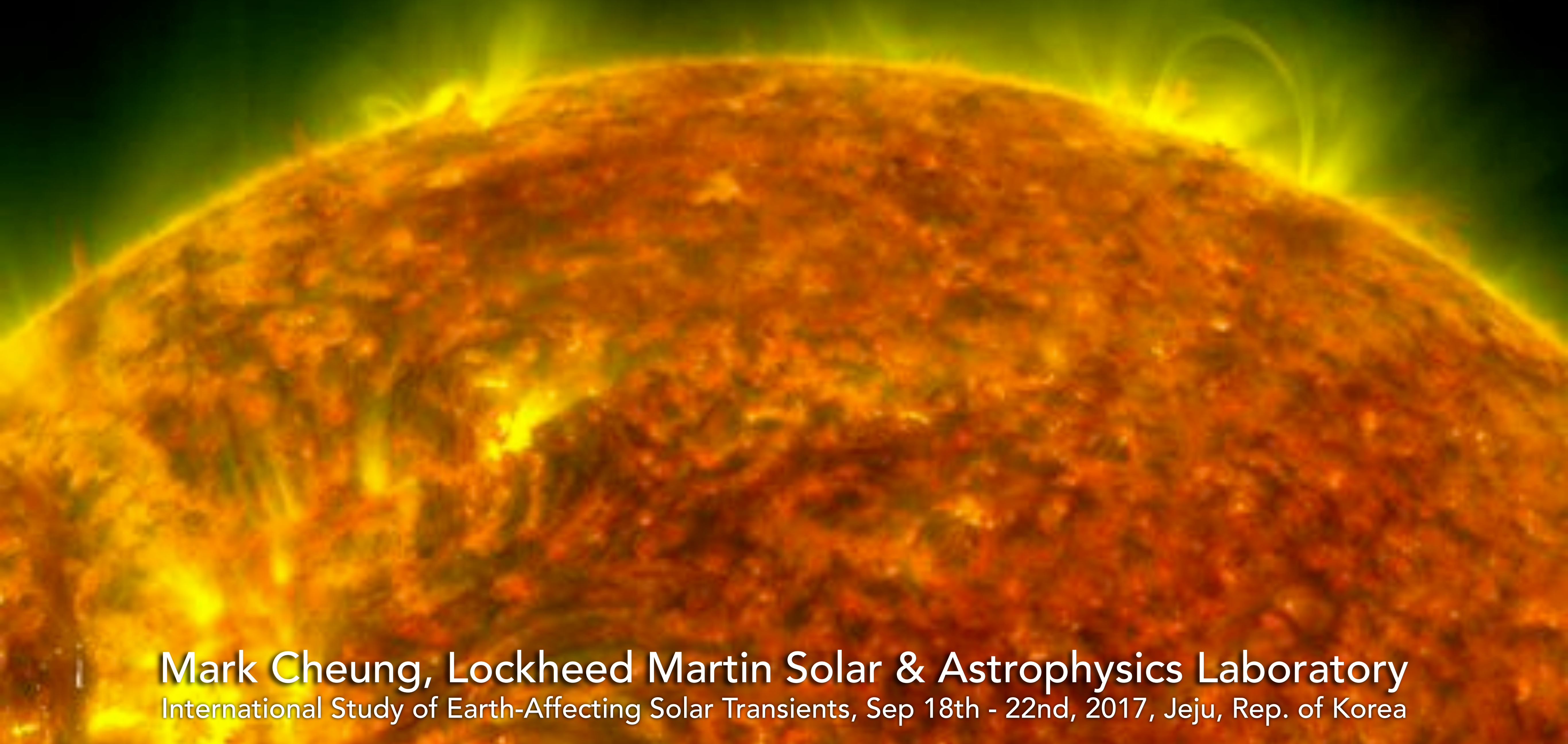
Data-Driven Evolving Models of the Solar Corona



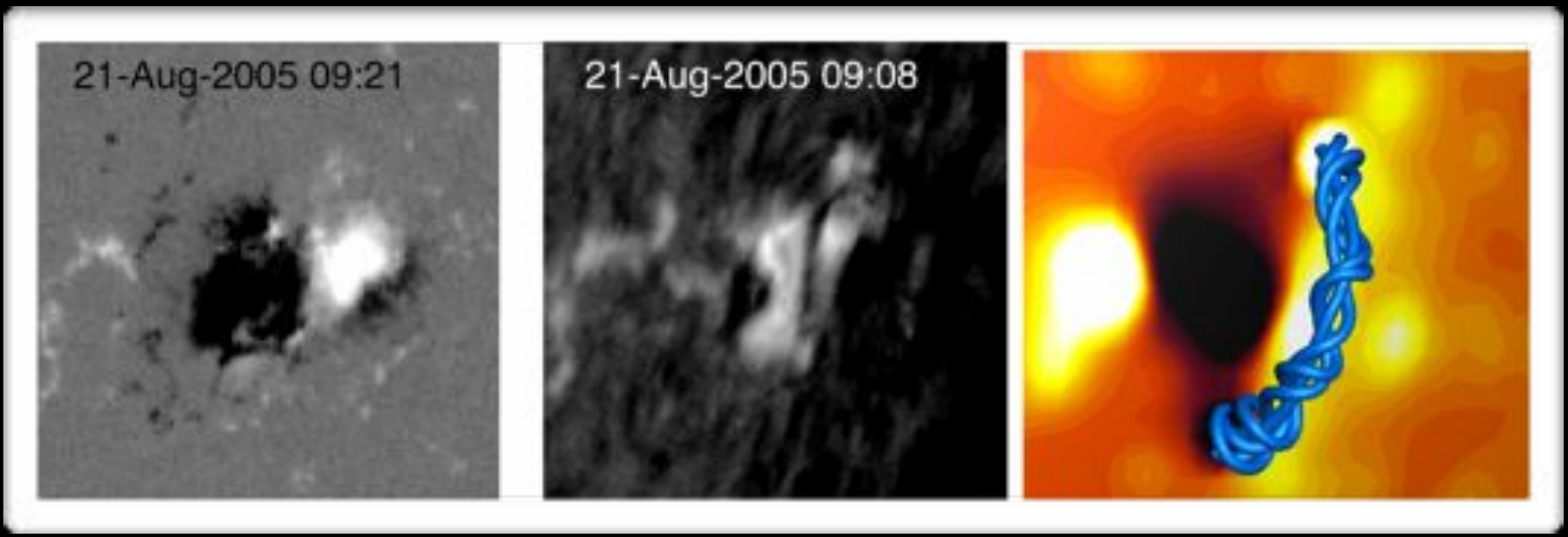
Mark Cheung, Lockheed Martin Solar & Astrophysics Laboratory

International Study of Earth-Affecting Solar Transients, Sep 18th - 22nd, 2017, Jeju, Rep. of Korea

Opportunities: Data + Modeling

- Data-inspired Models: Simplified setups to mimic observed scenarios
- Data-Constrained Models: Time-independent models satisfying observations at an instant in time
- Data-Driven Models: Time-dependent models evolved in response to evolving boundary conditions

Examples of Data-inspired Models

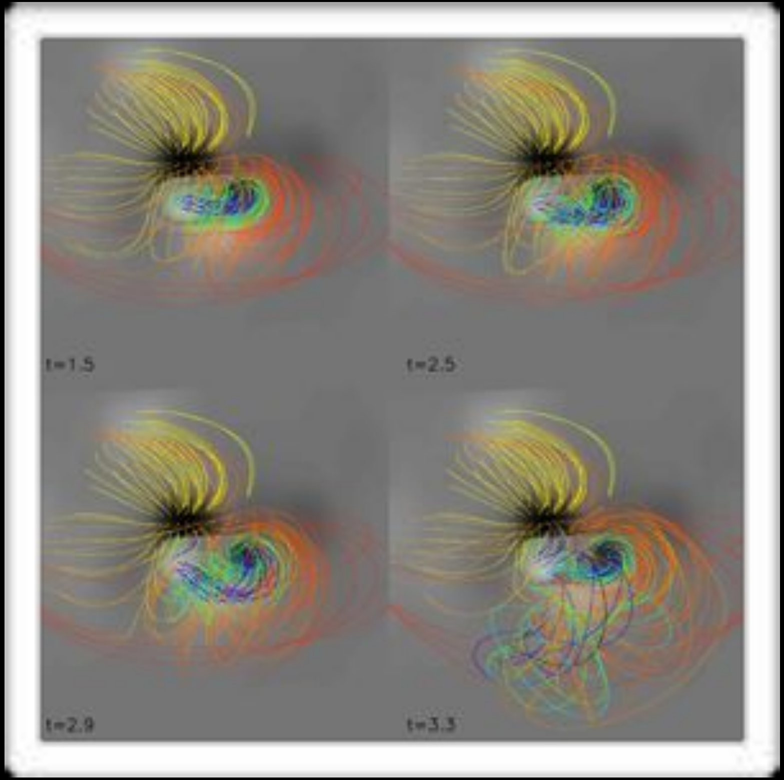


Left: Lugaz et al. (2011, ApJ)

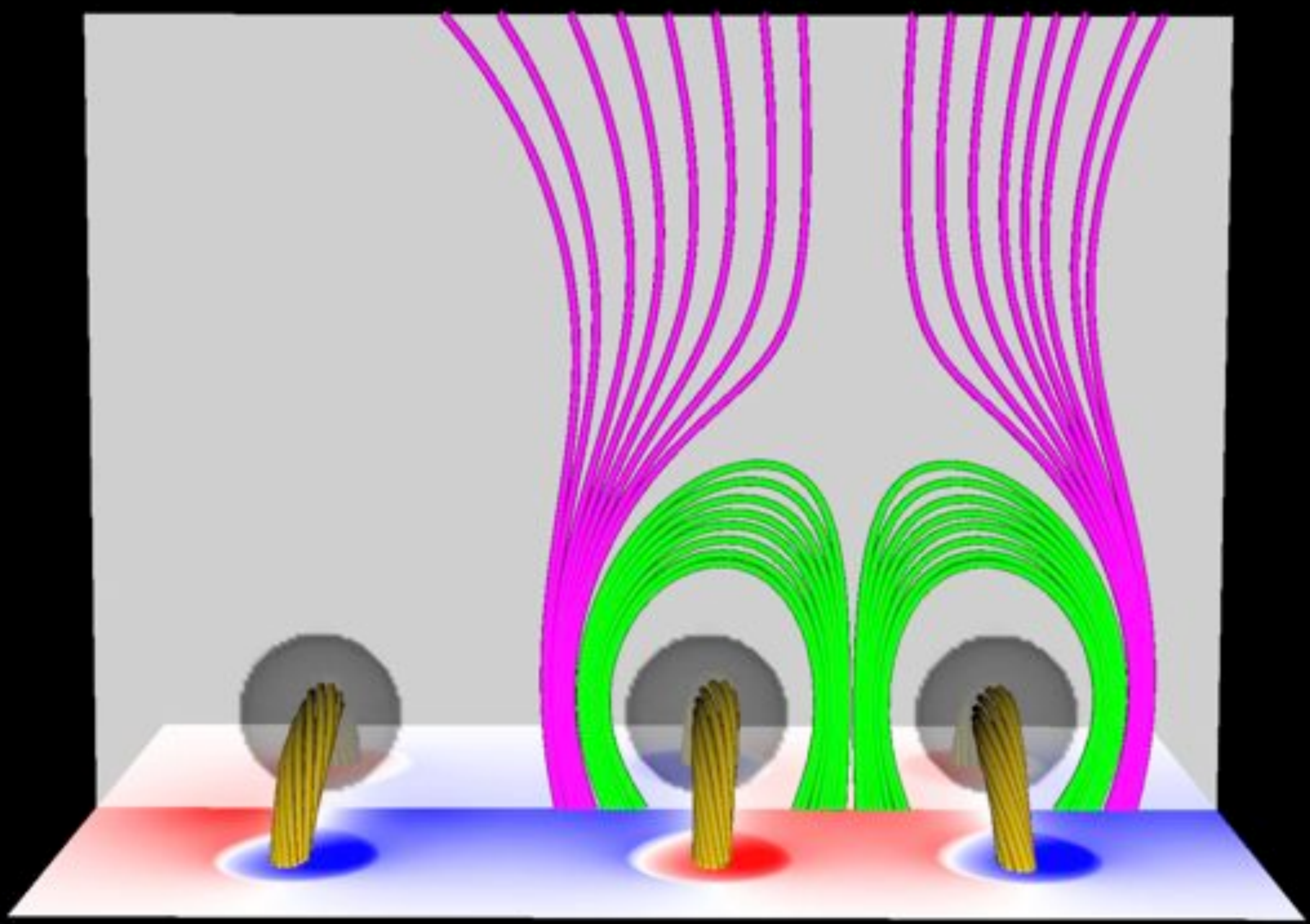
- Idealized flux rope inserted into background field extrapolated from a synoptic magnetogram.
- MHD evolution of the non-force-free initial condition leads to a CME

Right: Fan (2011, ApJ)

- Smoothed MDI magnetogram of AR 10930 so that B=3 kG -> 200 G
- A twisted flux rope was emerged into the pre-existing sunspot. The interaction between the two magnetic systems leads to an eruption

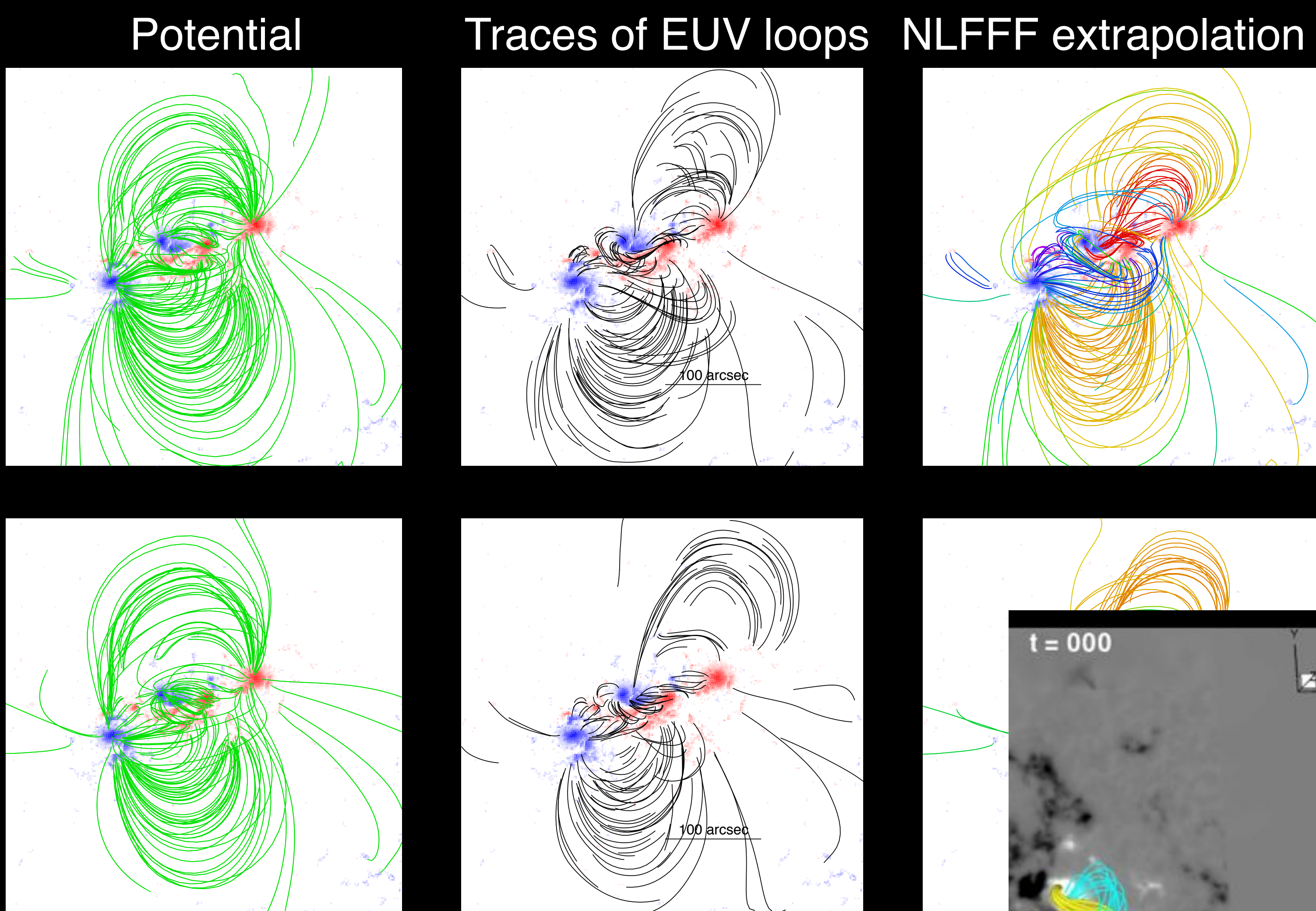


Examples of Data-inspired Models

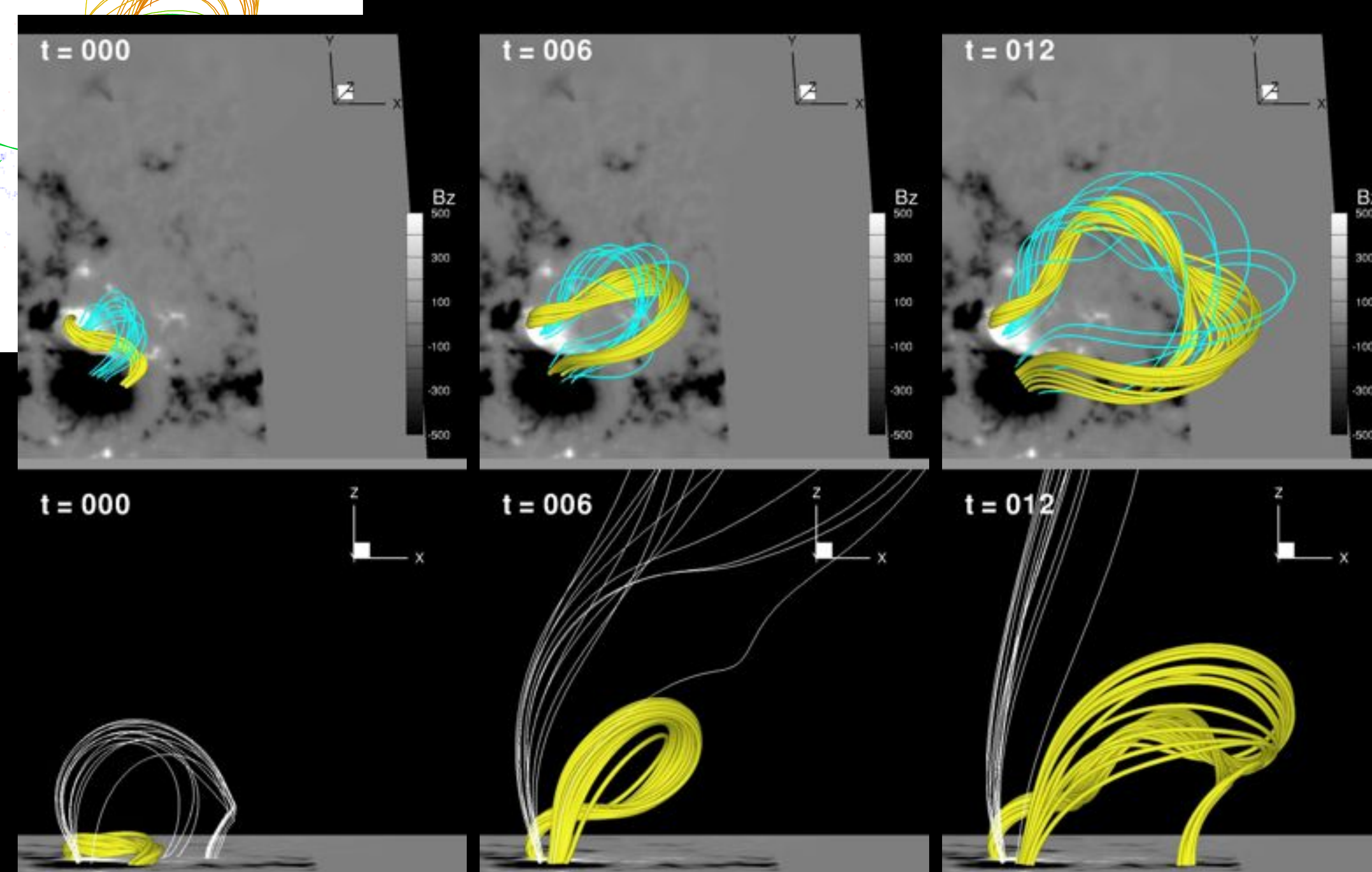


Torok et al. (2011, ApJL): MHD model of sympathetic eruptions inspired by Aug 1st 2010 events

Examples of Data-Constrained Models

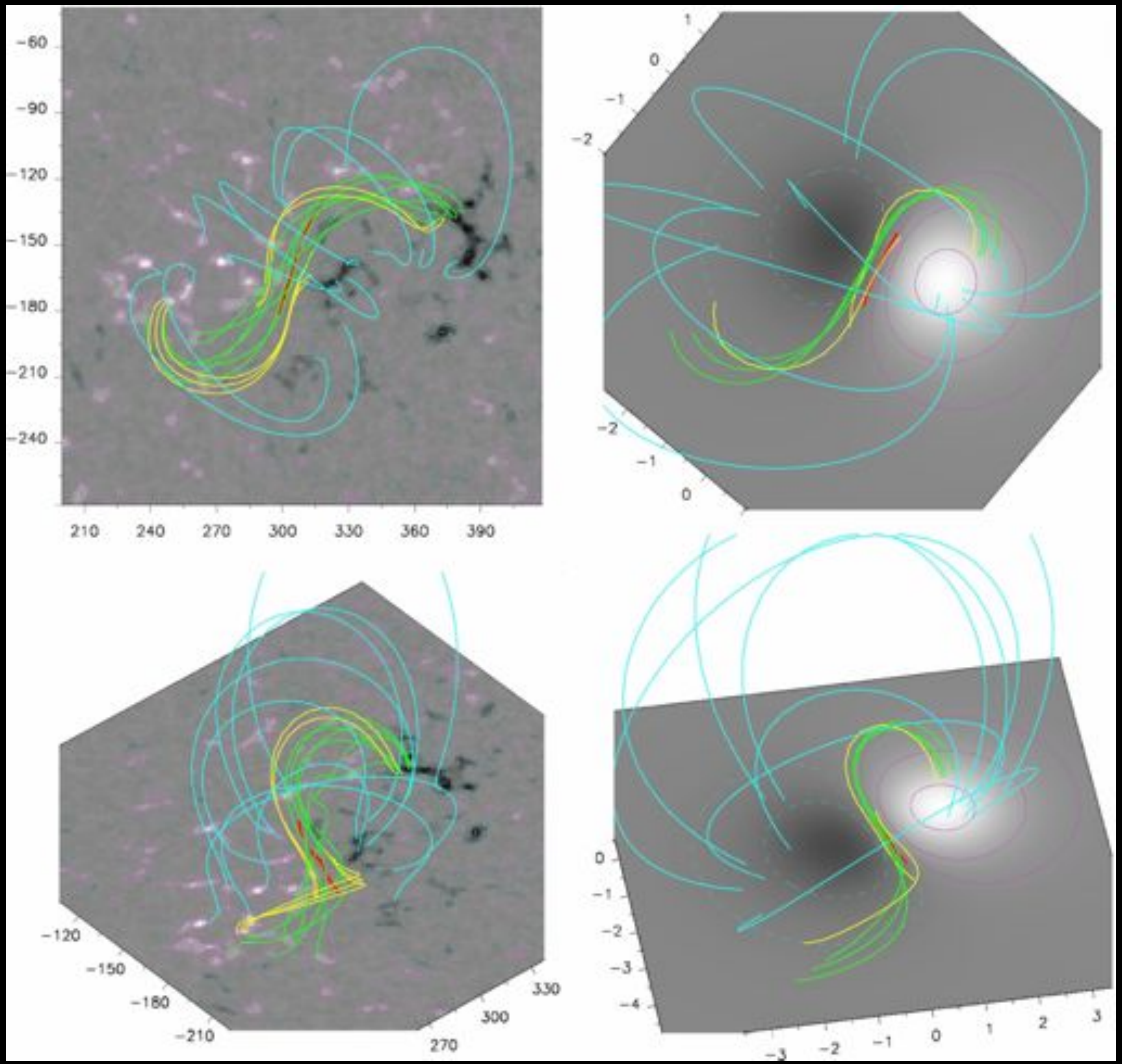


Left: Malanushenko et al. (2014): Use line-of-sight B and EUV loops to constrain NLFFF field (as opposed to using vector magnetograms).



Right: Jiang et al. (2013): Use vector magnetogram for NLFFF extrapolation, then feed the model field into an MHD code. This leads to an eruption. NB: The vector B at the bottom boundary is fixed in time in the MHD model.

Examples of Data-Constrained Models



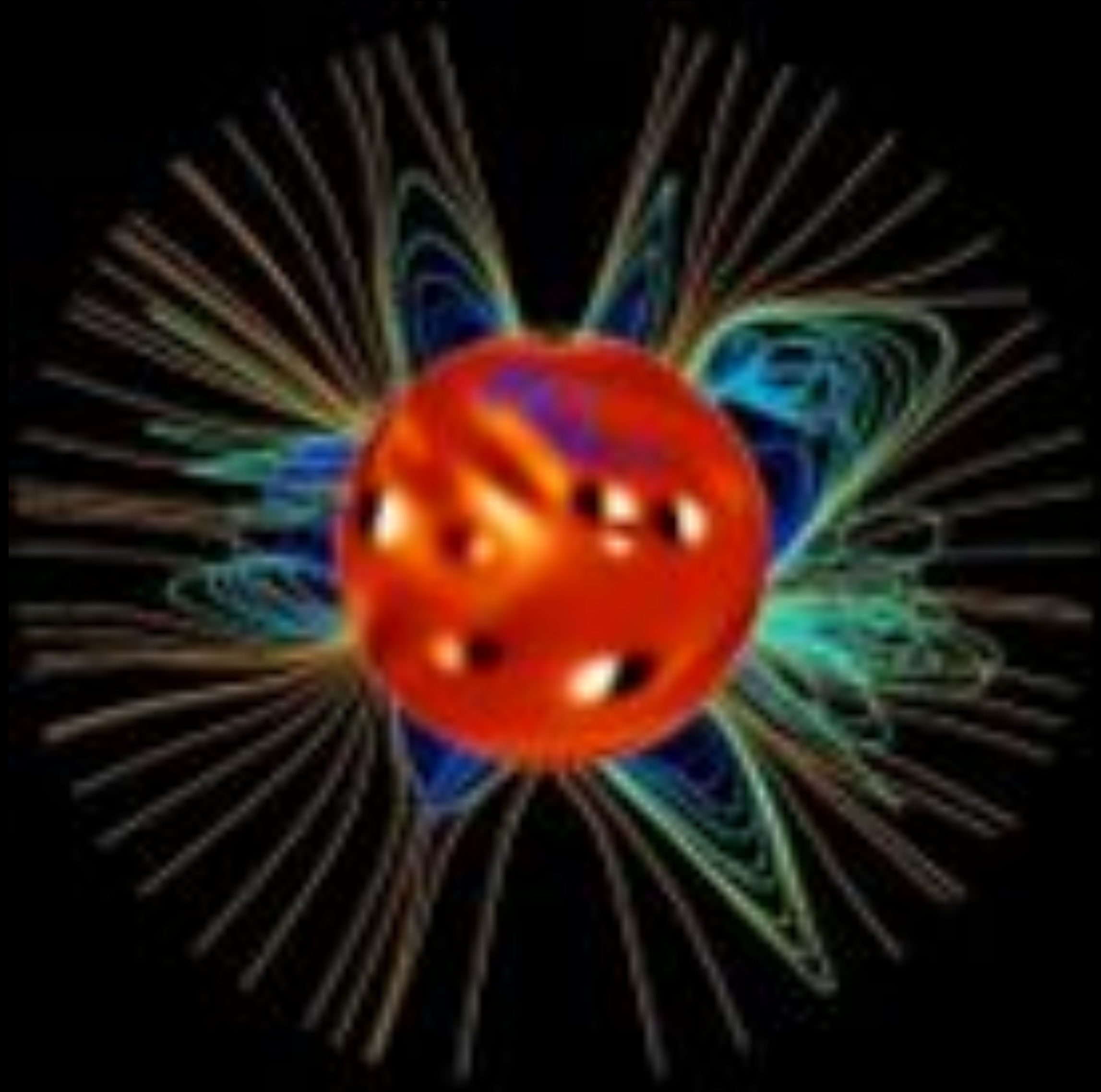
Flux rope insertion (data-constrained magnetofrictional model)

MHD model (data-inspired)

Savcheva et al. (2012): Comparison of sigmoid models shows consistent magnetic topologies between NLFFF and MHD models of sigmoids.

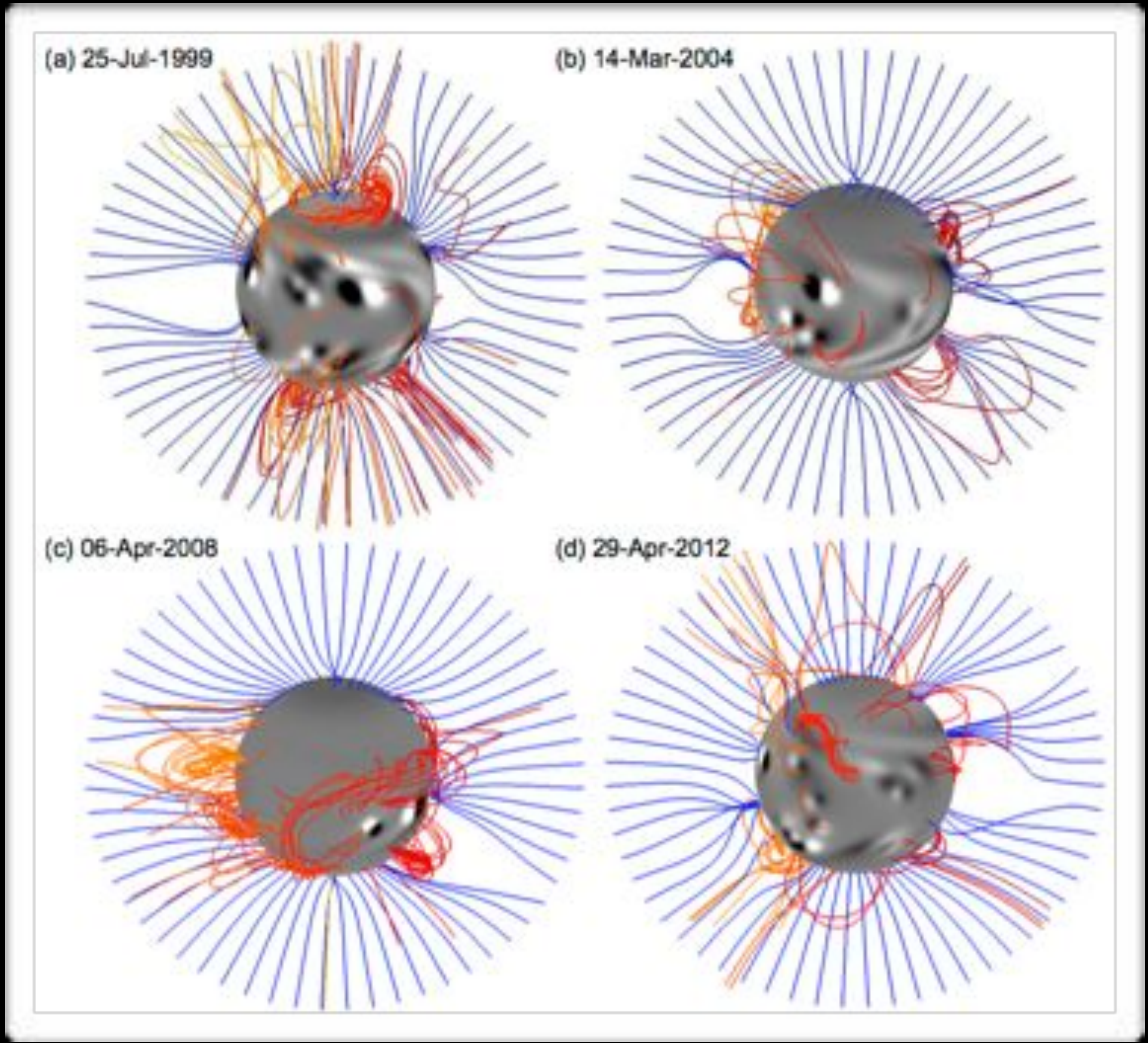
Data-Driven Models

- Van Ballegooijen, Priest & Mackay (2000)
  - – Solve induction equation with velocity proportional to Lorentz force:
  - –Yeates, Mackay & Van Ballegooijen (2008)
  - –Global magnetofrictional model of coronal field in response to observed changes in photospheric field, including
    - •Differential rotation, meridional circulation
    - •Flux dispersal and cancellation
    - •Appearance of AR-scale, twisted bipoles
  - –Correctly reproduces filament chirality and location
  - –Memory of corona ~ 6 weeks to a few months



Yeates, Mackay & Van Ballegooijen 2008
See also Yeates 2013

Data-Driven Models



Data-driven models have time-dependent boundary conditions. The solar atmosphere / 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

<u>These models have memory.</u>

Above: Non-potential models of the global solar coronal field from 1996 to 2012 (Yeates, 2014, Sol Phys, 289, 631). In this model, the data-driving is performed by emerging idealized 3D bipoles with magnetic flux contents, tilt angles and locations commensurate with active regions detected in NSO/Kitt Peak synoptic maps* (longitudinal B flux density near central meridian constructed over Carrington rotations). *We'll get back to this.

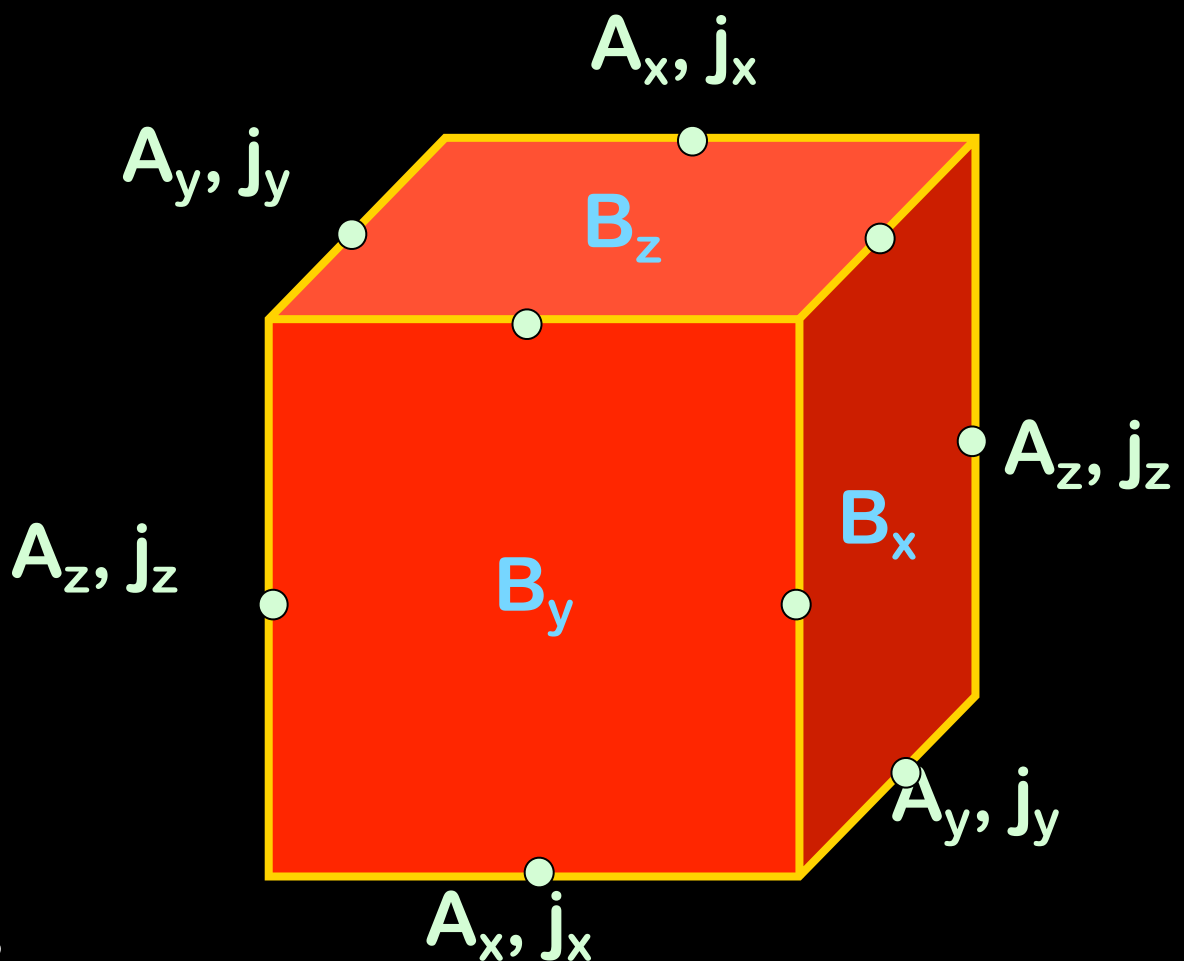
Magnetofriction

- Balance of Lorentz force and fictitious frictional force (Yang, Sturrock & Antiochos, 1986; Craig & Sneyd 1986)
  - Plasma velocity proportional to Lorentz force: $v = \nu^{-1}$ jxB where ν 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).
- Valori, Kliem & Fuhrmann 2007 used magnetofriction for non-linear force-free field (NLFFF) extrapolation using a single vector magnetogram.
- Our approach is different from NLFFF extrapolation. Instead of a single magnetogram, we use temporal sequence of magnetograms to advance the model forward in time.

Magnetofriction: Implementation

- Based of method described in Van Ballegooijen, Priest & Mackay (2000)
- Induction Equation for ***A***
- Staggered Cartesian grid
  - A_i, j_i at midpoint of cell edges along i-th direction
  - $\boldsymbol{B_i}$ at center of cell face with normal vector in i-th direction
- Spatial derivatives: 2nd order finite difference
- Magnetic diffusivity: either anomalous or slope limiter.
- Time integration: Explicit 2nd order
- MPI parallelized by domain decomposition
- See Cheung & DeRosa (2012) for details

$$\frac{\partial \vec{A}}{\partial t} = \vec{v} \times \vec{B} - \eta \vec{j}$$



Coronal Global Evolutionary Model (CGEM)

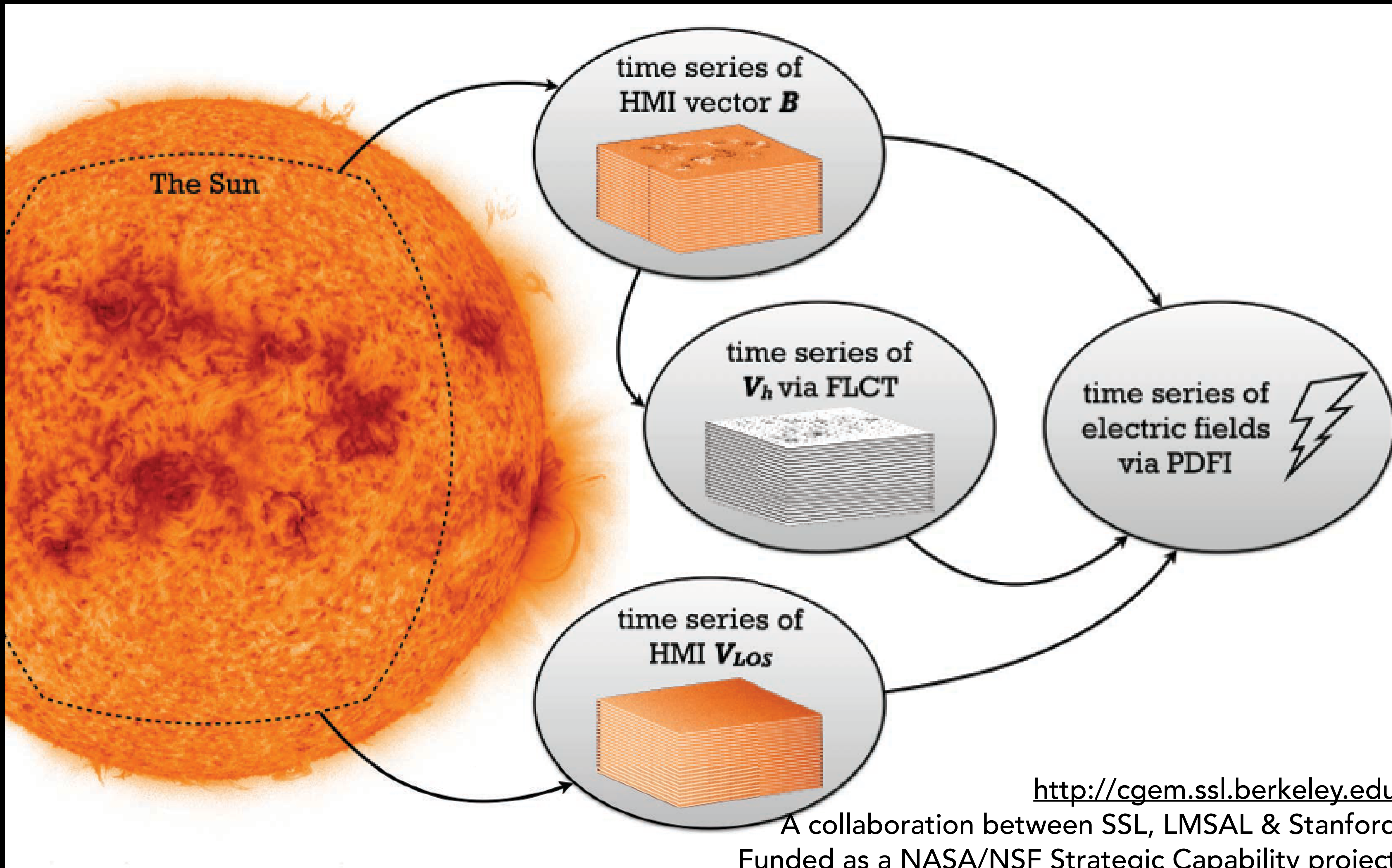
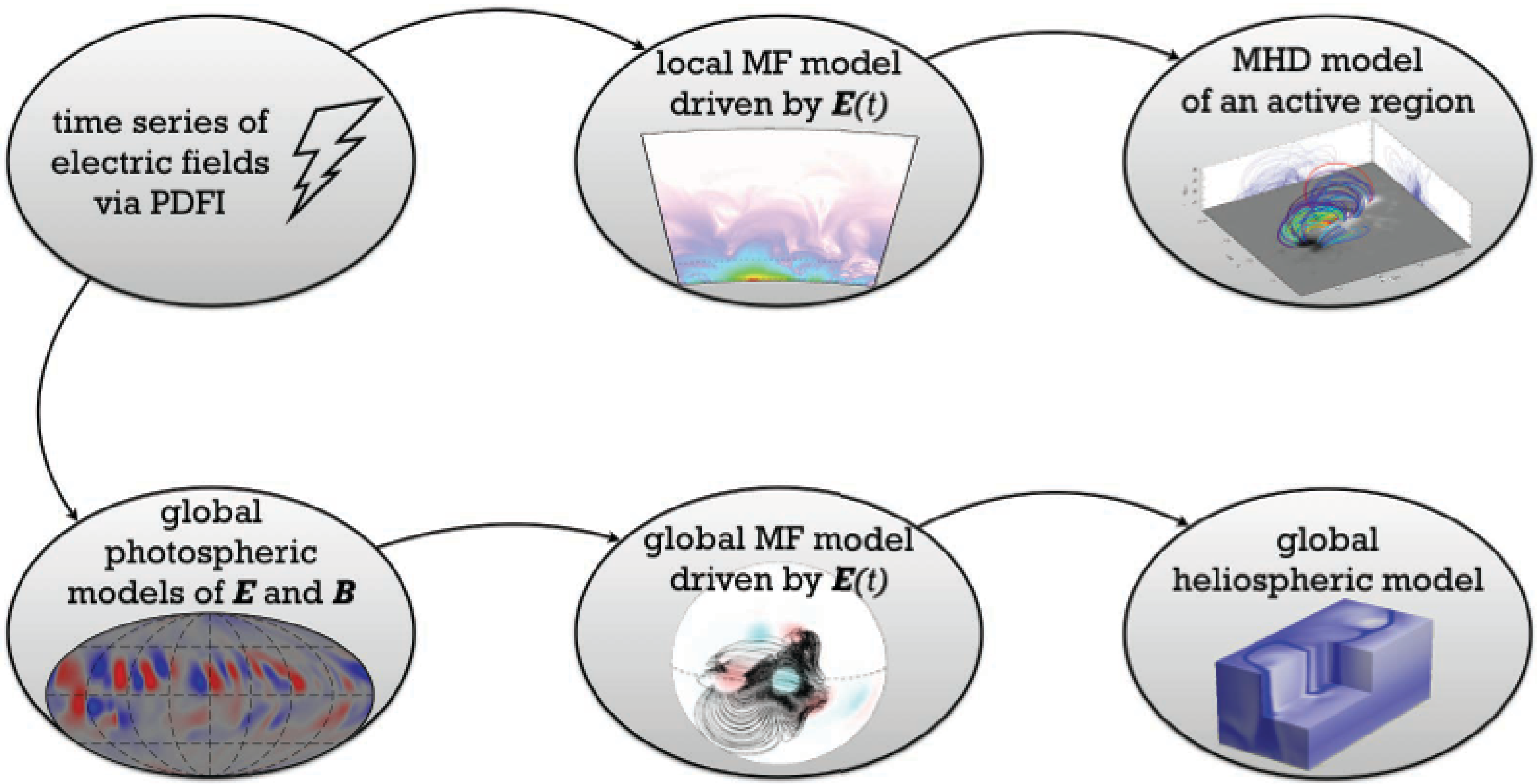


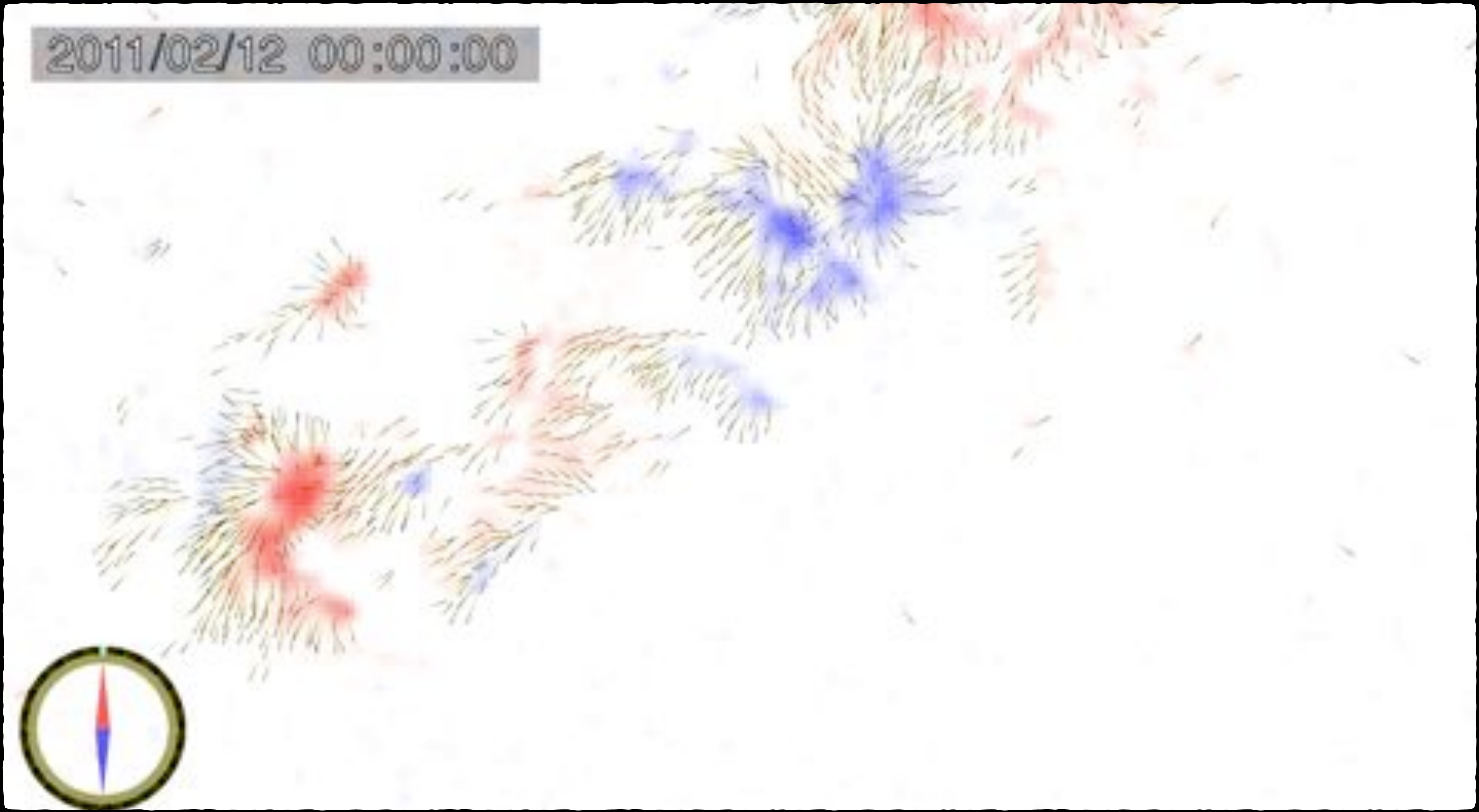
Figure 1 – Workflow diagram showing how the D4 deliverables feed enhanced data products (corrected HMI vector magnetograms, calibrated Doppler maps, and local correlation tracking velocities) into the D3 deliverable (electric field inversion software) to produce a time series of photospheric electric field maps. The quantity B is the photospheric magnetic field, V_{los} is the Doppler velocity, and V_h is the horizontal velocity at the photosphere.

Coronal Global Evolutionary Model (CGEM)

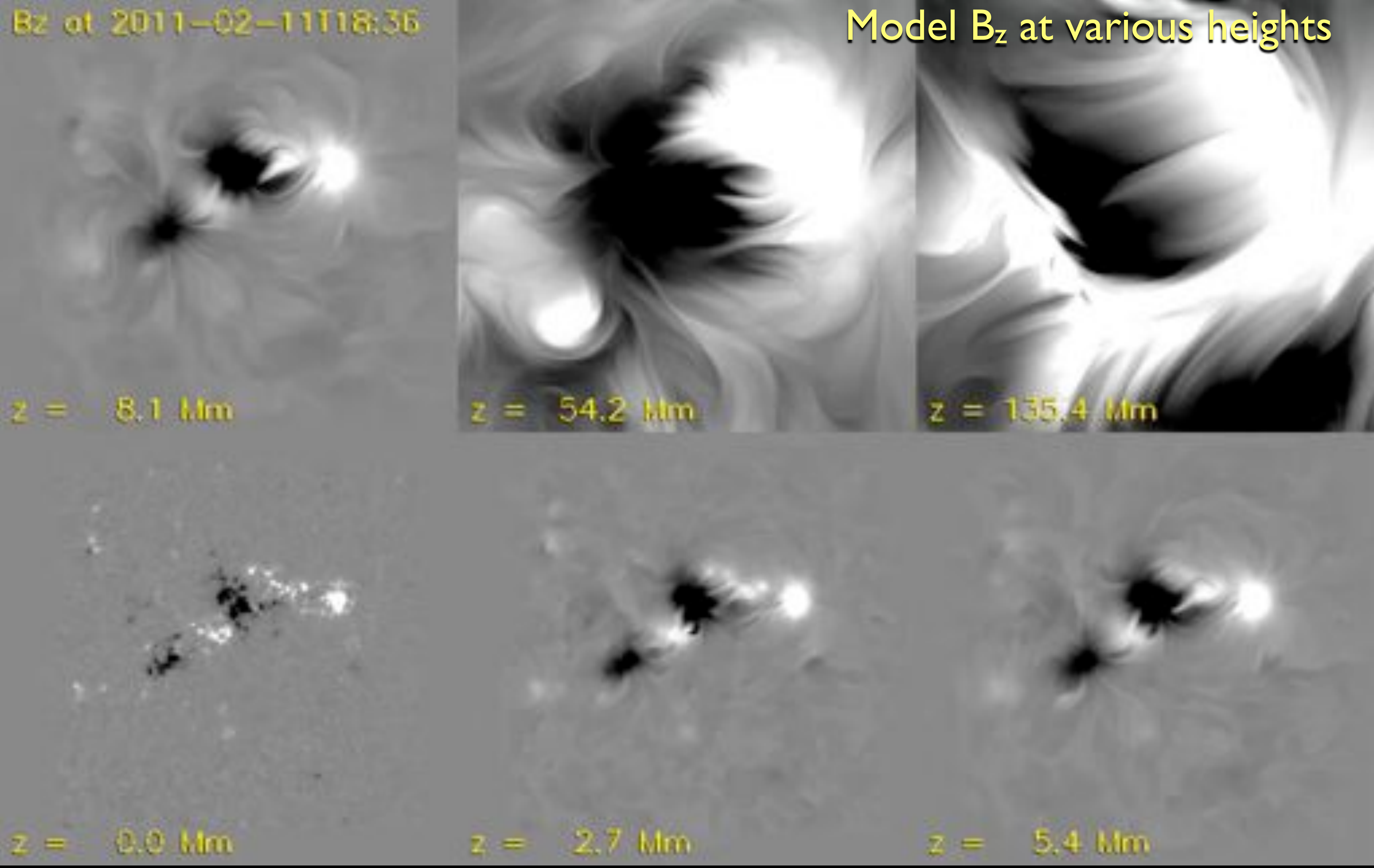


http://cgem.ssl.berkeley.edu
A collaboration between SSL, LMSAL & Stanford
Funded as a NASA/NSF Strategic Capability project

Figure 2 – The electric field maps can be used to drive local MF models above active regions (D1), and/or be ingested into global flux transport models (D2), which are used to drive the global MF model (D1). The output from MF models can then be used as the starting point for MHD simulations in active regions (D5), or global coronal and heliospheric MHD models (D6).

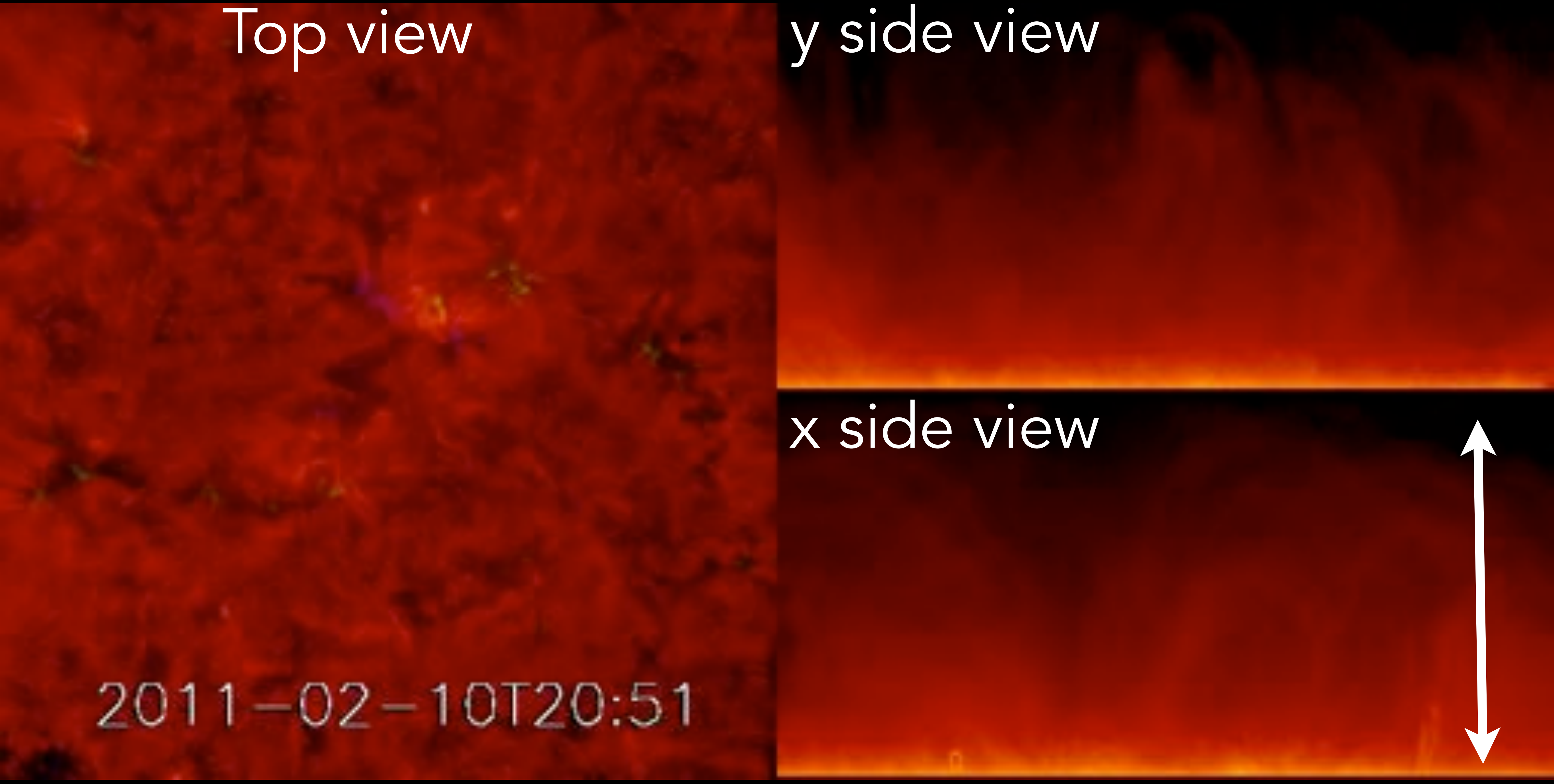


HMI vector magnetogram sequence of NOAA AR 11158
Credit: Keiji Hayashi (HMI)



Cartesian data-driven model MF of NOAA AR 11158

Visualization of Field Lines

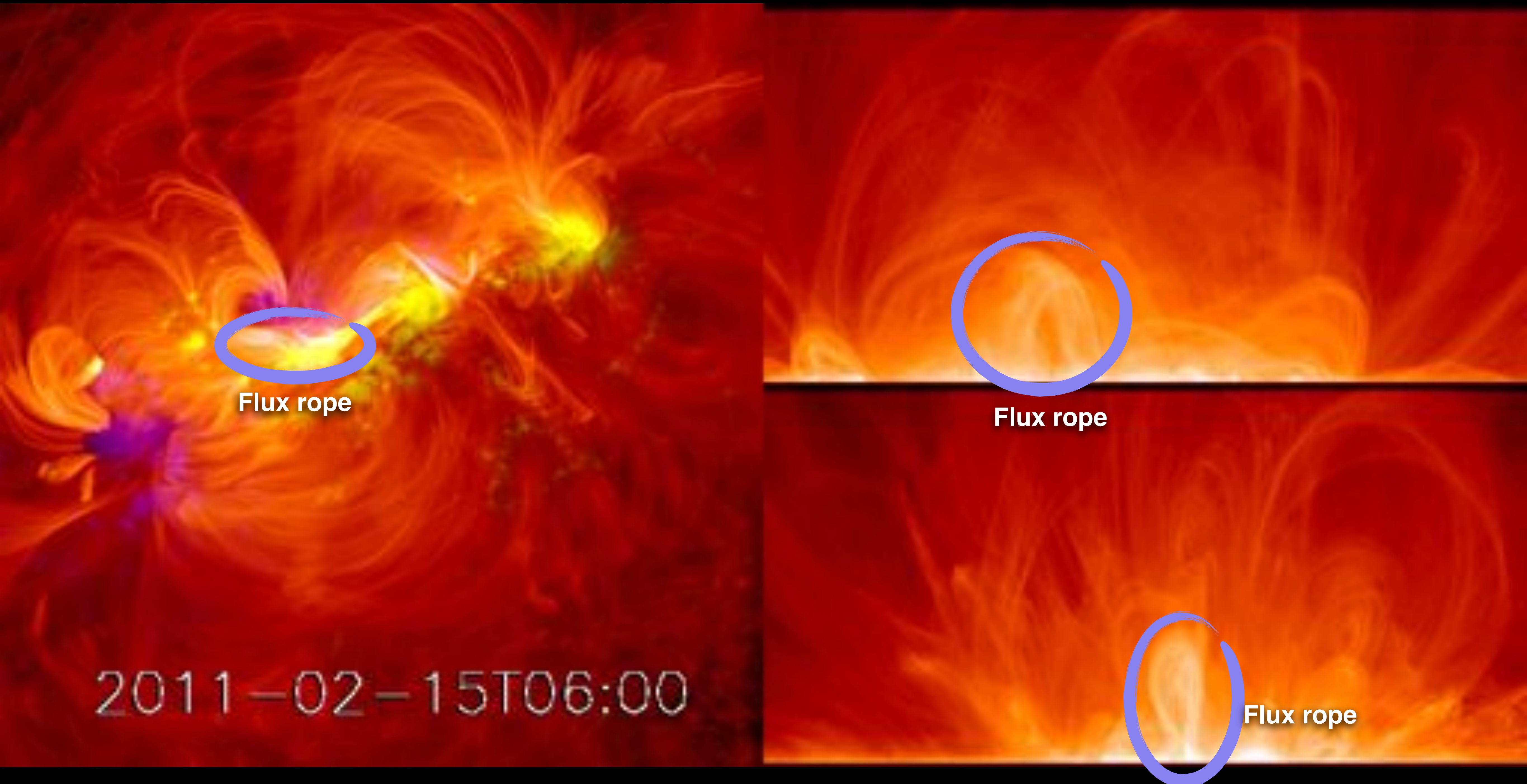


Only the lowest 66 Mm shown: Not one-to-one aspect ratio.

Orange ~ $\int_{los} \langle j^2 \rangle dl$, *where* $\langle j^2 \rangle$ *is fieldline-averaged* j^2

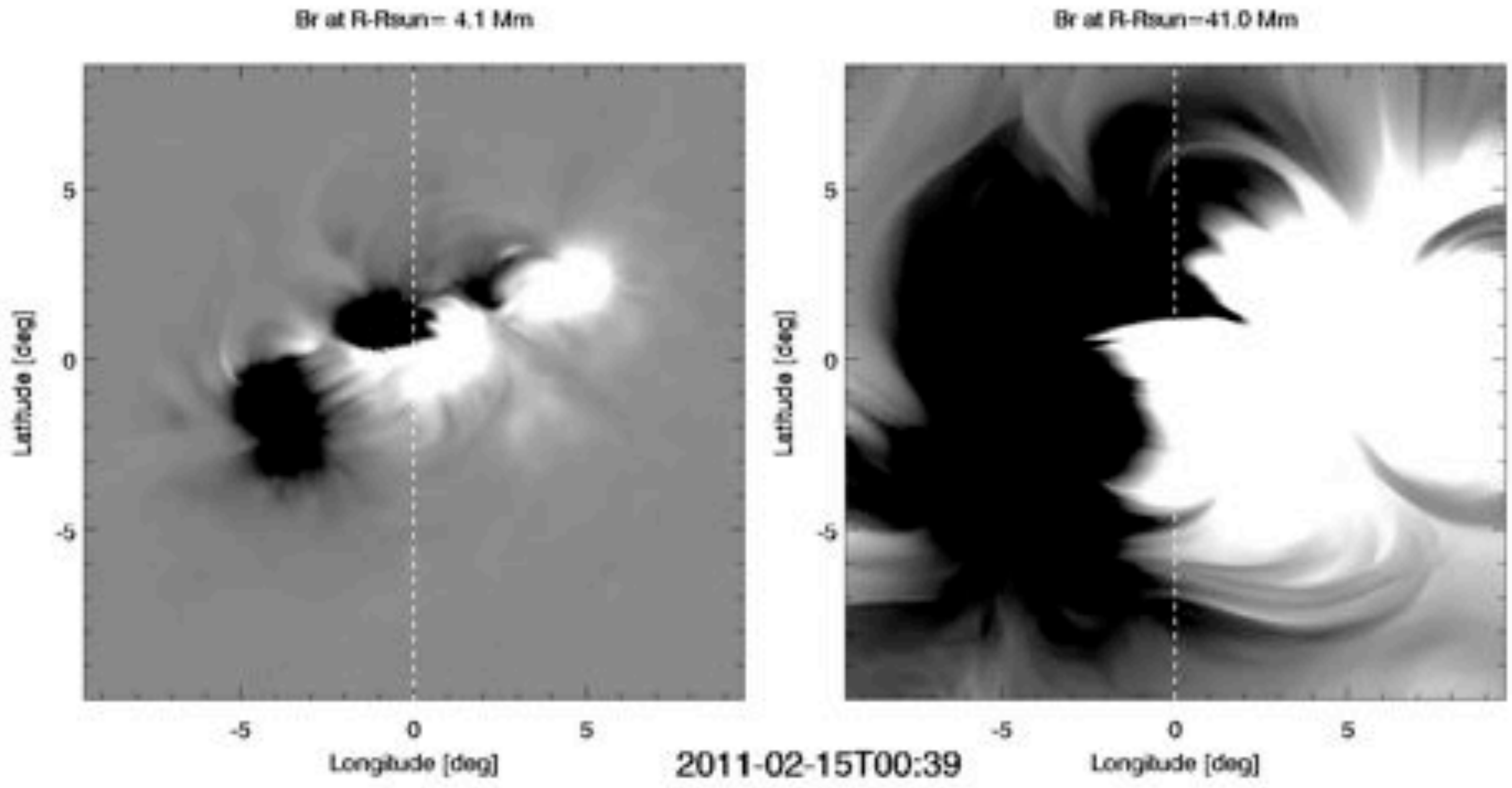
Positive polarity B_r

Negative polarity B_r

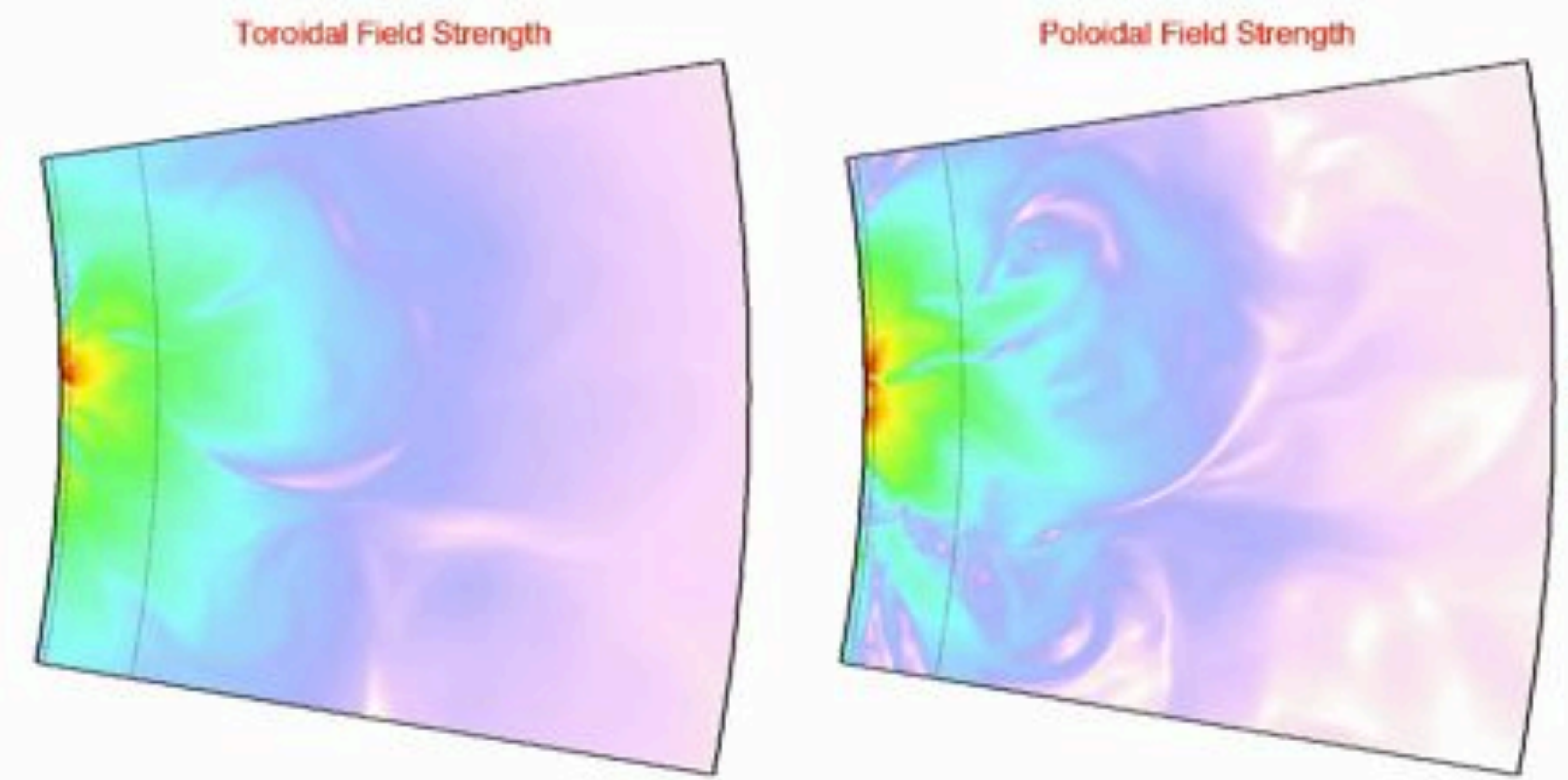


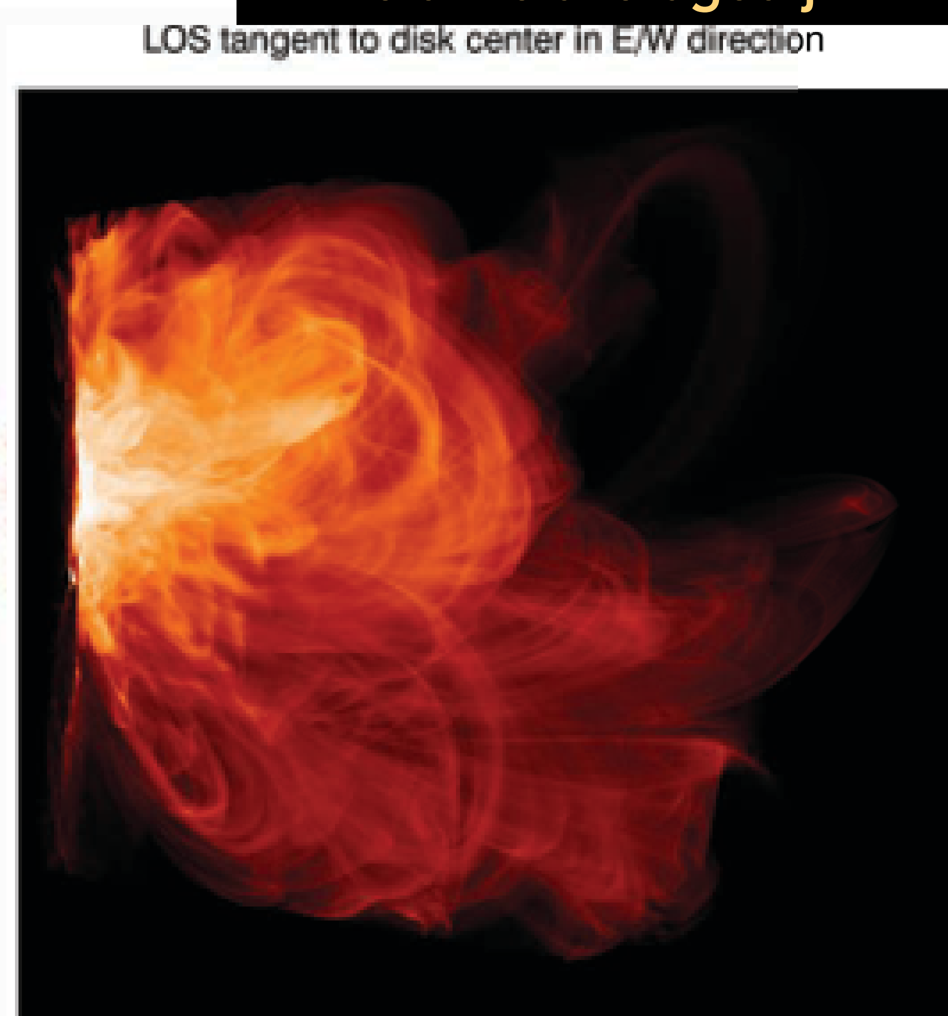
- There is no impulsive eruption at the time of the observed X-flare. However, moments before this time, a current-carrying flux rope is observed to form and is eventually ejected, though the rise time is on the order of hours.
- An extension of this work is to use the destabilized configuration as the initial condition for an MHD simulation.

Data-Driven NOAA AR 11158 model in a spherical wedge

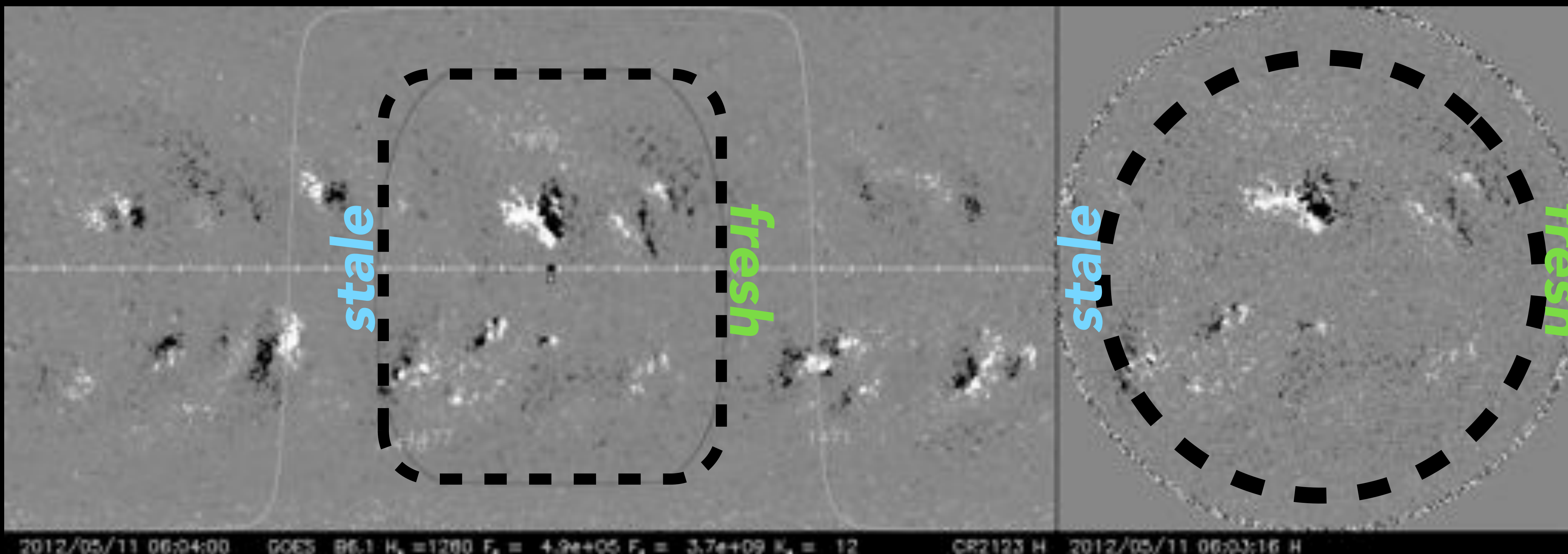


Orange ~ $\int_{los} \langle j^2 \rangle dl$, where $\langle j^2 \rangle$ is fieldline-averaged j^2





Solar Rotation Unrolls the Solar Magnetic Landscape



Above: SDO/HMI magnetogram feeding Schrijver's 'atomic' Surface Flux Transport Model

The Sun rotates, letting us progressively update the magnetic map.

Magnetic patterns off the west (right) limb are ***fresh***.

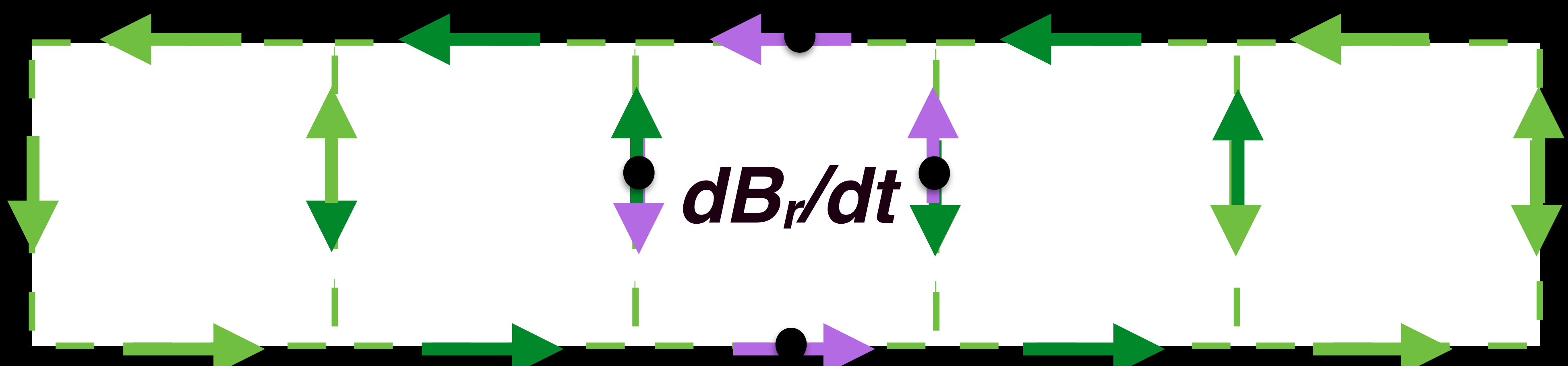
Magnetic patterns off the east (left) limb are ***stale***.

Large flux imbalances can occur when ARs rotate onto the disk.

Constrained Surface Flux Transport

- Magnetohydrodynamics (MHD) models need $\boldsymbol{E_t}$ at the bottom boundary.
- Think of a SFT model that operates with electric fields ***E***. Instead of Eq. (1) on the previous slide, just use **Faraday's Induction Equation**:

$$dB_r/dt = -curl\ \mathbf{E_t}$$



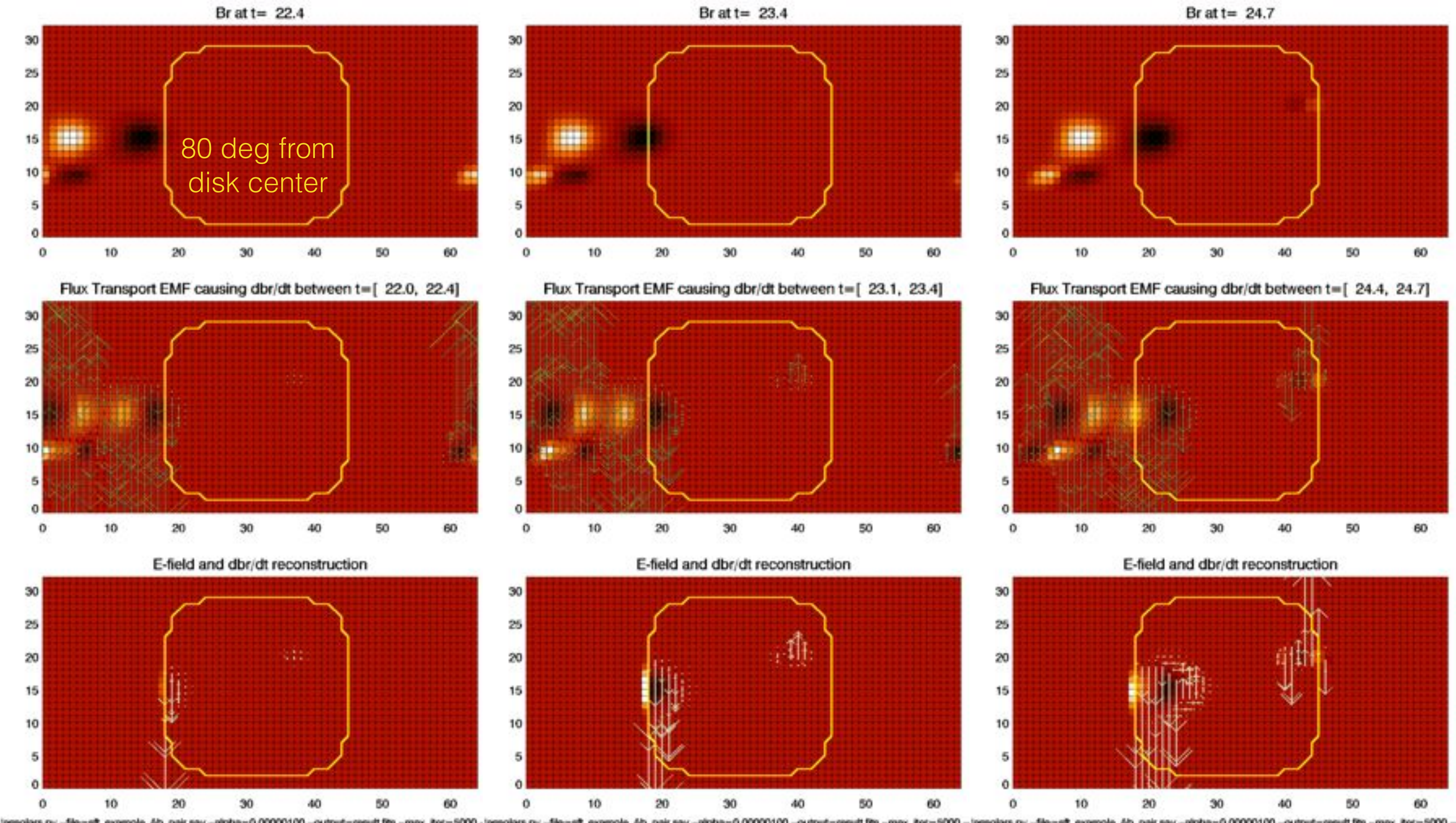
Calculate ***dB$_r$/dt*pixel area*** of each pixel as

- circulation of $\boldsymbol{E_t}$ about the pixel.

Example of a Constrained SFT Model

The above toy model treats differential rotation + AR emergence.

Dealing with incomplete dB_r coverage



E-field inversion (enforcing compactness of solution) using only the front-side dB_r.

NASA Frontier Development Lab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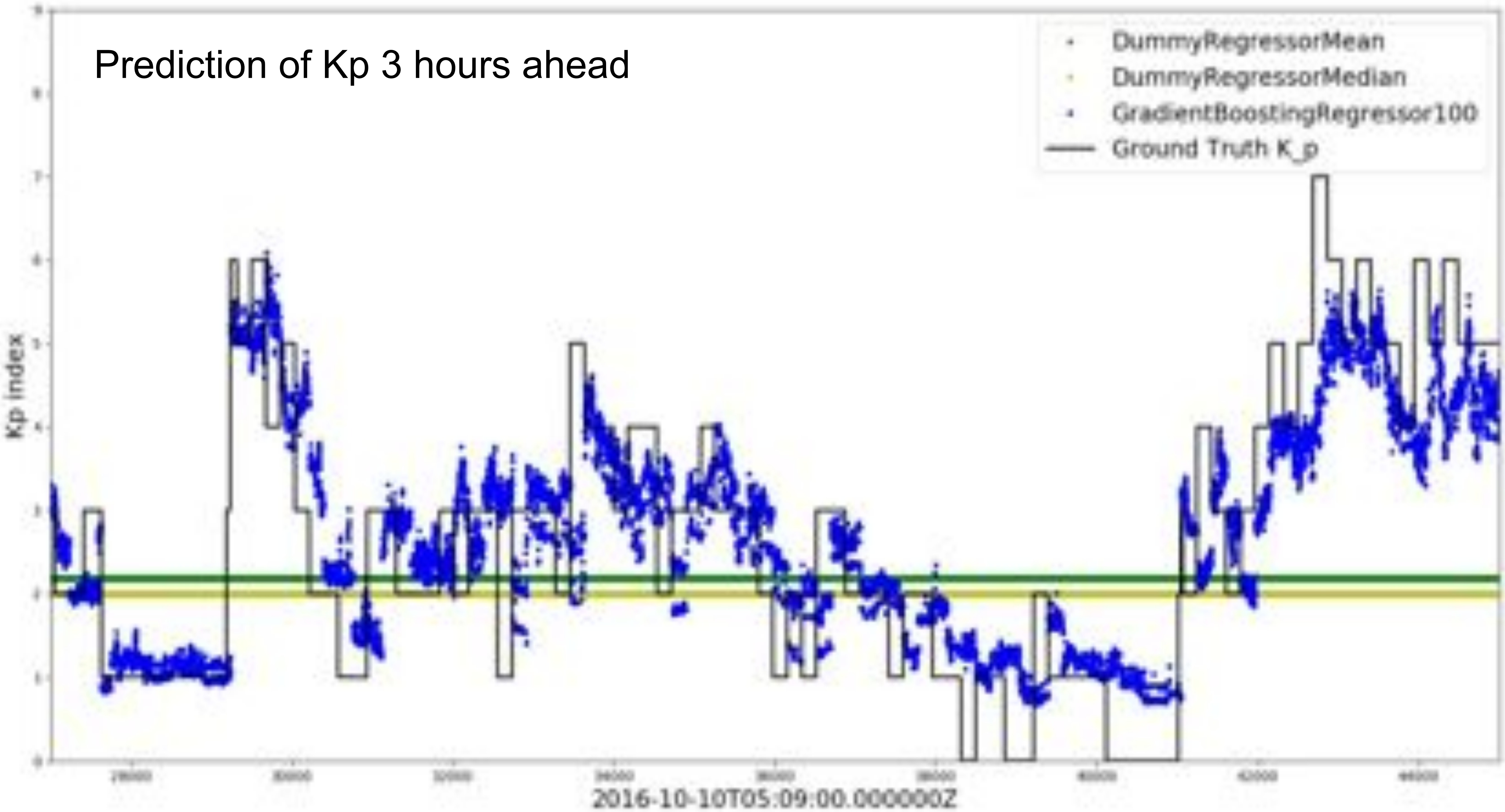
SPACE WEATHER: SOLAR TERRESTRIAL INTERACTIONS

MACHINE LEARNING

Project 1	Project 2	Open Source ML Frameworks
Recurrent Neural Nets (RNNs) (Geomag + Solar Wind)	**Ensemble** (Geomag + Solar Wind + Kp)	python
Long Short Term Memory (LSTM)	Gradient Boosting AdaBoosting Random Forest Gaussian Process Bagging Extra Trees	scikit learn Keras TensorFlow

GRADIENT BOOSTING RESULTS

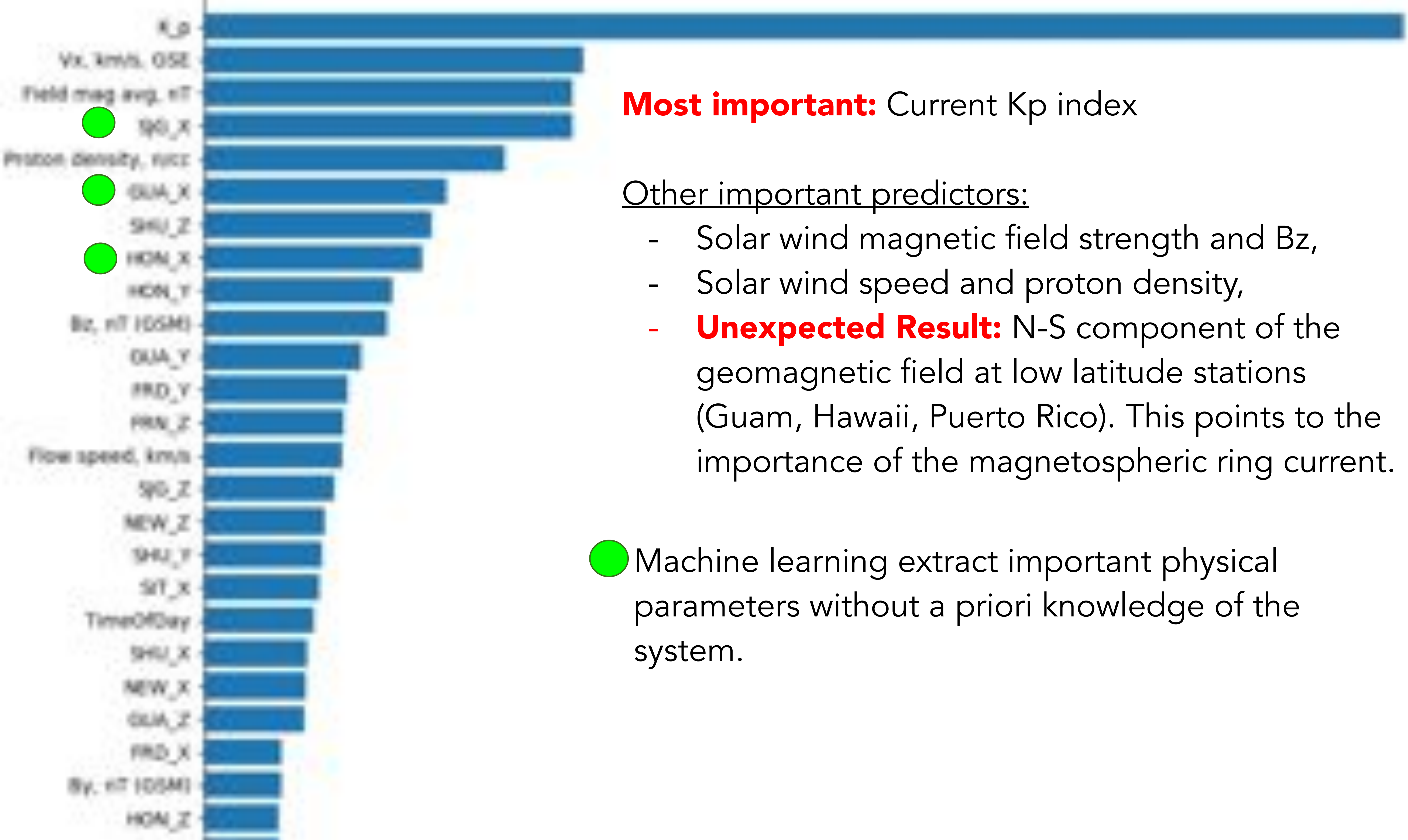


METRIC: MEAN SQUARED ERROR

ML method	1h ahead	3h ahead	6h ahead
Persist	0.007	0.020	0.025
Mean	0.046	0.046	0.046
Median	0.048	0.048	0.048
Gradient Boosting	0.007	0.015	0.021
Adaptive Boost	0.012	0.018	0.032
Extra Trees	0.009	0.021	0.027
Random Forest	0.015	0.015	0.026

FEATURE DISCOVERY

This plot shows the relative importance of the physical parameters for Kp prediction.



Most important: Current Kp index

<u>Other important predictors:</u>

- Solar wind magnetic field strength and Bz,
- Solar wind speed and proton density,
- **Unexpected Result:** N-S component of the geomagnetic field at low latitude stations (Guam, Hawaii, Puerto Rico). This points to the importance of the magnetospheric ring current.

Machine learning extract important physical parameters without a priori knowledge of the system.

Summary

- Magnetofriction is a data-driven model which allows us to track how the non-potential solar coronal field evolves over time-scales of hours to weeks.

- SDO/HMI vector magnetograms provide critical information about photospheric driving (e.g. homologous helical jet example). CGEM would not be possible with SoHO/MDI magnetograms and synoptic magnetograms (from MDI or from ground-based observatories).

- The spherical version of the MF code (adapted from the pre-existing Cartesian version) to be delivered to the CCMC. In addition, we expect to maintain some continuous runs close to the data (JSOC at Stanford and LMSAL). The 3D magnetic field configurations can serve as initial conditions for MHD codes (CGEM and external).

- Frontier Development Lab: **Attempt/preliminary results** on Kp index prediction. Please keep an eye out for call for applications for FDL 2018.