Data-Driven Simulations Of Coronal Fields in Active Regions

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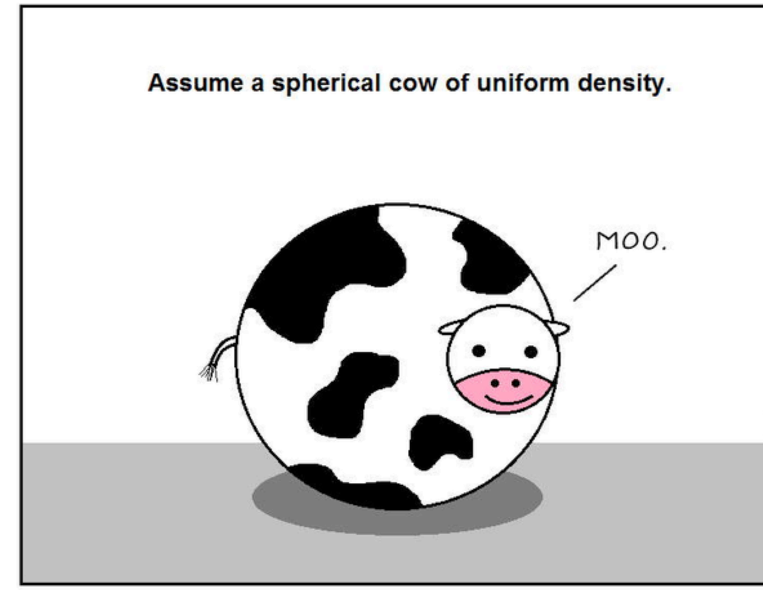
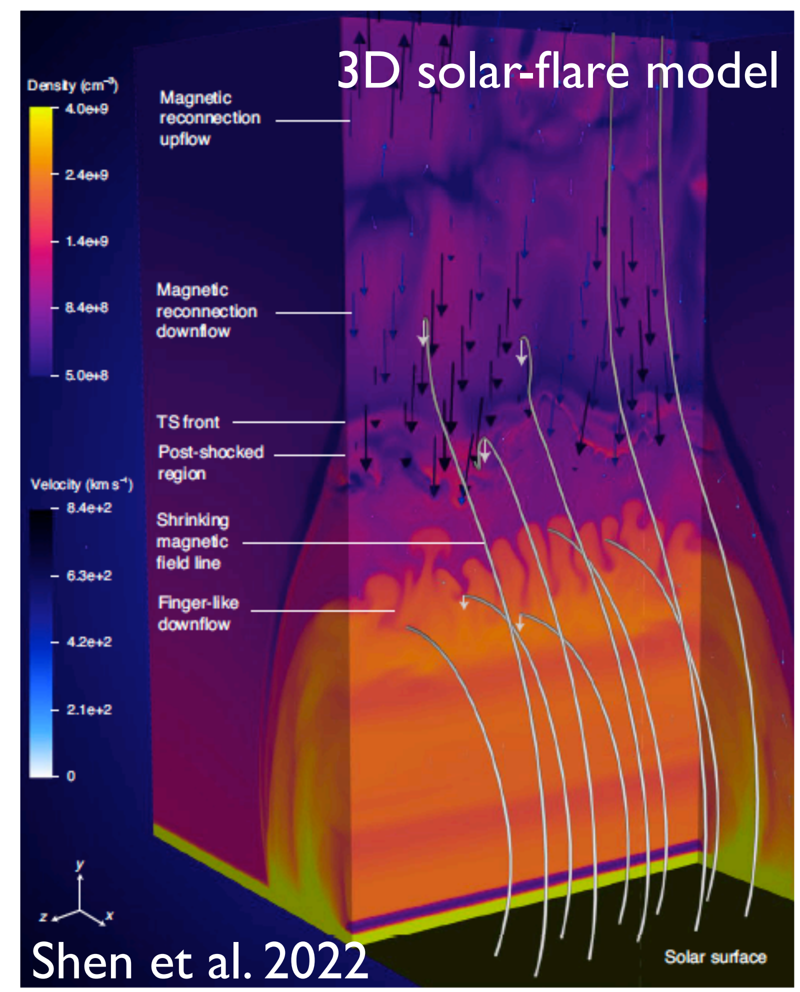
ISSI October 6 2022

We Have Different Flare Models to Understand The Details of Energy Storage and Release

- <u>1D Flare models</u>
  - Mainly focus on release process and not the trigger to understand flare thermal, magnetic and particle properties



- <u>3D Flare Models</u>
  - Some cover <u>release only</u>
  - Others cover <u>multi-day evolution</u> to understand both storage and release; NB: most of these focus on magnetism (e.g. simplified plasma treatment); Let's look at these storage & release models



Among Models that Cover Details of Both Flare Energy Storage & Release Are

- Static models (without memory):
    - E.g. *extrapolations*
- Dynamic models (with memory):
    - data-inspired
    - data-constrained models
    - data-driven models

*became popular since 2012 when SDO started observing vector magnetic **B at the photosphere***

Current data-driven models

Magneto-frictional ("MHD light")

Evolve coronal field using induction equation:

$$\begin{cases} \frac{\partial \mathbf{A}}{\partial t} = \mathbf{V} \times \mathbf{B} - \eta \mathbf{J} \\ \mathbf{B} = \nabla \times \mathbf{A}, \quad \mathbf{J} = \nabla \times \mathbf{B} \\ \mathbf{V} = \frac{\mathbf{J} \times \mathbf{B}}{\nu_0} \end{cases}$$

η - magnetic diffusivity, **V** - plasma velocity, **J** - current density, ν_0 - magnetofrictional coefficient

$$\frac{\partial \mathbf{A}}{\partial t}\bigg|_{r=R_\odot} = -E^{\text{phot}}\bigg|_{r=R_\odot}$$

Uses B^{phot} to find E^{phot} for BC

Used to model quasi-static evolution of active regions for several days before it erupts

Full MHD

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Full MHD

Solves full set of equations:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0$$

$$\frac{\partial \rho \boldsymbol{v}}{\partial t} + \nabla \cdot \left[\rho \boldsymbol{v}\boldsymbol{v} + \left(p + \frac{B^2}{8\pi}\right)\boldsymbol{I} - \frac{\boldsymbol{B}\boldsymbol{B}}{4\pi} - \boldsymbol{\Pi}\right] = \rho \boldsymbol{g}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} + c\nabla \times \boldsymbol{E} = 0$$

$$\frac{\partial e}{\partial t} + \nabla \cdot (e\,\boldsymbol{v}) = -p\nabla \cdot \boldsymbol{v} + \frac{\eta}{4\pi}J^2 + \Phi + Q$$

where $c\boldsymbol{E} = -\boldsymbol{v} \times \boldsymbol{B} + \eta \boldsymbol{J}$

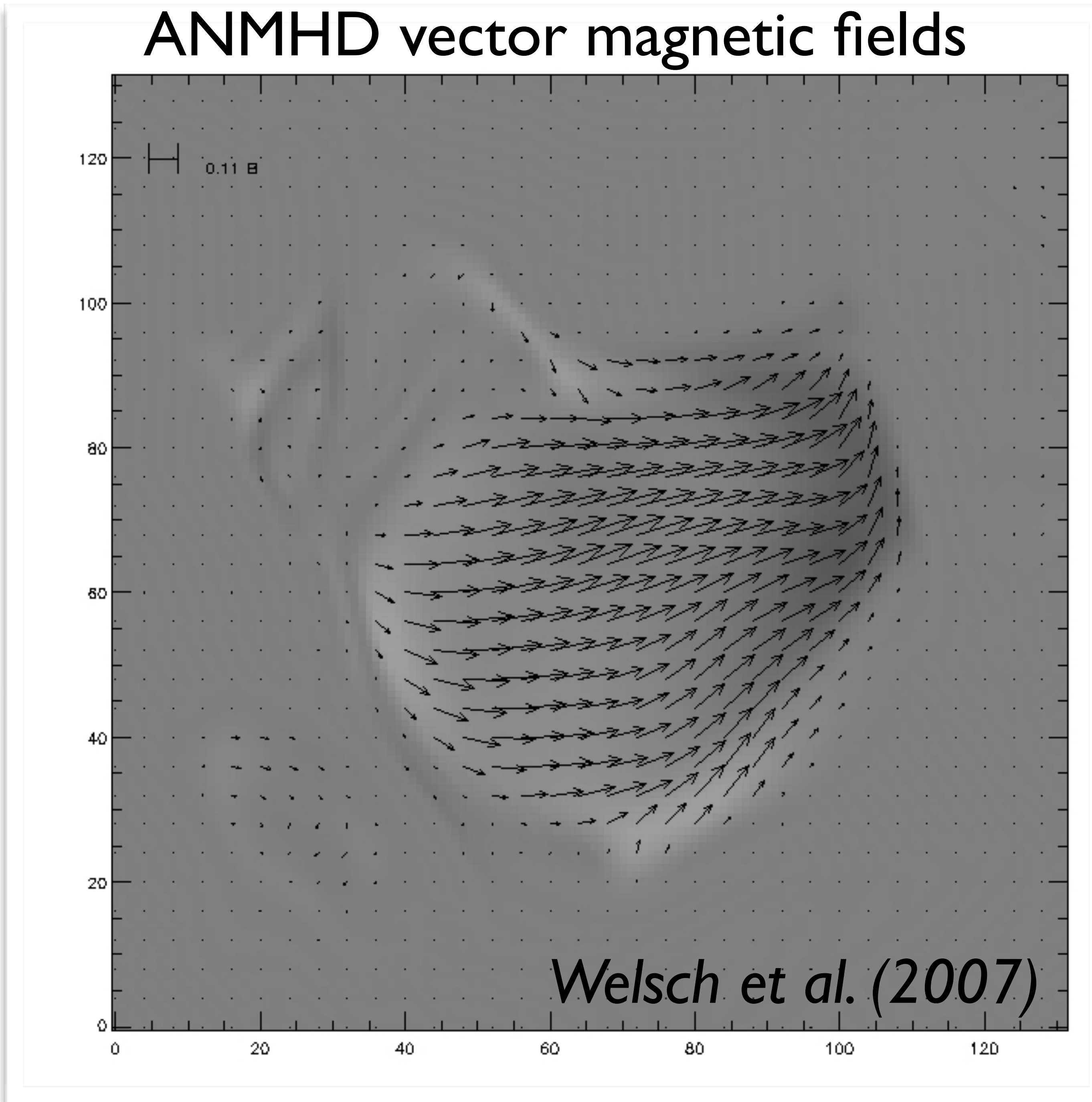
Uses B^{phot} to find E^{phot} and dE^{phot}/dr for BC

Used to model eruptive evolution of an active region for several hours during eruption

Hoeksema et al. 2020

These Data-driven Methods Need Not Only **B** But Also Electric Fields **E.**

- Many methods to derive electric fields from B: e.g. PDFI, DAVE4VM
- Many existing methods were validated with ANMHD simulation of emerging bipole, where **V** & **B** are known.
- Good reconstruction results for e.g. PDFI and DAVE4VM
- **-** Sun is more complex than that.



Finding photospheric electric fields is hard

1. From horizontal velocity **V** and magnetic field **B**

$$\mathbf{E} = -\mathbf{V} \times \mathbf{B}$$

V inversion methods: tracking methods & inductive methods

November & Simon 1988, Fisher & Welsch 2008, Longcope 2004, Kusano et al. 2002, Welsch et al. 2007

DAVE4VM (Differential Affine Velocity Estimator for Vector Magnetograms, Schuck, 2008):

Input:

Full **B**

$$\begin{cases} \frac{\partial B_z}{\partial t} + \nabla_h \cdot (B_z \mathbf{V}_h - V_z \mathbf{B}_h) = 0 \\ \mathbf{E} = -\mathbf{V} \times \mathbf{B} \end{cases}$$

Finding photospheric electric field

2) From Faraday's law, ideal MHD and observed **B** and V_{Dopp}

(1) $$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \qquad \mathbf{E} = -\mathbf{V} \times \mathbf{B}$$

<u>Established methods to solve the problem:</u>

PDFI (PTD-Doppler-FLCT-Ideal) method (Kazachenko, Fisher, Welsch 2014)

<u>Input</u>: Full **B**, Vdopp

$$\begin{cases} \mathbf{E} = \mathbf{E}_I - \nabla\psi \\ \nabla \times \mathbf{E}_I = -\frac{\partial \mathbf{B}}{\partial t} \\ \nabla^2\psi = -\nabla \cdot \mathbf{E} = \nabla \cdot (\mathbf{V} \times \mathbf{B}) \end{cases}$$

inductive

non-inductive

Cheung et al. 2012, 2015
Mackay et al. 2014 etc.

B_z only

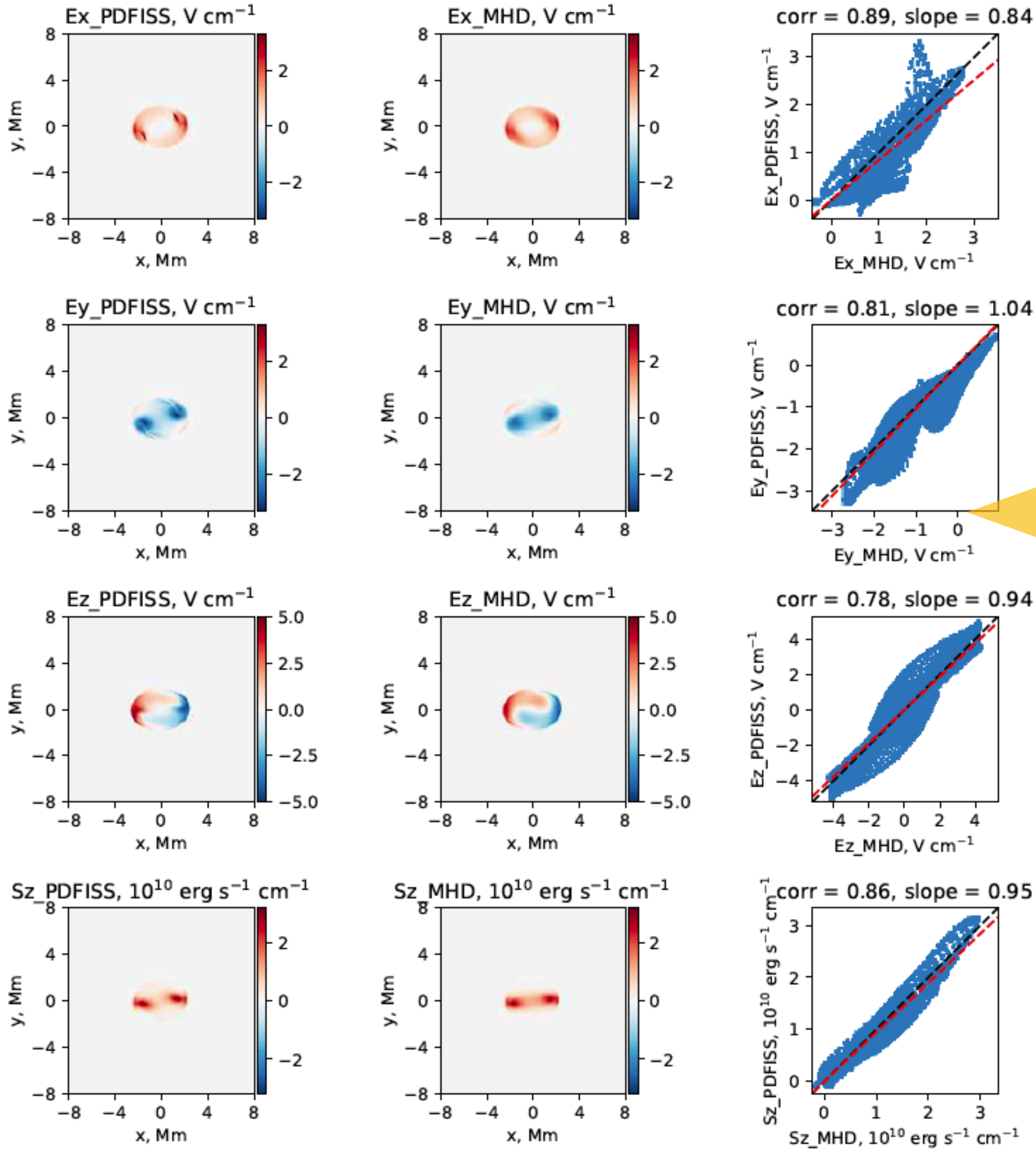
Full **B**

$$\begin{cases} \nabla\psi = 0 & (0) \\ \nabla_h^2\psi = -\nabla_h \cdot \mathbf{E}_h = -\Omega B_z & (1) \\ \nabla_h^2\psi = -\nabla_h \cdot \mathbf{E}_h = -U(\nabla \times \mathbf{B}) \cdot \hat{\mathbf{z}} & (2) \end{cases}$$

free parameters

Yeates et al. 2017 B_z only (1)$_z$

Tremblay et al. 2015, 2017 MEF (Longcope 2004)



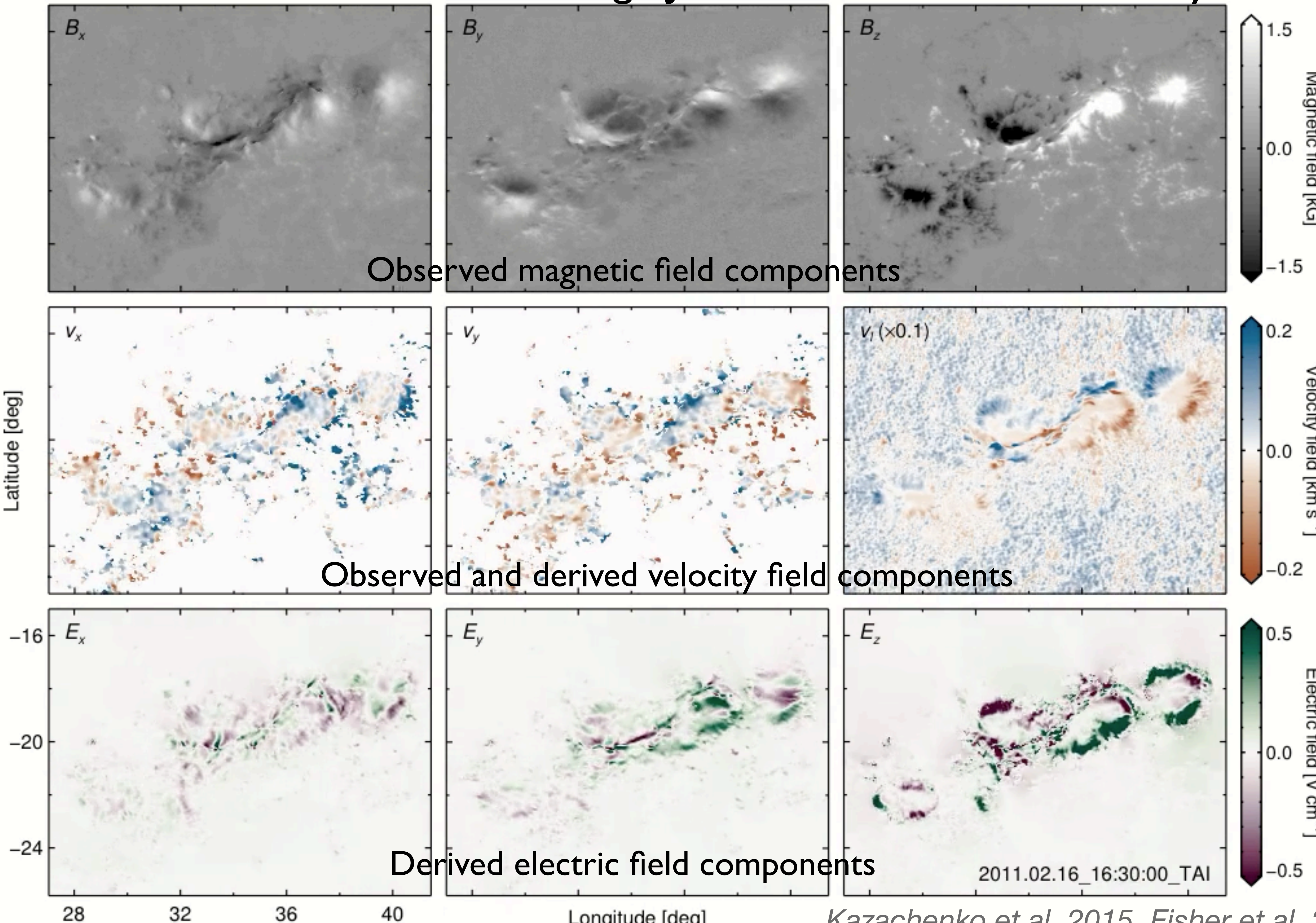
In *Afanasev et al. 2021* we tested PDFI with a more more realistic simulation of an emerging AR from MFE simulation (by Y. Fan)

We found that

- PDFI performs well during emergence.
- Not so well during rotation — the center of the sunspot has too little structure in **B**.
- *Good news*: Might only be a problem in simulations.
- Working on it…

See Afanasev et al. 2021, ApJ

Here is an example of PDFI electric fields for AR 11158.
These E-fields are available through JSOC for all ARs observed by SDO!

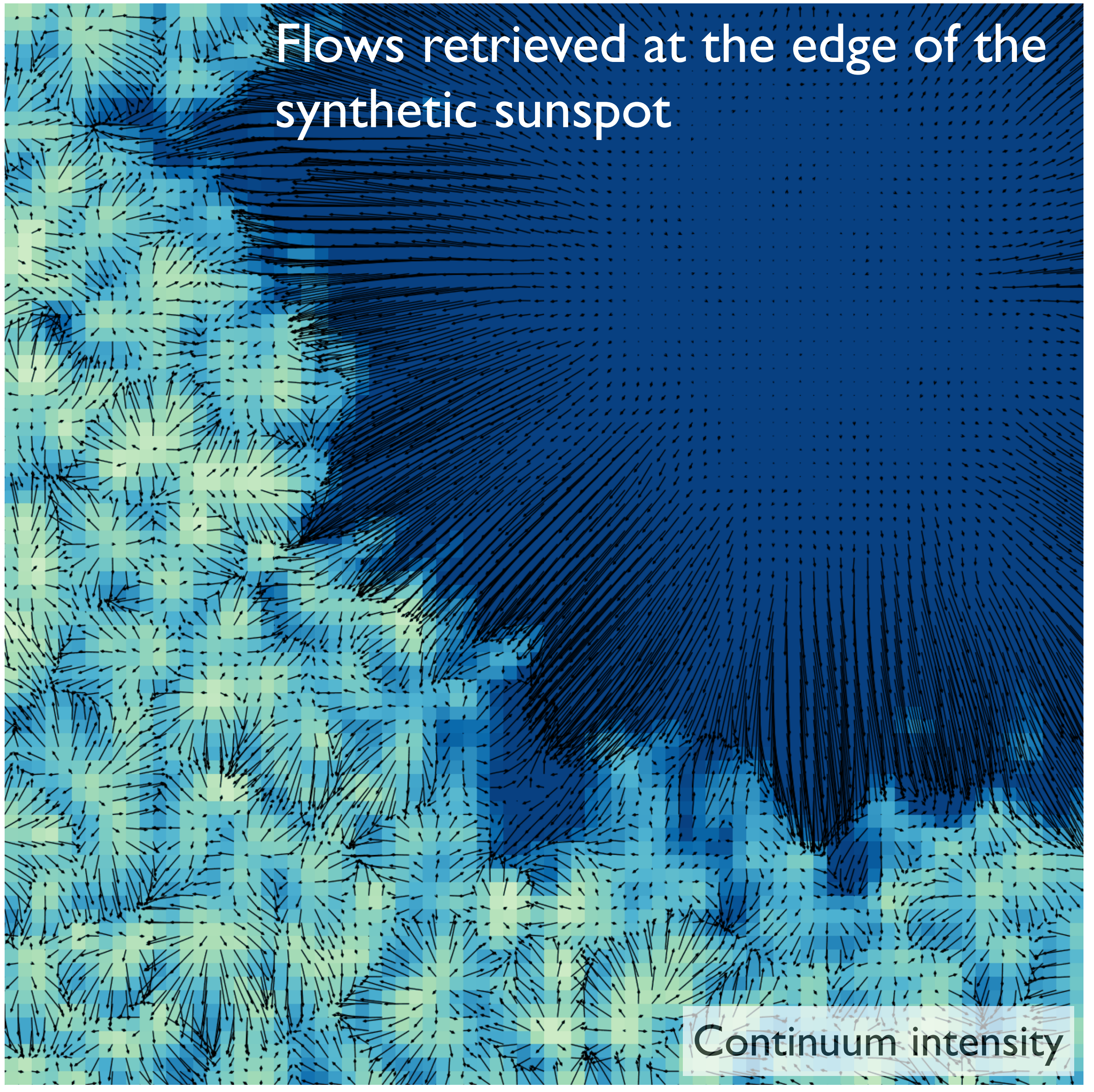


Kazachenko et al. 2015, Fisher et al. 2020

Besides Physics-based E-inversion Methods, There Are Machine-Learning Methods

- Here is an example of work by *Benoit Tremblay*: horizontal flows derived using DeepVel velocity (or E) inversion method.

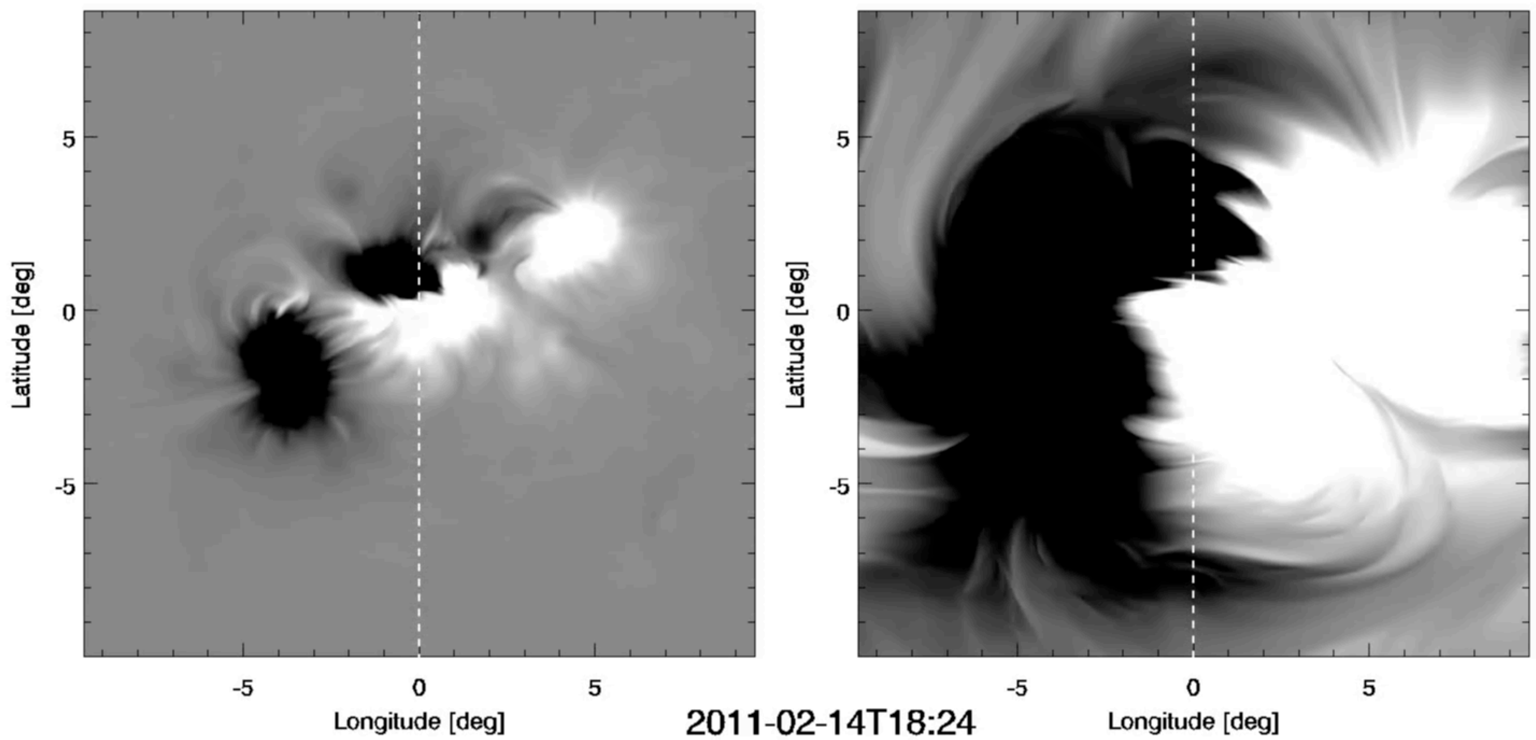
- DeepVel uses a neural network trained on a simulation, where flows are known, to find flows (or **E**) for the actual observations.



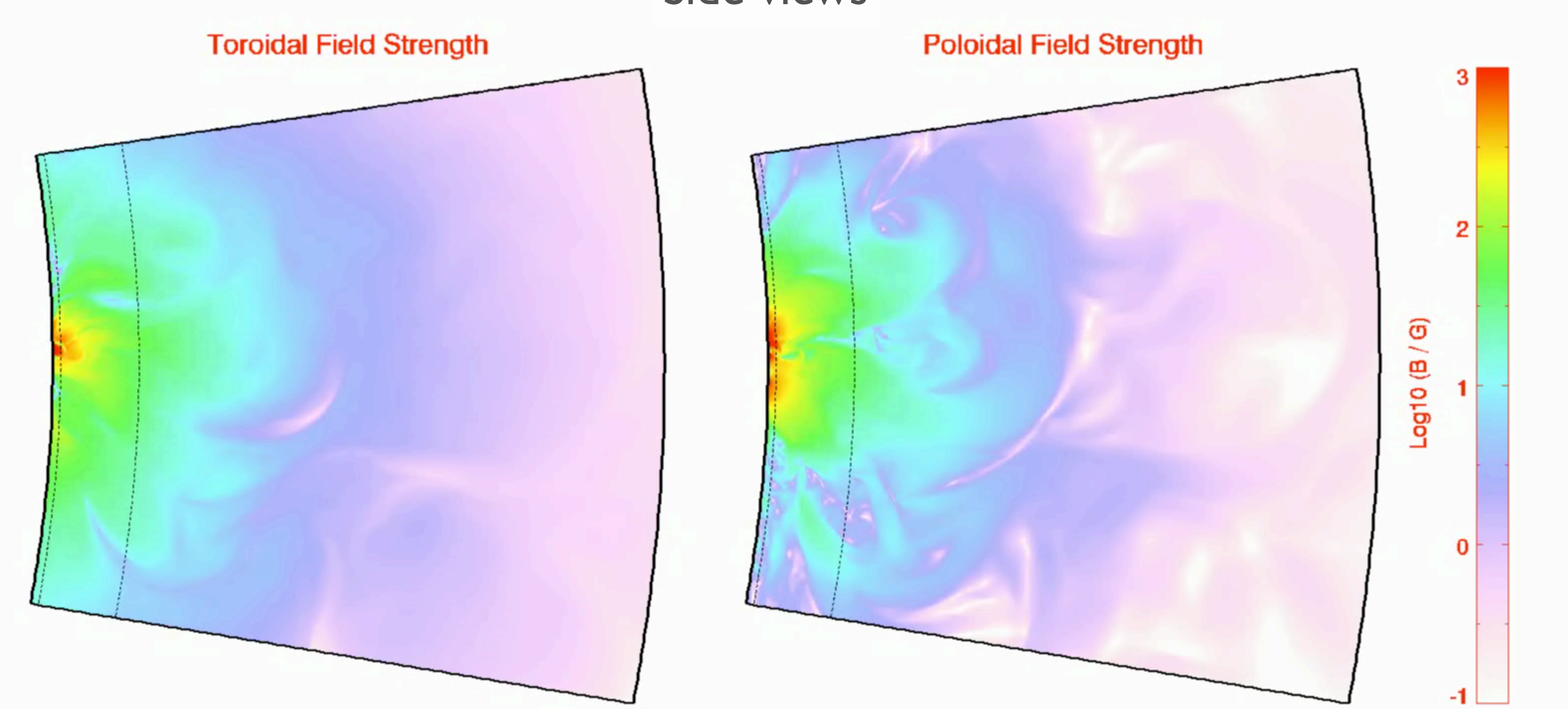
Tremblay et al. 2021; also 2022 (in prep.)

In Hoeksema et al. 2020, PDFI Electric Fields were Used to Run a Quasi-Static Magneto-frictional Model of Coronal Magnetic field

Br at 4.1 Mm (low transition region) Br at 41 Mm (upper transition region)



Side views

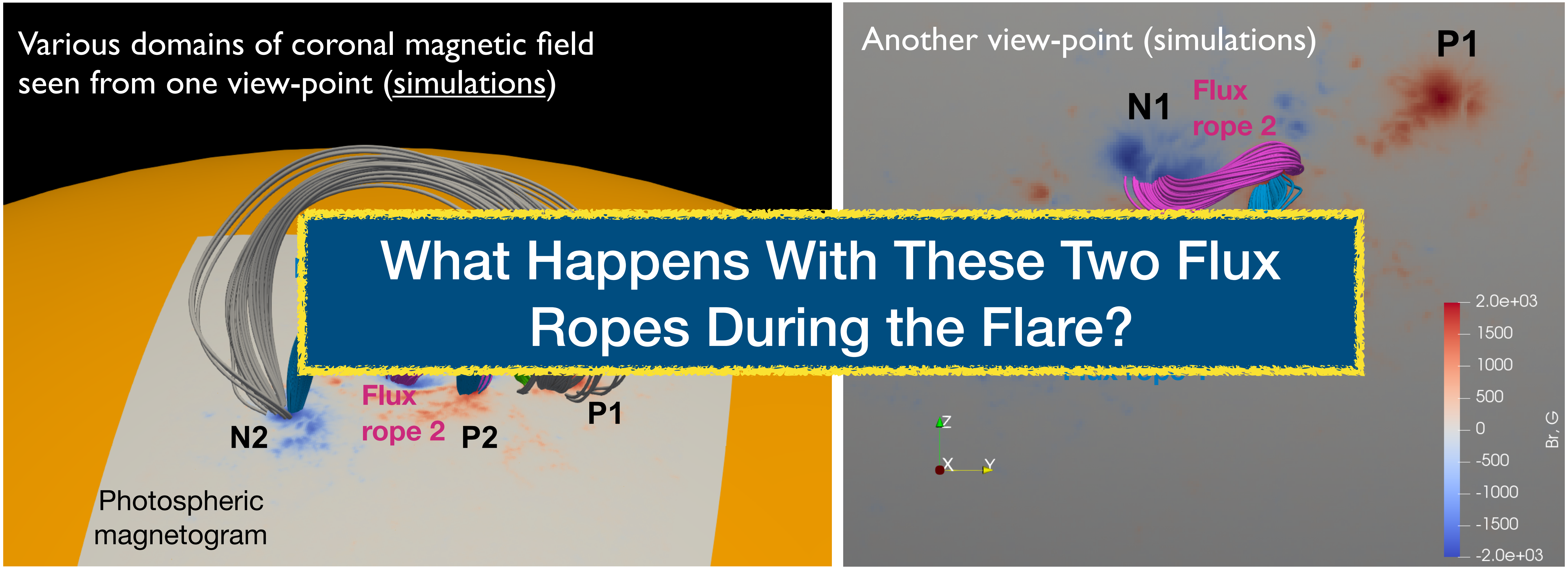


<u>Example of magnetofrictional simulation</u>: coronal magnetic field (at different heights) evolving in response to observed photospheric magnetic field driving during 6.4 days;

We observed a gradual build-up of sheared/twisted magnetic fields

Hoeksema et al. 2020

When We Looked at P*re-eruptive Magnetic field* Configuration From This Simulation, We Found Two Twisted Flux Ropes

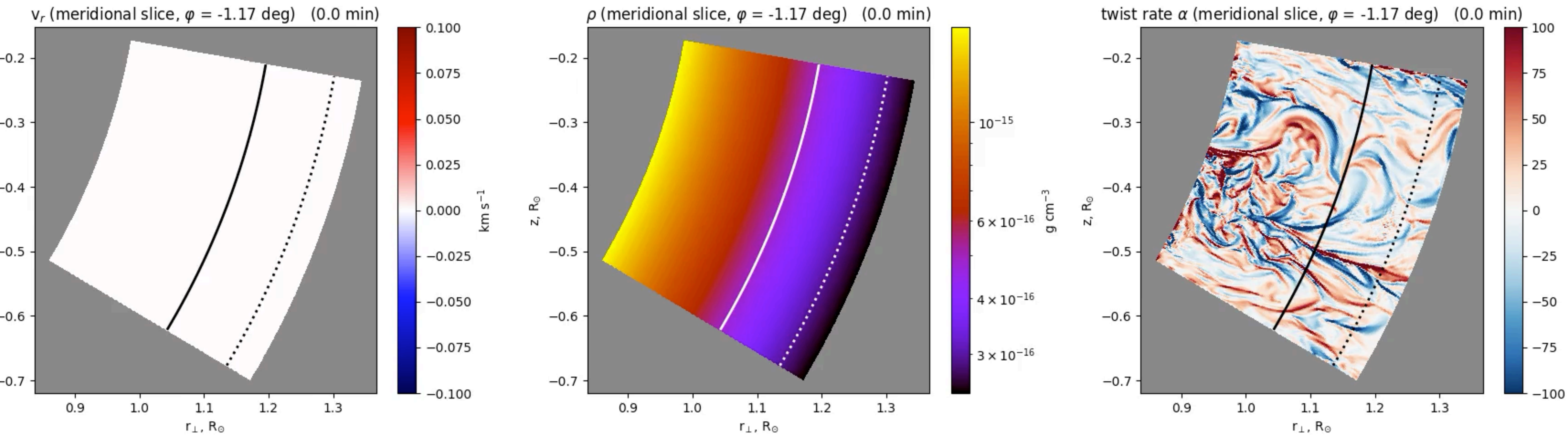


What Happens With These Two Flux Ropes During the Flare?

Afanasev et al. 2022 in prep

We Used The Field From This Quasi-static Simulation as an Initial State for a More Realistic MHD Run (MFE, Y. Fan)

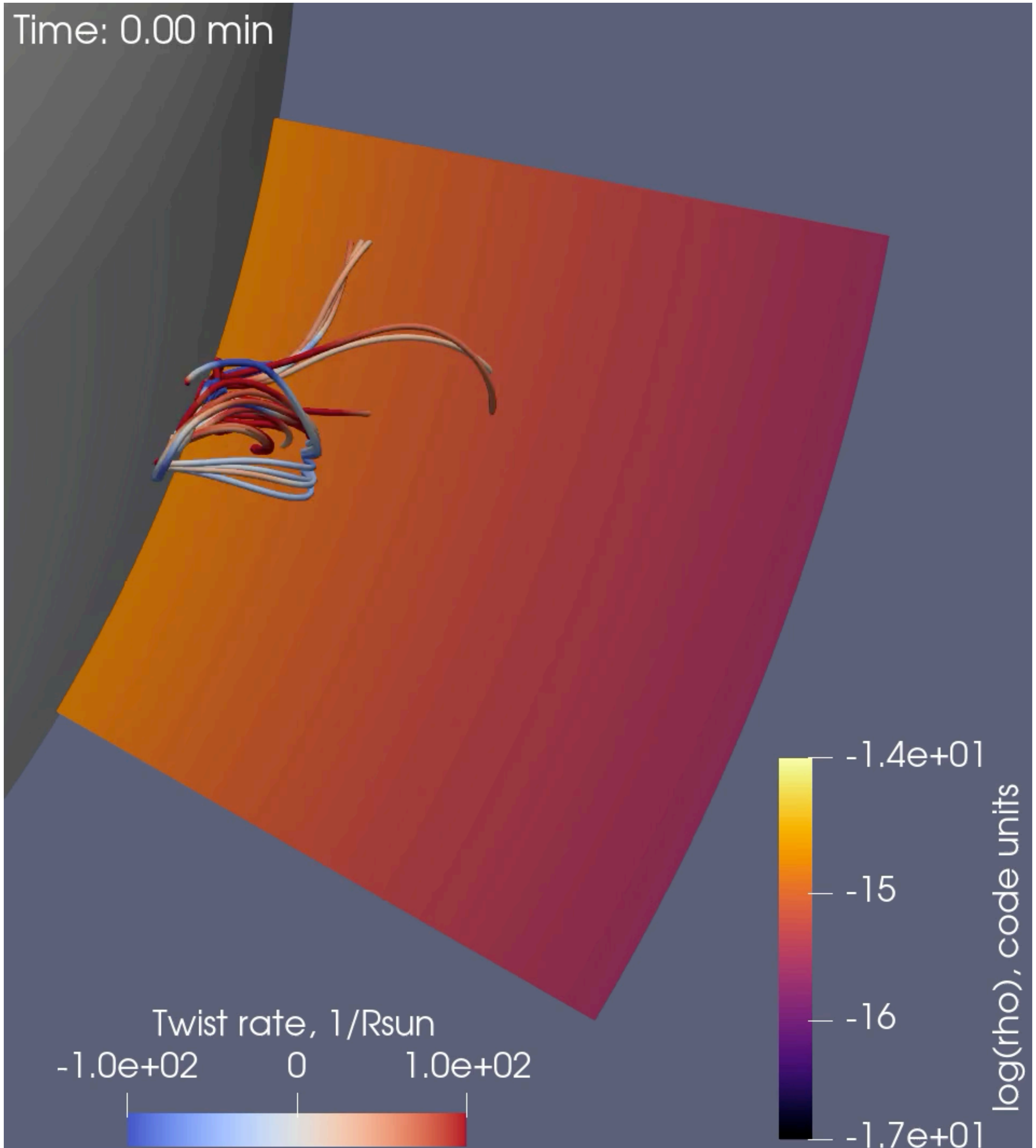
Radial Velocity | Density | Twist per unit length



Looks like an eruption, but is it?

Afanasev et al. 2022 in prep

To Verify that We Have an Eruption, We Tracked a Set of Points Originating Close to Two Flux Ropes



Left: **B** Field lines following Lagrangian particles with density as a background.

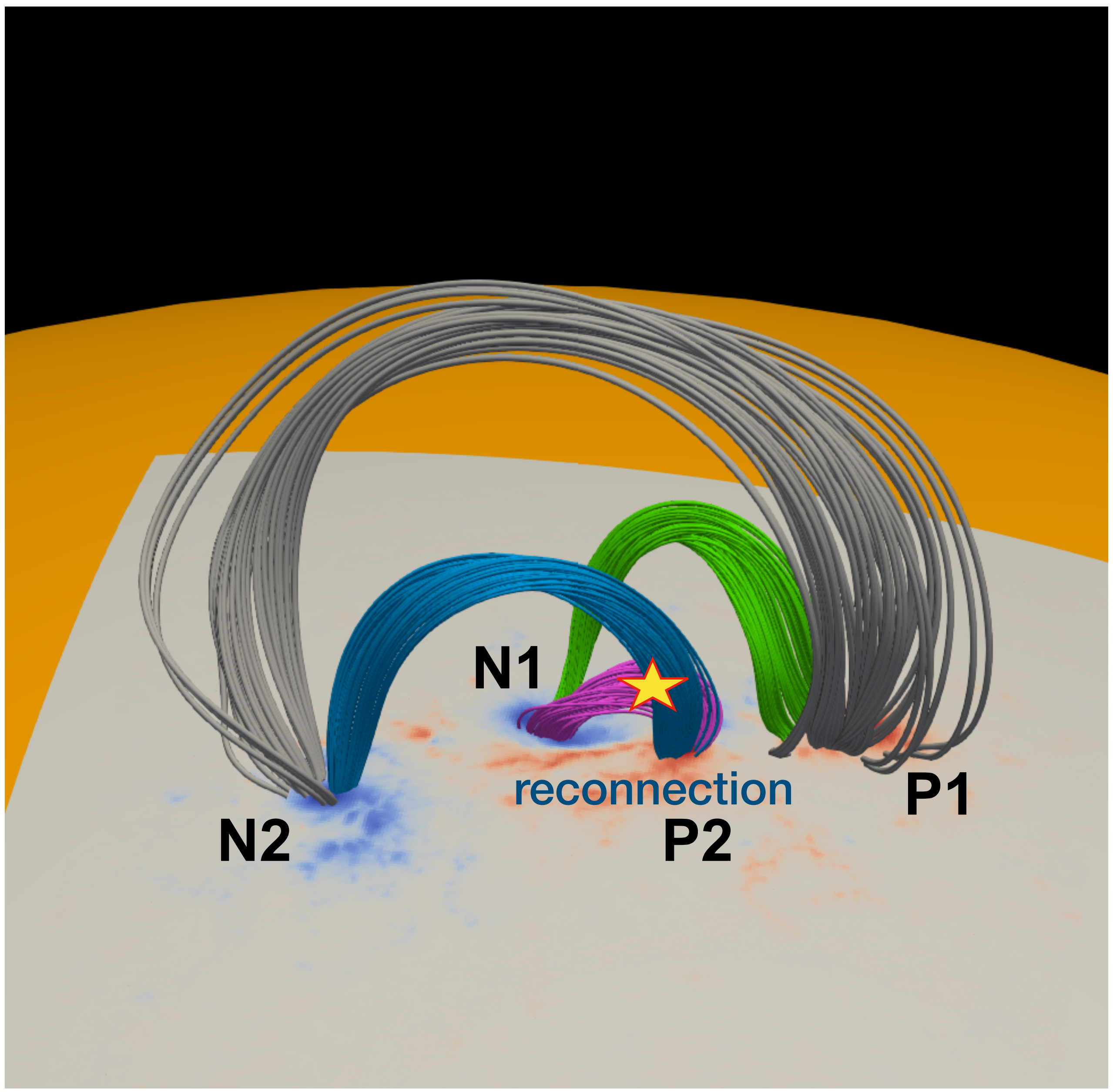
Dark cavity (where twisted **B** is sitting) that leaves the domain.

Eruption!

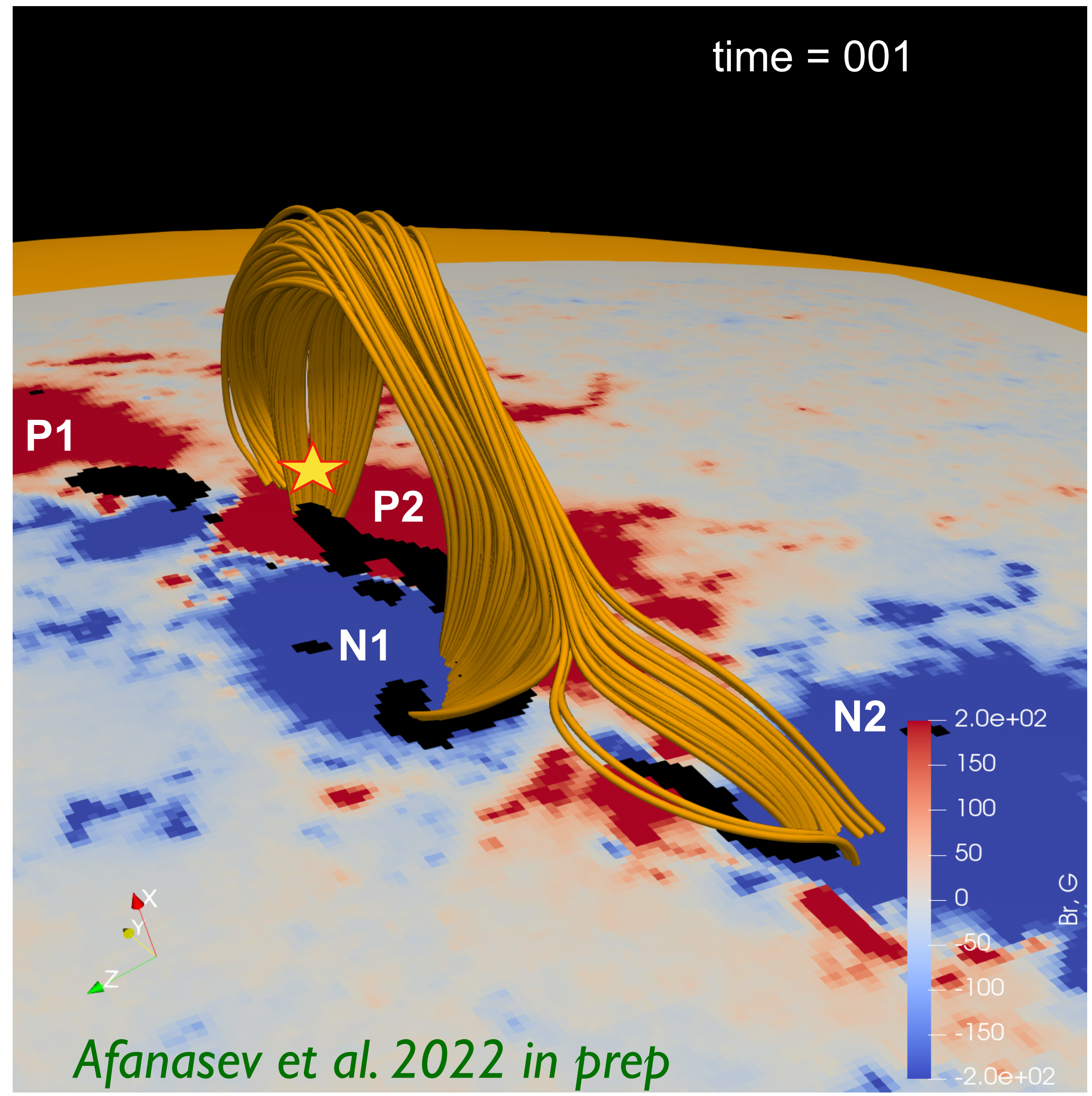
Afanasev et al. 2022 in prep

What's the Trigger? Looks Like Reconnection Between Two Flux Ropes

Pre-eruption: oppositely twisted initial flux rope N1-P2 and N2-P2



Eruption: The two systems reconnect forming new P2-(N1-N2)



What are Key Observations to Constrain Flare Models?

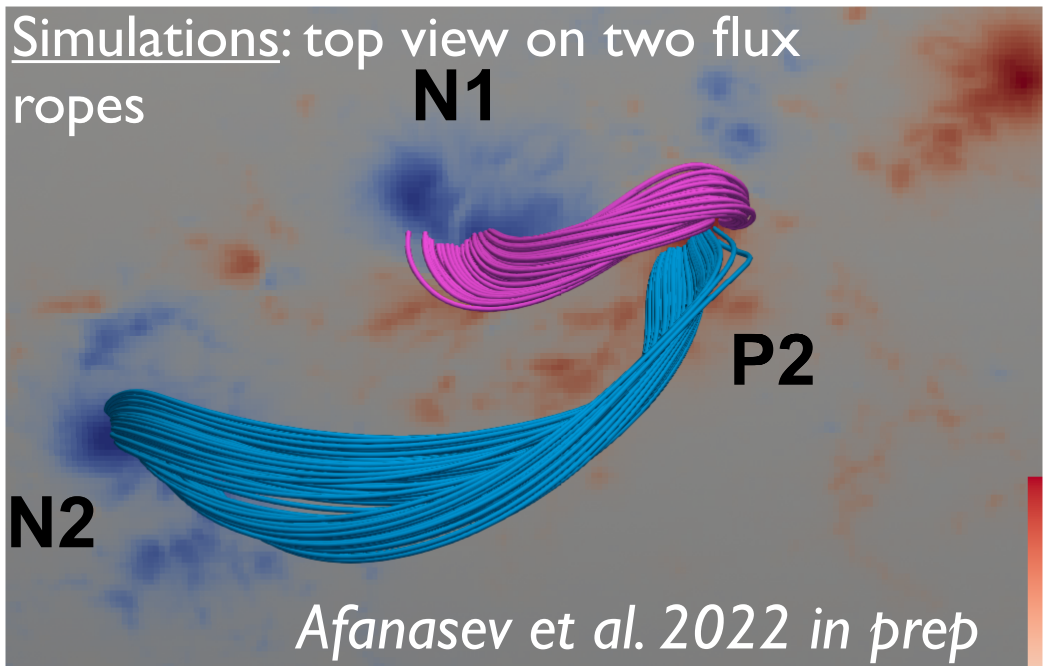
In the next several slides I will talk about two examples:

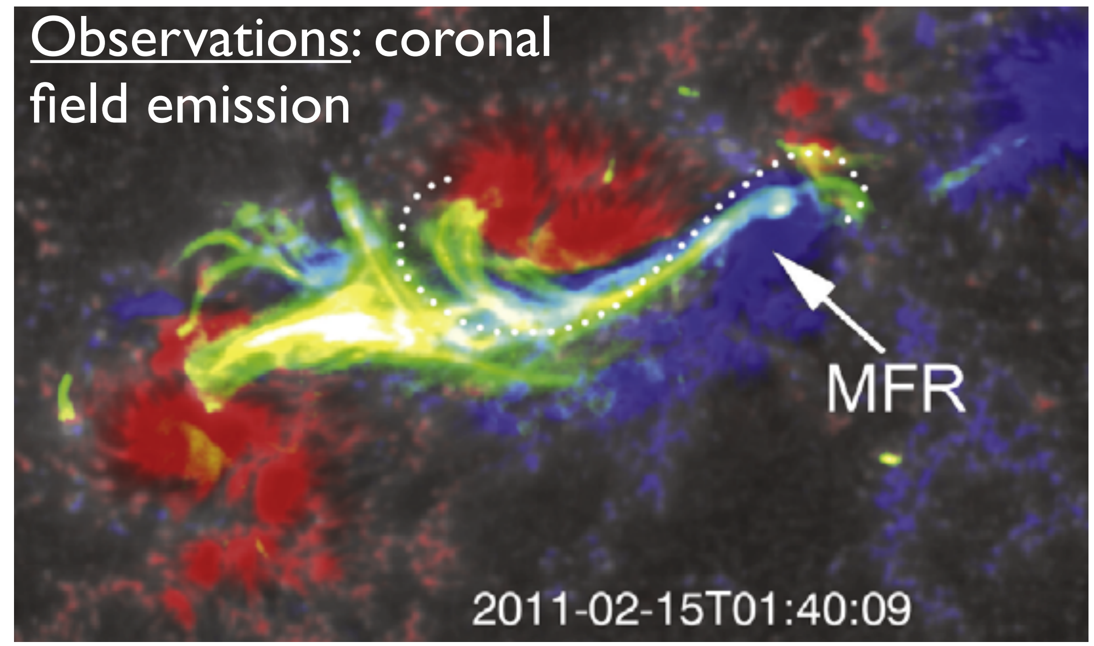
- Observed coronal emission as a proxy for reconnection region dynamics
- Observed chromospheric emission as a proxy for reconnection region magnetism: ribbons

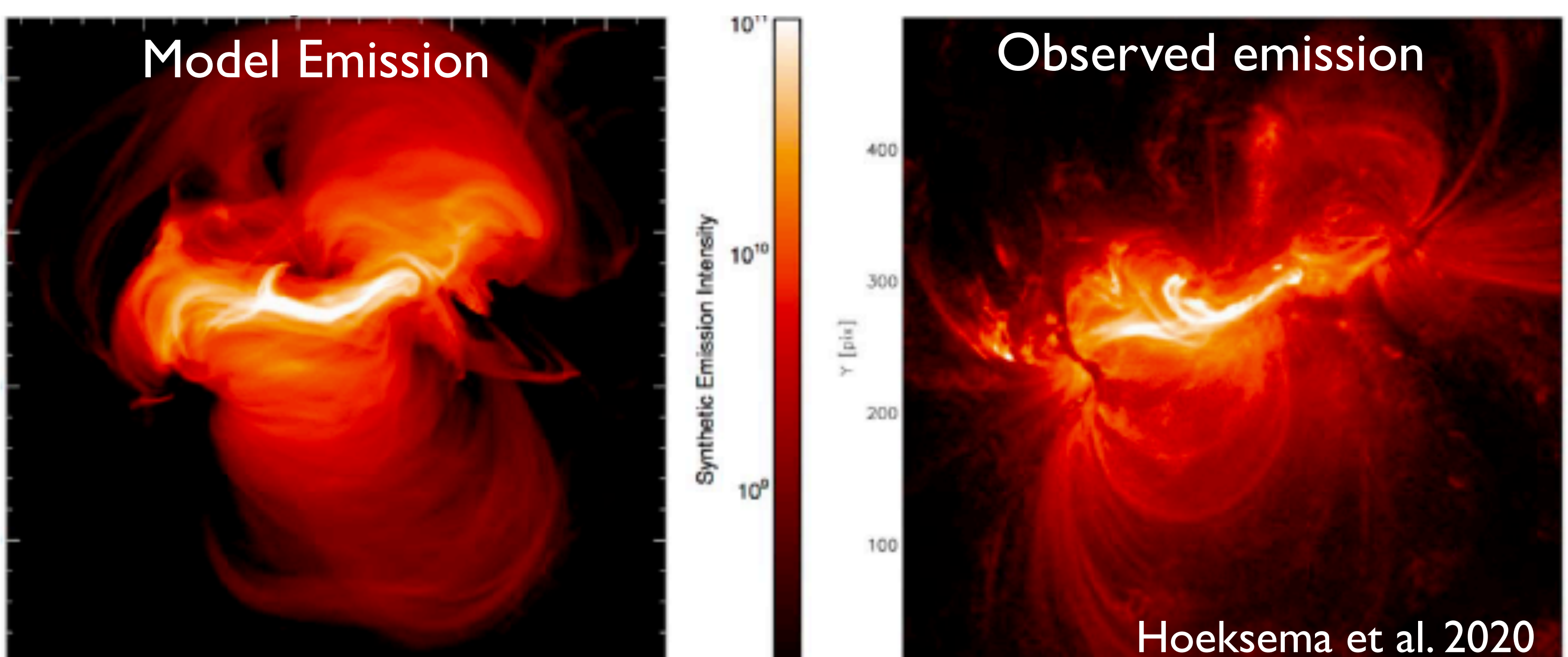
1. Observed Coronal Emission

Tells us about the reconnection region properties, post-flare coronal field dynamics and particles

Chintzoglou et al. 2019





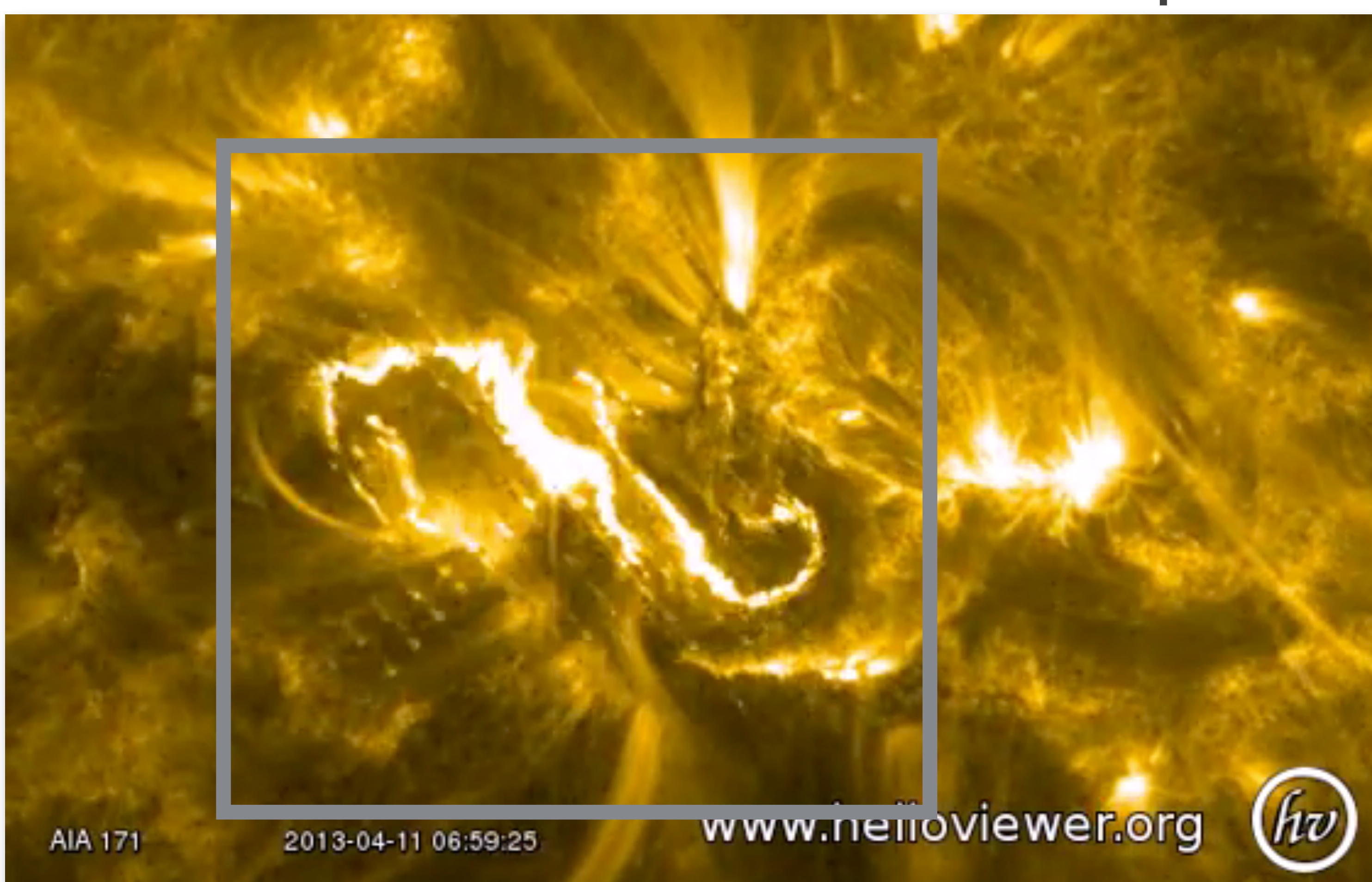


Note, general agreement between simulations & observations

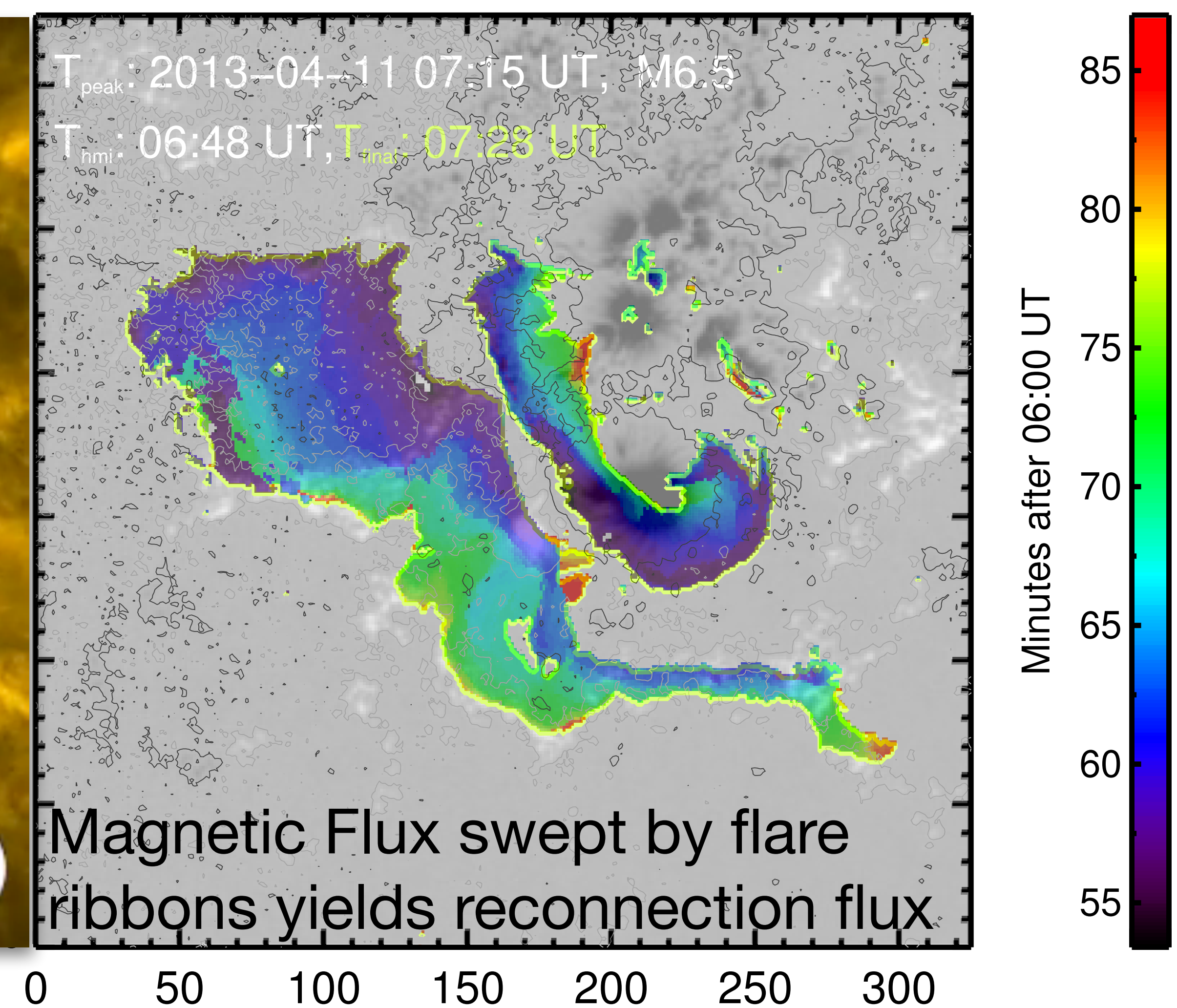
2. Observed Chromospheric Emission or Flare Ribbons

Footpoints of reconnected field lines and serve proxy for reconnection above

M6.5 flare, SDO 171A, chromosphere



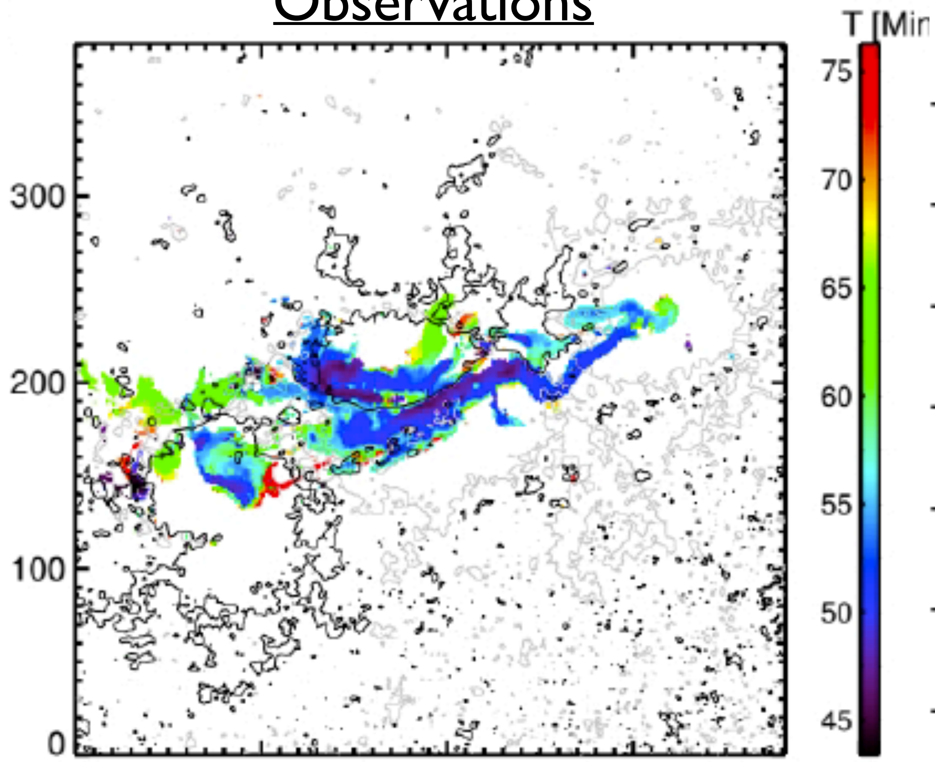
Ribbon evolution over Br contour



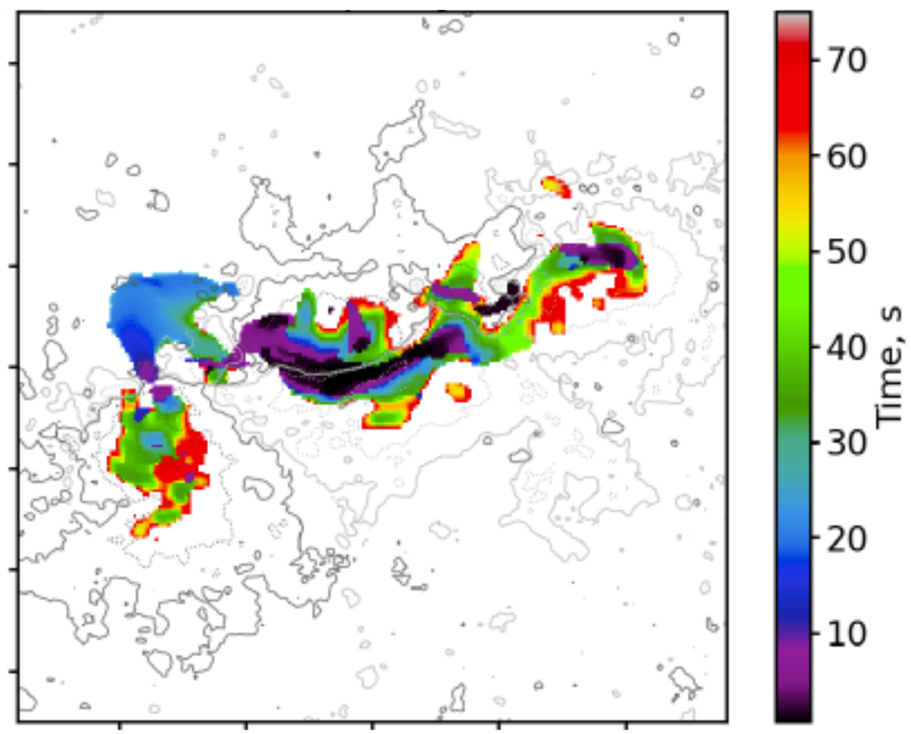
Here is Comparison of Observed And Modeled Flare Ribbons and Reconnection Fluxes

Motion of flare ribbons over B_r map colored by time

Observations



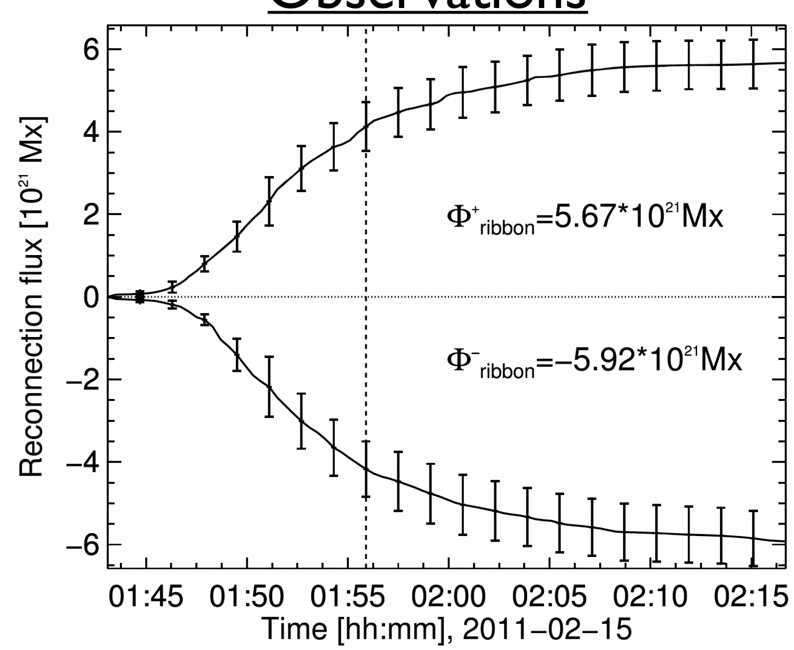
Simulations



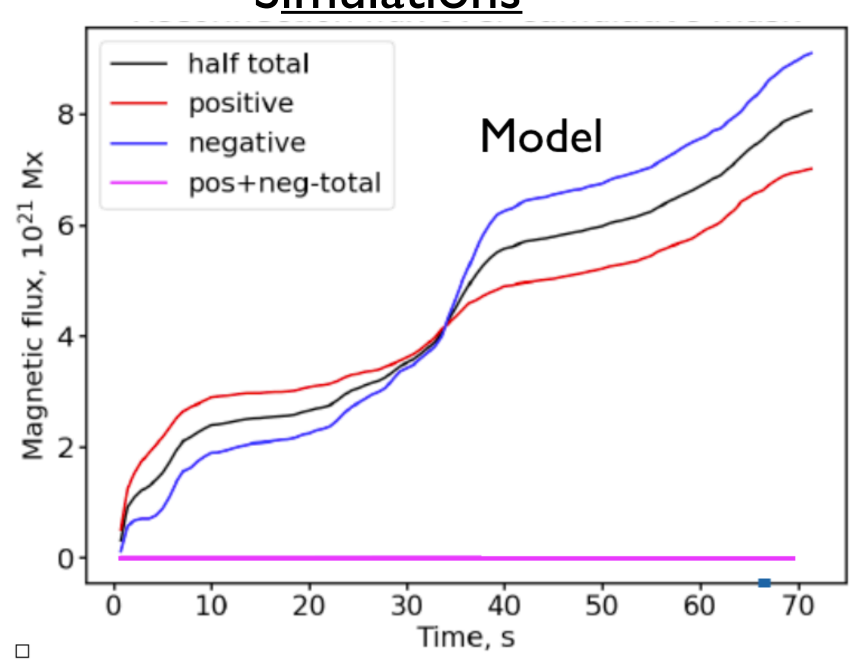
Similar ribbons morphology and evolution

Reconnection flux vs. time

Observations



Simulations



Similar reconnection fluxes: (6 vs. 8) x 10^{21} Mx

Afanasev et al. 2022 in prep

Take-home Message: Data-Driven Models for Coronal Magnetic Fields:

- DD-models allow us to derive the global magnetic-field structure before and during eruption including
  - Gradual storage of magnetic energy ~days;
  - Formation of sheared and twisted magnetic field structures before the eruption;
  - Sudden energy release due to reconnection;
- *Main drawback so far*:
  - Computationally expensive! Only few events!
  - Use simplified physics => do not capture details of energy release, e.g. currently cannot predict flare timing.

For our ISSI effort me and Andrei Afanasev will

- Run magnetofrictional simulation for a selected active region as it evolves over the disk
- We will use HMI observations (B, Vdopp and derived PDFI electric fields to) for the lower boundary conditions from t=0 till t=t(interest).
- We will use potential field as an initial condition at t=0
- Requirements for the AR: emerging on the visible side of the disk (as AR 11158) or has a simple structure so that B(t=0)=Bp is a valid assumption