Approach to Integrate Global-Sun Models of Magnetic Flux Emergence and Transport for Space Weather Studies

Nagi N. Mansour
NASA Ames Research Center

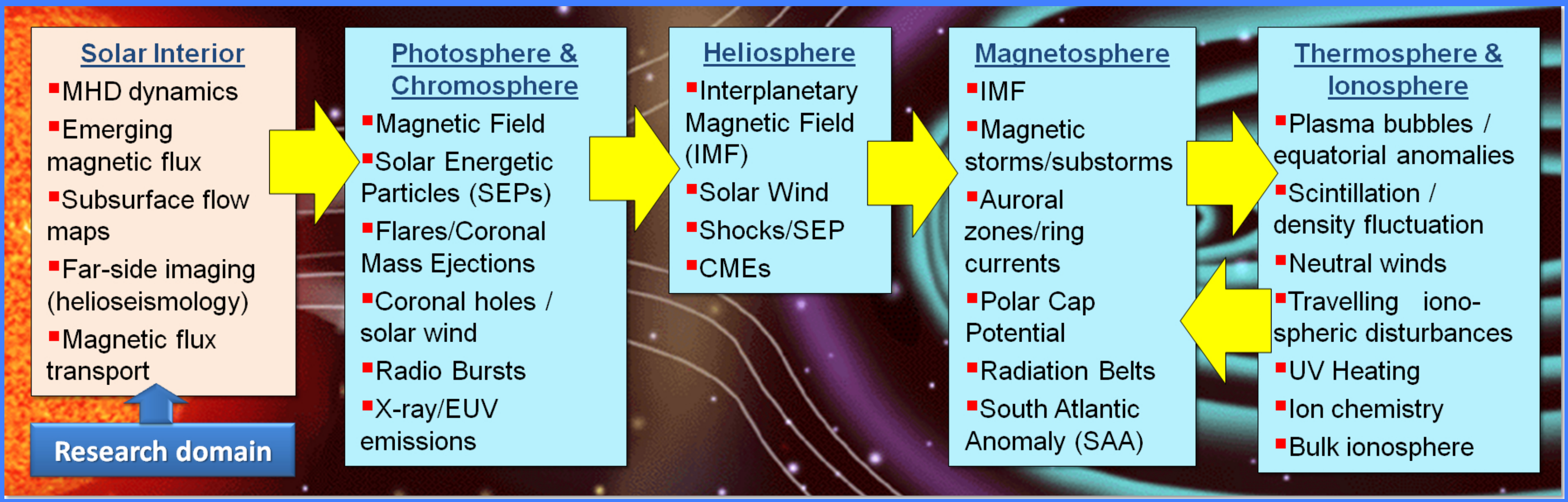
LWS TR&T NASA/NSF Partnership for
Collaborative Space Weather Modeling program

The 7th Community Coordinated Modeling Center (CCMC) Workshop
Annapolis, MD – March 31-Apr 04, 2014

Co-Investigators

Air Force Research Laboratory
C. Henney, Nick Arge
University of Michigan
W. Manchester
New Jersey Institute of Technology
A. Kosovichev
Stanford University
P. Scherrer, J. Zhao
National Center for Atmospheric Research/HAO
Y. Fan
Michigan State University
R. Stein
Los Alamos National Laboratory
H. Godinez, J. Koller
NASA Ames Research Center
A. Wray, P. Mehrotra
NASA Goddard Space Flight Center
T. Duvall

Sun-to-Earth Coupling



- Acoustic travel-time signals can now predict flux emergence up to two days in advance.
- Time-distance helioseismology can now map subsurface flows more than 20 Mm deep and has discovered strong shear flows associated with flares and Coronal Mass Ejections.

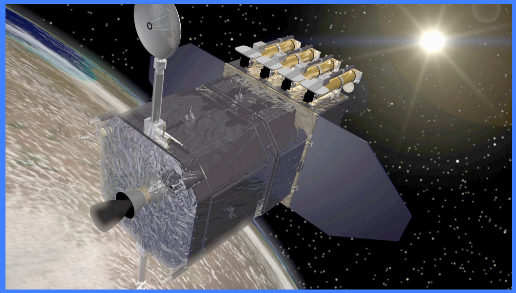
Synopsis of the Project

Two major elements to the effort:

1. Forecast (Technology) - Enhance the Air Force Data Assimilation Photospheric flux Transport model (ADAPT) by assimilating SDO-HMI data
2. Understanding (Science) - Develop Coupled Models for Emerging flux Simulations (CMES) within the Space Weather Modeling Framework (SWMF) by coupling:

    a) FSAM code, Fan [2008]: Deep convection zone.
    b) Stagger code, Stein et al. [2011]): Subsurface and photoshpere.
    c) Corona Module in BATSRUS, Fang et al. [2012]: Subsurface to the Corona.

Enabling Developments



SDO

High-quality data greatly increased spatial and time resolution

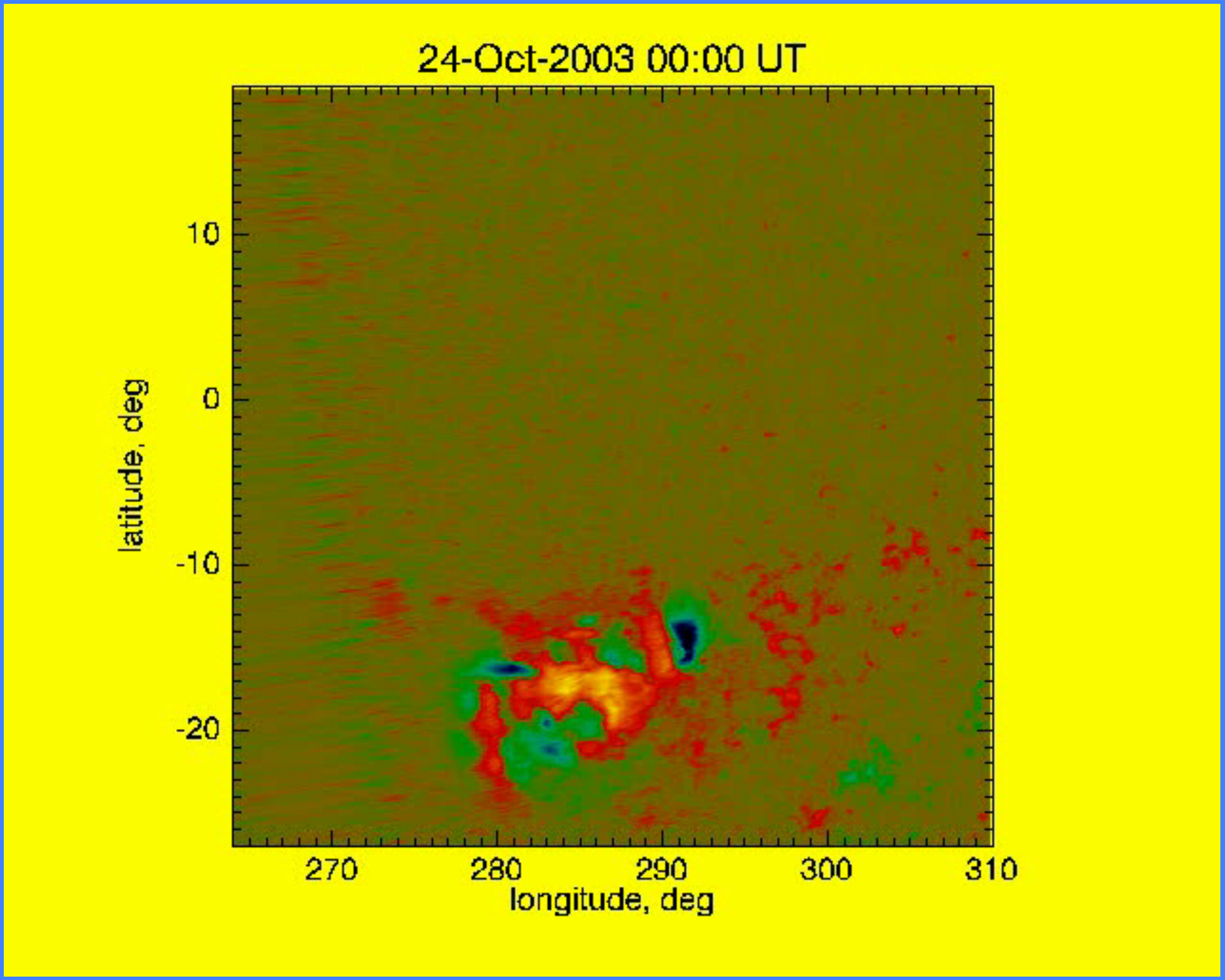
Pflop/s + HF physics software

Simulations previously unrealistic are now possible

Advancements in Observation Methods

- 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 helioseismology 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.)
- …

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

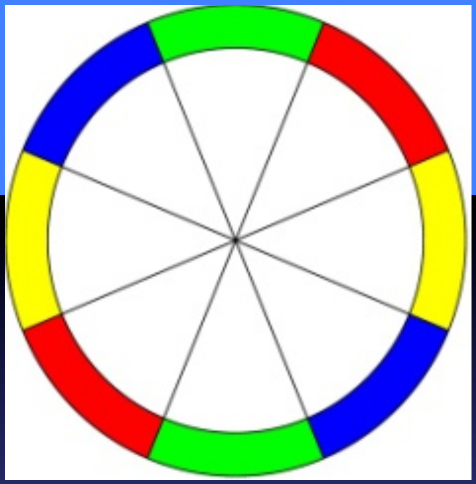


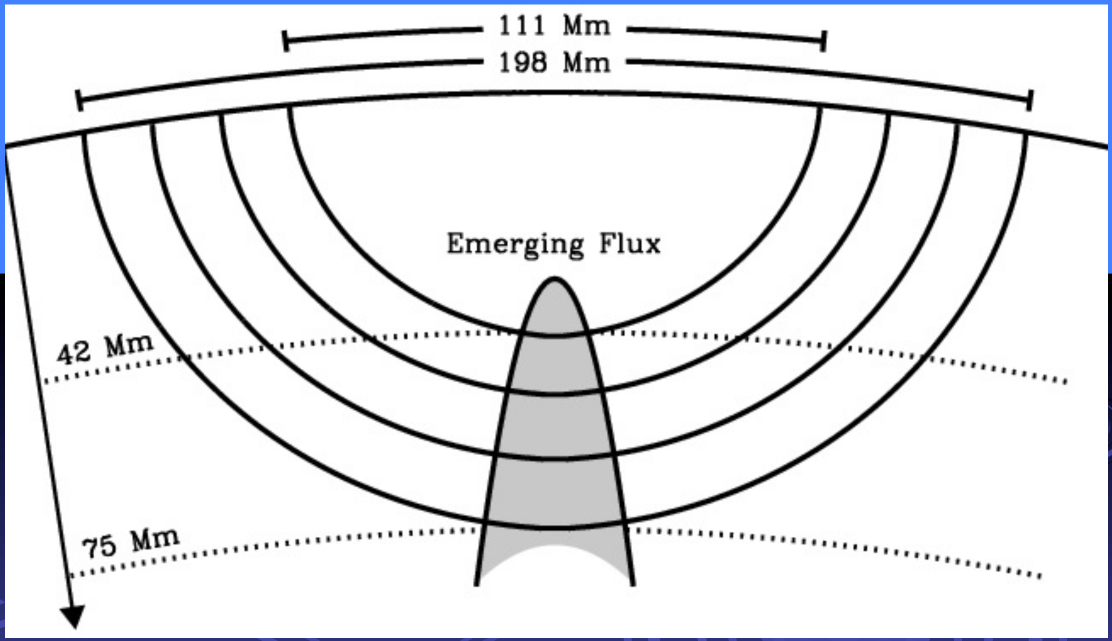
Courtesy. Kosovichev, 2013

New 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

Averaging quadrants

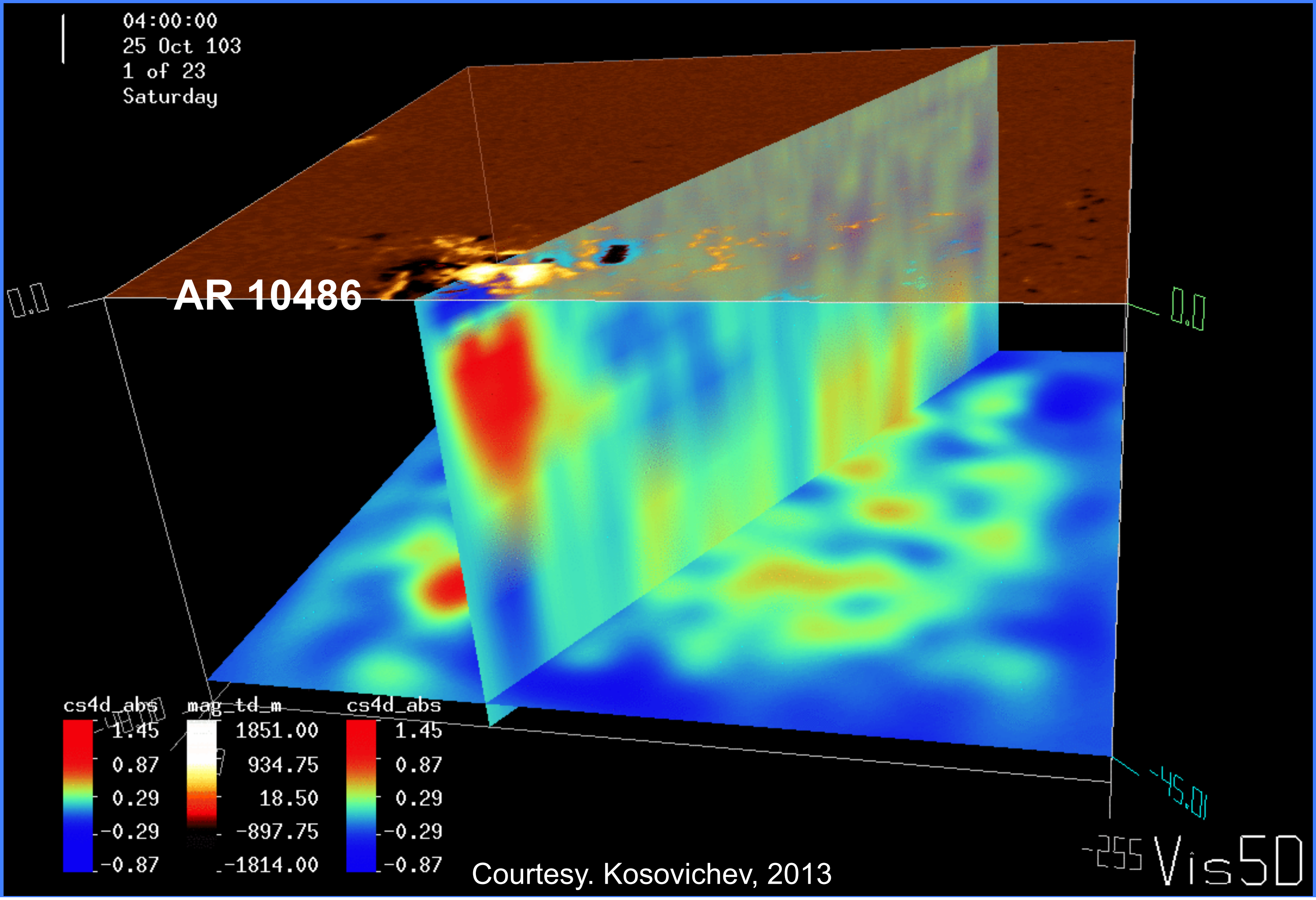




Ilonidis et al (2011)

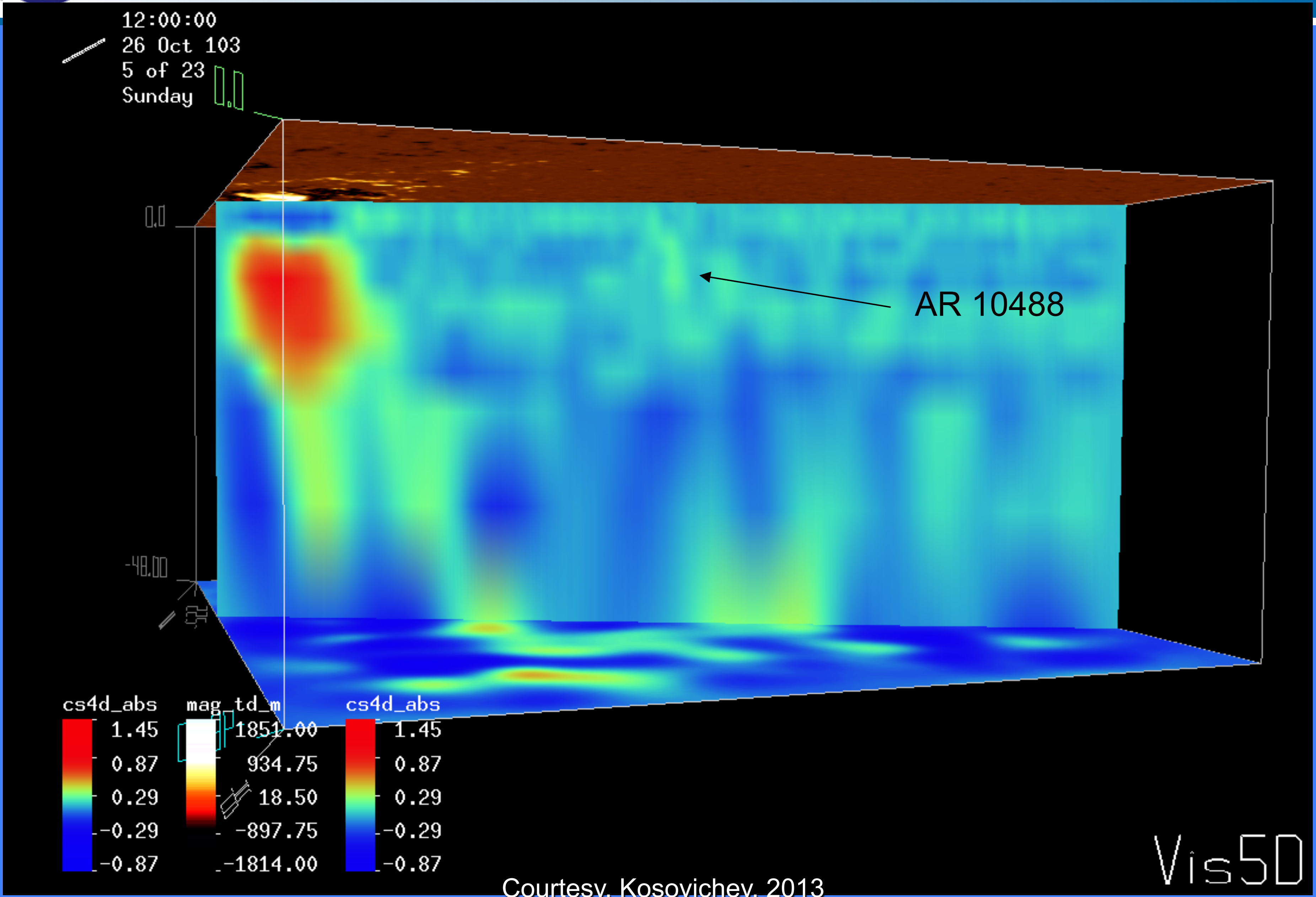
Sound-speed map and magnetogram (depth of the lower panel: 45 Mm)

AR 10486 on October 25, 2003, 4:00 UT



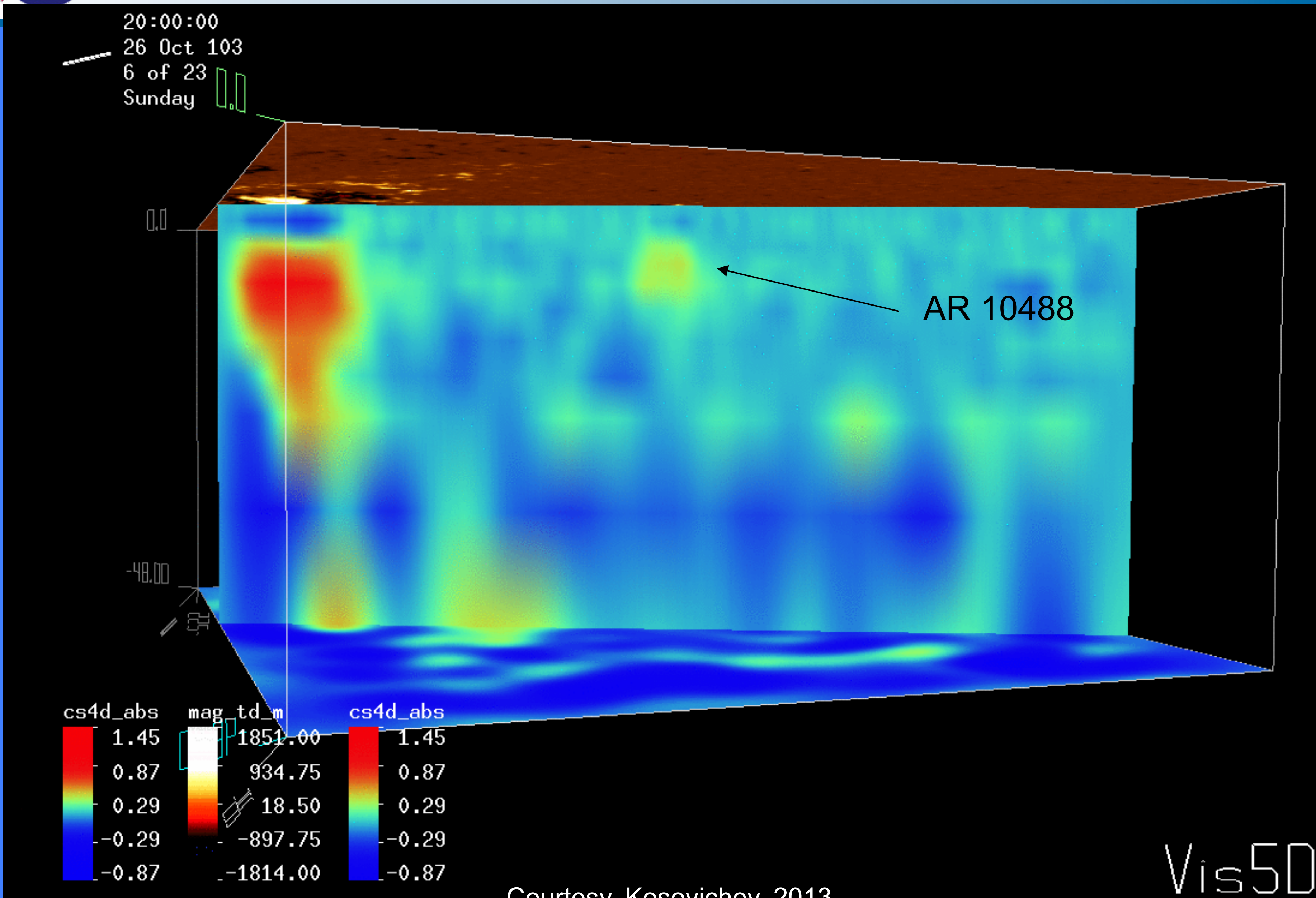
Courtesy. Kosovichev, 2013

AR 10486 on October 26, 2003, 12:00 UT
AR 10488 is emerging



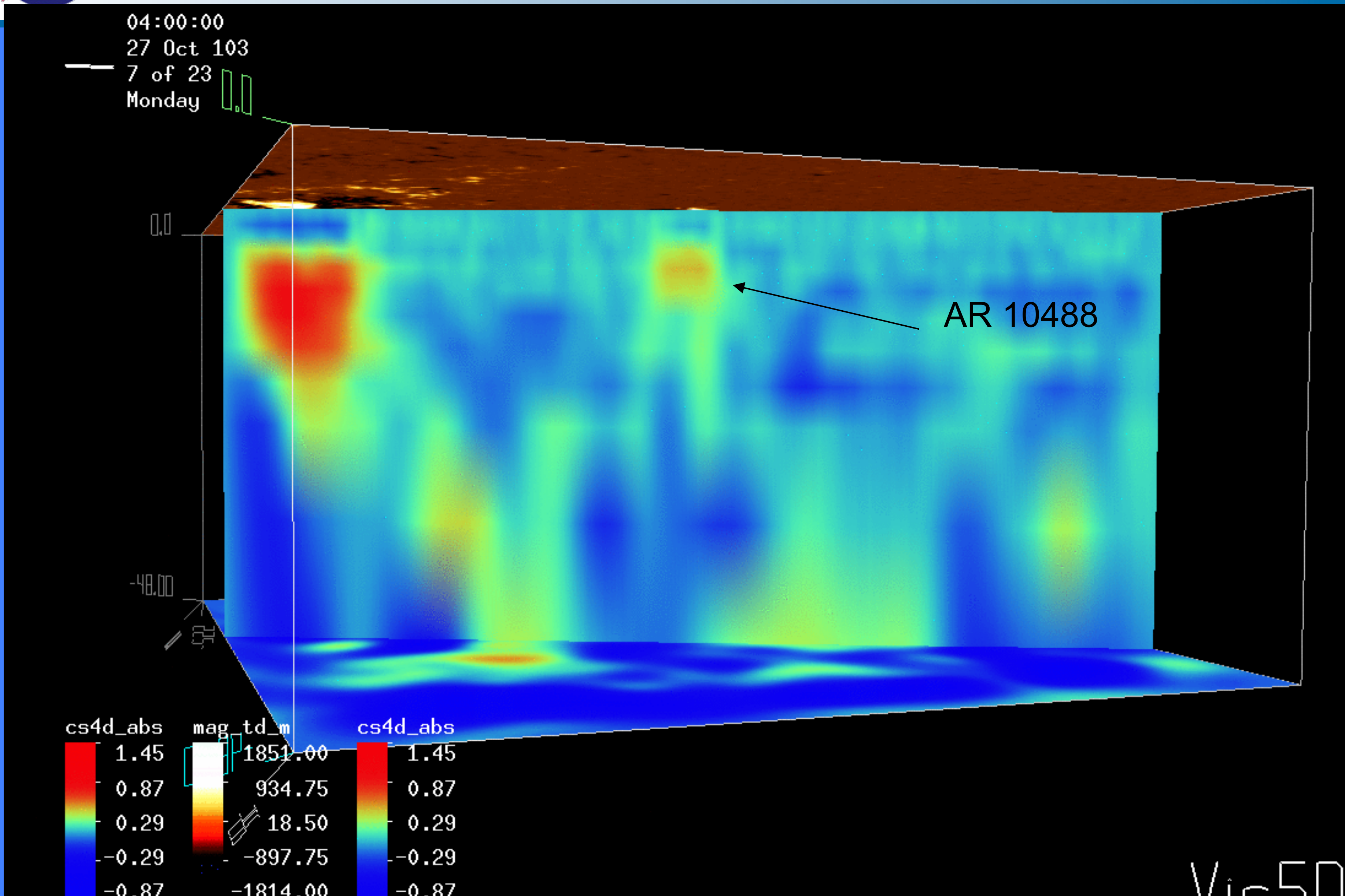
Courtesy. Kosovichev, 2013

Emergence of AR 10488, October 26, 2003, 20:00 UT



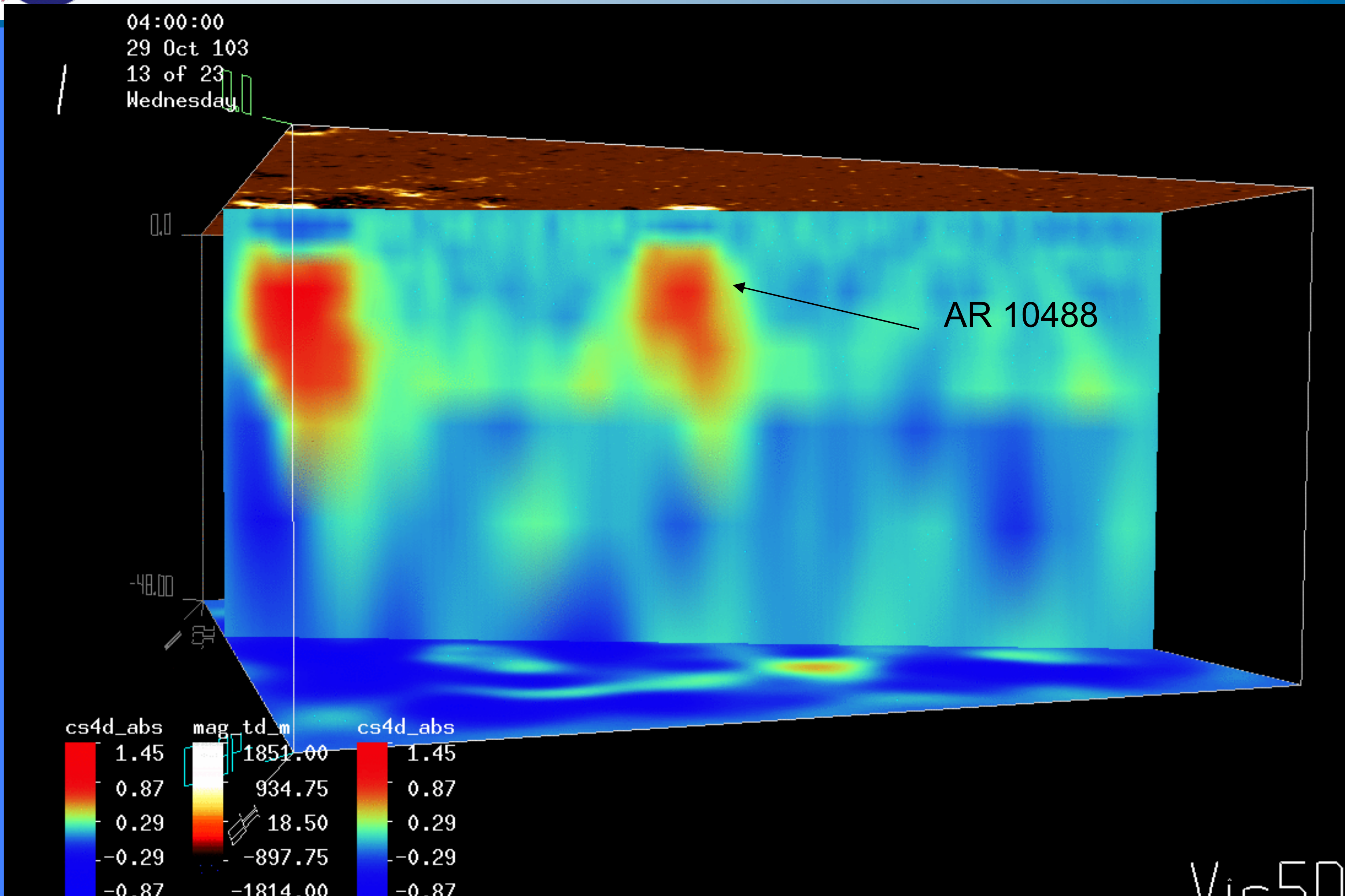
Courtesy. Kosovichev, 2013

Emergence of AR 10488, October 27, 2003, 4:00 UT



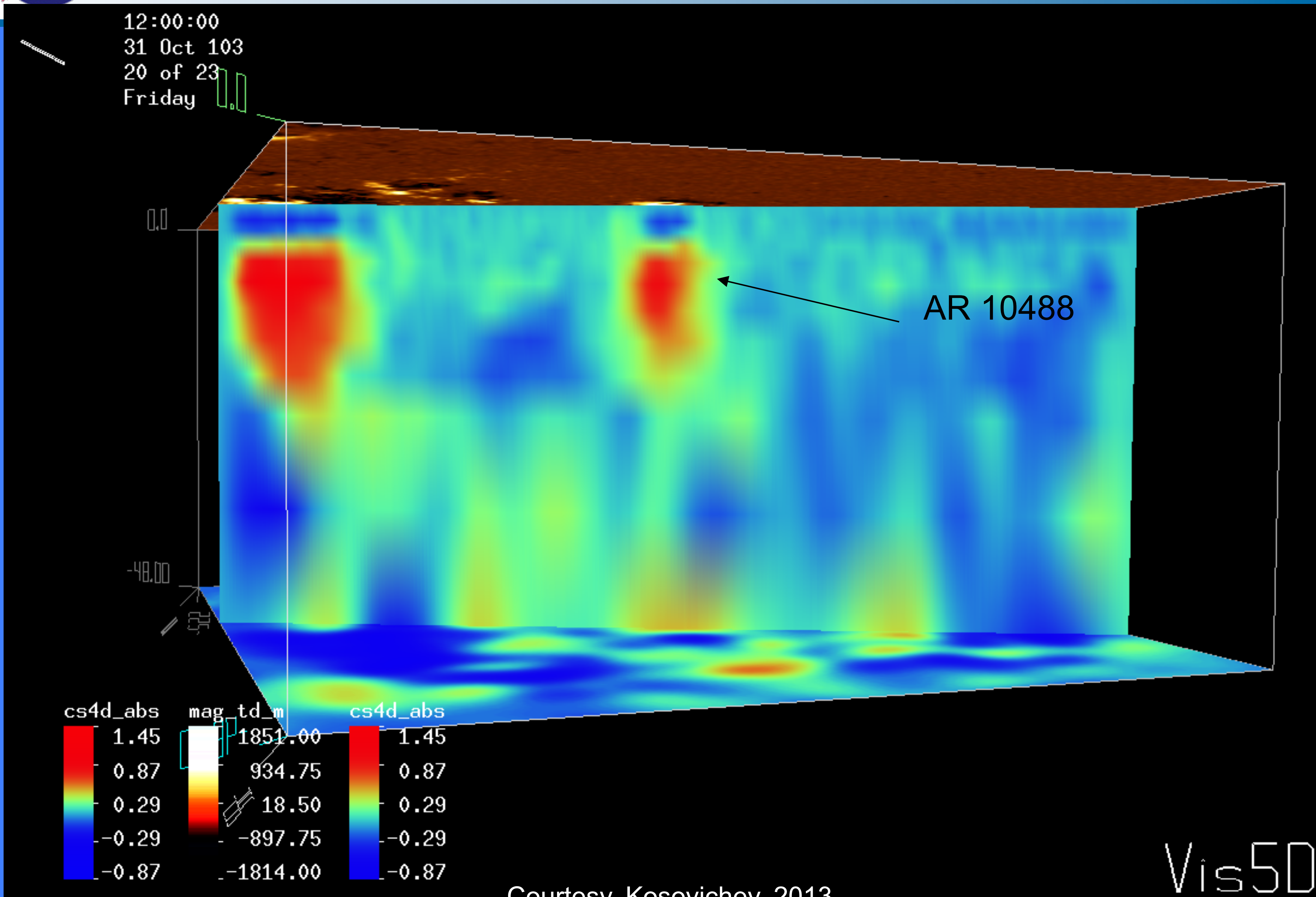
Courtesy. Kosovichev, 2013

Growth and formation of sunspots of AR 10488, October 29, 2003, 4:00 UT



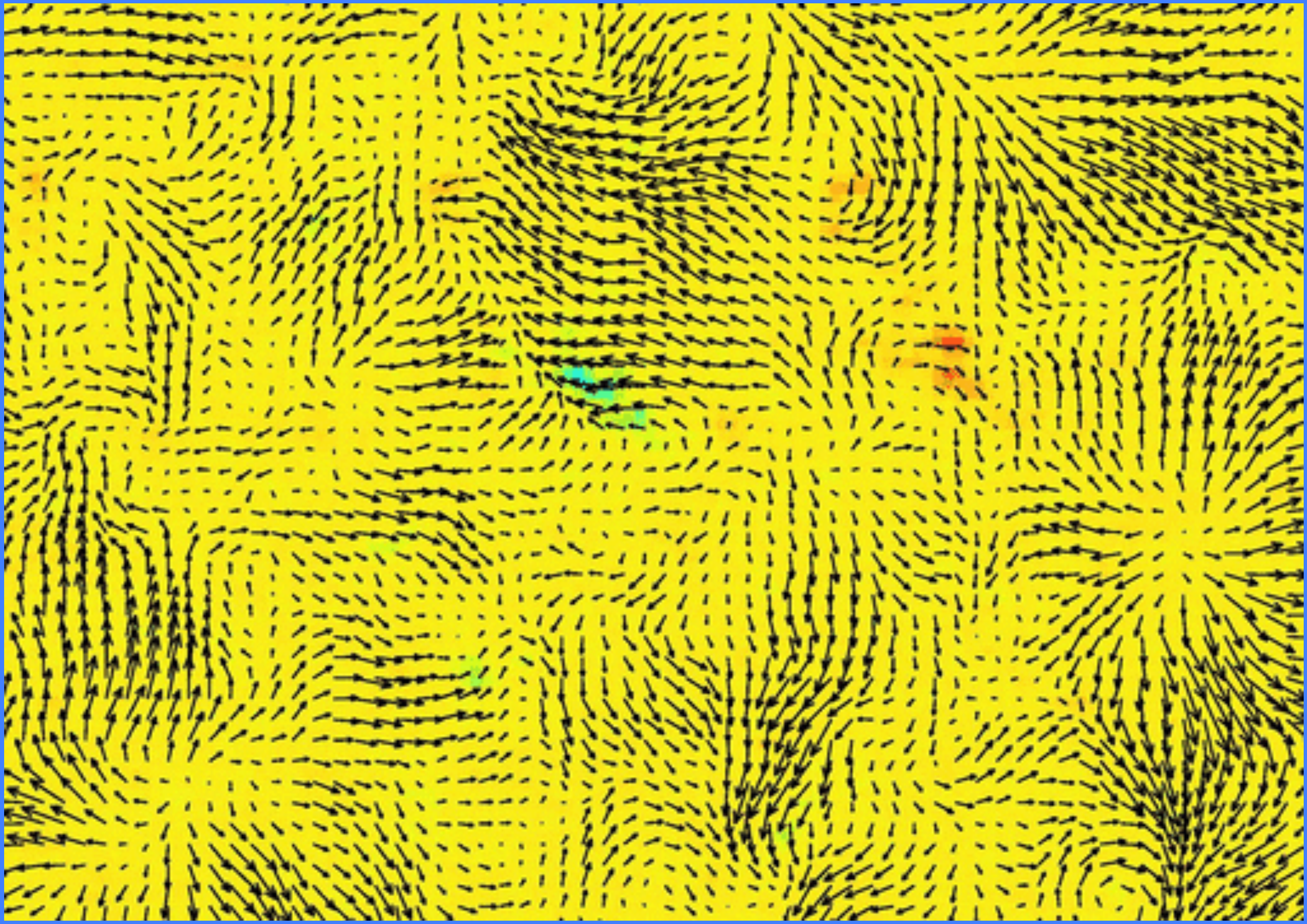
Courtesy. Kosovichev, 2013

Growth and formation of sunspots of AR 10488, October 31, 2003, 12:00 UT

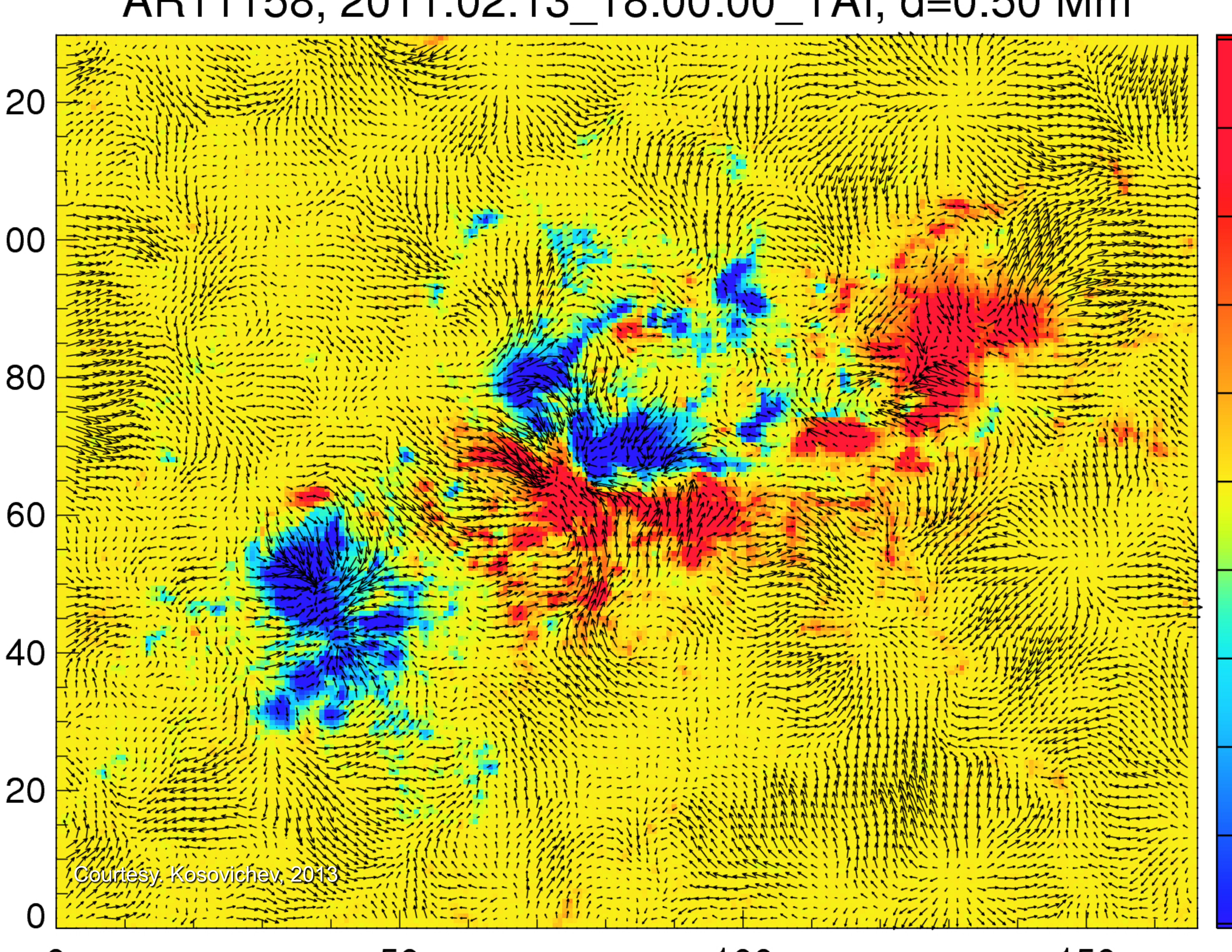


Courtesy. Kosovichev, 2013

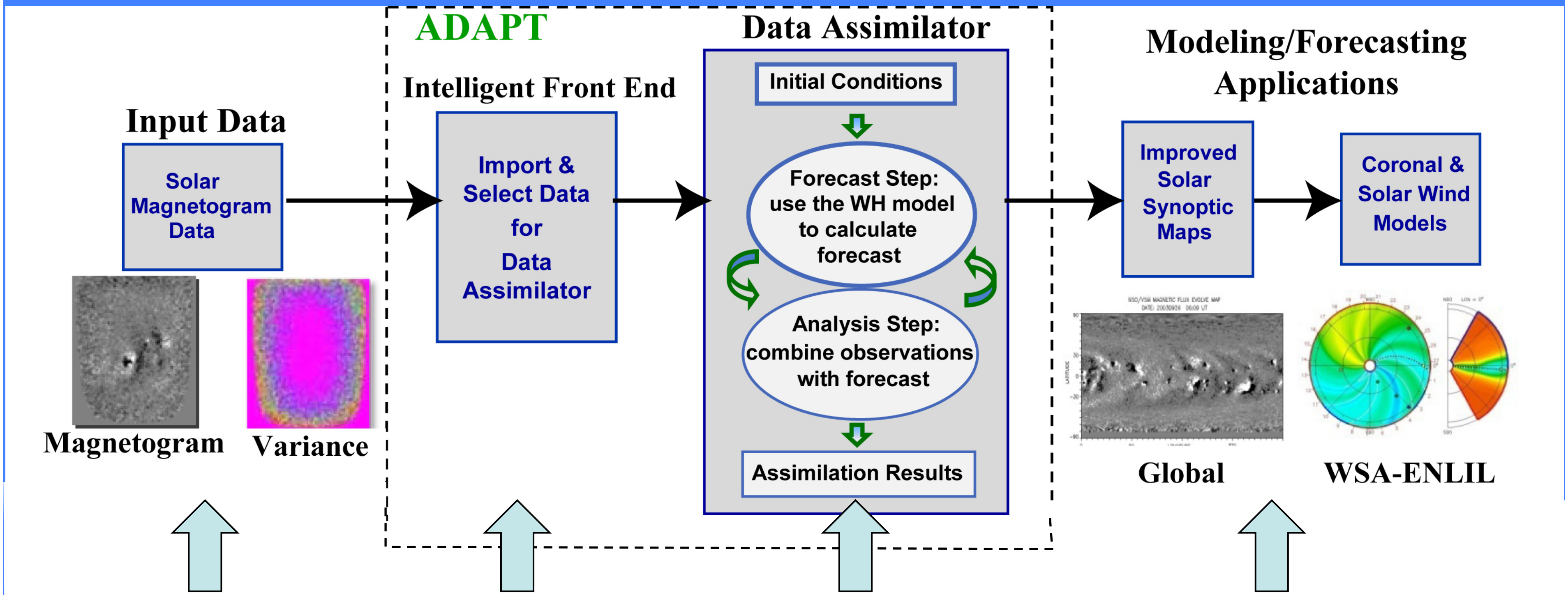
Photospheric magnetic field and subsurface flows at depth 0-1 Mm in AR 11158



Courtesy. Kosovichev, 2013


AR11158, 2011.02.13_18:00:00_TAI, d=0.50 Mm
20
00
80
60
40
20
0
Courtesy: Kosovichev, 2013

Space Weather Forecast



New Input Data

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

New MHD Models

- Emerging Flux MHD
- High-Res Flux-Transport
- Global Sun Models
- Far-Side Images

New Data Assimilation

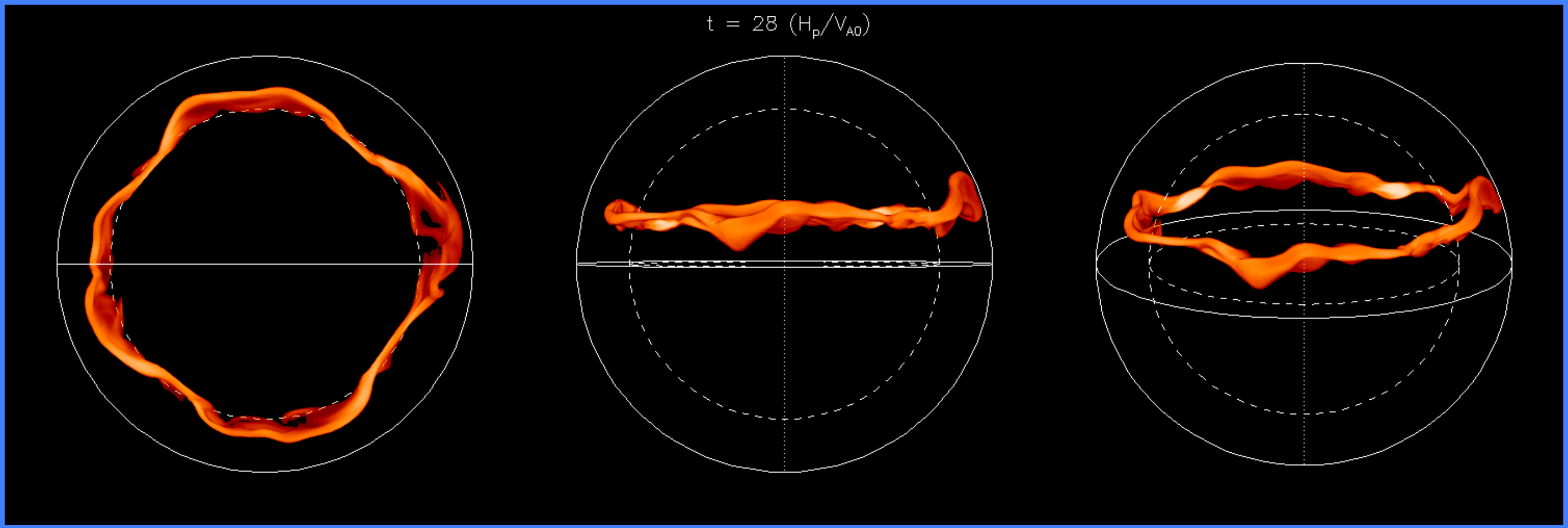
- Localized Ensemble Transform Kalman Filter

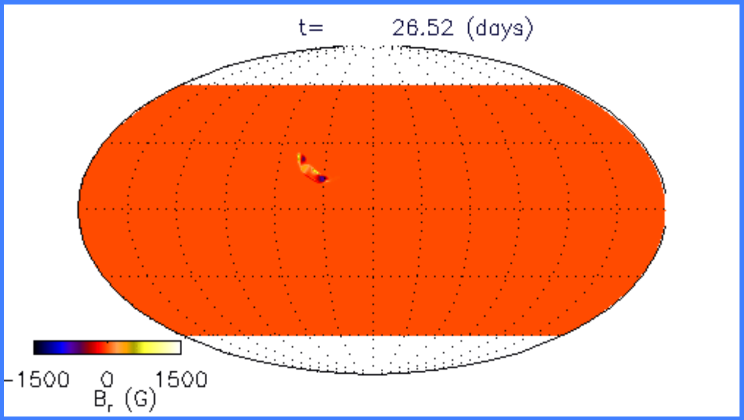
New Modeling/Forecasting

- Real-Time Global Vector Magnetic Field Maps
- Advanced Prediction of Magnetic Flux Emergence

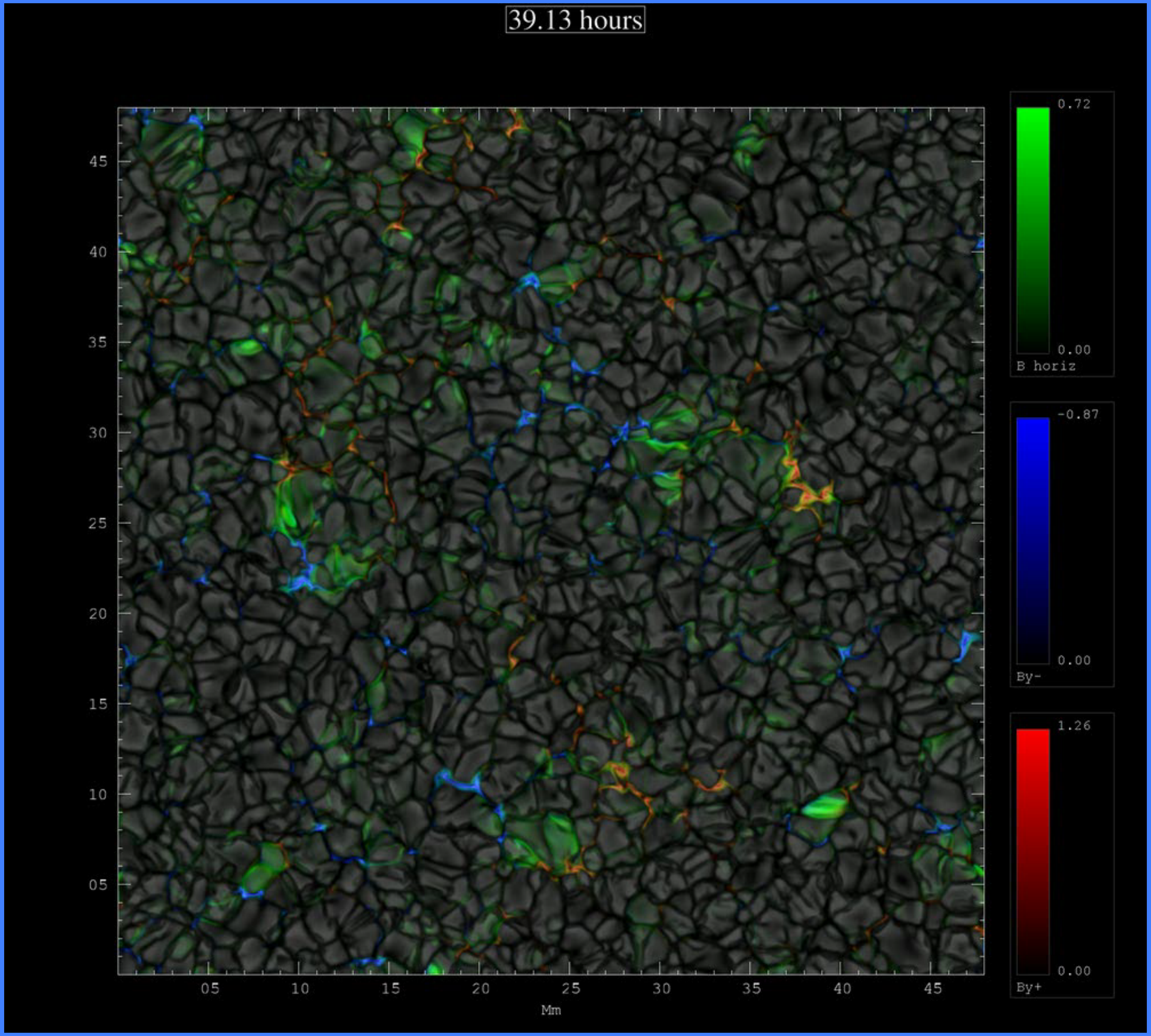
FSAM results (Y. Fan)

Emerging flux with realistic convection





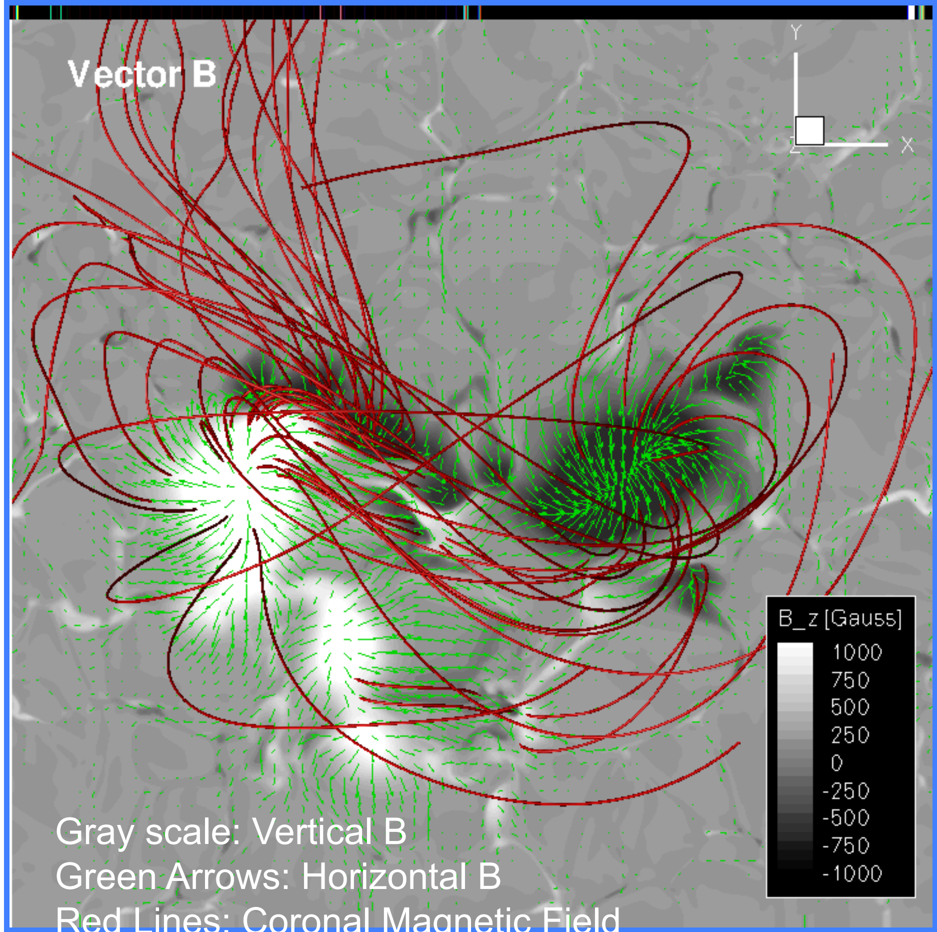
STAGGER (R. Stein)

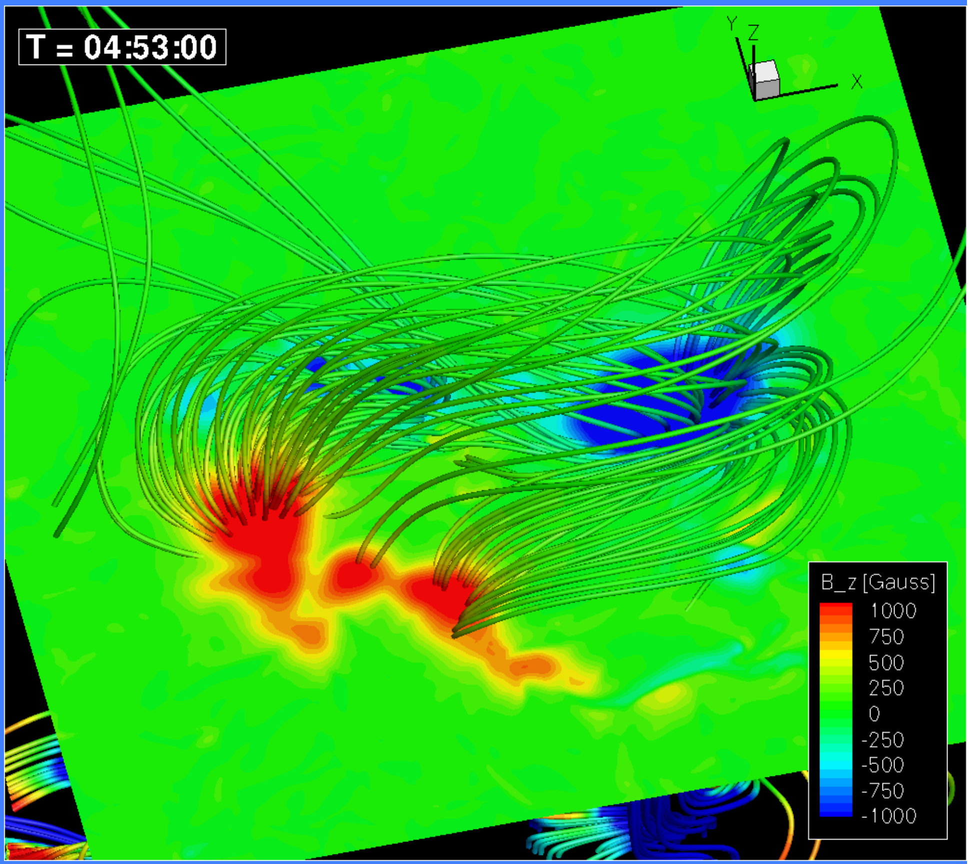


Simulations showing micro-pore emergence

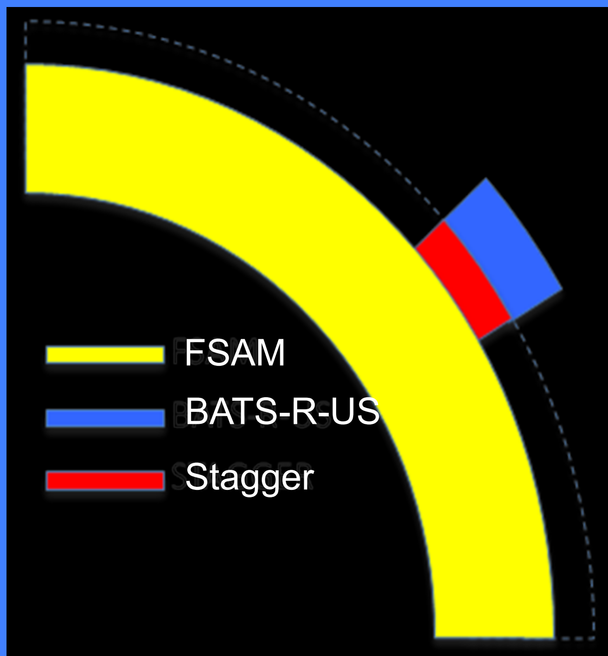
Active Region Formation (W. Manchester)

Similarity between Flux Emergence observations and simulations.

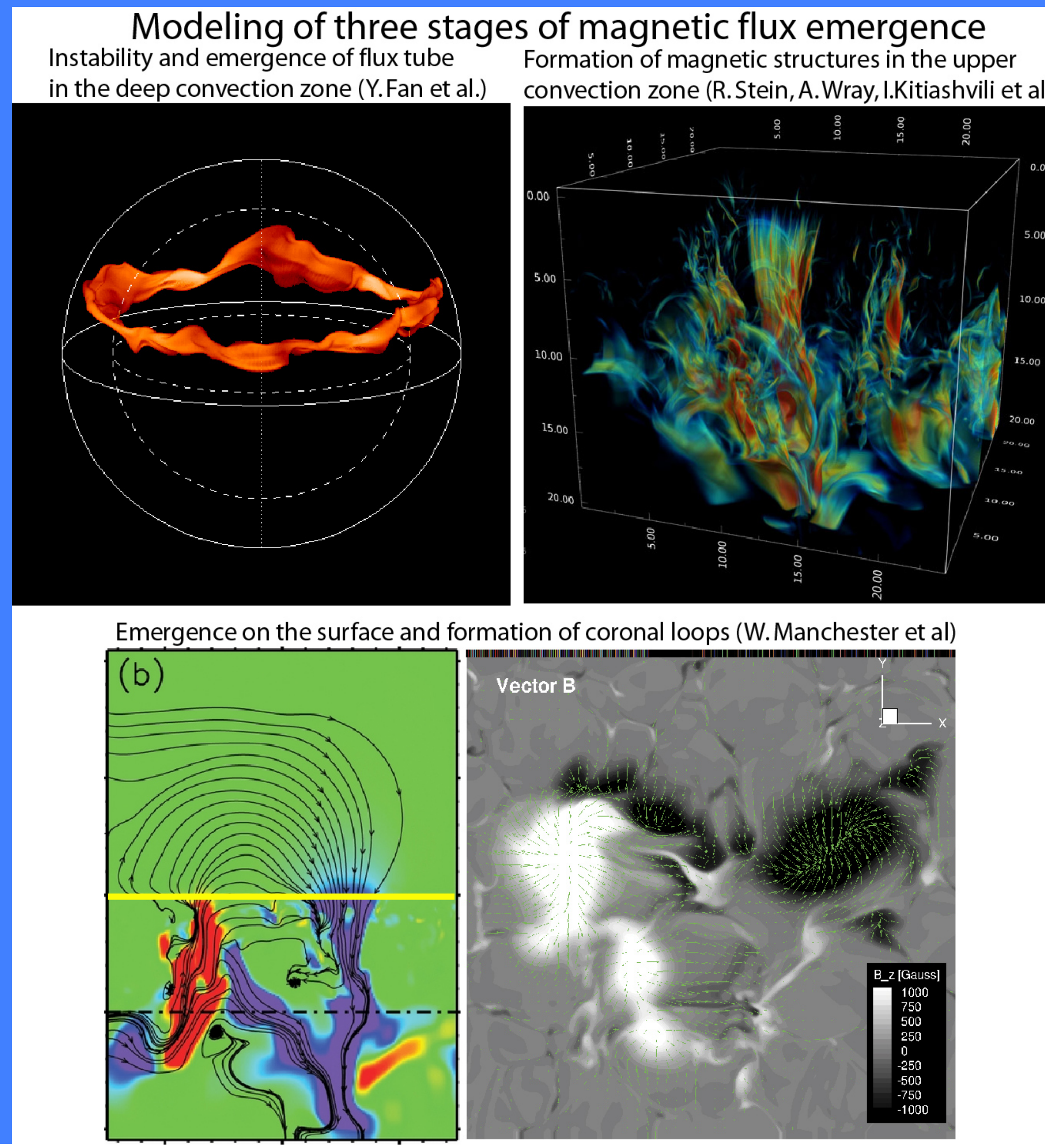




Coupling Models from the Interior to the Corona



- Schematic of the optimal physical domains for FASM, BATS-R-US, and Stagger. The anelastic MHD code, FASM, is optimal below 20Mm. The MHD code with realistic radiative transfer, Stagger, is optimal from 30 M to the photosphere. The MHD code with approximate radiative transfer, BATS-R-US, is optimal from 30Mm to the corona.



Team Report on integration of FSAM into SWMF and on FSAM simulations of convective dynamo and emerging flux in the solar convective envelope

Yuhong Fan and Fang Fang

National Center for Atmospheric Research

Code Development and Integration of FSAM into SWMF

- Convert and optimize the FSAM code
  - From original F77 to F90 version, compatible with SWMF.
  - Improve the efficiency in message passing and adopt routines from the SWMF.
  - Integrate FSAM into SWMF as its Convective Zone (CZ) component following standards and conventions of other existing components.

Code Development and Integration of FSAM into SWMF

- FSAM can run as a stand-alone mode
  - Multiple test cases are available in SWMF/CZ/FSAM/src/problems:
    - Test run from a solar convection zone background with seed fields: *make test*
    - Convective dynamo run from seed fields or from a restart file:

      make prob PROBS=dynamo RUNDIR=rundirname

      make prob_rst PROBS=dynamo RUNDIR=rundirname
    - A run of isolated rising flux tube in stable cz:

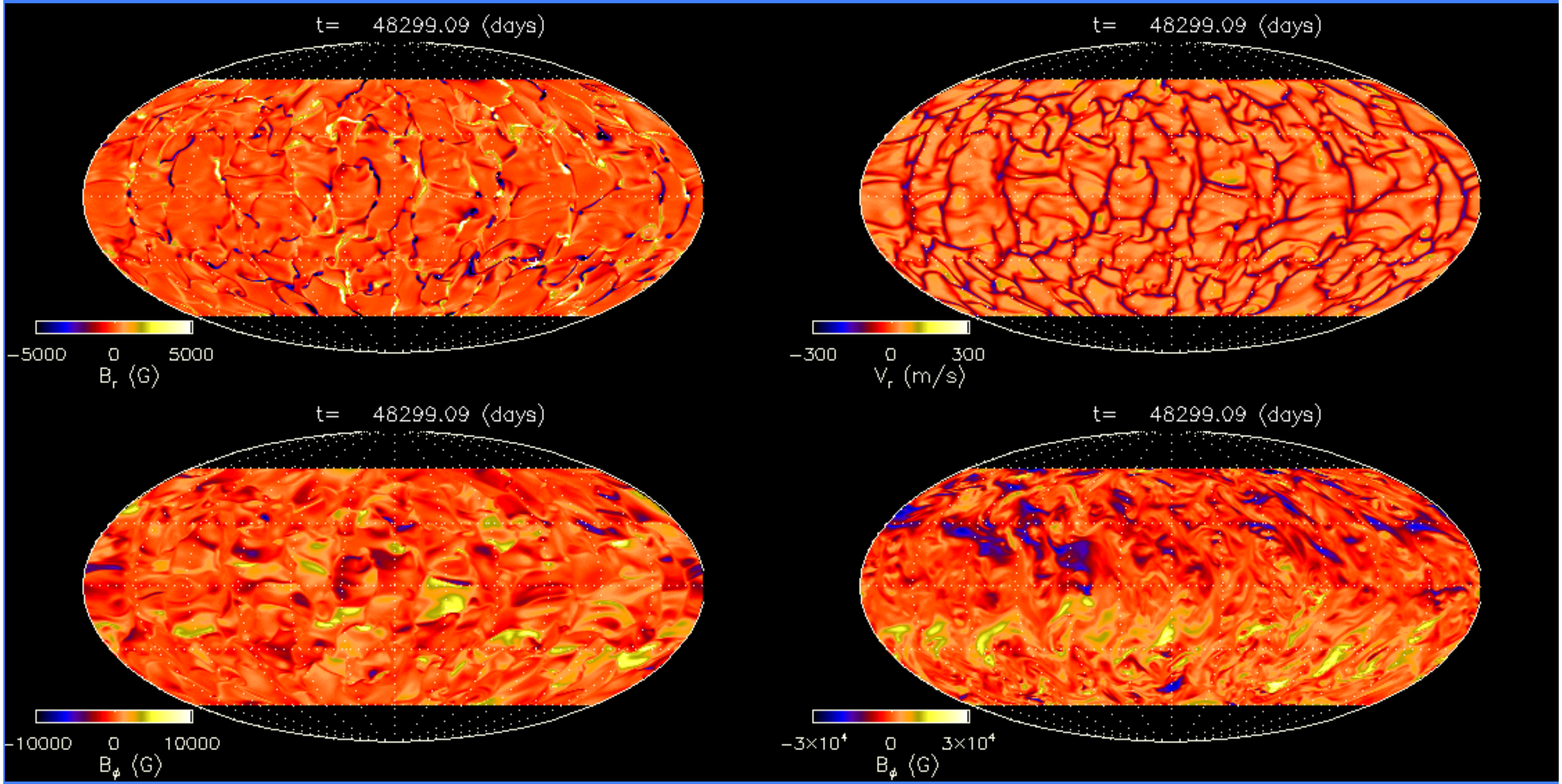
      make prob PROBS=risetube_qcz RUNDIR=rundirname
    - A hydro run for comparison with ASH:

      make prob PROBS=benchA RUNDIR=rundirname
    - New problems can be created by adding new SWMF/CZ/FSAM/src/problems/*newprobdir* with the necessary files following previous examples

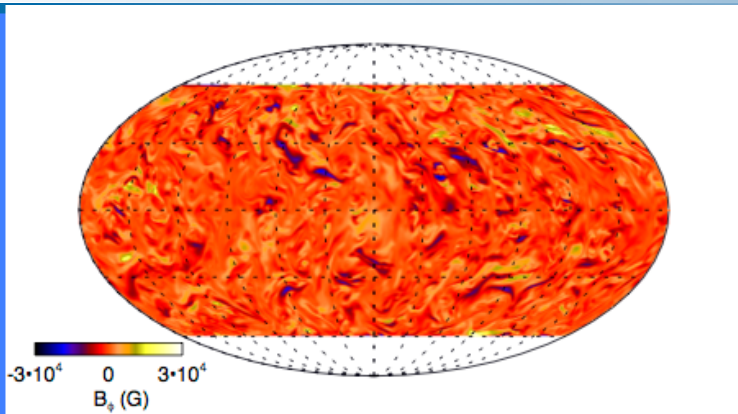
Code Development and Integration of FSAM into SWMF

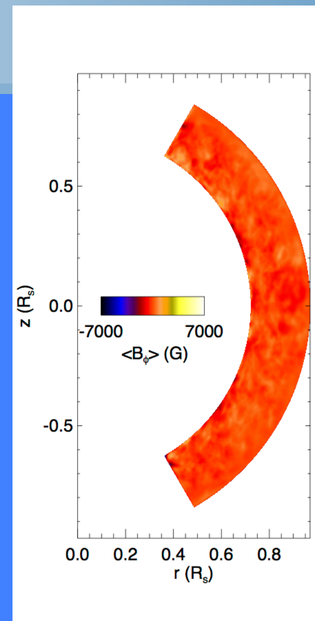
- FSAM can run as a deep Convective Zone component of SWMF
  - Wrapper file available in SWMF/CZ/FSAM/srcInterface
  - Can be set by *Config.pl –v=CZ/FSAM*
  - Routine test available in SWMF: *make test_cz*

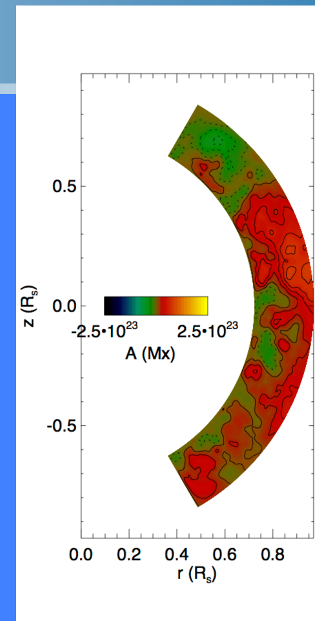
FSAM Solar dynamo simulations

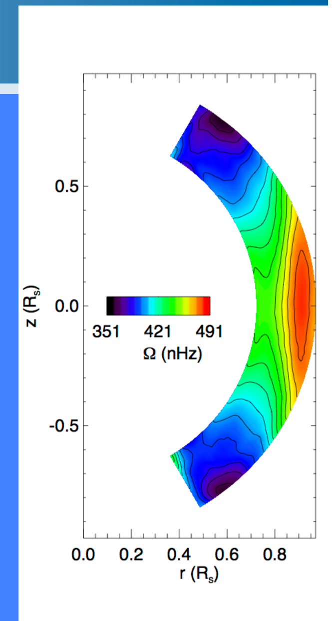


FSAM Solar dynamo simulations

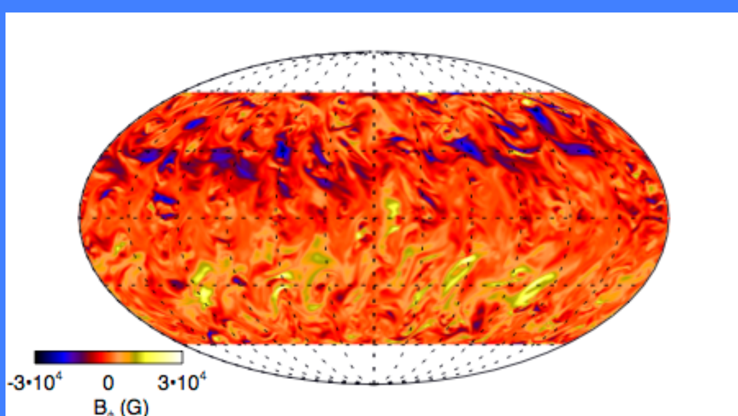


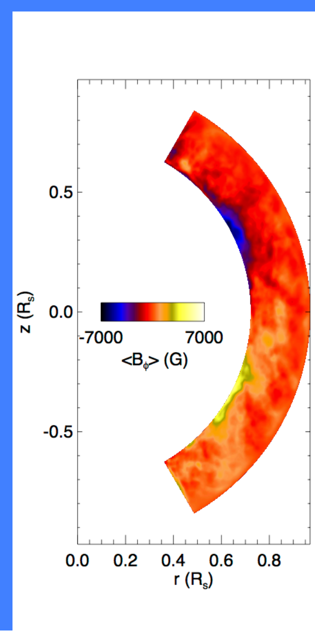


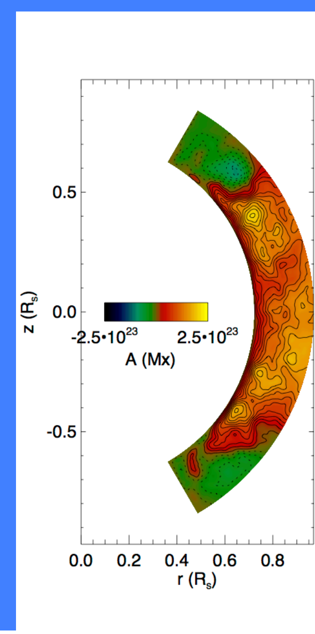


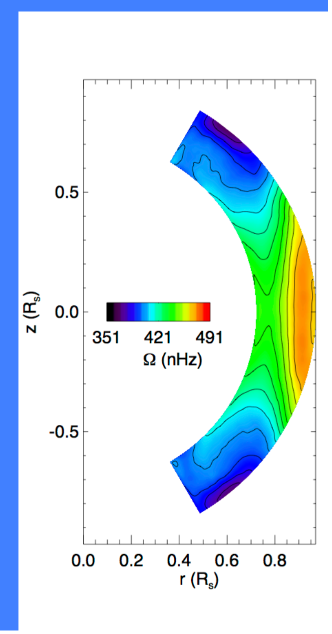


minimum

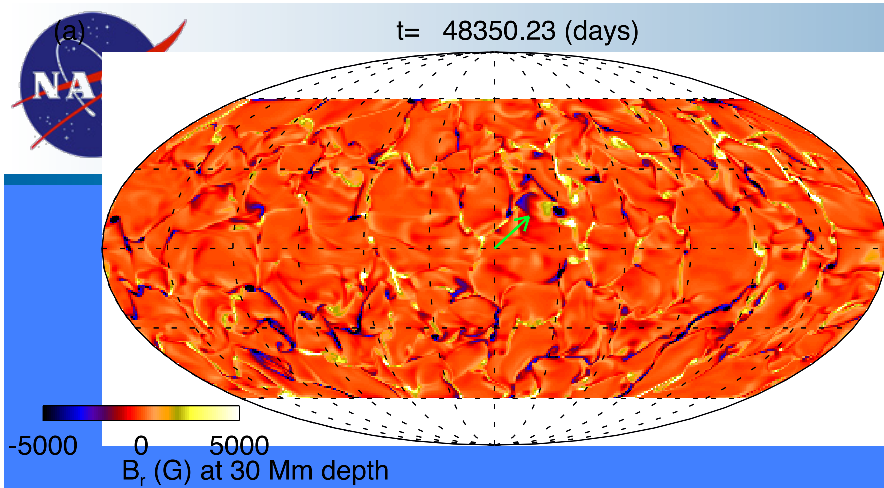


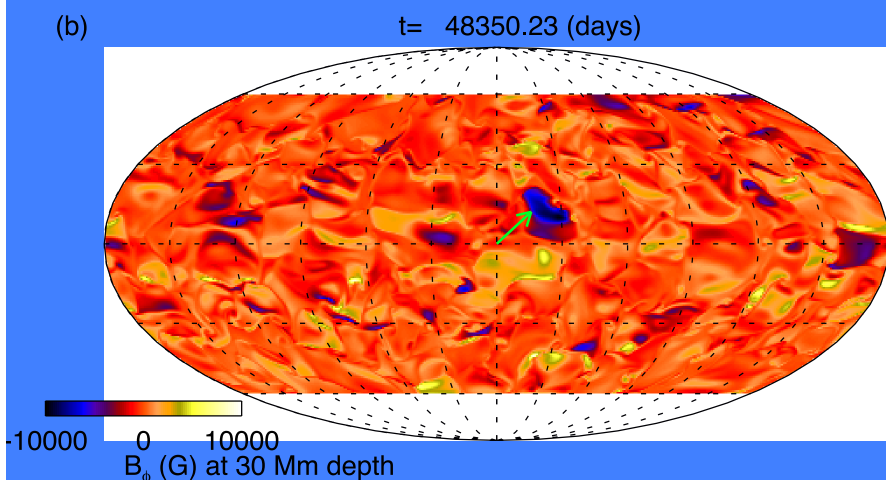


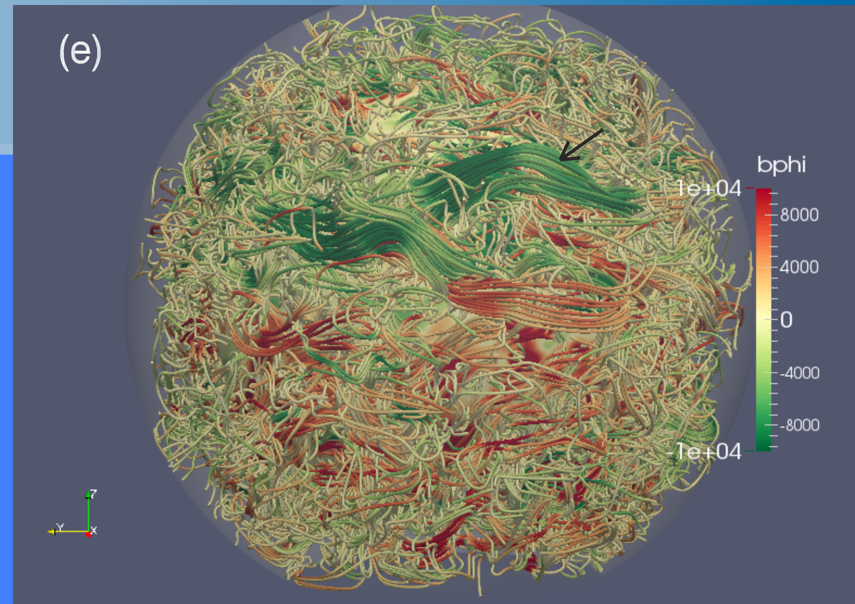


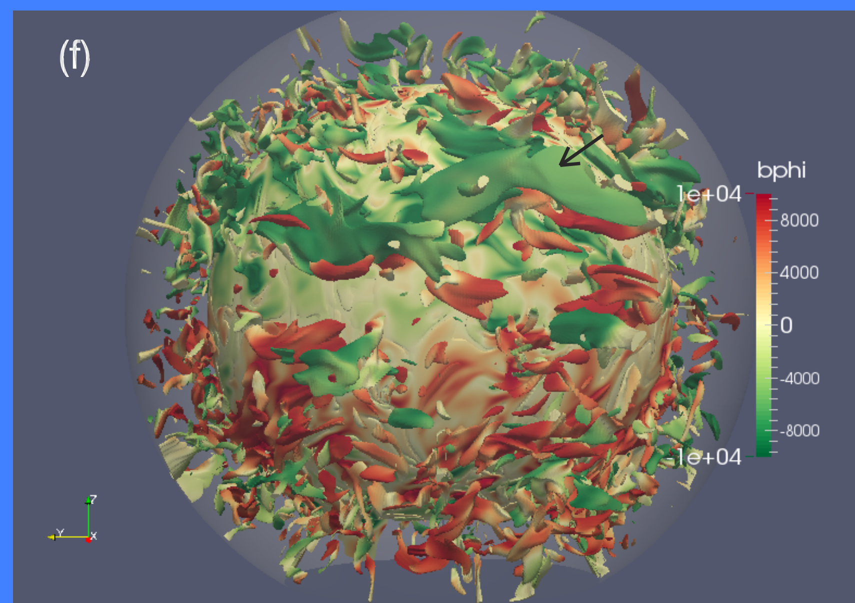


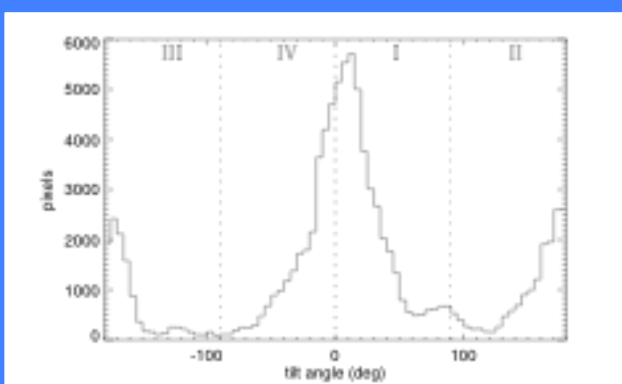
maximum











Conform to Hale's rule
by 2.4 to 1 in area
Tilt angle 7.5° ± 1.6°

STAGGER - Stein

Coupling strategy with FSAM:

- Extend realistic modeling of the Convective Zone (CZ) from current depth (~20 Mm) to 30 Mm in order to reach the upper limit of the anelastic approximation (FSAM).
- At this depth ideal fluid equation of state holds, the radiative transfer is mostly diffusive transport, the turbulent velocities are of the same order as in FSAM.

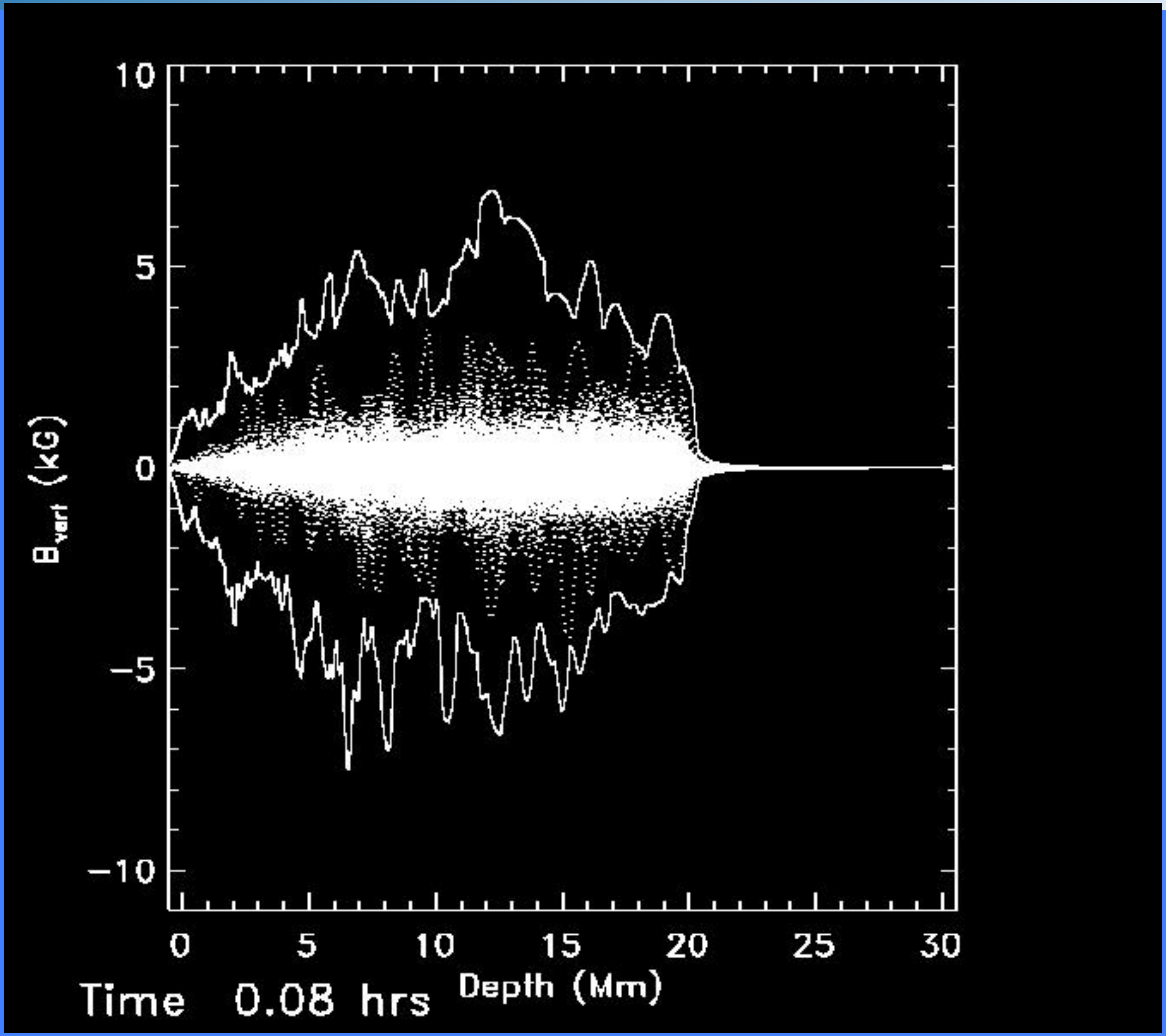
Next:

- incorporate STAGGER into SWFM

Challenges to be tackled:

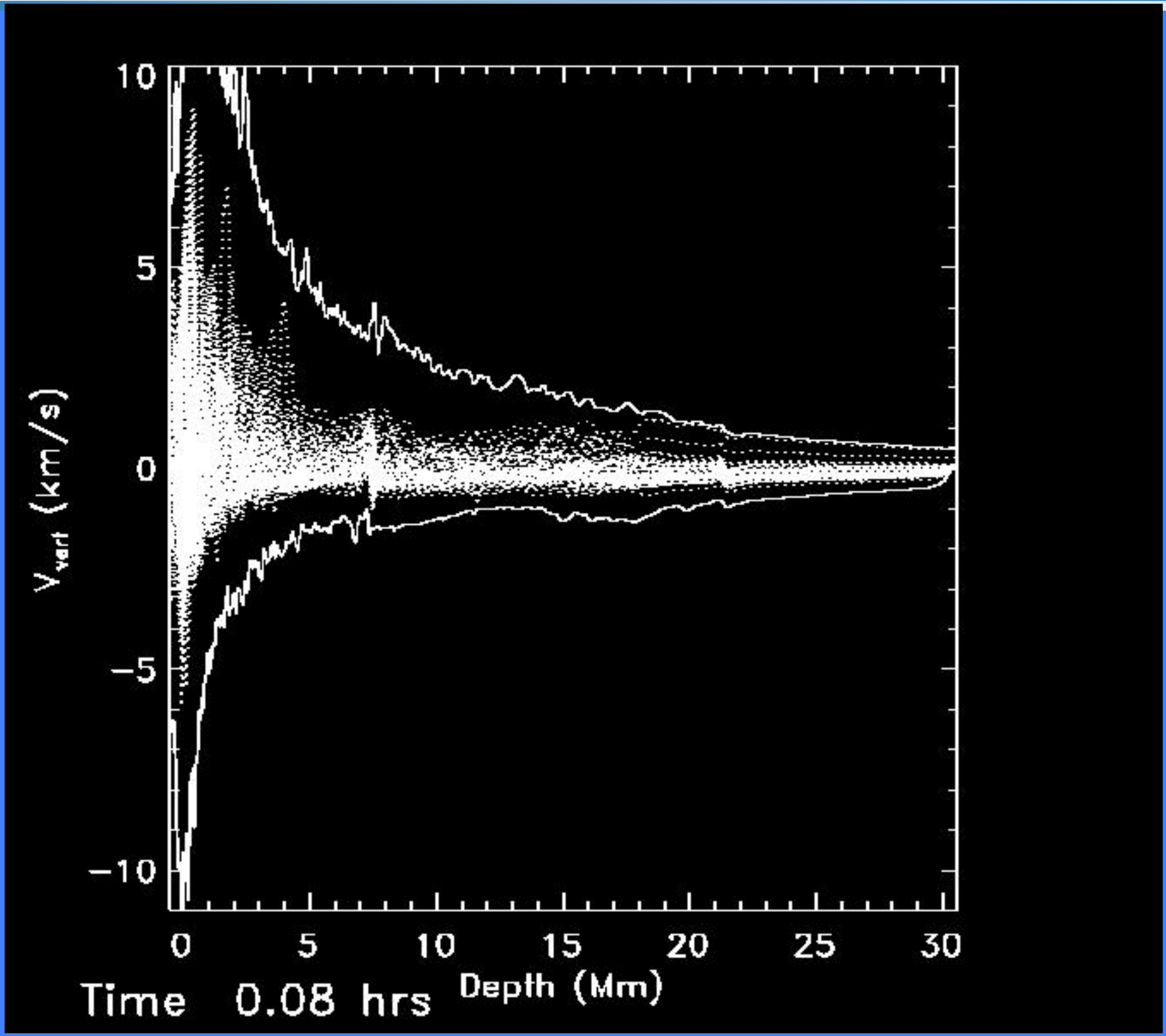
- Matching a periodic domain to a non-periodic domain
- Matching the time advancement: FSAM time step is order minutes, STAGGER is of order seconds

Evolution of the magnetic field



Solid lines are the maximum and minimum of the vertical magnetic field as a function of depth, dashed lines are at scattered locations

Evolution of the vertical velocity



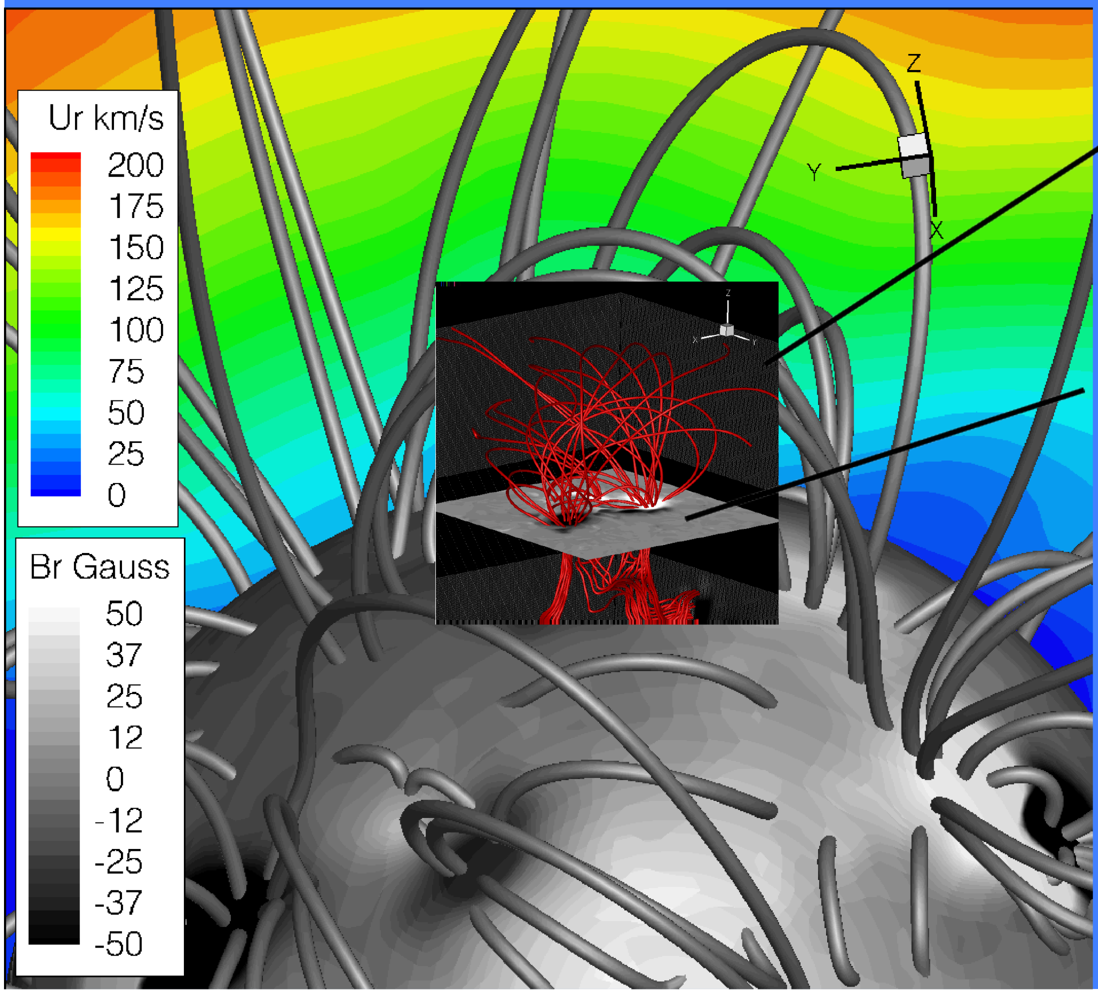
Solid lines are the maximum and minimum of the vertical velocity as a function of depth, dashed lines are at scattered locations

Coupling the Convection Zone to the Corona

Chip Manchester
University of Michigan

Coupling the Convection Zone to the Corona

- Send data from convection zone model (CZ) to solar coronal model (SC) at locations of the chromosphere layer, and outer boundary of CZ above the chromosphere. (repeat and reverse for two-way coupling)



Couple at the outer sides of the CZ domain above the chromosphere

Couple CZ to SC at the chromospheric layer which is the lower boundary of SC

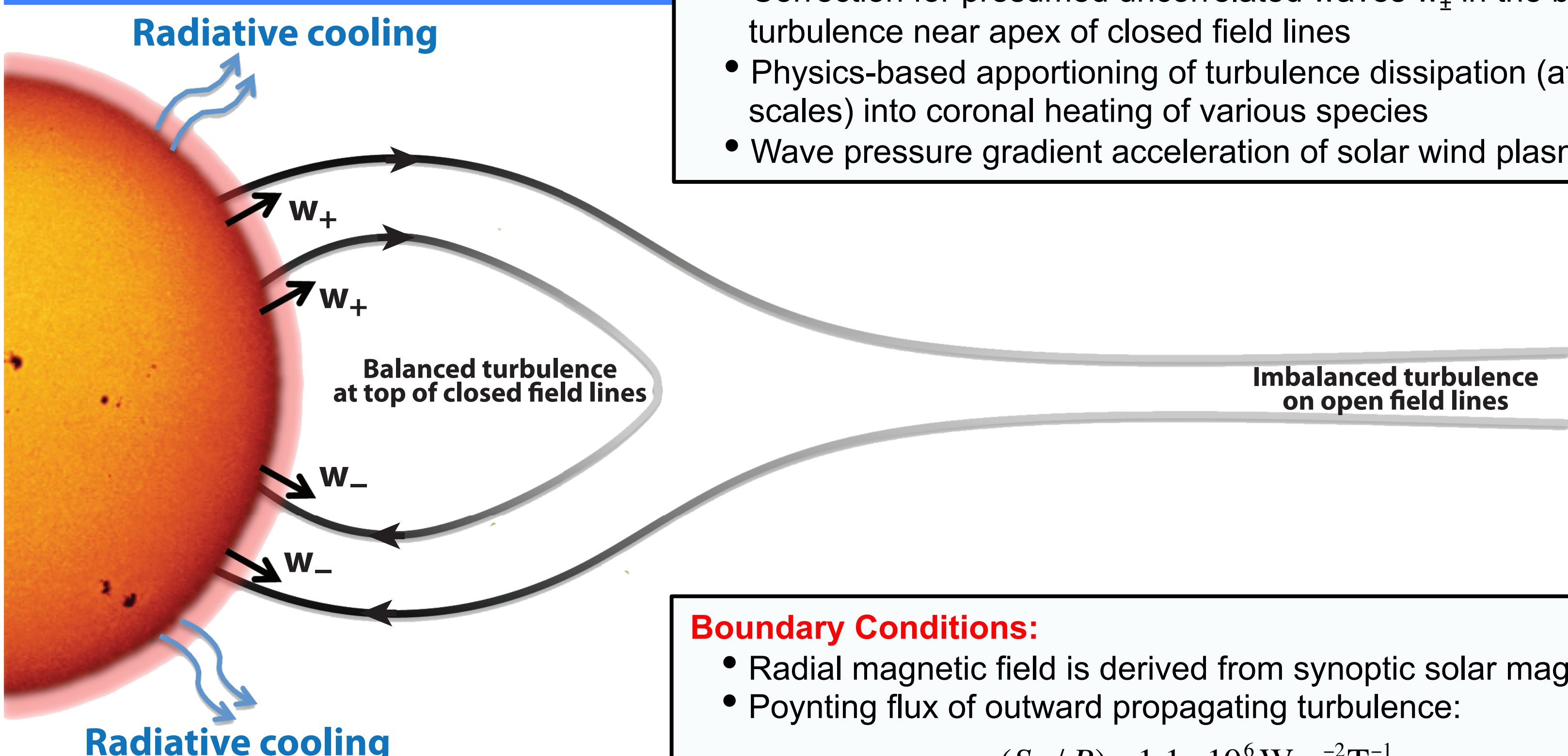
Next generation of CZ model being developed is in spherical coordinates and will extend to a depth of 30 Mm and a height of 200 Mm

Alfvén wave turbulence model

van der Holst et al. ApJ **782**, 81 (2014).

XMHD physics:

- Separate $T_{p||}$, $T_{p\perp}$ and T_e
- WKB equations for parallel and antiparallel propagating turbulence ($w_{\pm}$)
- Non-WKB physics-based reflection of $w_{\pm}$ results in turbulent cascade
- Correction for presumed uncorrelated waves $w_{\pm}$ in the balanced turbulence near apex of closed field lines
- Physics-based apportioning of turbulence dissipation (at the gyro-kinetic scales) into coronal heating of various species
- Wave pressure gradient acceleration of solar wind plasma

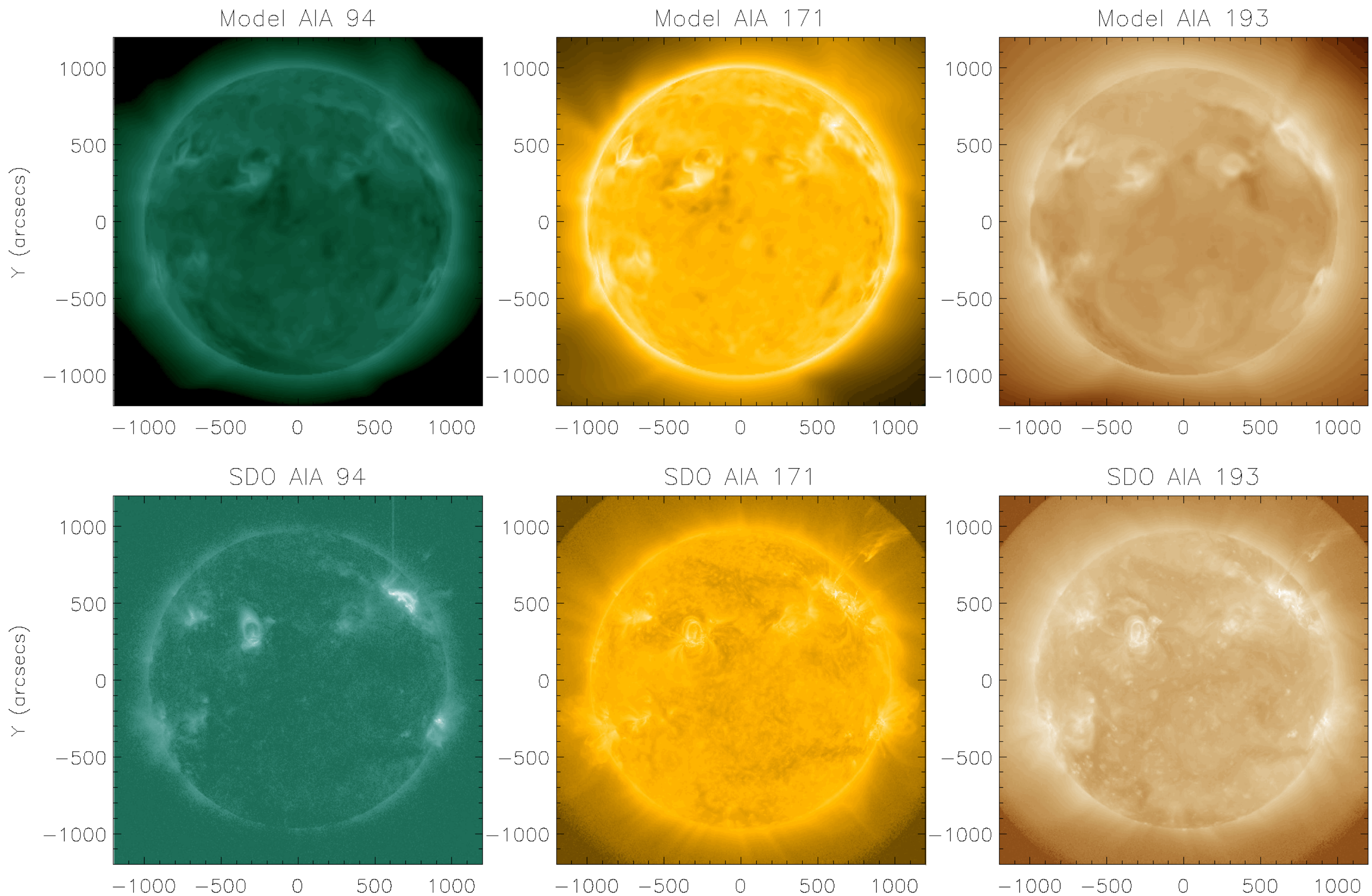


Boundary Conditions:

- Radial magnetic field is derived from synoptic solar magnetograms
- Poynting flux of outward propagating turbulence:

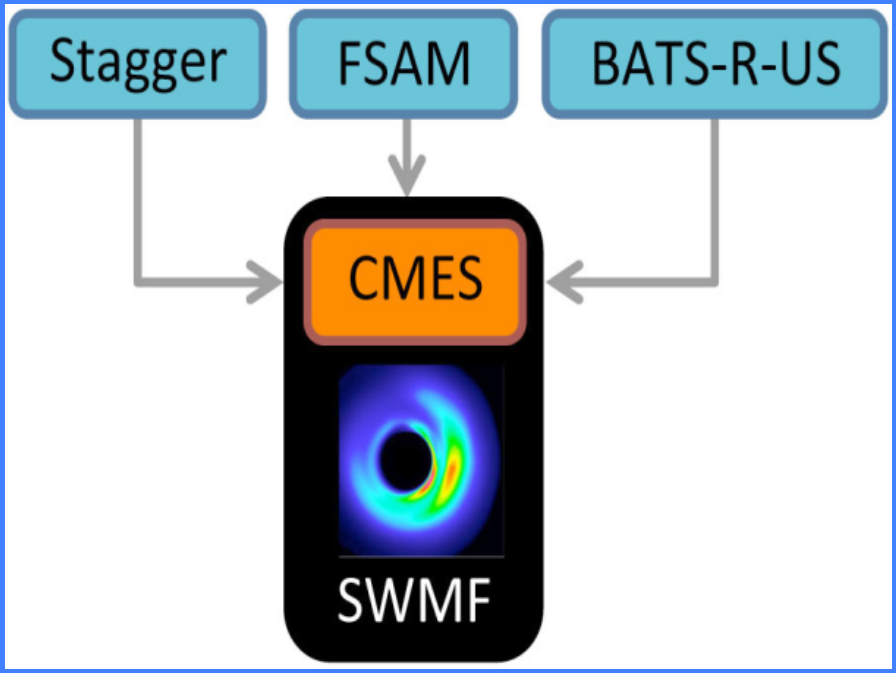
$$(S_A / B) = 1.1 \times 10^6 \, \mathrm{W m^{-2} T^{-1}}$$

EUV images for CR2107



Technology Deliverable

Coupled Models for Emerging flux Simulation (CMES)

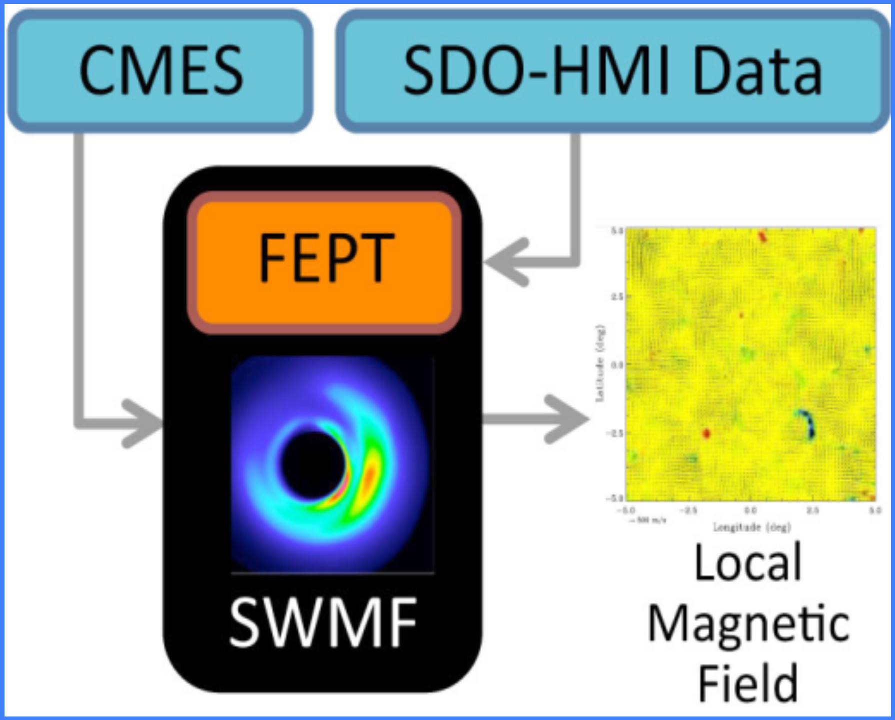


CMES will be made available to the community within the SWMF

Technology Deliverable (tentative)

Flux Emergence Prediction Tool (FEPT)

CMES+Data assimilation



FEPT will be made available to the community within the SWMF

Summary

- *Enhance ADAPT to assimilate SDO observations and helioseismology derived data into space weather forecasts.*

- *Develop coupled MHD models of flux emergence to enable modeling the 3D evolution of active region flux emergence from the bottom of the convection zone to the solar corona, connecting the properties of active region at the surface and in the corona to the deep convective zone.*

- *This is a transformative step in understanding solar magnetic activity and crucial for developing space weather prediction capabilities.*

- *NEXT STEP: Data assimilation of helioseismology derived observations into realistic simulations.*