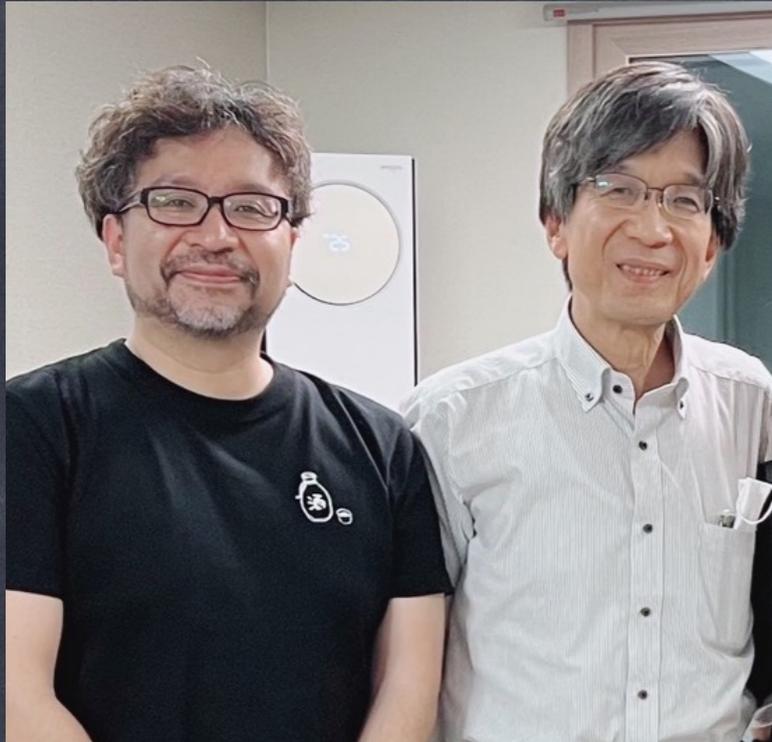
The background is a collage of four images: top-left shows a bright sun and a satellite; top-right shows a server room with blue and green lights; bottom-left shows a large white dome structure on a rocky shore; bottom-right shows a 3D simulation of colorful magnetic field lines.

Data-based Magnetohydrodynamic Simulations for Solar Eruptions

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Center for Solar-Terrestrial Research,
New Jersey Institute of Technology
Satoshi.Inoue@njit.edu

Who am I?



Name: Satoshi INOUE (Assistant Prof.)

Affiliation: Center for Solar-Terrestrial Research, New Jersey Institute of Technology.

Ph.D. : Hiroshima University (2006: Under Prof. Kanya Kusano)

Research Interest: Modeling of the coronal magnetic field, MHD simulation of solar eruptions.



Solar MHD Group: Postdoc x2, Grad students x2, Undergraduate students x 3, High school student x1

References

Referece I:Coronal Magnetic Field

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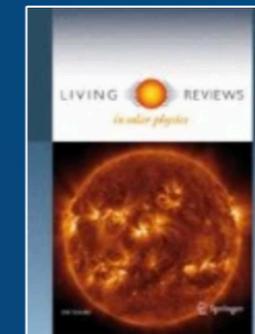
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Abstract



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Magnetohydrodynamics modeling of coronal magnetic field and solar eruptions based on the photospheric magnetic field

[Satoshi Inoue](#) 

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Abstract

In this paper, we summarize current progress on using the observed magnetic fields for magnetohydrodynamics (MHD) modeling of the coronal magnetic field and of solar eruptions, including solar flares and coronal mass ejections (CMEs). Unfortunately, even with the existing state-of-the-art solar physics satellites, only the photospheric magnetic field can be measured. We first review the 3D extrapolation of the coronal magnetic fields from

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Reference III: Data-driven MHD Sim.

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Data-driven modeling of solar coronal magnetic field evolution and eruptions

Chaowei Jiang • Xueshang Feng • Yang Guo • Qiang Hu

Open Access • Published: April 01, 2022 • DOI: <https://doi.org/10.1016/j.xinn.2022.100236> •

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Public summary

Public summary

Graphical abstract

- Data-driven models offer a novel avenue to study solar coronal magnetic fields

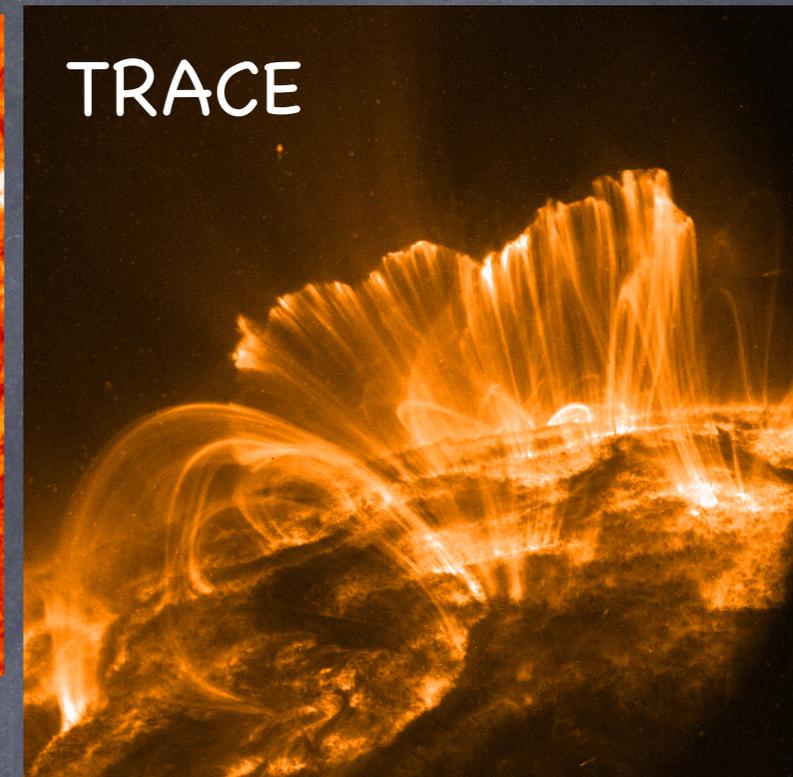
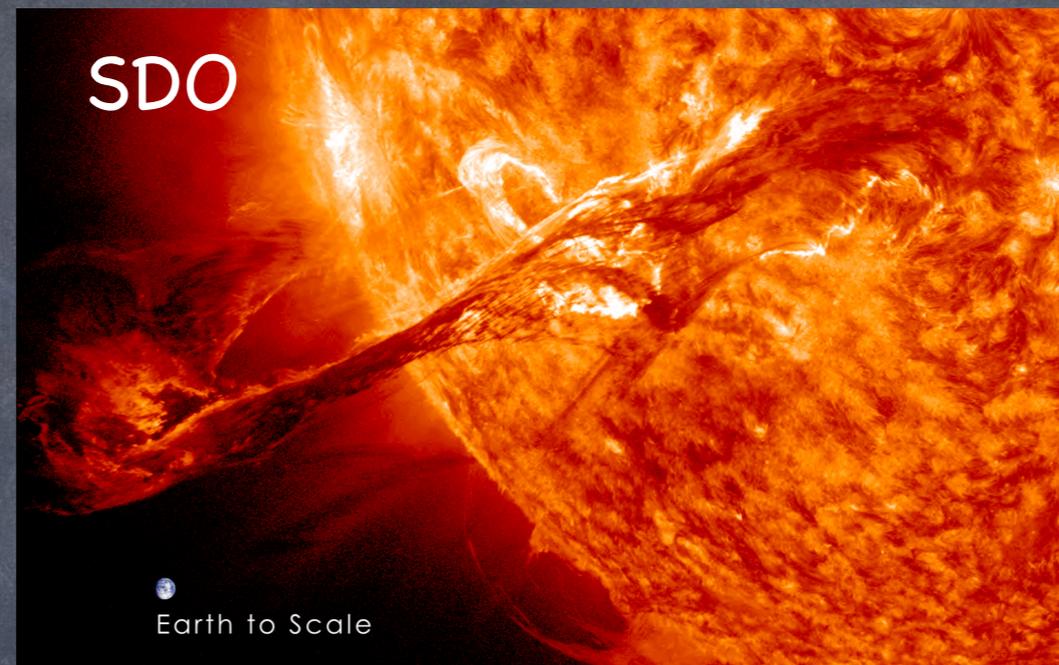
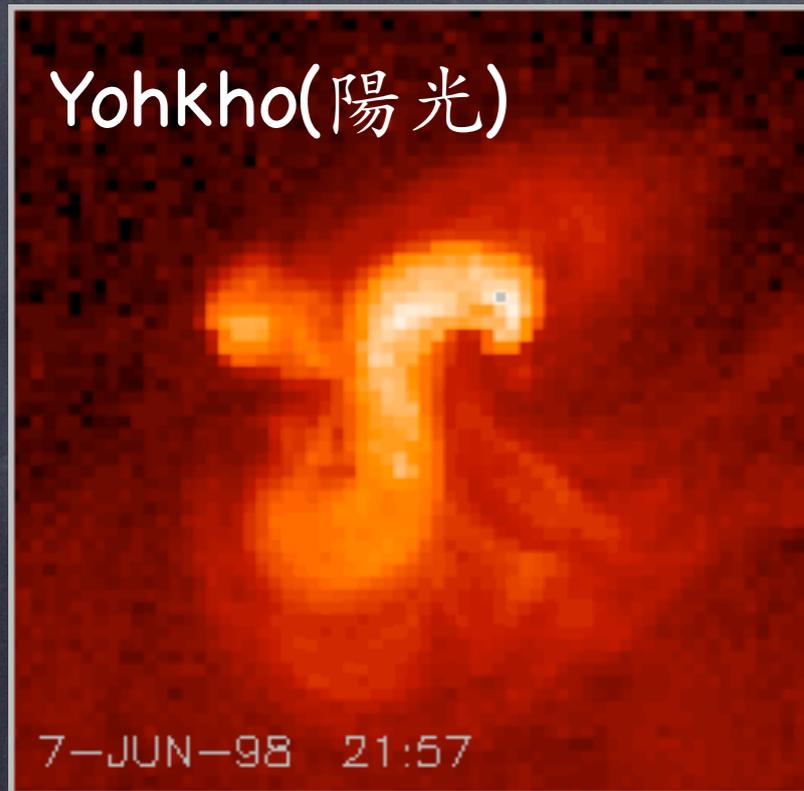
Keywords

- Such numerical models are directly driven by continuously

ADVERTISEMENT

Introduction

Solar Coronal Magnetic Field



- ✓ The plasma structure changes significantly, before, during, and after the eruption.

What is this energy source?

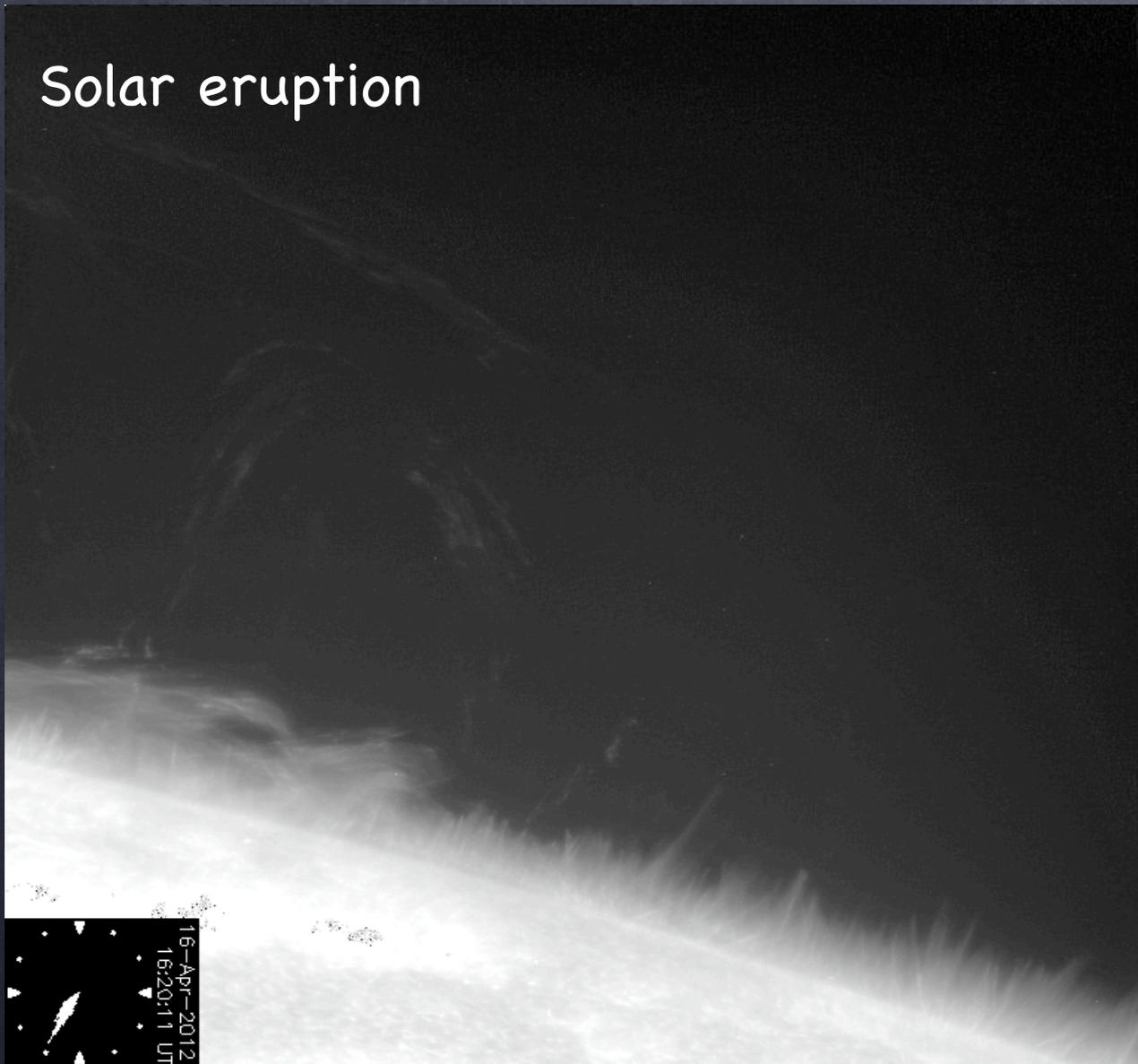
Magnetic energy accumulated in the coronal magnetic field!

Dynamics of Solar Coronal Magnetic Field

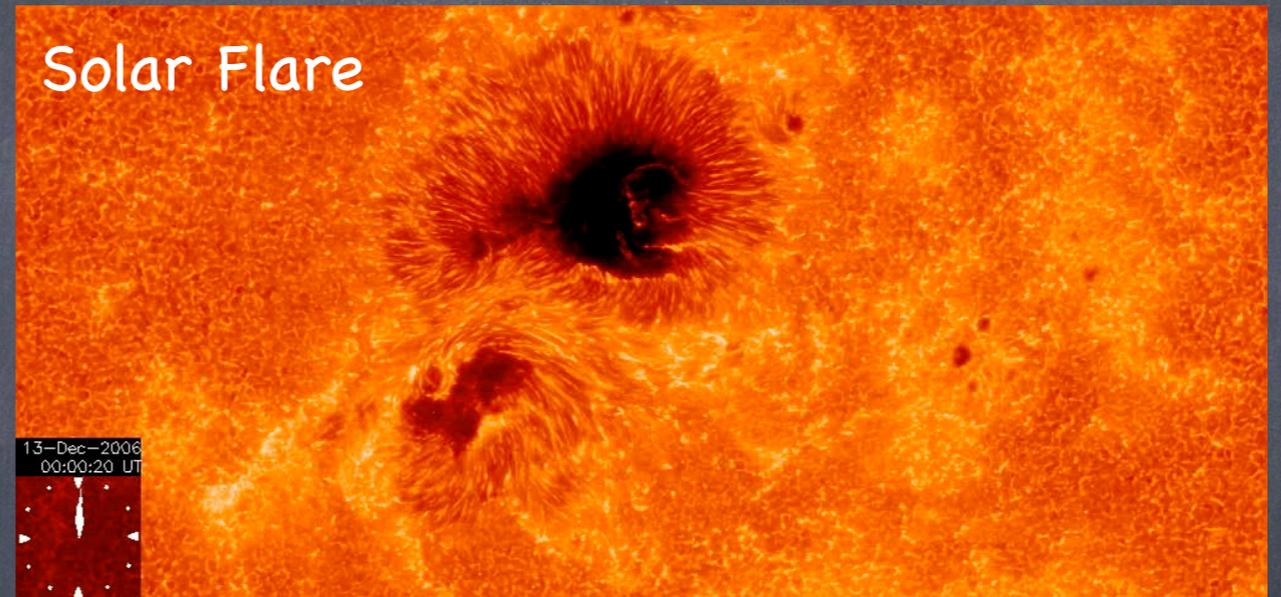
Courtesy of T.J. Okamoto

Courtesy of T.J. Okamoto

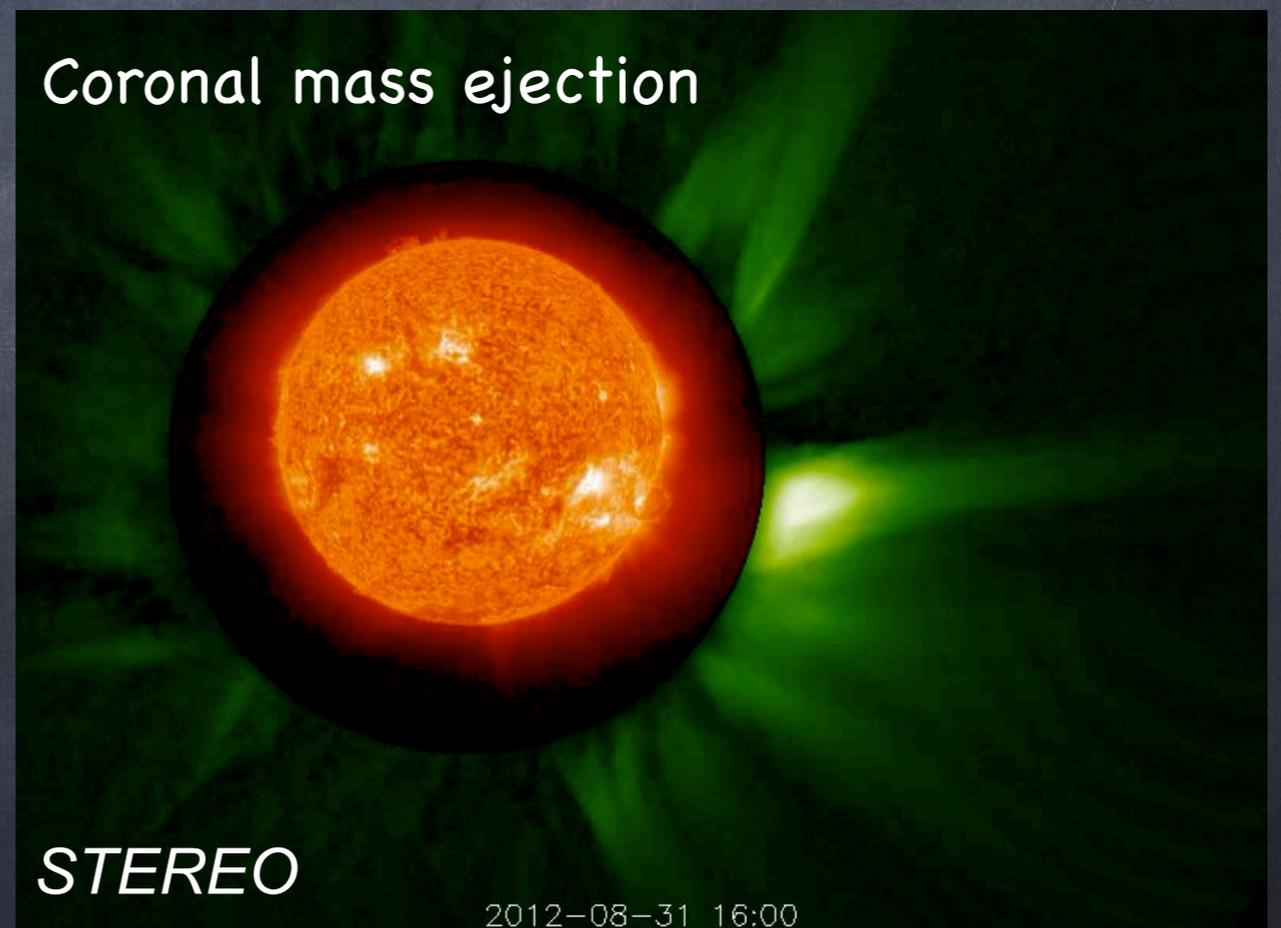
Solar eruption



Solar Flare

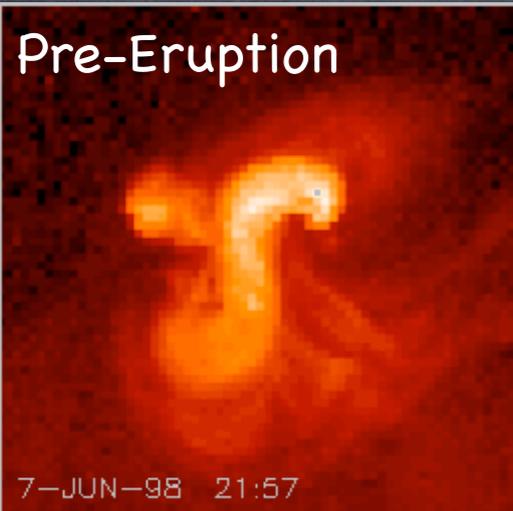


Coronal mass ejection



Dynamics of Solar Coronal Magnetic Field

Observations



Solar flare (during the eruption.)

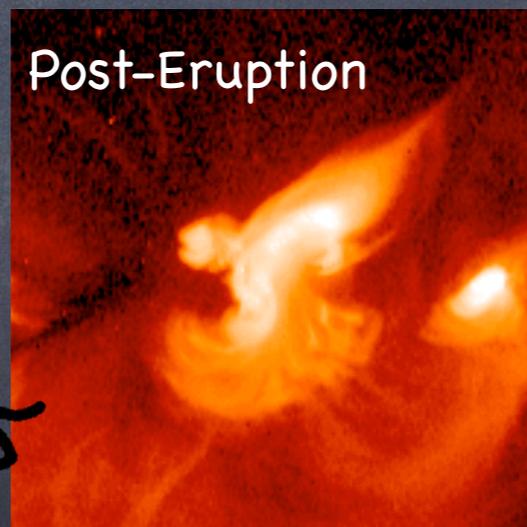
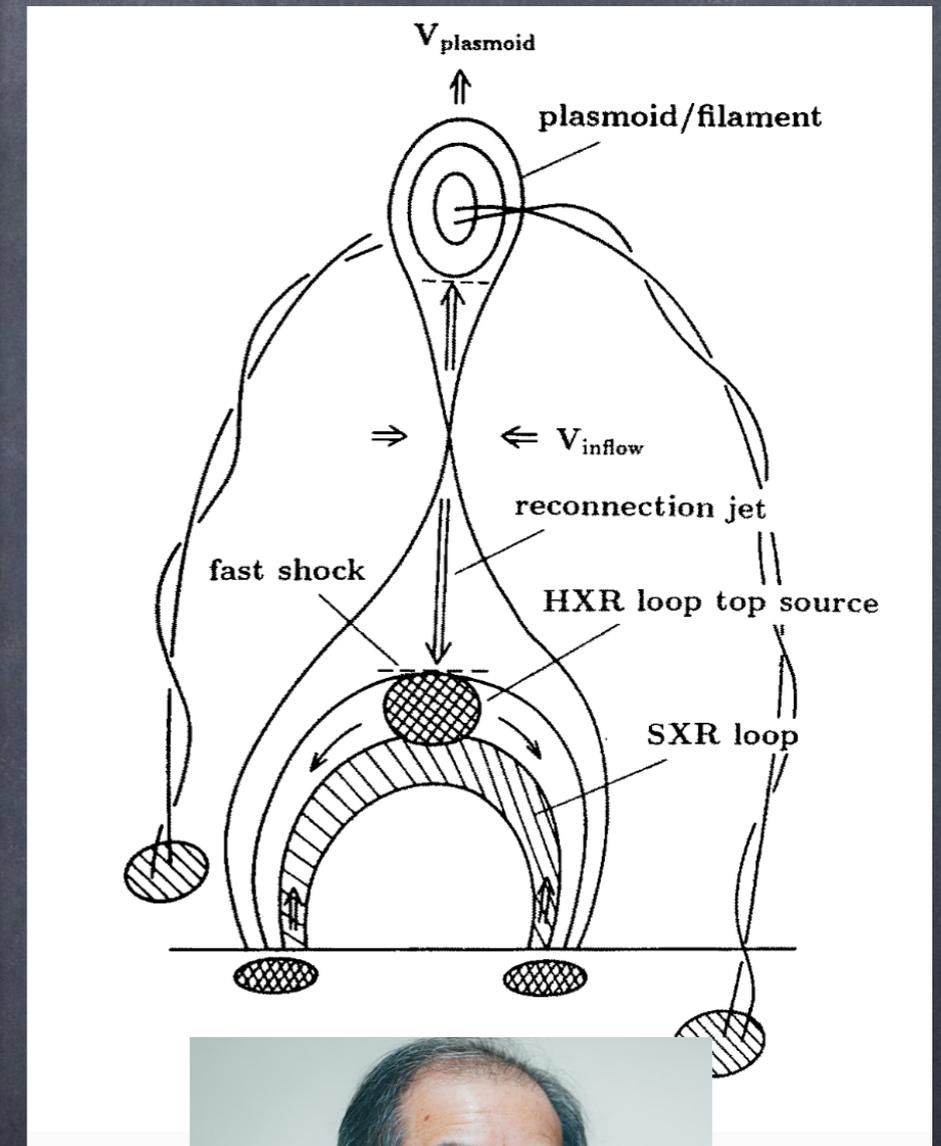


Image (Shibata 1996)

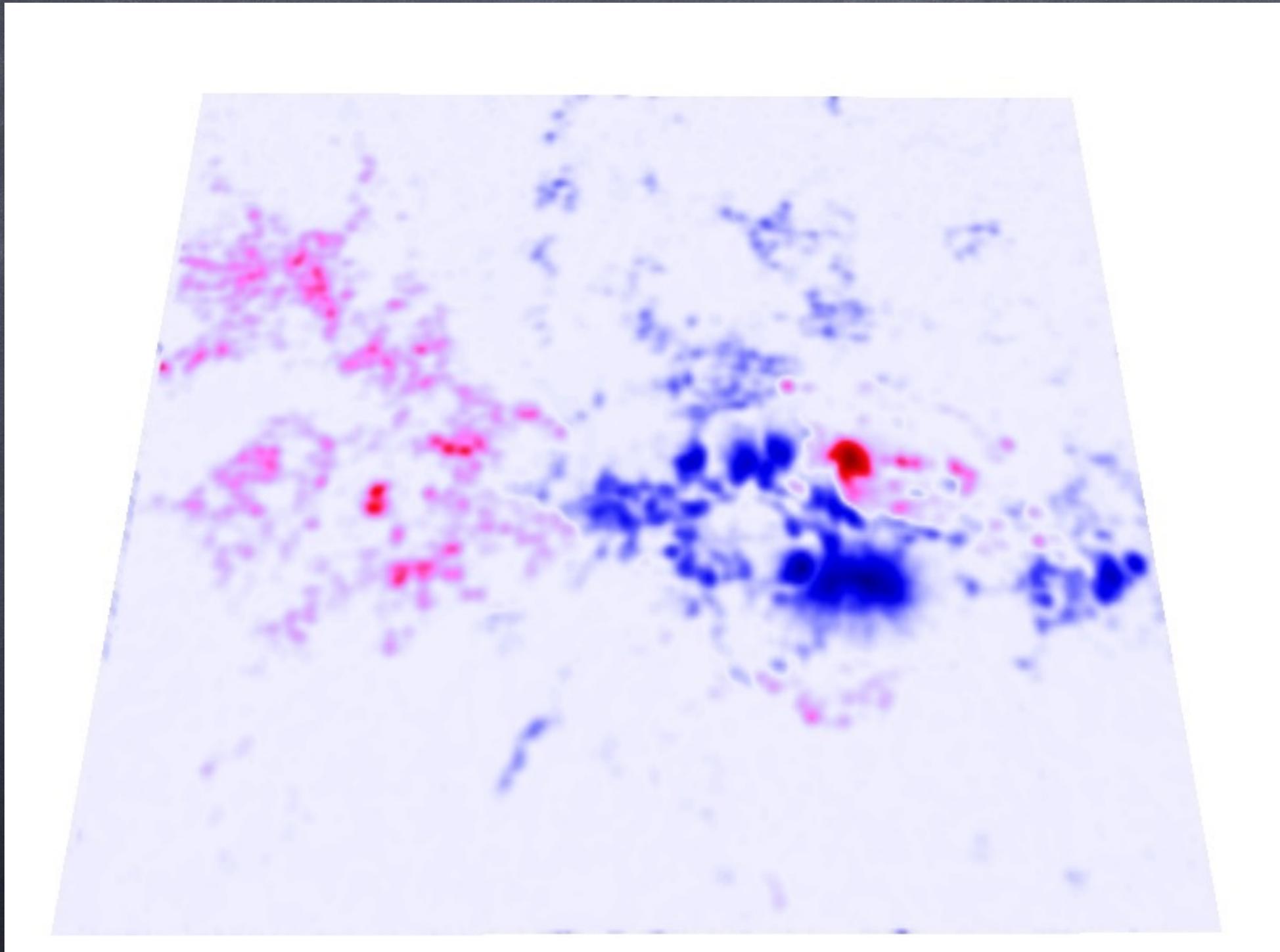


Observations provide only partially information!



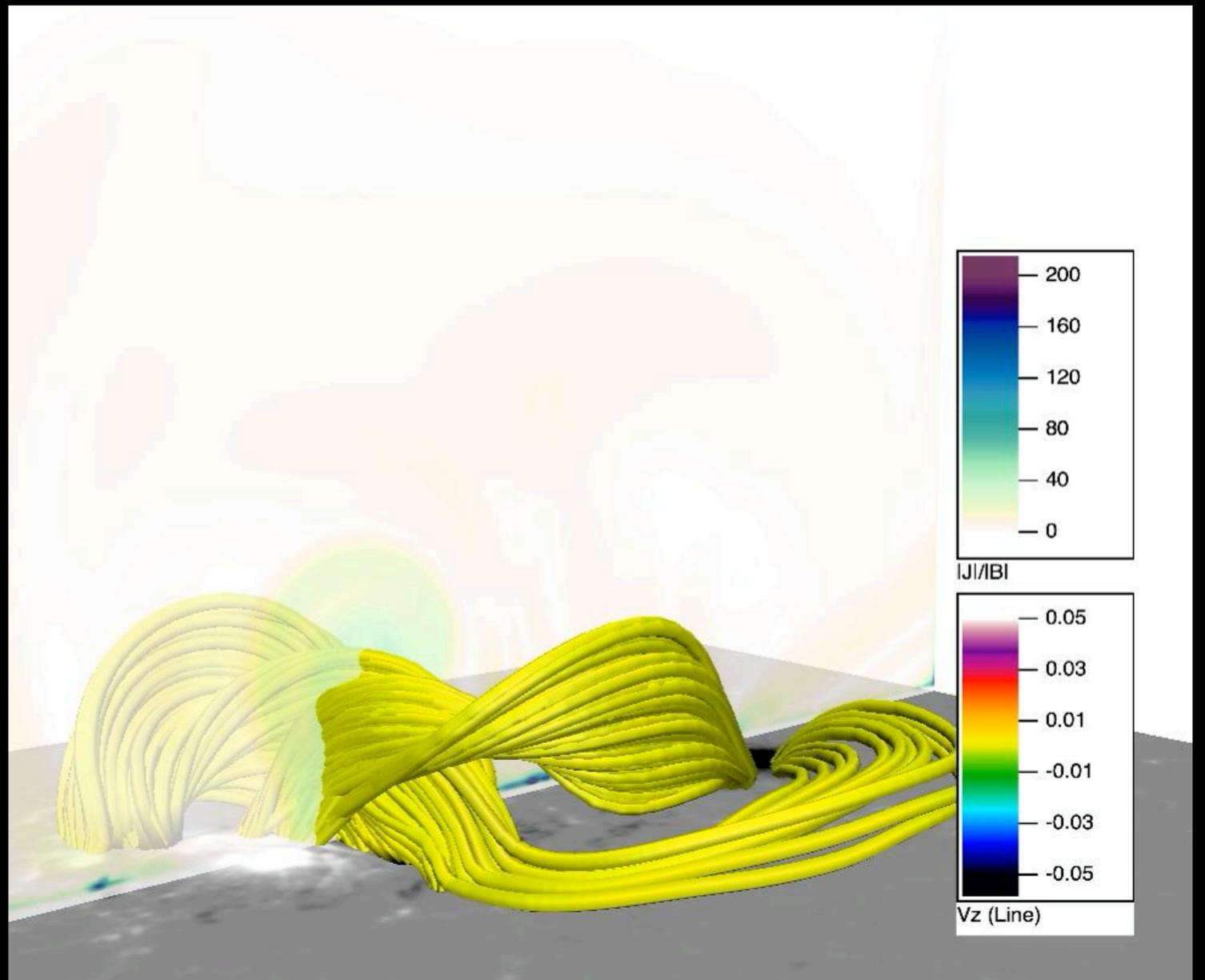
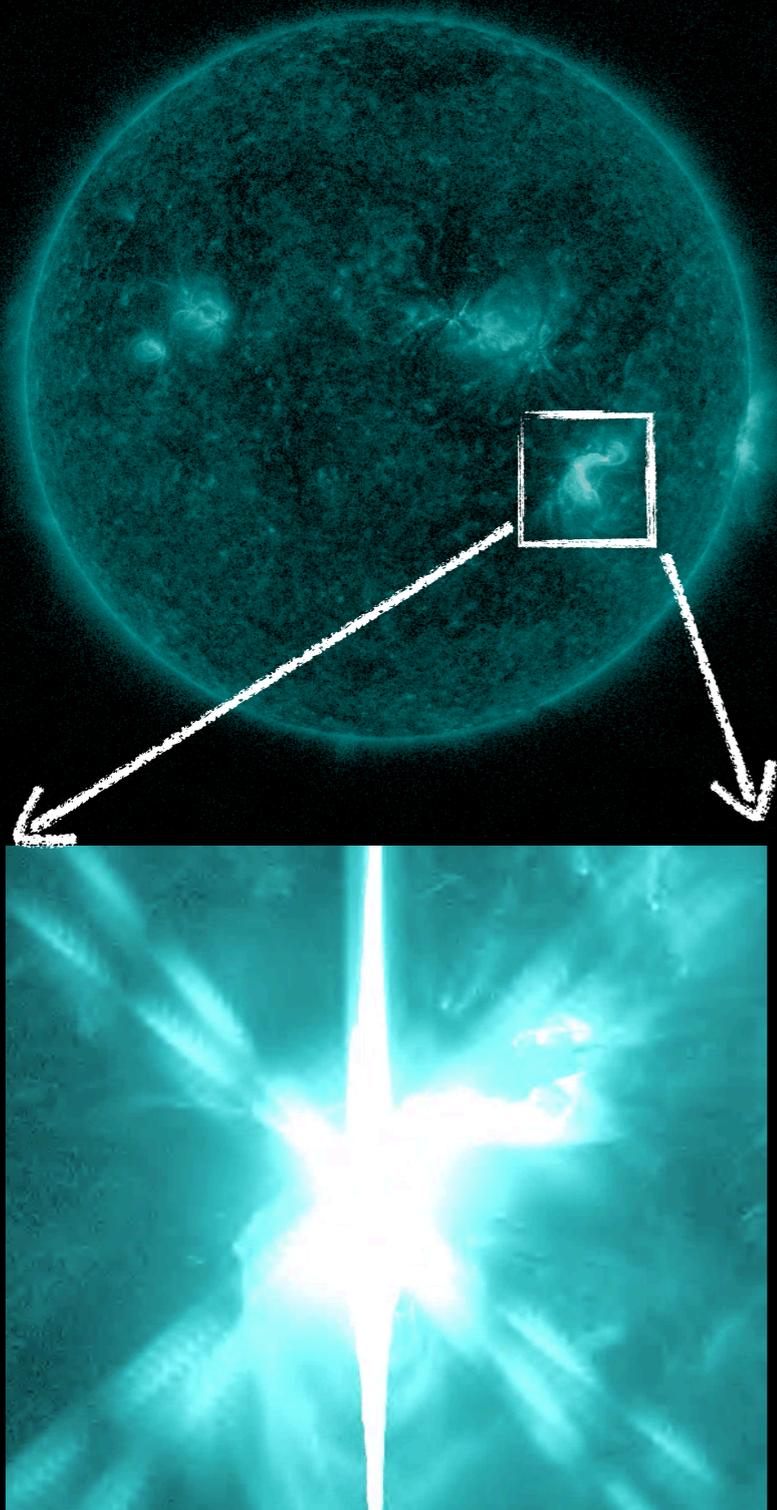
Solar magnetic field observation

Observation provides only the magnetic field of the solar surface!



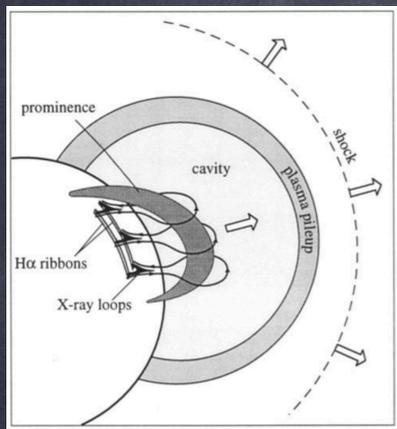
In this Lecture

How do we extrapolate the 3D magnetic field ?
How does solar eruption occurs?

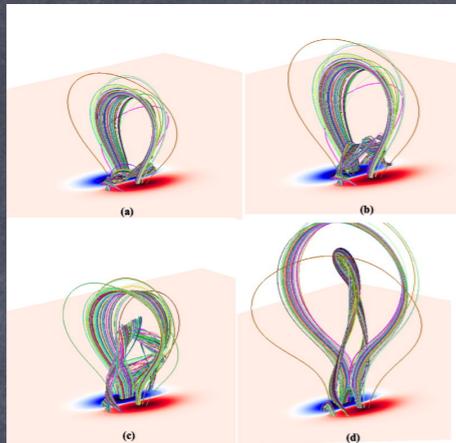


History of modeling of solar eruption

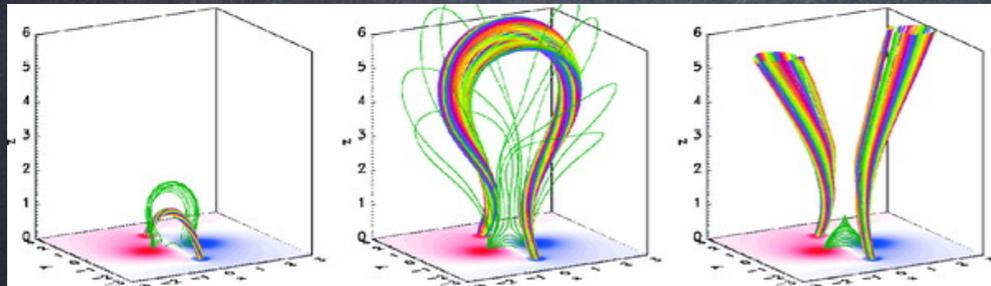
2000



Forbes+ 2000



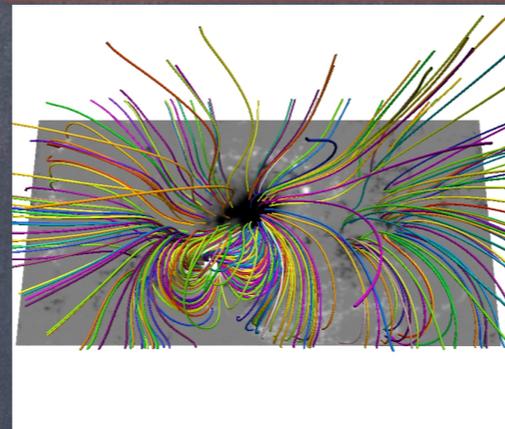
Amari + 2003



Török & Kliem 2005

2006

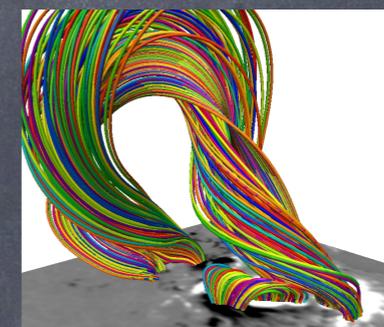
Nonlinear-Force-Free Field (NLFFF)



Inoue + 2011

2013

Data-Constrained Sim.

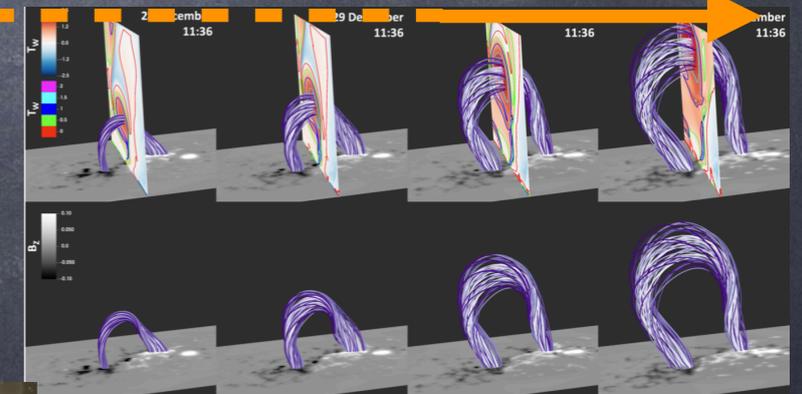


Inoue + 2018

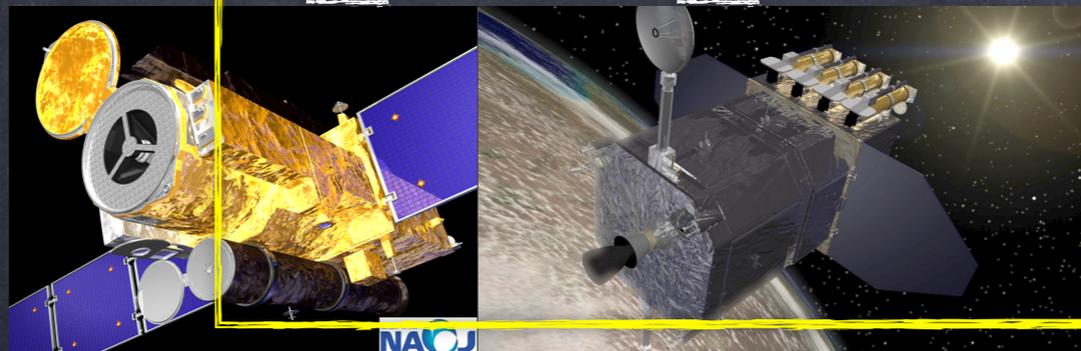
2016

2020

Data-driven Sim.



Price + 2020



NAOJ

Modeling of "Static" Solar Coronal Magnetic Field

$$\mathbf{J} \times \mathbf{B} = 0$$

Force-free Field.

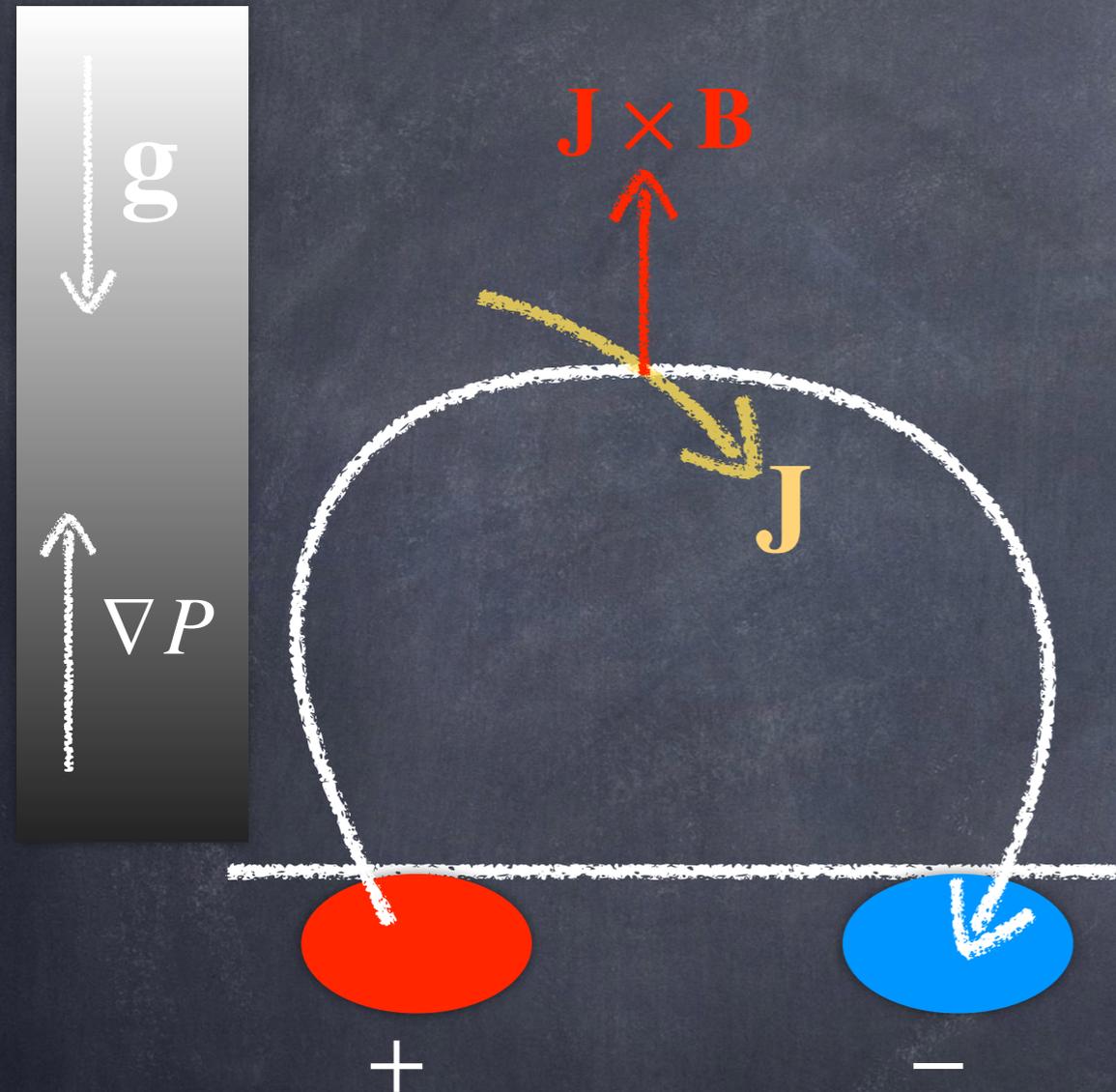
Magnetohydrostatic Condition

What force is working on a coronal loop?

$$\mathbf{J} \times \mathbf{B} - \nabla P + \rho \mathbf{g}$$

If the coronal loop meets the equilibrium condition

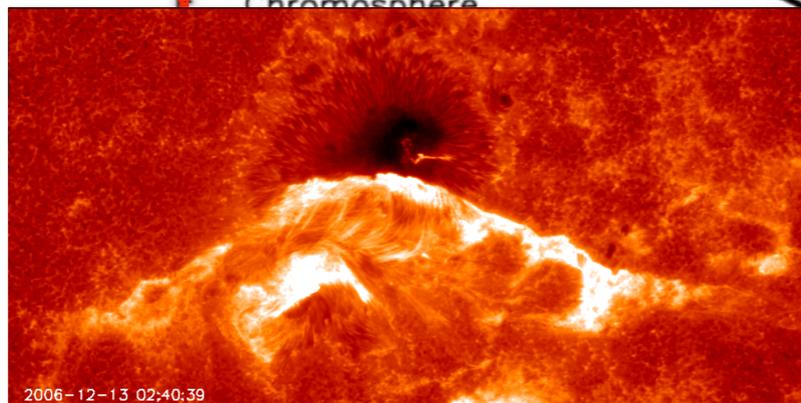
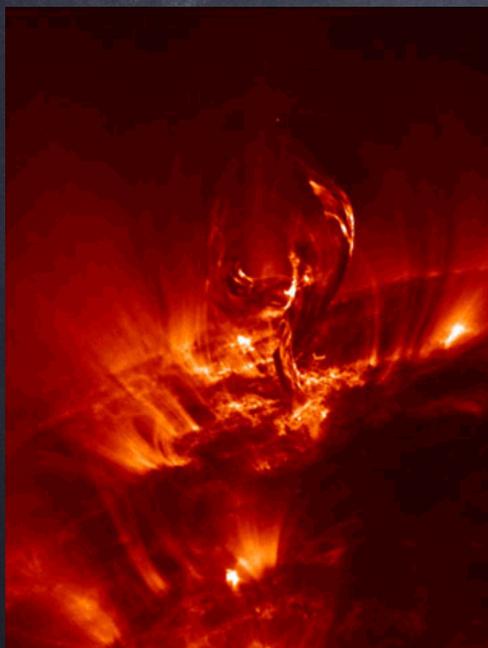
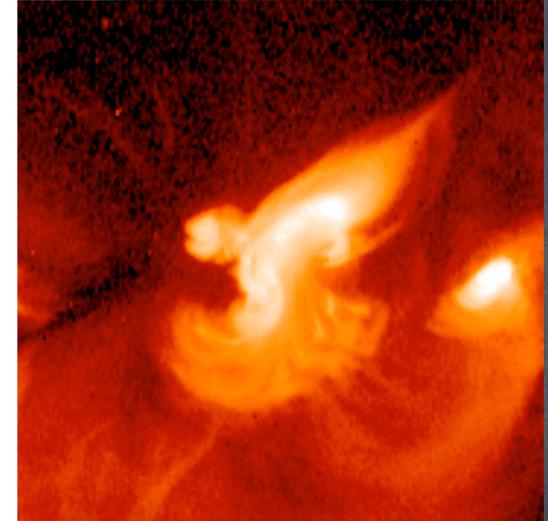
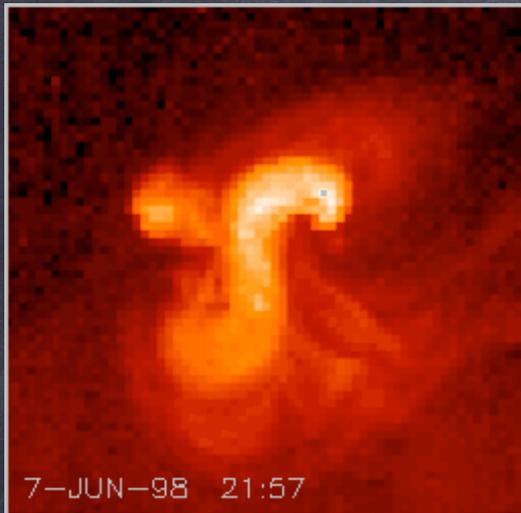
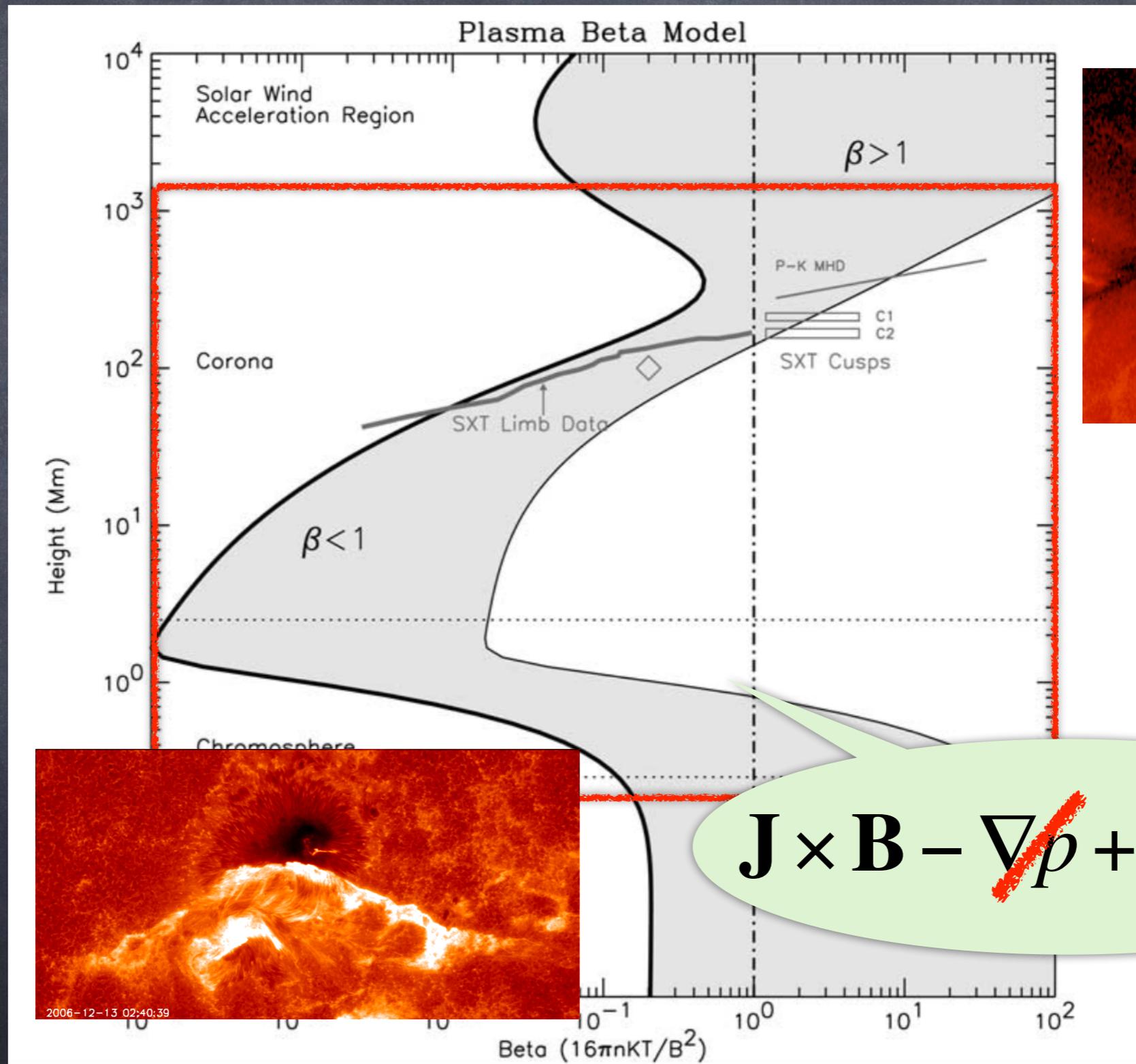
$$\mathbf{J} \times \mathbf{B} - \nabla P + \rho \mathbf{g} = 0$$



We have to find a solution, \mathbf{B} , satisfying above equation.

Plasma $\beta = (P/B^2)$ in the Solar Corona

Gary, G. A., 2001, Solar Physics



Force-free field ($\mathbf{J} \times \mathbf{B} = \mathbf{0}$)

Description of a Force-free field.

$$\mathbf{J} \times \mathbf{B} = \mathbf{0}$$

Magnetic field \mathbf{B} is parallel to the electric current \mathbf{J} .

$$\mathbf{J} = \alpha(\mathbf{r})\mathbf{B}$$

α is a coefficient, but it is a function of space.

$$\nabla \times \mathbf{B} = \alpha(\mathbf{r})\mathbf{B}$$

Ampere's law

Nonlinear equation...

Let's approximate (linearize) it!!

✓ Potential field: Electric current $\mathbf{J} = \mathbf{0}$. $\longrightarrow \nabla \times \mathbf{B} = \mathbf{0}$

✗ A unique solution is guaranteed if the normal component of \mathbf{B} is given at the boundary (see supplementary materials.).

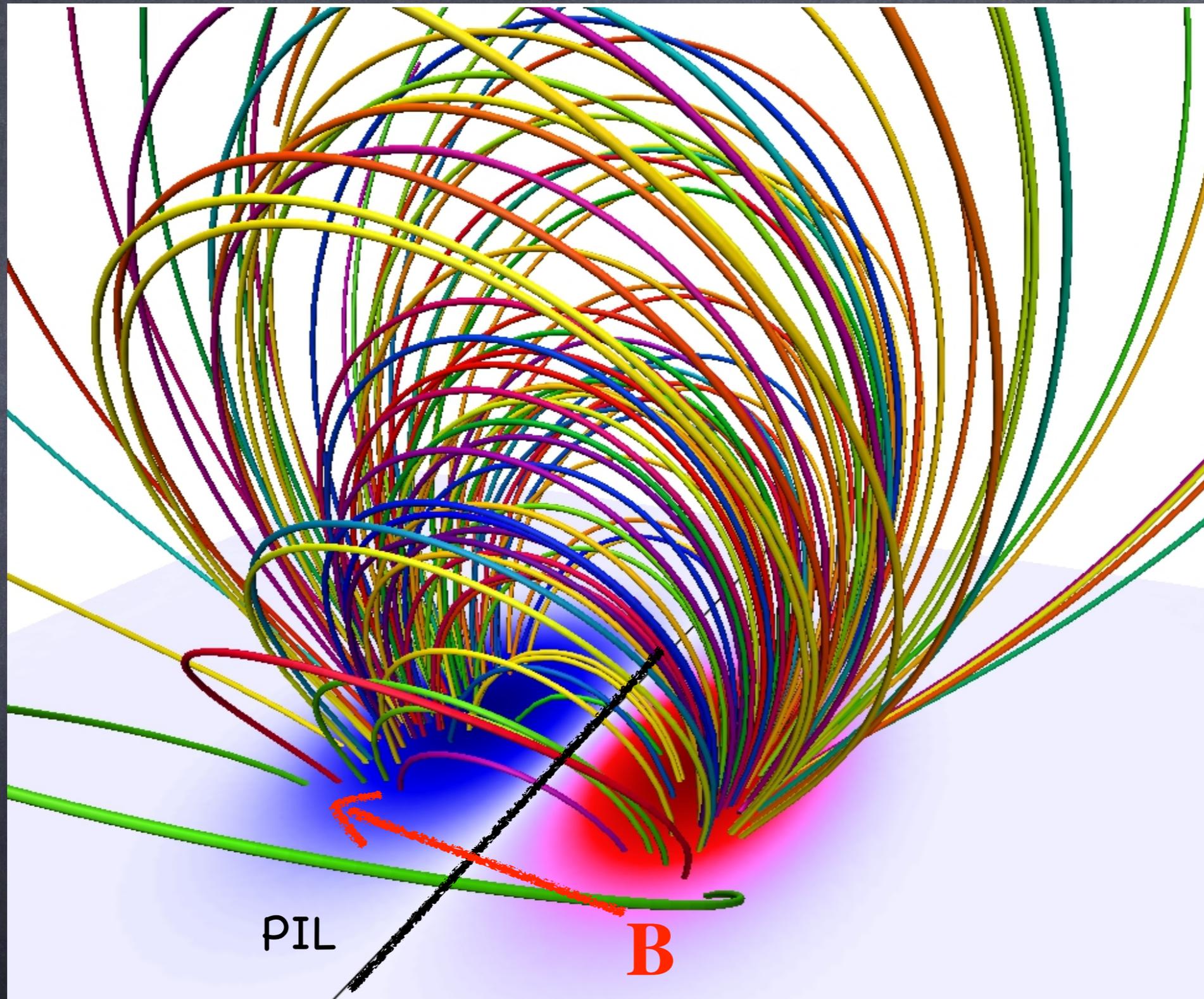
✗ The potential field has no free magnetic energy that cannot produce the active phenomena (see supplementary materials.).

✓ Linear force-free field $\alpha = \text{constant}$. $\longrightarrow \nabla \times \mathbf{B} = \alpha\mathbf{B}$

✗ An analytical solution exists under the given B.C B_n and α . The magnetic field of the entire active region is sheared...

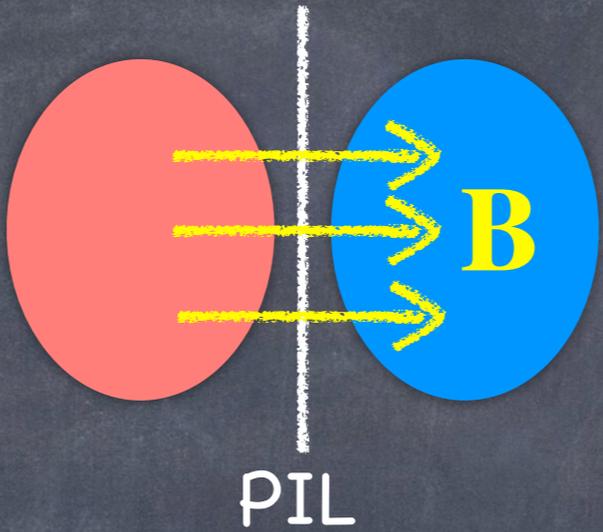


Potential Field



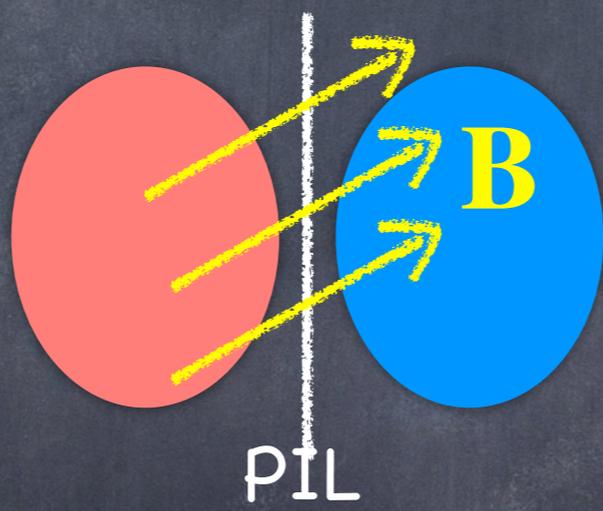
Potential Field, Linear Force-Free, Nonlinear Force-Free

✓ Potential field
 $\nabla \times \mathbf{B} = 0$

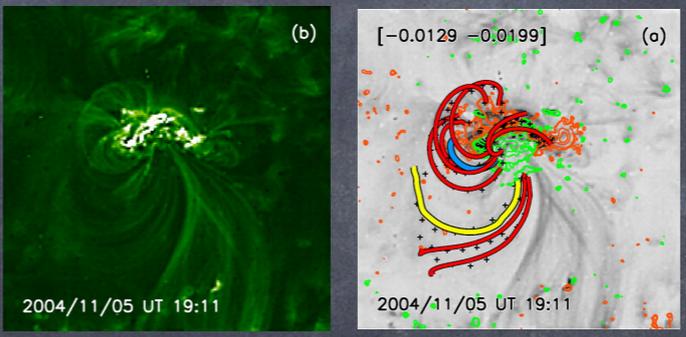


- PIL is perpendicular to the field lines.
- Unique solution is guaranteed.
- Minimum energy state under the given BC.

✓ Linear force-free field
 $\nabla \times \mathbf{B} = \alpha \mathbf{B}$



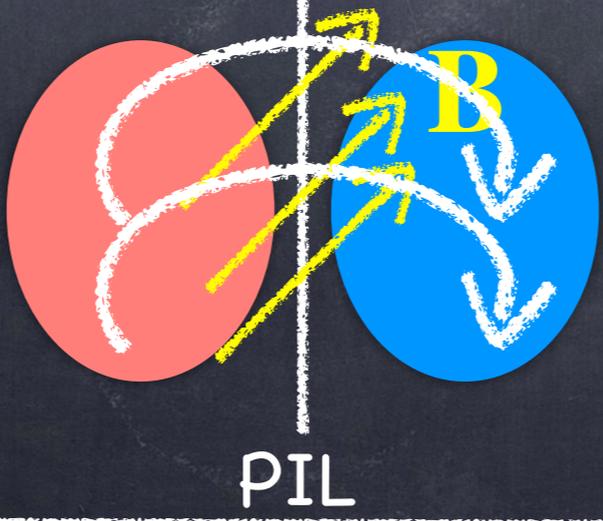
- The field lines are sheared.
- All field lines are sheared.



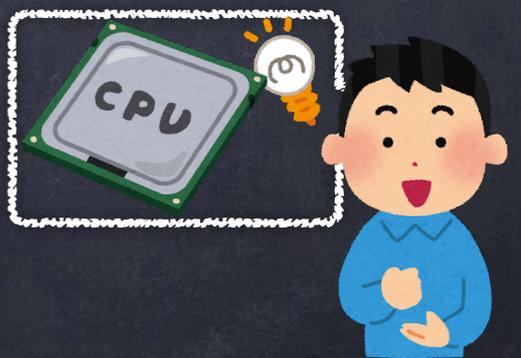
Lim et al. 2007

α is a parameter to fit the observation.

✓ Non-Linear force-free field
 $\nabla \times \mathbf{B} = \alpha(\mathbf{r})\mathbf{B}$



Nonlinear equation...



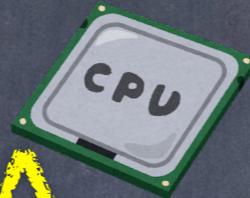
Nonlinear Force-free Field (NLFFF) Extrapolations

Nonlinear Force-free Field (NLFFF) Extrapolation

Attempting to find the solution of the force-free equation.

$$\mathbf{J} \times \mathbf{B} = 0 \quad \text{or} \quad \nabla \times \mathbf{B} = \alpha(\mathbf{r})\mathbf{B}$$

Region of
interest



Okay, I solve the equation until the solution can reach the force-free condition.

We solve an equation to satisfy $\mathbf{J} \times \mathbf{B} = 0$ and $\nabla \cdot \mathbf{B} = 0$.

Optimization method.
Grad-Rubin method.
MHD relaxation method.
⋮
⋮
⋮

Solar surface

The observed B_x, B_y, B_z are given at the bottom surface.

The Common Issues in the NLFFF Extrapolation

- ✓ $\mathbf{J} \times \mathbf{B} = 0$ is a nonlinear equation, so **hard to find the analytical solution.**
- ✓ Photospheric mag \mathbf{B} has three components, B_x, B_y, B_z . They do **NOT satisfy the force-free condition (Metcalfe 1994, Kawabata 2020 etc.).**
- ✓ Potential and linear force-free field extrapolations require only B_z component. The other components are automatically determined. When the other components are given, **no guarantee uniqueness of the solution, or the existence of the solution itself.**
- ✓ There are many methods to extrapolate the force-free magnetic field. Which one is best?

MHD-Relaxation Method

Valori + 2005, Jiang + 2011, Inoue+2014...

We solve zero-beta MHD equations until the Mag B reaches the (near) force-free state.

Zero-beta MHD equations

$$\checkmark \rho(\mathbf{r}, t) = |\mathbf{B}(\mathbf{r}, t)|$$

$$\checkmark \rho \frac{\partial \mathbf{v}}{\partial t} = -\rho \mathbf{v} \cdot \nabla \mathbf{v} + \mathbf{J} \times \mathbf{B} + \nu \nabla^2 \mathbf{v}$$

$$\checkmark \frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B} - \nabla \phi$$

$$\checkmark \frac{\partial \phi}{\partial t} = -c_h^2 \nabla \cdot \mathbf{B} - \frac{c_h^2}{c_p^2} \phi$$

$$\checkmark \nabla \times \mathbf{B} = \mathbf{J}$$

1. The potential field is prepared as the initial condition. This is extrapolated from the observed B_z .
2. Tangential components B_x and B_y are replaced by the observed values at the solar surface.
3. The zero-beta MHD equations are iterated until the magnetic field converges to near the force-free state.

What is $\frac{\partial \phi}{\partial t} = -c_h^2 \nabla \cdot \mathbf{B} - \frac{c_h^2}{c_p^2} \phi$?

Cleaning the errors from Div B (Dedner + 2002).

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B} - \nabla \phi$$

$$\frac{\partial \phi}{\partial t} = -c_h^2 \nabla \cdot \mathbf{B} - \frac{c_h^2}{c_p^2} \phi$$



$$\frac{\partial^2 (\nabla \cdot \mathbf{B})}{\partial t^2} + \frac{c_h^2}{c_p^2} \frac{\partial (\nabla \cdot \mathbf{B})}{\partial t} = c_h^2 \nabla^2 (\nabla \cdot \mathbf{B})$$

$$\frac{\partial^2 (\nabla \cdot \mathbf{B})}{\partial t^2} + \frac{c_h^2}{c_p^2} \frac{\partial (\nabla \cdot \mathbf{B})}{\partial t} = c_h^2 \nabla^2 (\nabla \cdot \mathbf{B})$$



$$\frac{\partial^2 (\nabla \cdot \mathbf{B})}{\partial t^2} = c_h^2 \nabla^2 (\nabla \cdot \mathbf{B})$$

Advection eq. of div B.

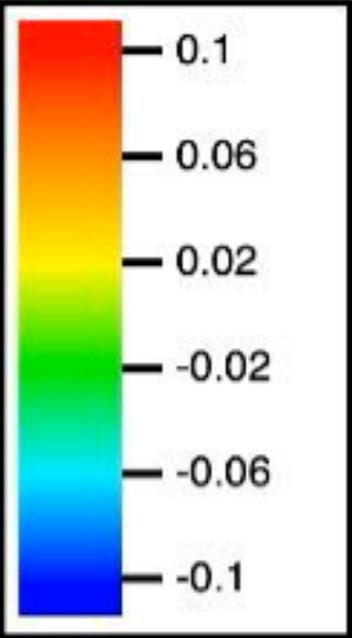
$$\frac{\partial^2 (\nabla \cdot \mathbf{B})}{\partial t^2} + \frac{c_h^2}{c_p^2} \frac{\partial (\nabla \cdot \mathbf{B})}{\partial t} = c_h^2 \nabla^2 (\nabla \cdot \mathbf{B})$$



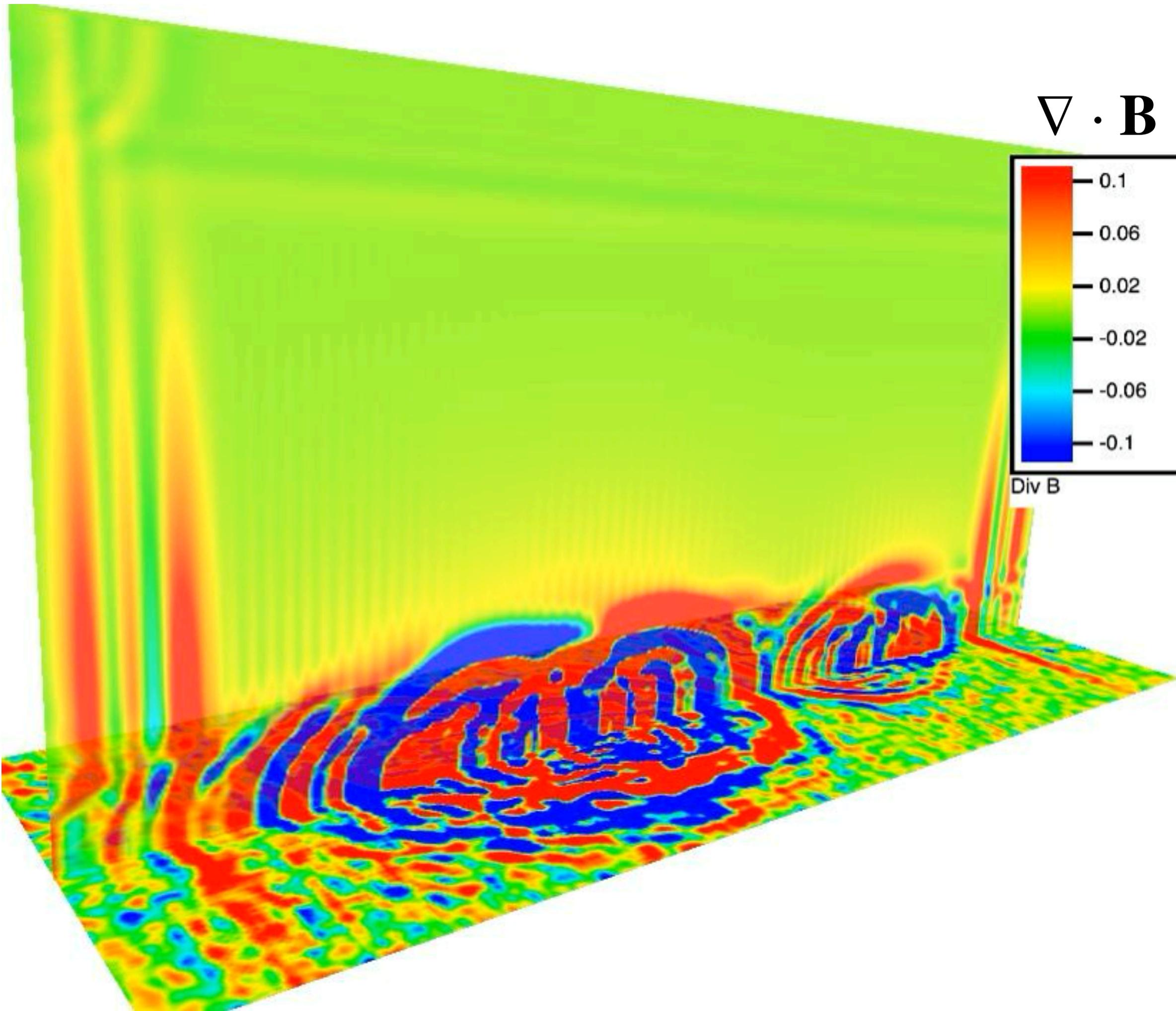
$$\frac{c_h^2}{c_p^2} \frac{\partial (\nabla \cdot \mathbf{B})}{\partial t} = c_h^2 \nabla^2 (\nabla \cdot \mathbf{B})$$

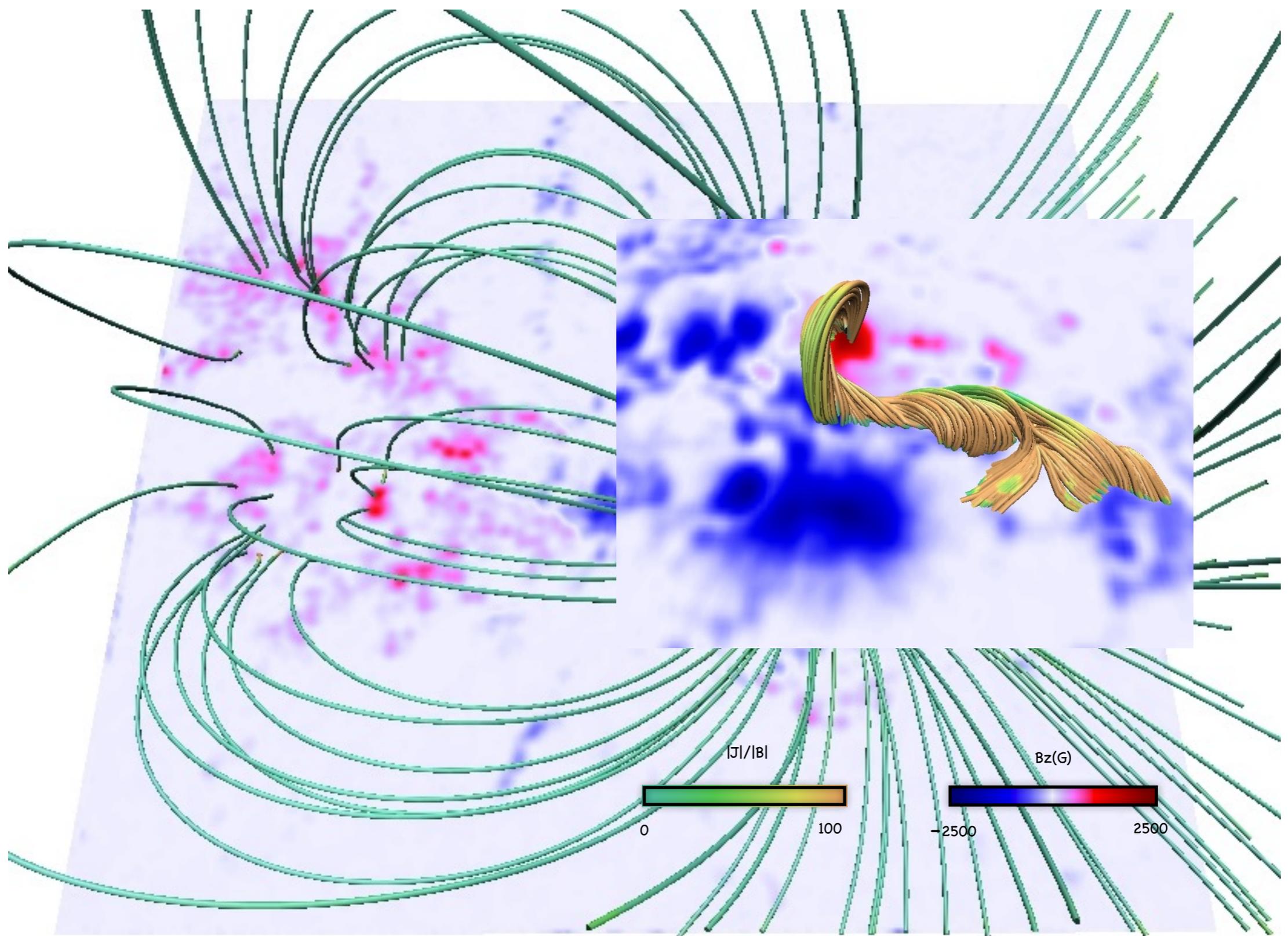
Diffusion eq. of div B.

$$\nabla \cdot \mathbf{B}$$



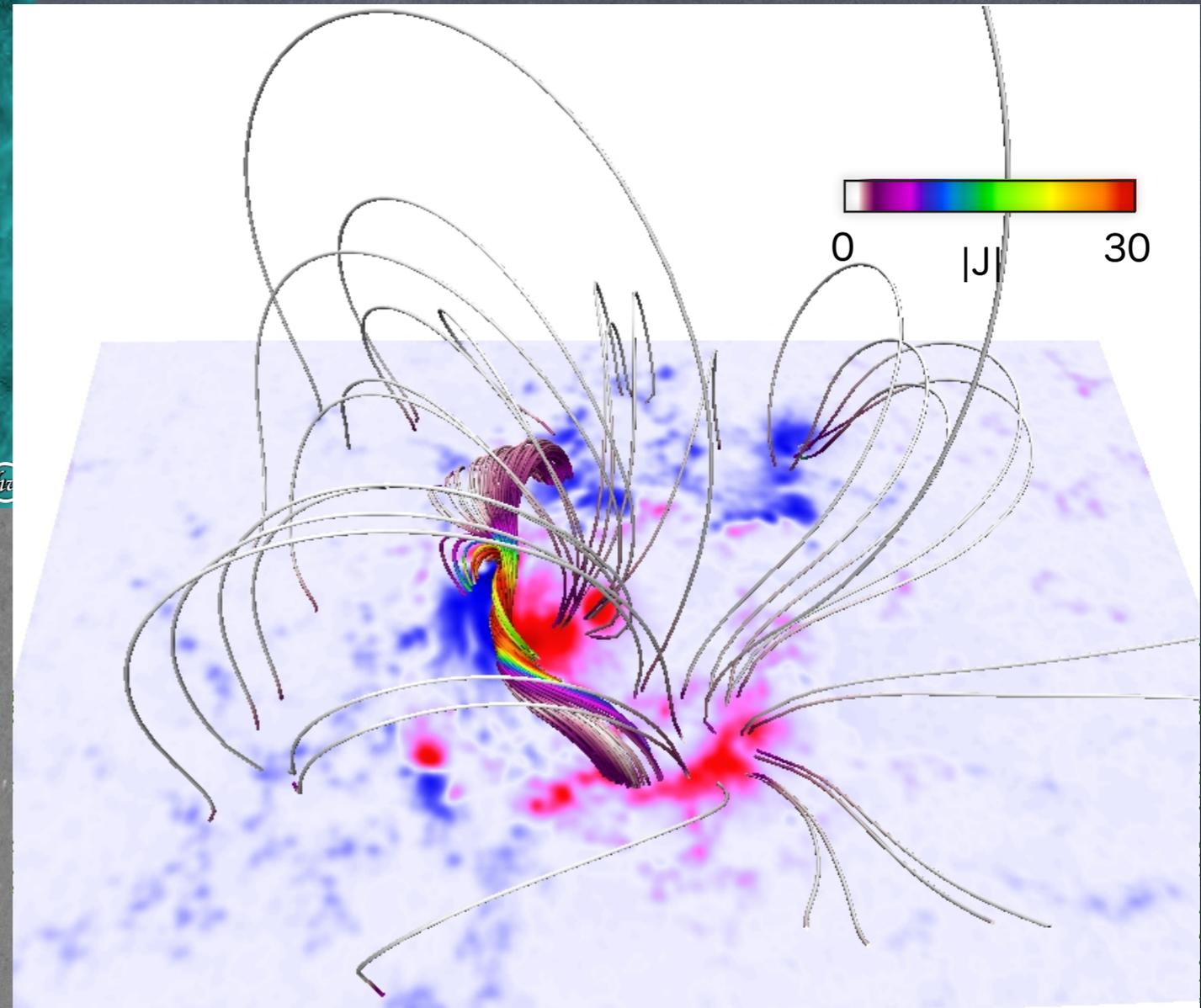
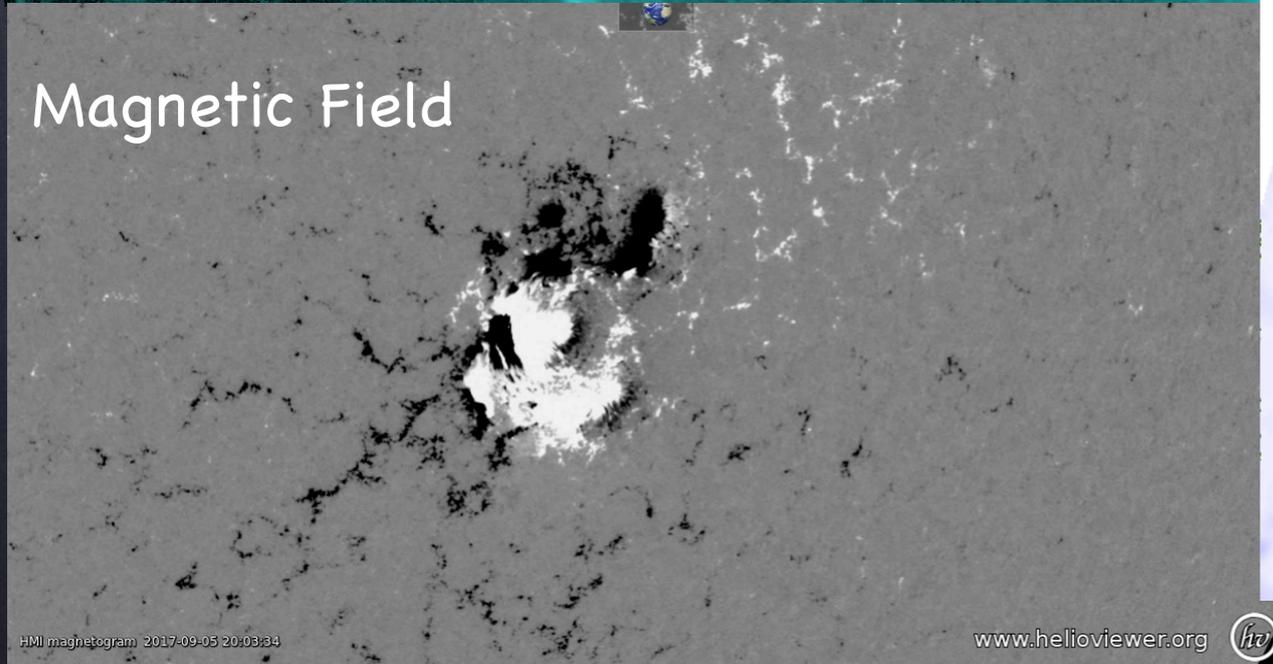
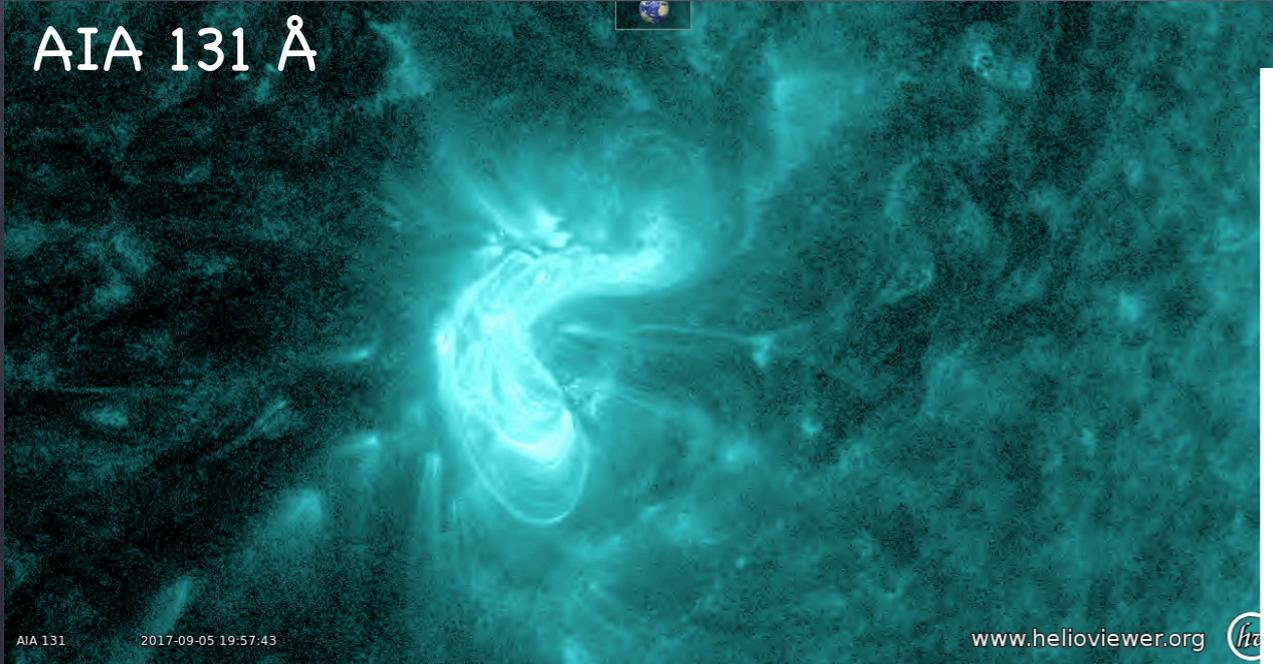
Div B





3D Magnetic Field in AR12673

Solar Active Region 12673, X2.2 and X9.3 @ Sep. 6 2017

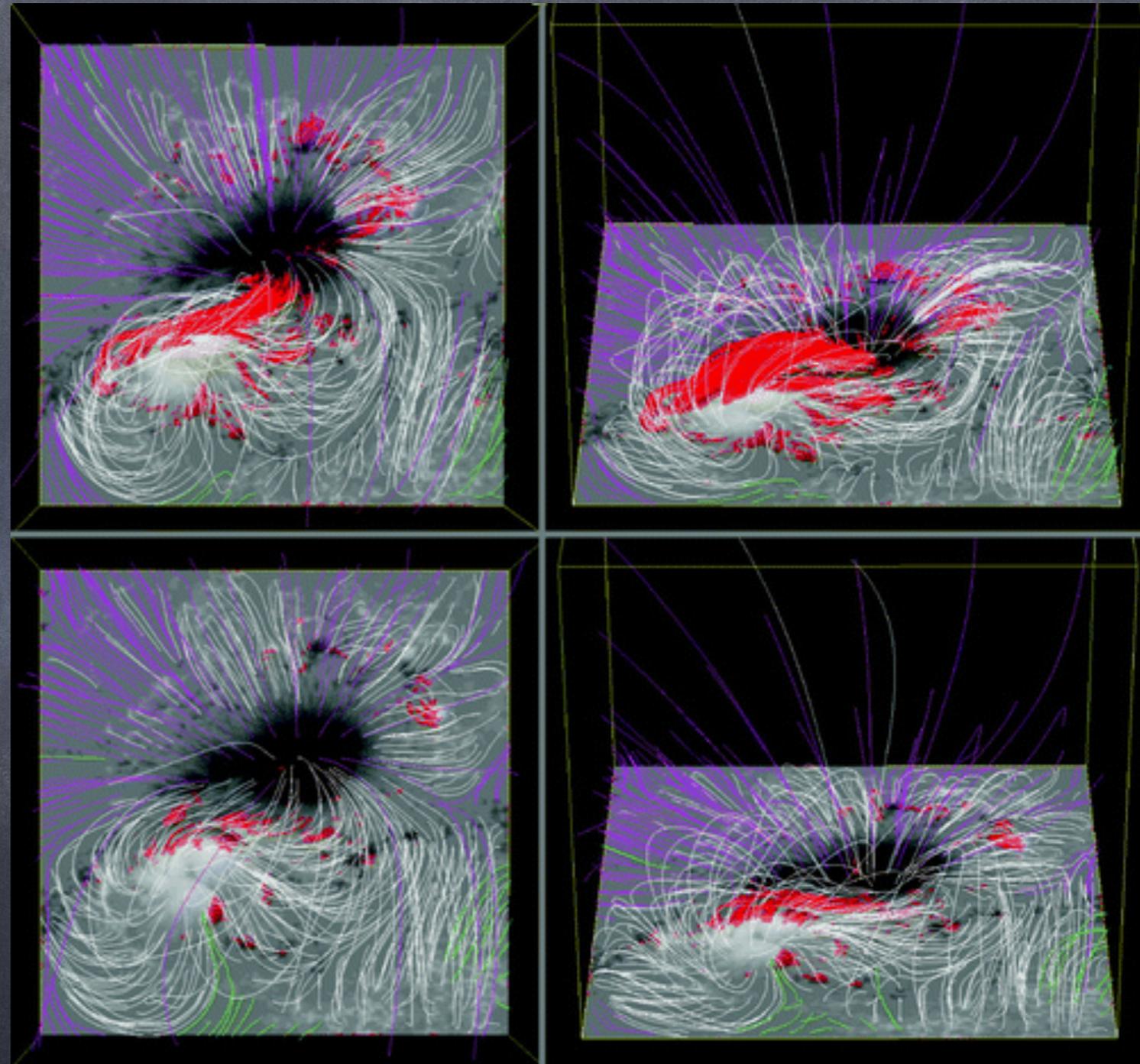
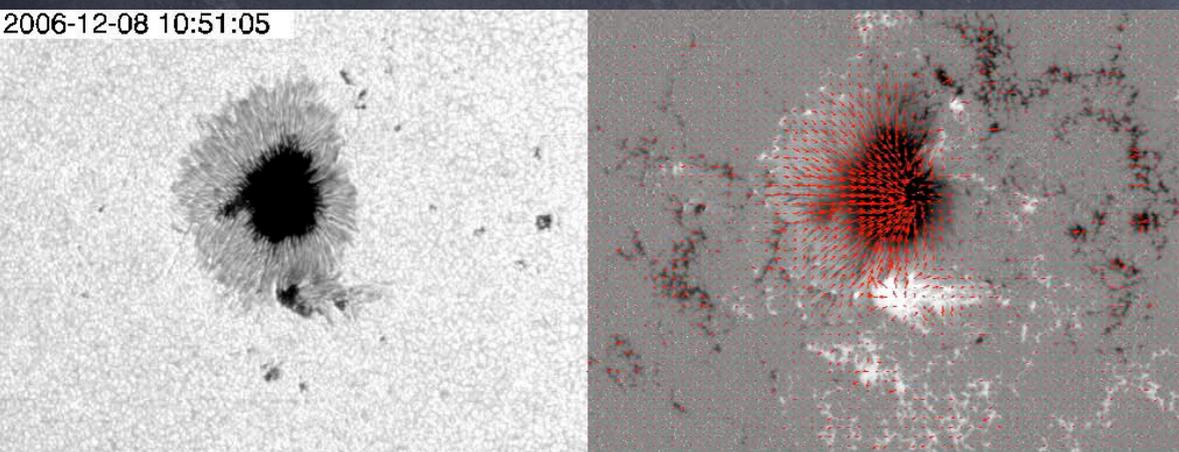
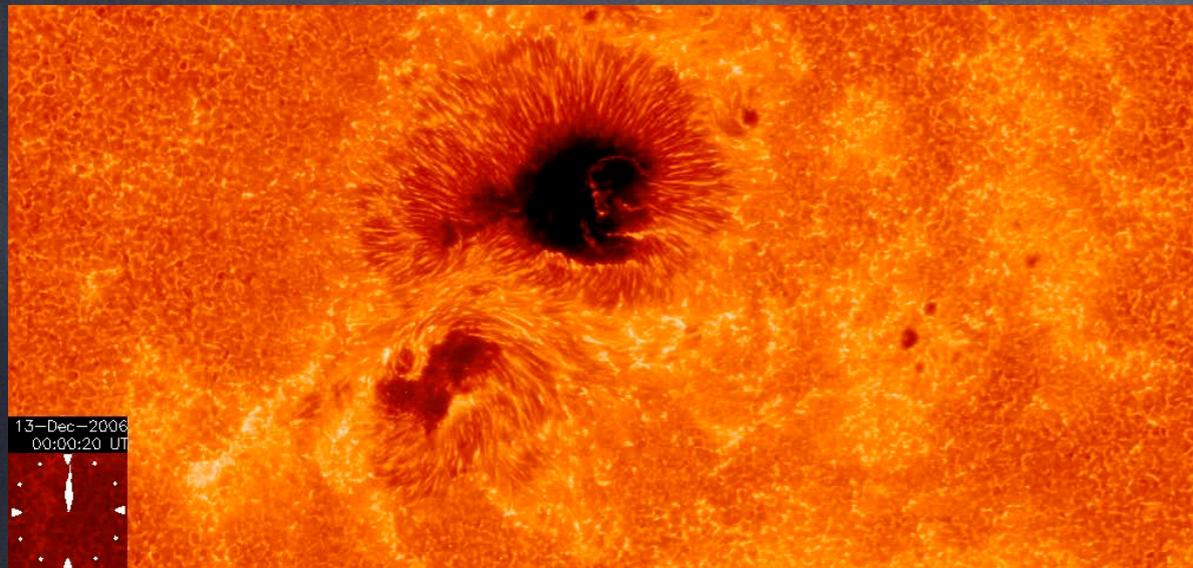


Achievements of the NLFFF

NLFFF Before and After the Flare

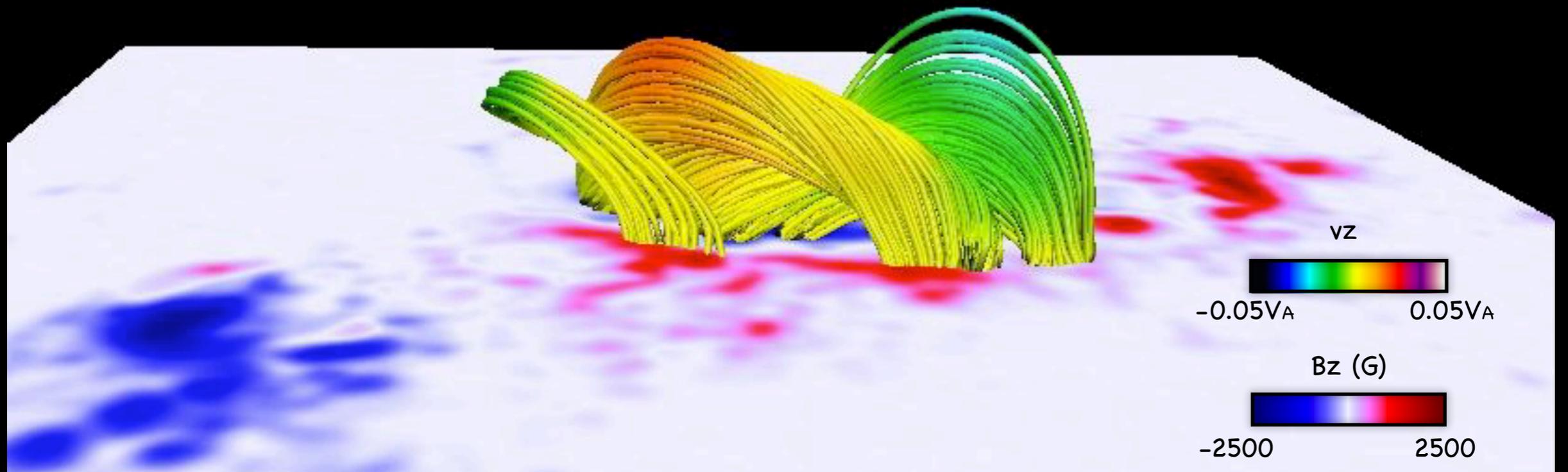
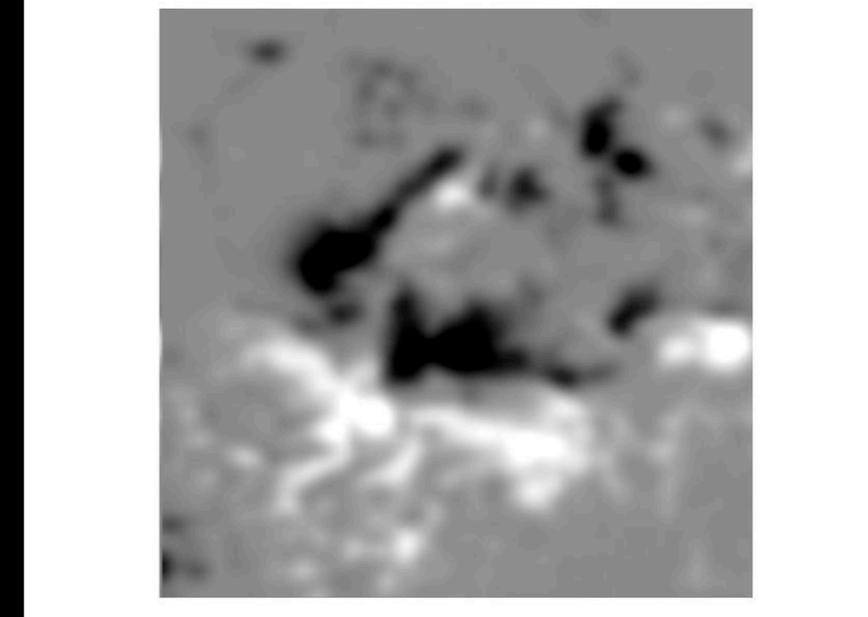
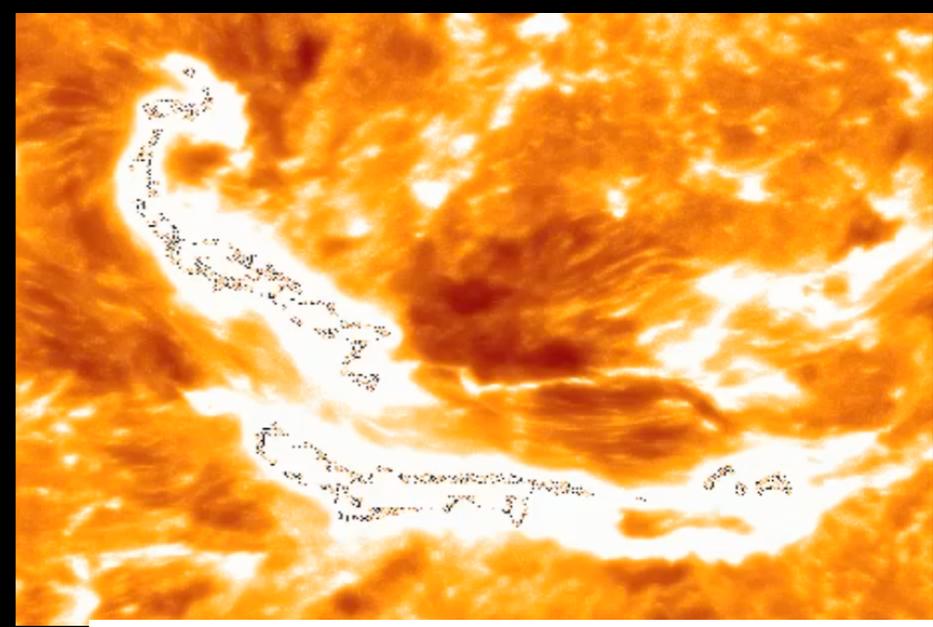
Solar Active Region 10930
X3.4 flare@Dec. 13 2006

Schrijver et al. 2008 ApJ



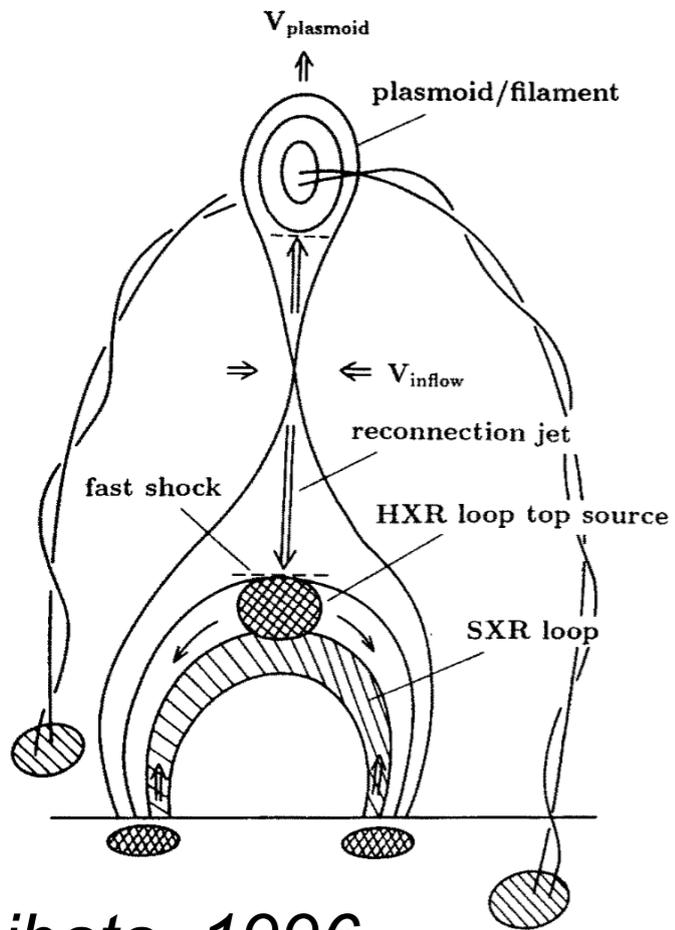
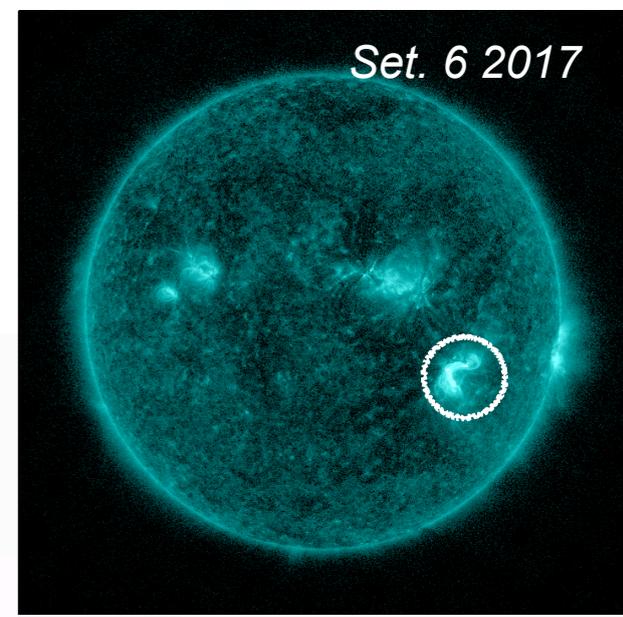
MHD Sim. of Solar Eruption in AR11158

Inoue+2018 Nature Communications

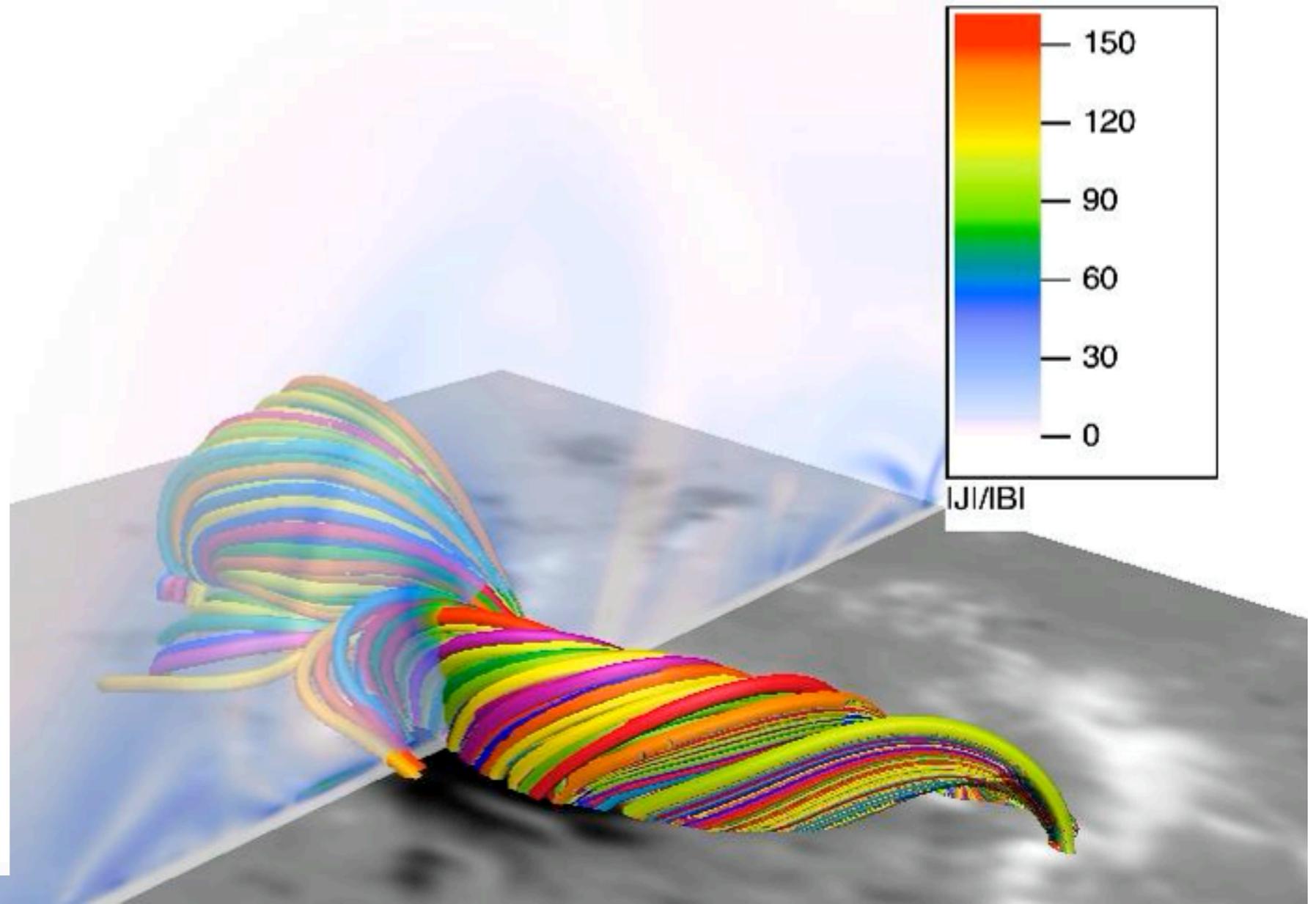


MHD Sim. of Solar Eruption in AR12673

Inoue et al. 2018 ApJ



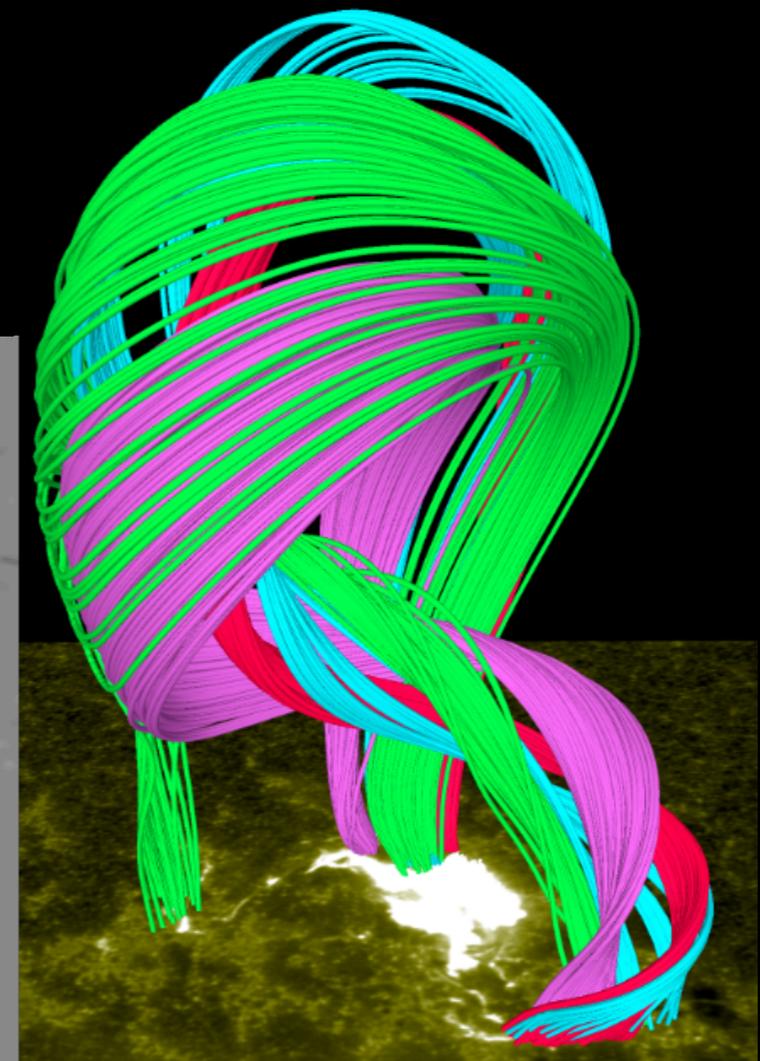
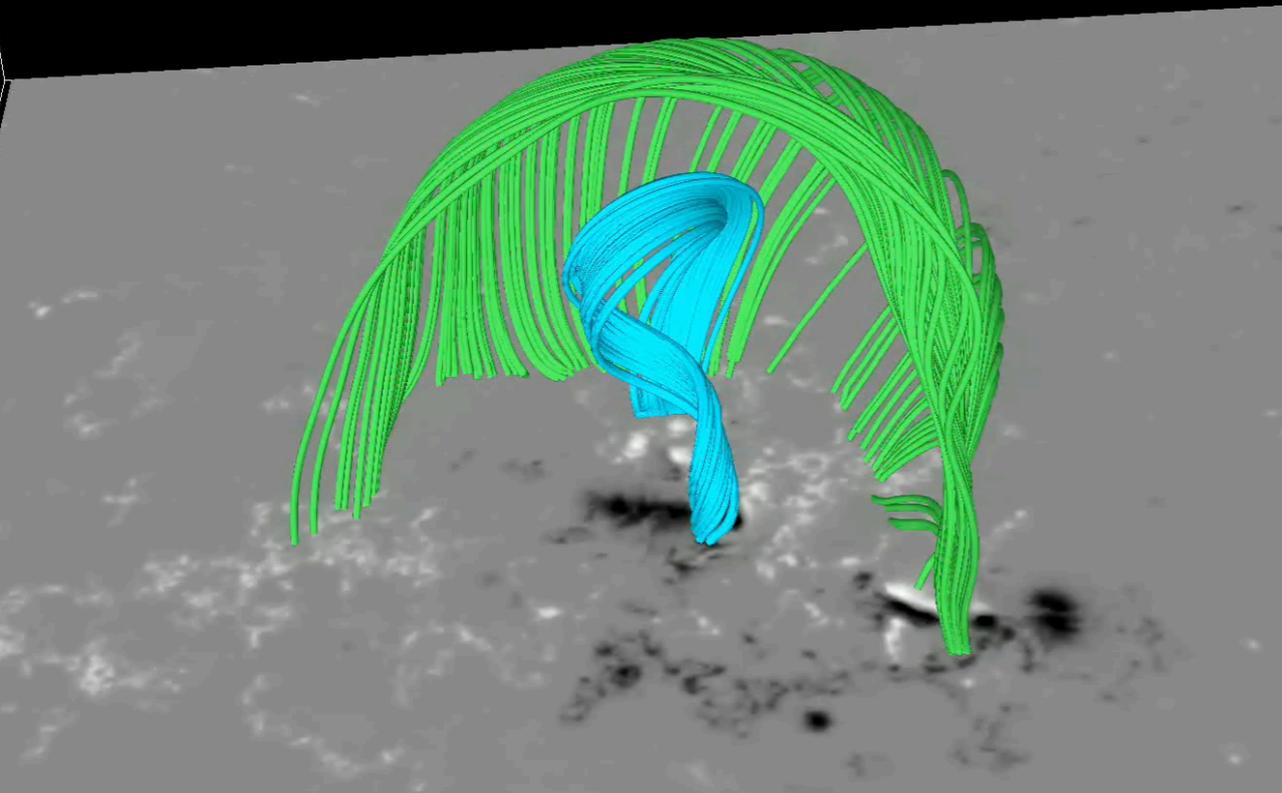
Shibata 1996



MHD Sim. of Solar Eruption in AR11261



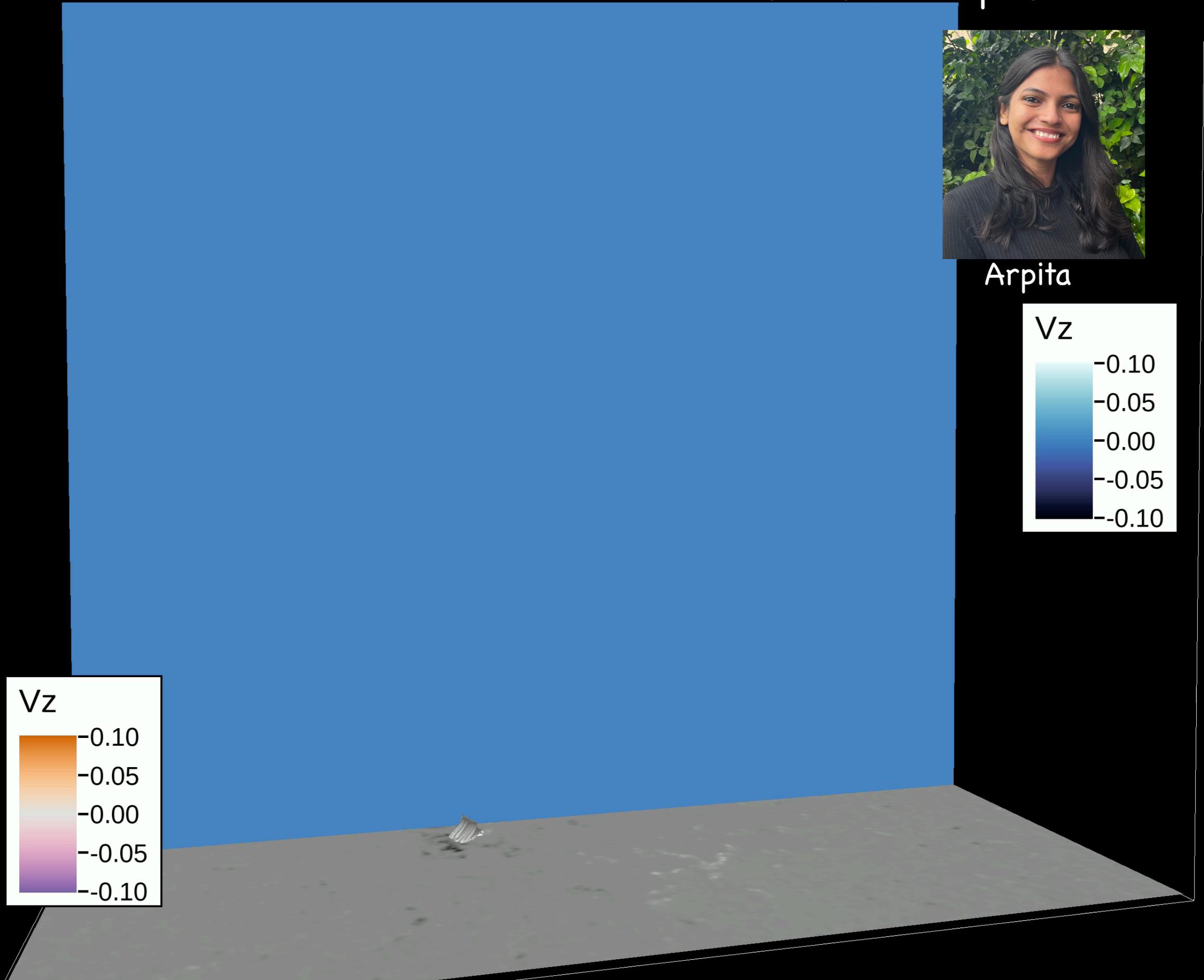
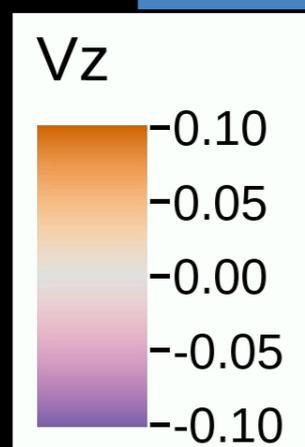
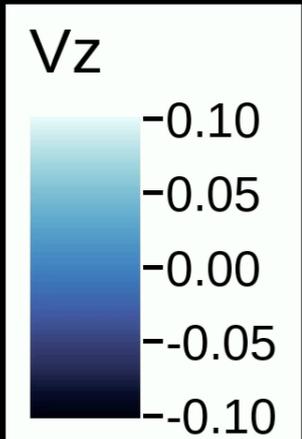
Mr. Kei Matsumoto



MHD Sim. of Solar Eruption in AR11283



Arpita

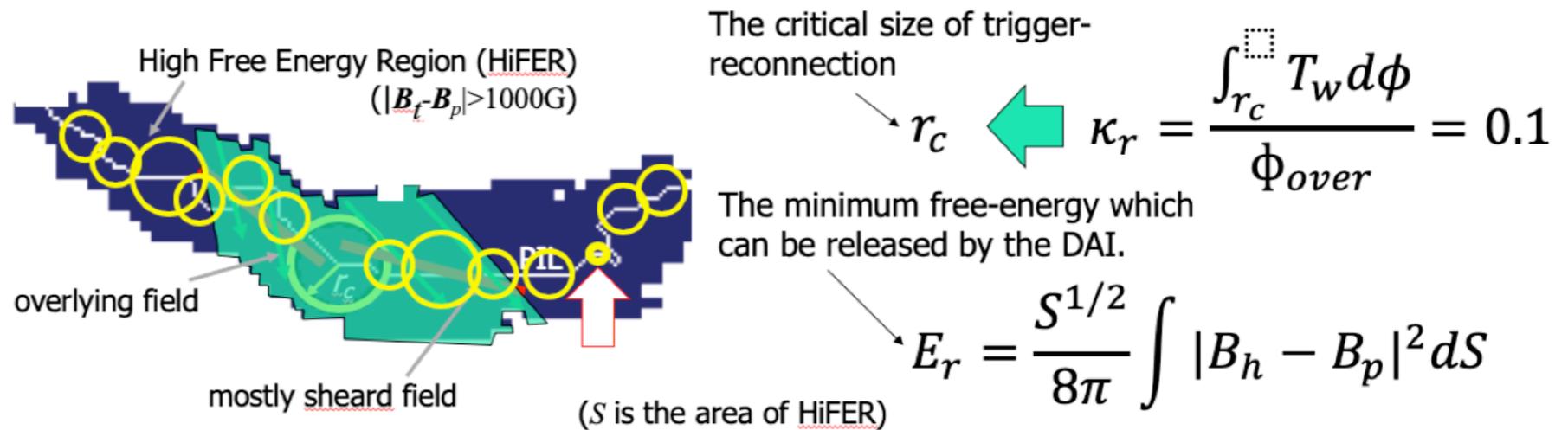
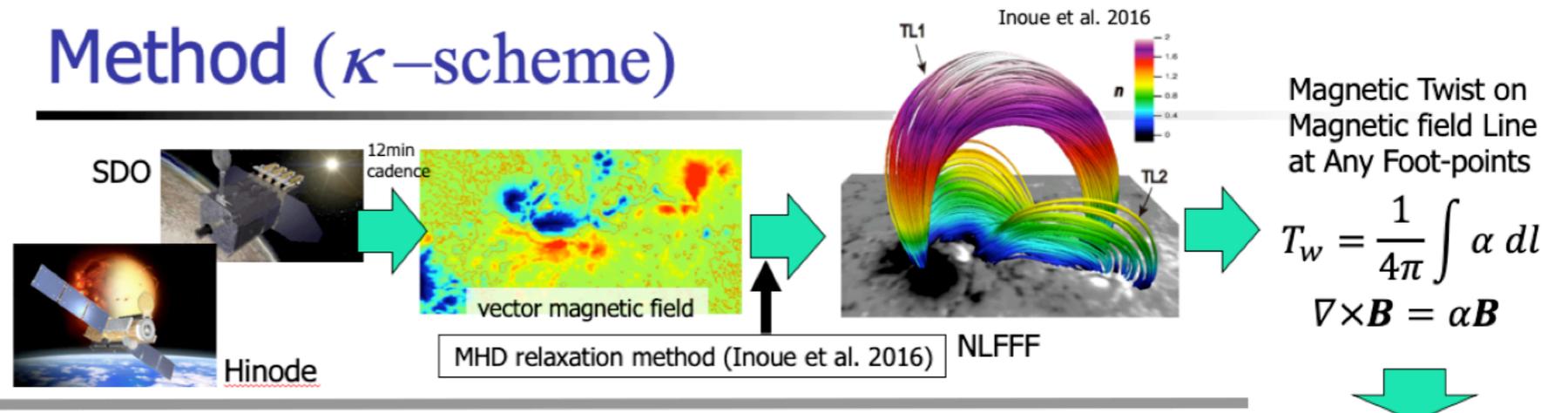


Solar Flare Prediction for X flares

We successfully predict the huge solar flares more than X2.0!
Kusano + Science 2020



Method (κ -scheme)



物理学に基づく方法により差し迫
巨大太陽フレアを予測することが

A physics-based method that can predict imminent large solar flares

• Prediction of M- and C- flares

- ✓ Prediction of the flare in non- δ type sunspot.
- ✓ Prediction of the filament eruption from quite region.

• Prediction of CMEs.

- ✓ Clarify the physics of the CME initiations.



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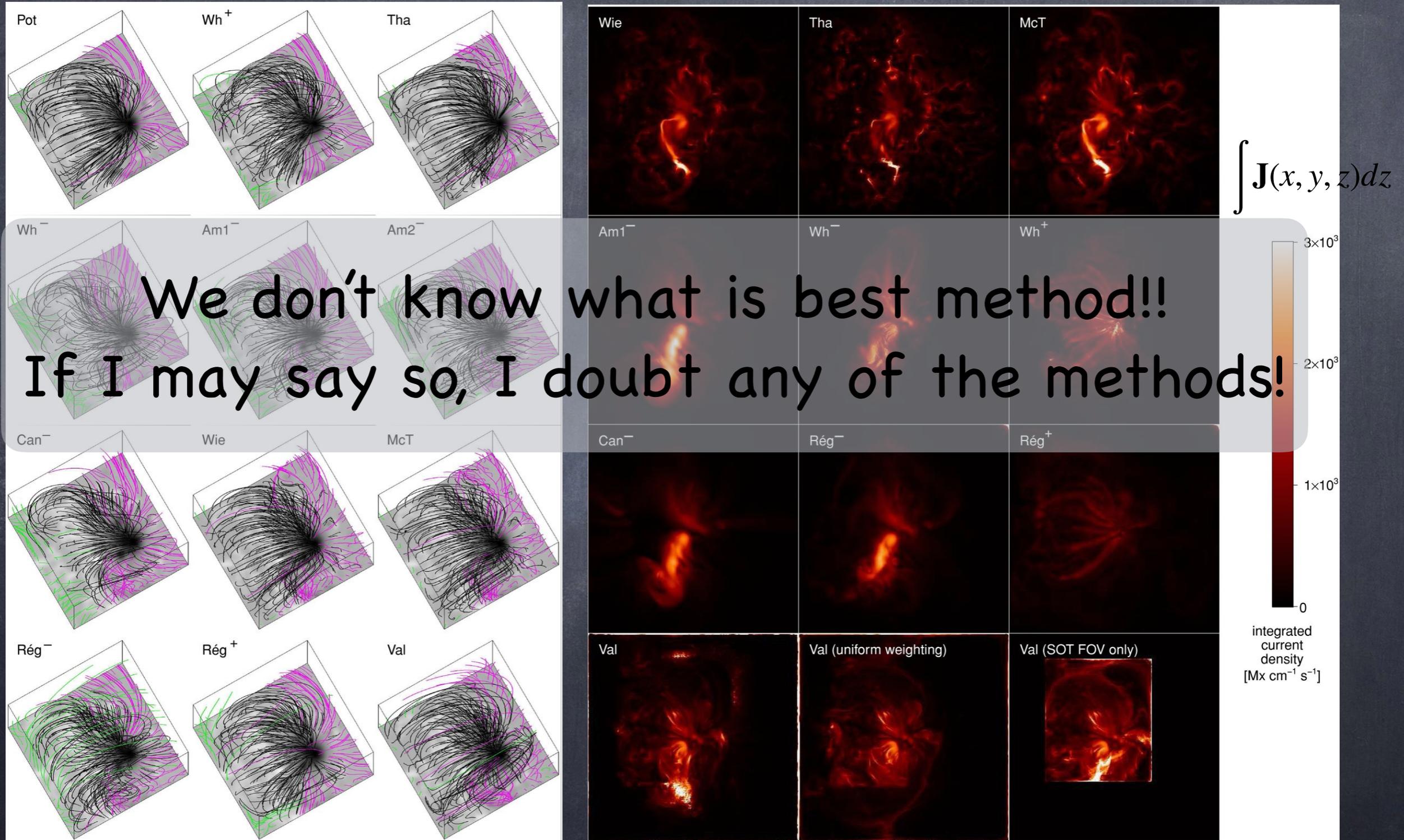
³ Institute for Advanced Research, Nagoya University

全著者リスト: <https://science.sciencemag.org/content/369/6503/587.full>

上左から草野 完也、伊集 朝哉
下左から伴場 由美、井上 諭

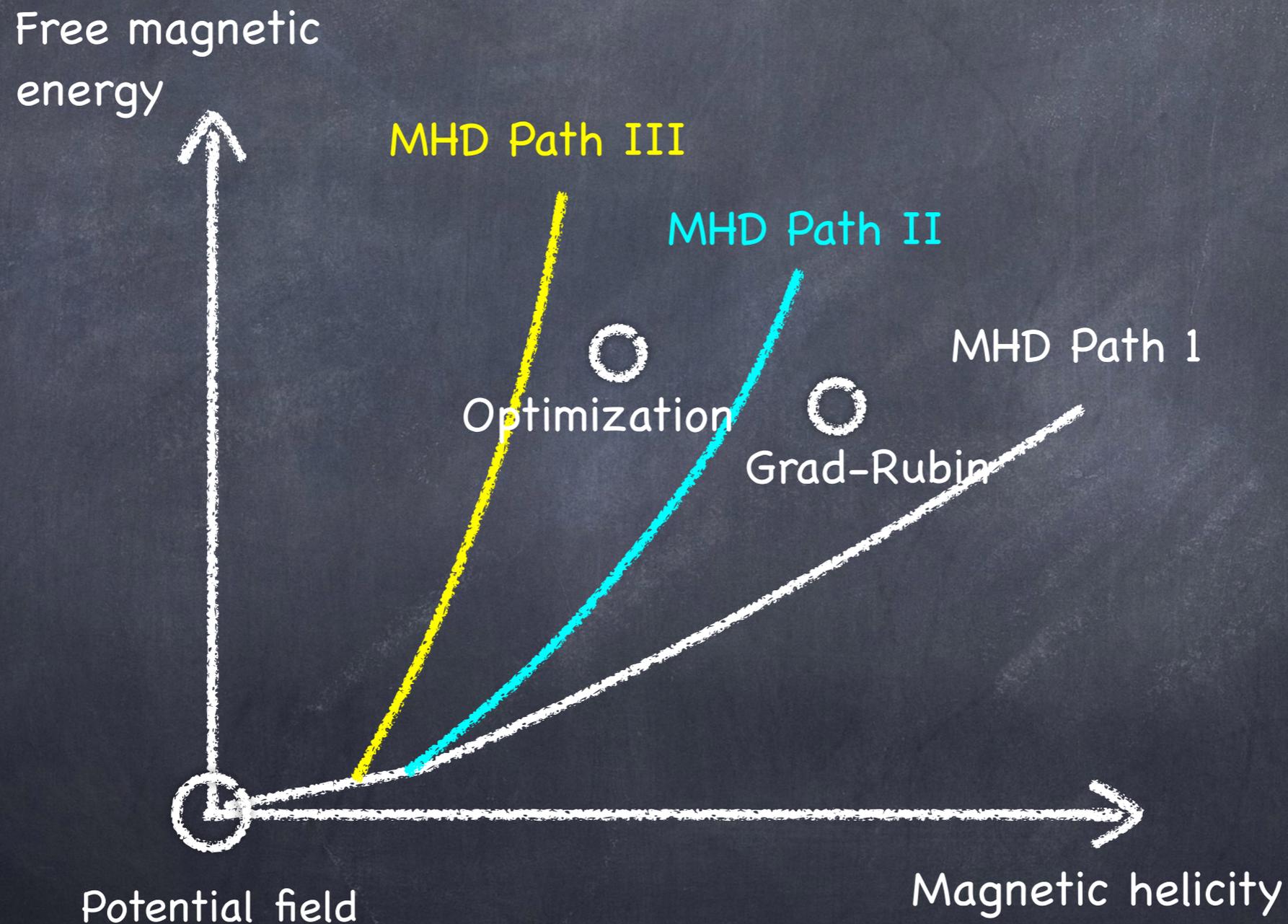
Dark side of the NLFFF

DeRosa et al. 2009 ApJ



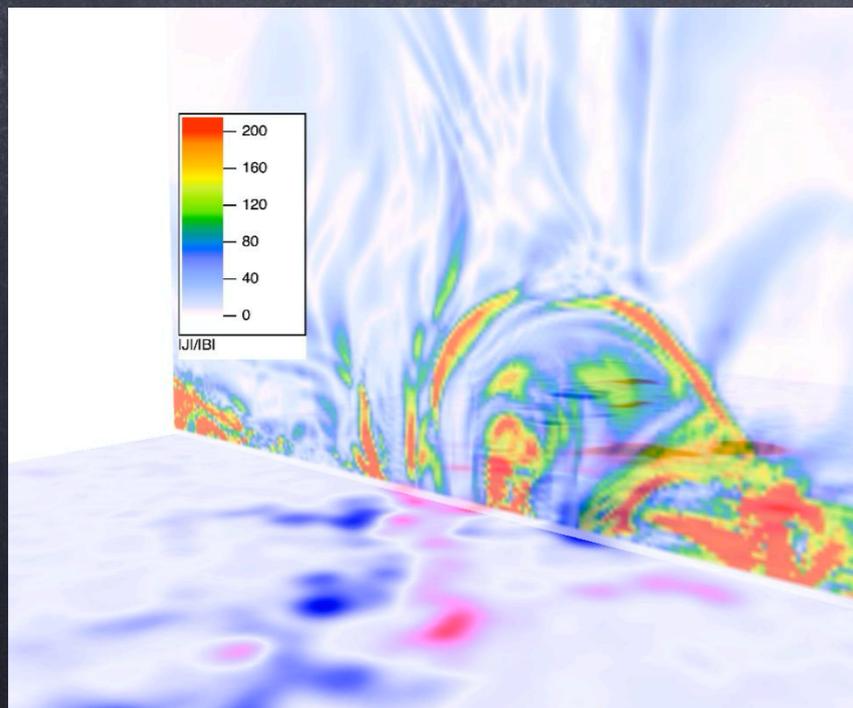
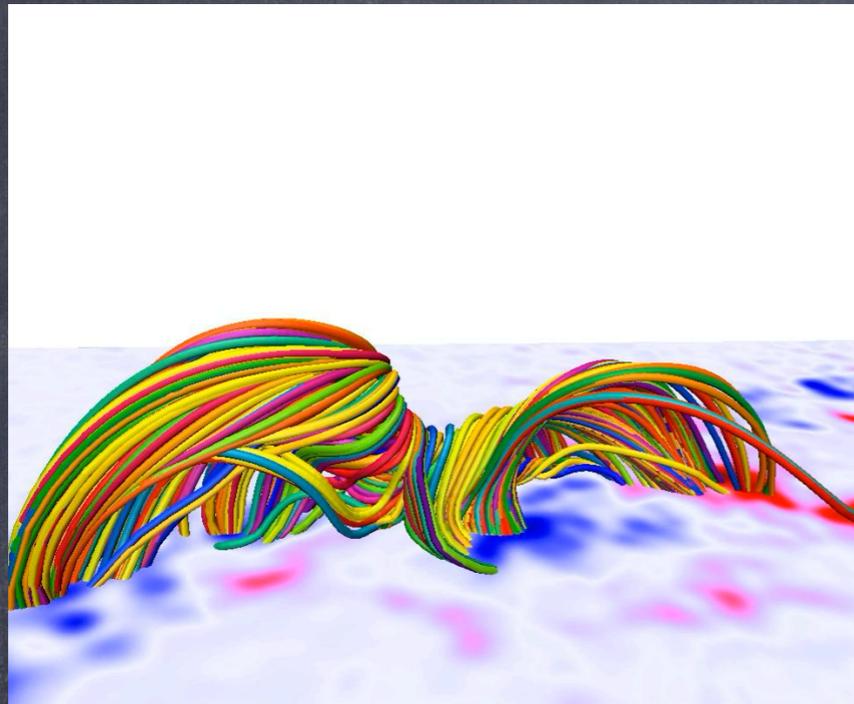
Why do I use the MHD Relaxation Method?

The MHD Relaxation Method is a physics-based model!!

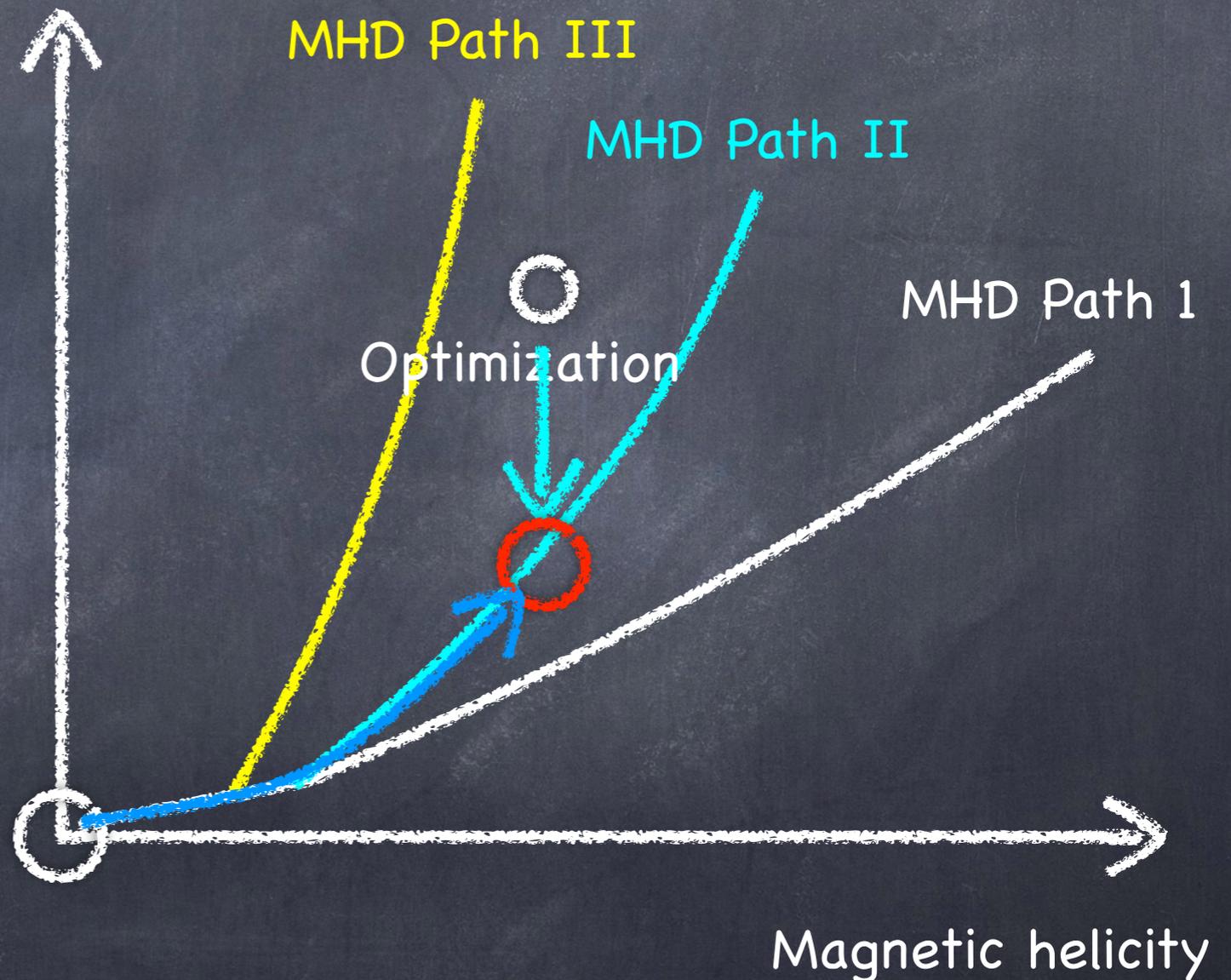


Why do I use MHD Relaxation Method?

NLFFF (Optimization)



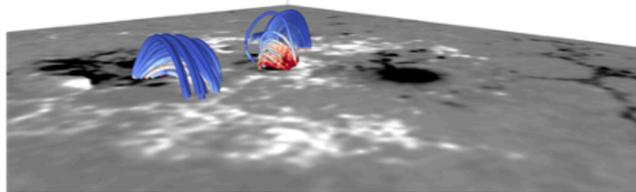
Magnetic energy



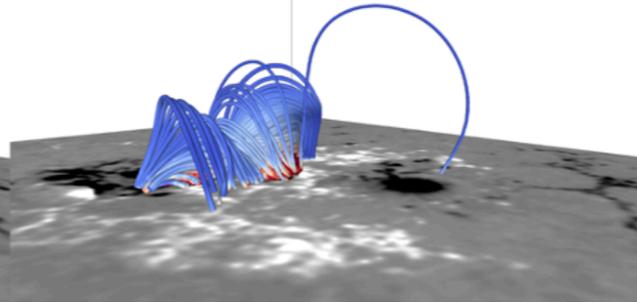
Non-force-free field extrapolation ($\mathbf{J} \times \mathbf{B} - \nabla P = 0$)

Evolution of 3D magnetic field

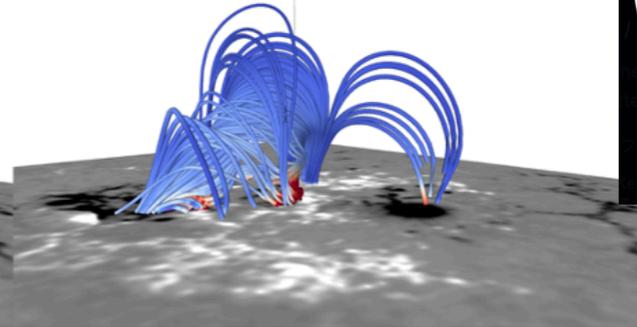
(a) Scheme A, $n = 2000$



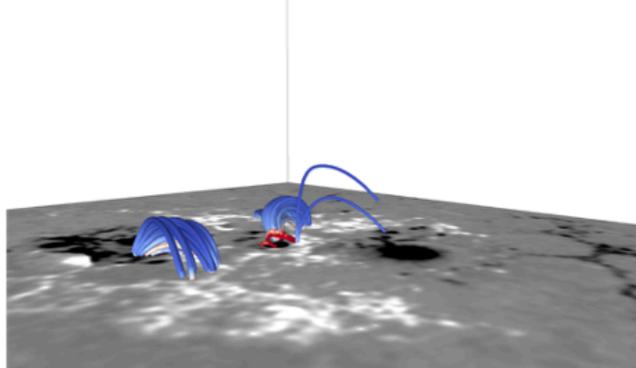
(b) Scheme A, $n = 16000$



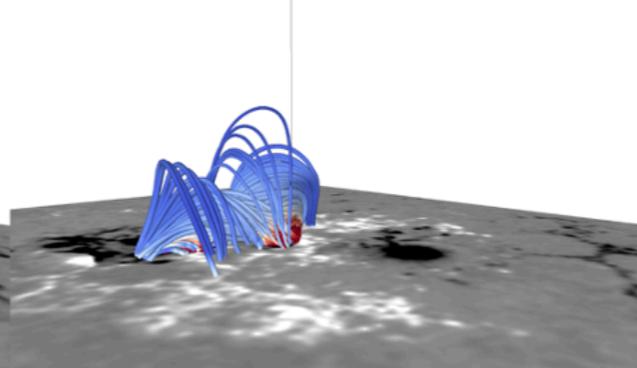
(c) Scheme A, $n = 30000$



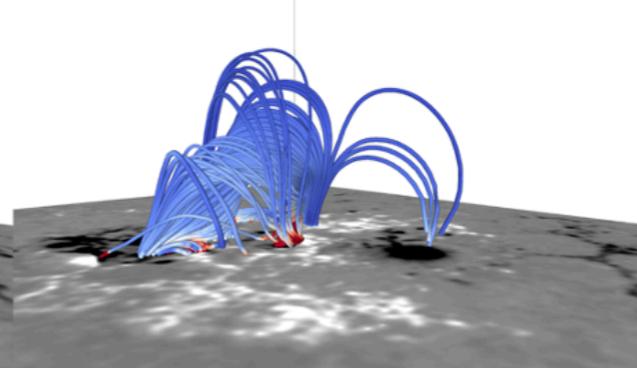
(d) Scheme B, $n = 2000$



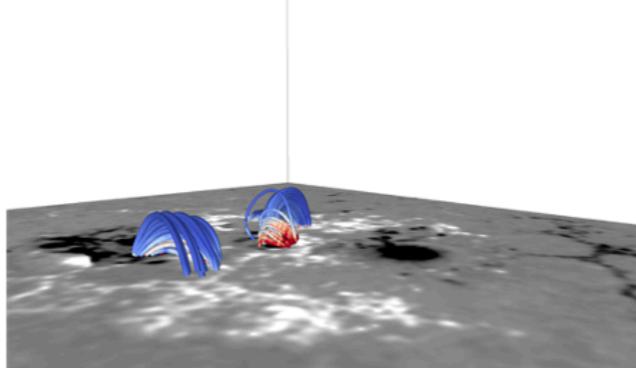
(e) Scheme B, $n = 16000$



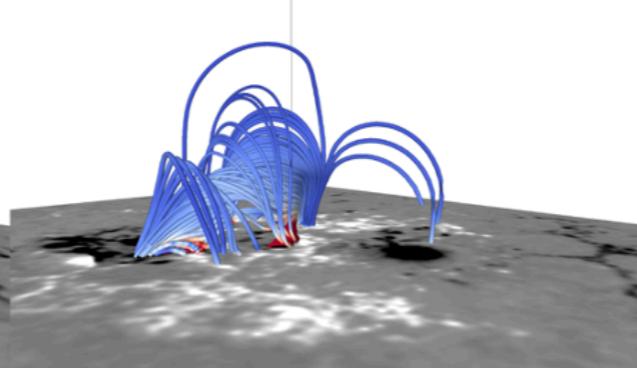
(f) Scheme B, $n = 30000$



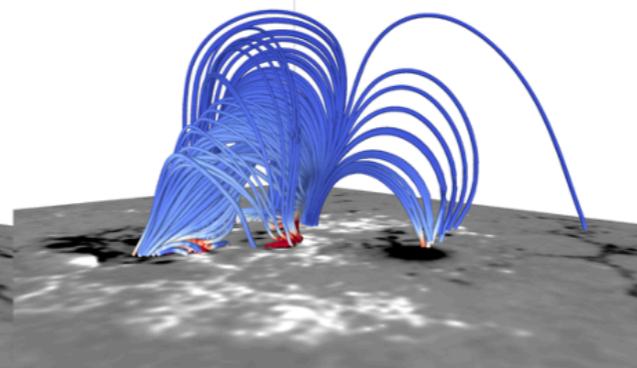
(g) Scheme C, $n = 2000$



(h) Scheme C, $n = 16000$



(i) Scheme C, $n = 30000$



Boundary conditions (p, \mathbf{B}): von Neumann



D. Yamasaki

Data-constrained and -driven MHD Simulations

What are data-constrained and -driven simulations?

How to handle the following equation at the bottom surface?

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

Initial condition is along with the observations (potential field, or NLFFF).
But **the handling of the B.C. is different.**

Data-constrained MHD simulation (Use the Photo.B. at specific time).

- ✓ The normal component (B_z) is fixed.
- ✓ The horizontal B (B_x, B_y) is freely moving.
- ✓ In some cases, three-components are fixed.. **this is not good.**

Data-driven MHD simulation (Use the time-varying Photo B.).

- ✓ Time-varying photo B is applied to the bottom boundary condition.

How to drive the coronal magnetic field ?

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

✓ Driven by the time-varying velocity

- ✓ The time-varying velocity field is derived from the time-varying photo. B.
- ✓ Mag. B is updated by the induction equation.



No guarantee that Updated B matches with observed (photo.) B.

✓ Driven by the time-varying Electric field

- ✓ The time-varying electric field is derived from the time-varying photo. B.



E is not determined as a unique solution.

✓ Driven by the time-varying Electric field and the velocity.



This condition is inconsistent with the induction equation.

One of E-driven Methods (Hayashi+2018, Inoue+2023)

$$\frac{\partial B_z}{\partial t} = -\mathbf{z} \cdot \nabla \times \mathbf{E}^{(1)}$$

$$\frac{\partial \mathbf{B}_{h:df}}{\partial t} = -\nabla \times \mathbf{E}^{(2)}$$

Tangential field which satisfies $\nabla \cdot \mathbf{B}_{h:df} = 0$.

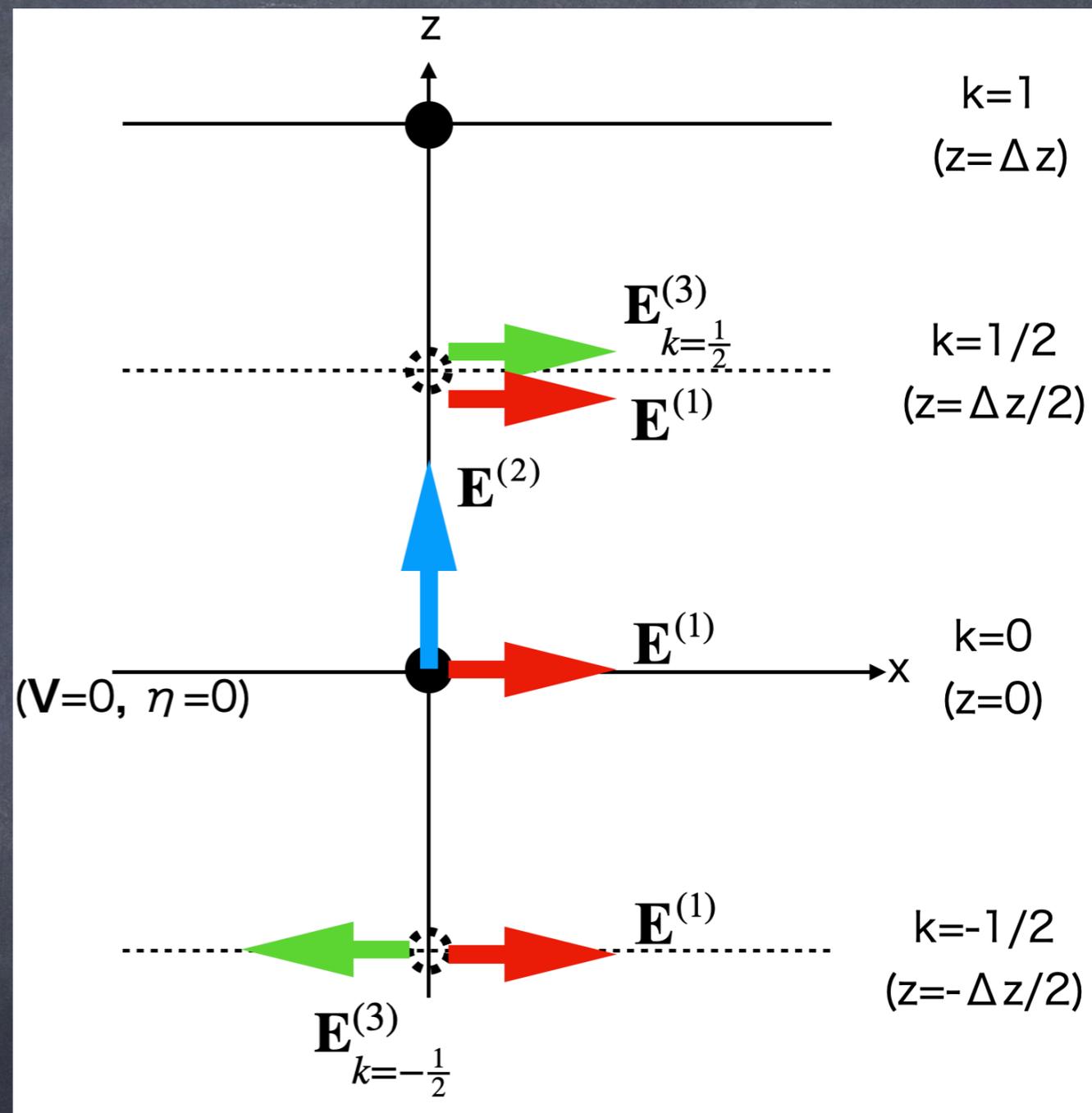
$$\frac{\partial \mathbf{B}_{h:cf}}{\partial t} = -\nabla \times \mathbf{E}^{(3)}$$

Tangential field which satisfies $\nabla \times \mathbf{B}_{h:cf} = 0$.

Where $\mathbf{B}_h = \mathbf{B}_{h:df} + \mathbf{B}_{h:cf}$

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times (\mathbf{E} + \nabla \phi)$$

Solution is not uniquely determined. We can find another combination by taking another gauge.

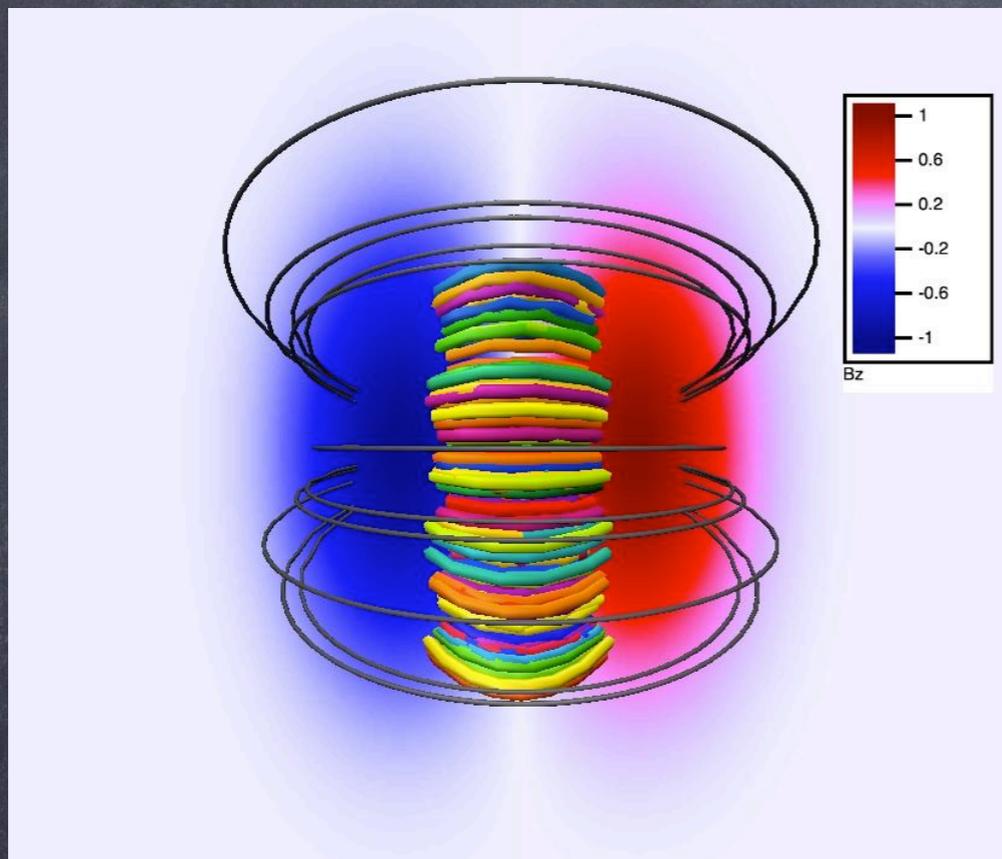


- ✓ Obtained \mathbf{E} can reproduce the photo.B.
- ✓ $\nabla \cdot \mathbf{B} = 0$ is held.

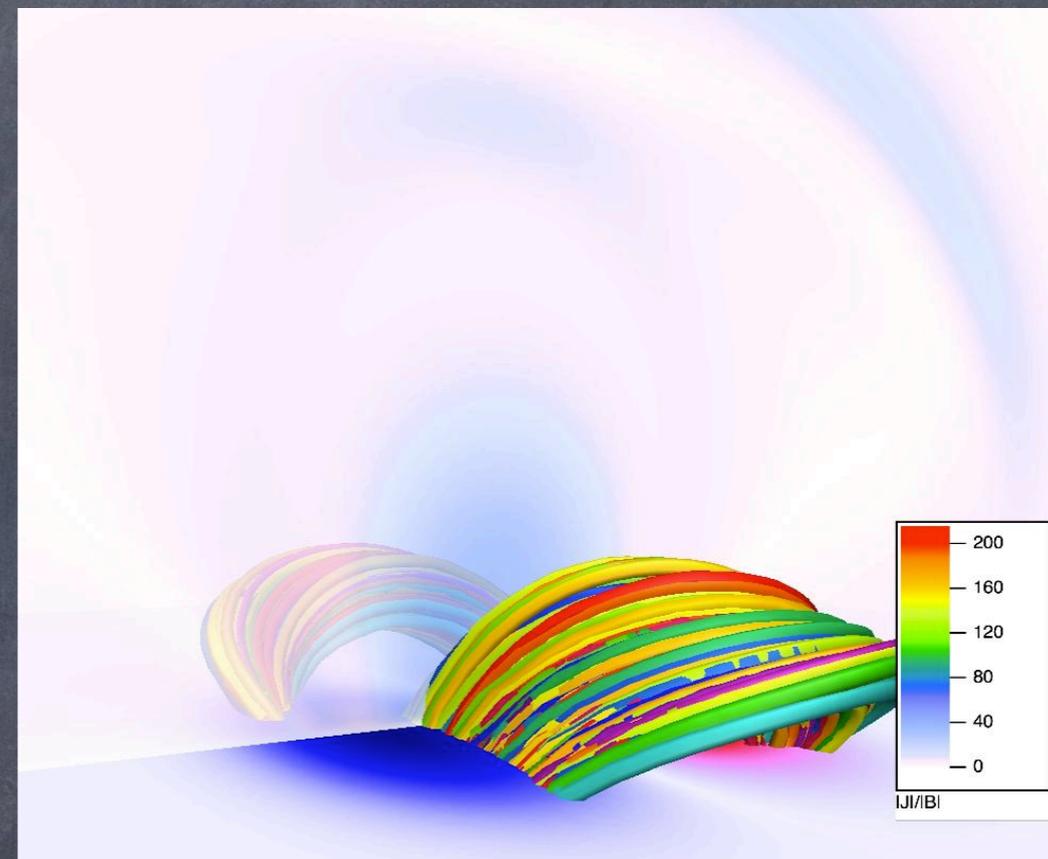
Benchmark test is required

Amari et al. 2000, 2003a and b, Aulanier et al. 2010, 2012 etc.

(i) Sigmoid formation



(ii) Eruption of the magnetic field

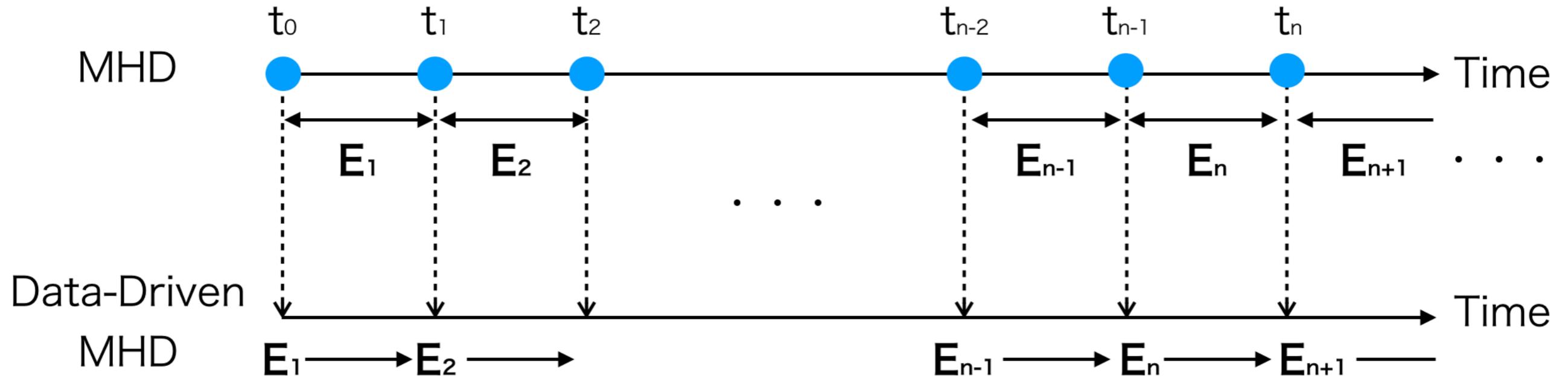


Reference magnetic field: velocity is given on the surface.

(i) Sigmoid is formed: twisting motion is given on the sunspot.

(ii) Eruption of the magnetic field: Converging motion is given on the sunspot.

How to drive the Coronal magnetic Field?



$$\frac{\partial \mathbf{B}_z}{\partial t} = -\mathbf{z} \cdot \nabla \times \mathbf{E}^{(1)} \quad \longrightarrow \quad \nabla_h^2 \Phi^{(1)} = -\frac{\partial \mathbf{B}_z}{\partial t} \quad \longrightarrow \quad \mathbf{E}^{(1)}$$

$$\frac{\partial \mathbf{B}_{h:df}}{\partial t} = -\nabla \times \mathbf{E}^{(2)} \quad \longrightarrow \quad \nabla_h^2 \Phi^{(2)} = -\mathbf{z} \cdot \left(\nabla \times \frac{\partial \mathbf{B}_{h:df}}{\partial t} \right) \quad \longrightarrow \quad \mathbf{E}^{(2)}$$

$$\frac{\partial \mathbf{B}_{h:cf}}{\partial t} = -\nabla \times \mathbf{E}^{(3)} \quad \longrightarrow \quad \nabla_h^2 \Phi^{(3)} = \frac{1}{2} \Delta_z \nabla \cdot \left(\frac{\partial \mathbf{B}_{h:cf}}{\partial t} \right) \quad \longrightarrow \quad \mathbf{E}^{(3)}$$

A Zero-Beta MHD Simulation

Zero-beta MHD equations are applied to data-constrained and -driven simulations.

✓ $\frac{\partial \rho}{\partial t} = -\nabla \cdot \rho \mathbf{v}$ or $\rho(\mathbf{r}, t) = |\mathbf{B}(\mathbf{r}, t)|$

Continuous equation

✓ $\rho \frac{\partial \mathbf{v}}{\partial t} = -\rho \mathbf{v} \cdot \nabla \mathbf{v} + \mathbf{J} \times \mathbf{B} + \nu \nabla^2 \mathbf{v}$

Equation of equation

✓ $\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B} - \nabla \phi$

Induction equation

✓ $\frac{\partial \phi}{\partial t} = -c_h^2 \nabla \cdot \mathbf{B} - \frac{c_h^2}{c_p^2} \phi$

Remove errors from $\nabla \cdot \mathbf{B}$

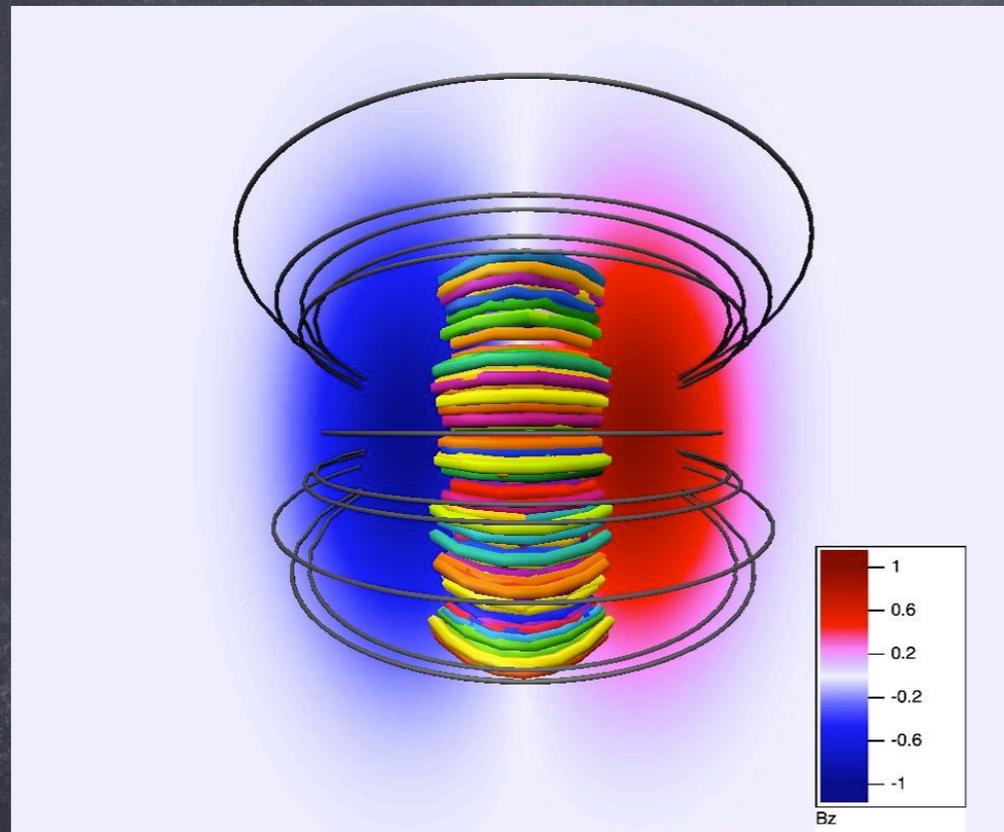
✓ $\nabla \times \mathbf{B} = \mathbf{J}$

Ampere's law

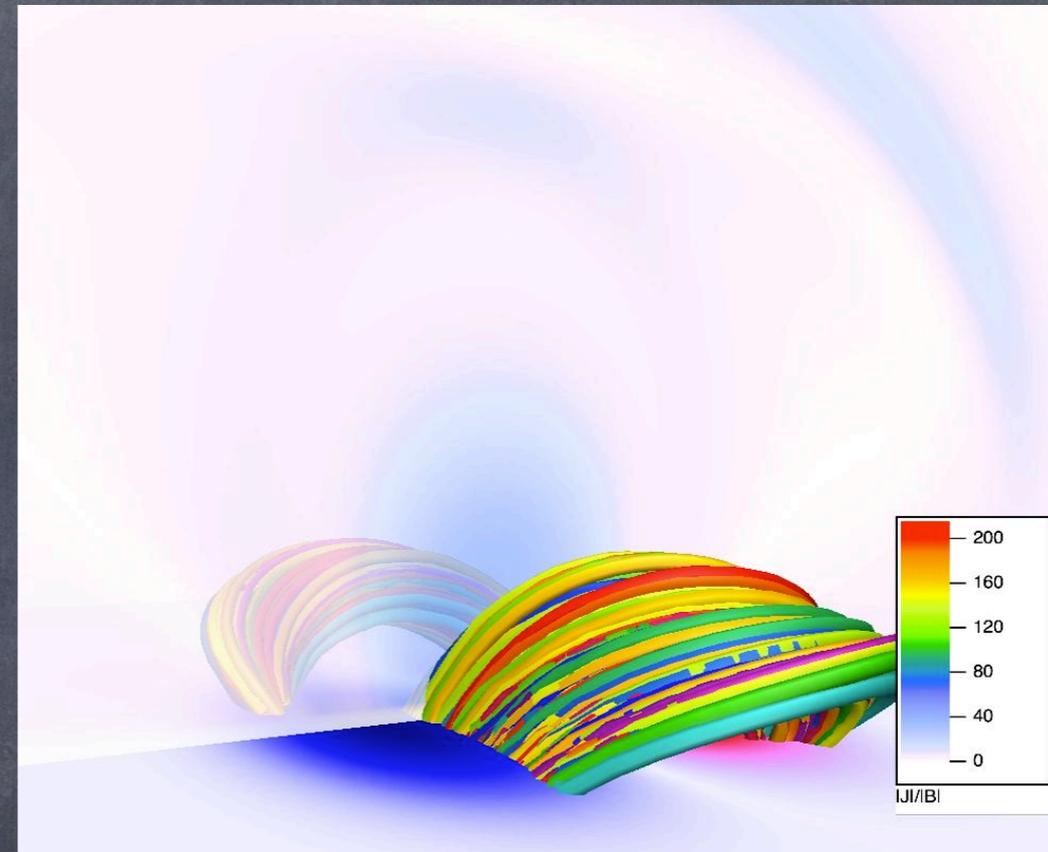
Results of data-driven MHD Sim.

Inoue, Hayashi & Miyoshi, ApJ

(i) Sigmoid formation



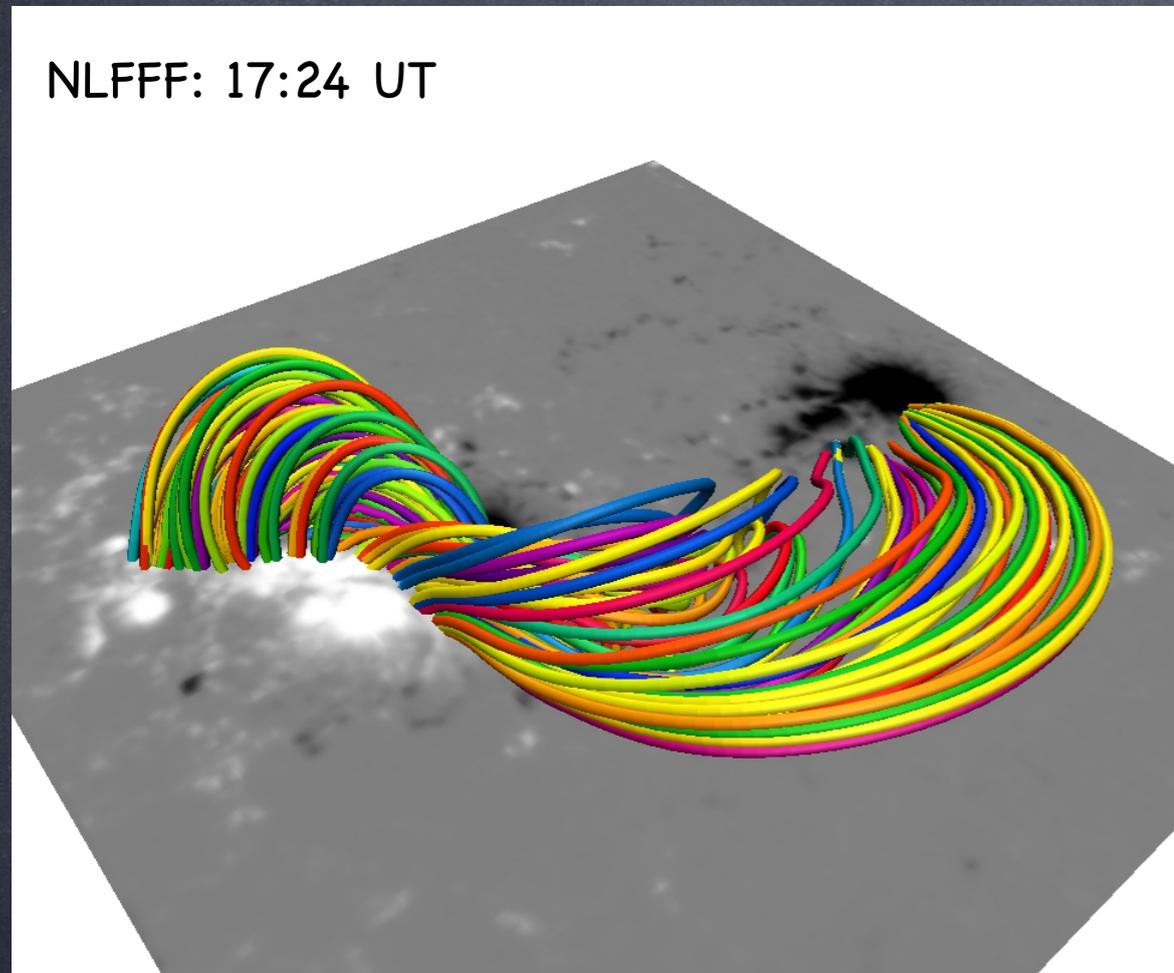
(ii) Eruption of the magnetic field



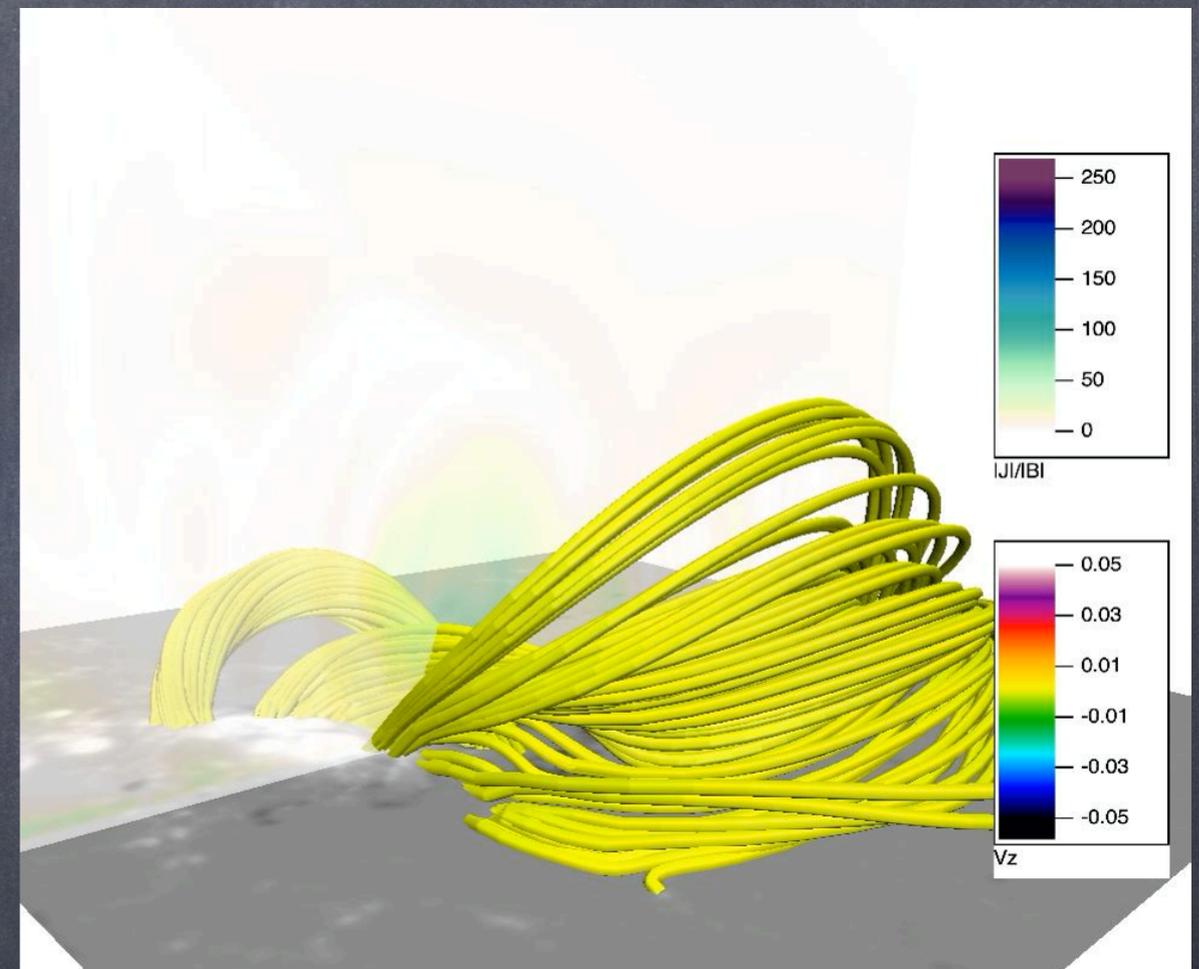
Both stages are reproduced well by data-driven MHD simulation.

Data-Driven MHD simulation of AR12371

NLFFF before the flare.



Mag B. (15 min. before the flare) created by data-driven sim.



Magnetic configurations are much different between the NLFFF and the one obtained from the data-driven MHD simulation.

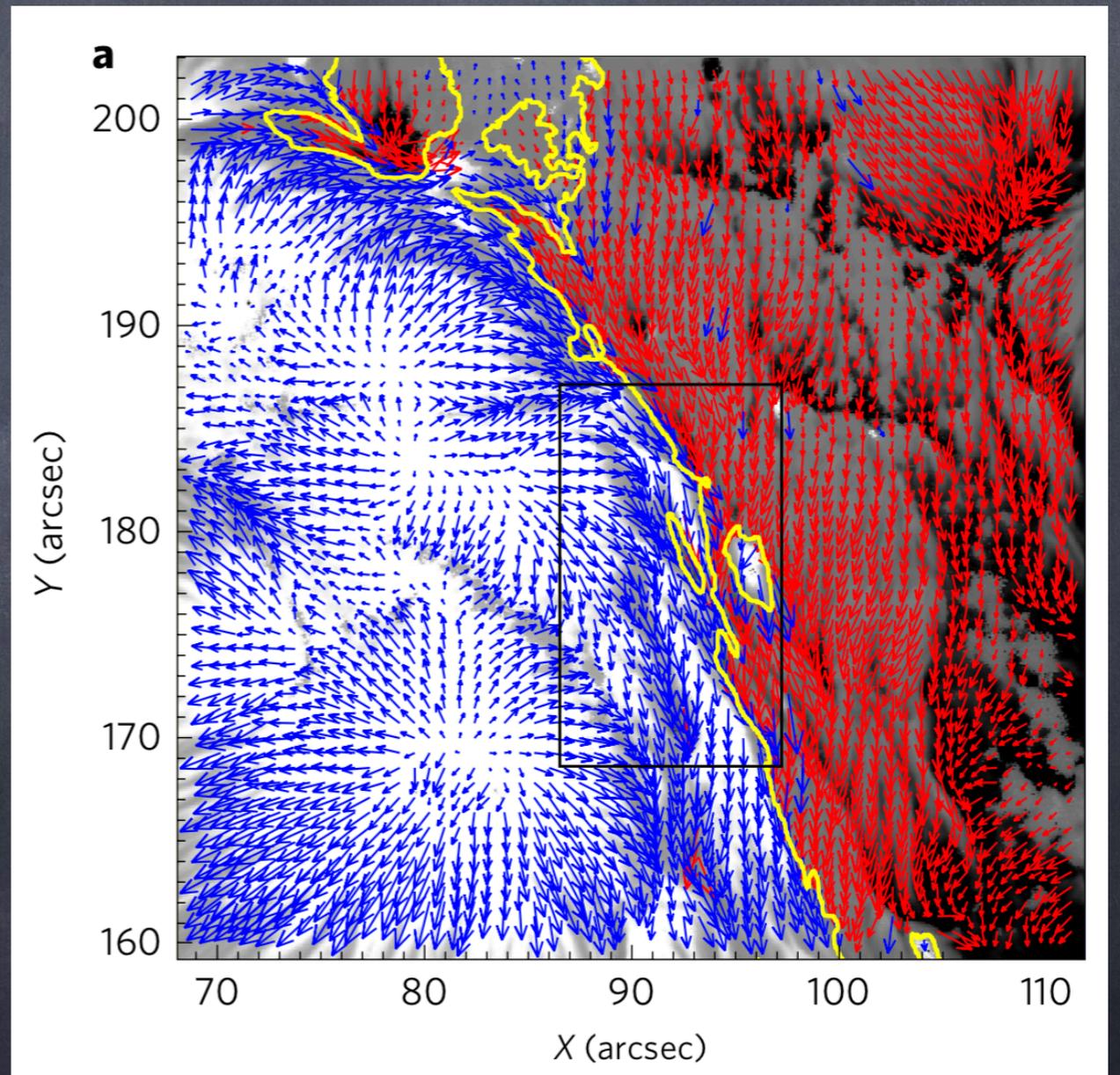
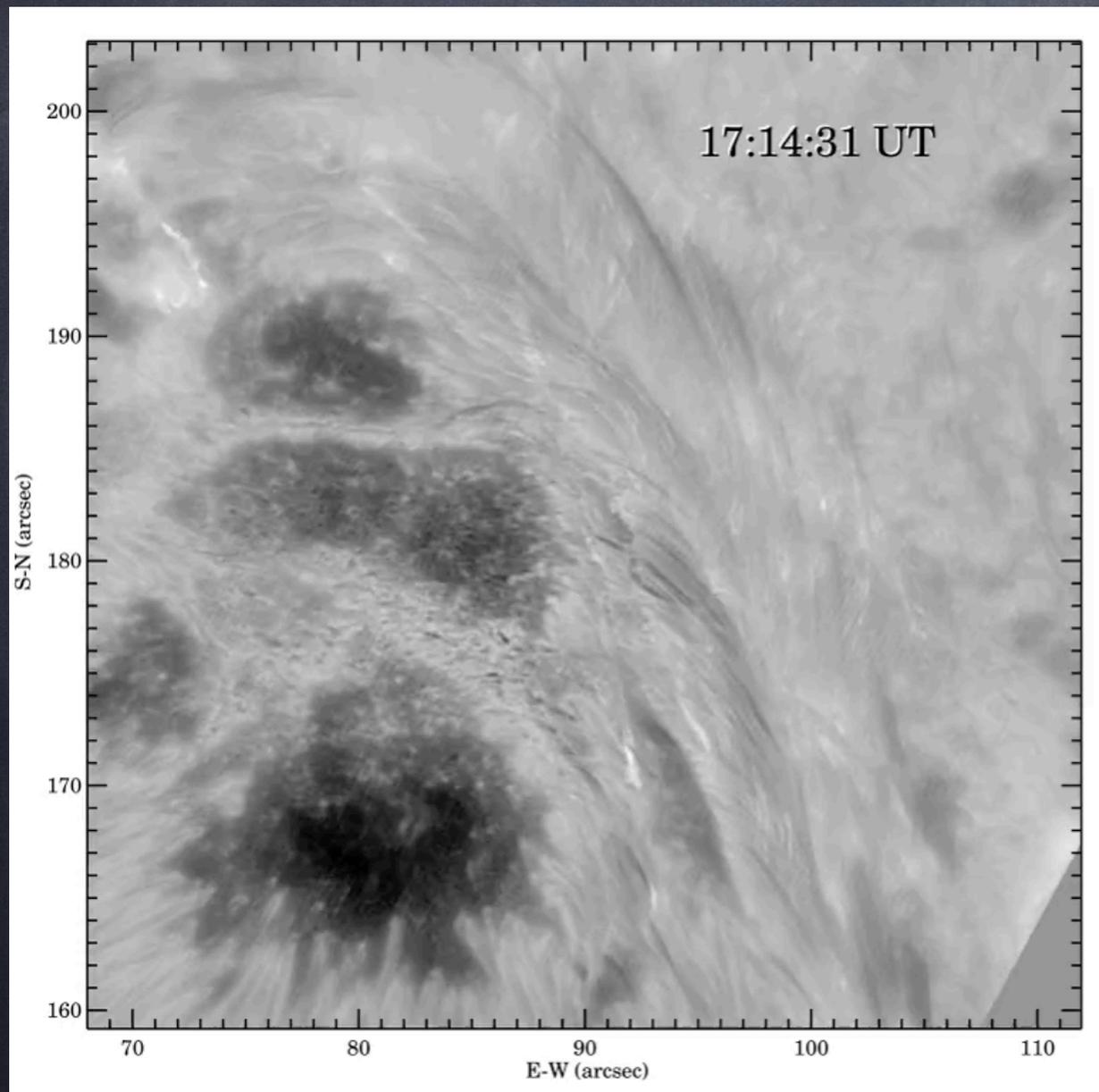
Latest Achievement

Motivation of This Study

Solar flare observed by Goode Solar Telescope (GST)
at Big Bear Solar Observatory (BBSO)

GST Observation

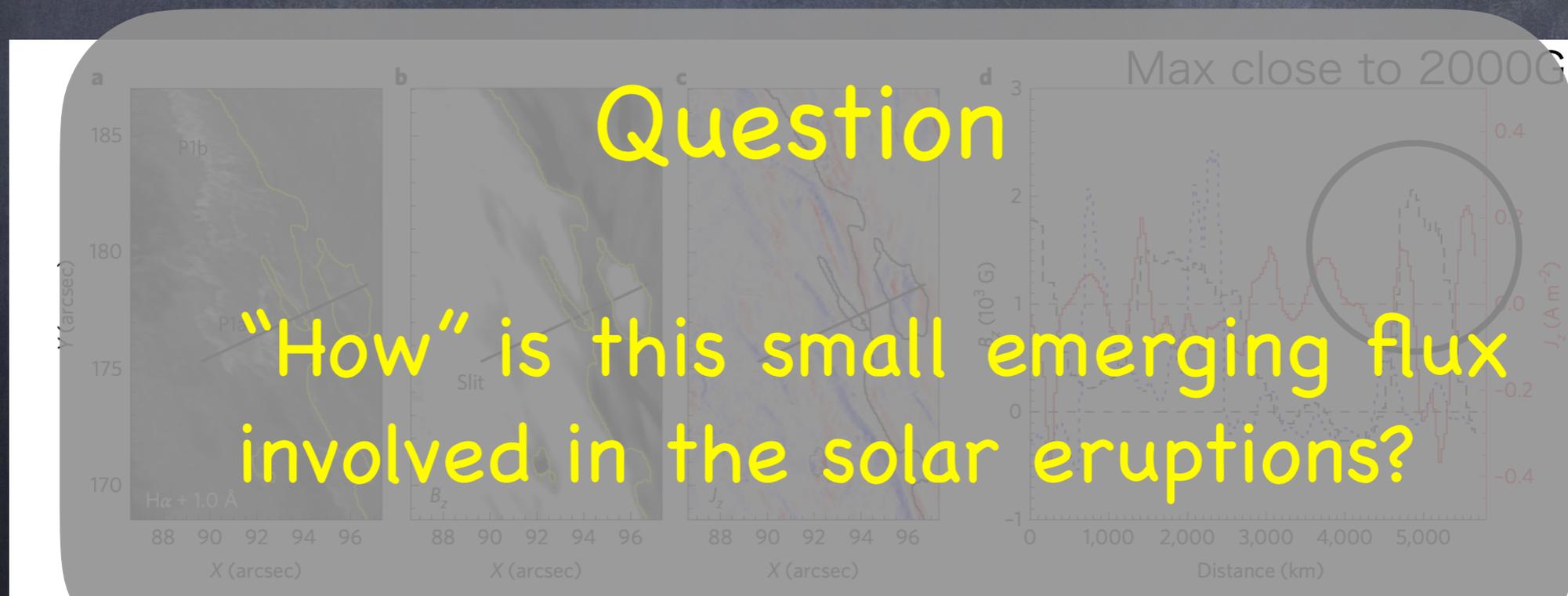
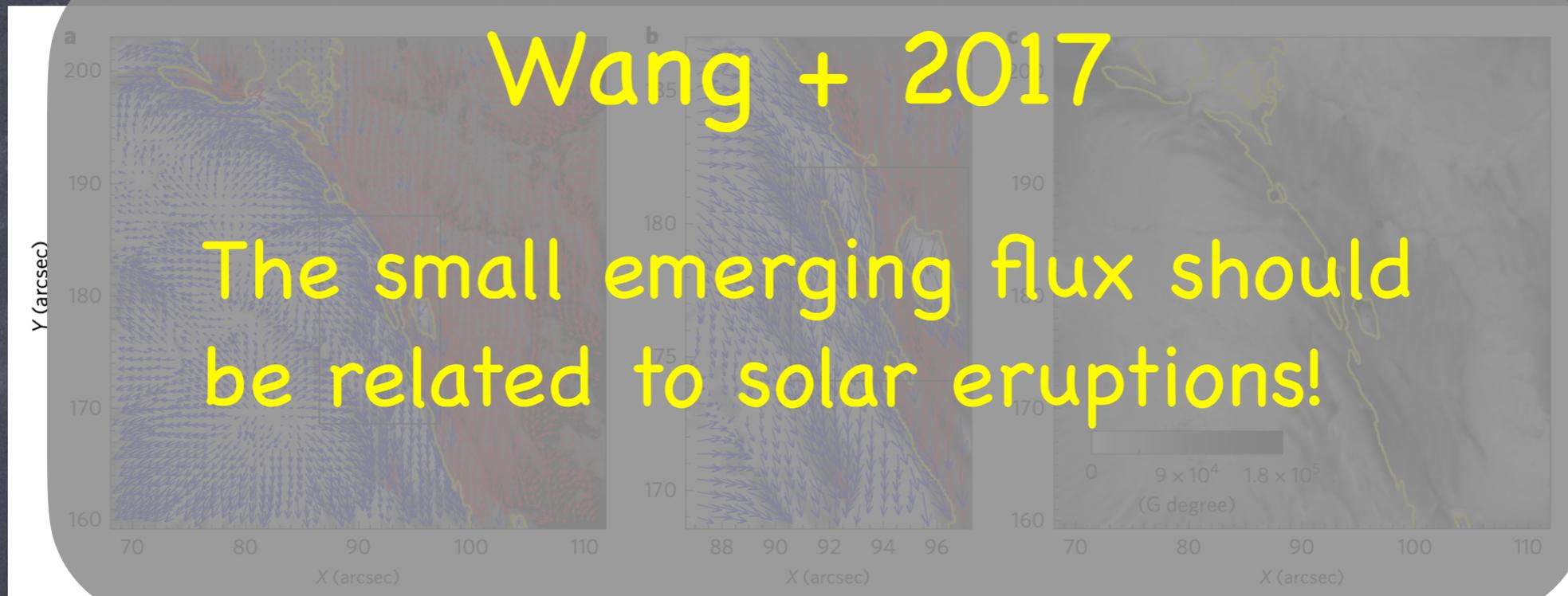
Wang et al. 2017



Magnitude of Small-scale Emerging Flux

scaled between -1500G and 1500G

Wang + 2017



Recipe of Numerical Method

Zero-beta MHD equations

$$\checkmark \rho(\mathbf{r}, t) = |\mathbf{B}(\mathbf{r}, t)|$$

$$\checkmark \rho \frac{\partial \mathbf{v}}{\partial t} = -\rho \mathbf{v} \cdot \nabla \mathbf{v} + \mathbf{J} \times \mathbf{B} + \nu \nabla^2 \mathbf{v}$$

$$\checkmark \frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B} - \nabla \phi$$

$$\checkmark \frac{\partial \phi}{\partial t} = -c_h^2 \nabla \cdot \mathbf{B} - \frac{c_h^2}{c_p^2} \phi$$

$$\checkmark \nabla \times \mathbf{B} = \mathbf{J}$$

I. Nonlinear force-free field extrapolation

NLFFF extrapolation (Inoue+2014), which is 1 hour before an M6.5 flare, is carried out. However, the NLFFF is almost static field.

II. Data-driven MHD simulation.

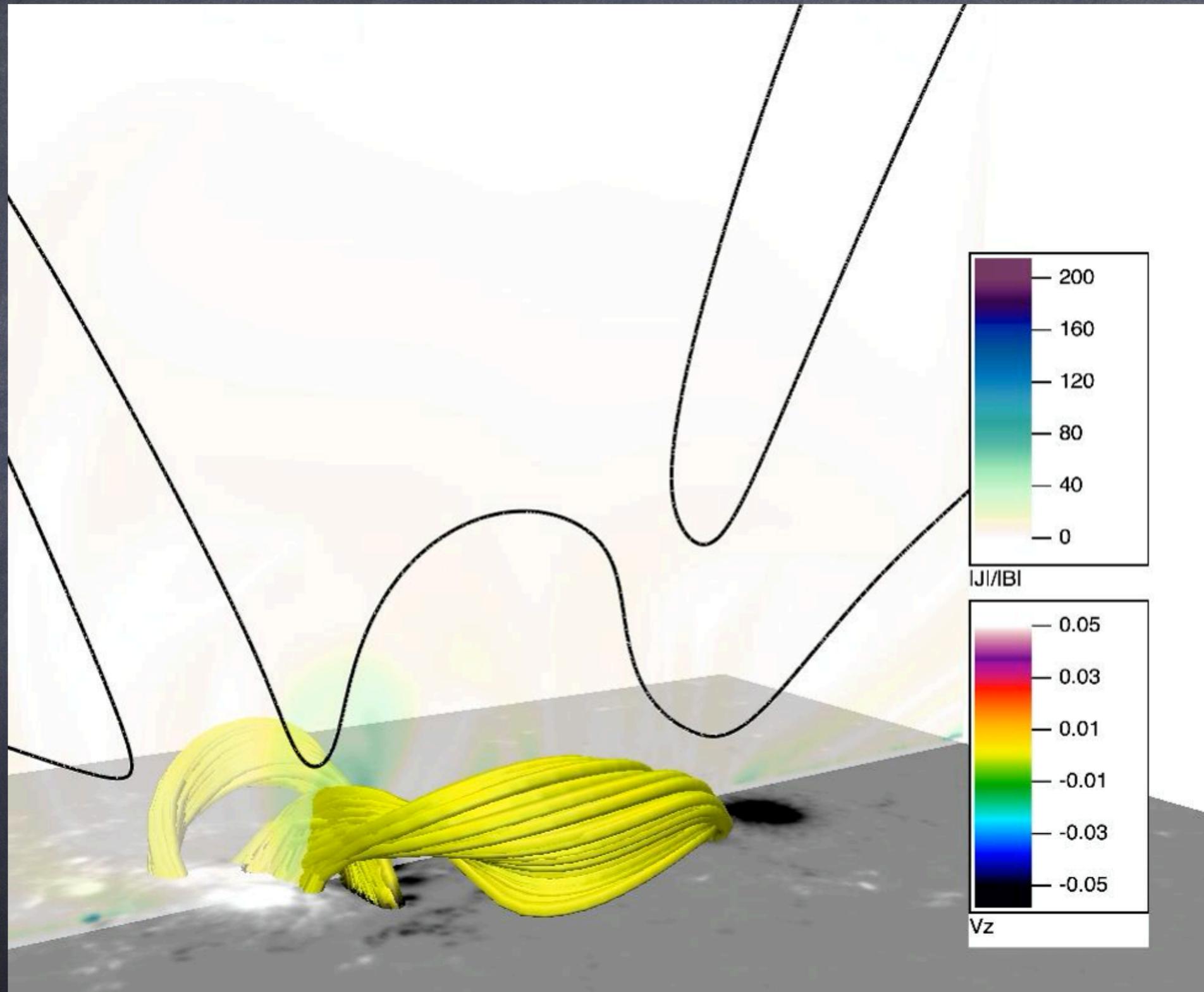
Data-driven MHD simulation (Hayashi +2018, Inoue+2023) is conducted using NLFFF as the initial condition. We create the pre-eruption magnetic field which is non-static field.

III. Data-constrained MHD simulation.

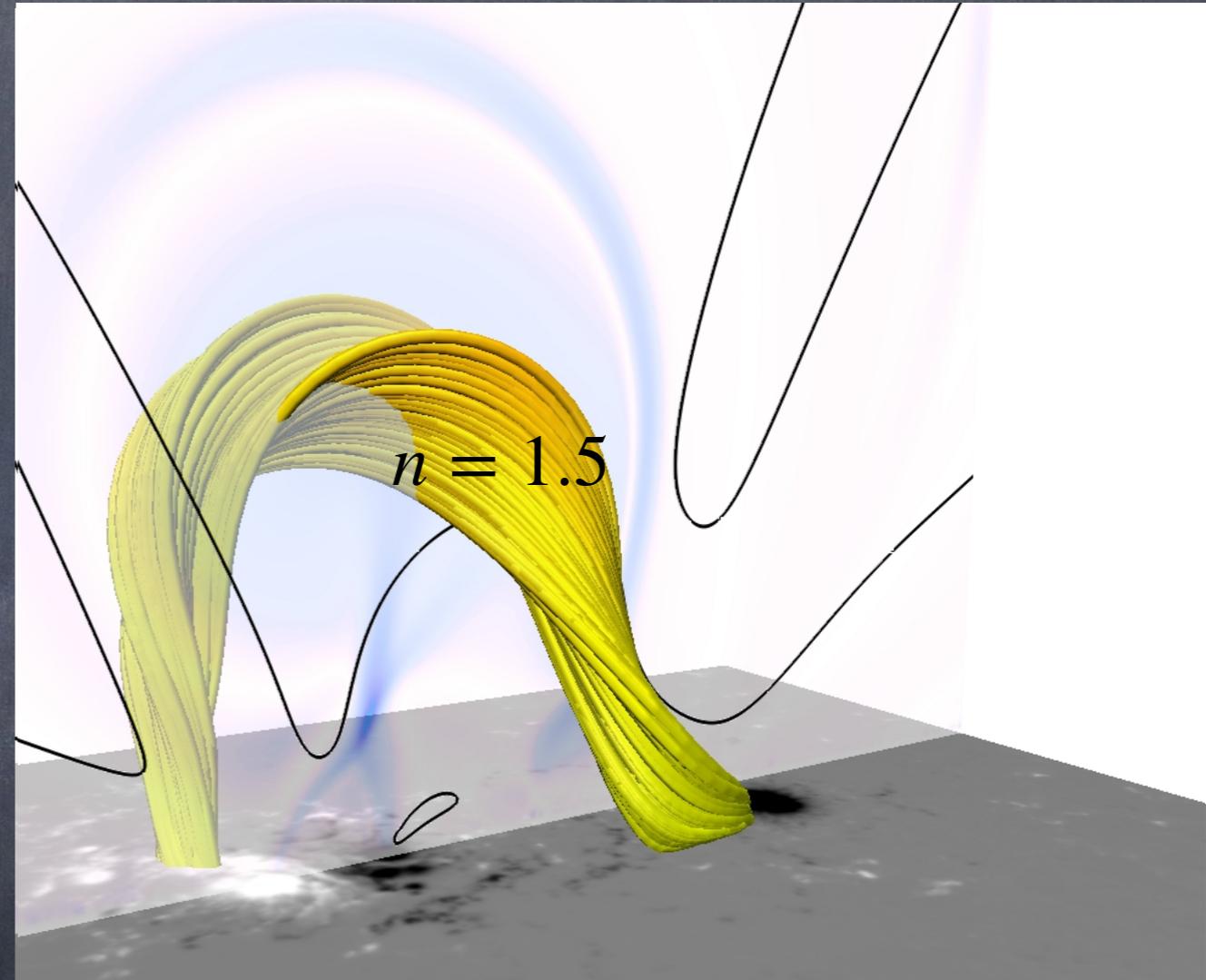
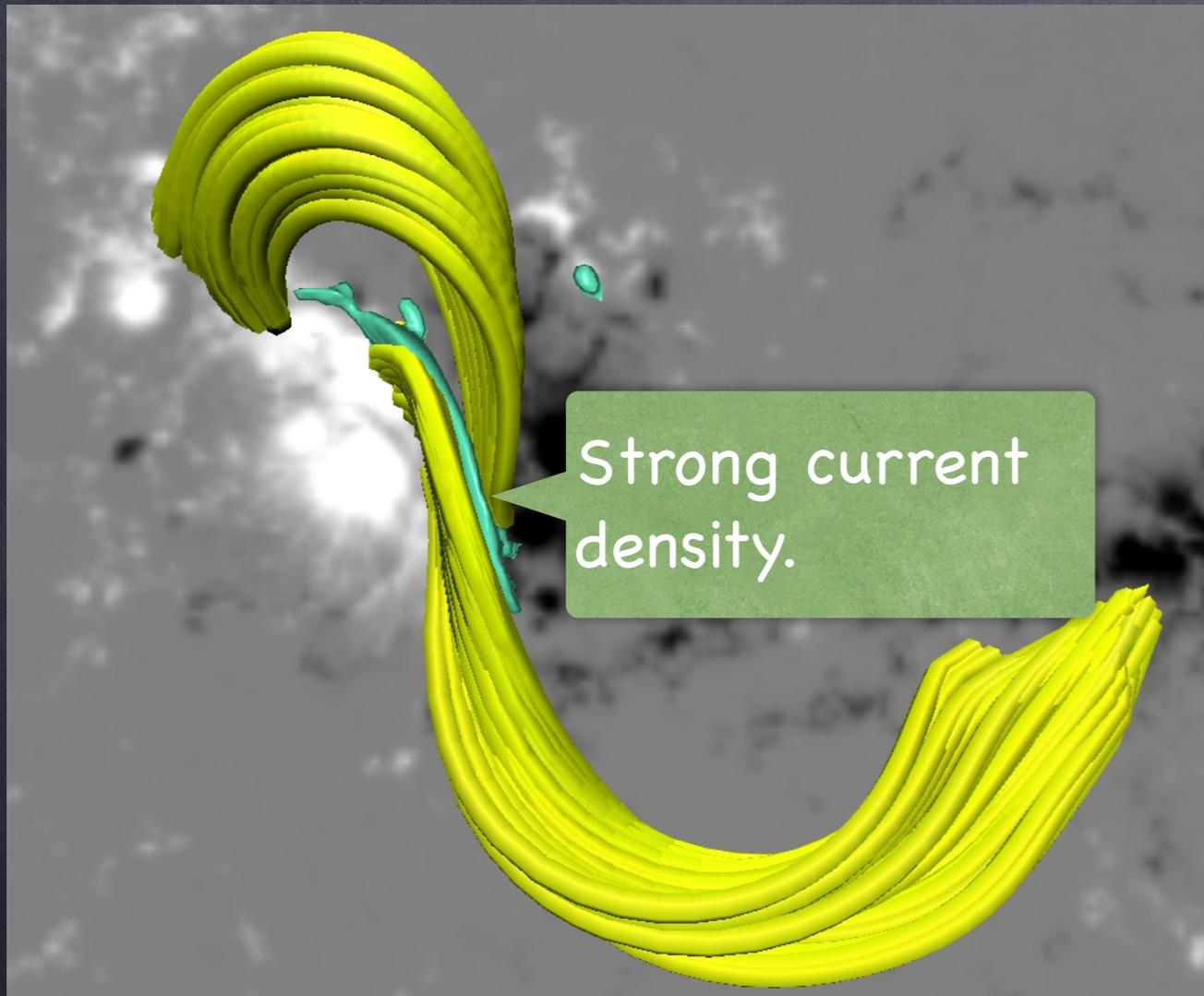
Data-constrained MHD simulation (Inoue+2016) is conducted using mag B. created by the data-driven MHD sim.

B_x and B_y at the bottom are free.

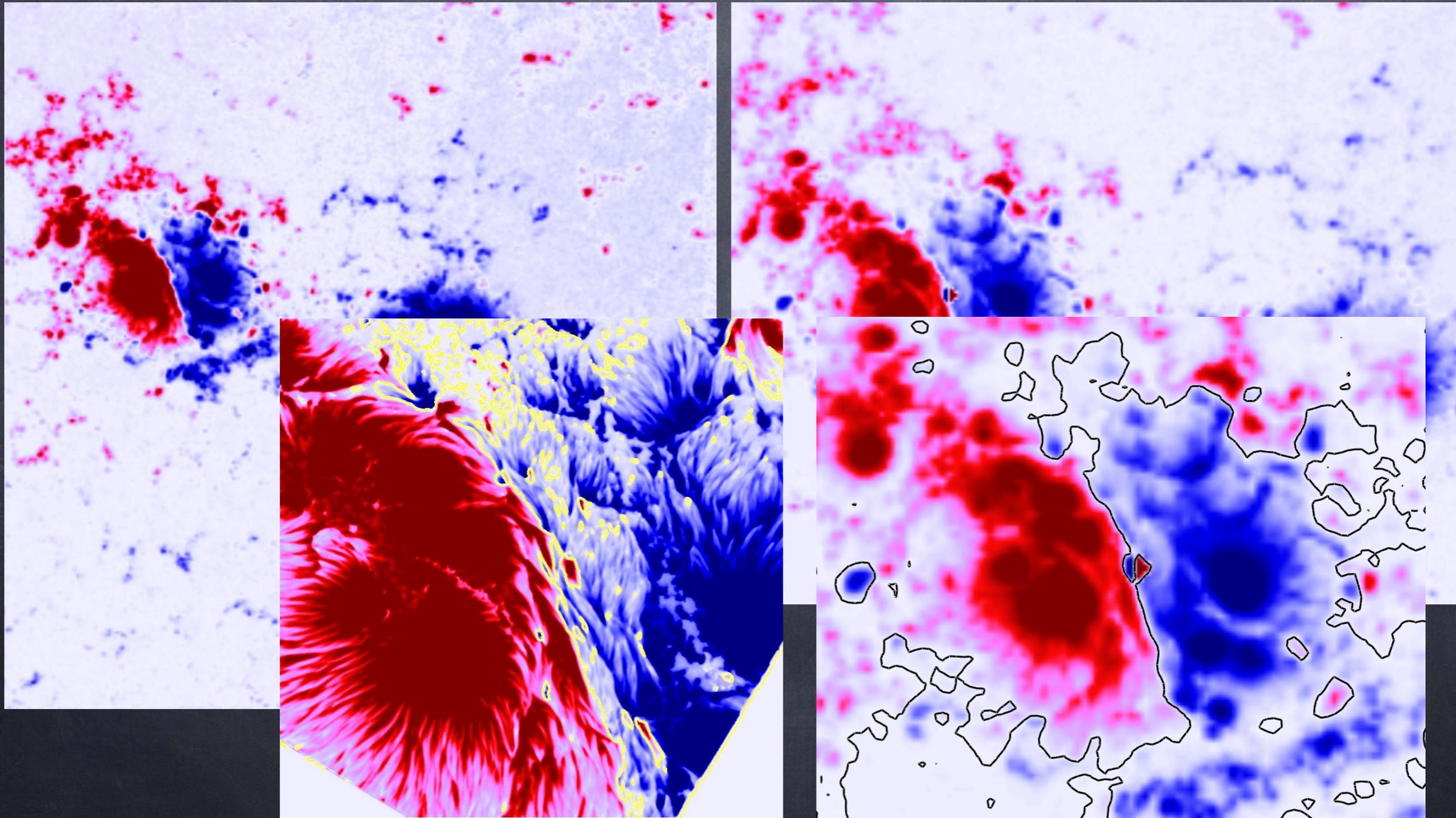
Data-driven MHD Sim. W/O Emerging Flux



Overview of the Eruption

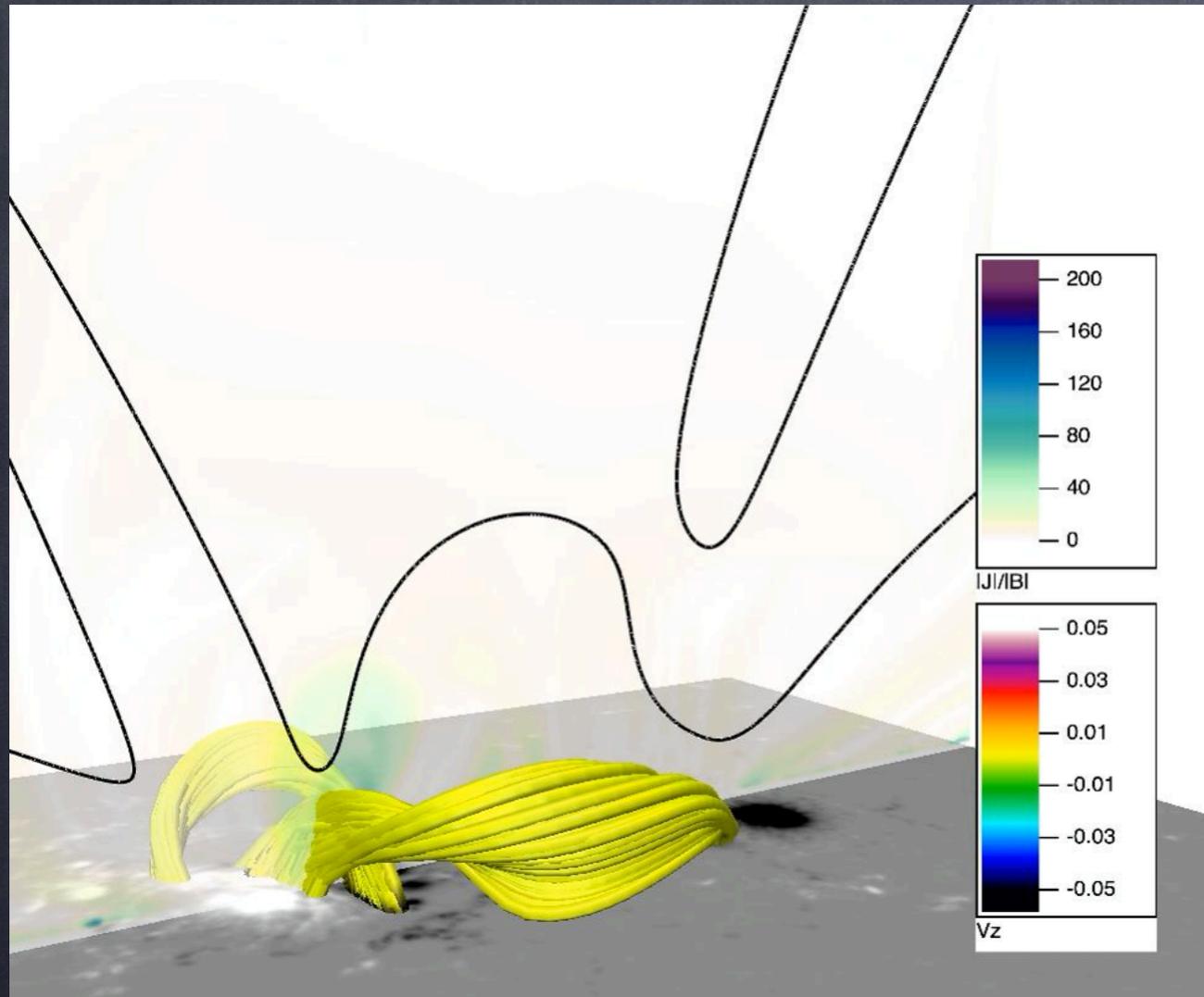


Modeled Small-scale Emerging Flux

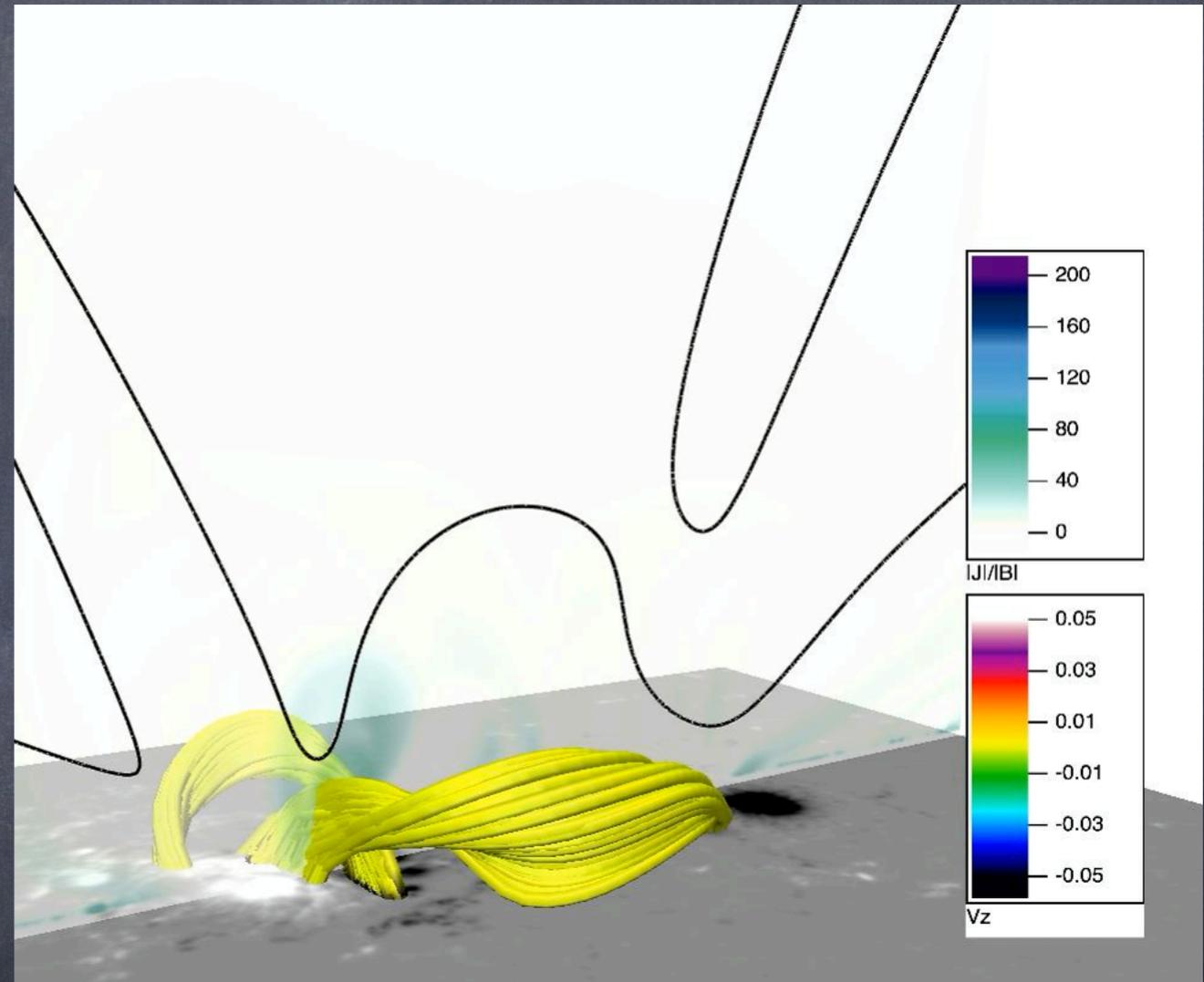


With/Without Small-scale EMF

Without small-scale EMF

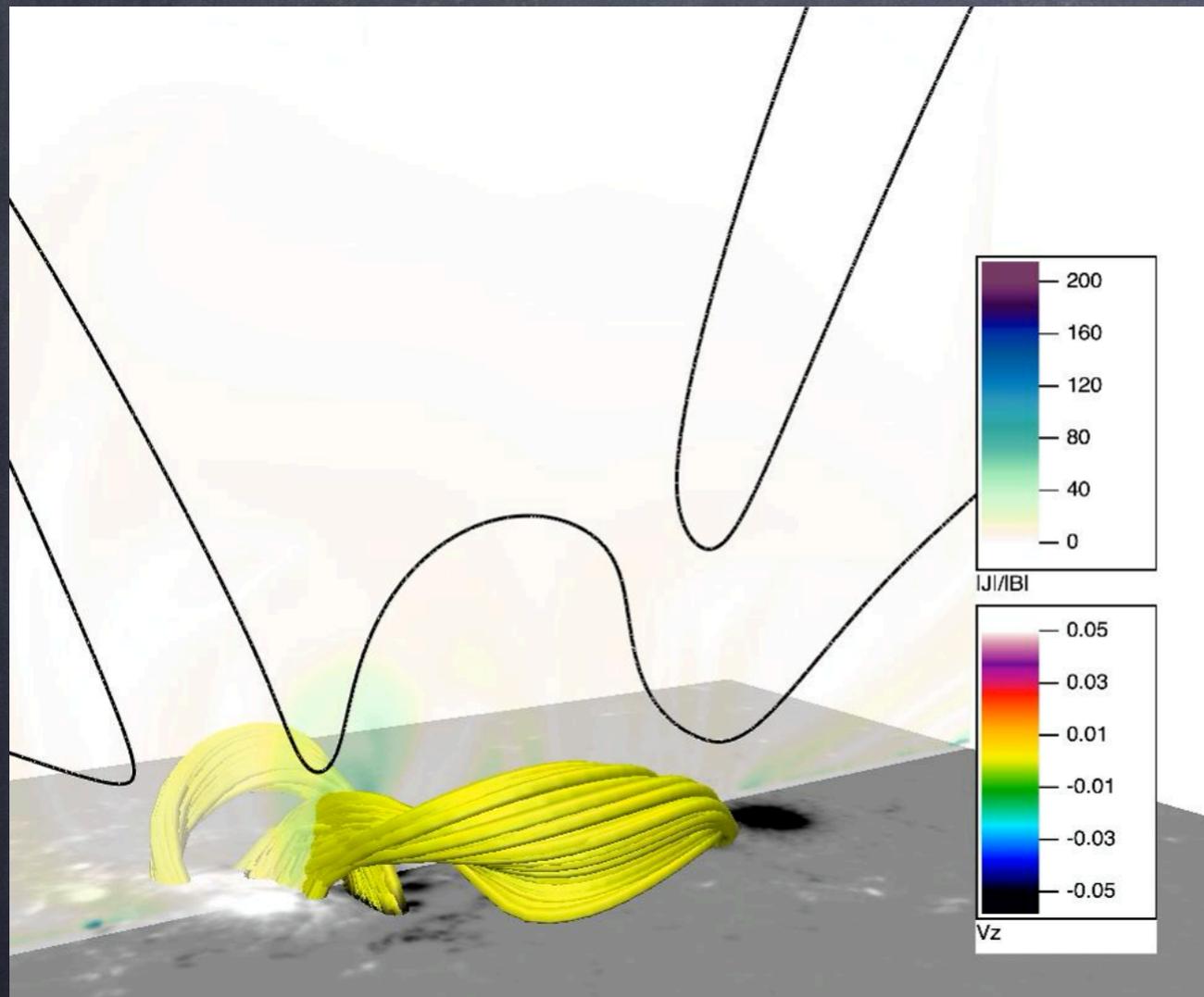


With small-scale EMF

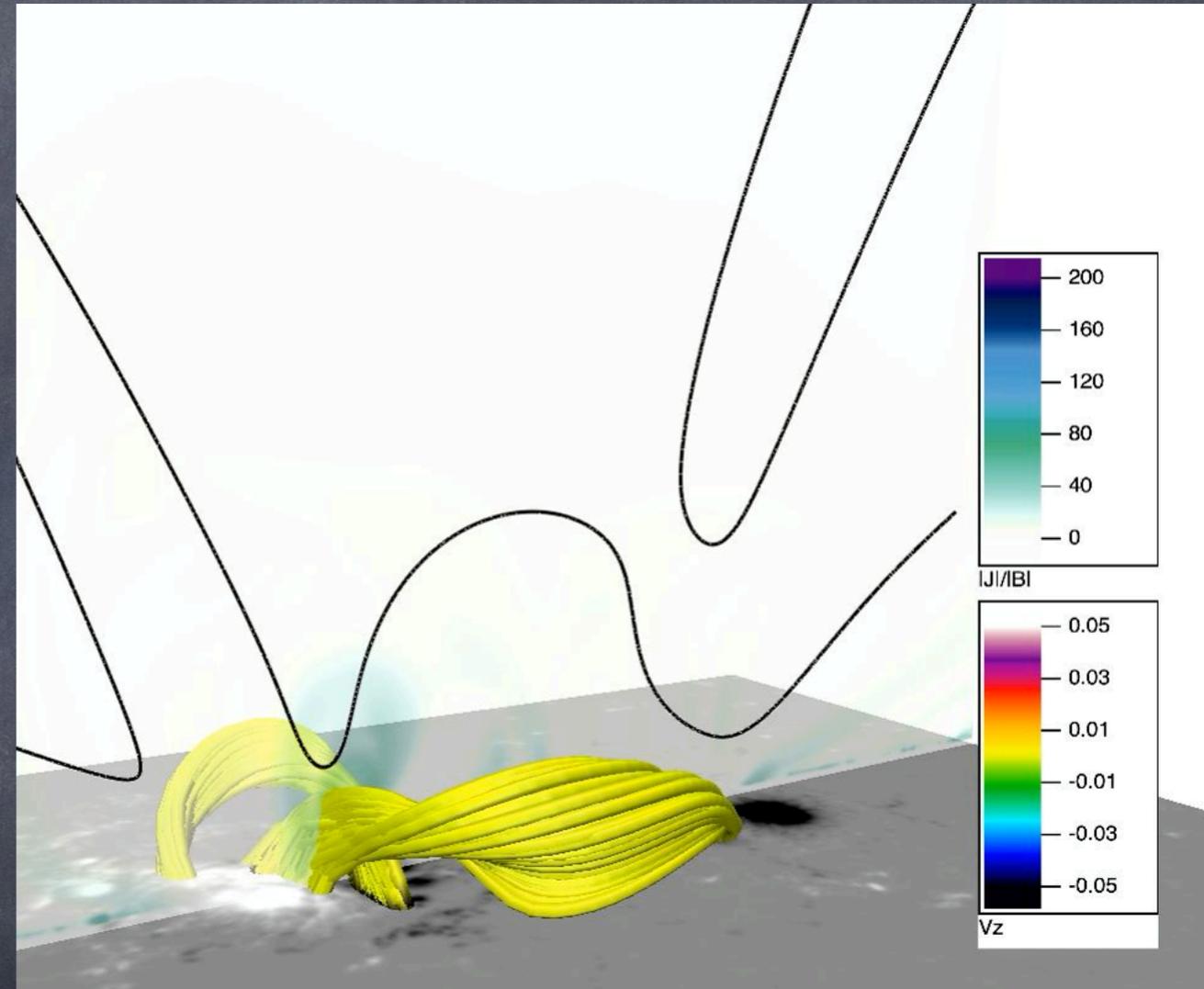


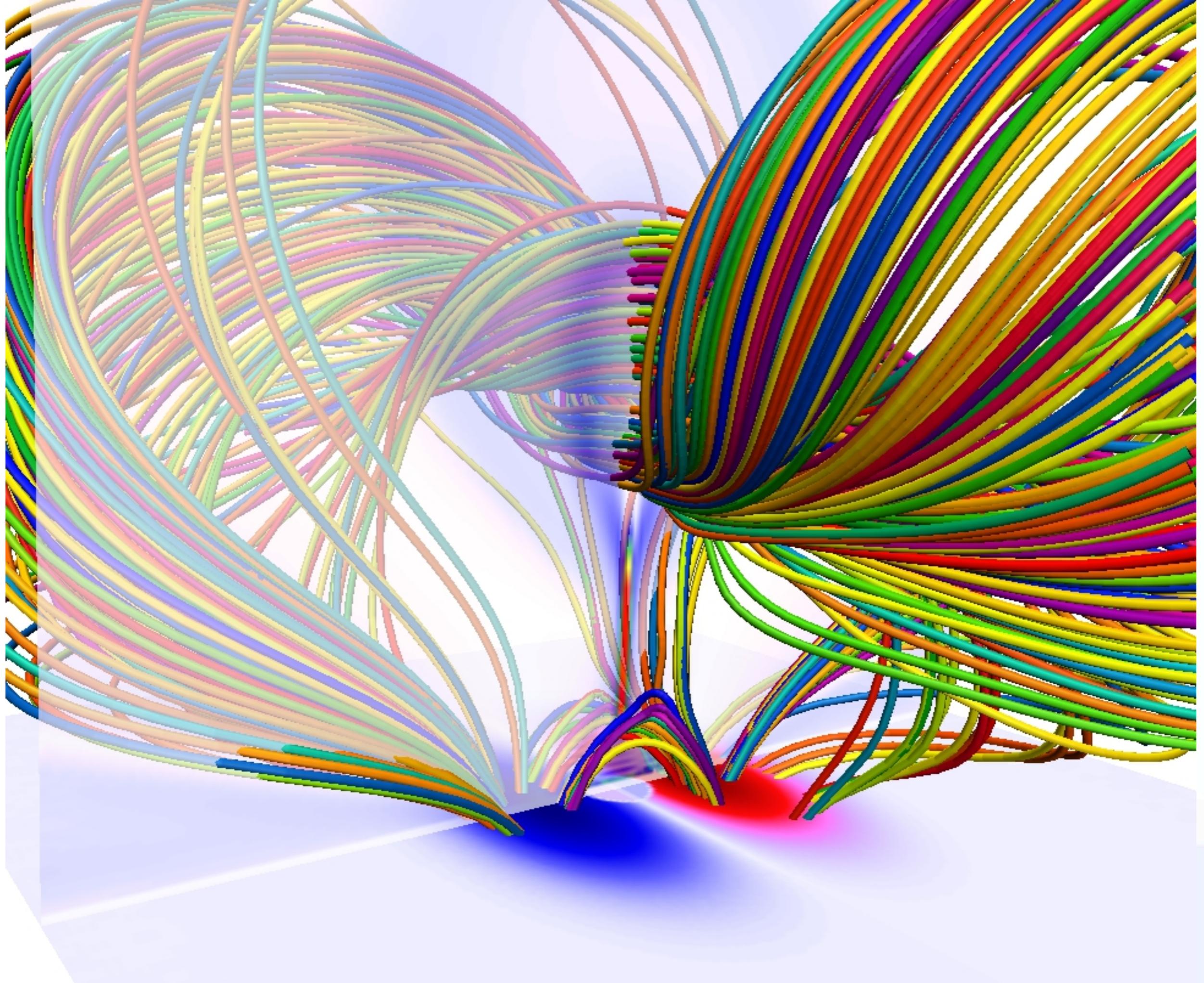
With/Without Disturbances

No disturbances



With disturbances





Summary

- ✓ Please understand what is advantage/disadvantage in software for force-free extrapolation, MHD simulation you will use.
- ✓ If you did not, you cannot understand the physical significant of output data.
- ✓ The science paper written with the data you don't understand well is NOT reliable.

I hope that young students join and inject energy into the field of data-based MHD modeling.