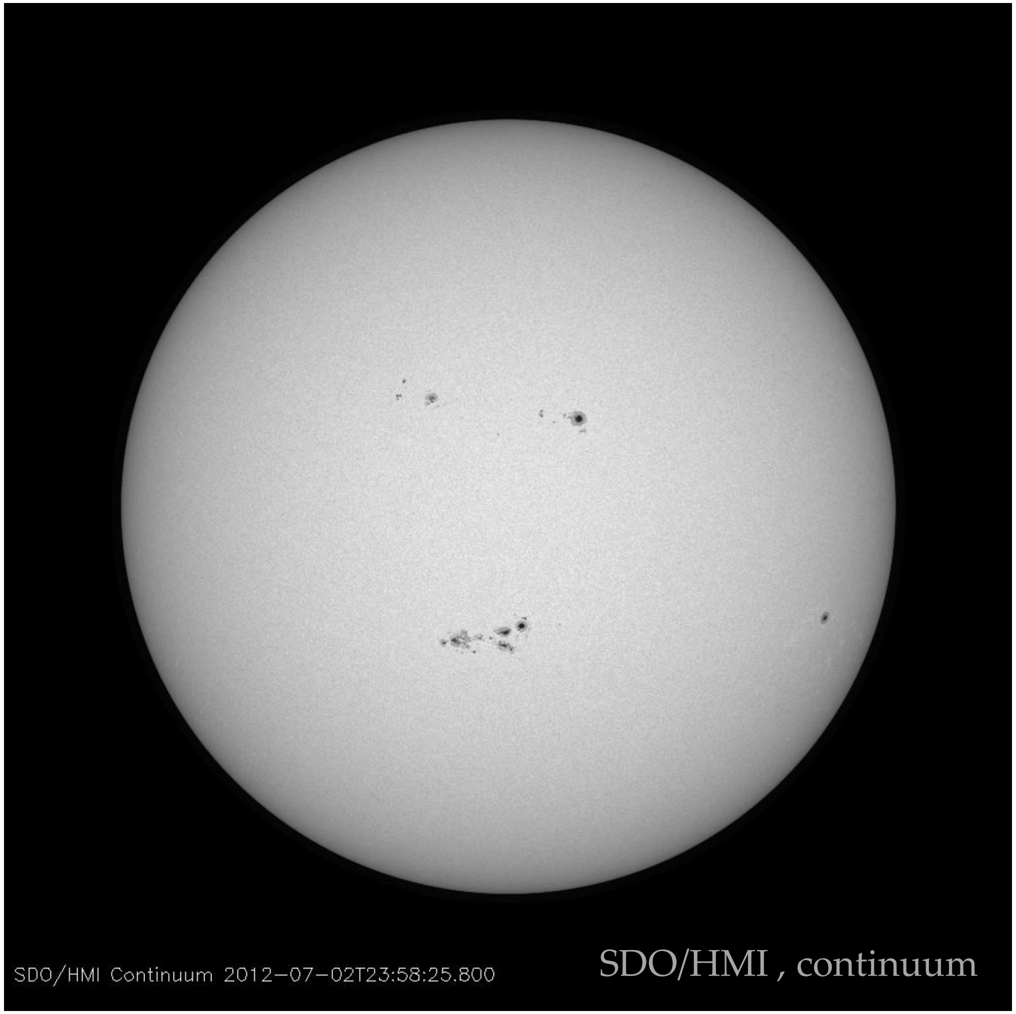
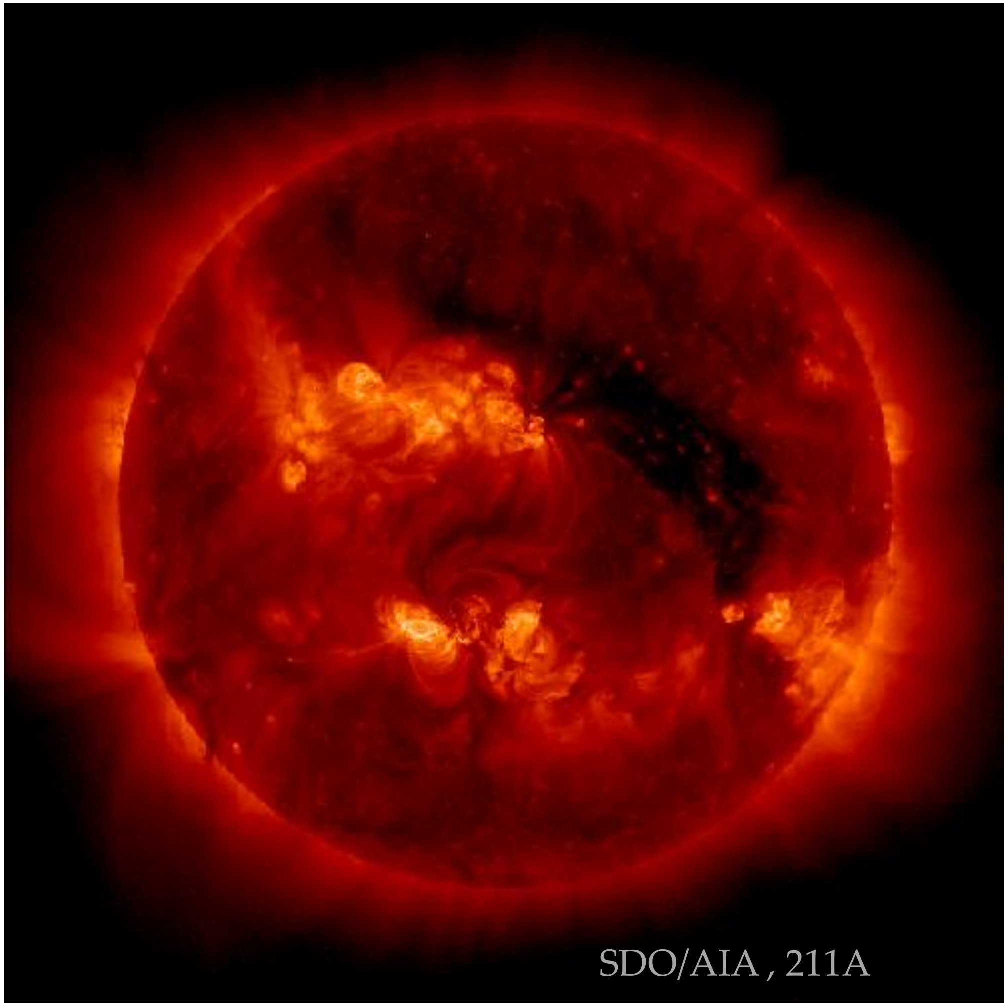
Using Observations to Understand the Causes of Space Weather

Anny Malanushenko (HAO)

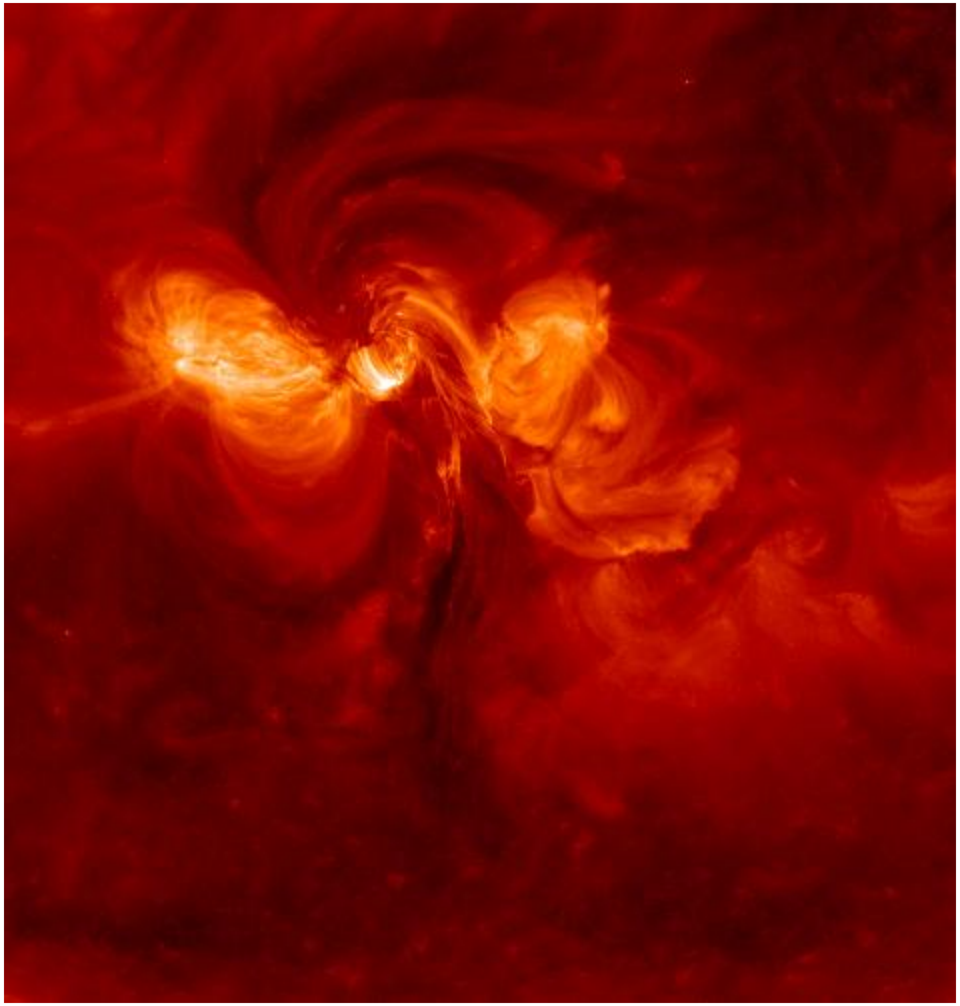
The Sun: in visible light



The Sun: in Extreme Ultraviolet



The Sun: Eruptive Activity



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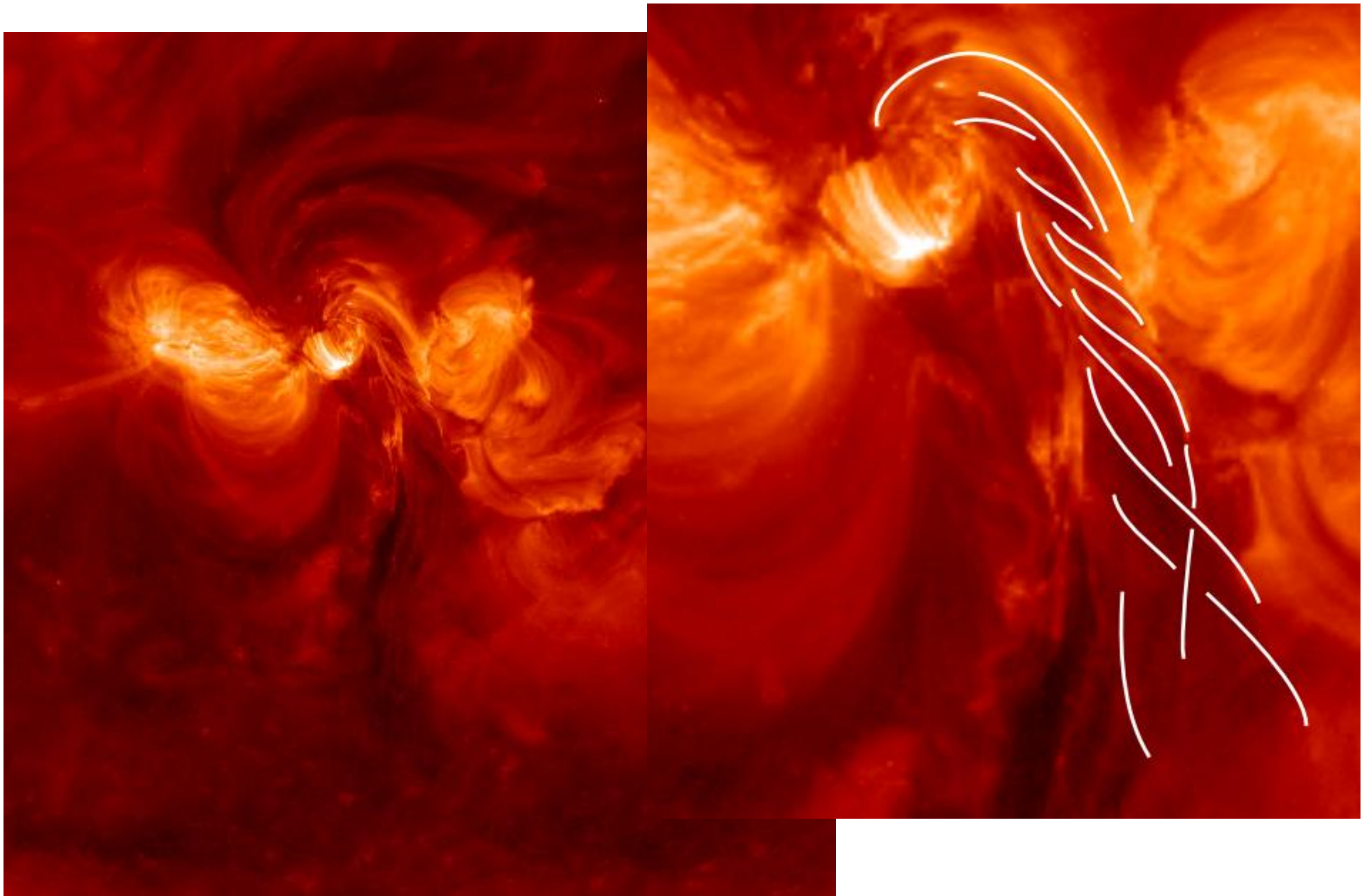

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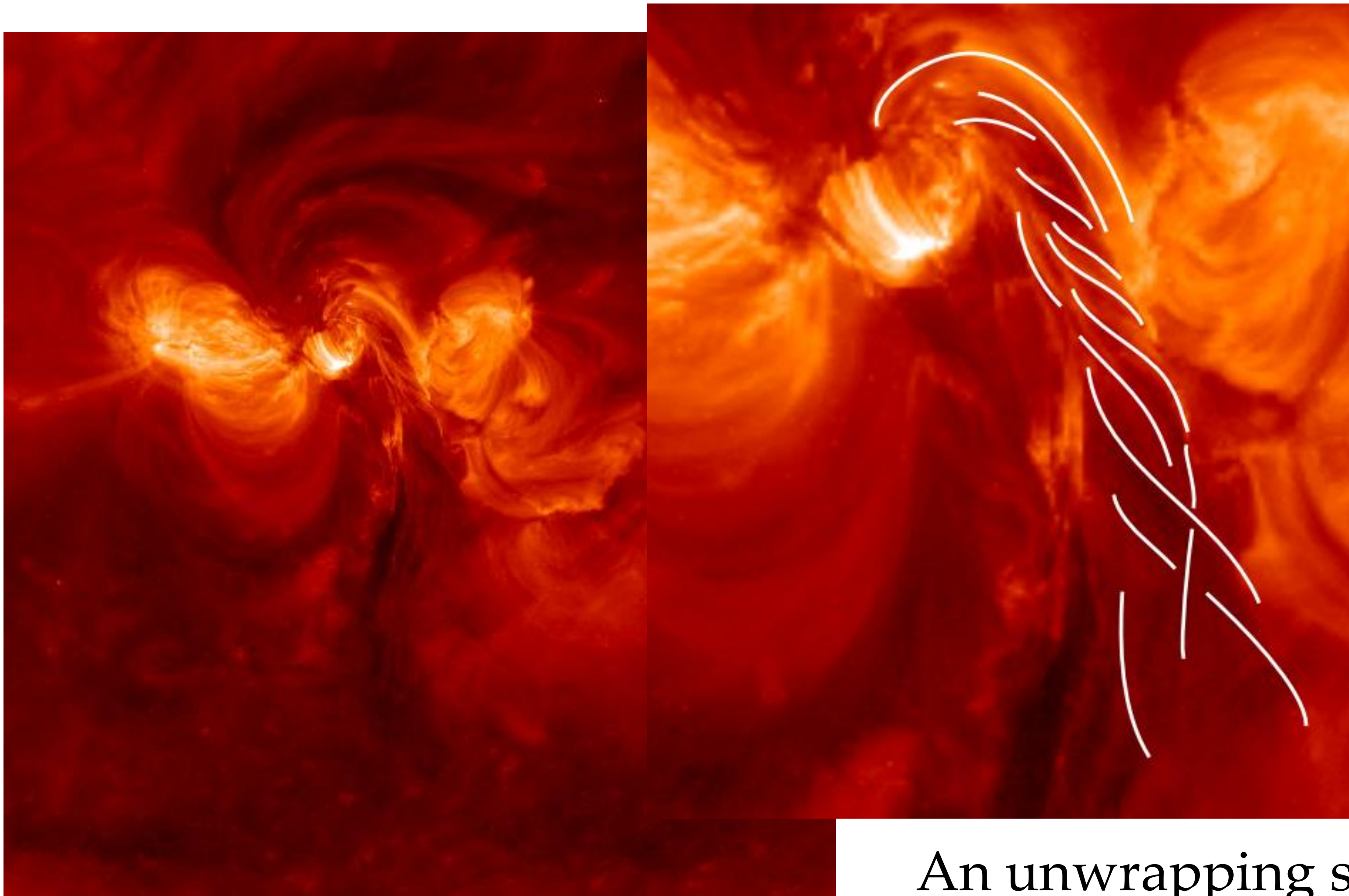

An unwrapping structure!

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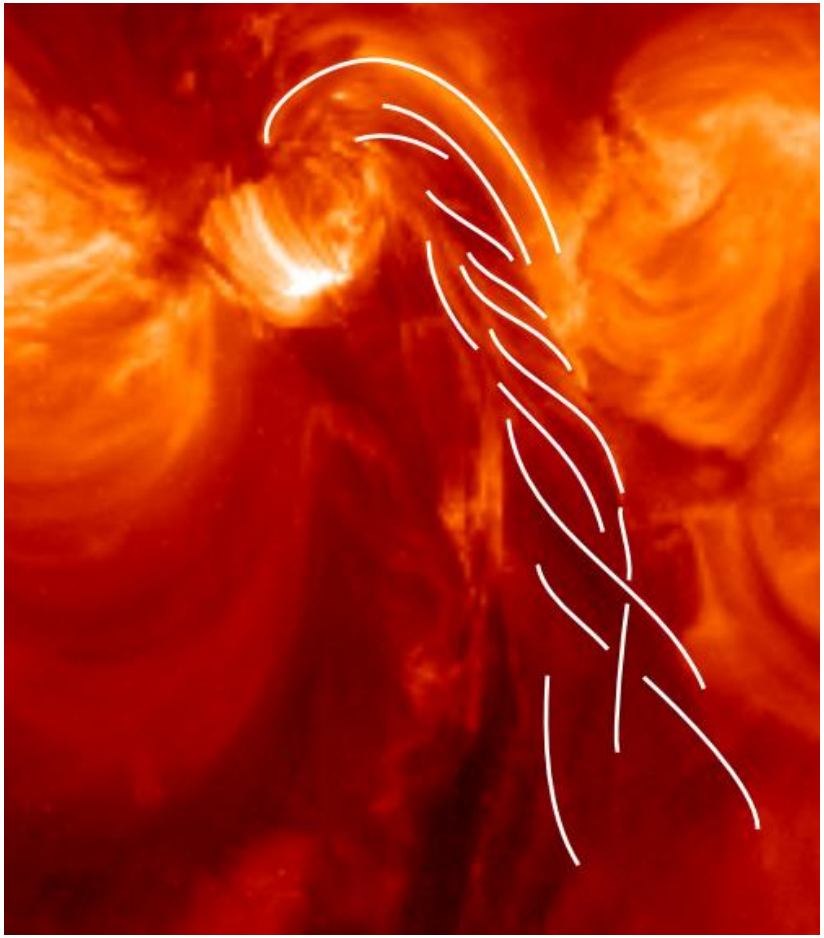
but what exactly is "unwrapping"?



Short answer:

magnetic field lines.

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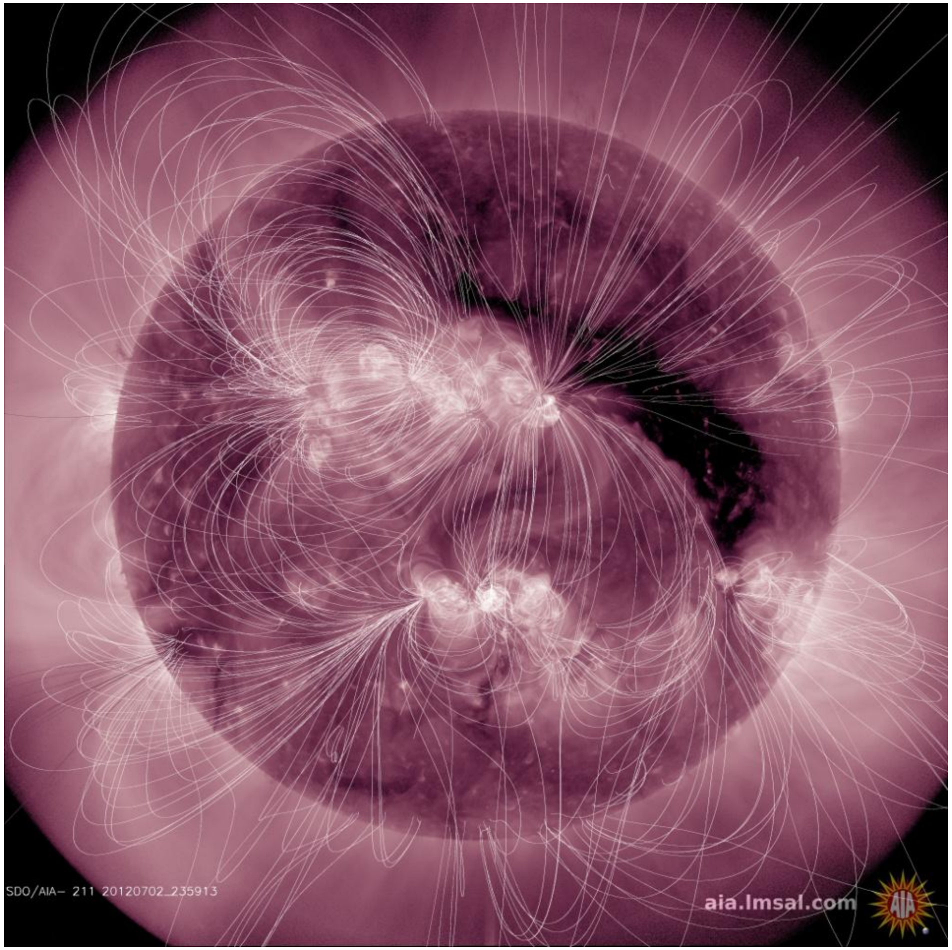

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magnetic field lines.

Plasma is frozen-in, and:

- In atmosphere:
  $P_G/P_B \ll 1$, **B** drives plasma

- Below the surface:
  $P_G/P_B \gg 1$, plasma drives **B**

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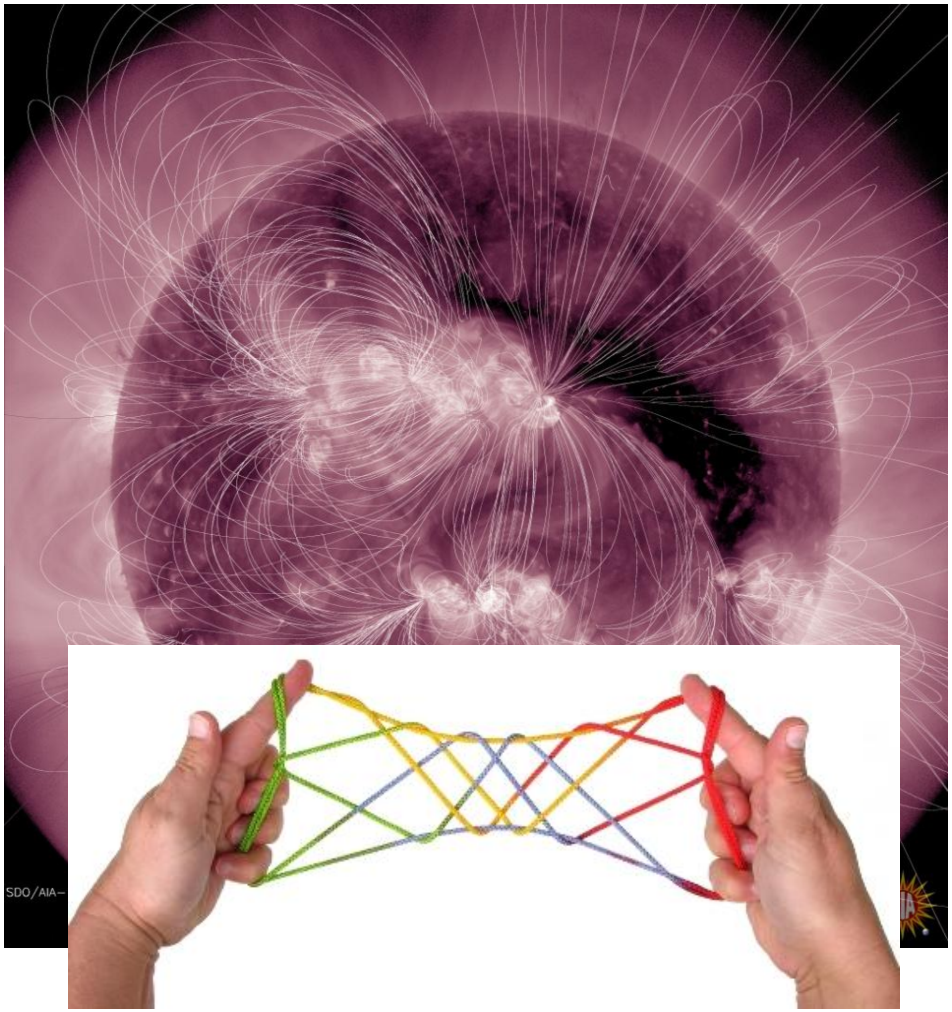

Photo: String Figure Magazine, Vol. 11, N.1 (March 2006)

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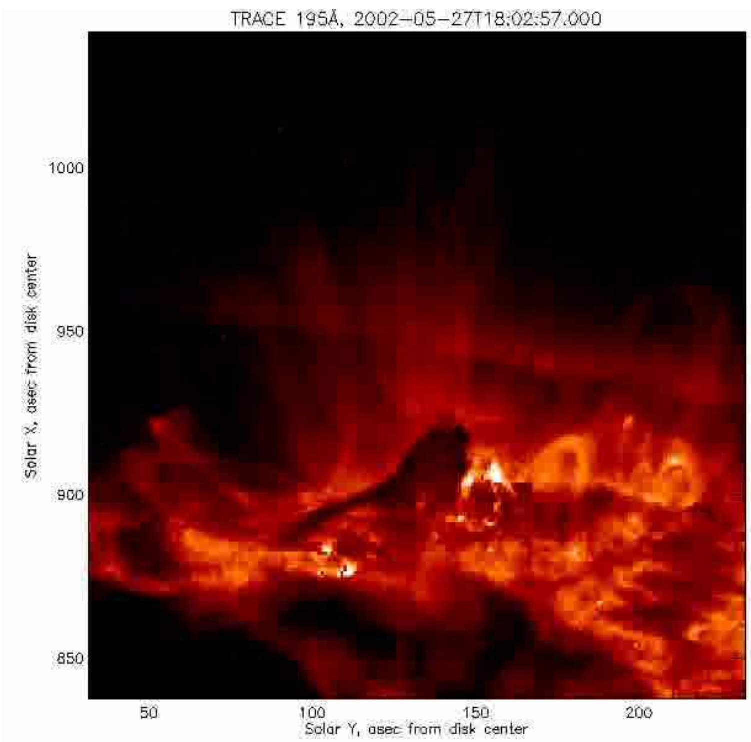
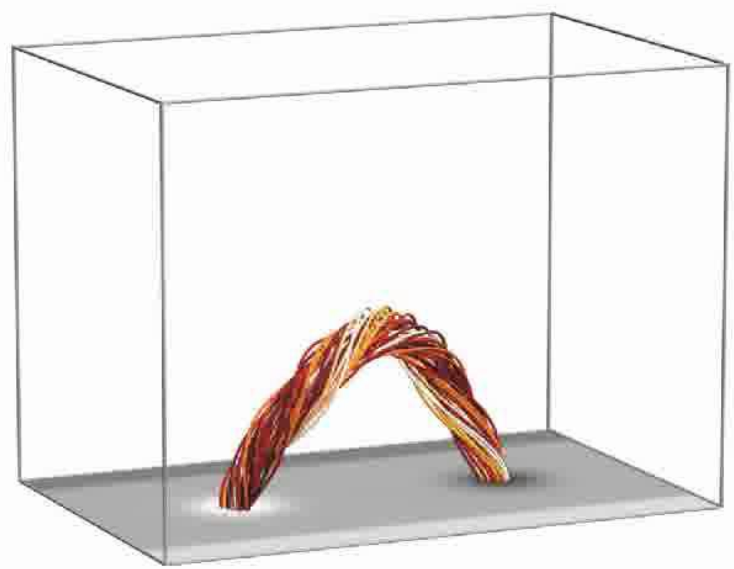
Magnetic field lines in the atmosphere get entangled as their footpoints move around

Consequences… solar eruptions!

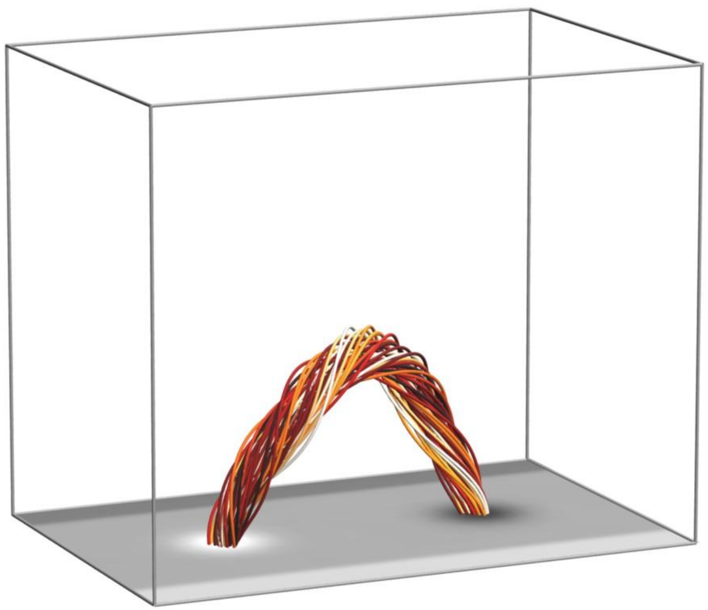
- A field too tangled may become unstable and explode
- Example: when *twisted* flux tube gets twisted beyond some critical value





Twist in magnetic equilibria

Idealized case:



Tw: total turns about the axis

Twist in magnetic equilibria

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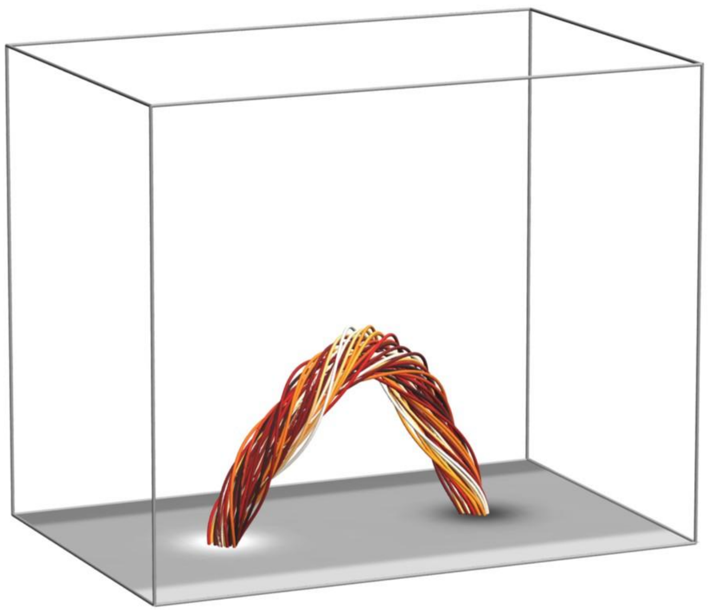

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"kink unstable" if Tw≥1.5

Hood & Priest (1979)

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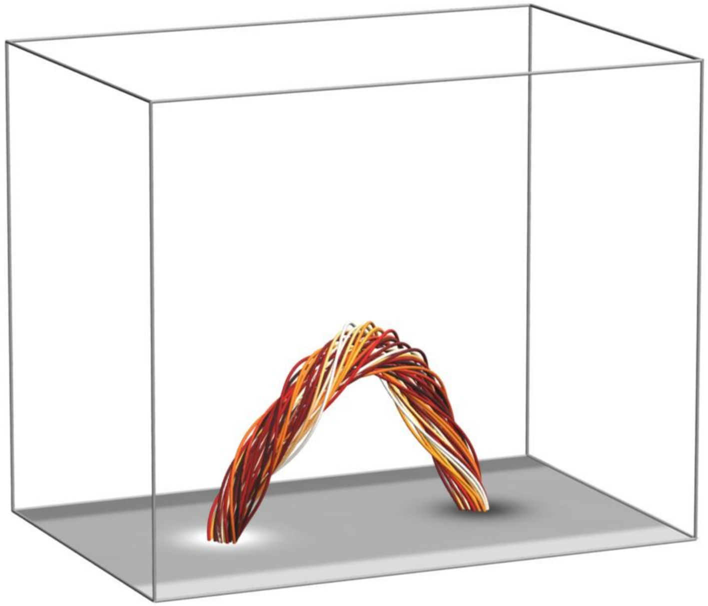

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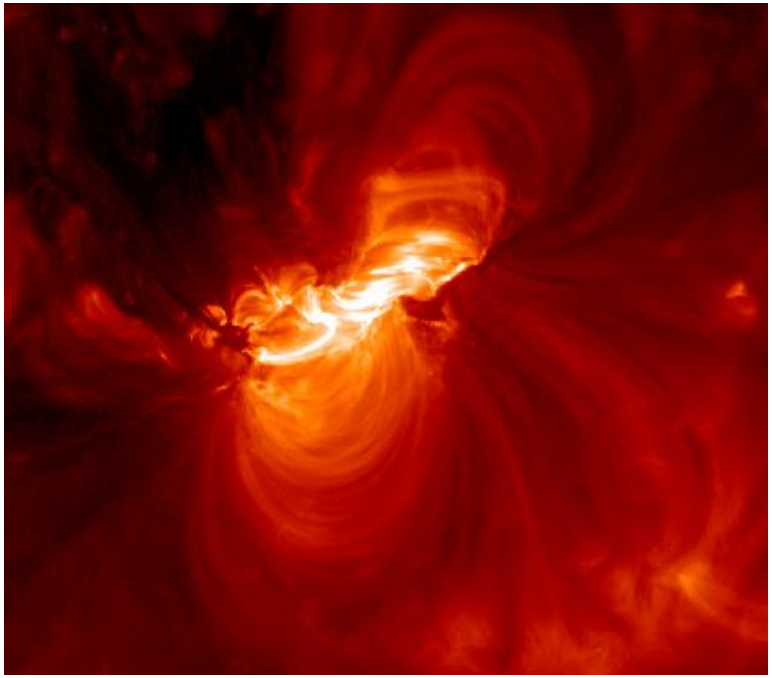
Actual observations:



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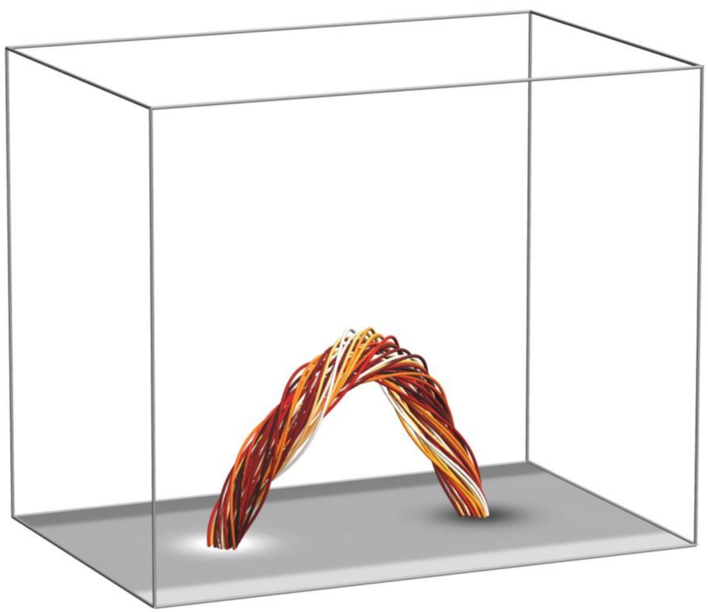

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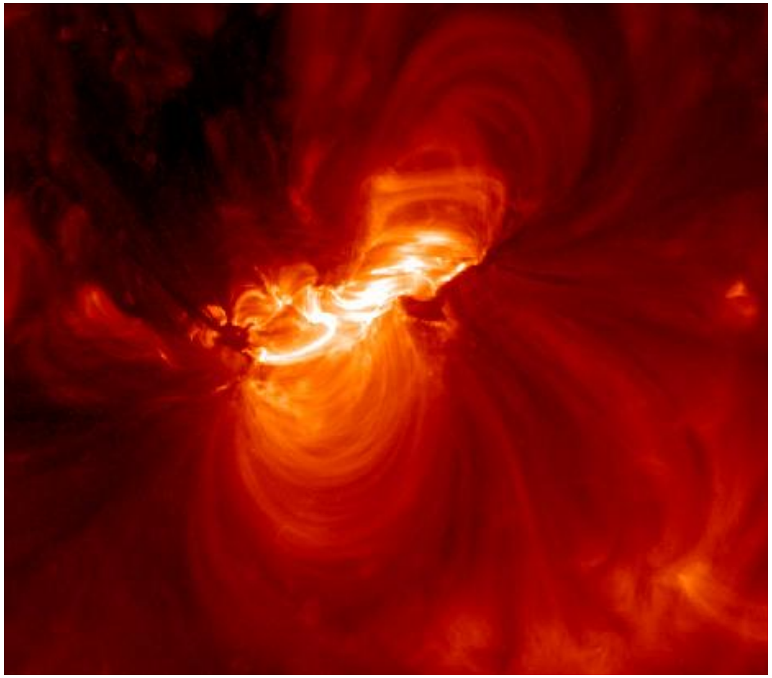

How to measure?

Twist in magnetic equilibria

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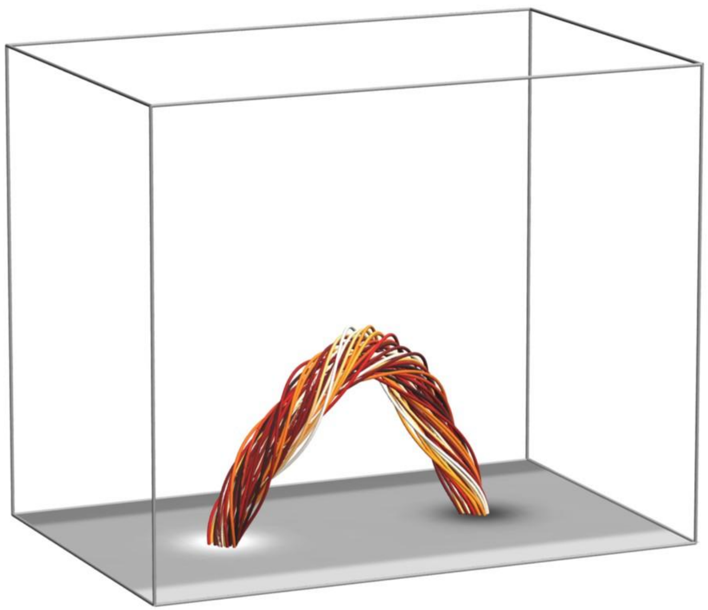

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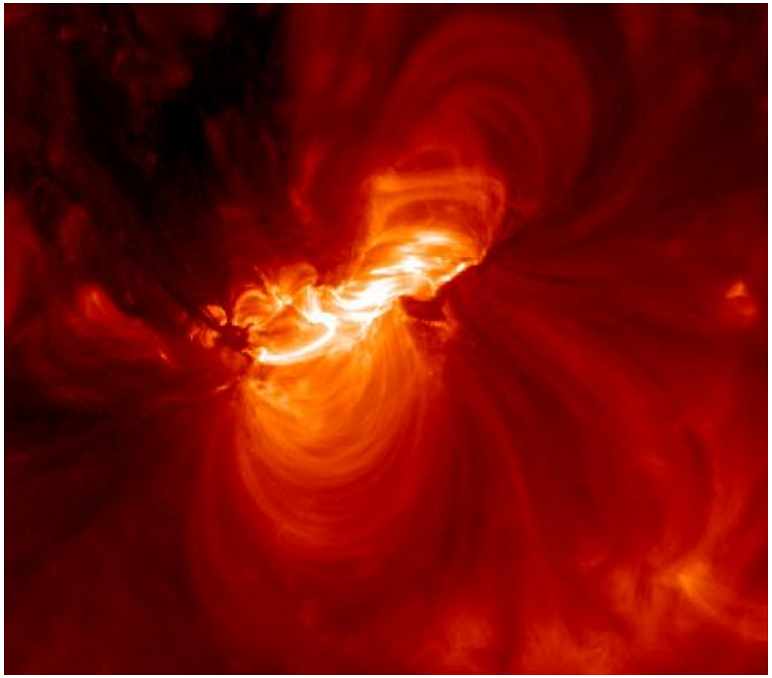

How to measure?
What to measure?

Twist in magnetic equilibria

Magnetic equilibrium in the corona: $\mathbf{F_L}=0$

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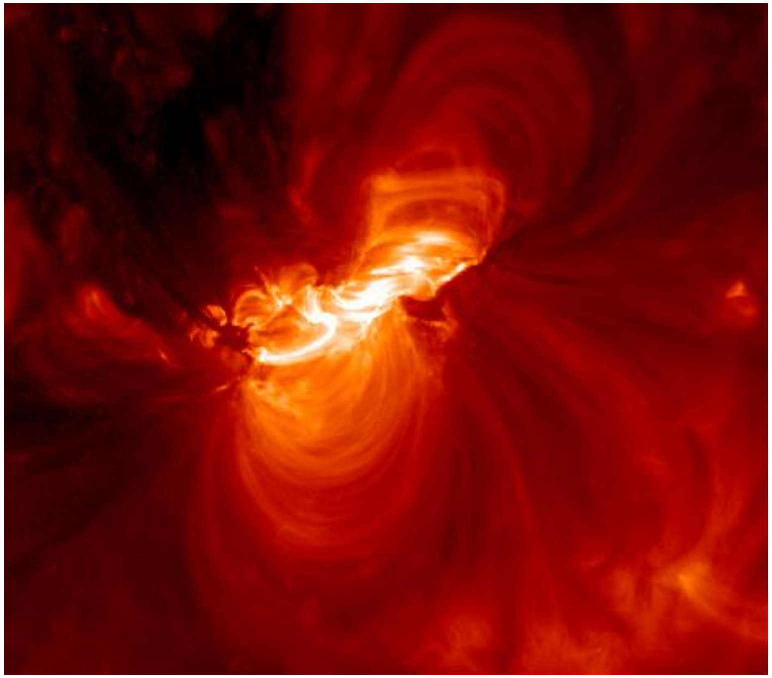

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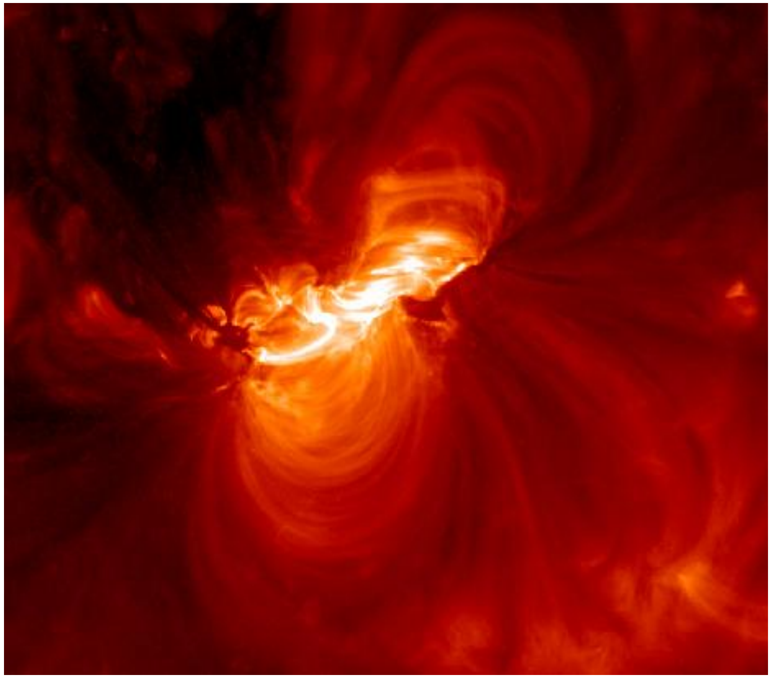

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Force-free parameter α is closely related to twist!

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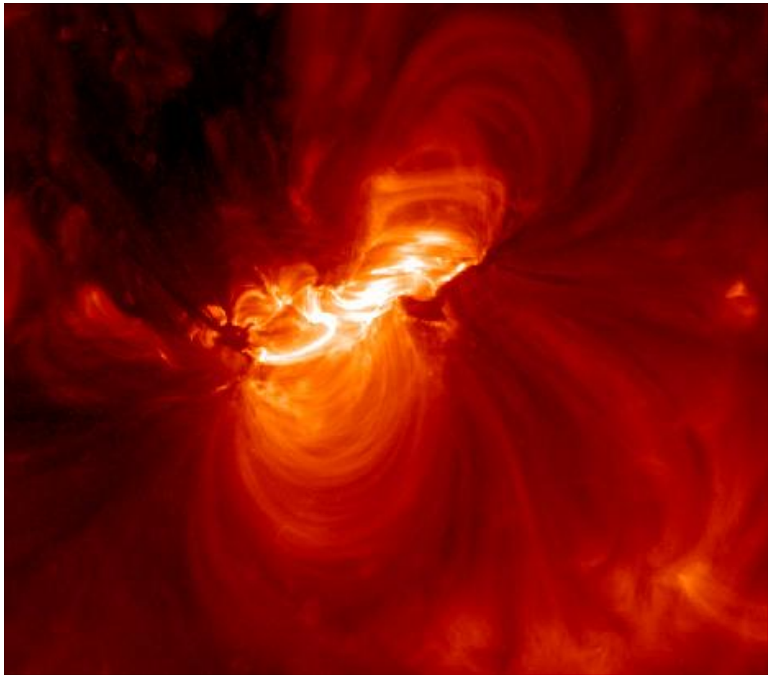

How to measure?
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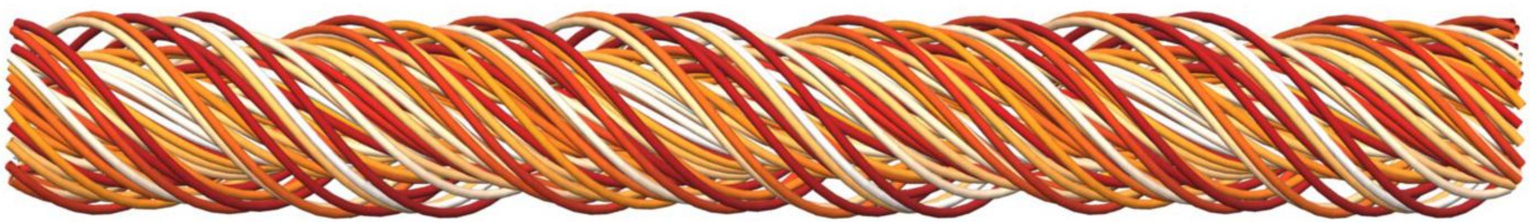
Force-free field: $\nabla \times \mathbf{B} = \alpha \mathbf{B}$

In a straight uniformly twisted flux tube,
α is angle per unit length.



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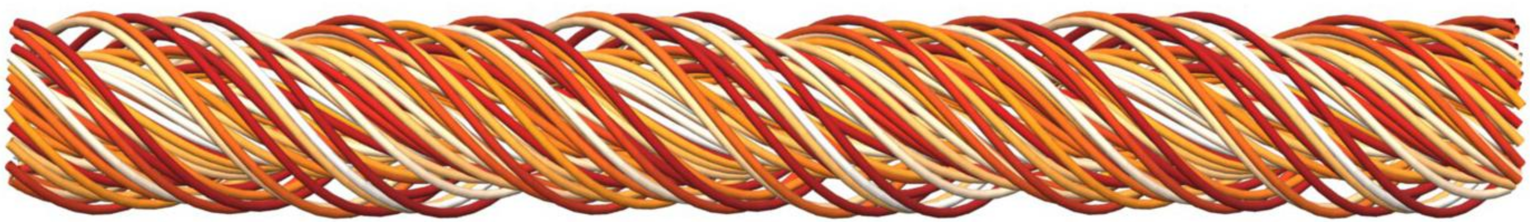
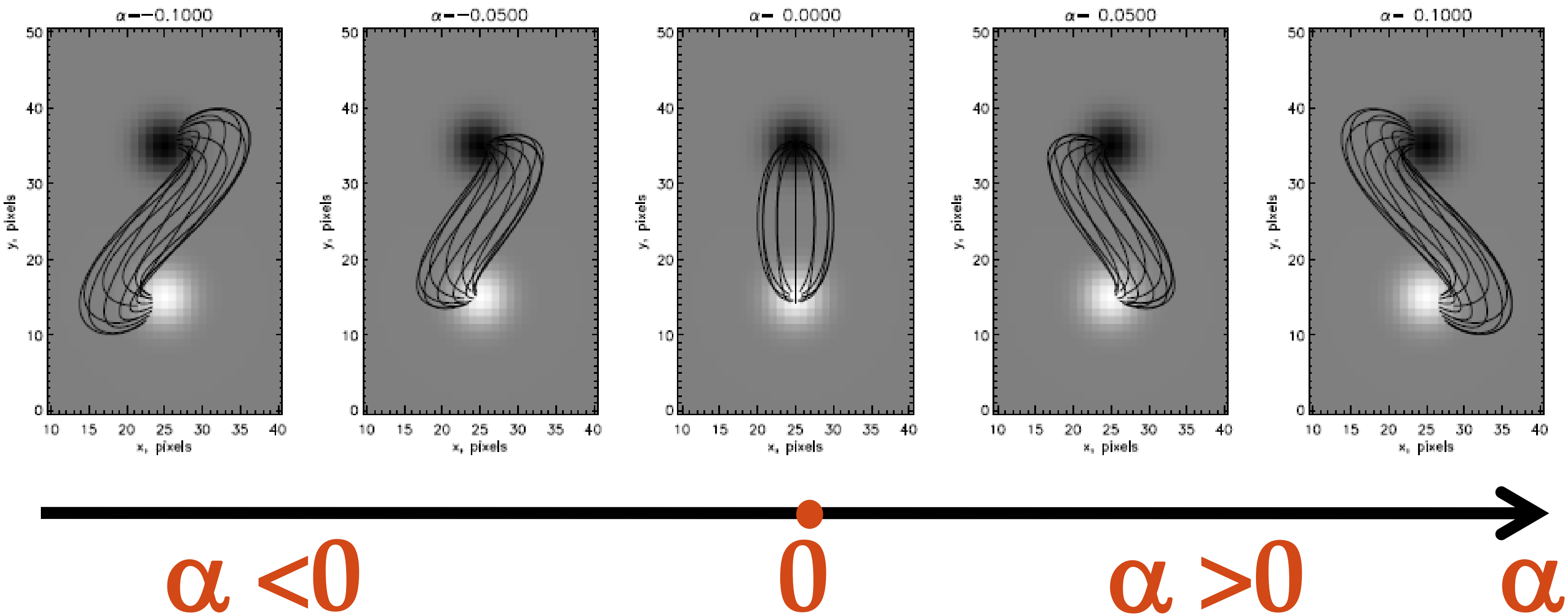


In general, α is still closely related to
the shape of field lines.

Force-free field: $\nabla\times\mathbf{B}=\alpha\mathbf{B}$

Intuitive insight: α is closely related to twist of field lines



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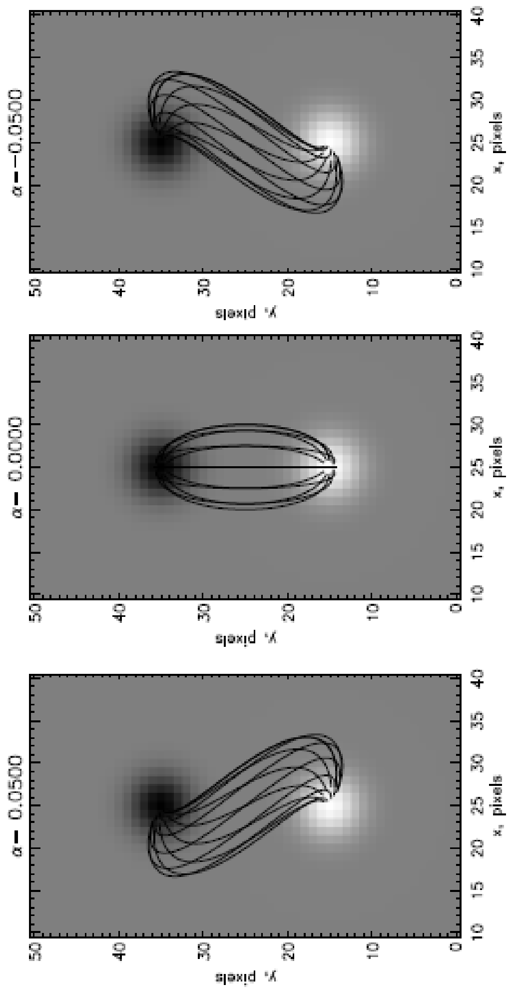

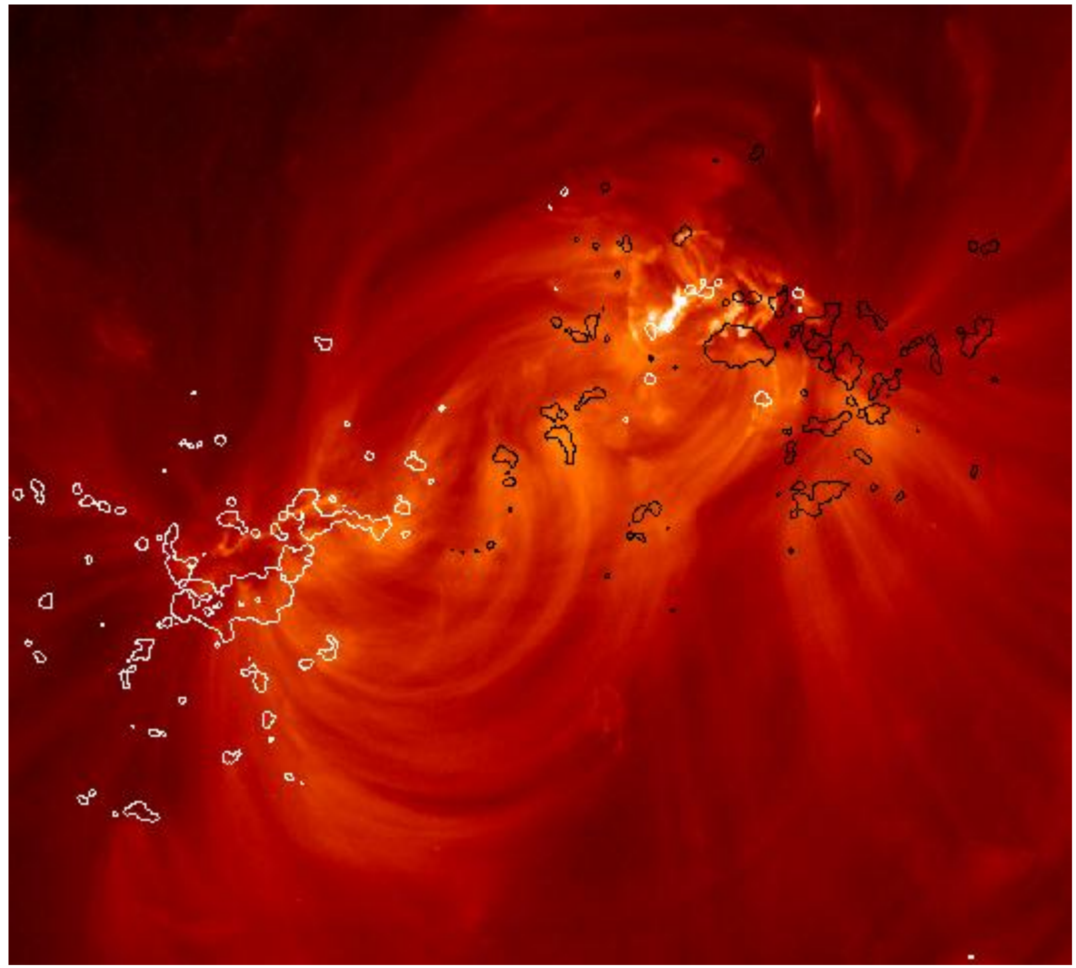

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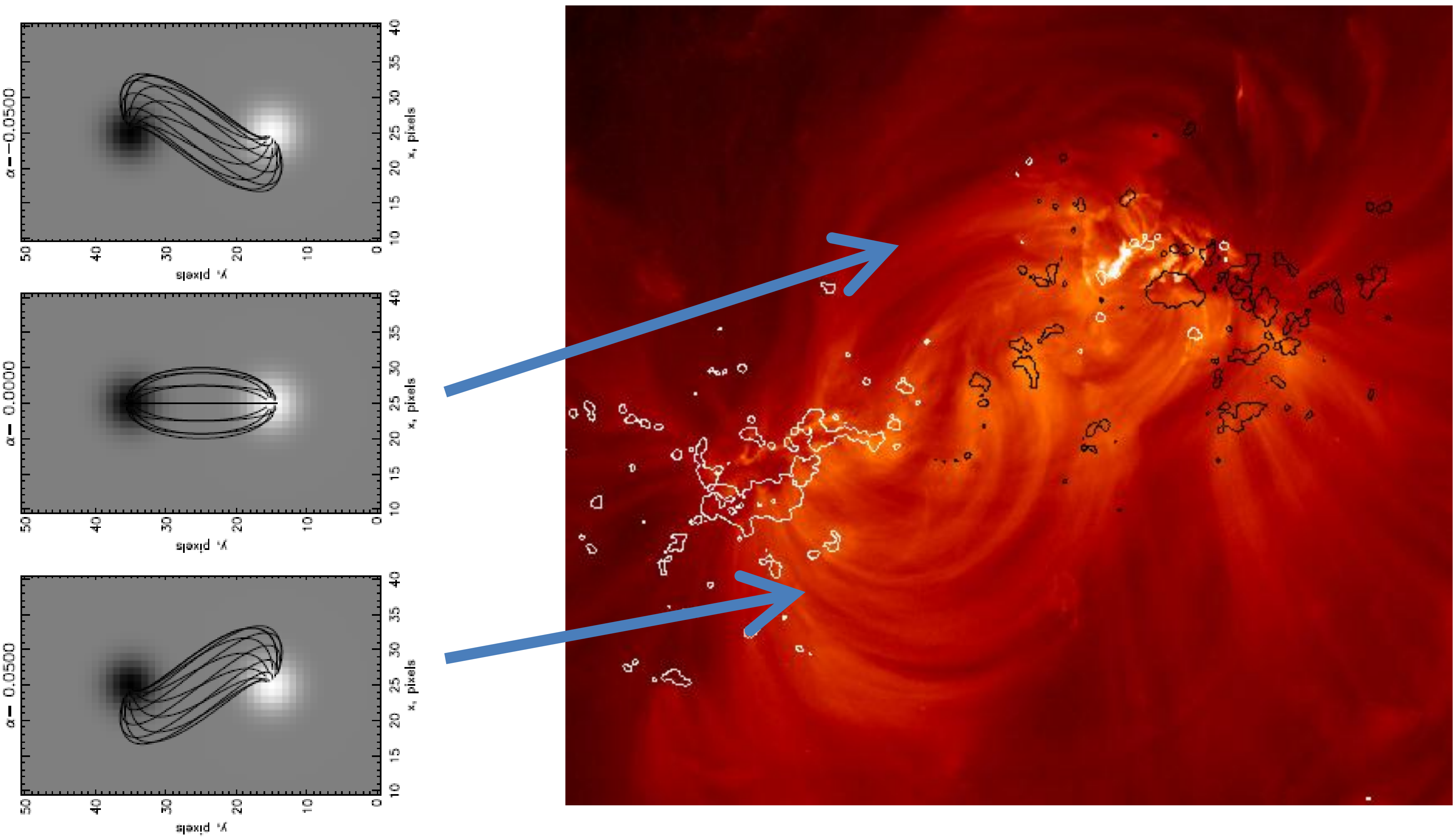

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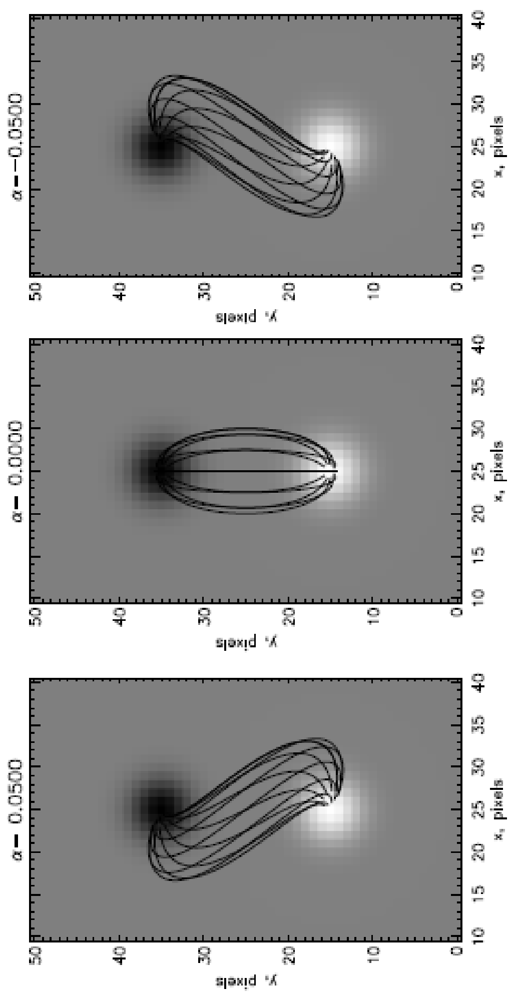

Const-α fields:

easy to calculate;

don't always work.

can't "combine" them

$\nabla\times(\mathbf{B}_1+\mathbf{B}_2)\neq\alpha(\mathbf{B}_1+\mathbf{B}_2)$ if $\alpha_1\neq\alpha_2$.

In general, the equation

$$\nabla^2\mathbf{B}+\alpha^2\mathbf{B}=\mathbf{B}\times(\nabla\alpha)$$

is non-linear.

Non-linear force-free field:

$$\nabla^2\mathbf{B}+\alpha^2\mathbf{B}=\mathbf{B}\times(\nabla\alpha)$$

Pros:

- Correct

Cons:

- Hard to solve
- Different methods give different answers
- B.C.: needs full **B** at z=0
  (B_x and B_y are needed for getting α)
- Have B.C. where the equations don't work!

(Demoulin et. al., 1971; DeRosa et. al., 2009)

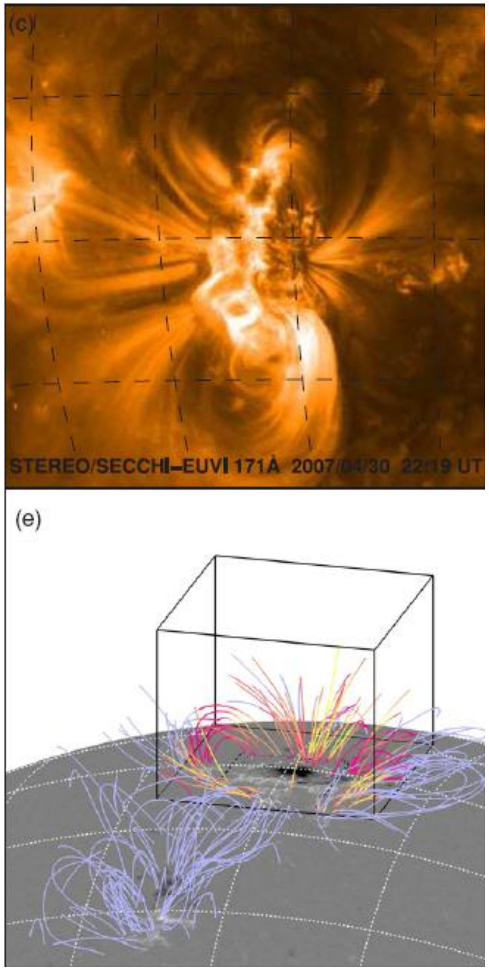

Fig. 1 from DeRosa et. al., 2009

Non-linear force-free field:

$$\nabla^2 \mathbf{B} + \alpha^2 \mathbf{B} = \mathbf{B} \times (\nabla \alpha)$$

Pros:

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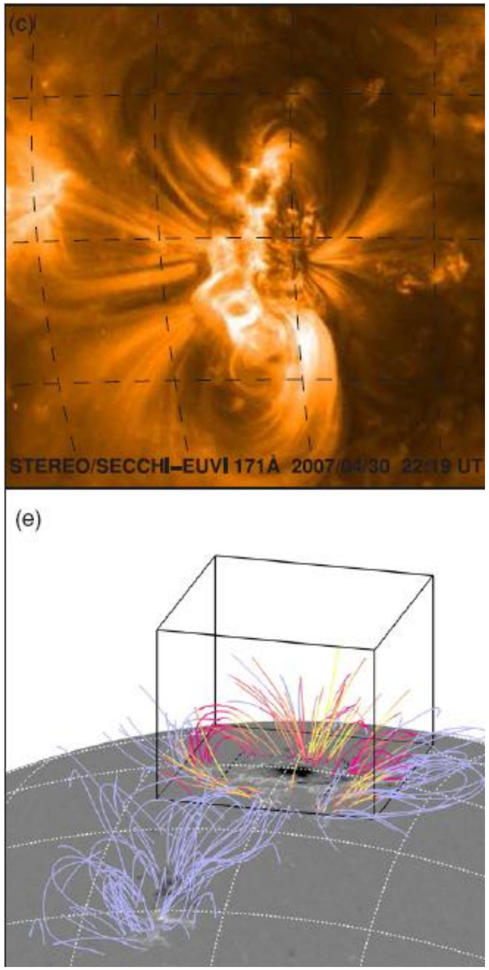
Bypass?

(Demoulin et. al., 1971; DeRosa et. al., 2009)



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Non-linear force-free field:

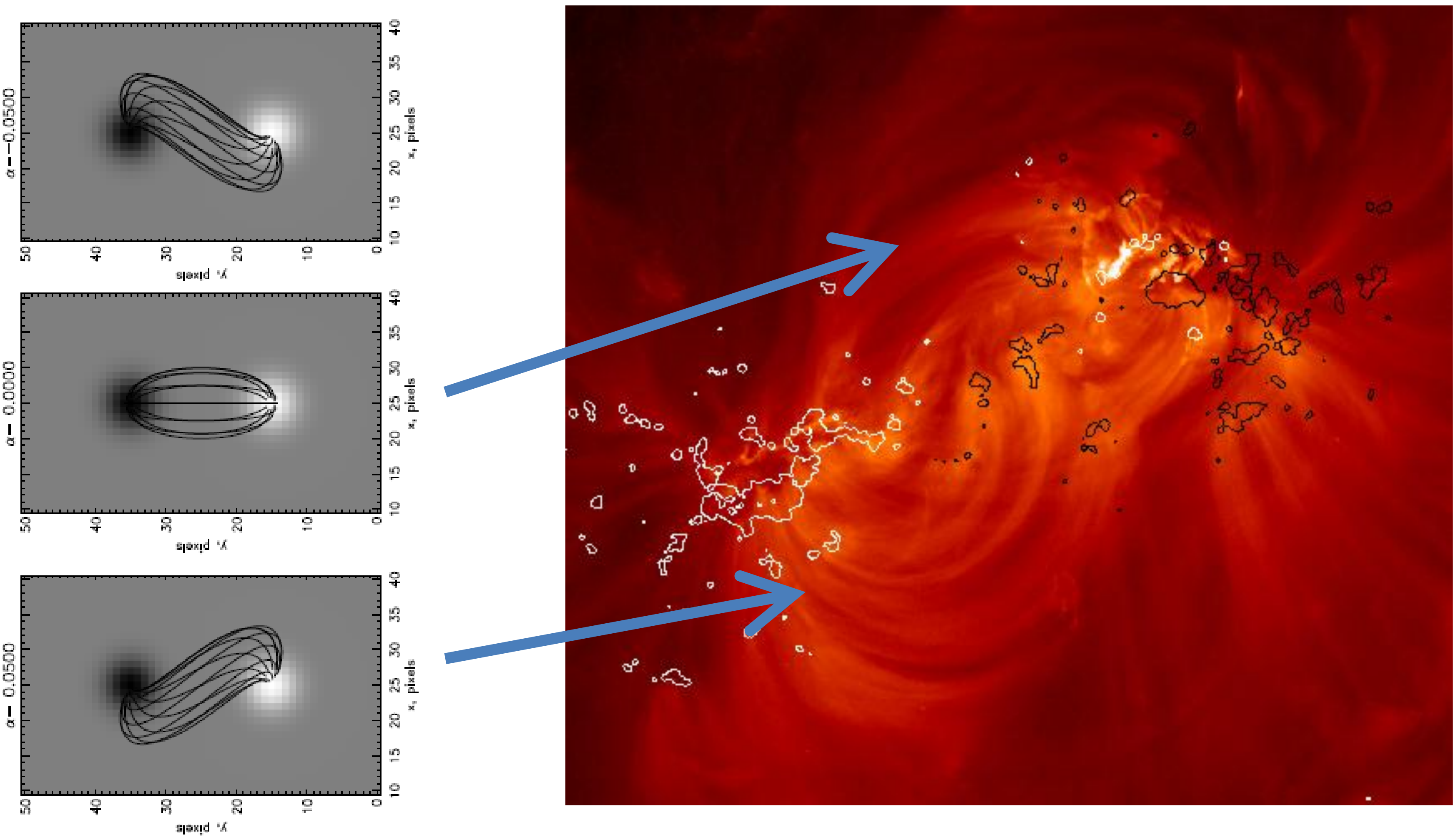
$$\nabla^2 \mathbf{B} + \alpha^2 \mathbf{B} = \mathbf{B} \times (\nabla \alpha)$$

We can bypass B.C. problem:

Use coronal images as extra constraints!

Non-linear force-free field:

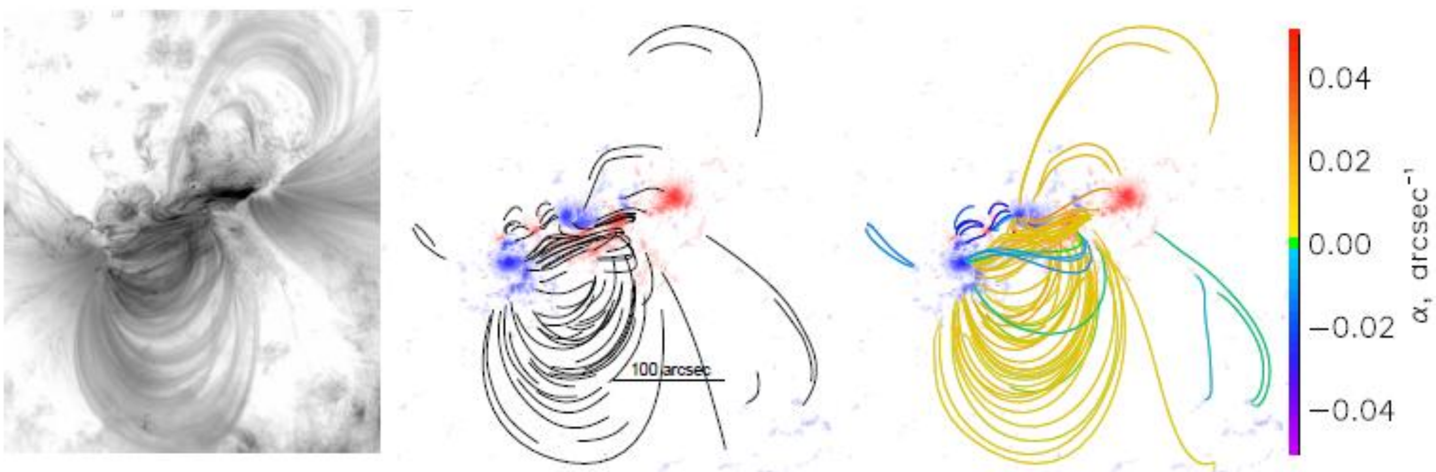
using loops to understand the field structure!



Non-linear force-free field:

using loops to understand the field structure!

Step 1: convert images to “usable” data
(by comparing to const-α fields
to deduce α’s and 3D paths of visible structures)



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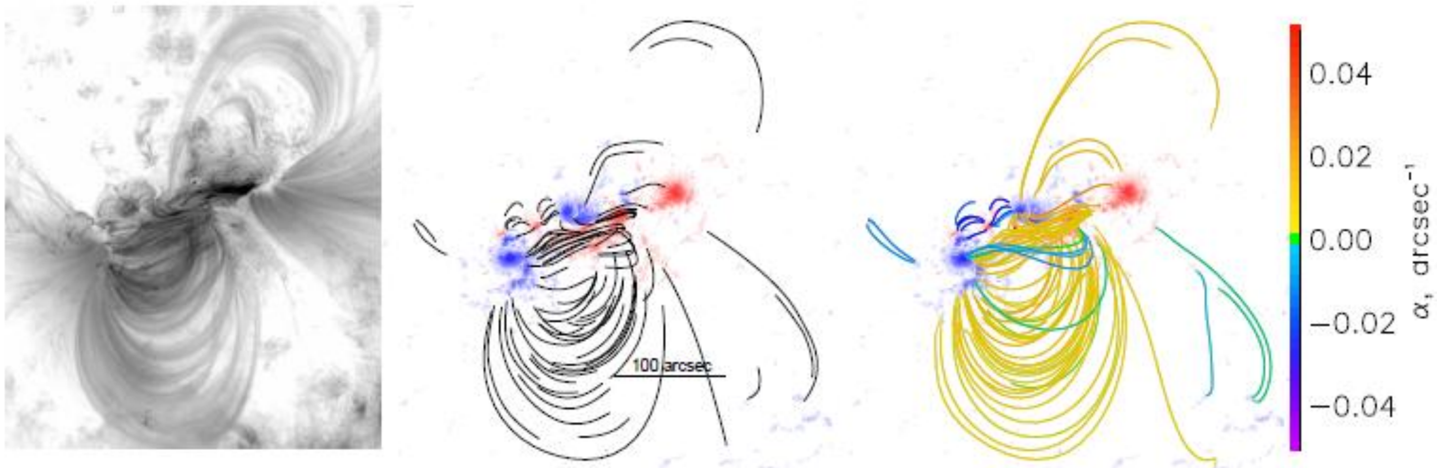


Alternative: a plasma modeler (for example) might wish to model an equilibrium which has desired α’s along the desired tracks!

Non-linear force-free field:

using loops to understand the field structure!

Step 2: use evaluated (or desired) α's and 3d trajectories and line-of-sight field component to solve the PDE.

Basic idea: "give me a field which matches constraints in the volume as closely as possible, while satisfying a given PDE as closely as possible."

Non-linear force-free field:
using loops to understand the field structure!

Step 2: use evaluated (or desired) α's and 3d trajectories and line-of-sight field component to solve the PDE.

Basic idea: "give me a field which matches constraints in the volume as closely as possible, while satisfying a given PDE as closely as possible."

Normal approach: PDE+(boundary conditions).

Hack: PDE+(constraints in the volume)!

possible use in other areas: a PDE, elliptic w.r.t. one variable and hyperbolic w.r.t. the other variable; hyperbolic initial state is poorly known at boundary but known on streamlines in the volume.

Grad-Rubin Iteration

(1958)

Problem:

$\nabla\times\mathbf{B}=\alpha\mathbf{B}$, $\mathbf{B}\cdot\nabla\alpha=0$

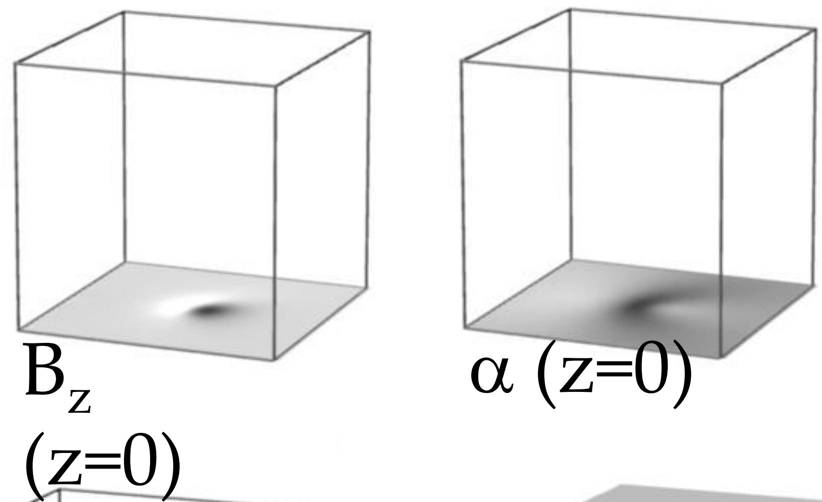
Iteration:

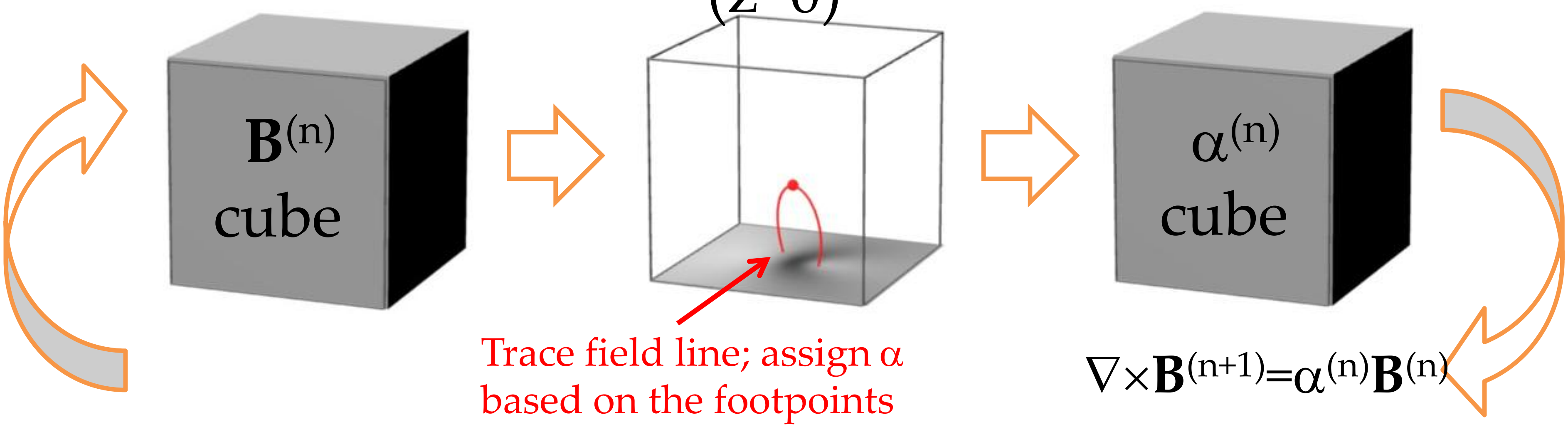
$\mathbf{B}^{(0)} \Rightarrow \mathbf{B}^{(0)}\cdot\nabla\alpha^{(0)}=0$

$\Rightarrow\nabla\times\mathbf{B}^{(1)}=\alpha^{(0)}\mathbf{B}^{(0)}$

$\Rightarrow \mathbf{B}^{(1)} \Rightarrow \alpha^{(1)} \Rightarrow \ldots$

Initial data:





Quasi Grad-Rubin Iteration

(general idea)

Problem:

$\nabla\times\mathbf{B}=\alpha\mathbf{B},\ \mathbf{B}\cdot\nabla\alpha=0$

Iteration:

$\mathbf{B}^{(0)} \Rightarrow \mathbf{B}^{(0)}\cdot\nabla\alpha^{(0)}=0$

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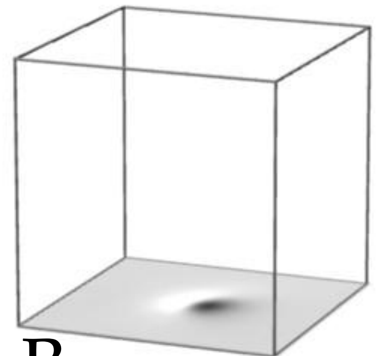
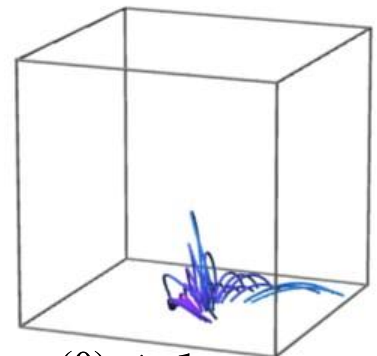
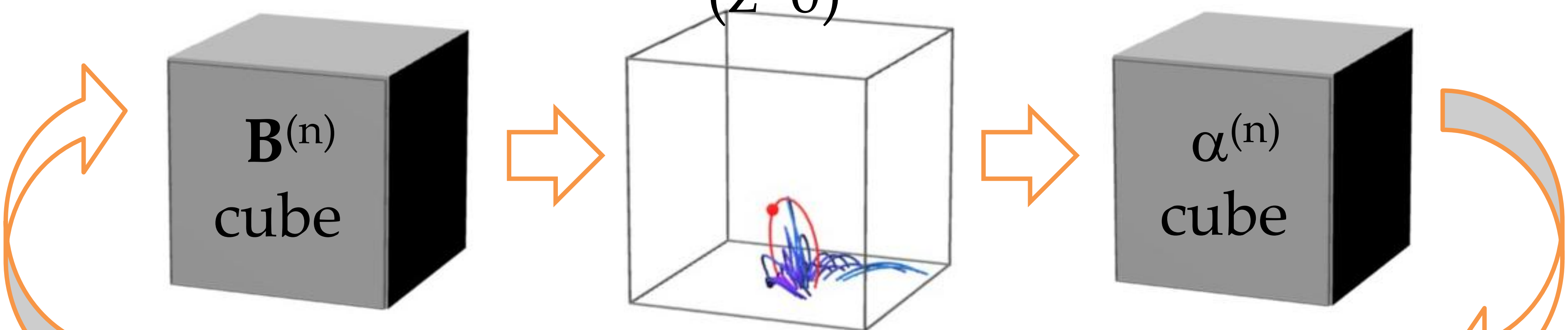


B_z (z=0)



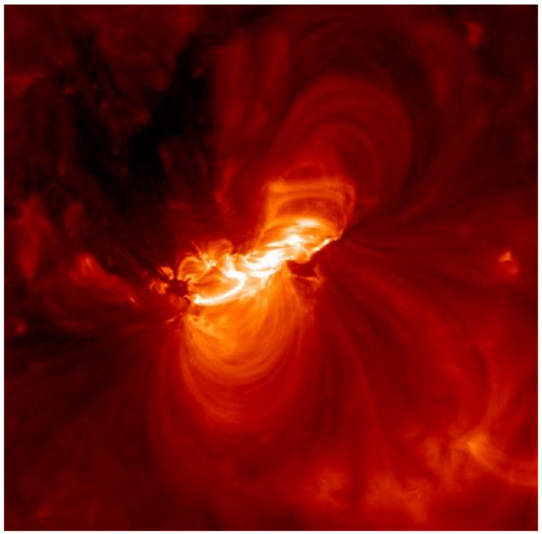
$\alpha^{(0)}$ (along trajectories

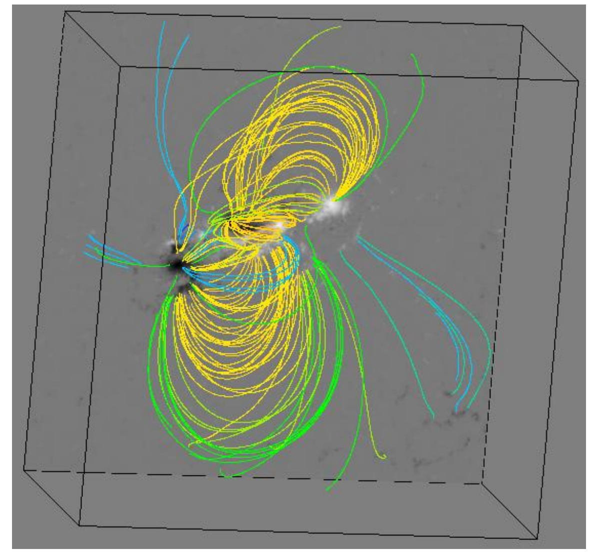


Trace field line; assign $\alpha^{(n)}$ based on the average $<\alpha^{(n-1)}>$

$\nabla\times\mathbf{B}^{(n+1)}=\alpha^{(n)}\mathbf{B}^{(n)}$

Coronal images as guides for magnetic modeling: Quasi Grad-Rubin





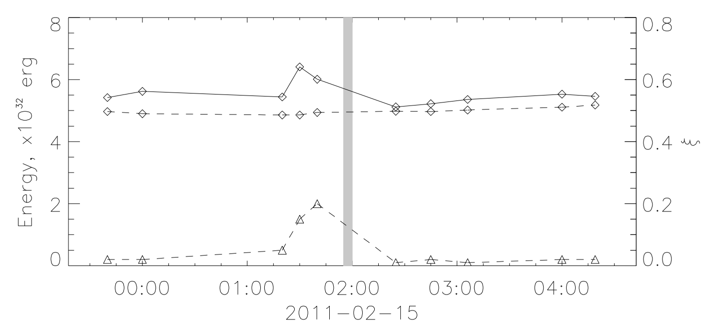
Key results:

-realistic representation of coronal features

-not very sensitive to choice of loops
 in quiescent and post-flare stages

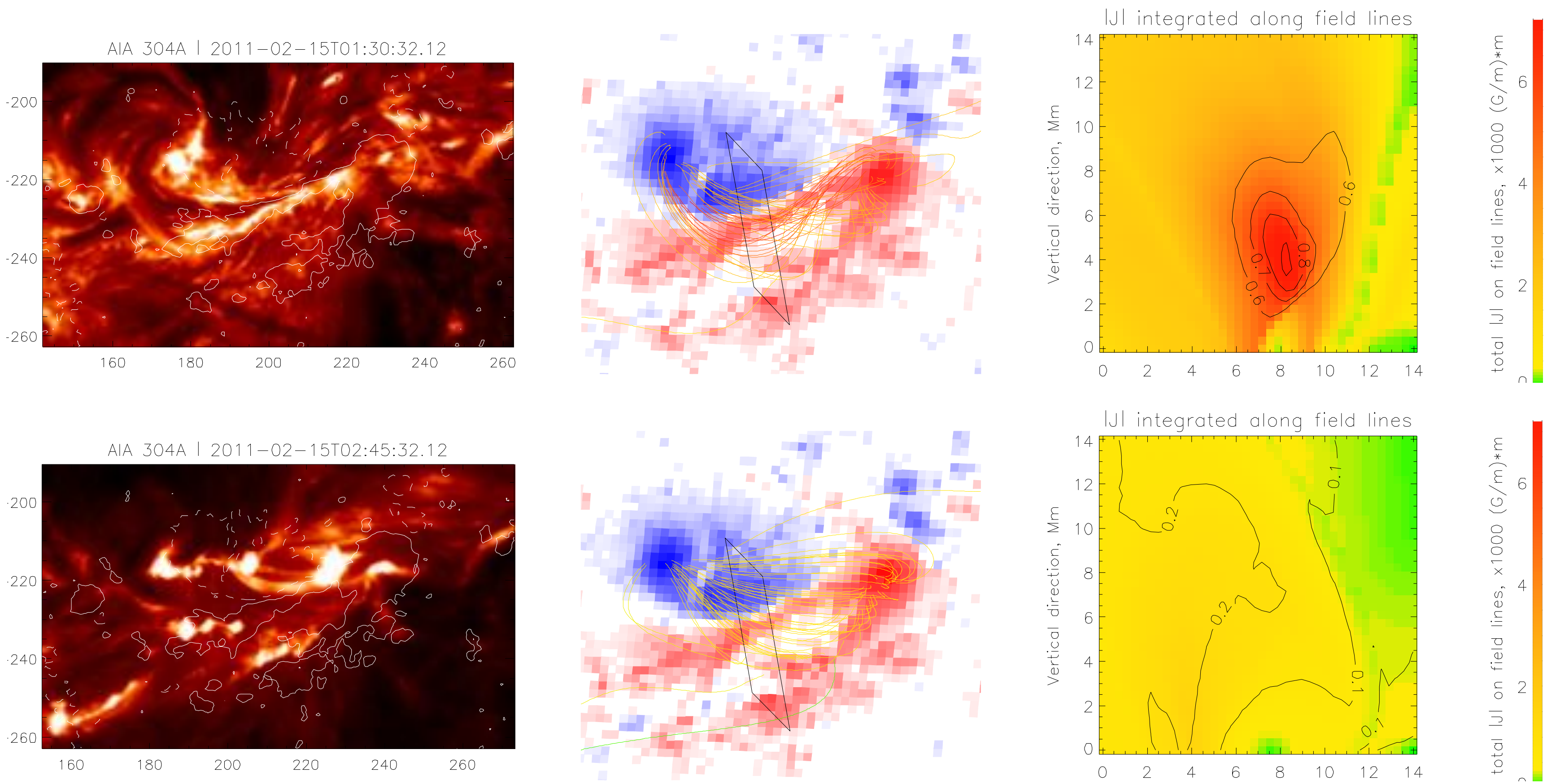
-more sensitive in pre-flare stages

-a successful estimate of energy release



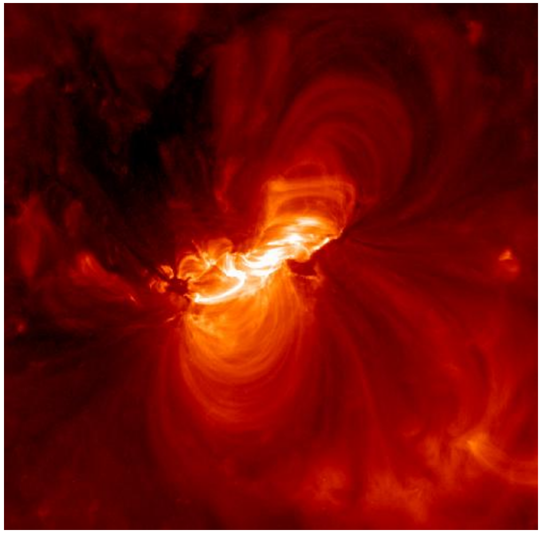
Malanushenko et al (2014)

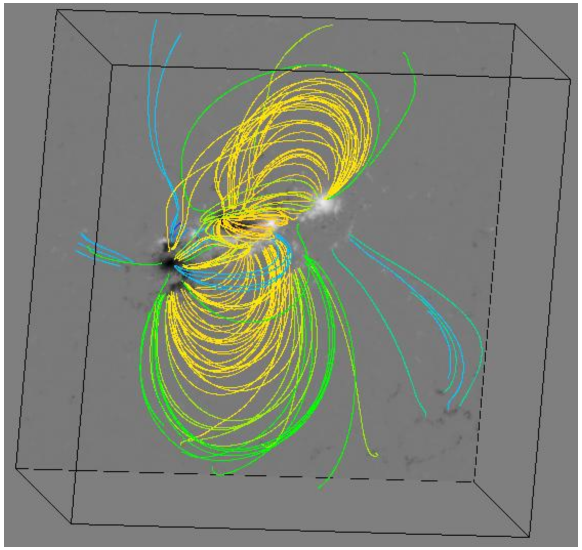
Coronal images as guides for magnetic modeling



QGR is a working tool for modeling the coronal magnetic field.

Using coronal images
to understand solar eruptions





Evolving a model of the *actually observed* and *actually erupted* structure in an MHD simulation.

Using coronal images
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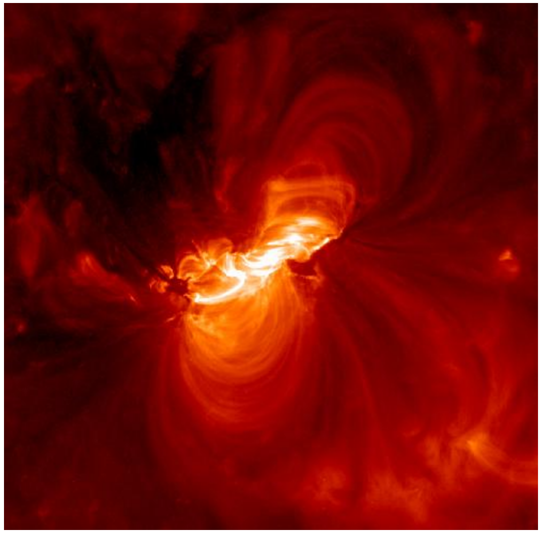
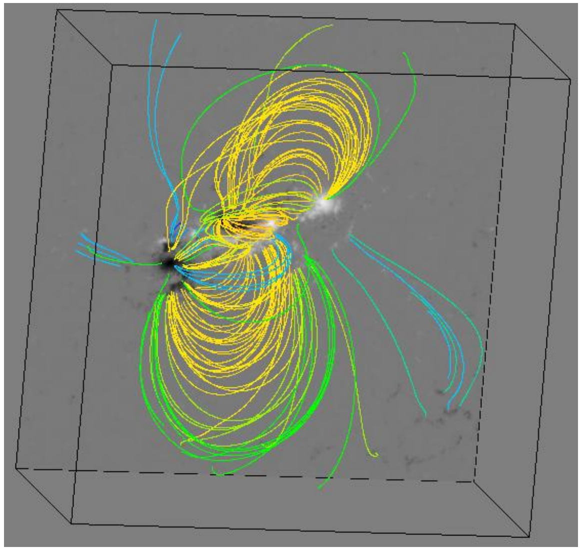


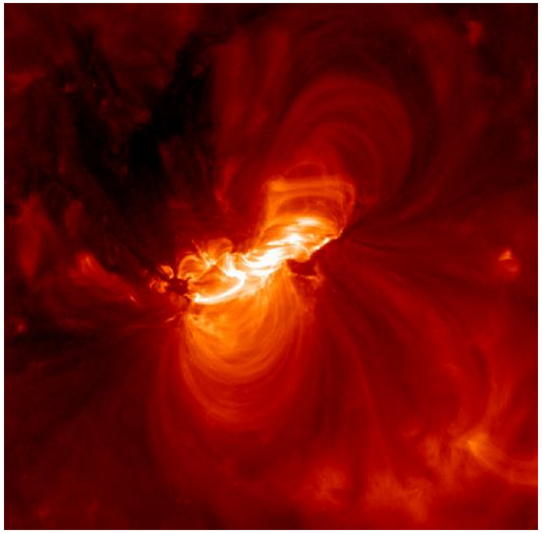


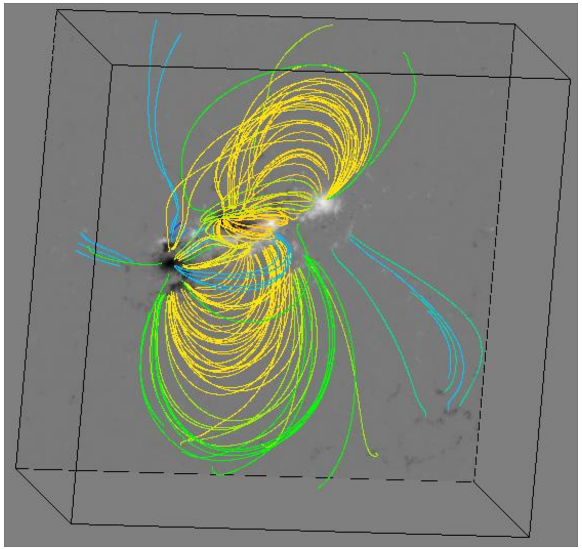
Evolving a model of the *actually observed* and *actually erupted* structure in an MHD simulation.

Results so far (preliminary)

- the structure appears to be stable
- the driving that was *thought* to make it erupt, makes it reconnect and relax but not erupt!

Using coronal images
to understand solar eruptions





Evolving a model of the *actually observed* and *actually erupted* structure in an MHD simulation.

Goal:

- understand what made it erupt in an *actually observed* way;
- provide a model of an observed CME for the space weather modeling.