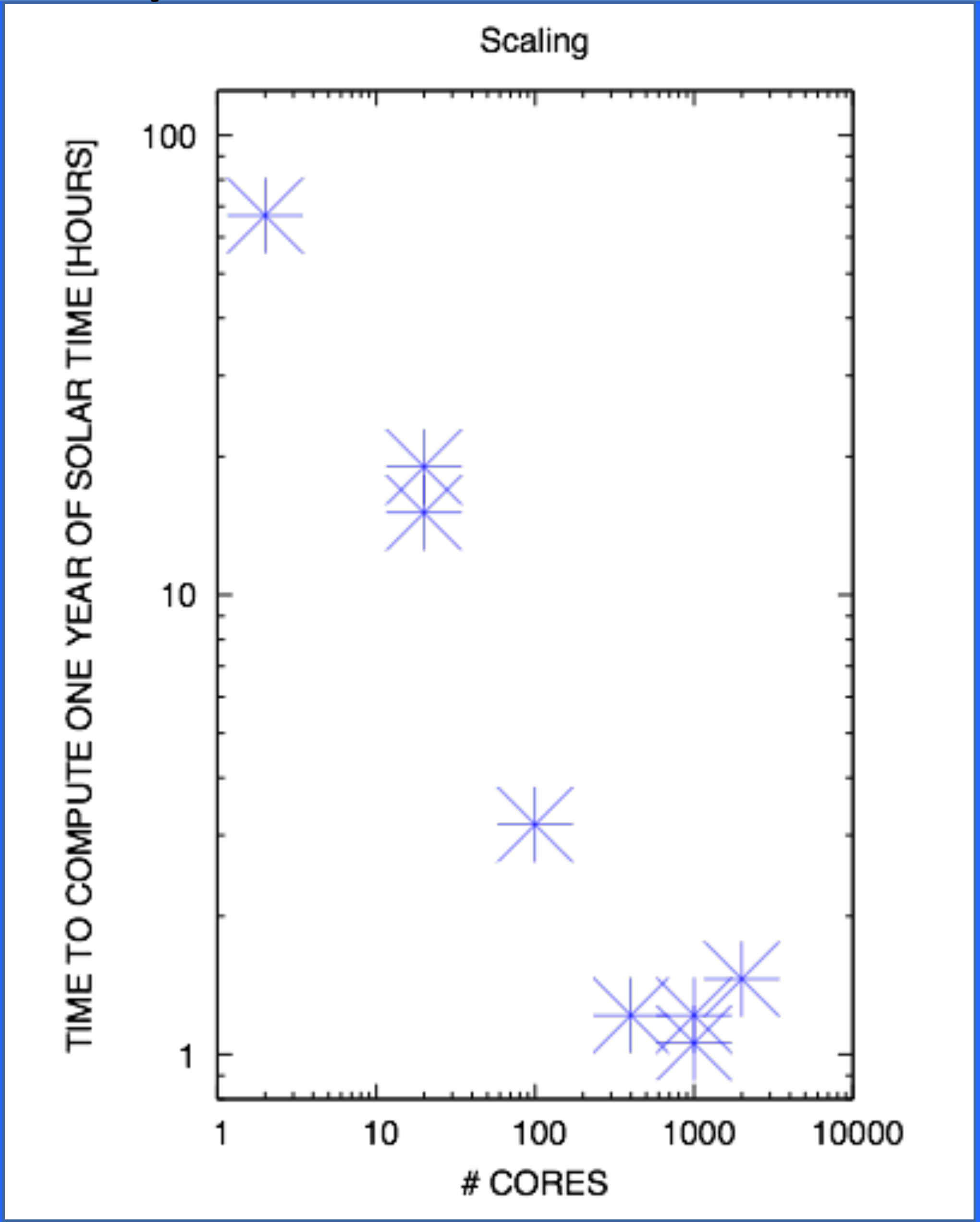
SURF: Surface Flux Transport Code

Resolution:

- ✓ Physical space (latitude x longitude Gauss grid): 2,048 x 1,024
- ✓ Spectral space (spherical harmonic degree): 0<=l<=683

Parallelization:

- ✓ Hybrid OpenMP + MPI;
- ✓ At l=683 resolution efficient to ~400 cores
- ✓ Computing 1 year of solar time takes little over 1 hour on NASA's Pleiades supercomputer



SURF: Surface Flux Transport Code

Governing equations:

Advection-diffusion equation for the radial magnetic field on the solar surface

$$\partial_t B_r + \vec{V}_h \cdot \nabla B_r = \eta \nabla^2 B_r$$

small diffusivity
(for numerical stability only)

advection

$$\vec{V}_h = \vec{U}_a + M(B_r)\vec{W}$$

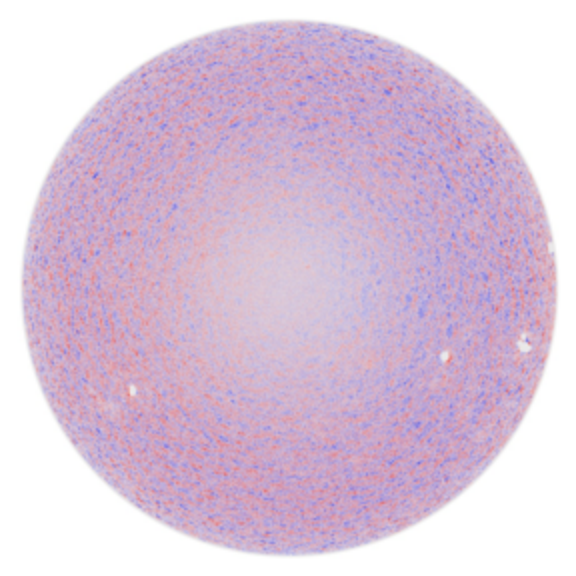
axisymmetric
component
differential rotation +
meridional flow derived
from HMI data

Active region mask

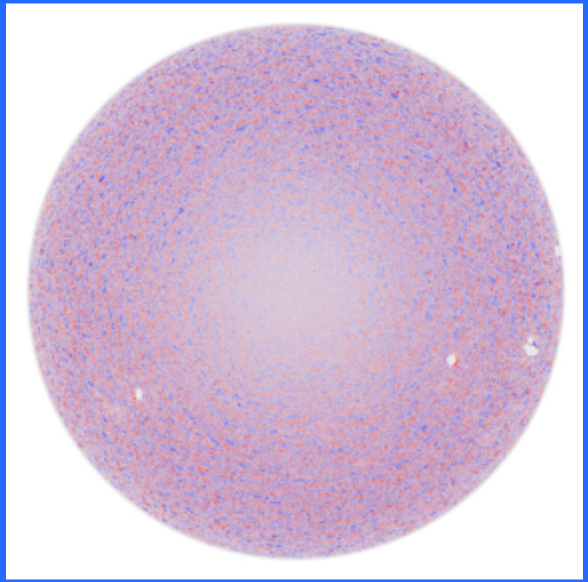
supergranules flow
(Hathaway et al., APJ 2016)
advected by the axisymmetric flow,

$$\partial_t \vec{W} + \vec{U}_a \cdot \nabla \vec{W} = 0$$

Characterizing the Sun's Photospheric Convection Spectrum



Doppler Signal w/ Artifacts



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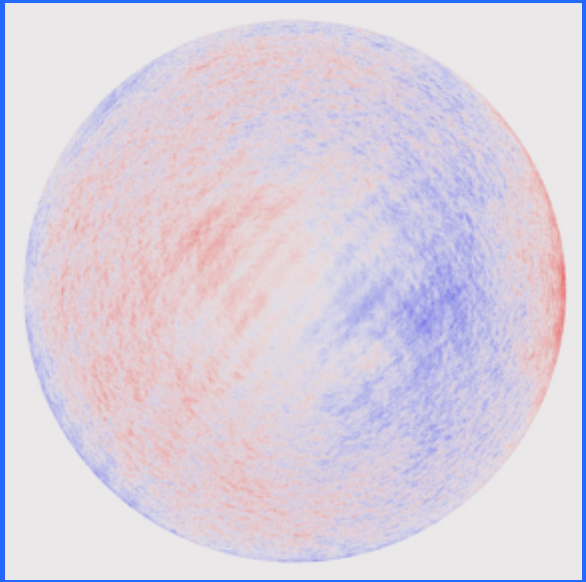
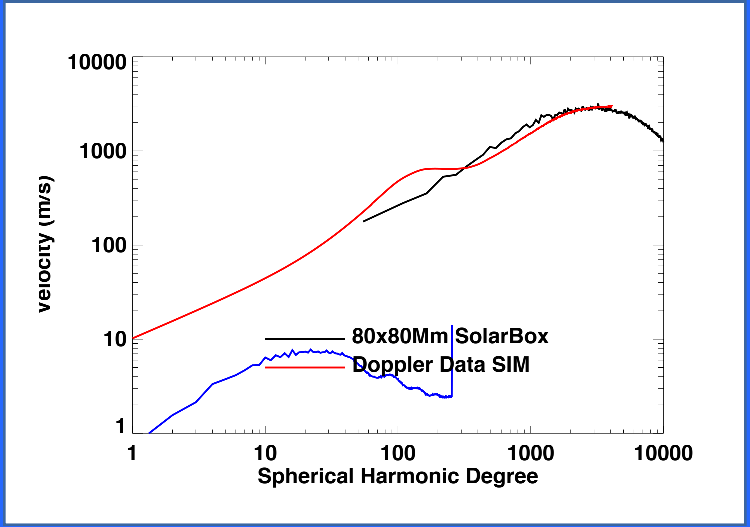
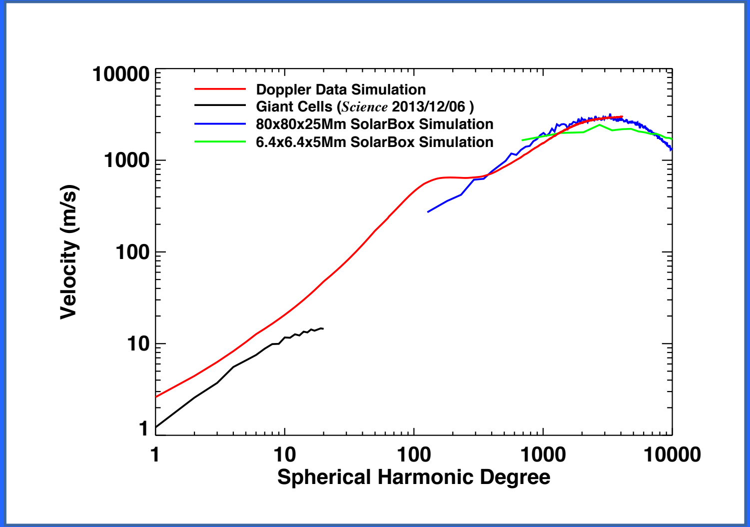
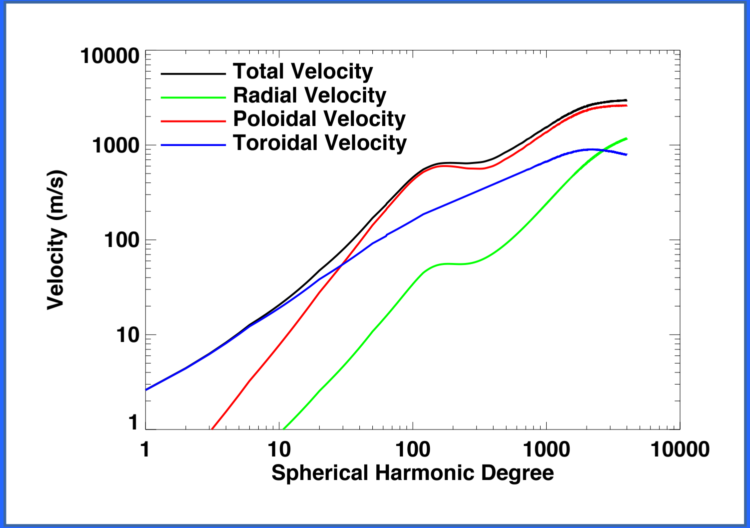


Artifacts



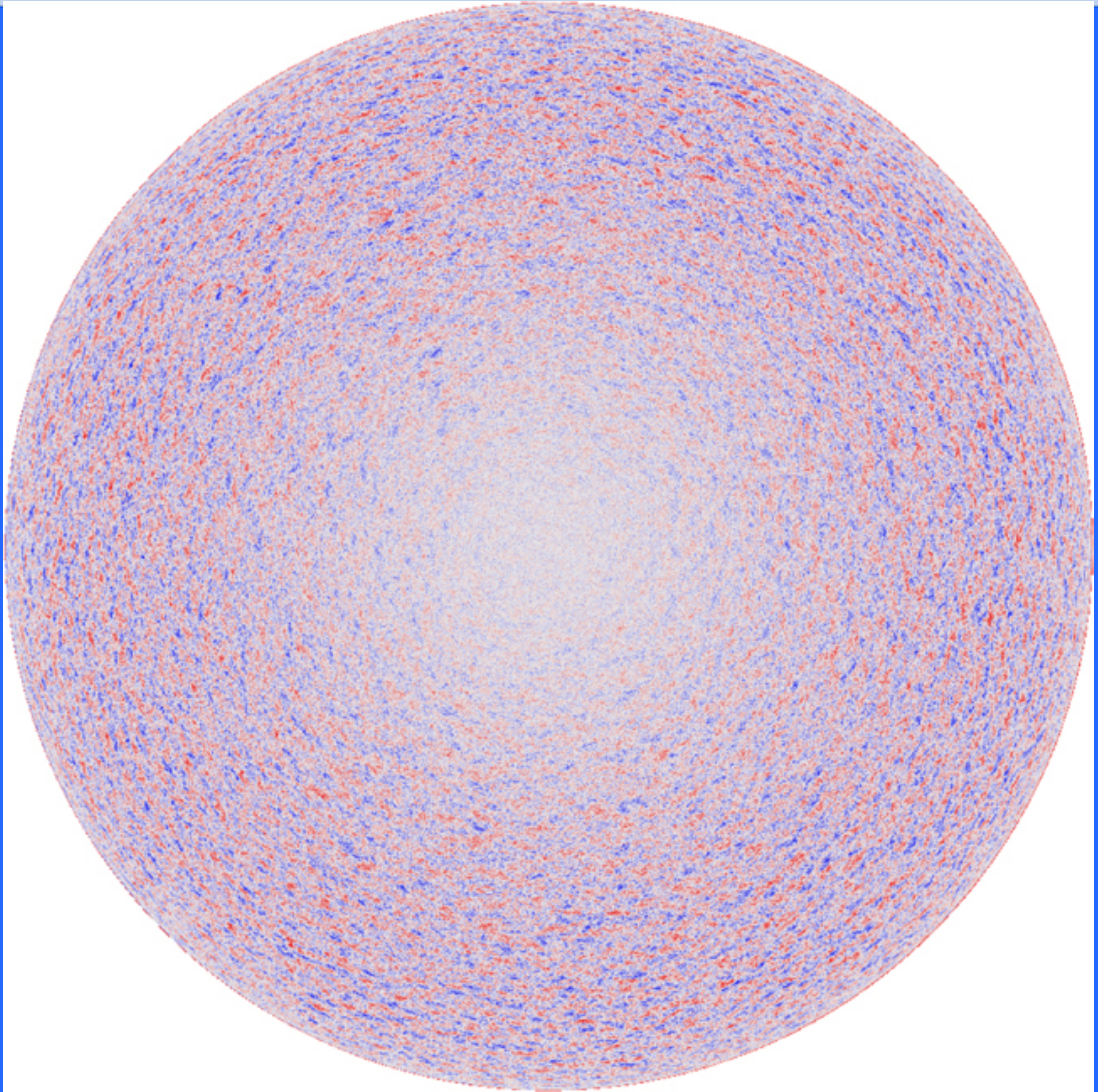




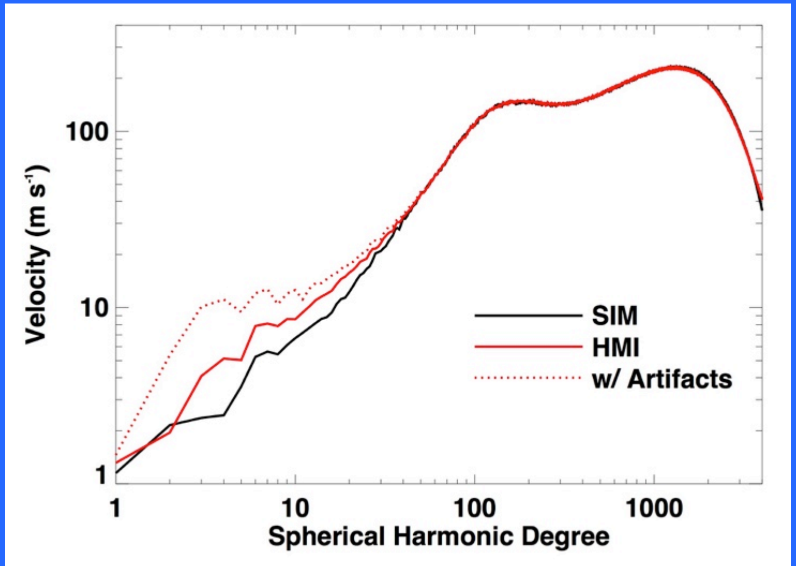
Hathaway/Teil/Norton/Kitiashvili (ApJ, 2015)

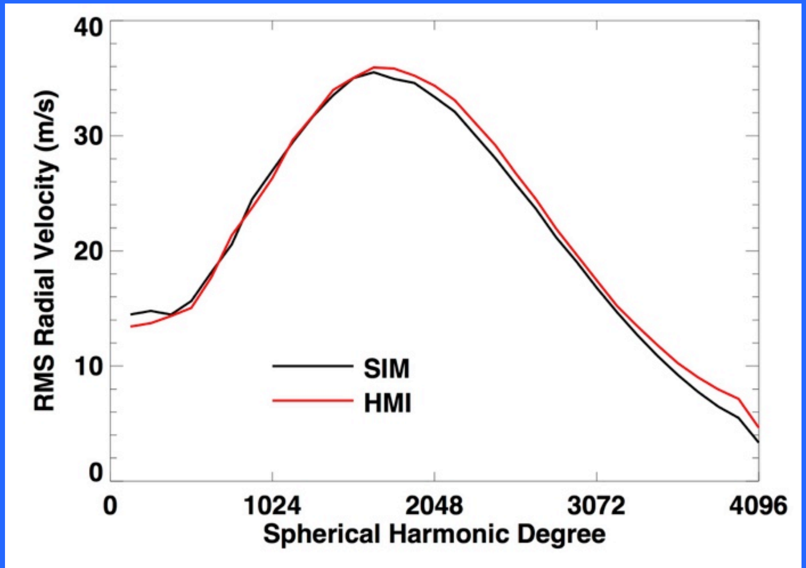
Simulated Doppler image

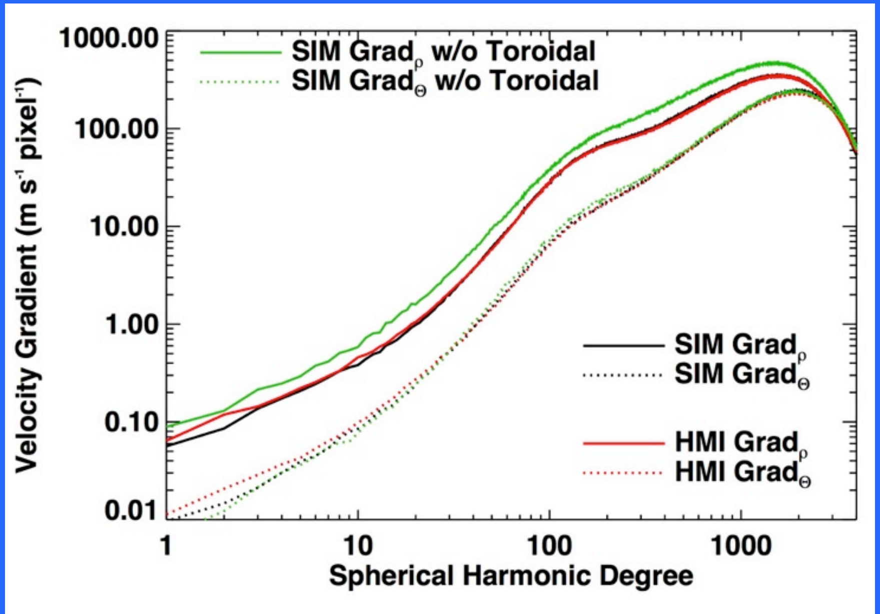
Hathaway/Teil/Norton/Kitiashvili (ApJ, 2015)



HMI/Data Simulation Comparison





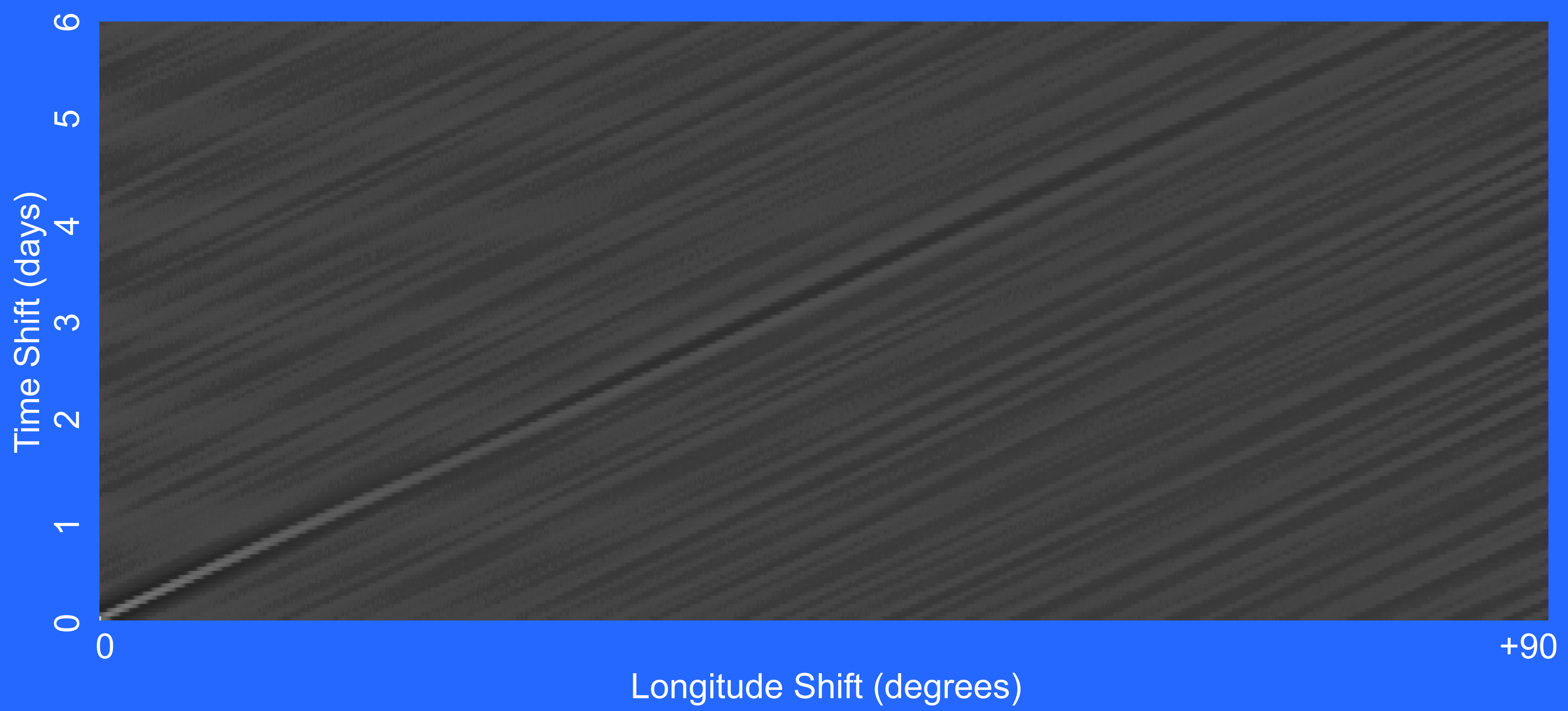


Construct simulated data from a spectrum of vector spherical harmonic components. The spectrum is adjusted until it matchs with HMI: 1) the spherical harmonic spectrum of the Doppler velocities, 2) the rms radial velocity Doppler signal, and 3) the Grad$_\rho$ and Grad$_\theta$ spectra.

Poloidal flows dominate at wavenumbers above 30, Toroidal flows dominate below. Radial flows are only 3% of the horizontal flows at low wavenumbers but become 50% at the highest wavenumbers.

Courtesy: Hathaway, 2018

Cross-Correlation Data



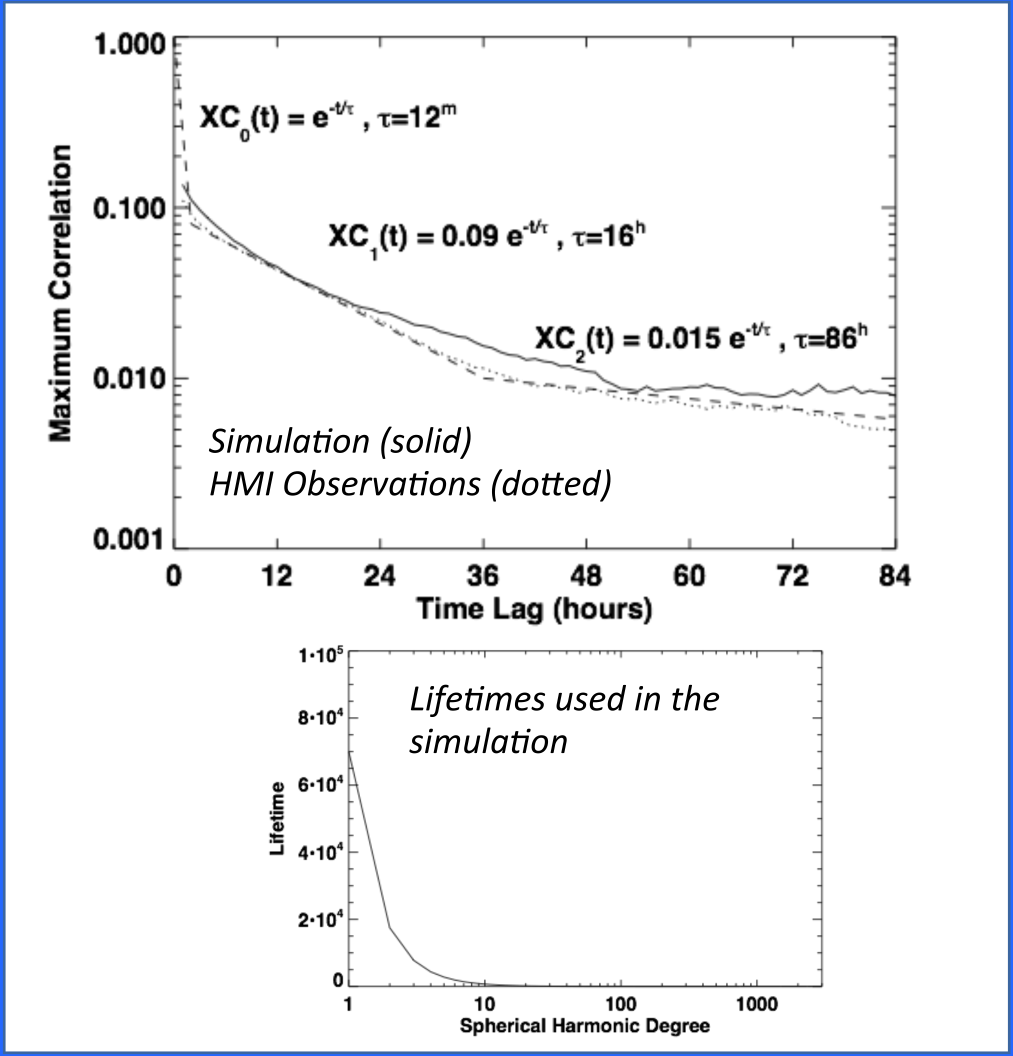
A 2-month average of 1440 (24×60) individual cross-correlations.

Courtesy: Hathaway, 2018

SURF: *A Surface Flux Transport Code*

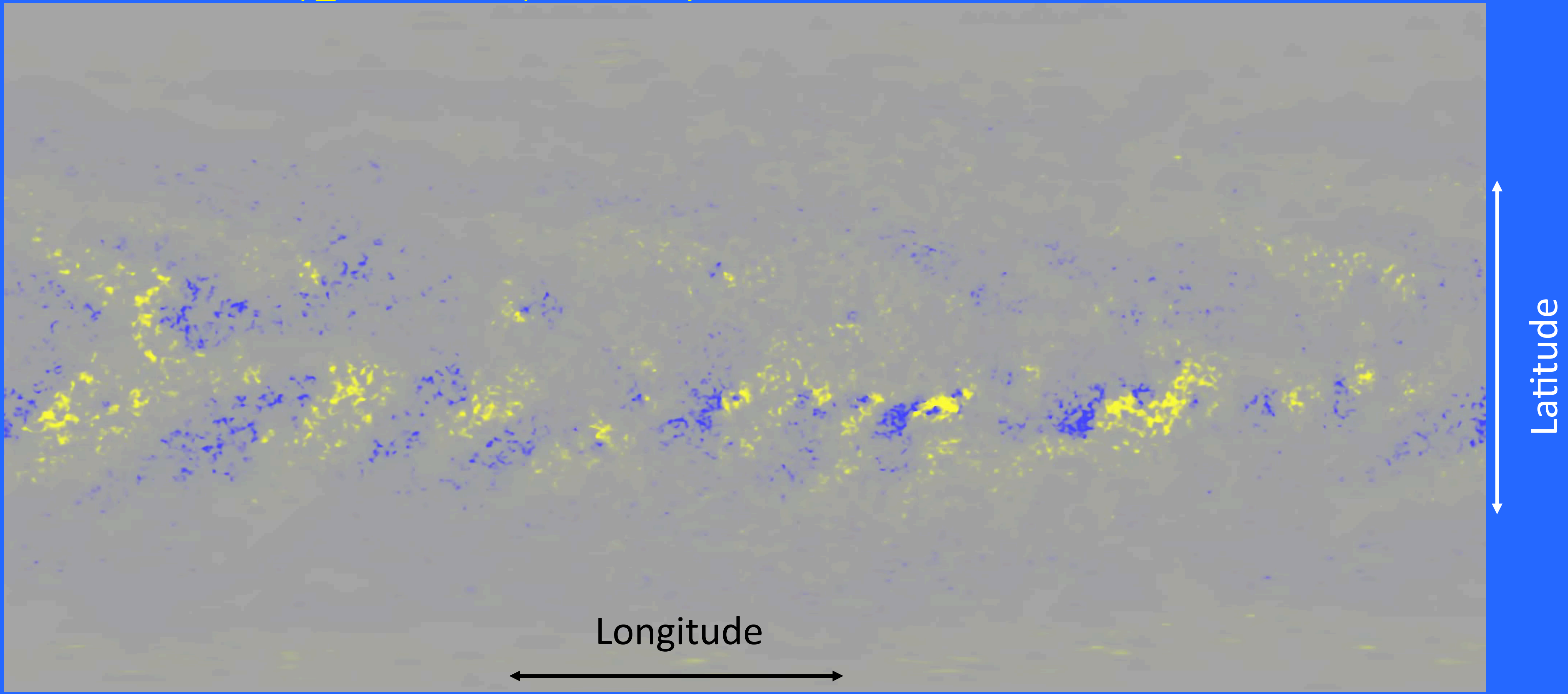
Comparison of cross-correlation between Observation and realistic model for the supergranular flow

- Procedure:
  - Compute disk images of line-of-sight velocity (simulation only)
  - Remove large scale flows
  - Project to heliographic coordinates
  - Line-of-sight “de-projection”
  - Compute cross-correlation between strip at the equator with itself time-lagged and shifted in longitude
- Result:
  - Cross-correlation decays in time since flow structures on the sun (granules, supergranules) have finite lifetime
  - We have found a lifetime dependence (as function of l) for which the resulting cross-correlation compares well with the observation



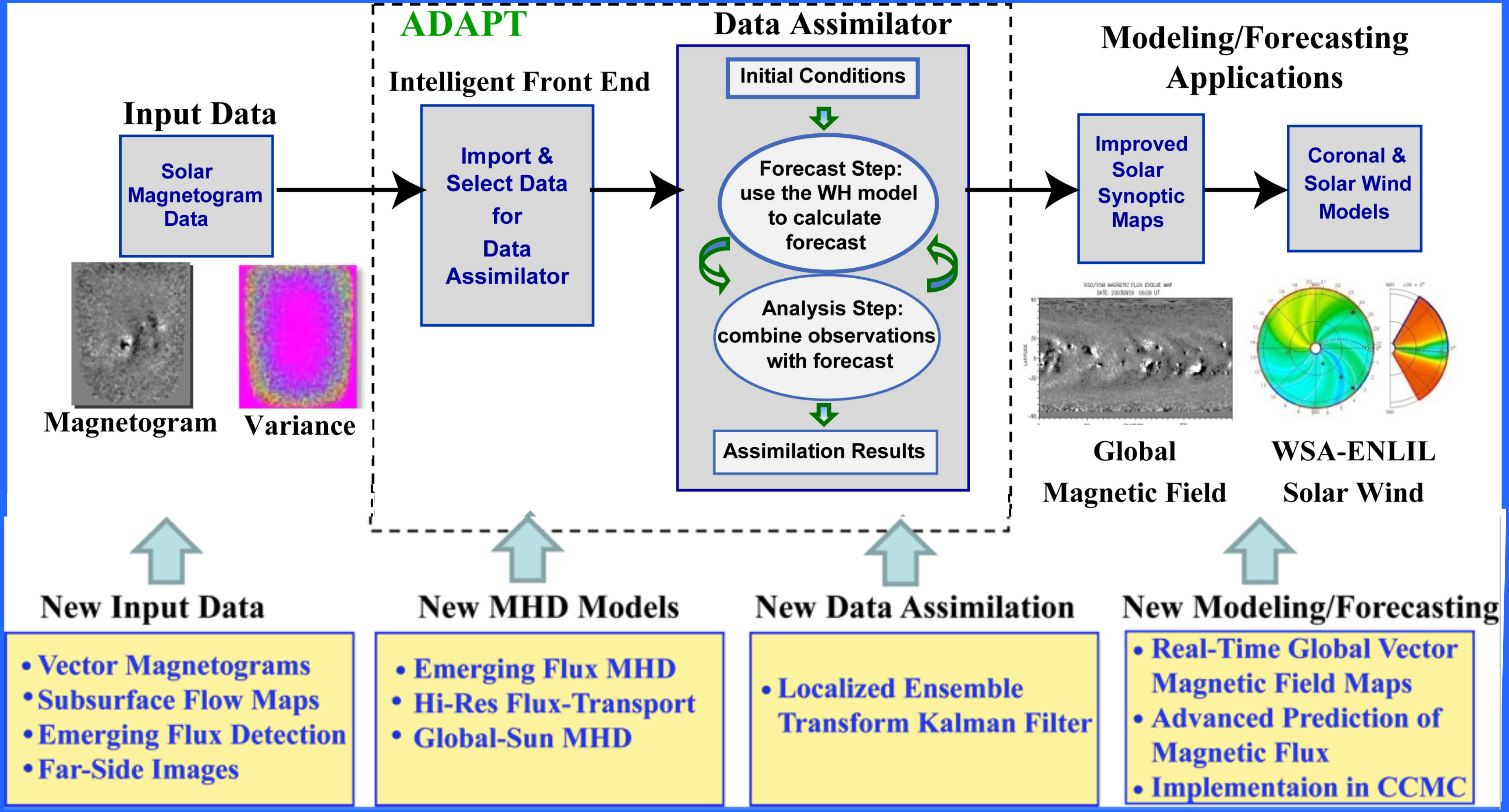
Example: decay of magnetic flux by supergranules

Initial condition:Snapshot from D.Hathaway’s simulation as; **No new flux injected;**
Transported for about 7 months (1 day is 0.5 sec in movie);
4096x2048 resolution (l_max = 1365); time step of 14.4 mins



Vision for a modern Space Weather Forecast

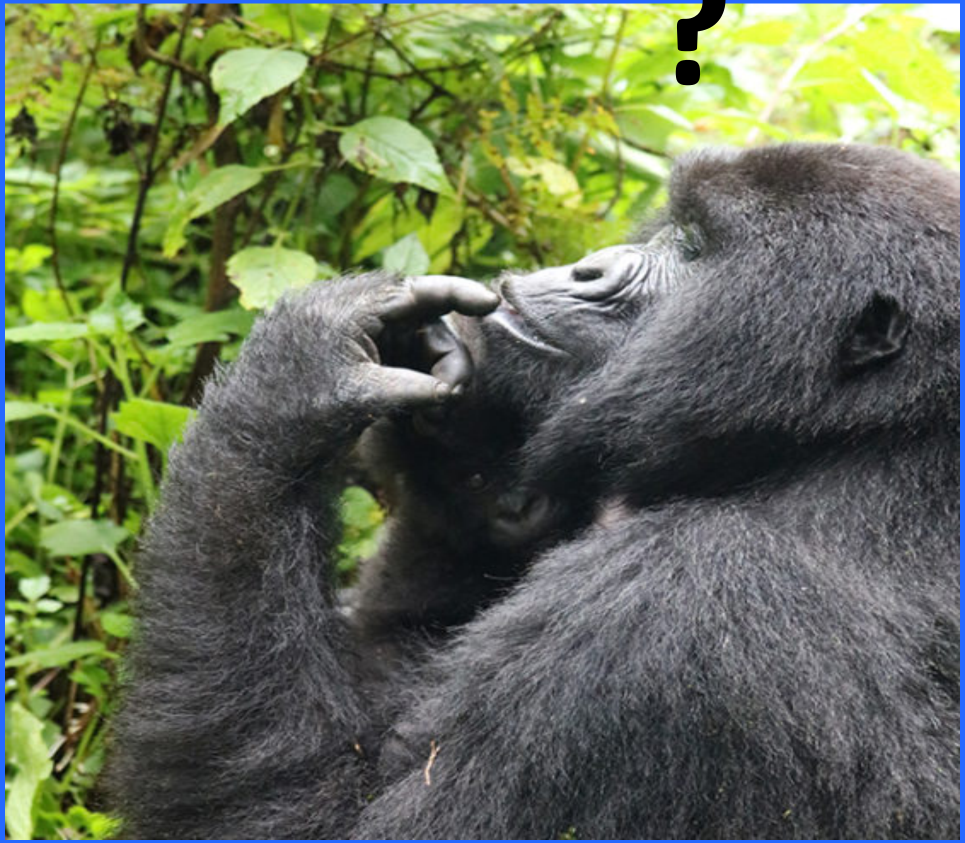
What the future will look like



Forget about the Physics

Observations + machine learning

?



THANK YOU