Evolving Models of Stellar Photospheric and Coronal Magnetic Fields

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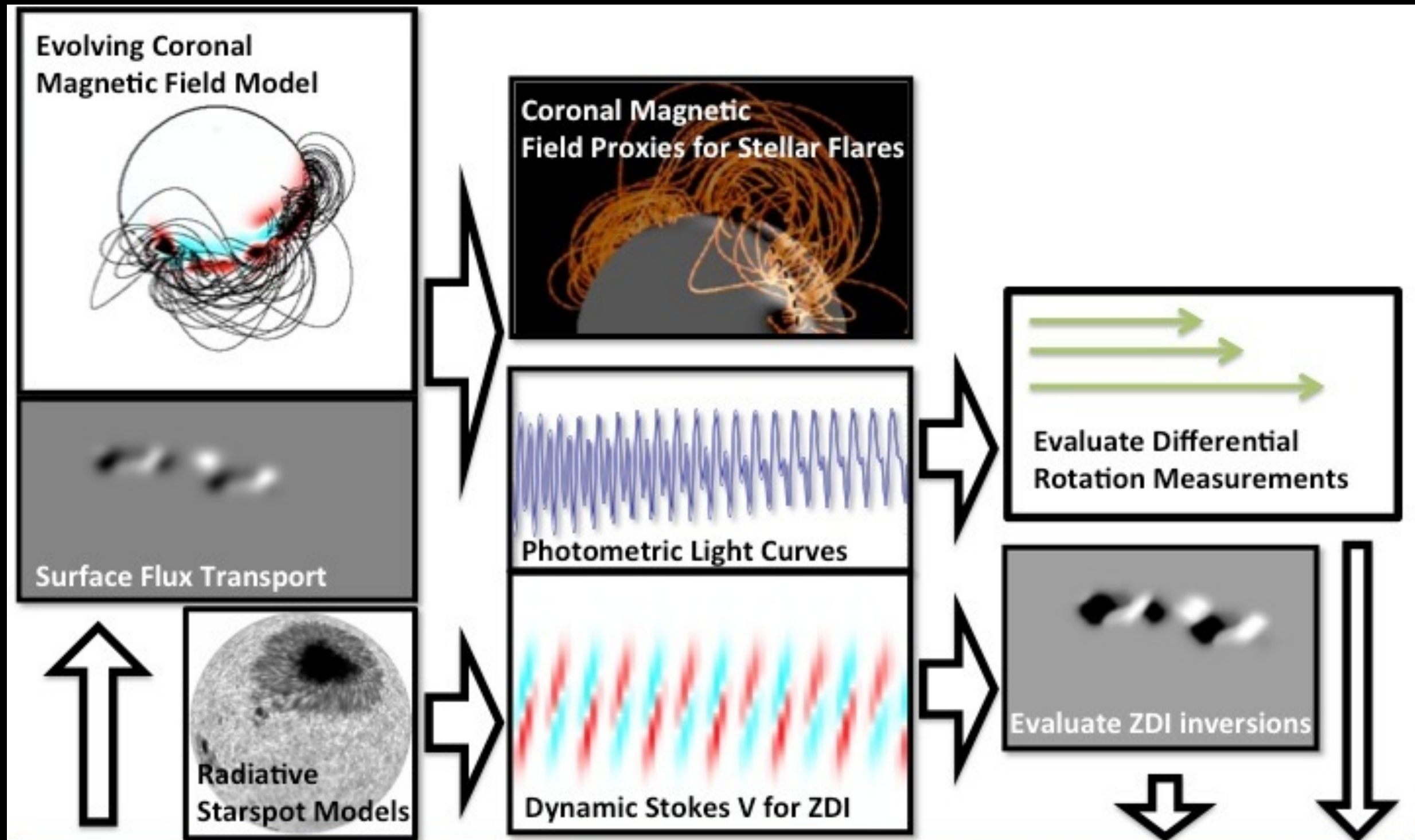
Context

This 4-year project (starting Jan 2016) is part of NASA's Living With A Star Focus Science Team (FST) on Solar-Stellar Connections.

- Ben Brown (U. Colorado), *Stellar Insights into Solar Magnetism: Exploring Fundamental Dynamo Physics Across the Lower Main Sequence*

- Derek Buzasi (Florida Gulf Coast U), *Exploring the Solar-Stellar Connection Using K2*

- Ofer Cohen (SAO), *The Heliosphere in Time: Scaling Heliospheric Parameters with Stellar Evolution of Solar Analogs and Studying Heliospheric Consequences of Young Active Suns*

- Marc DeRosa (LMSAL), *Evolving Models of Stellar Photospheric and Coronal Magnetic Fields*

- Jay Johnson (PPPL), *Identifying Causal Relationships in Stellar Activity Cycle Dynamics*

- Steve Saar (SAO), *Observational Constraints and Tests for Dynamos in Solar-like Stars*

Science Questions

- What constraints can measurements of magnetic spots, differential rotation, and flares on other stars teach us about the solar dynamo?

- What are the limits of observational inference of magnetic fields and differential rotation on other stars?

- What are the coronal magnetic configurations associated with superflare events (as observed, e.g., in white light photometric data in Kepler)?

- What is the importance of well-known physical processes on the Sun (including flux emergence, differential rotation, turbulent diffusion) for magnetic activity on other stars?

Outline of project

Evolving Coronal Magnetic Field Model

Coronal Magnetic Field Proxies for Stellar Flares

Surface Flux Transport

Radiative Starspot Models

Photometric Light Curves

Dynamic Stokes V for ZDI

Evaluate Differential Rotation Measurements

Evaluate ZDI inversions

Collaborate with other members of the Focus Science Team:
- 3D convective dynamo simulations can provide parameters for Surface Flux Transport model
- Our tasks evaluating Zeeman Doppler Imaging (ZDI) and Differential Rotation measurements can inform the modeler about the robustness of these measurement techniques and what constraints they put on dynamo theory.

Surface Flux Transport

From Yeates & Mackay, 2012 (Living Reviews in Solar Physics)

2.2.1 Standard model

The standard equation of magnetic flux transport arises from the radial component of the magnetic induction equation under the assumptions that $v_r = 0$ and $\partial/\partial r = 0$.[1] These assumptions constrain the radial field component to evolve on a spherical shell of fixed radius, where the time evolution of the radial field component is decoupled from the horizontal field components. Under these assumptions, the evolution of the radial magnetic field, B_r, at the solar surface ($R_\odot = 1$) is governed by

$$\frac{\partial B_r}{\partial t} = \frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\left(-u(\theta)B_r + D\frac{\partial B_r}{\partial\theta}\right)\right) - \Omega(\theta)\frac{\partial B_r}{\partial\phi} + \frac{D}{\sin^2\theta}\frac{\partial^2 B_r}{\partial\phi^2} + S(\theta,\phi,t), \qquad (1)$$

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[1] Alternatively, the magnetic flux transport equation may be obtained through spatially averaging the radial component of the induction equation (see DeVore *et al.*, 1984 and McCloughan and Durrant, 2002).

In the standard flux transport model, the evolutionary equation is in terms of B_r, its gradients, transverse flows **u**, a turbulent diffusivity and a source/sink term S. S captures flux emergence and submergence.

Constrained Surface Flux Transport

- MF and MHD codes need E_t at the bottom boundary.

- To have a well-defined interface between the SFT code and overlying 3D magnetic model, it is best to be physically consistent.

- Think of a FT model that operates with **E**-electric fields. Instead of Eq. (1) on the previous slide, just start with Faraday's Equation:
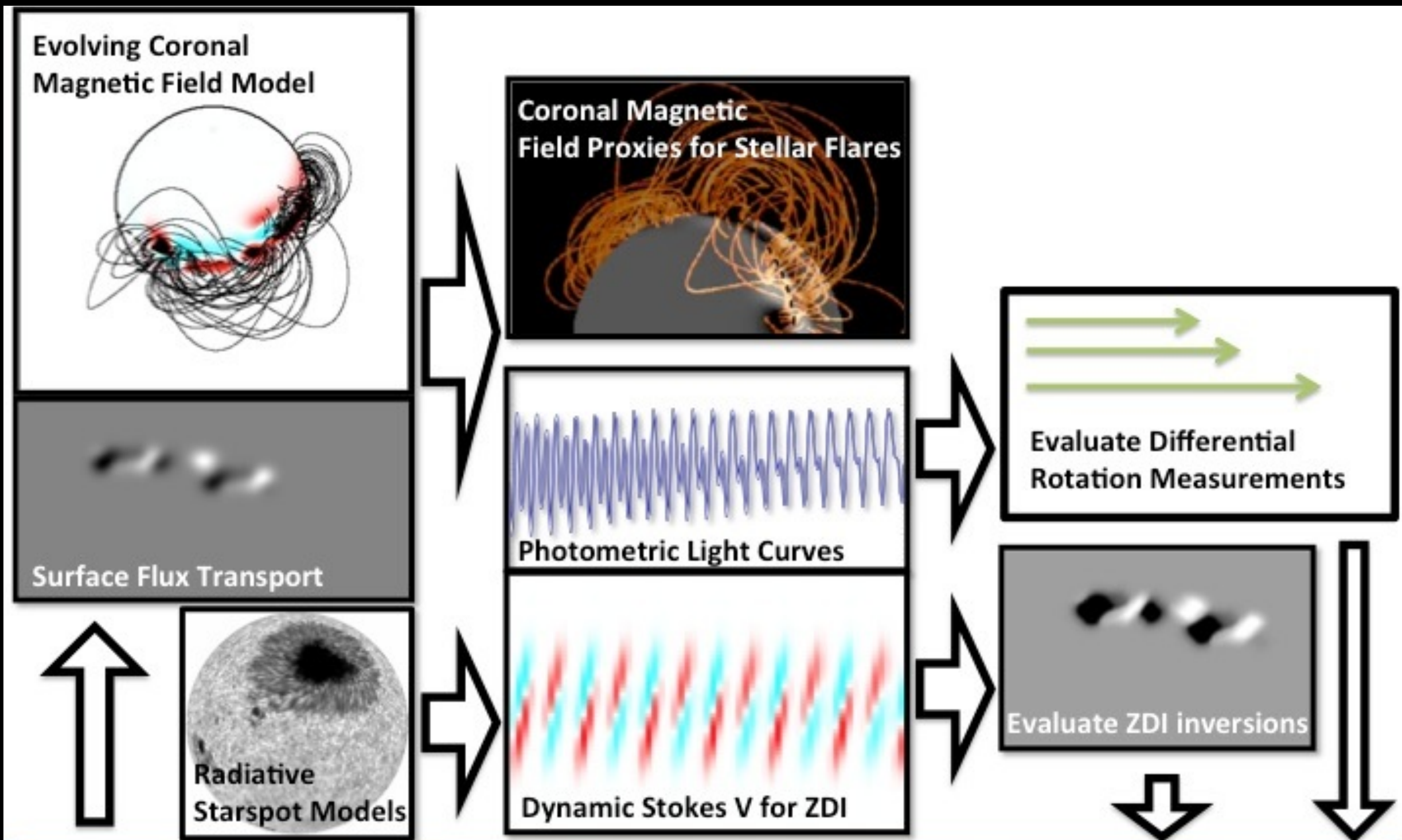
$$dB_r/dt = -curl\ E_t$$
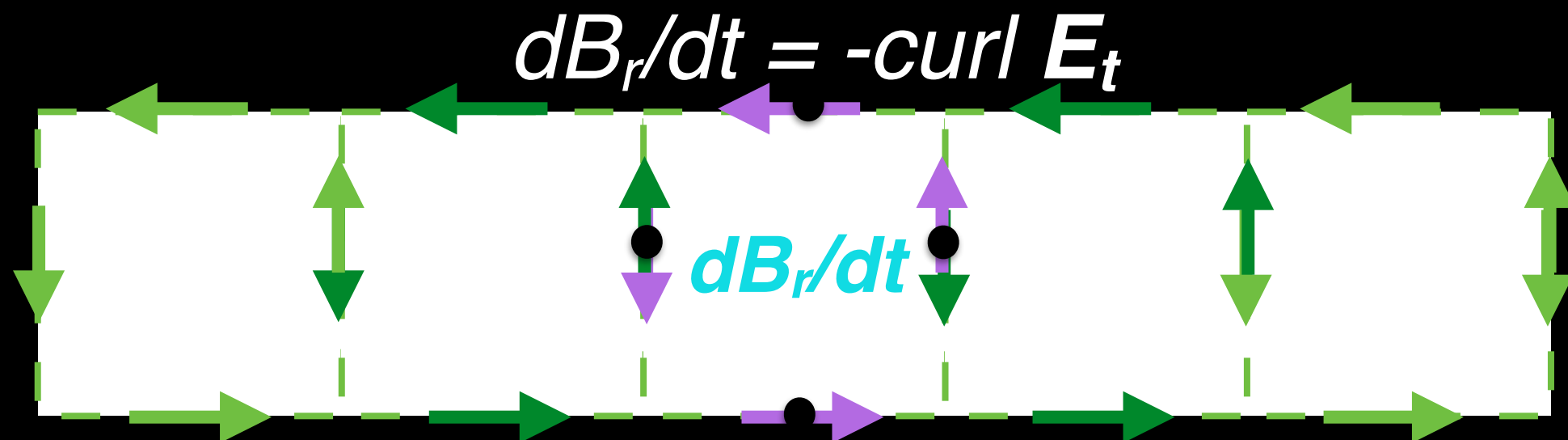
$$dB_r/dt$$

Calculate *dB_r/dt*pixel area* of each pixel as
- circulation of E_t about the pixel.

Benefit: No need to do inverse problem to get E-fields from output of SFT model.

Example of Constrained Surface Flux Transport

t =   157.49 dy
dt =   0.21873 dy
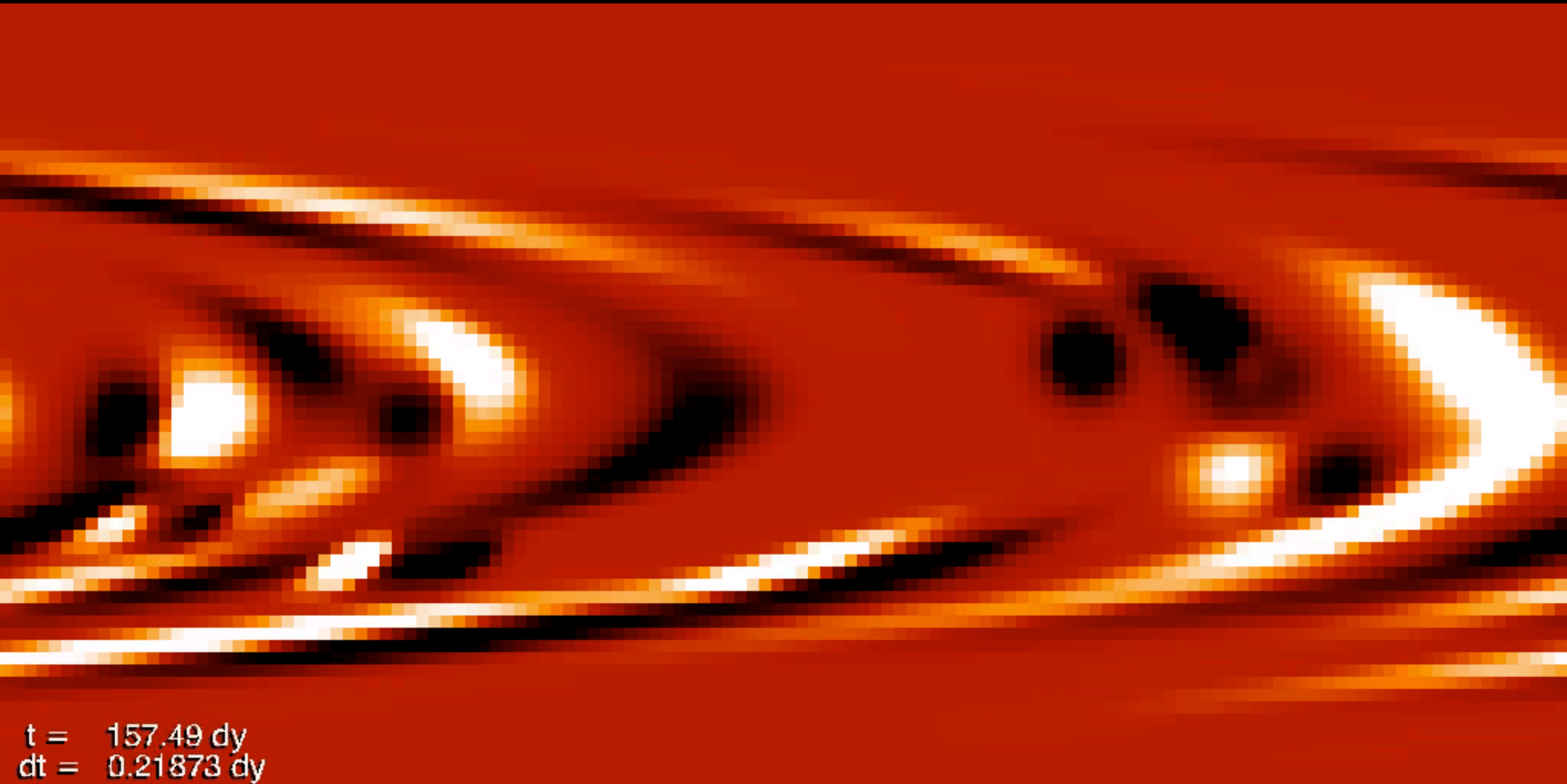
AR emergence by setting v_r contribution to transverse E.
Supergranule diffusion and meridional circulation switched off for this run.

Evolving Coronal Magnetic Field Model

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Evolving Coronal Magnetic Field Model

- <u>Magnetofriction</u>: Balance of Lorentz force and fictitious frictional force (Yang, Sturrock & Antiochos, 1986; Craig & Sneyd 1986)
  - Plasma velocity proportional to Lorentz force:
    $v = v^{-1} \, j \times B$ where v is the frictional coefficient
  - Evolve magnetic field according to Induction Equation
- Total magnetic energy in volume monotonically decreasing (provided net Poynting flux through boundaries is zero).

Bz at 2011-02-11T18:36
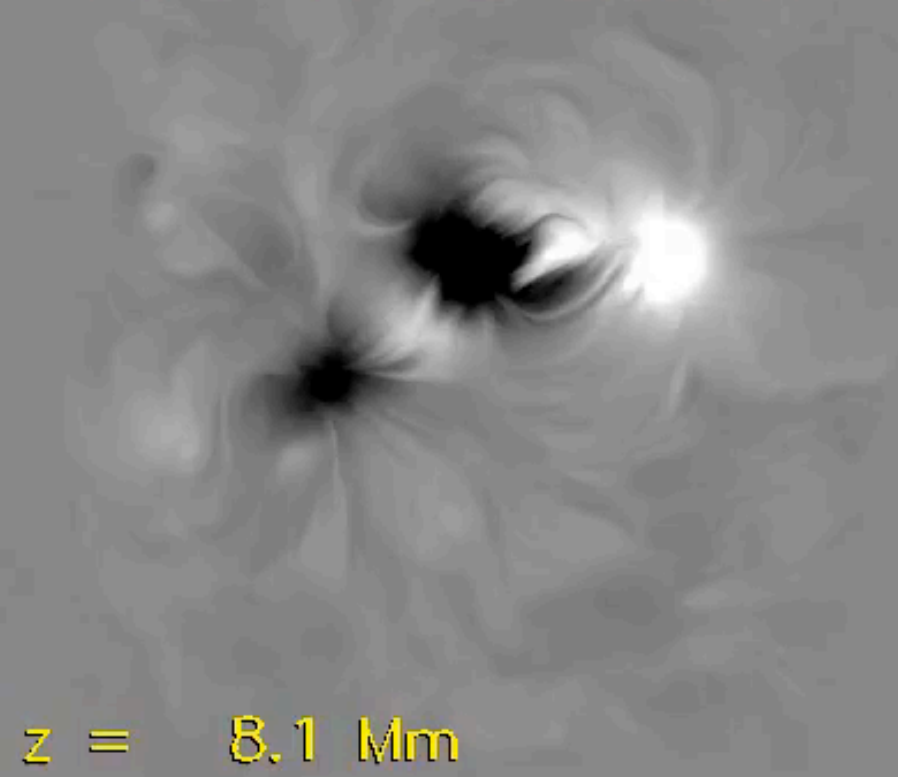
Model B$_z$ at various heights

z = 8.1 Mm

z = 54.2 Mm

z = 135.4 Mm

z = 0.0 Mm

z = 2.7 Mm

z = 5.4 Mm
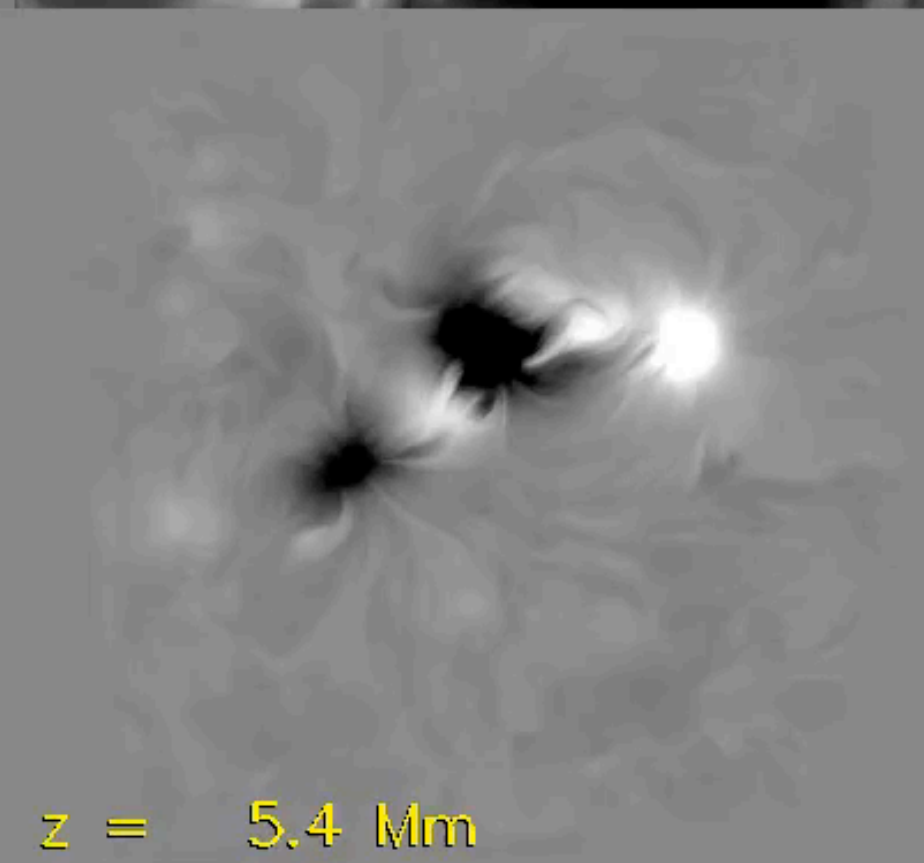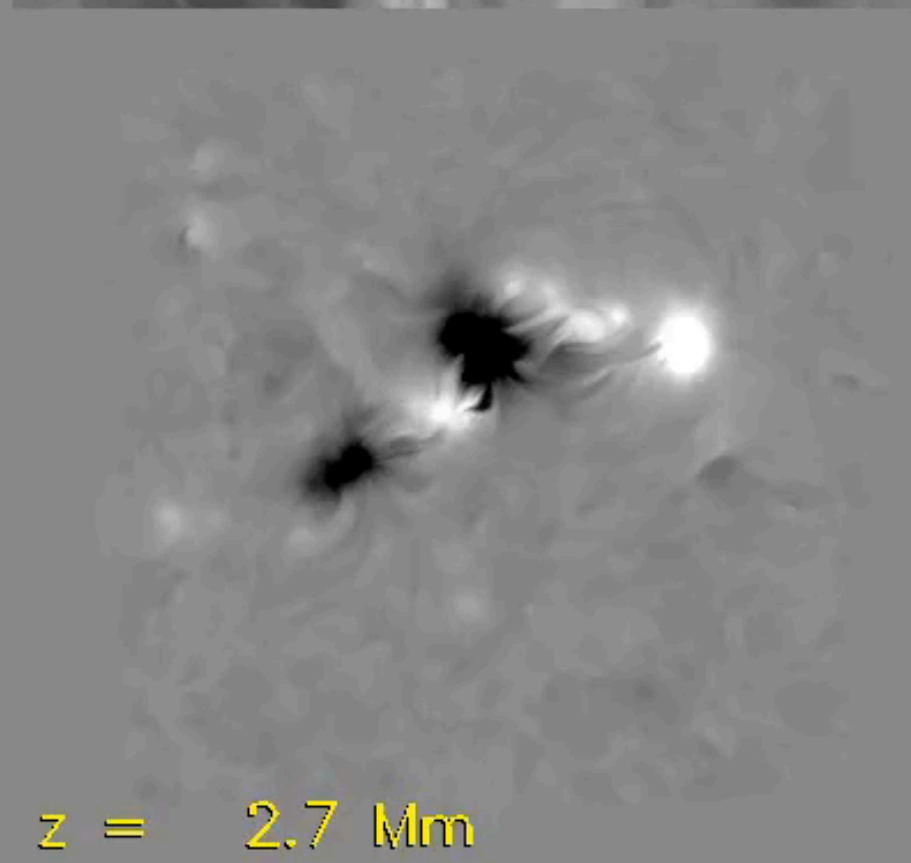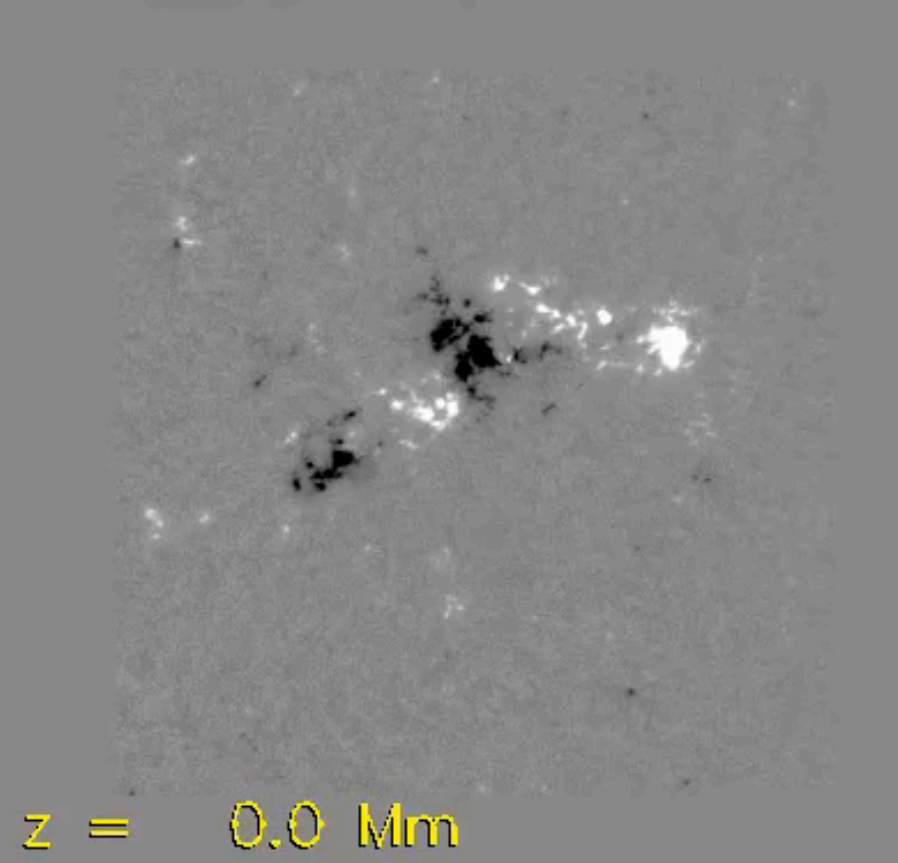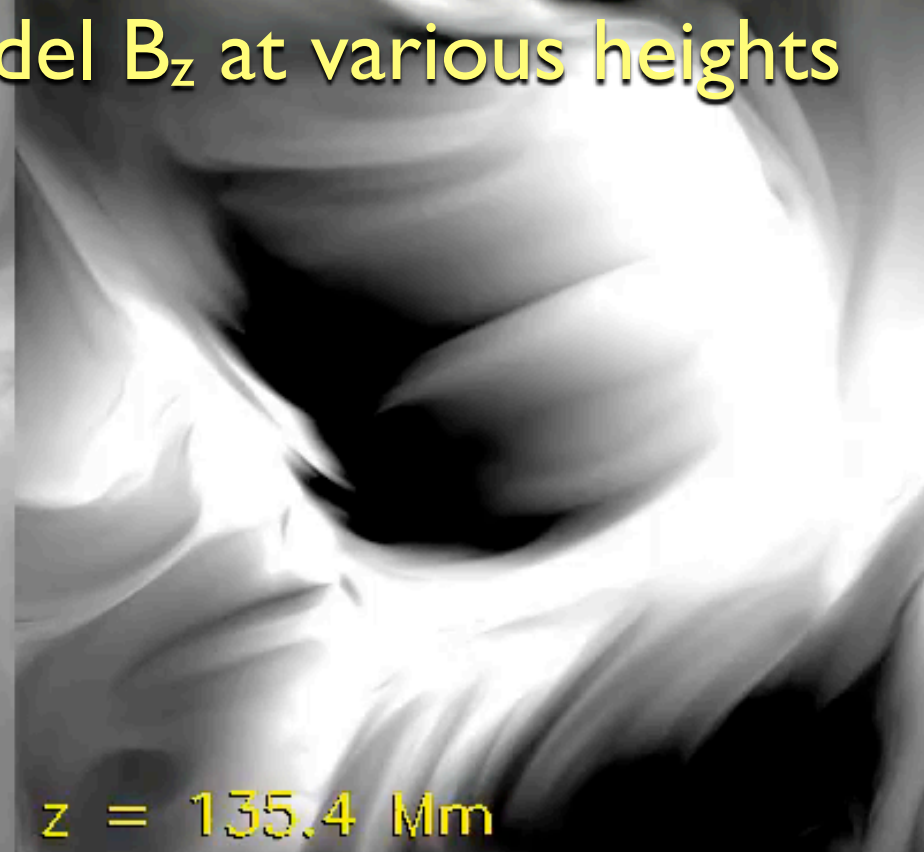
Cartesian data-driven model MF of NOAA AR 11158
using SDO/HMI magnetograms (Fisher et al., Space Weather, 2015)

Time-dependent Coronal Models

(a) 25-Jul-1999
(b) 14-Mar-2004
(c) 06-Apr-2008
(d) 29-Apr-2012
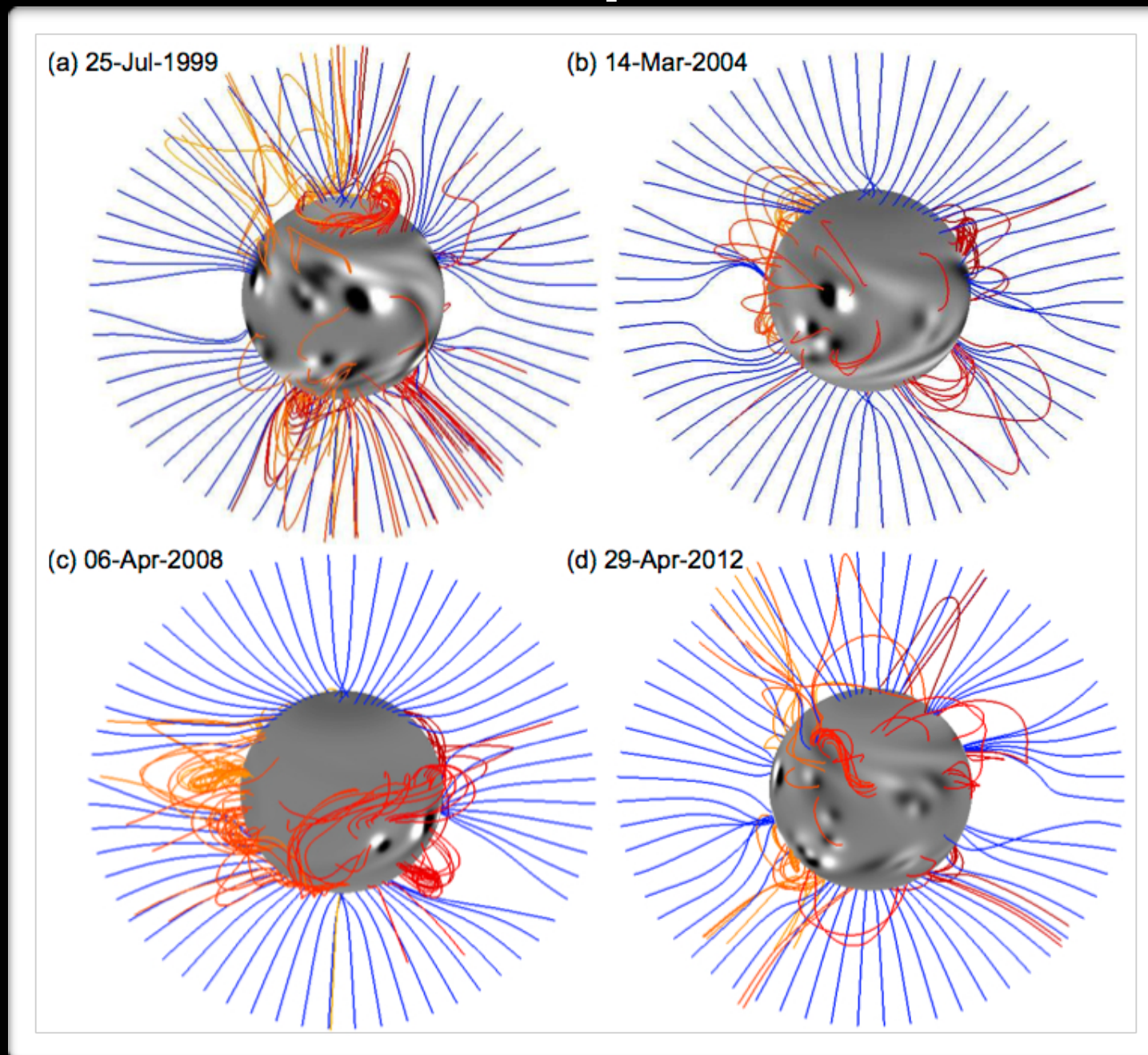
Data-driven models have time-dependent boundary conditions. The coronal B-field evolves in response to underlying driving at the photosphere from the following effects:

- Transverse (horizontal flows)
- Magnetic flux emergence and submergence
- (Turbulent) diffusion

These models have memory.

Above: Non-potential models of the global solar coronal field from 1996 to 2012 (Yeates, 2014, Sol Phys, 289, 631).

t =   0.21873 dy
dt =   0.21873 dy

Solar-like differential rotation, meridional circulation and supergranular diffusion switched off for this run.

Ic/<I> phase = 0.79, sin i = 0.77
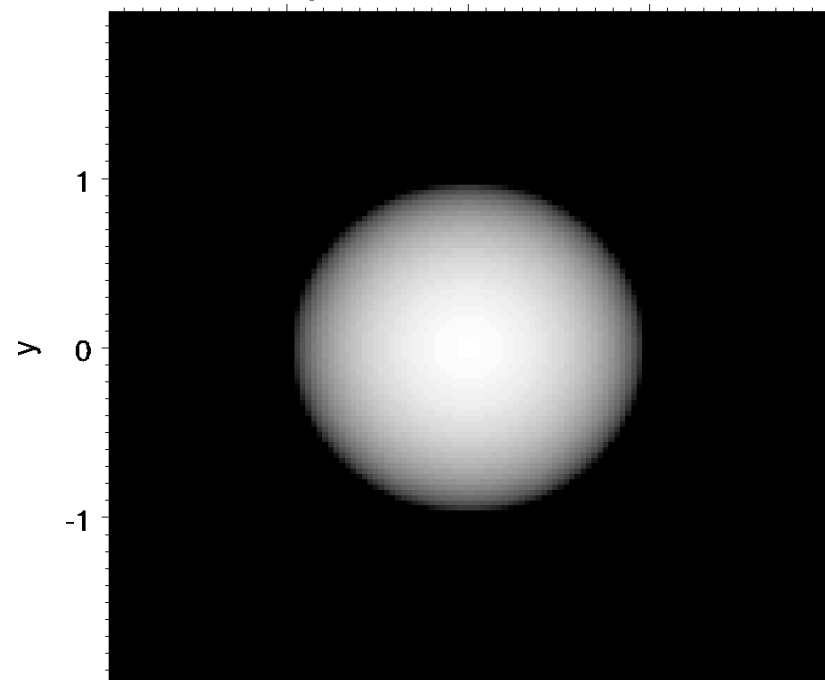
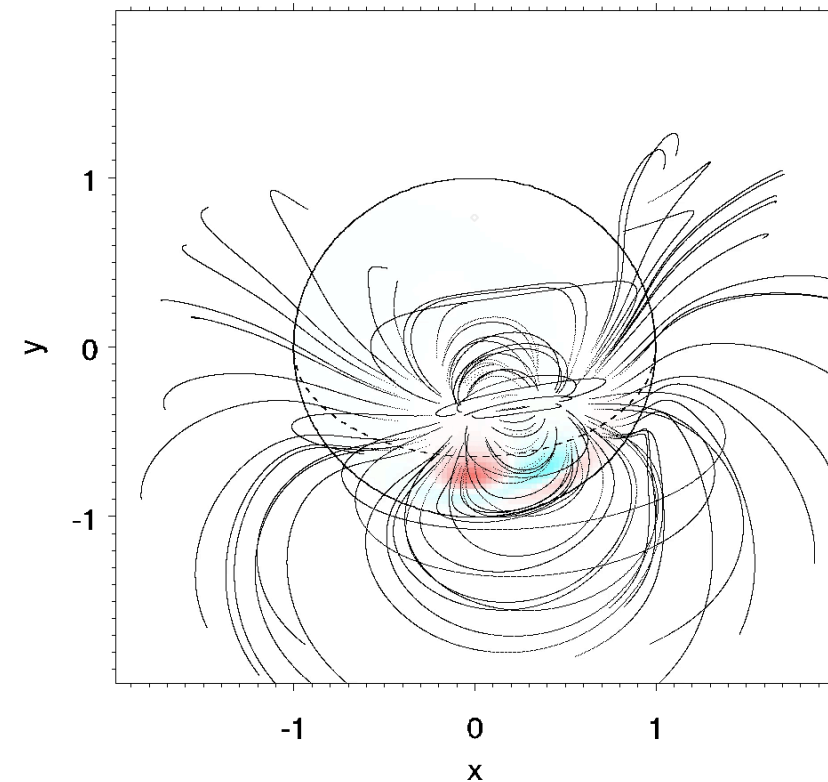LOS B [G] from Bvec, phase = 0.79

LOS B [G] from Bvec

Solar Rotation

Ic/<I> phase = 0.38, sin i = 0.77
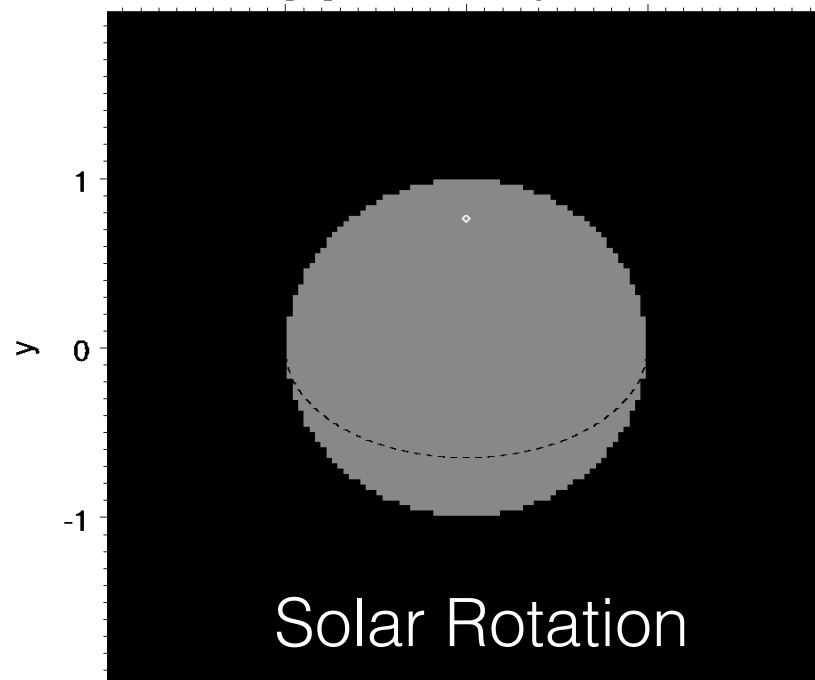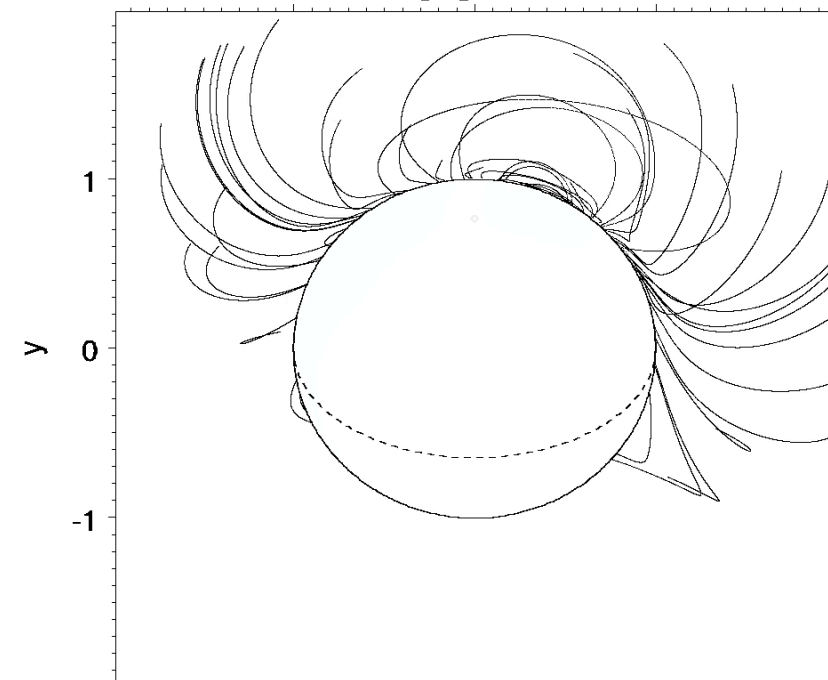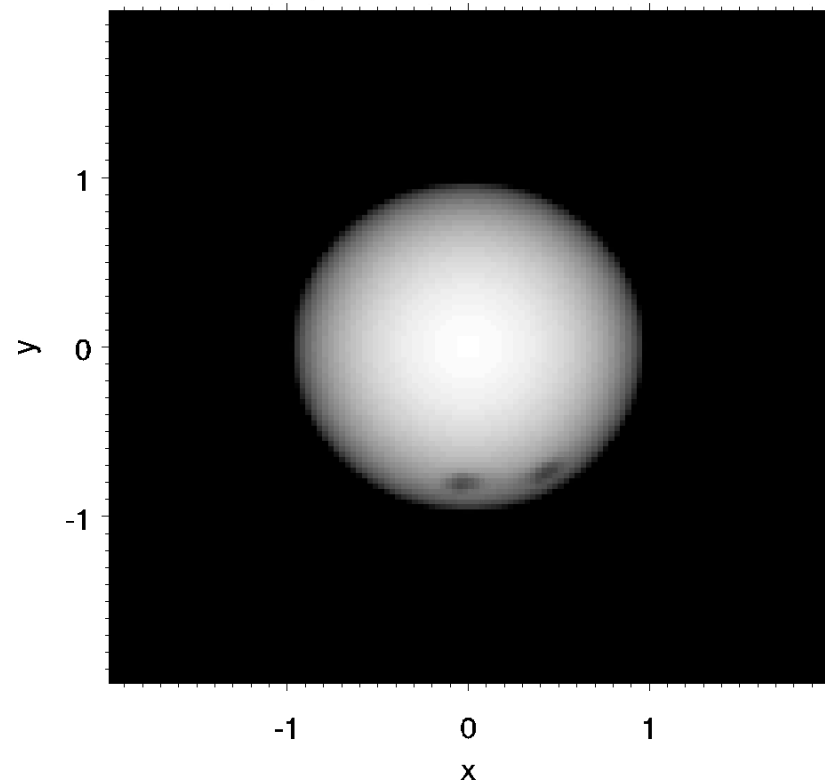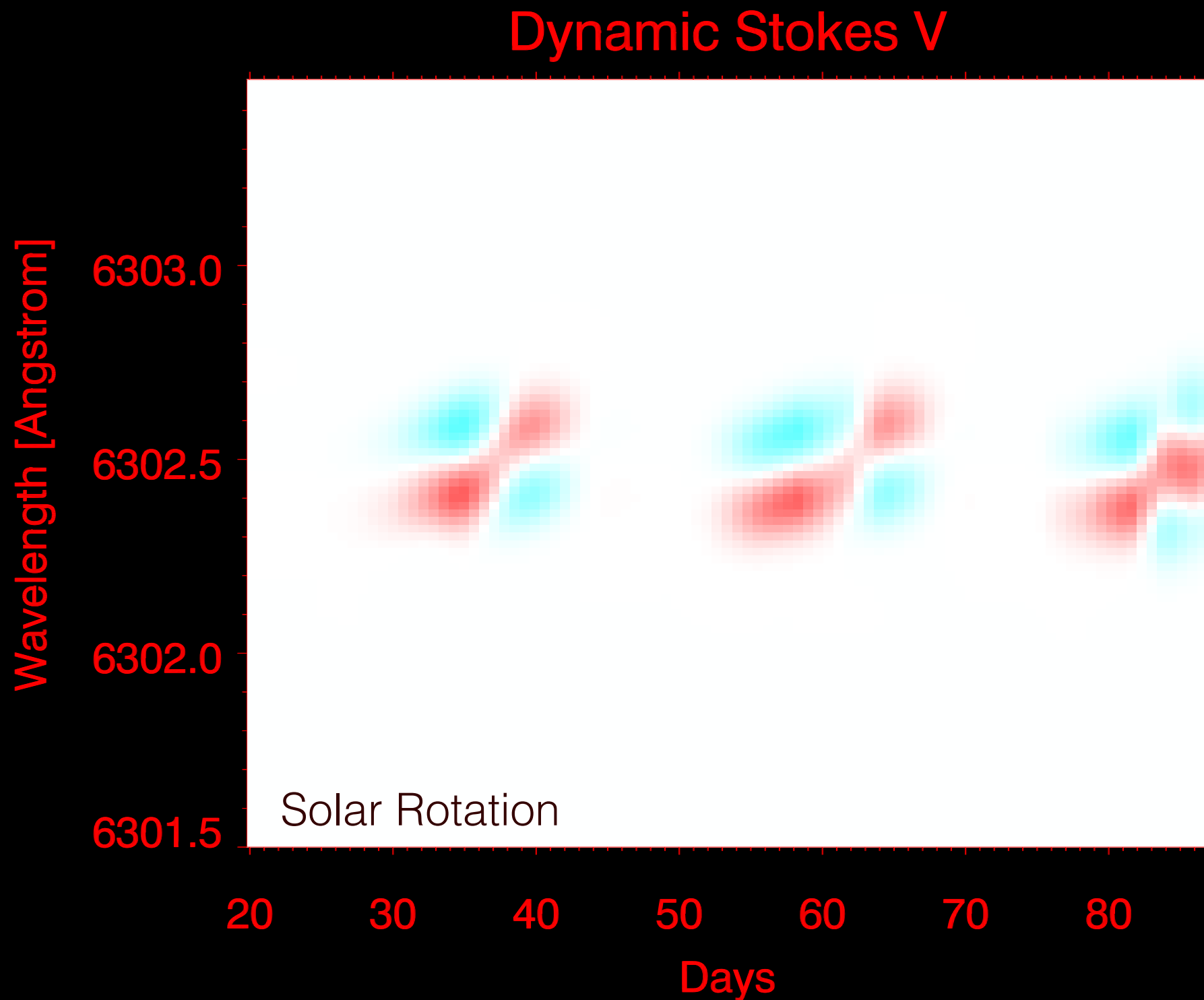
LOS B [G] from Bvec, phase = 0.38

LOS B [G] from Bvec

3x Solar Rotation
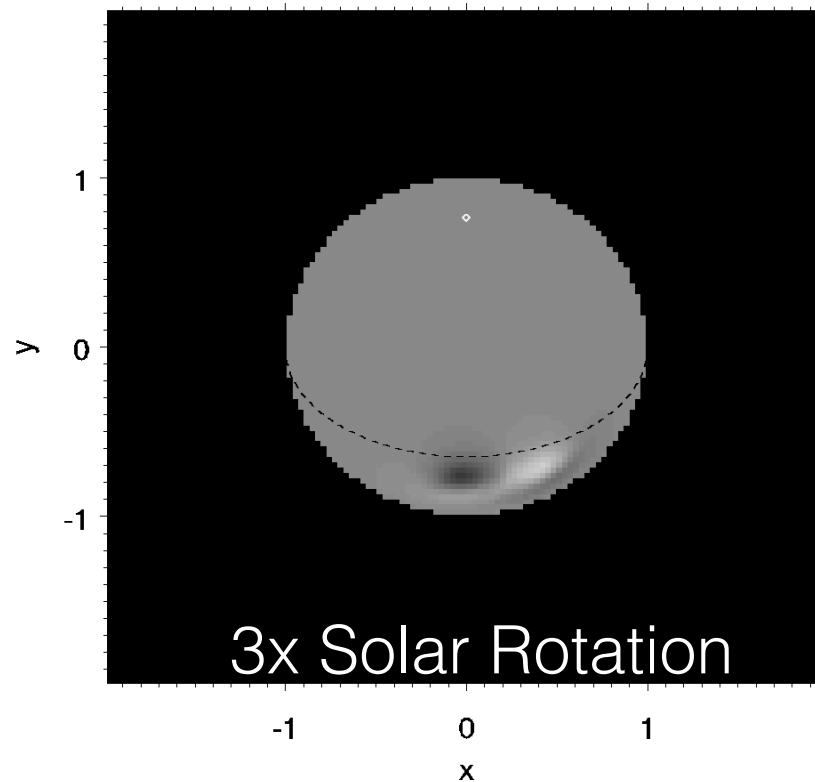
Synthetic white light image including
(1) limb darkening,
(2) Umbral darkening, but excluding
plage / faculae brightening.

Line-of-sight component of
the surface magnetic field.

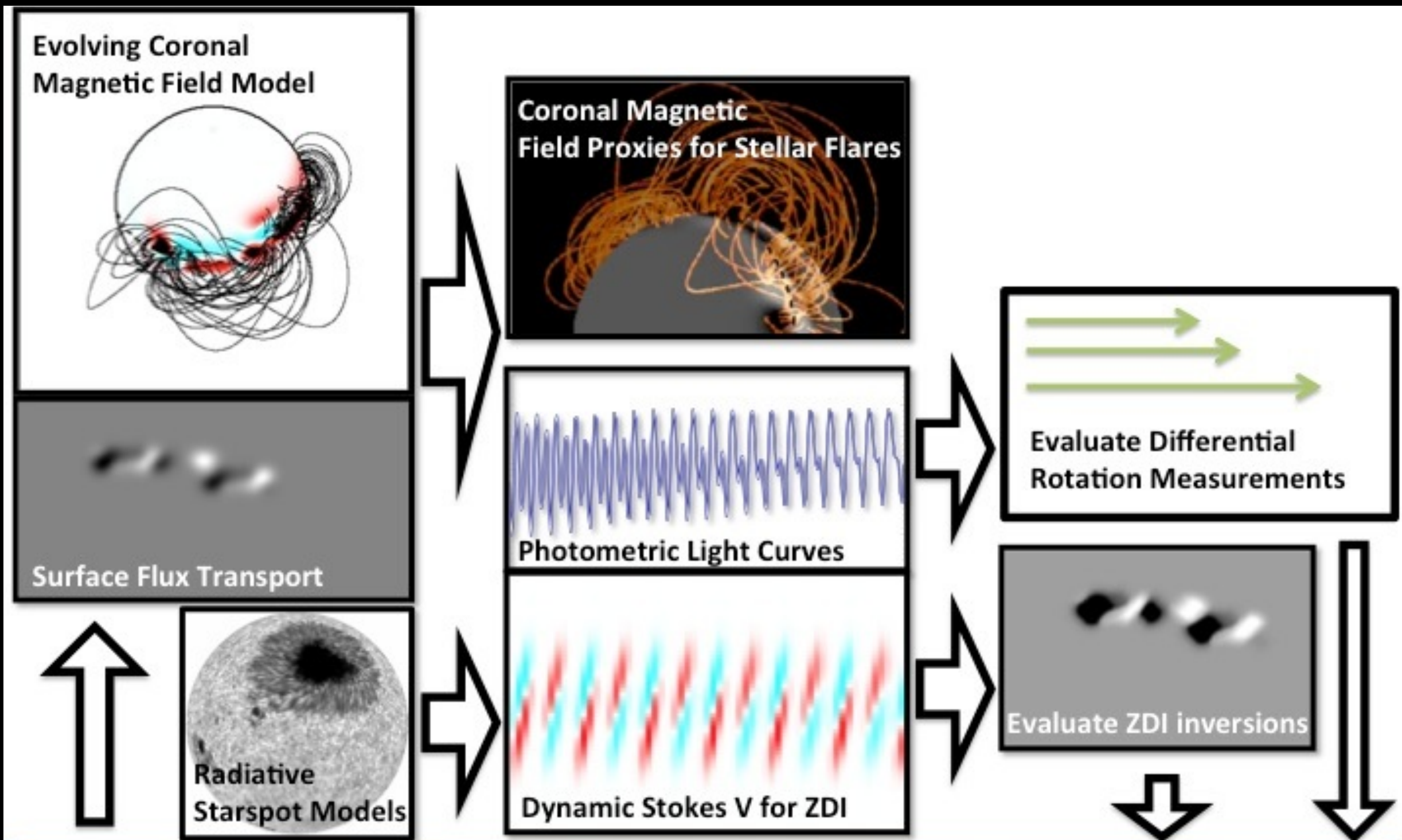Magnetofriction model of
the stellar coronal field.

Stokes parameters (Milne-Eddington)

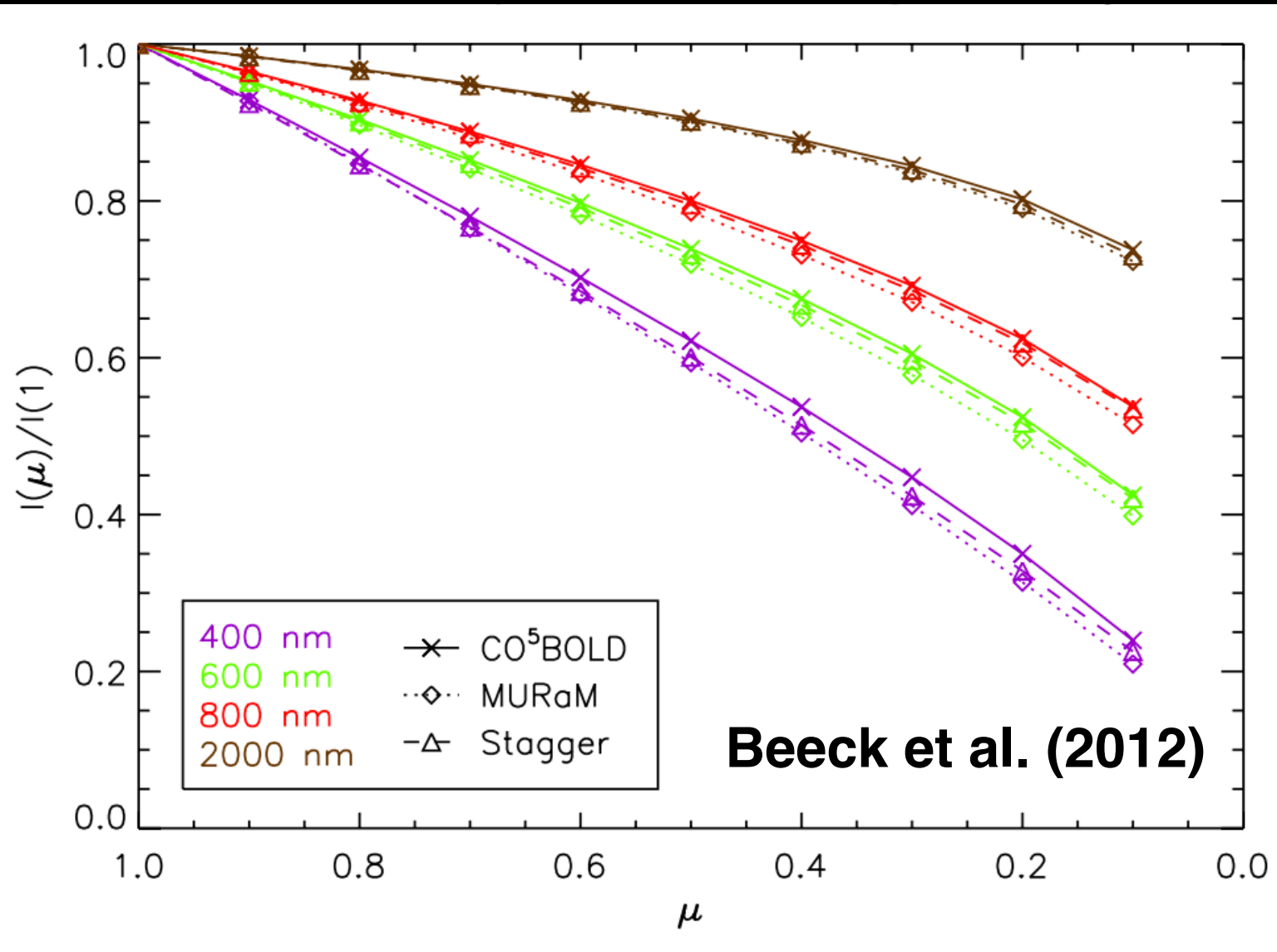Dynamic Stokes V

Solar Rotation

Zeeman Doppler Imaging data such as shown above (with appropriate noise) will be used to test inversions (collaborator Sandra Jeffers, U. Göttingen).

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The role of MHD models

Beeck et al. (2012)

Observation @ 488 nm, μ=0.5

Simulation with $\langle |B_z| \rangle$ = 400 G

Simulation with $\langle |B_z| \rangle$ = 200 G

Keller et al. (2004)

Radiative MHD models of near-surface (magneto)convection give guidance regarding the functional dependence of intensity on μ (i.e. center-to-limb variation) and |B|.
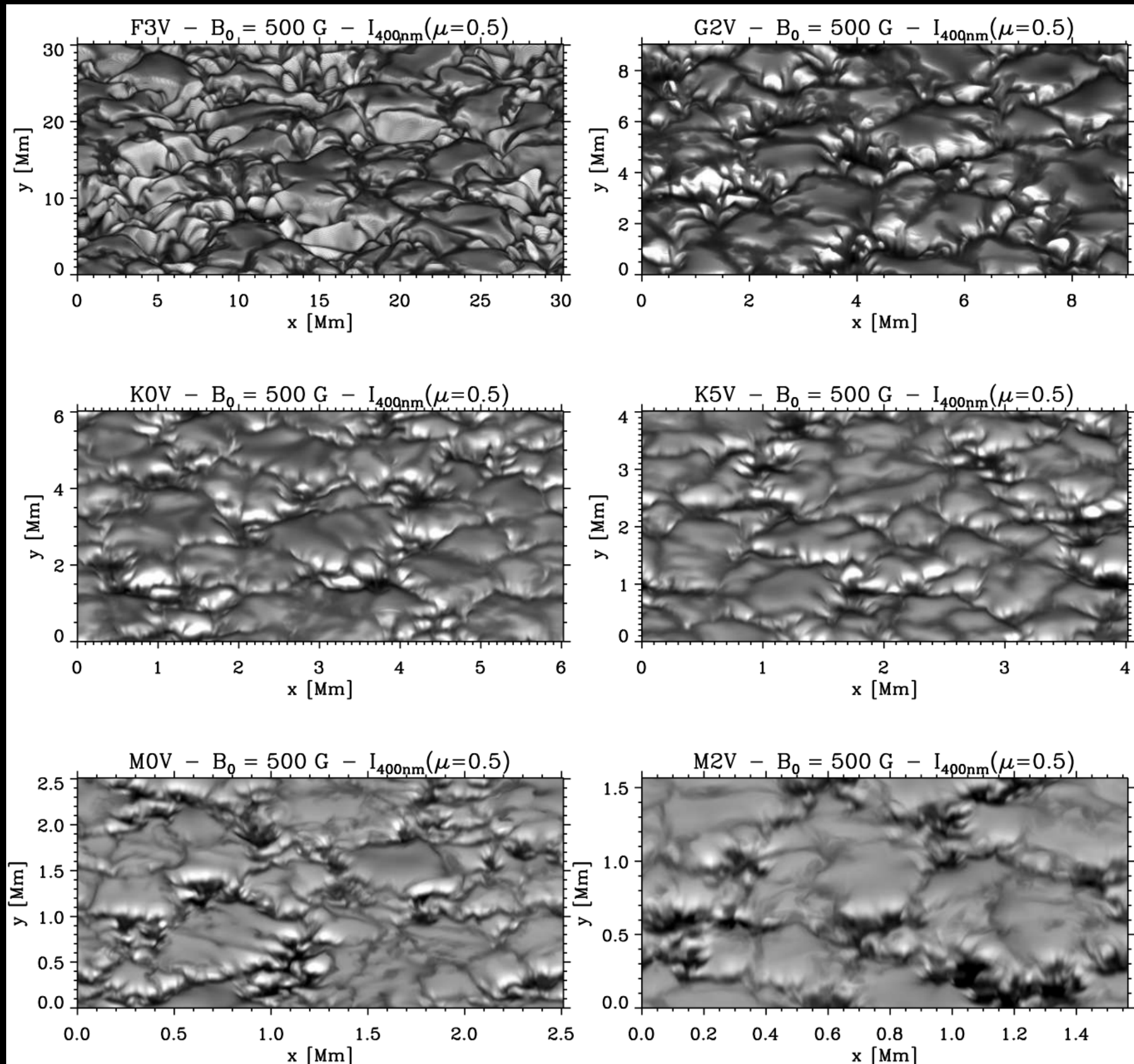
The role of MHD models

F3V

G2V

K0V

K5V

M0V

M2V
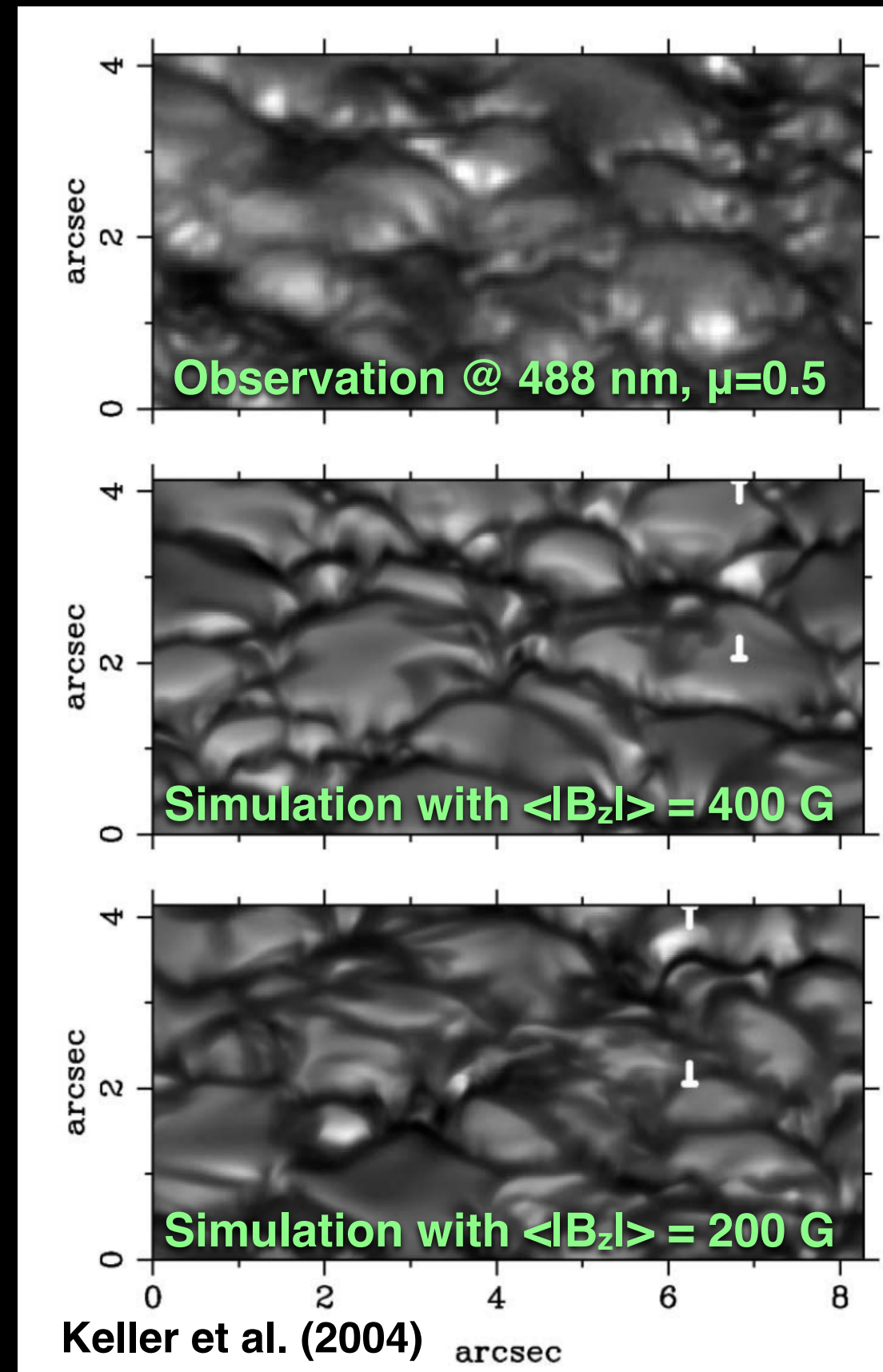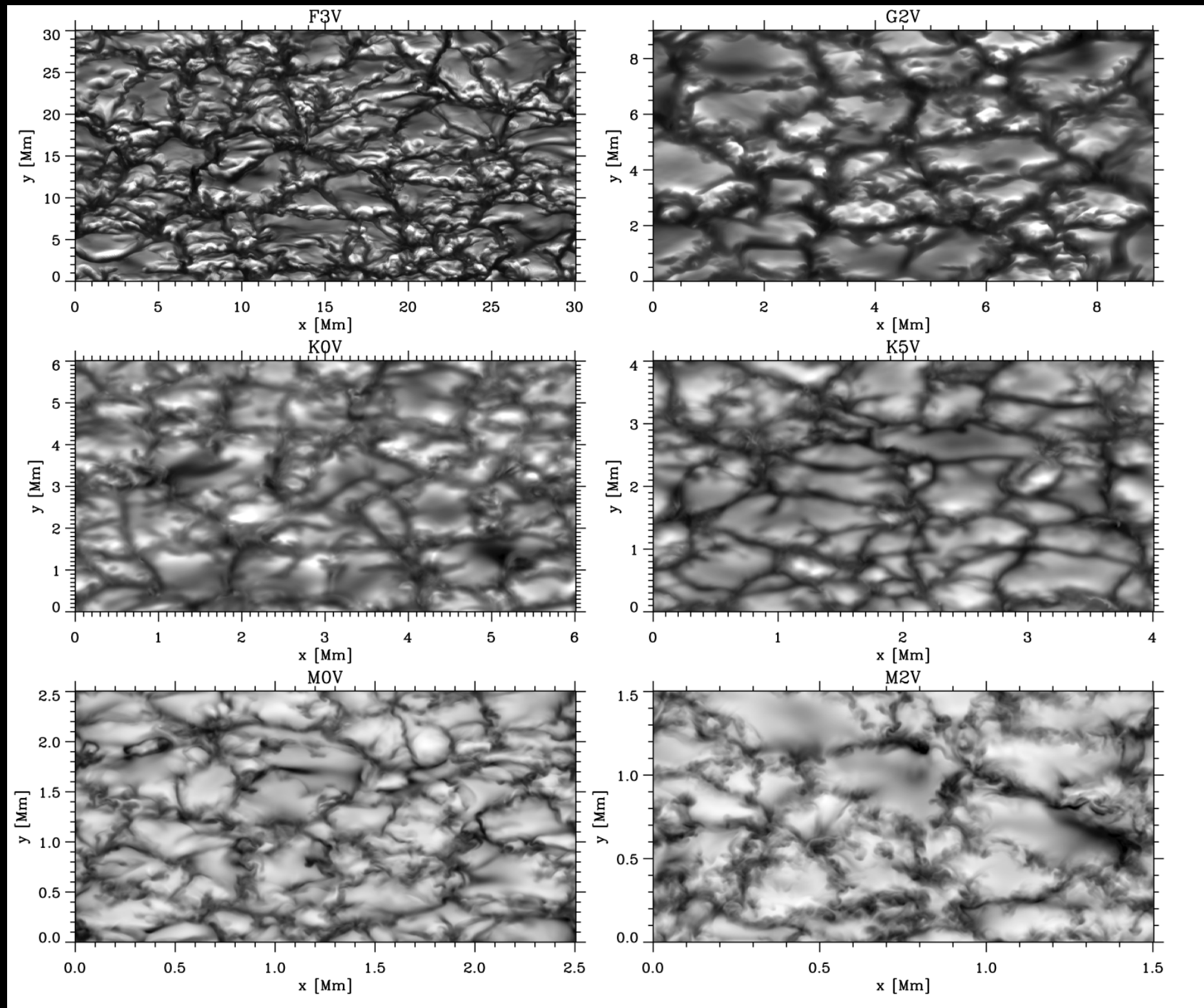
Beeck et al. (2013): Radiative HD models of near-surface convection in cool main sequence stars. Left: Synthetic intensity images in the wavelength band (400-410 nm) for $\mu = 0.5$.

The role of MHD models

Beeck et al. (2015): Radiative MHD models of magnetoconvection in cool main sequence stars. Left: Synthetic intensity images in the wavelength band (400-410 nm) for $\mu = 0.5$.
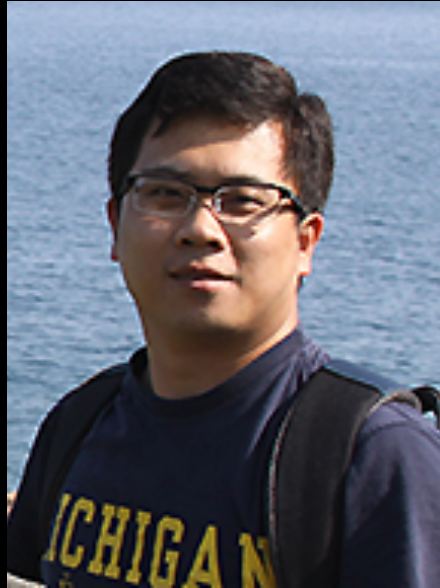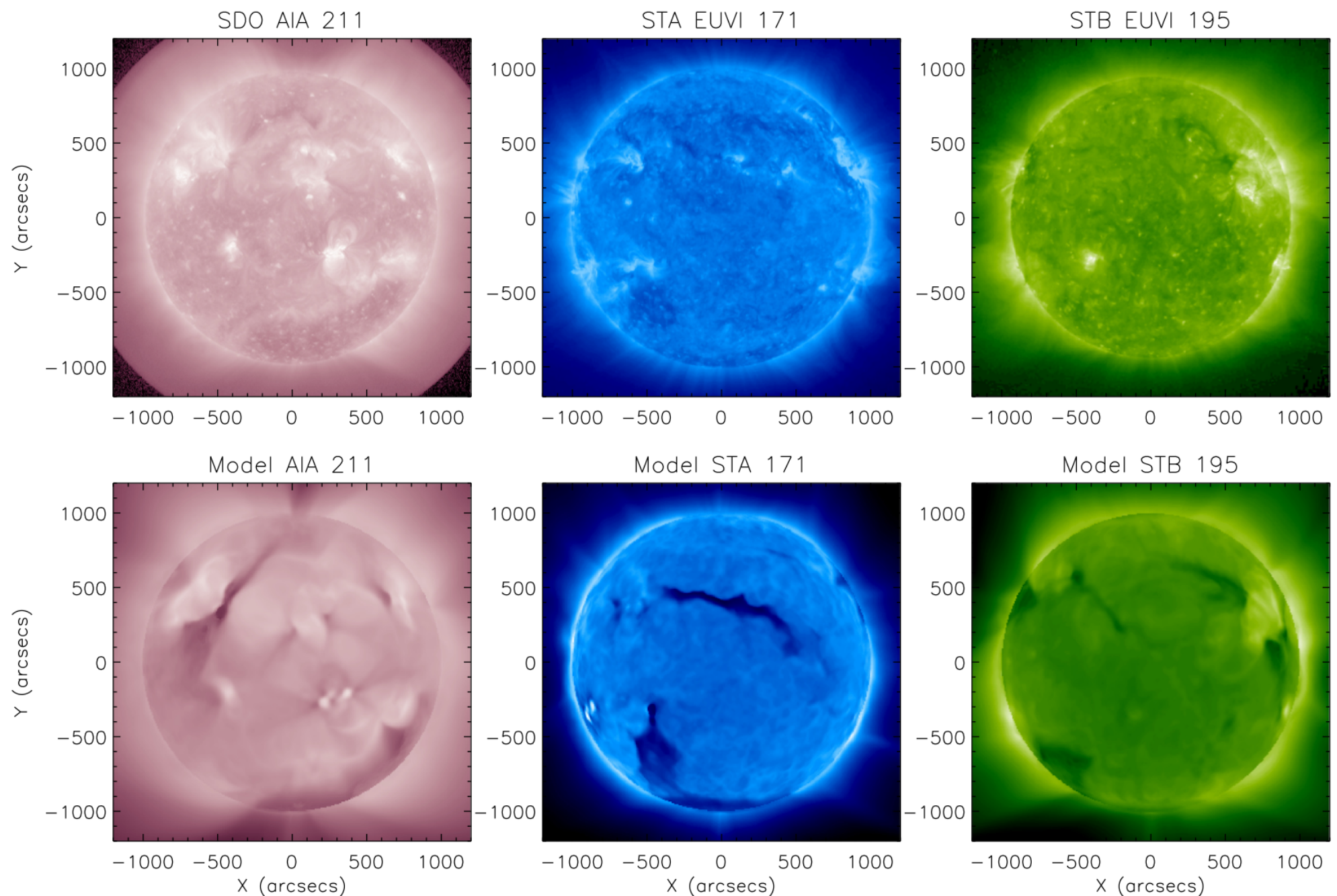
The M-type stars have no faculae.

The role of MHD models

t = 0.0 h

10 Mm

Sunspot simulation by Rempel et al. (2009)
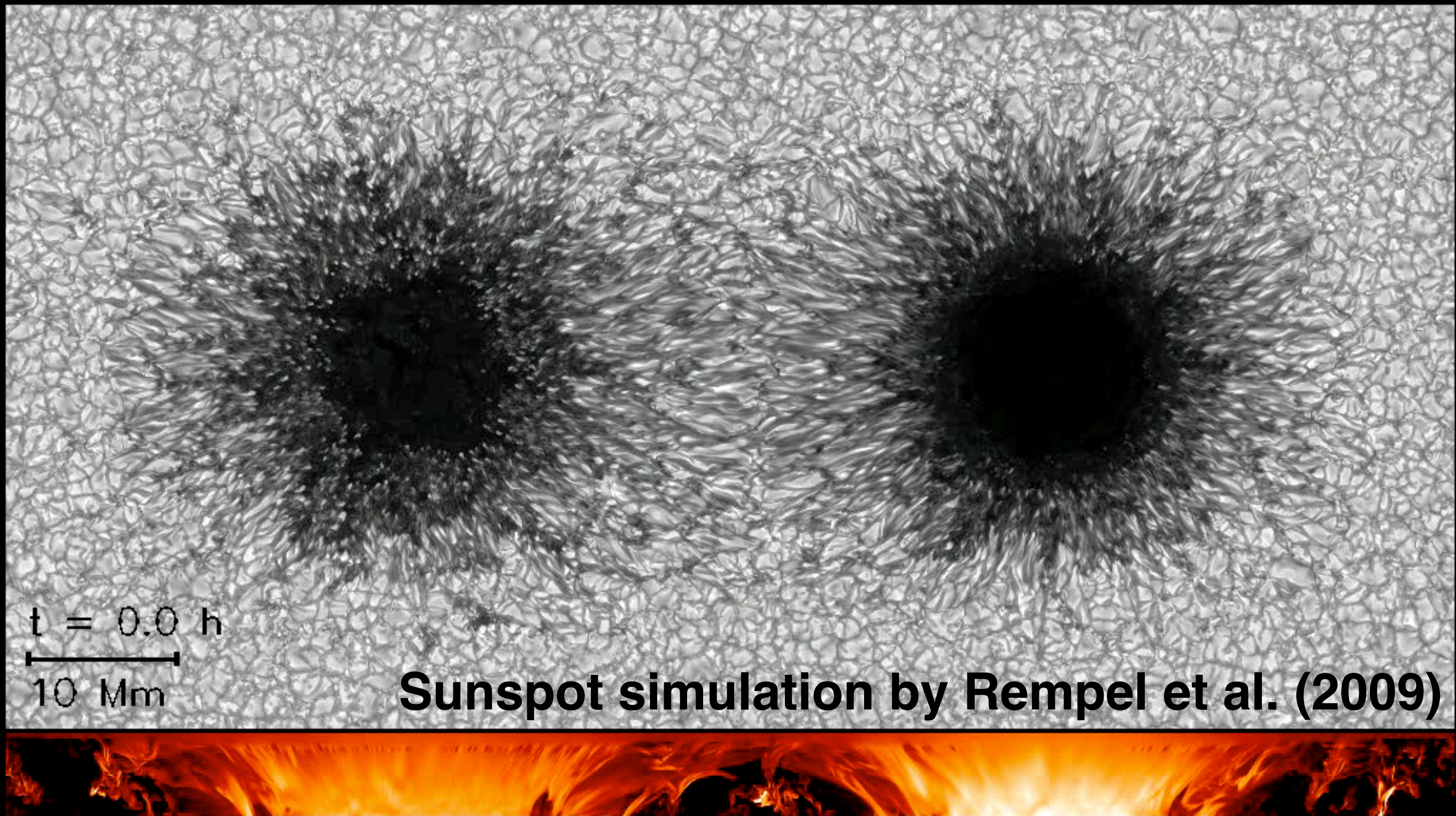
Collaborator B. Beeck aims to simulate starspots with MURaM.

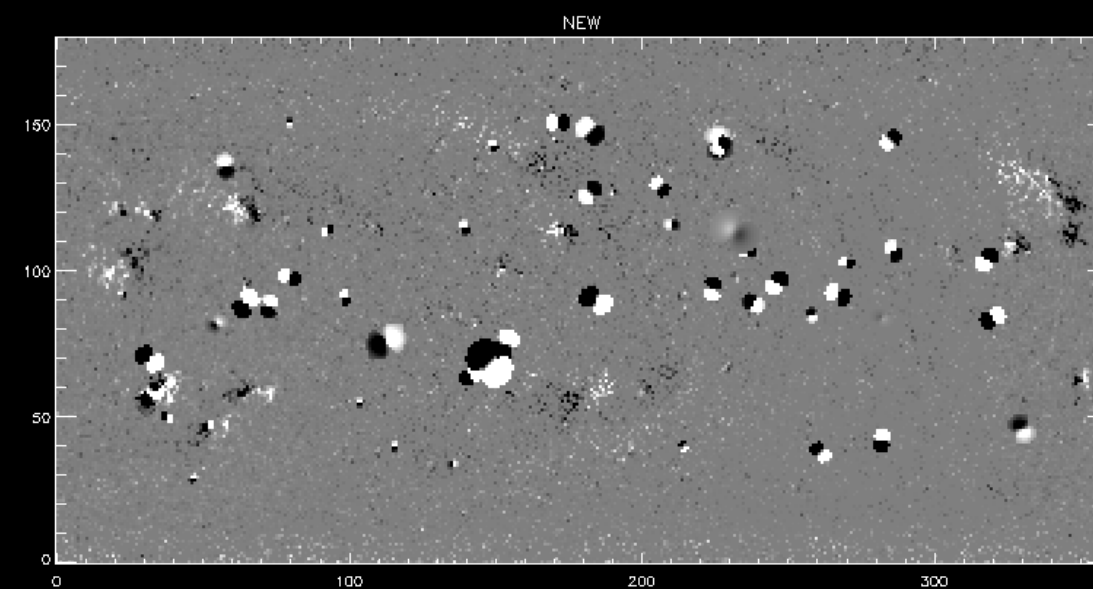# The role of MHD models

Meng Jin
NASA
Jack Eddy
Fellow
@ LMSAL

Alfvén Wave Solar Model (AWS☀M)

of the Feb 15th 2011 solar eruption starting from a Gibson-Low flux rope to study global coronal impacts and possible eruption sympathy (Jin et al., ApJ, 2016, in press).
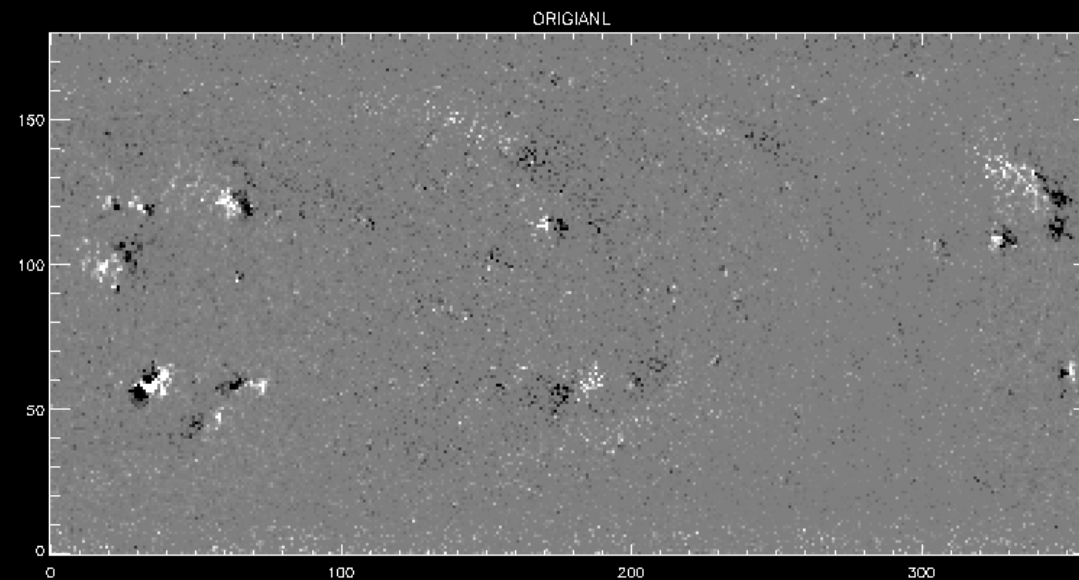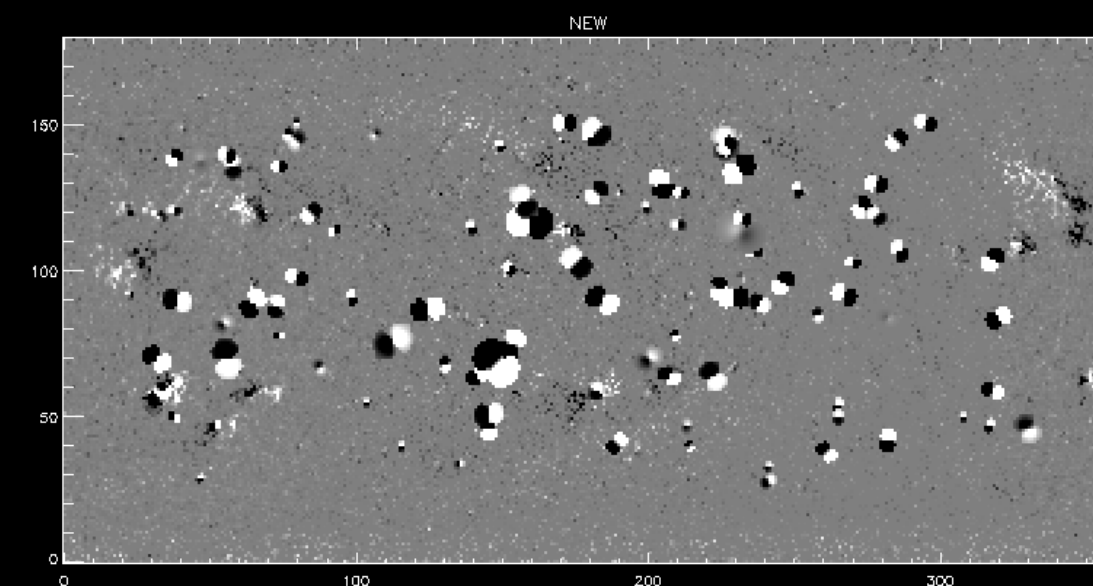
Original
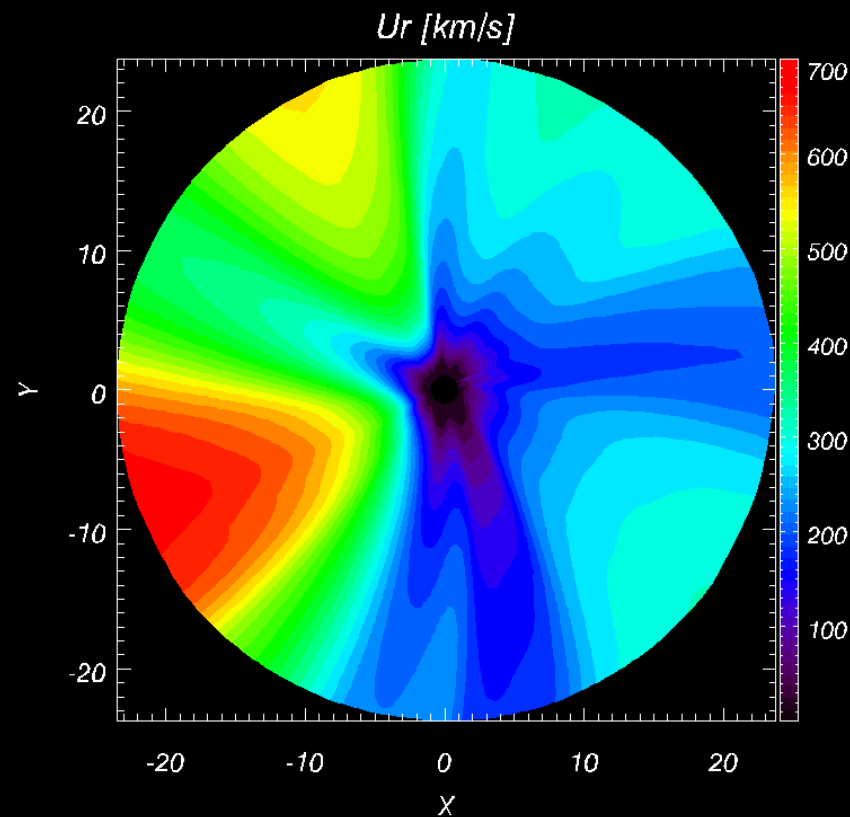
Average B: ~4 Gauss

+ 50 bipoles
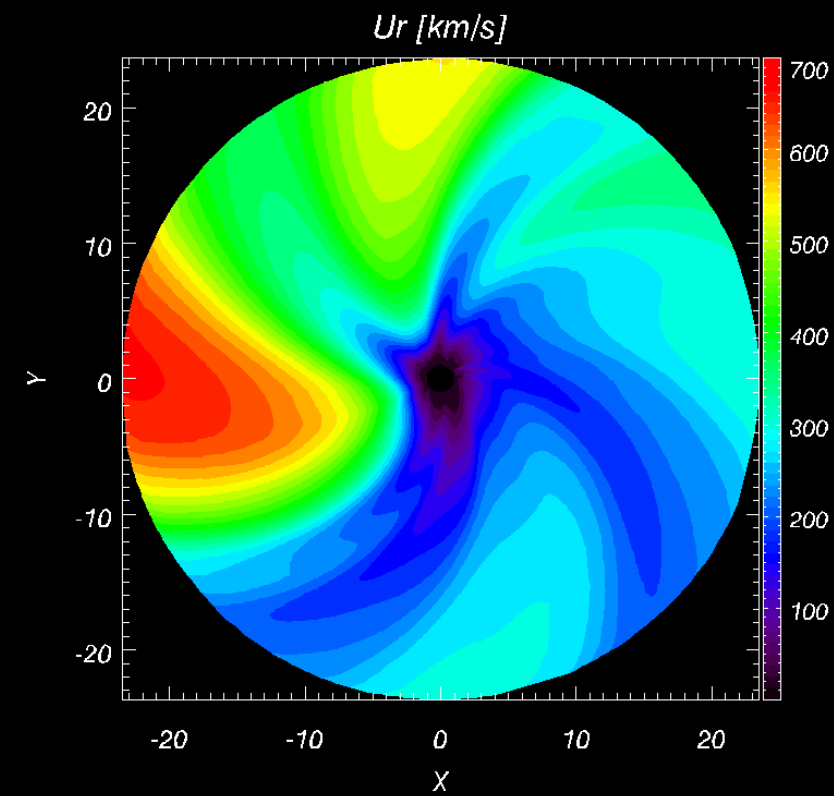
Average B: ~12 Gauss

+ 100 bipoles

Average B: ~20 Gauss
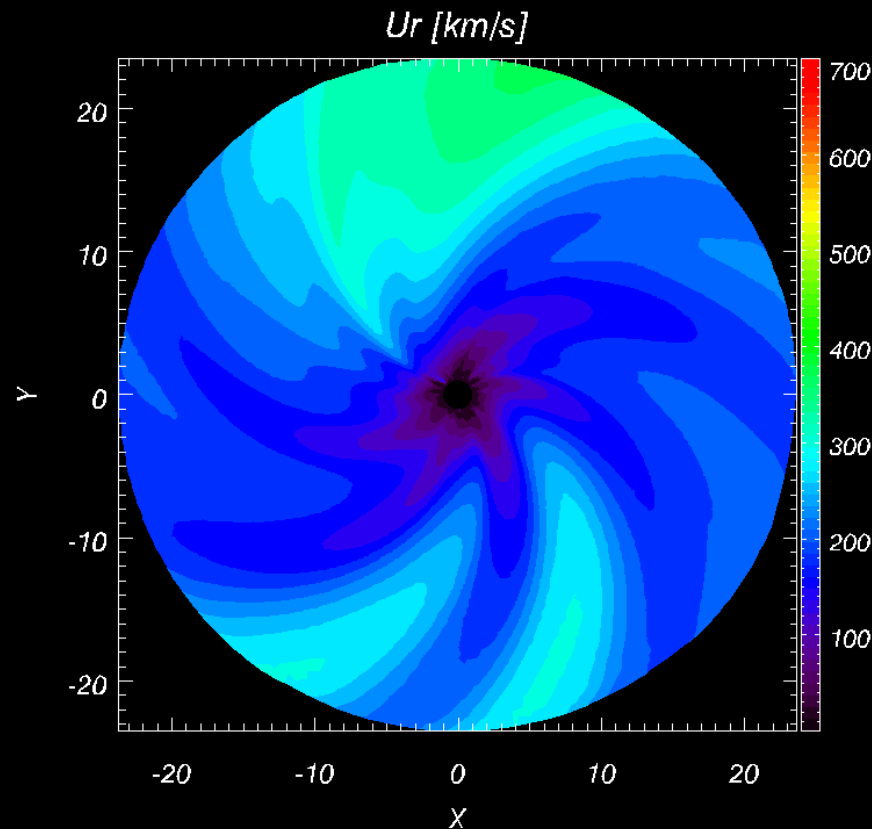
Influence on stellar wind

Case I
Solar Mag
$\Omega_\odot$

Case I
Solar Mag
$5\Omega_\odot$

Case III
Solar Mag
+ 50 ARs
$5\Omega_\odot$

Case IV
Solar Mag
+ 100 ARs
$5\Omega_\odot$
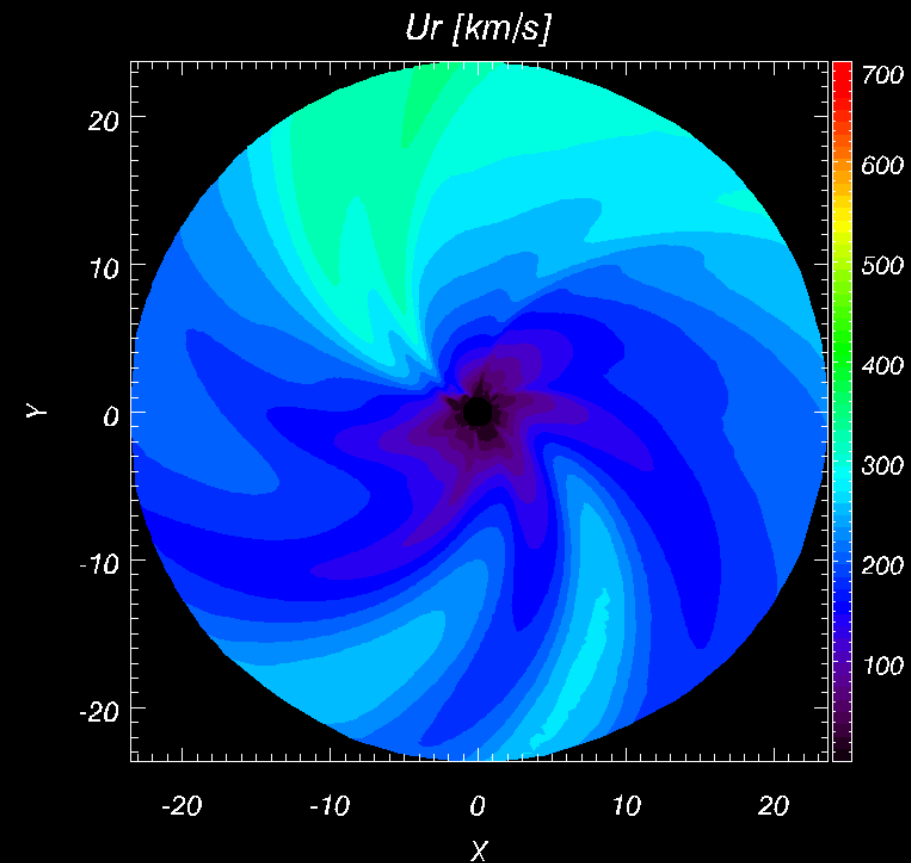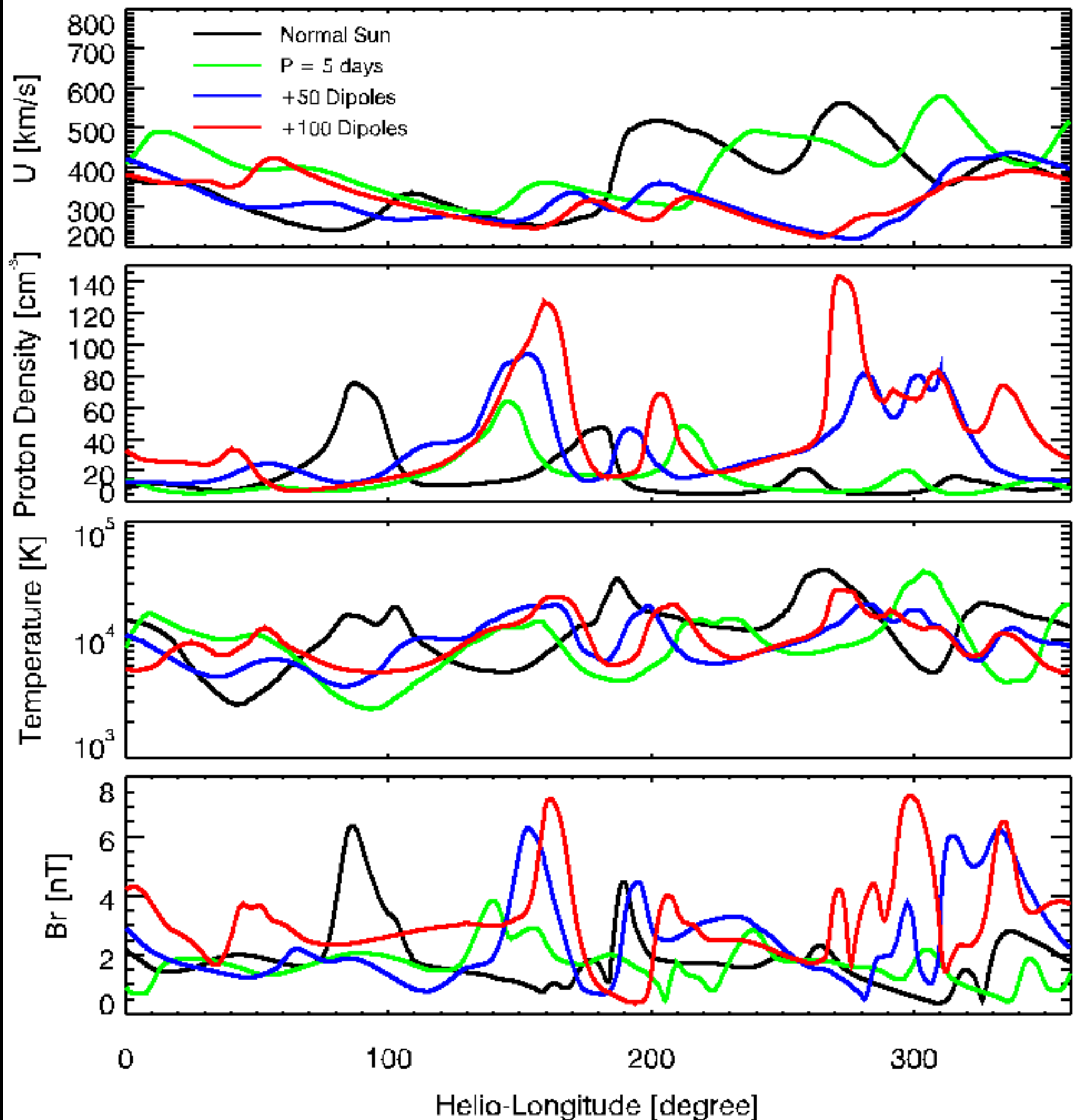
Solar wind properties @ 1 AU

Increase in Br & solar wind density associated with increase in activity.

Consider in the context of MAVEN results (Jakosky et al. 2015).

Summary

- We are developing a simplified model of evolving stellar photospheric and coronal magnetic fields based on a constrained surface flux transport model and a magnetofrictional model.

  - Parameter studies to be performed for solar-like stars (but can be extended to other types).

- Forward synthesis of disk-integrated observables allows us to test

  - Zeeman Doppler Image inversions on evolving fields,

  - Properties derived from photometric light curves.

- Radiative MHD models will be used for increasing the realism of synthetic observables, in particular for the center-to-limb variation and dependence on IBI.

- One aim is to generate evolving models that have unstable flux ropes. Simulating the eruption of these flux ropes using an MHD model (such as AWSOM) allows us to study the impact on the heliosphere and study the role of (super)flare sympathy.

Thank you