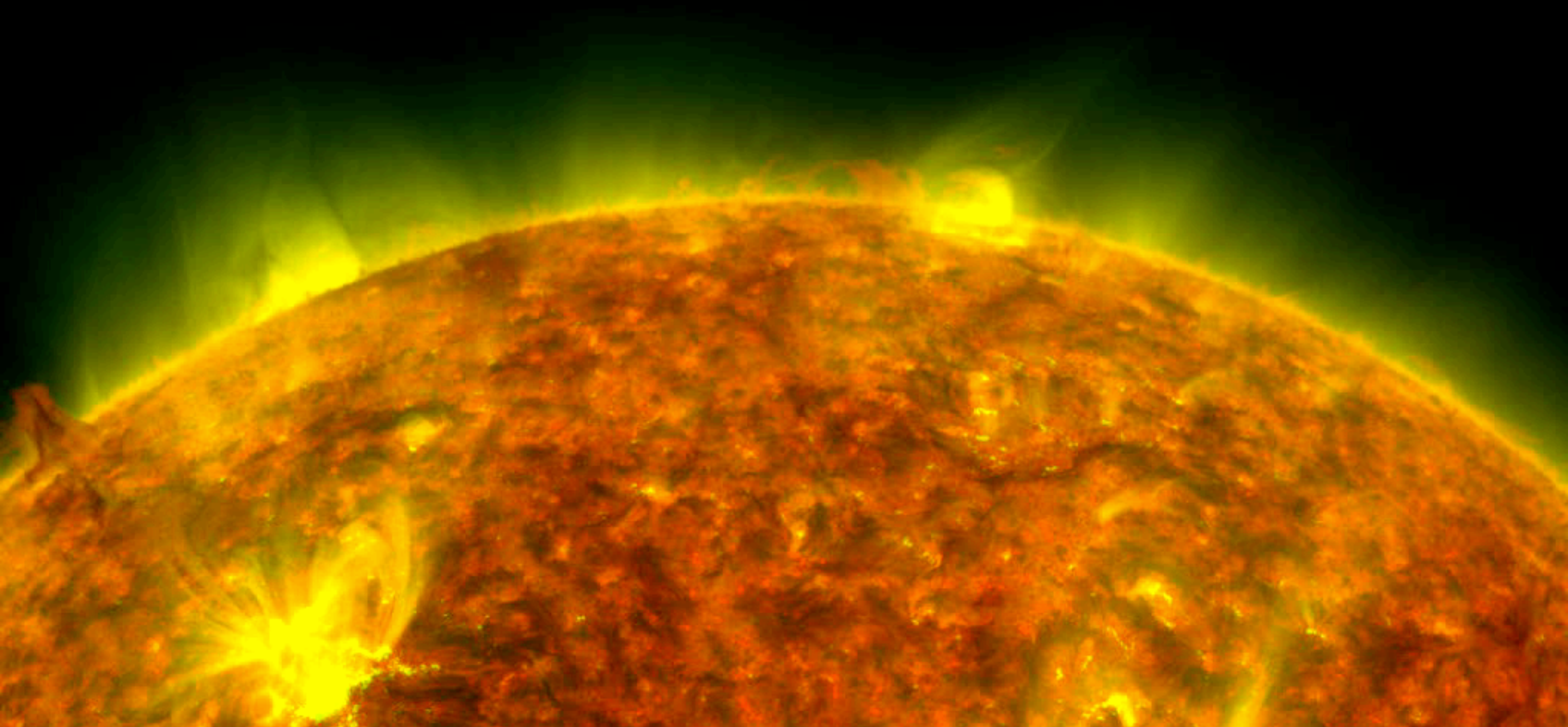
A Method for Data-Driven Global Models of the Solar Corona



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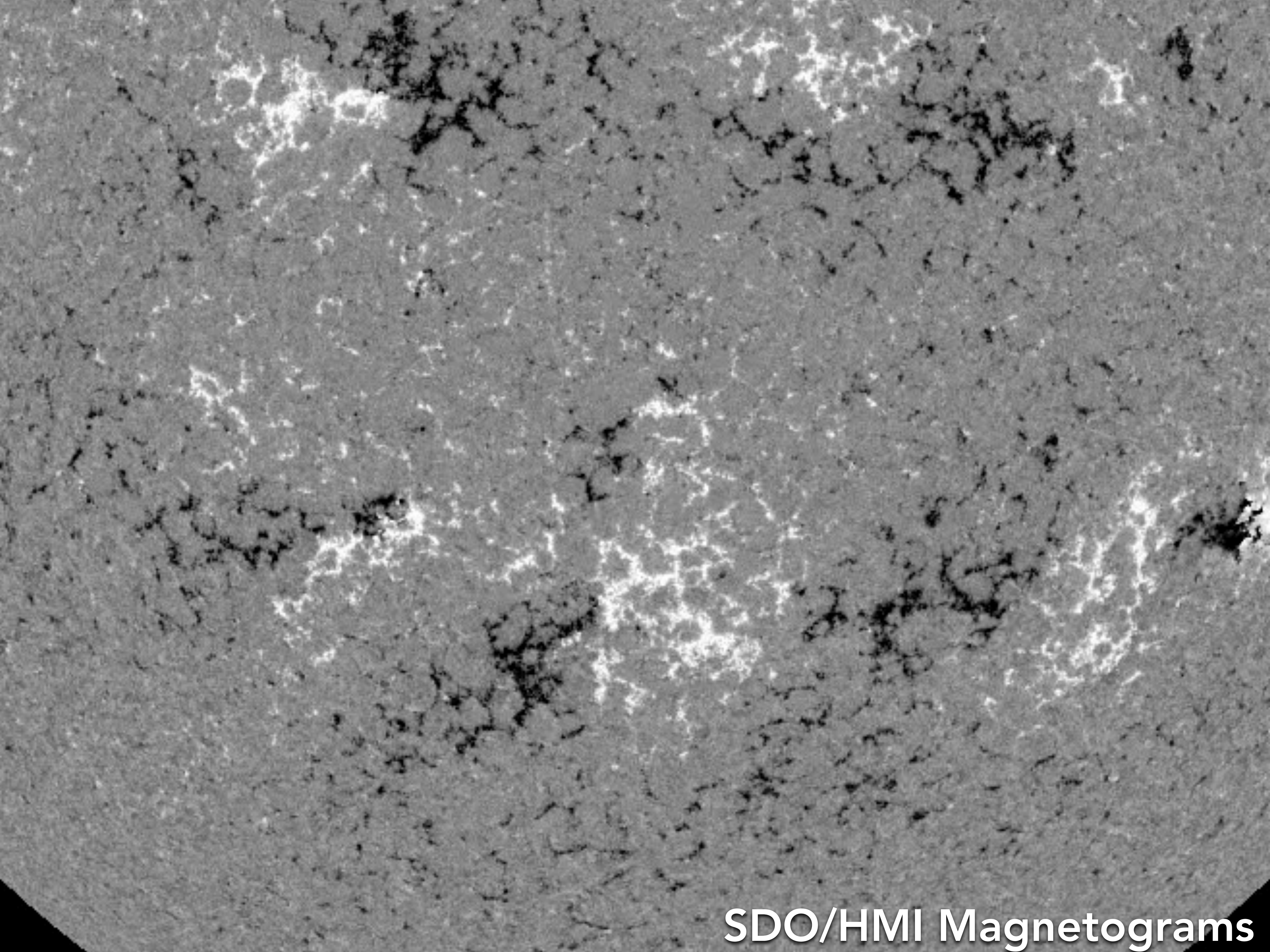
*CGEM is a NASA/NSF Strategic Capability Program

L5 in Tandem with L1 Workshop, London, UK, March 6th - 9th 2017


SDO/HMI Magnetograms

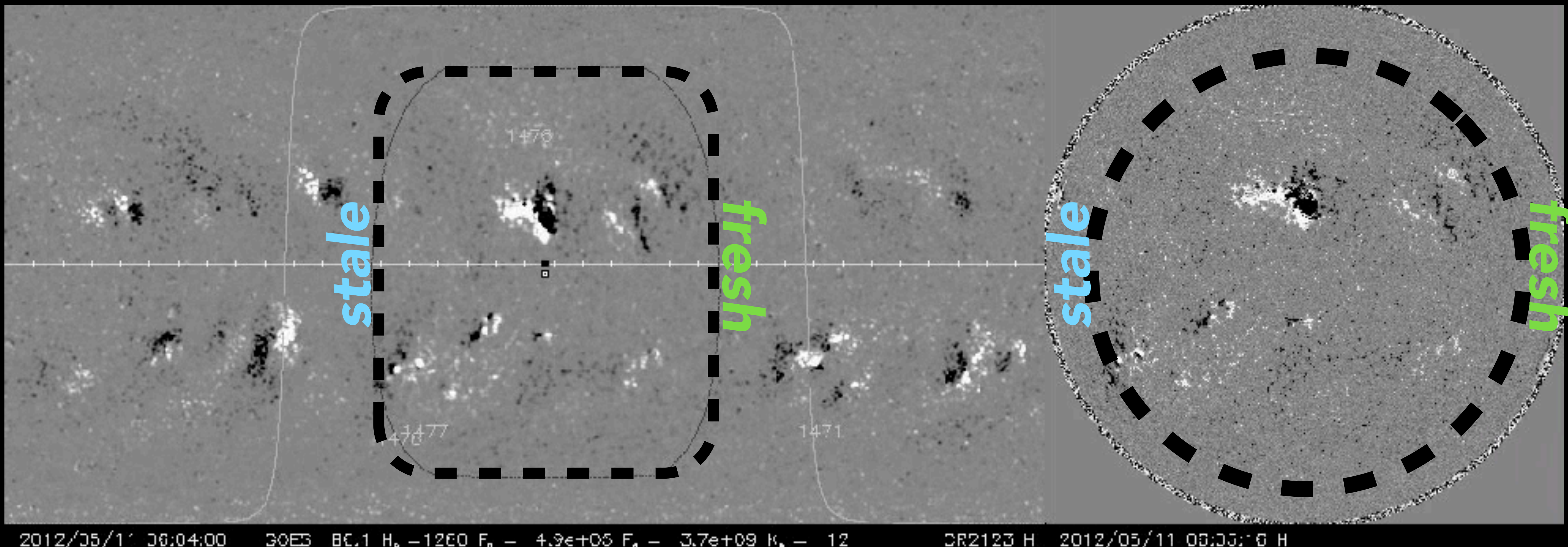
Aims

- Scientific: Understand how the global solar coronal magnetic field evolves, and how the coronal field structures the heliosphere.
- Research to Operations (R2C): Develop a data-driven model of the Sun's global field, and use it for better information (i.e. Space Weather prediction) and better decision making.

Challenges

- How do we deal with incomplete coverage (even with L5) of the solar surface?
- Without direct measurements of B in the corona, how do we construct 3D models of active regions (ARs, i.e. sunspot groups) magnetic fields?
- How do we capture the evolution of ARs over timescales of days and months?

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.

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

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

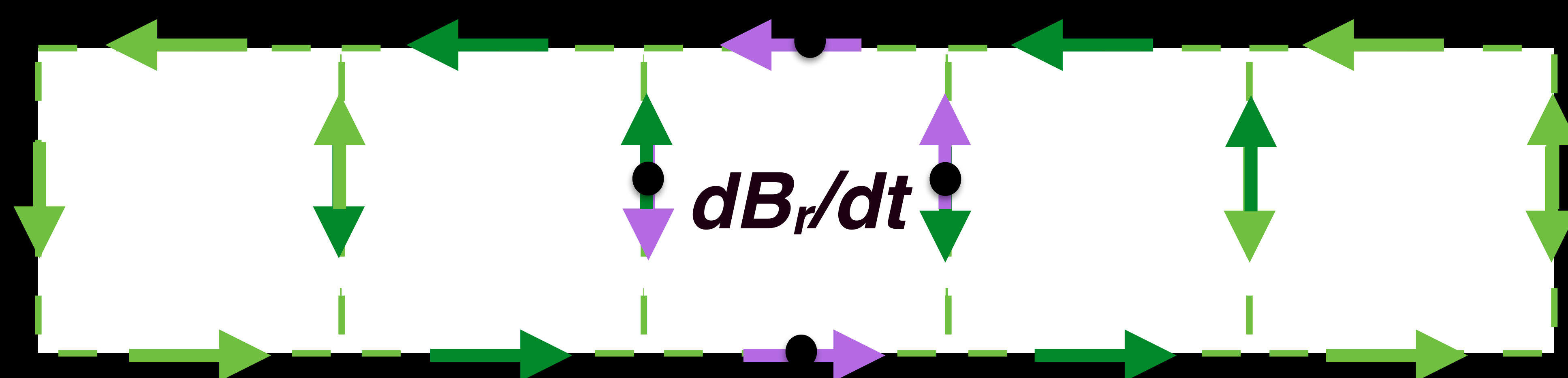
[1] Alternatively, the magnetic flux transport equation may be obtained through spatially averaging the radial component of the induction equation (see DeVore *et al.*, 1984 and McCloughan and Durrant, 2002).

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* (meant to capture magnetic flux emergence).

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 $\boldsymbol{E}$. Instead of Eq. (1) on the previous slide, just use **Faraday's Induction Equation**:

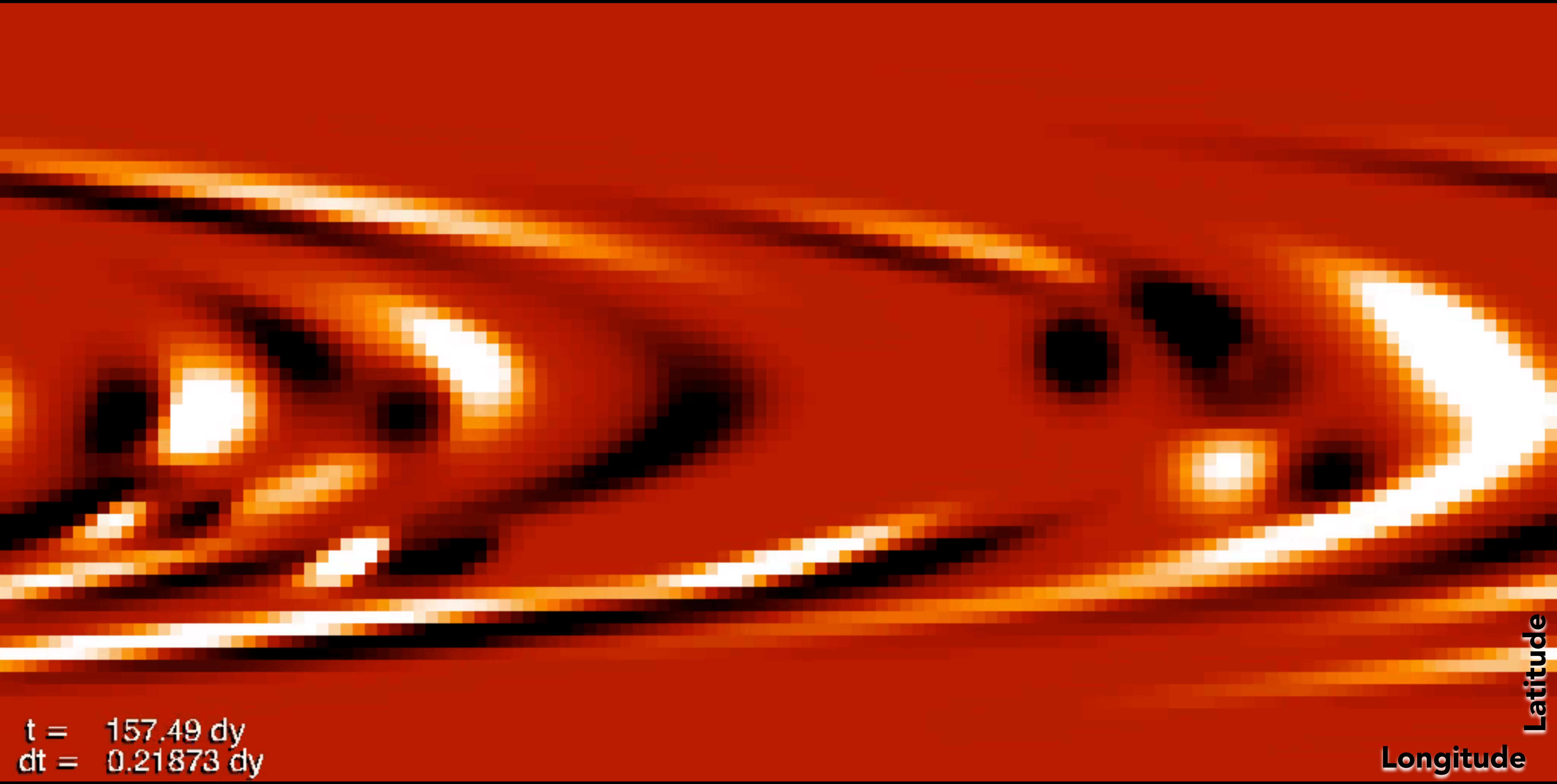
$$dB_r/dt = -curl\ \boldsymbol{E_t}$$



Calculate ***dB_r/dt*pixel area*** of each pixel as

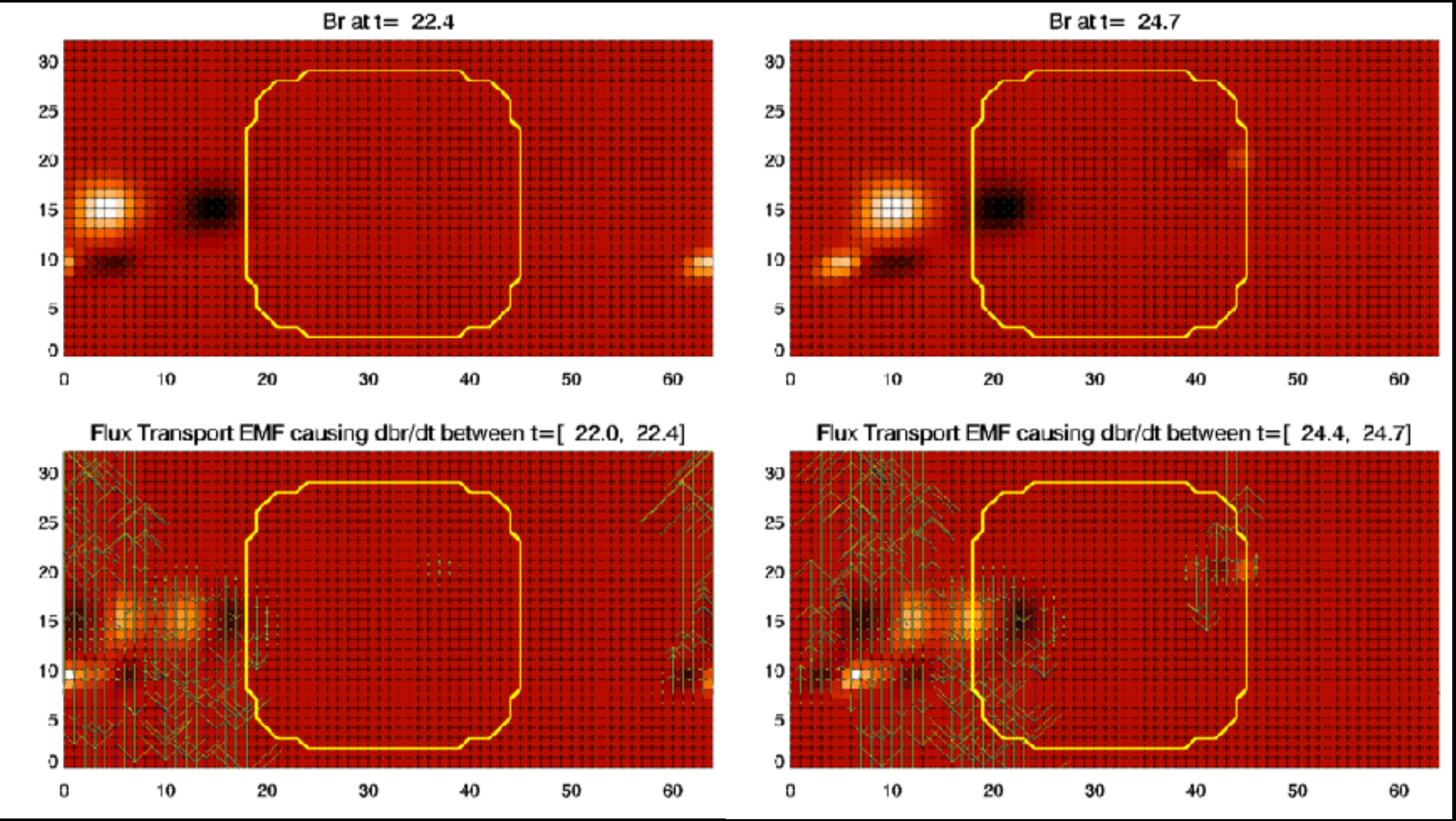
- circulation of E_t about the pixel.

Example of a Constrained SFT Model



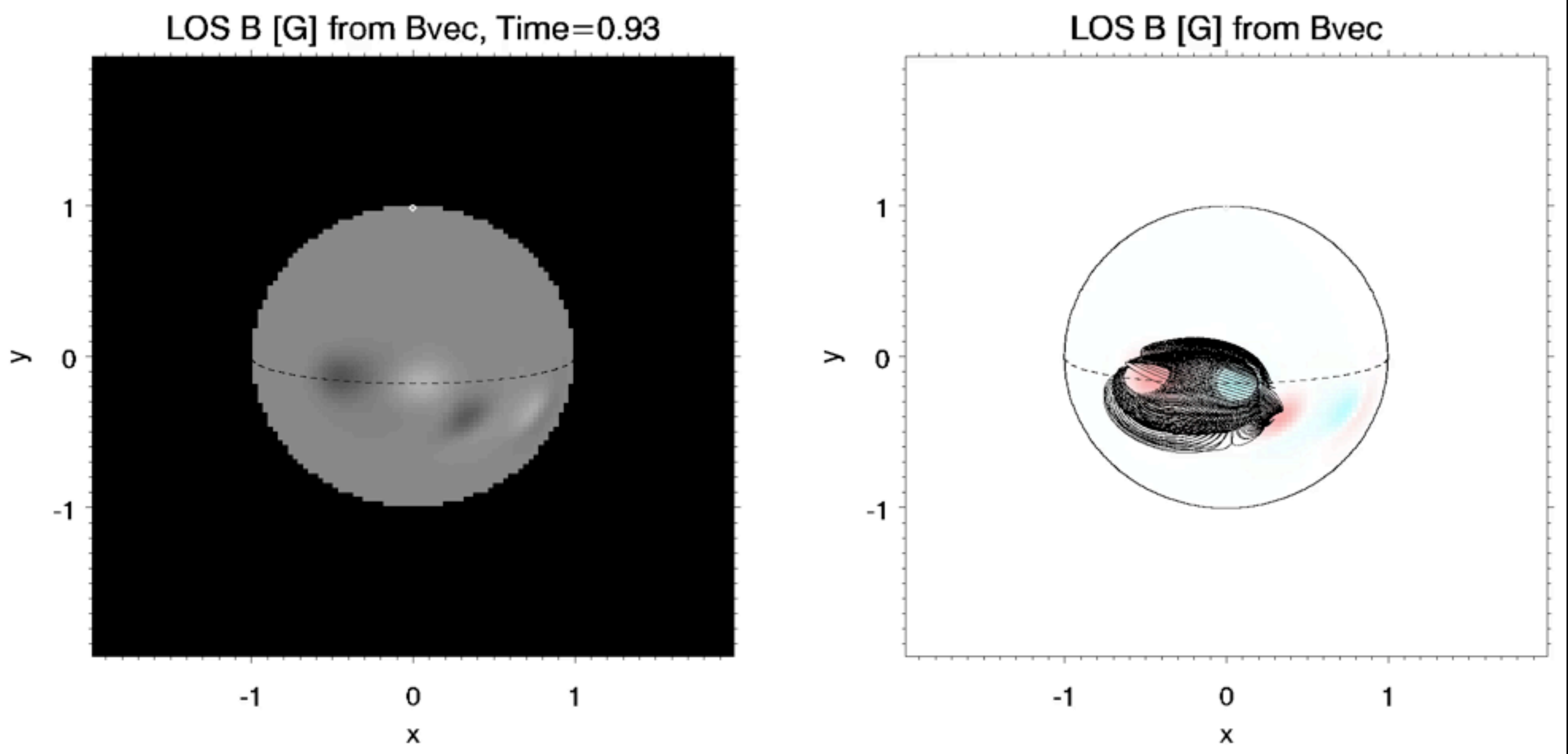
The above toy model treats differential rotation + AR emergence.

Flux Transport EMFs



Benefit: Apart from B_r, the Constrained Surface Flux Transport (CSFT) code outputs the electric fields (or equivalently, the EMFs) used to compute dB_r/dt.

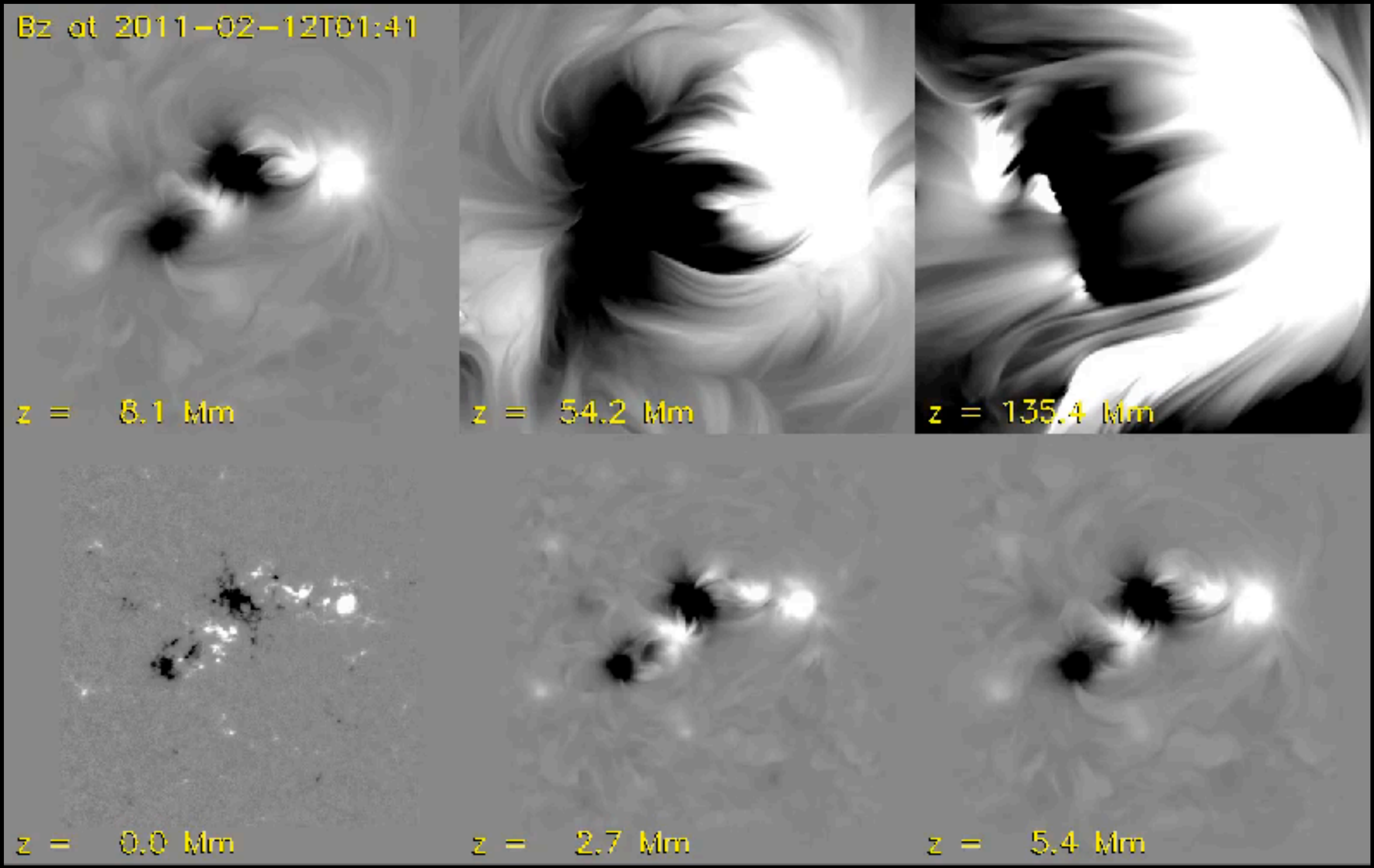
Global Evolving Coronal Field Model



- Electric fields from the Constrained SFT model can be used directly to drive coronal field evolution. See papers by van Ballegooijen, Mackay, Yeates and co-authors on magnetofrictional models of the coronal field. This example uses the code described in Cheung & DeRosa (2012) and Fisher et al. (2015).
- In this example, an AR emerges in the northern hemisphere and interacts with a pre-existing AR straddling the equator. The interaction between the two leads to transfer of magnetic flux so that the pair of leading (and following) polarities are magnetically connected.

Retrieving the Electric Field From Observed Magnetograms

- Kazachenko et al. (2014, ApJ, 795, 1, 19) developed and tested a method to retrieve photospheric electric fields from sequences of vector magnetograms and dopplergrams. This method is suitable for SDO/HMI data.



Model B_z at various heights

Data-driven model of NOAA AR 11158 over 5 days (Fisher et al. 2015, Space Weather, 13, 6)

Retrieving the Electric Field From Observed Magnetograms

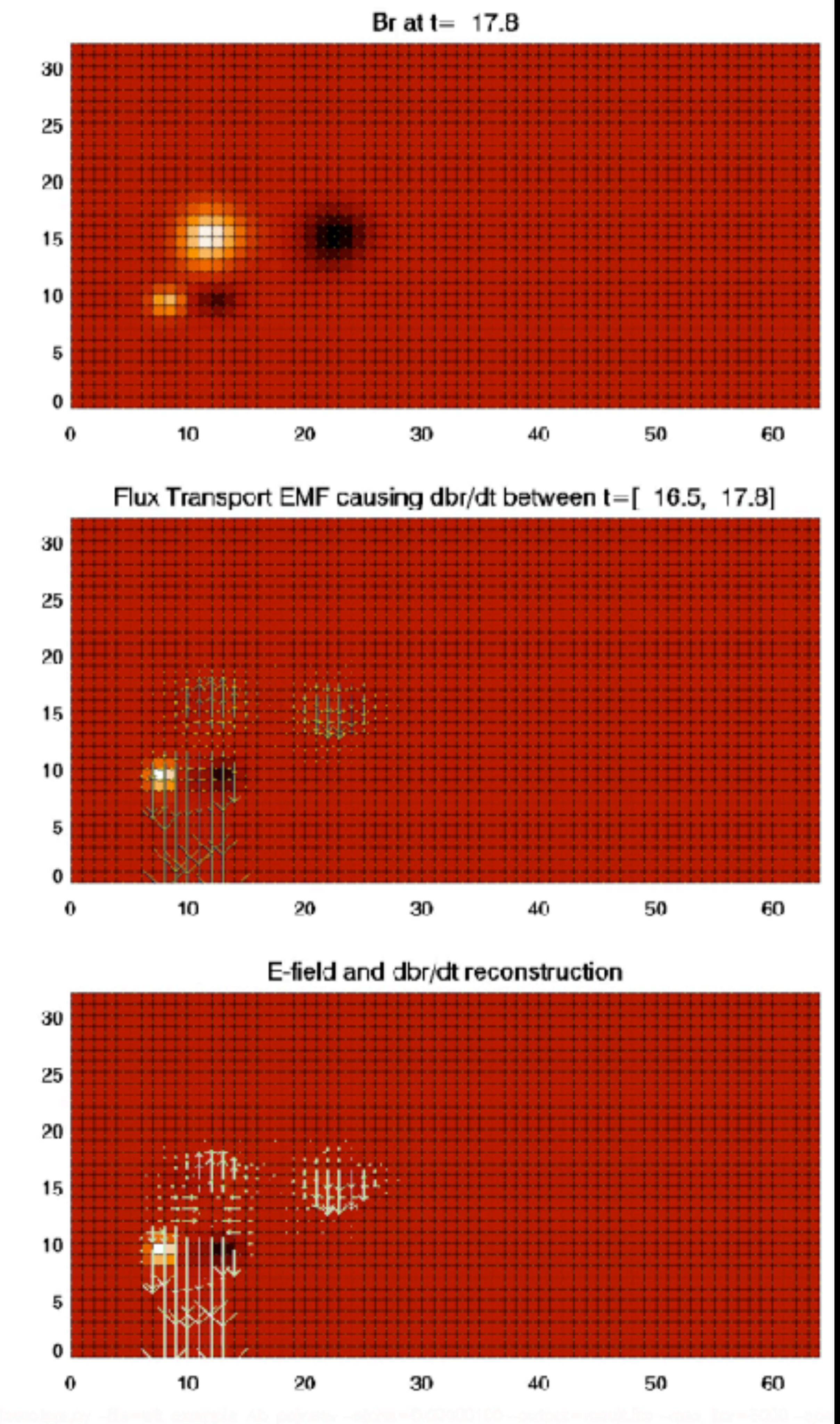
What if we only have measurements of B_r?

The Minimal Flux Transport (Sparse) Solution:

- The idea is to enforce spatial compactness of electric fields.
- Yeates (2017): Tested on full sphere magnetograms (complete B_r coverage). Works well, except when the input magnetograms are not flux balanced (e.g. in ADAPT and the atomic flux transport model of Schrijver).

Analogy with 15 puzzle

Minimize the transport rate of some quantity (in our case, B)

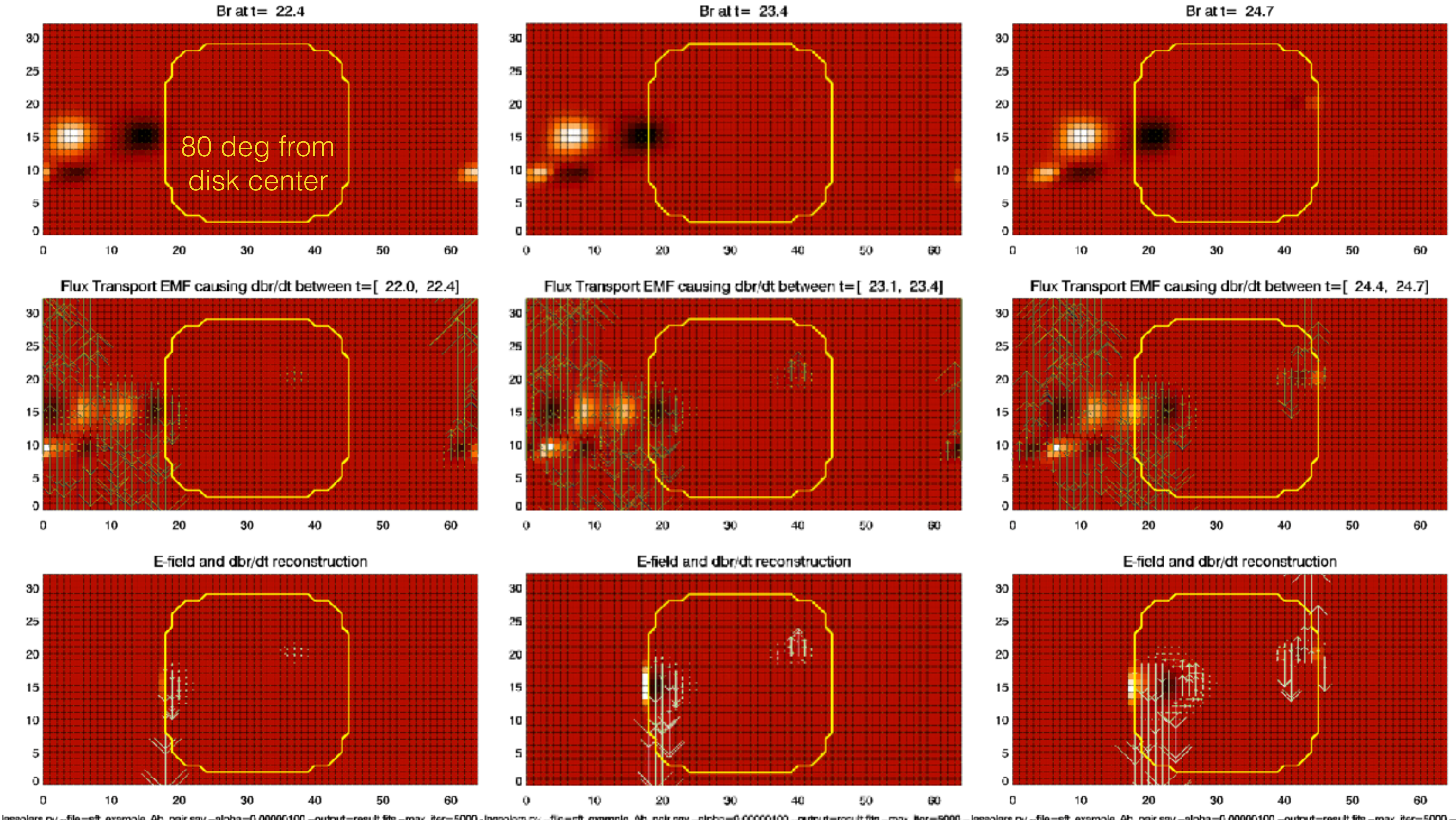


CSFT model of evolving B_r

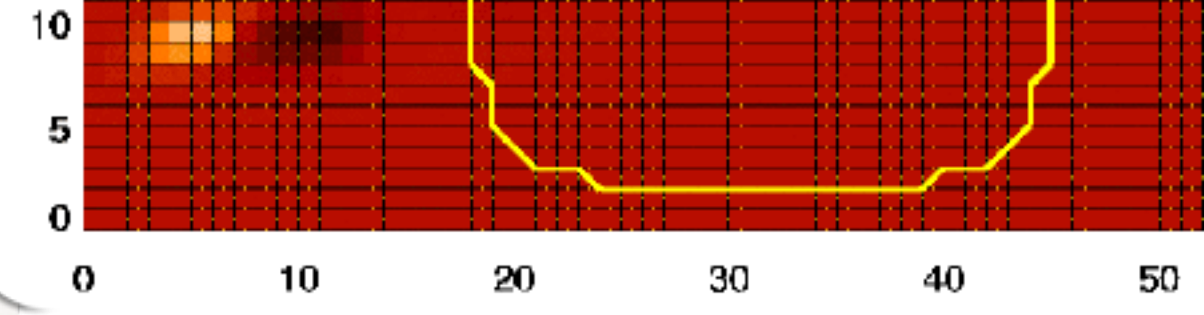
Green arrows: E-fields used by CSFT code to update B_r.

Off-white arrows: Sparse Electric field inversion for E-field

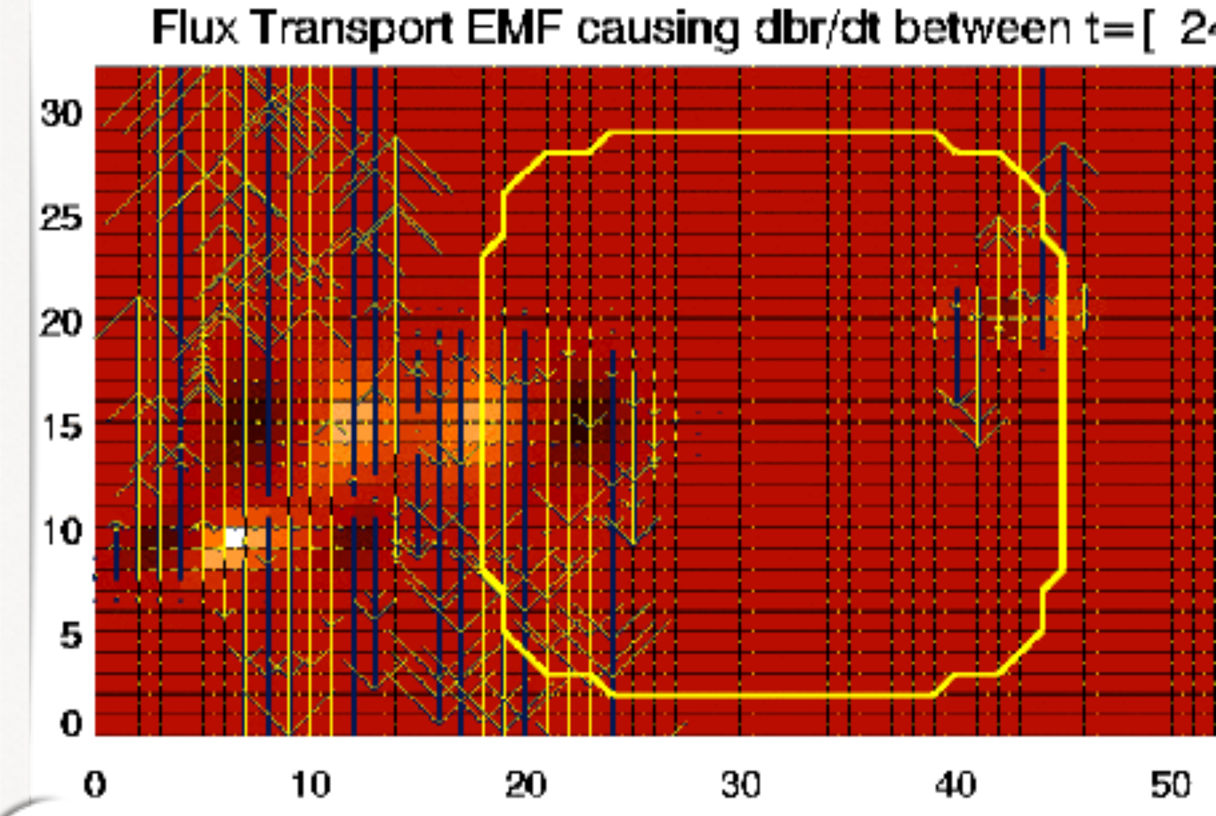
Dealing with incomplete dB_r coverage

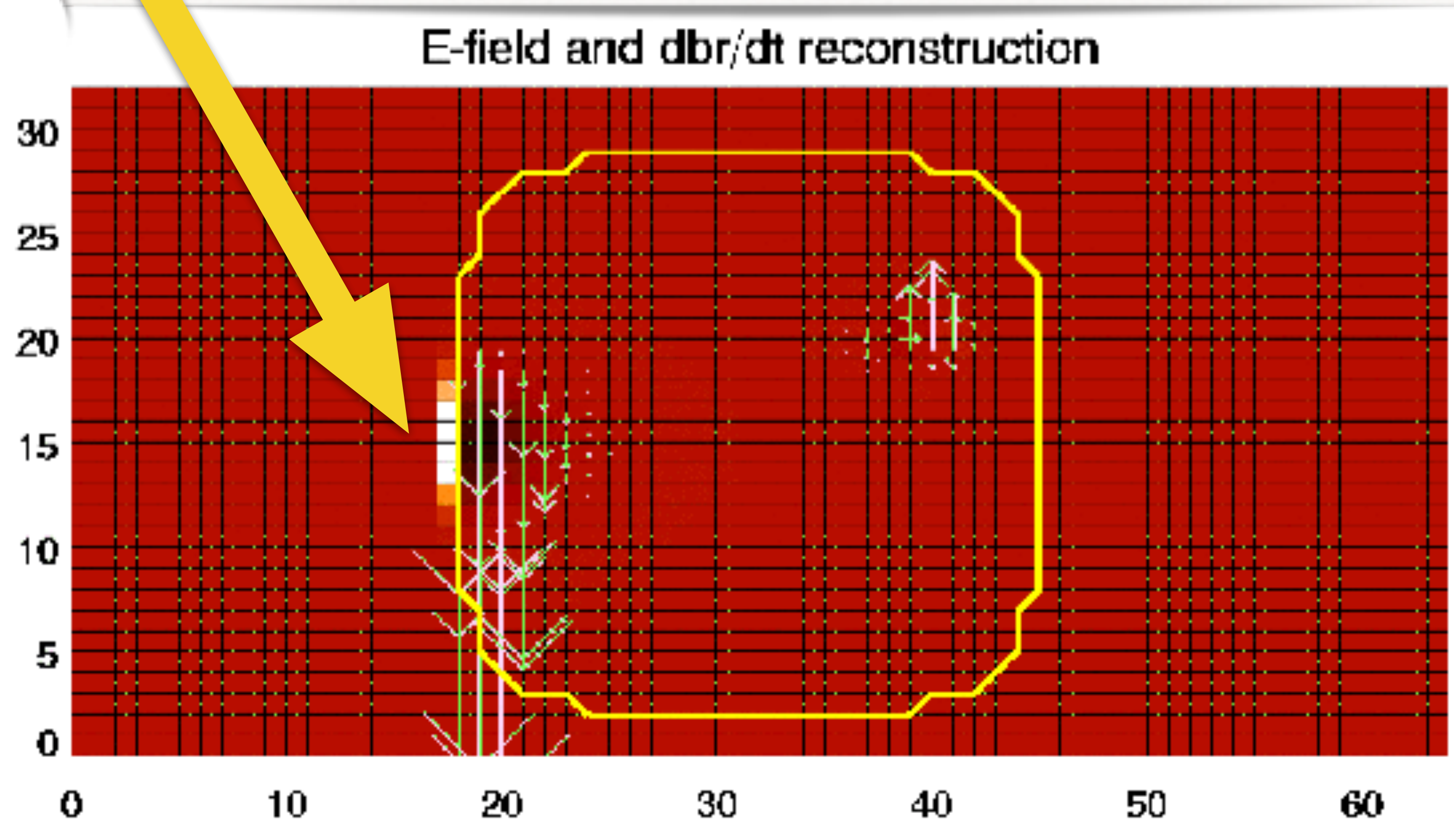


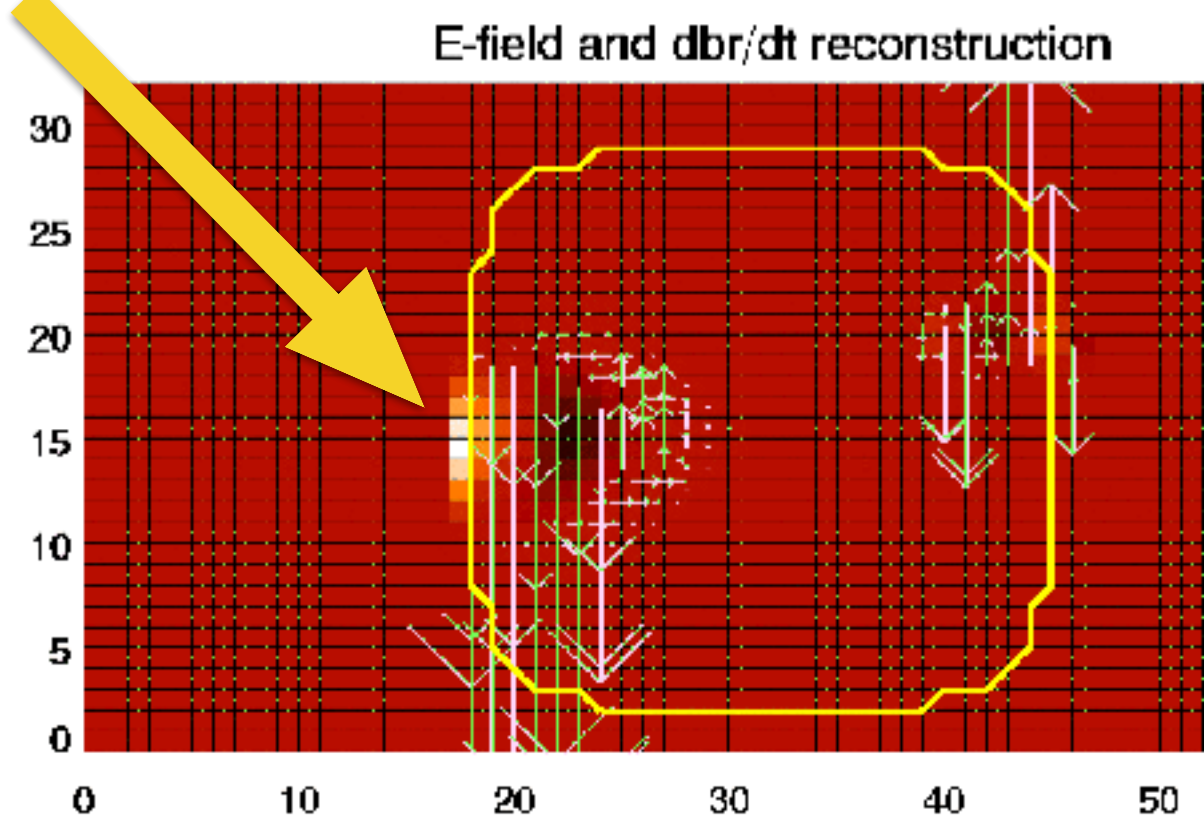
E-field inversion (enforcing compactness of solution) using only the front-side dB_r.

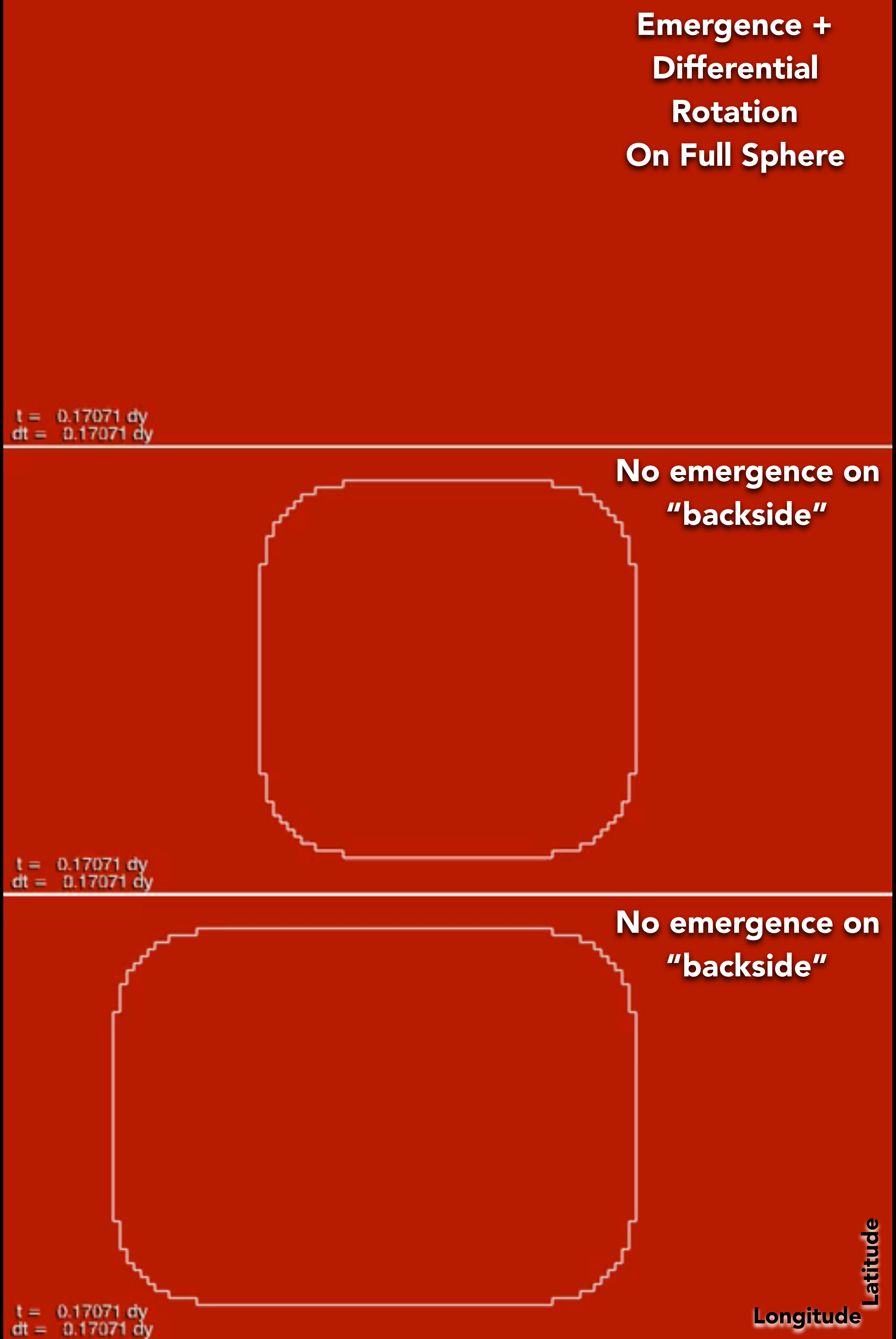


E-field computed for front-side only, but -curl E = dbr/dt over 4π steradians automatically gives balancing polarity across the boundary.





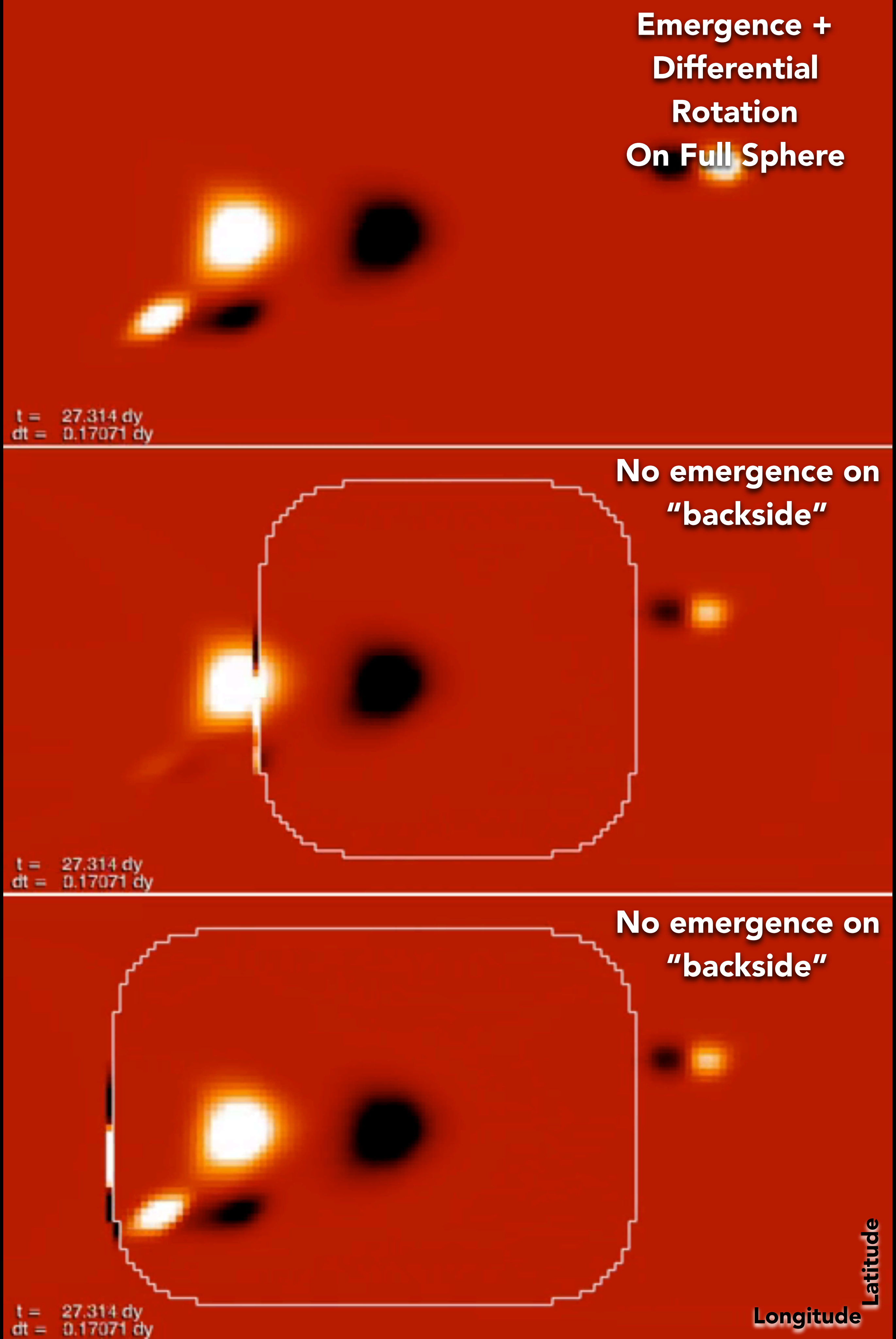




Ground Truth magnetogram (on a Stonyhurst Lon-Lat grid) from the constrained surface flux transport model

Imitate L1 magnetogram assimilation

Imitate L1+L5 magnetogram assimilation



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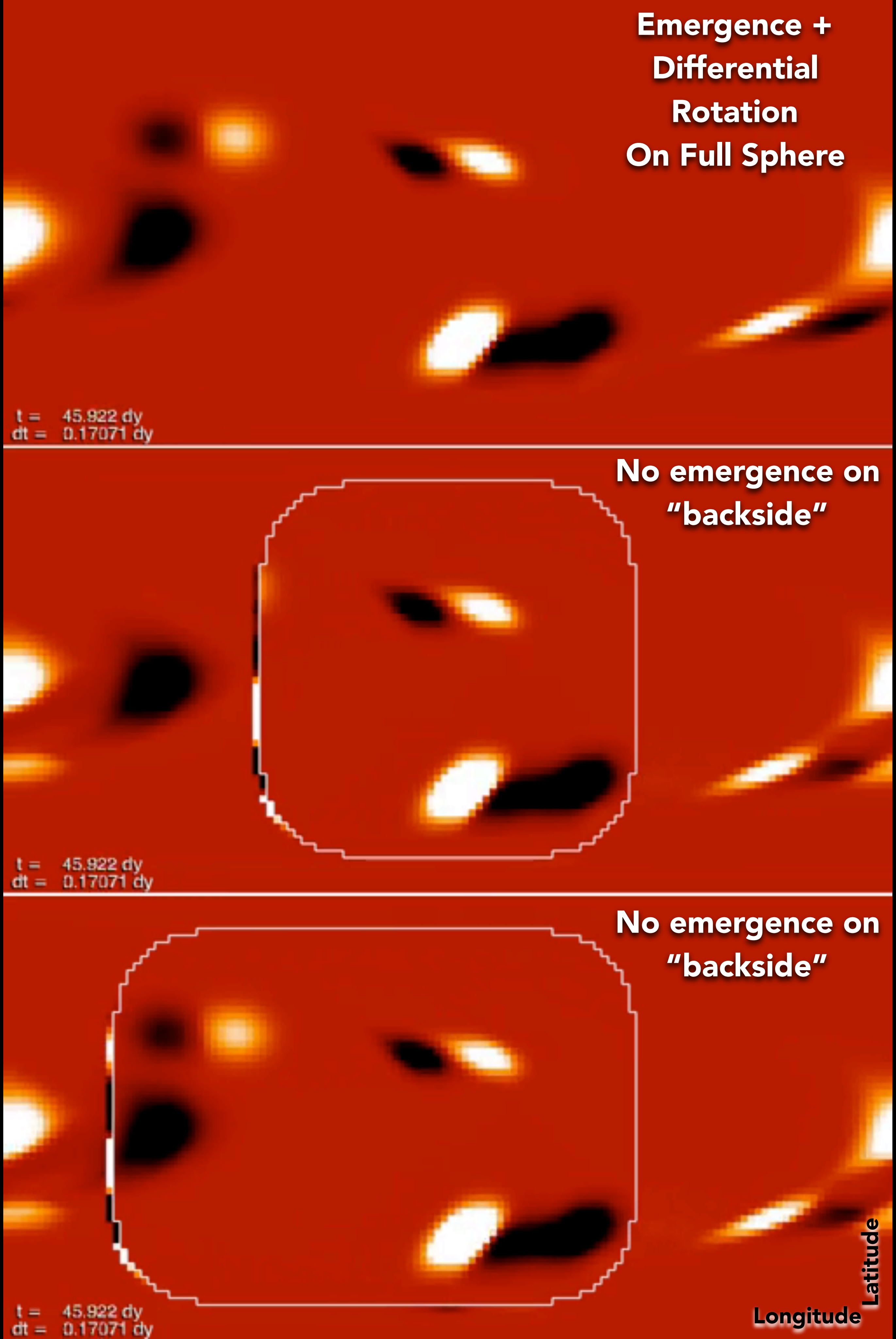

Ground Truth magnetogram (on a Stonyhurst Lon-Lat grid) from constrained surface flux transport model

Imitate L1 magnetogram assimilation

Imitate L1+L5 magnetogram assimilation

Summary

- A Constrained SFT model (DeRosa & Cheung, in prep.) removes the need for ad hoc source terms for newly emerged ARs.
- Ensures magnetic flux balance: No ad hoc monopole subtraction, which changes boundaries of coronal holes (and magnetic topology).
- Model + Frontside E-fields can be directly used as boundary conditions for coronal MHD or magnetofriction models.
- Application to test sequences of radial magnetic field maps with incomplete coverage: Having the L5 augmentation gives ~4 days additional lead time for assimilation of ARs that emerged on the backside. Monte Carlo models needed to quantify the range of benefits.
- Data-Driven modeling requires reliable data with consistent quality (e.g. stable point-spread function of the telescope). i.e. space mission. **Don't take SDO for granted.**
- The CGEM project plans to deliver the Surface Flux Transport Model and spherical magnetofrictional model to NASA's Community Coordinated Modeling Center (CCMC) in the coming 12 months.

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Backup slides