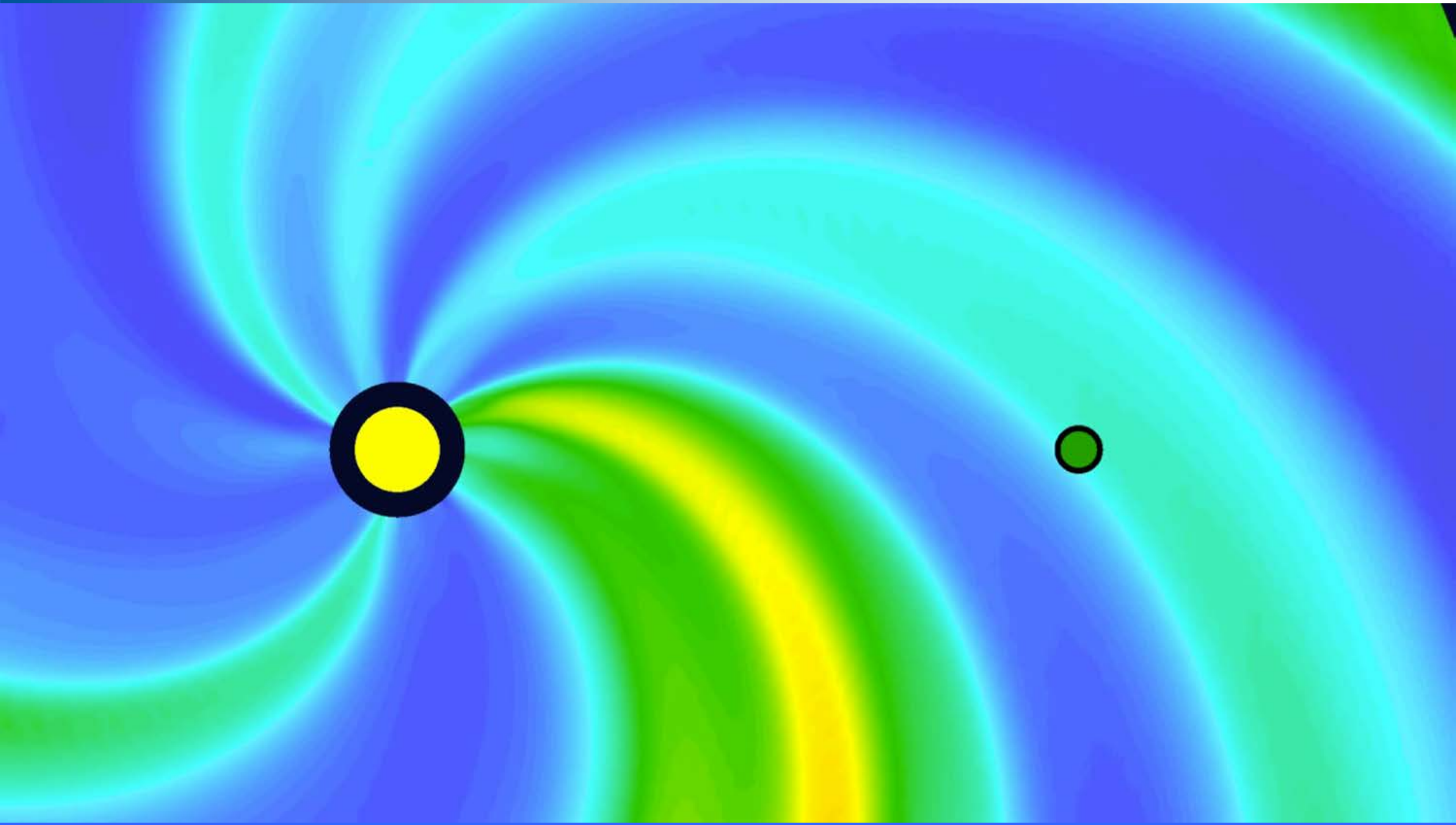
Integrated Real-Time Modeling System for Heliospheric Space Weather Forecasting

Nagi N. Mansour
NASA Ames Research Center

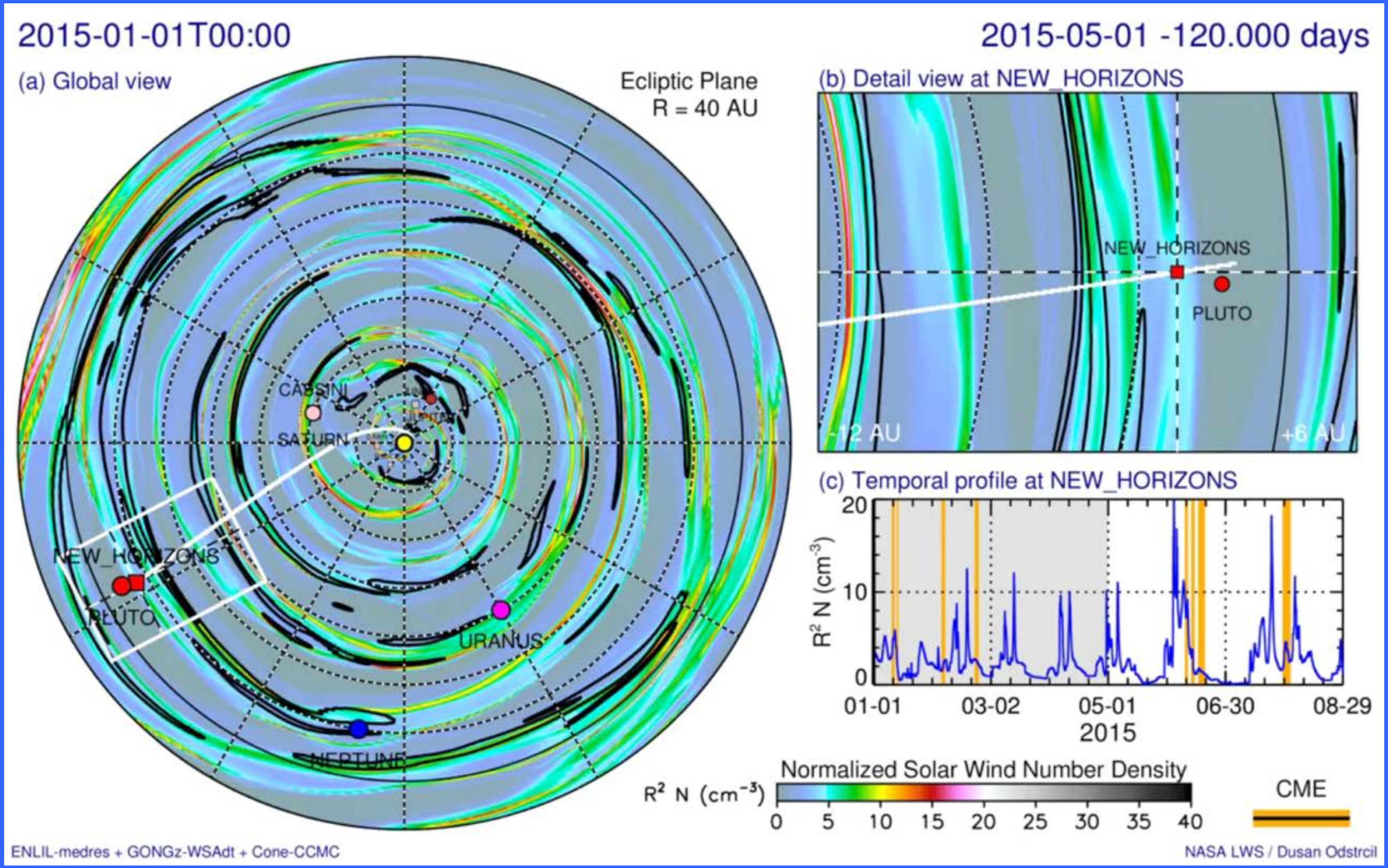
Roadmap for Reliable Ensemble Forecasting of the Sun-Earth System
NJIT, March 28-30, 2018

NOAA's advanced forecast Sun-Earth system



WSA-ENLIL

NASA's interest goes beyond Near Earth space weather



Pluto's atmosphere may be immersed in low-density rarefaction followed by GMIR shock

What changed?

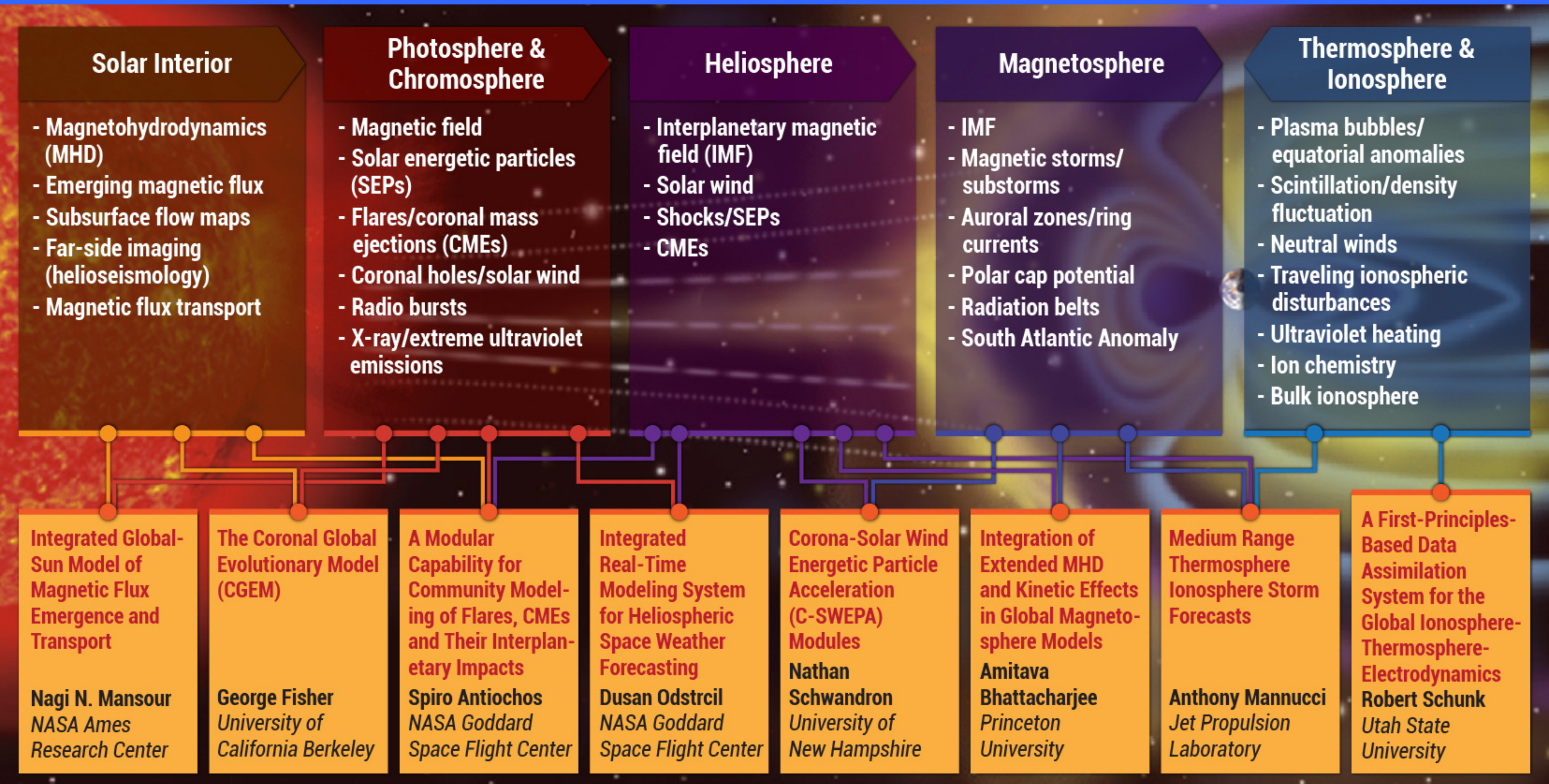
SDO

High-quality data at incredible spatial and time resolution

Pflop/s + HF physics software

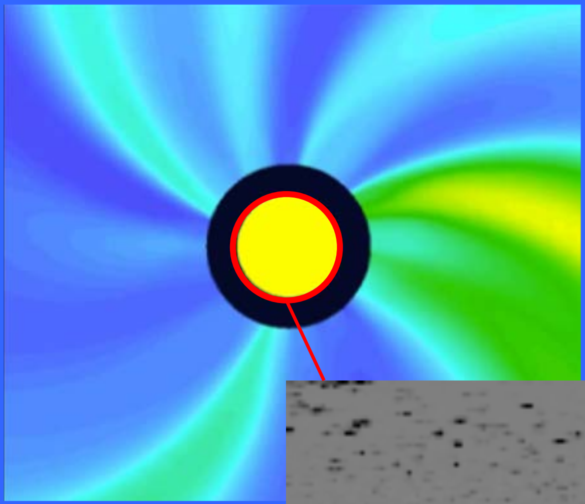
Simulations previously unrealistic are now possible

NASA/NSF Partnership for Collaborative Space Weather Modeling



Air force Data Assimilation Photospheric flux Transport (ADAPT)

The global solar photospheric magnetic field distribution serves as primary input to *all* coronal and solar wind models



ADAPT

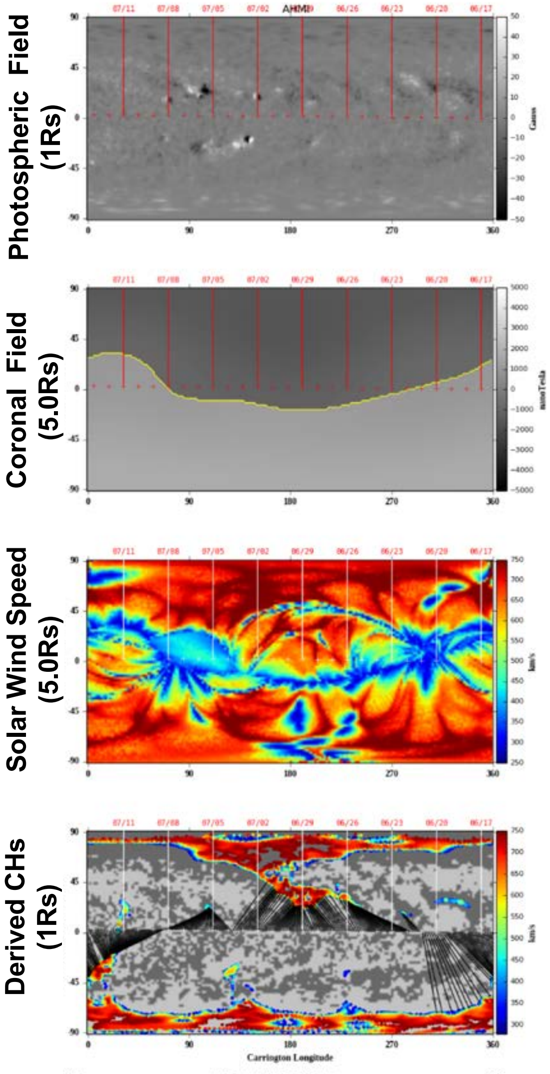
Modernizing operational technology

1. Enable adapt to read HMI Magnetograms

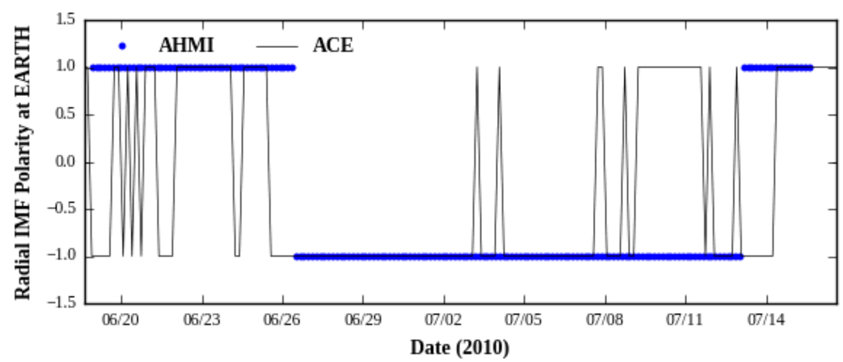
2. Modernize ADAPT to use SoA data assimilation technology

3. Far-side detection

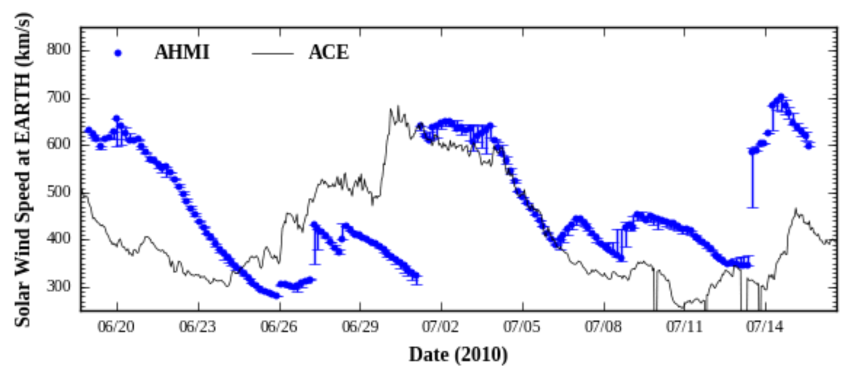
WSA 4.2 ADAPT HMI-Vector: coronal solutions & solar wind solutions



Radial IMF Polarity at Earth



Solar Wind Speed at Earth (km s^{-1})



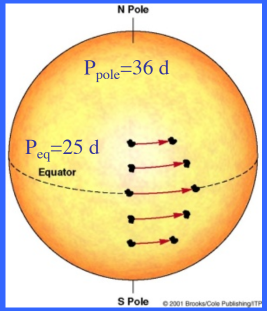
July 8, 2010 @ 20 UT

- ADAPT-HMI maps fully integrated into WSA 4.2
- Working on tuning solar wind empirical relationship

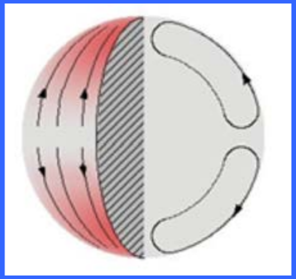
Modernizing the elements of the flux transport model

Overview: **The ADAPT flux transport model (Arge et al. 2009 & 2010) is based on Worden & Harvey (2000), which** ***accounts heuristically for known flows in the solar photosphere.***

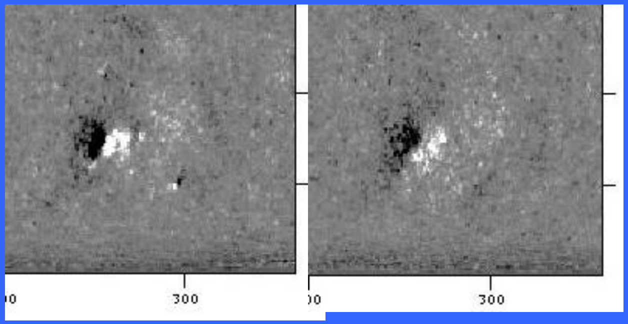
(1) Differential rotation



(2) Meridional flow



(3) Supergranular diffusion



(4) Random flux emergence

(5) New observation data assimilation

(6) An ENSEMBLE of solutions representing the model parameter uncertainties

Overview

– 2D advection-diffusion equation for radial magnetic field at the solar surface

– The magnetic field is advected with realist flow models using:

- Axisymmetric flow components: differential rotation and meridional flow; both derived from tracking magnetic features on the solar surface
- And a cellular flow component that mimics supergranules (Hathaway et al. 2010) which itself is advected with the axisymmetric flow

– Code uses pseudo-spectral method with spherical harmonic basis functions, and 4th-order Runge-Kutta for time advancement

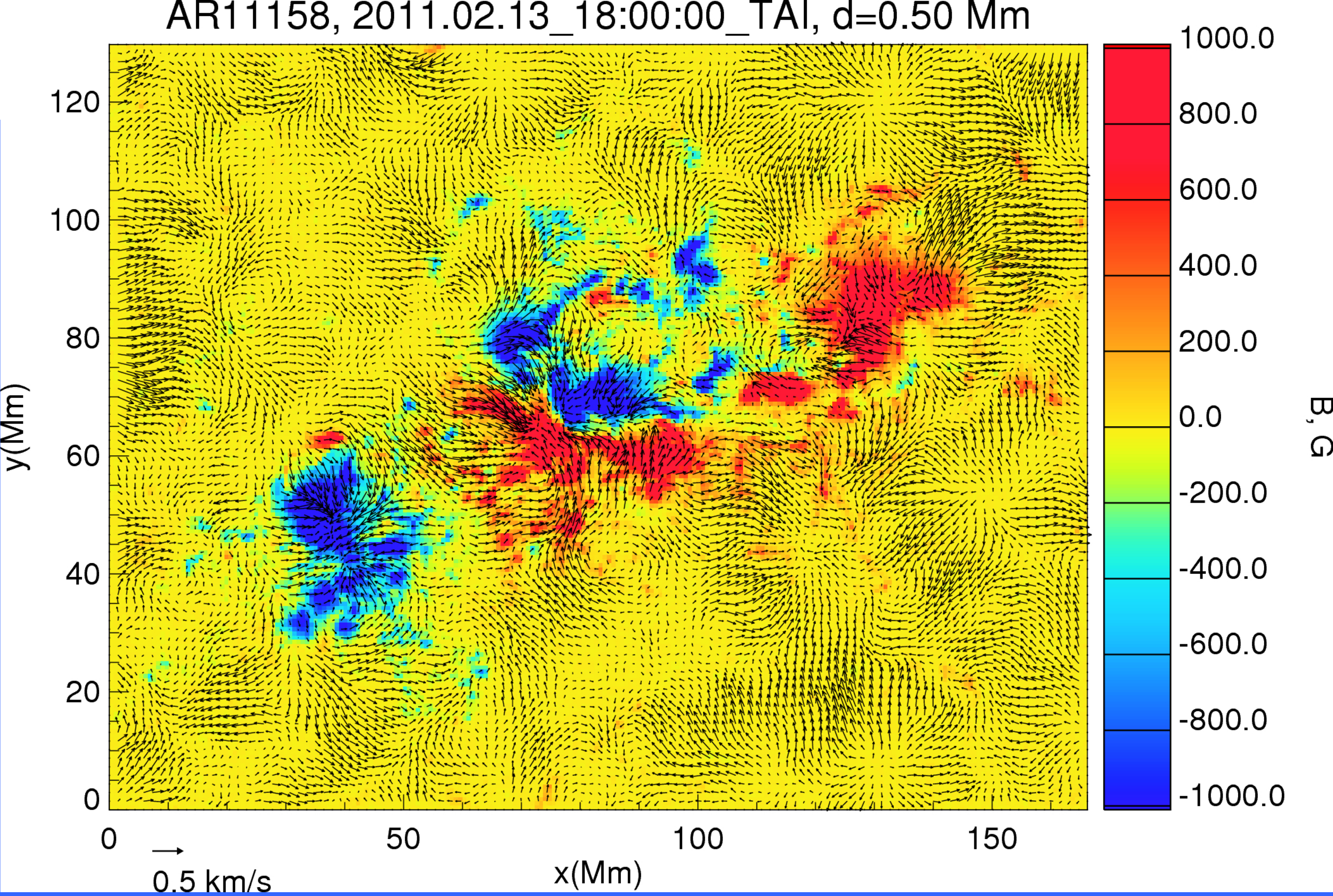
– Code can assimilate full disk HMI magnetograms using the technique of Upton & Hathaway, 2014

Achievement: Realistic model for supergranular flow

- Supergranular flow initialized with realistic power spectrum determined from solar observations
- Itself advected by meridional flow and differential rotation
- Simulated supergranules have finite lifetimes; this is accomplished by randomly changing the phase of each spherical harmonic components by a small amount such that a desired lifetime is achived
- Supergranule lifetime is prescribed as a function of spherical harmonic degree such that decay of flow cross-corrleation compares well with observations (see next slide)

Advancements in Observation Methods

- Far-side detection of flux emergence
- Detection of large solar active regions in acoustic travel-time signals before their emergence (from several hours to two days in advance.)
- Detection of the meridional flow by helioseismlogy methods.
- Mapping solar subsurface flow fields down to more than 20 Mm below the photosphere (discovery of strong shearing flows associated with flaring and CME activity.)
- …



Courtesy. Kosovichev, 2013

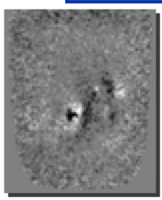
Vision for a modern
Space Weather Forecast

What the future should look like

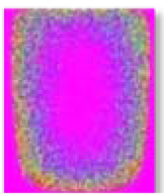
ADAPT

Input Data

Solar Magnetogram Data



Magnetogram



Variance

Intelligent Front End

Import & Select Data for Data Assimilator

Data Assimilator

Initial Conditions

Forecast Step: use the WH model to calculate forecast

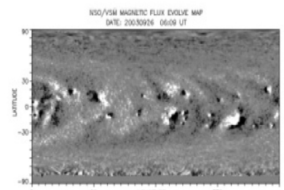
Analysis Step: combine observations with forecast

Assimilation Results

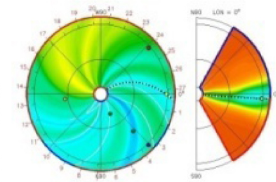
Modeling/Forecasting Applications

Improved Solar Synoptic Maps

Coronal & Solar Wind Models



Global Magnetic Field



WSA-ENLIL Solar Wind

New Input Data

- Vector Magnetograms
- Subsurface Flow Maps
- Emerging Flux Detection
- Far-Side Images

New MHD Models

- Emerging Flux MHD
- Hi-Res Flux-Transport
- Global-Sun MHD

New Data Assimilation

- Localized Ensemble Transform Kalman Filter

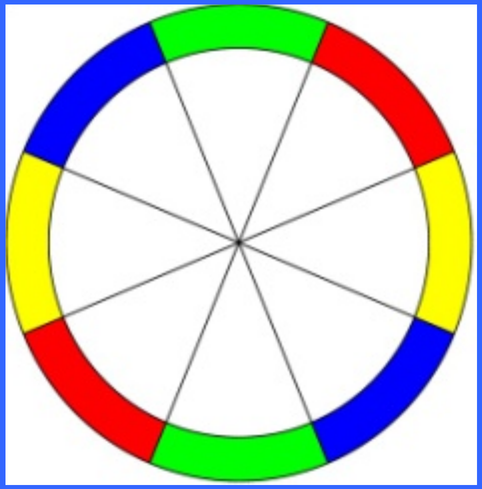
New Modeling/Forecasting

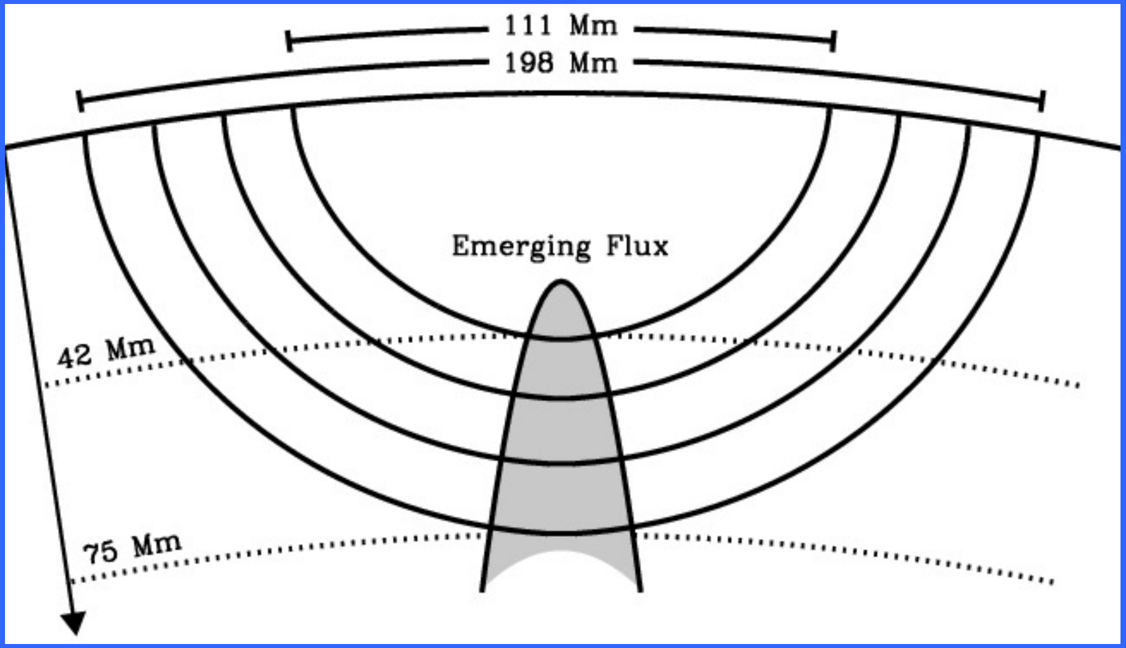
- Real-Time Global Vector Magnetic Field Maps
- Advanced Prediction of Magnetic Flux
- Implementaion in CCMC

+ machine learning

Examples of new advancements in observations: Methodology of detection of emerging flux

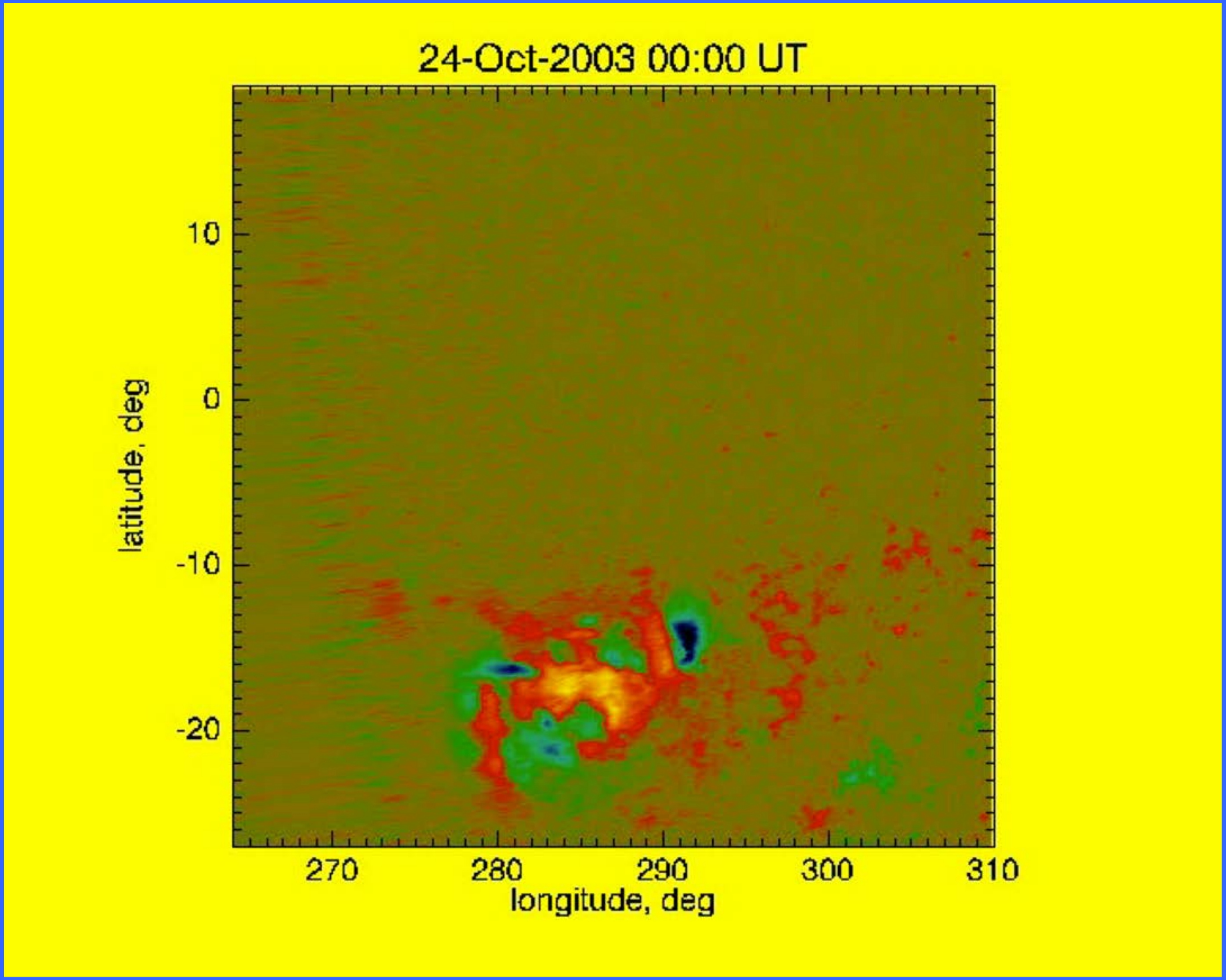
Deep-focus Time-Distance Helioseismology: solar oscillation signal is filtered to select acoustic waves traveling to depth 40-70 Mm (right), averaged over arcs (left), and cross-correlated for opposite arcs. Travel-time perturbations are measured by fitting Gabor wavelet. This method has been tested with 3 different instruments (MDI, HMI, GONG) for many quiet and emerging flux regions



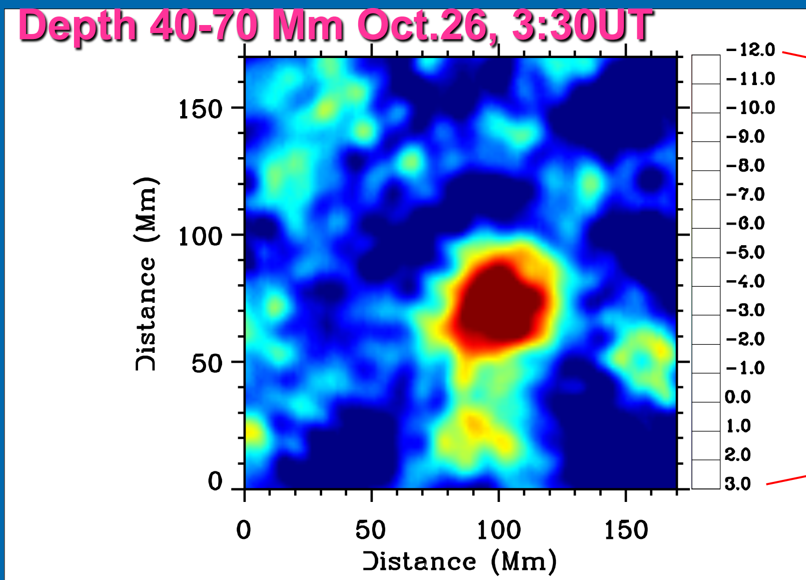


Ilonidis et al (2011)

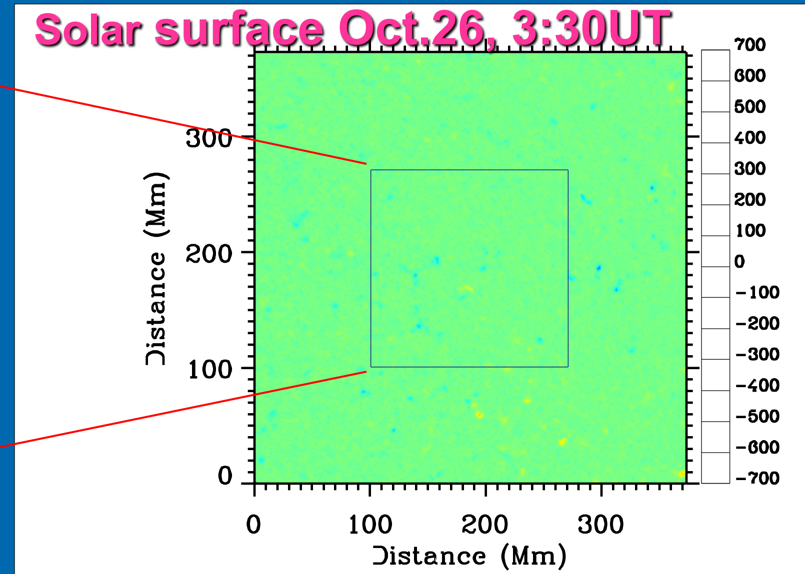
Emergence of AR 10488: Oct 24 – Nov 2, 2003



Results for AR 10488



03:30 UT 26 Oct 2003



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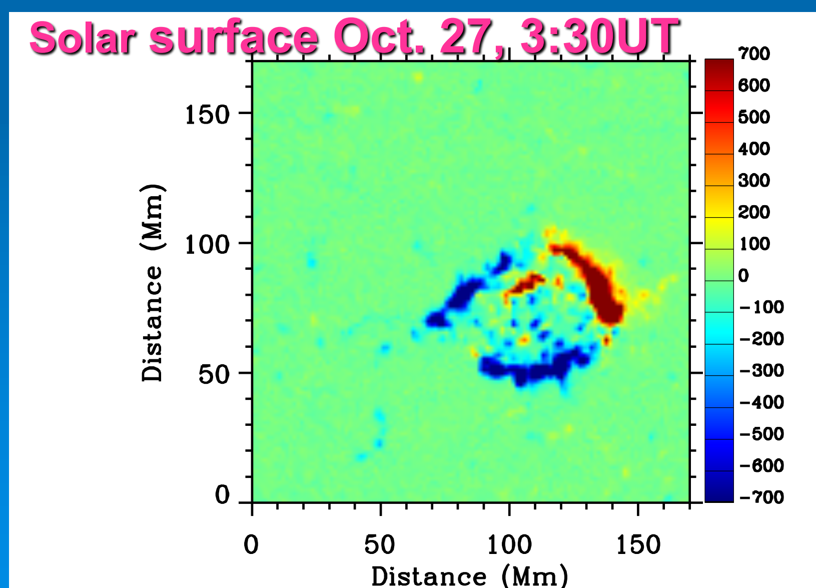


24h

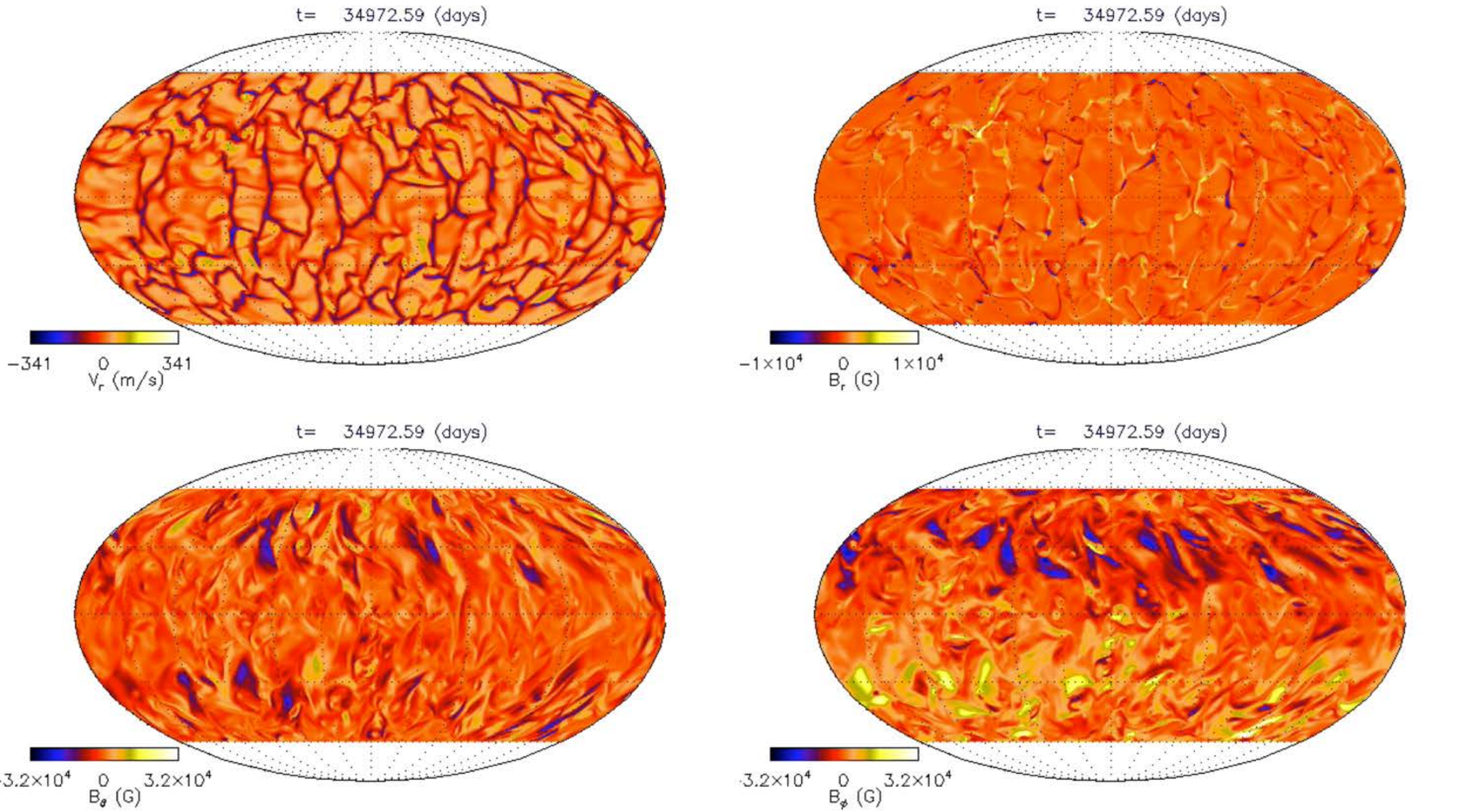
03:30 UT 27 Oct 2003

Realistic Models of Flux Emergence

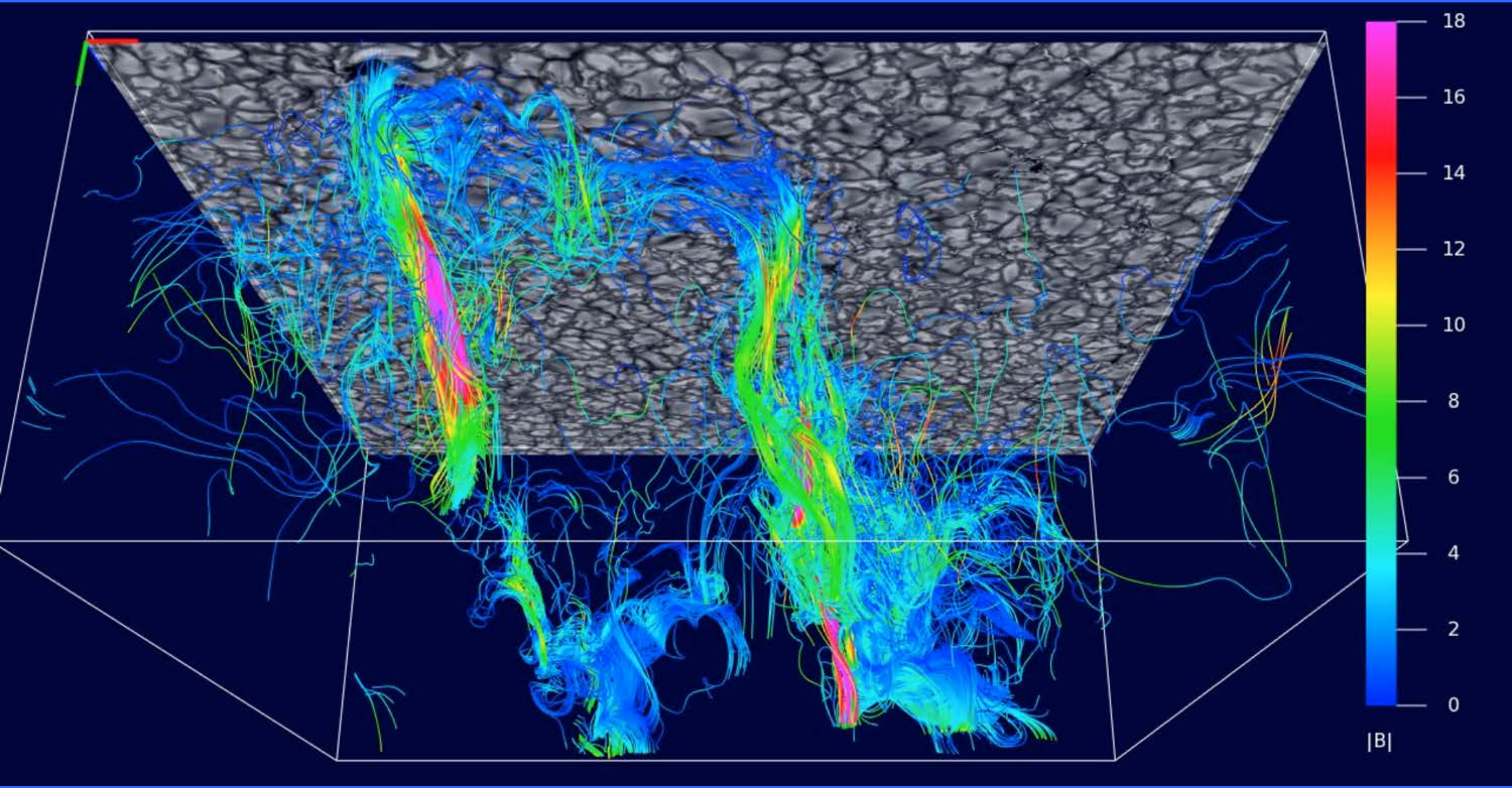
Numerical models of the conservation equations for Mass (Species), Momentum, Energy, Magnetic Flux.

Large range in time scales, spatial scales and dominant physics

From the Subsurface to the corona

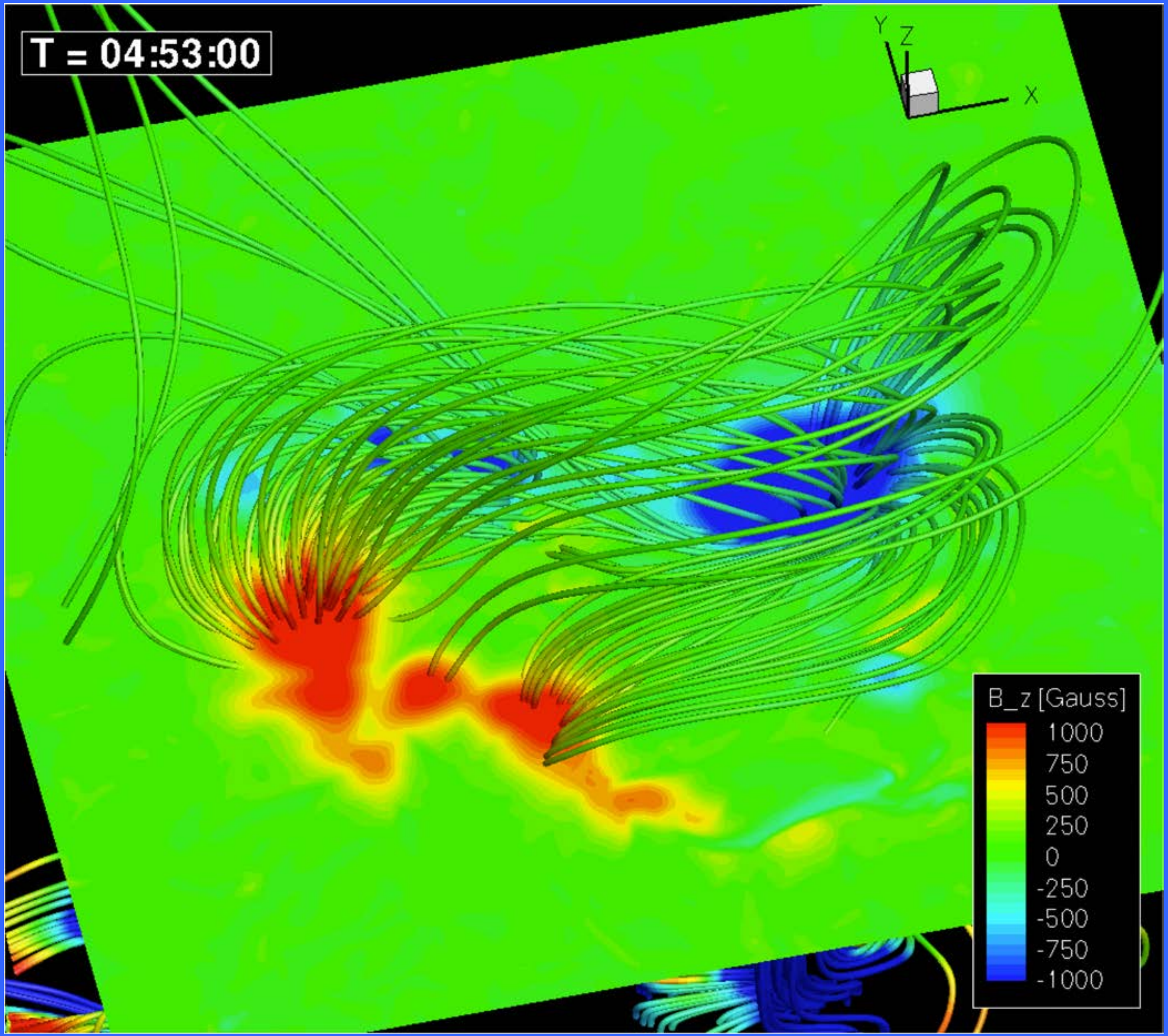


Subsurface High-Fidelity Simulations

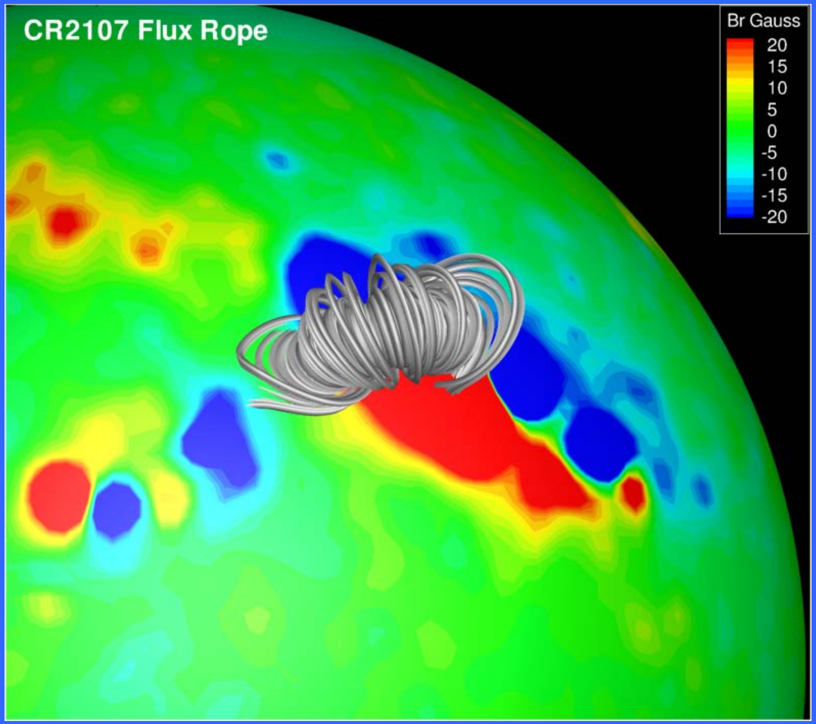


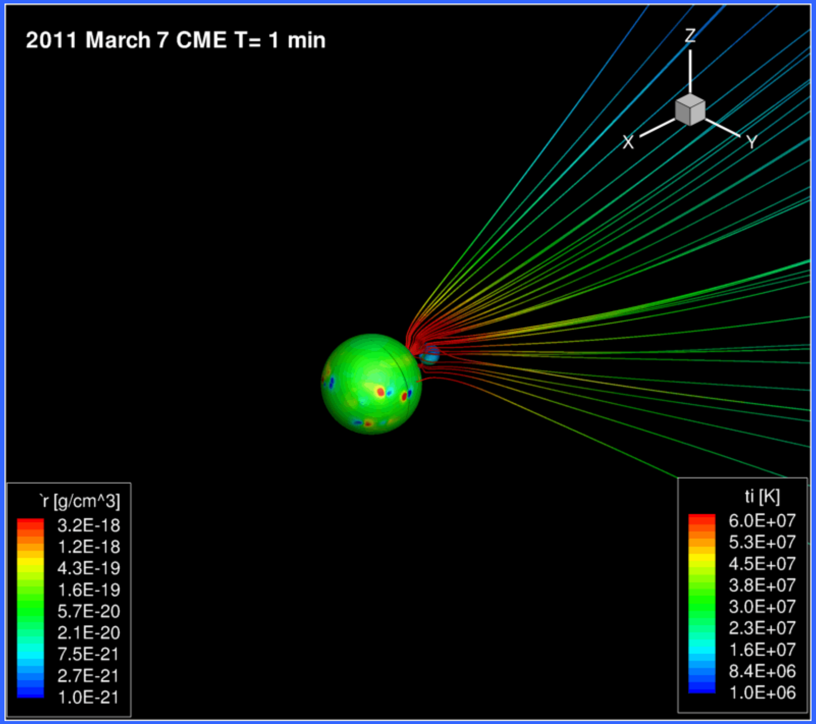
Courtesy. Stein, 2012

From the Subsurface to the corona



CME Initiation by Flux Rope Eruption



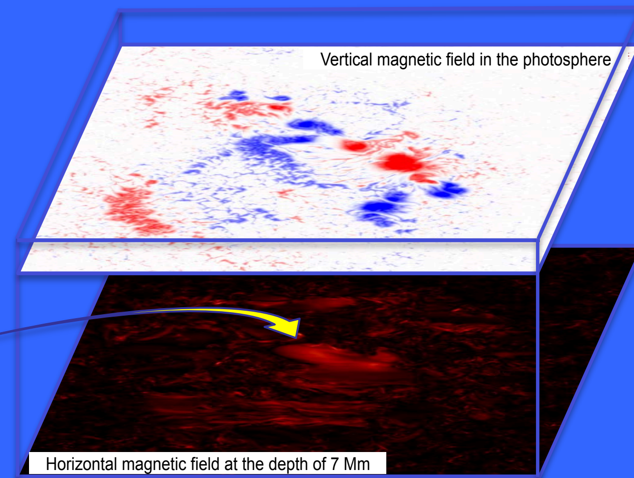


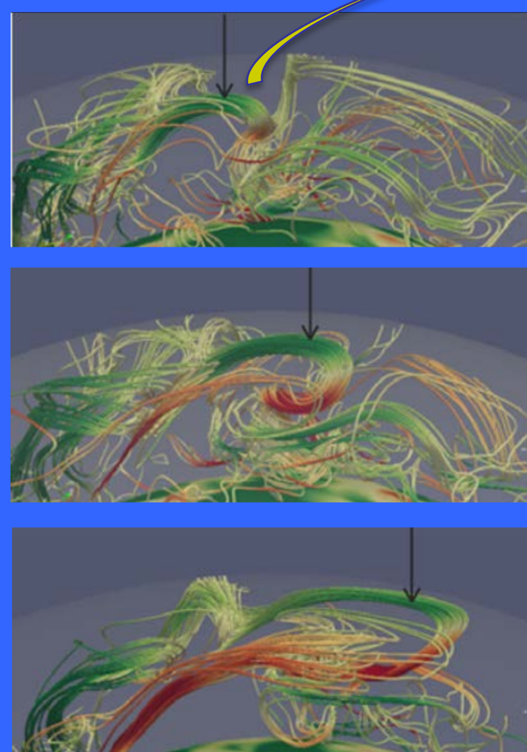
Analytical force-free flux rope model first developed by *Titov & Demoulin (1999).*

Meng Jin, W. Manchester et al. AGU Fall Meeting 2012

Coupling the deep interior to the surface
(*Chen, Rempel, and Fan, ApJ, 2017*)

Emerging flux bundles generated by FSAM simulation of convective dynamo *Fan & Fang, 2014*





Further emergence of the flux bundles to the photosphere
MURaM: Vögler et al. 2005 & Rempel, 2009

Lead Technology Questions

- How do we combine observations and models of the magnetic flux emergence, transport, interaction, and dispersion to determine the magnetic field distribution over the entire Sun?

How do we merge advancements in observations with advancements in numerical simulations to advance Space Weather forecast?

Recommendations

➢ **Solar Interior and photosphere**

Investments are needed in both science and **strategic capabilities**

Objective 1: Operation (Technology)

- Modernize current operational capabilities
- Automate and speed Helioseismology techniques
- Develop data assimilation technology for space weather
- Machine learning based forecastr

Objective 2: Understanding (Science)

- Ensure capability tools available to the community will facilitate our understanding of the dynamics of stars and their interactions with their planetary system