Insights From Idealized MHD Simulations of Flux Emergence in the Solar Atmosphere

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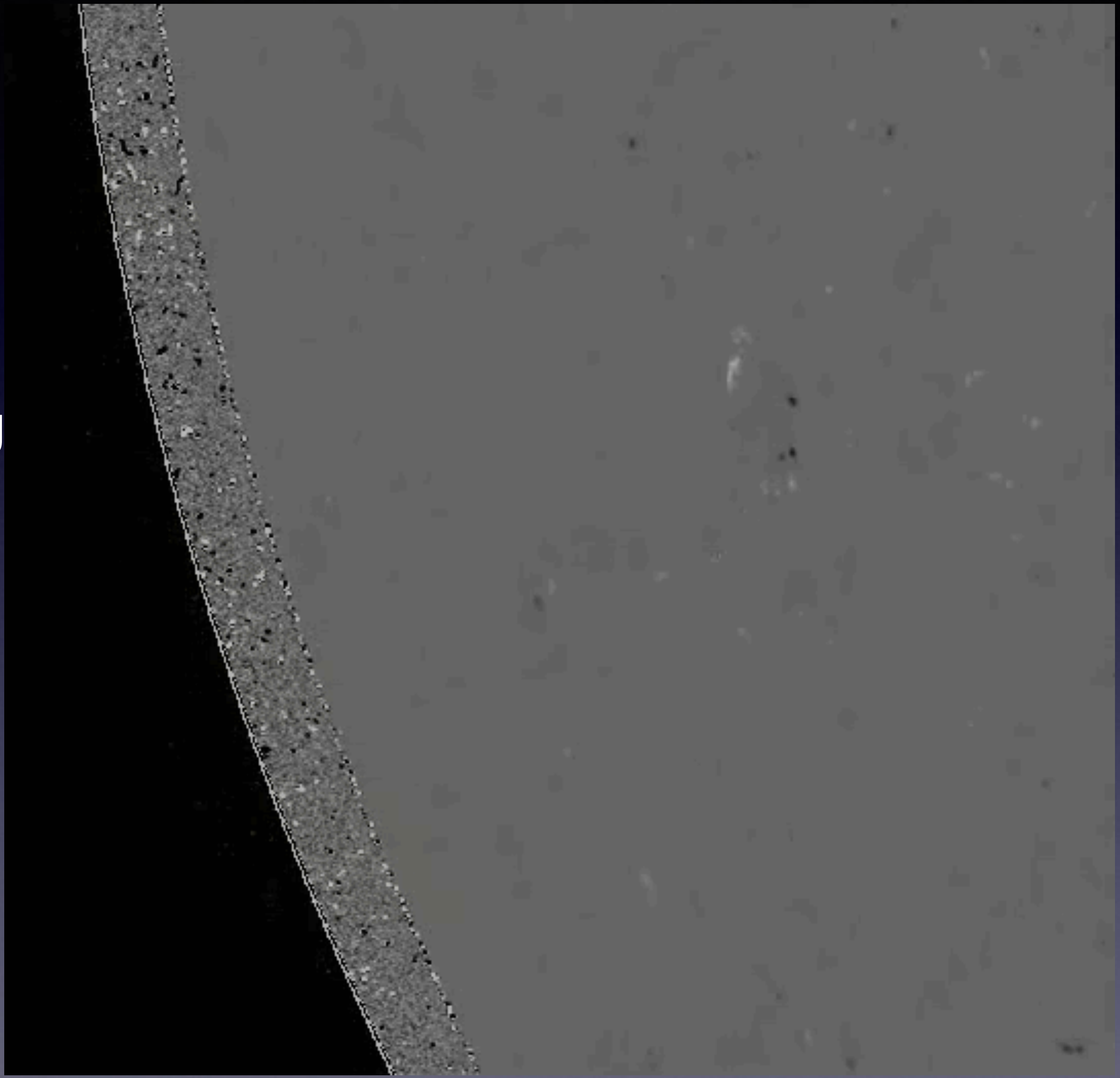
- Background
- MHD Simulations of Flux Rope Formation and Eruption
- Helicity Injection in the Solar Atmosphere
- Electrical Current Balance in the Corona
- What's next?

Solar Activity and Magnetism

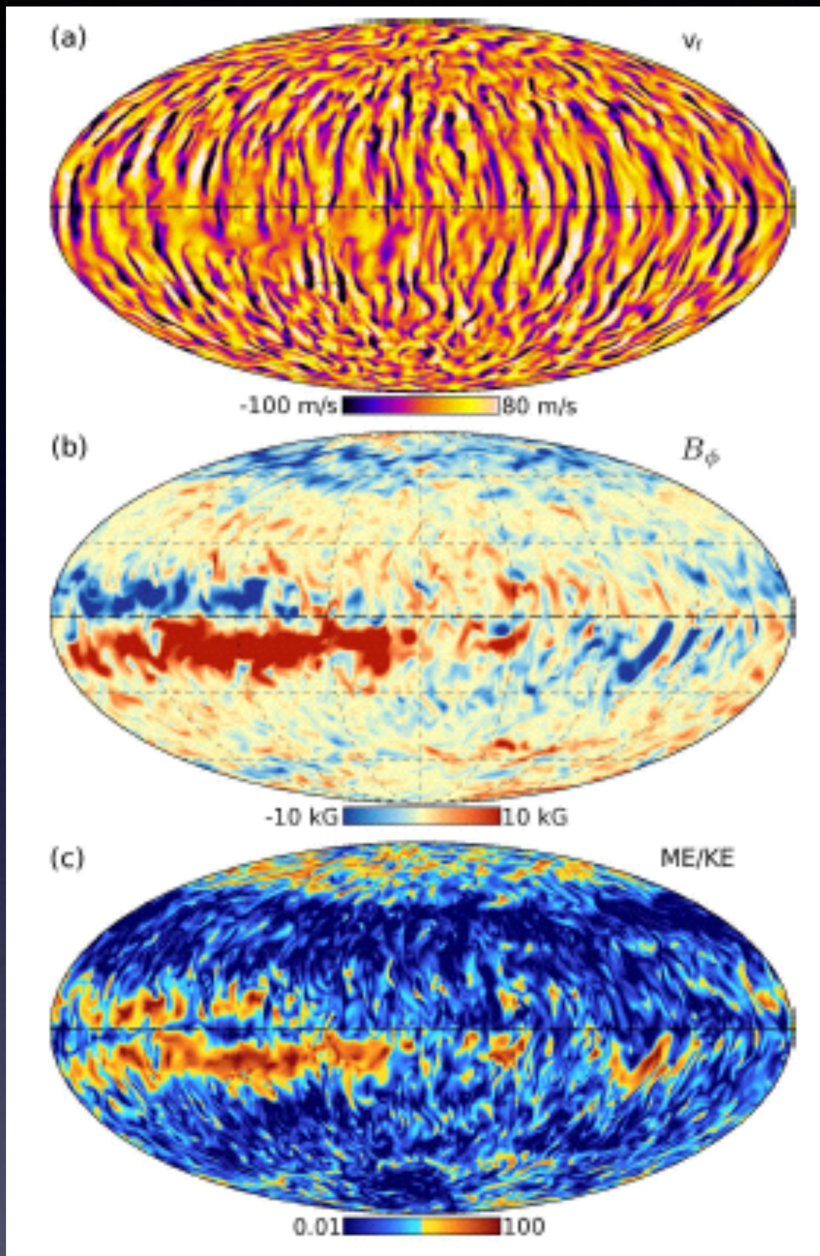
- Energy required for CMEs/eruptions/flares stored in the electric currents of coronal magnetic field $\mathbf{J} = \nabla \times \mathbf{B}$
- Most likely stored in twisted/sheared magnetic fields and flux ropes
- How are flux ropes formed/erupted in the corona?

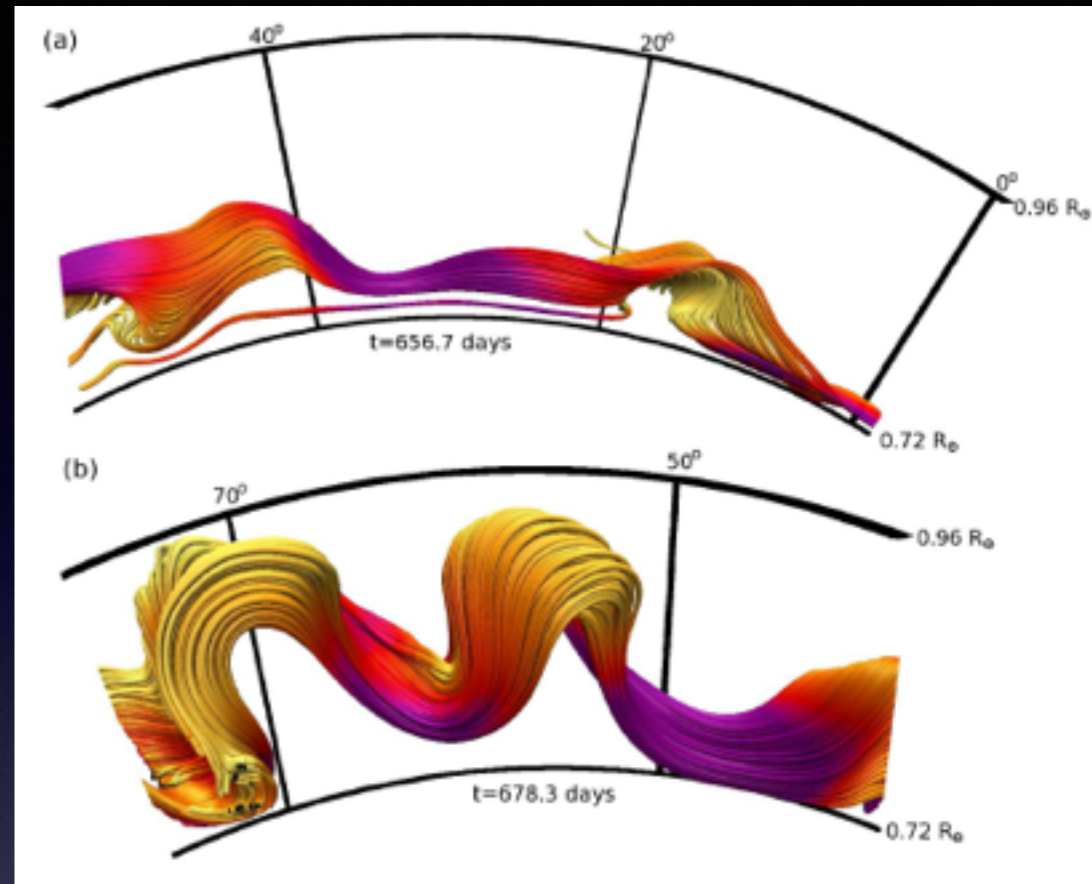
Solar Activity and Magnetic Flux Emergence

- Active regions are regions of strong magnetic field where the magnetic flux increases over hours-days
- Quiet AR typically a bipolar region with mainly potential (J=0) field
- Observed motions, such as shearing and sunspot rotation, build up gradients in magnetic field (current)
- Important quantity is the magnetic free energy
- What is the cause of these energization motions (emergence, shearing, rotation)
- Related to twisted flux tube emergence



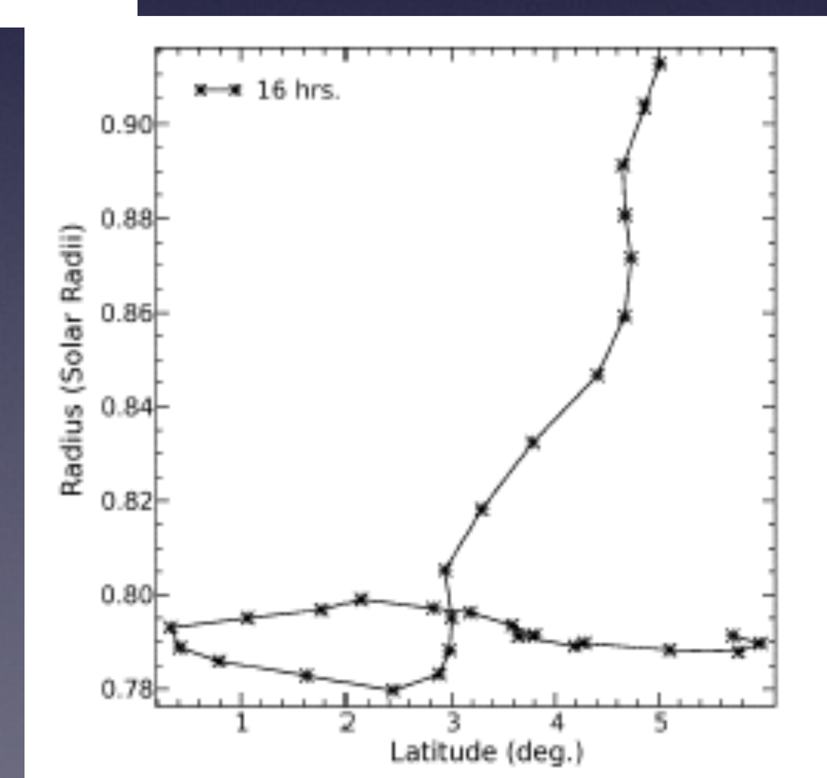
Buoyant Flux Tubes in Solar Dynamo Simulations





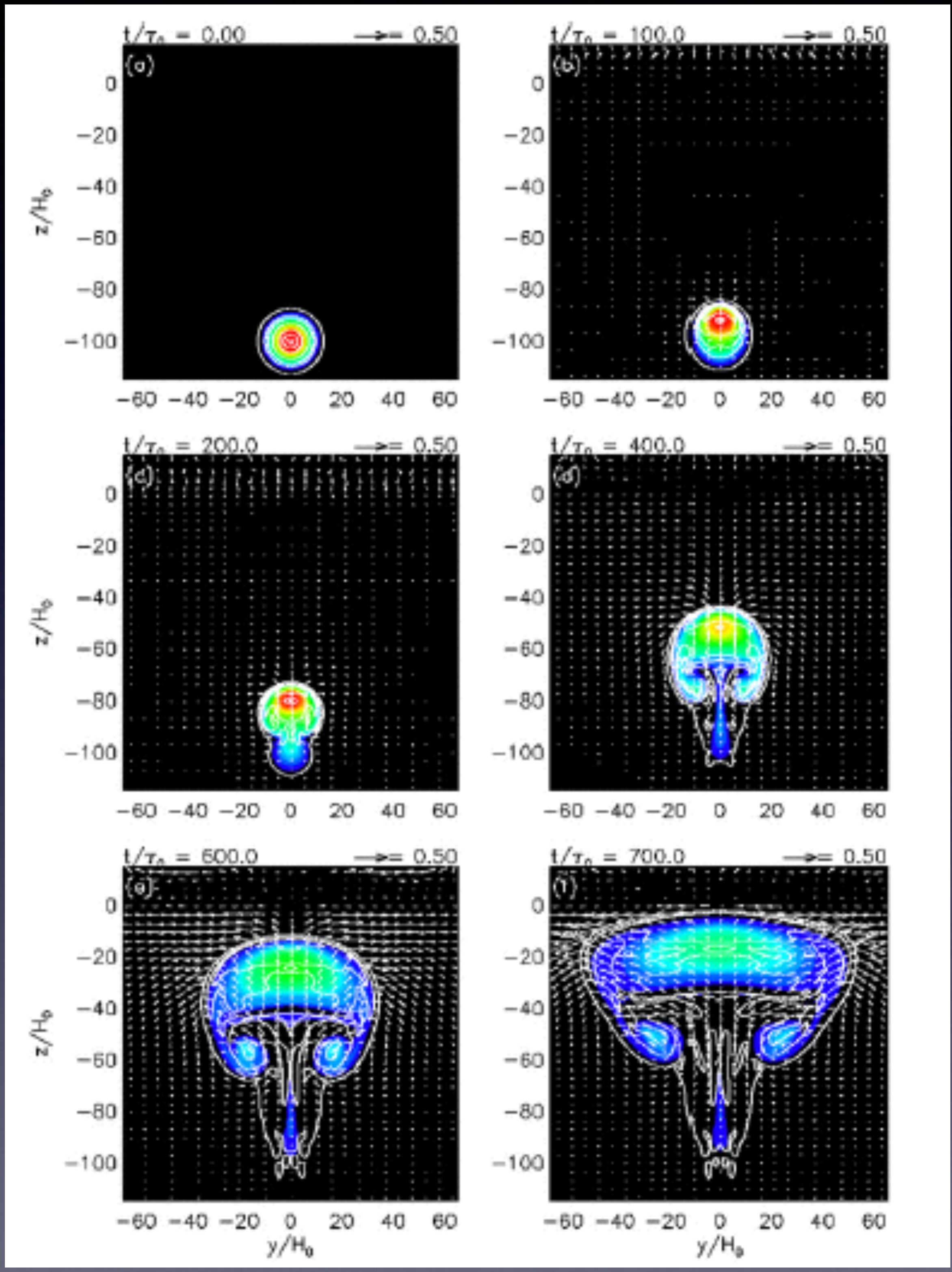
3D turbulent convective dynamo models (Nelson et al. 2014)

Courtesy: N. Nelson



Dynamo Models able to produce buoyant flux tubes that rise towards the surface - How do they emerge?

Brief History of Flux Emergence Studies



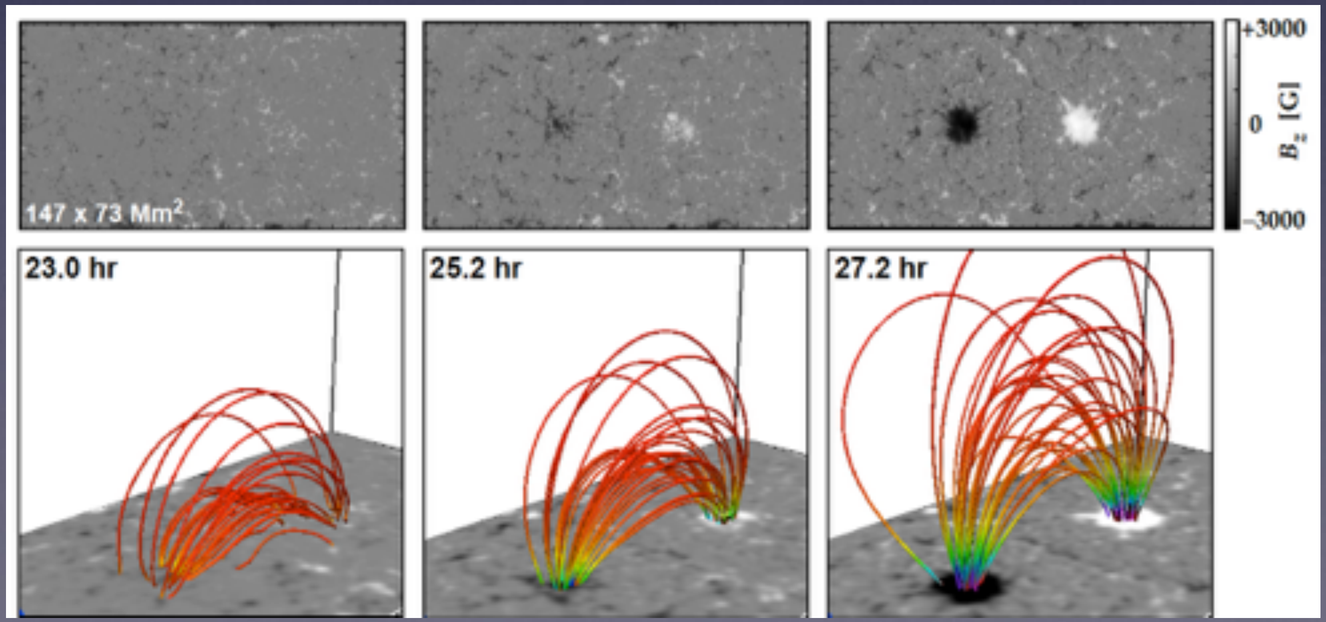
- See Solar Physics Living Review by Cheung
- Moreno-Insertis, Emonet (1998,1999)
  - Flux tubes need sufficient twist to survive shredding by vortical motions in the CZ
- Archontis (2004), Murray et al. (2006, 2008), Toriumi et al. (2011)
  - Two-step emergence
    - Coherent rise halts at top of convection zone
    - Further emergence is via the Magnetic Buoyancy Instability (MBI), or undular Parker mode (does this determine observed emergence rate?)
- Manchester (2004), Fan(2009), Mactaggart et al. (2009)
  - Very rare that CZ flux tube emerges bodily into corona
  - Partial emergence of twisted flux tube shows shearing and rotational motions

Open Questions Regarding Flux Emergence?

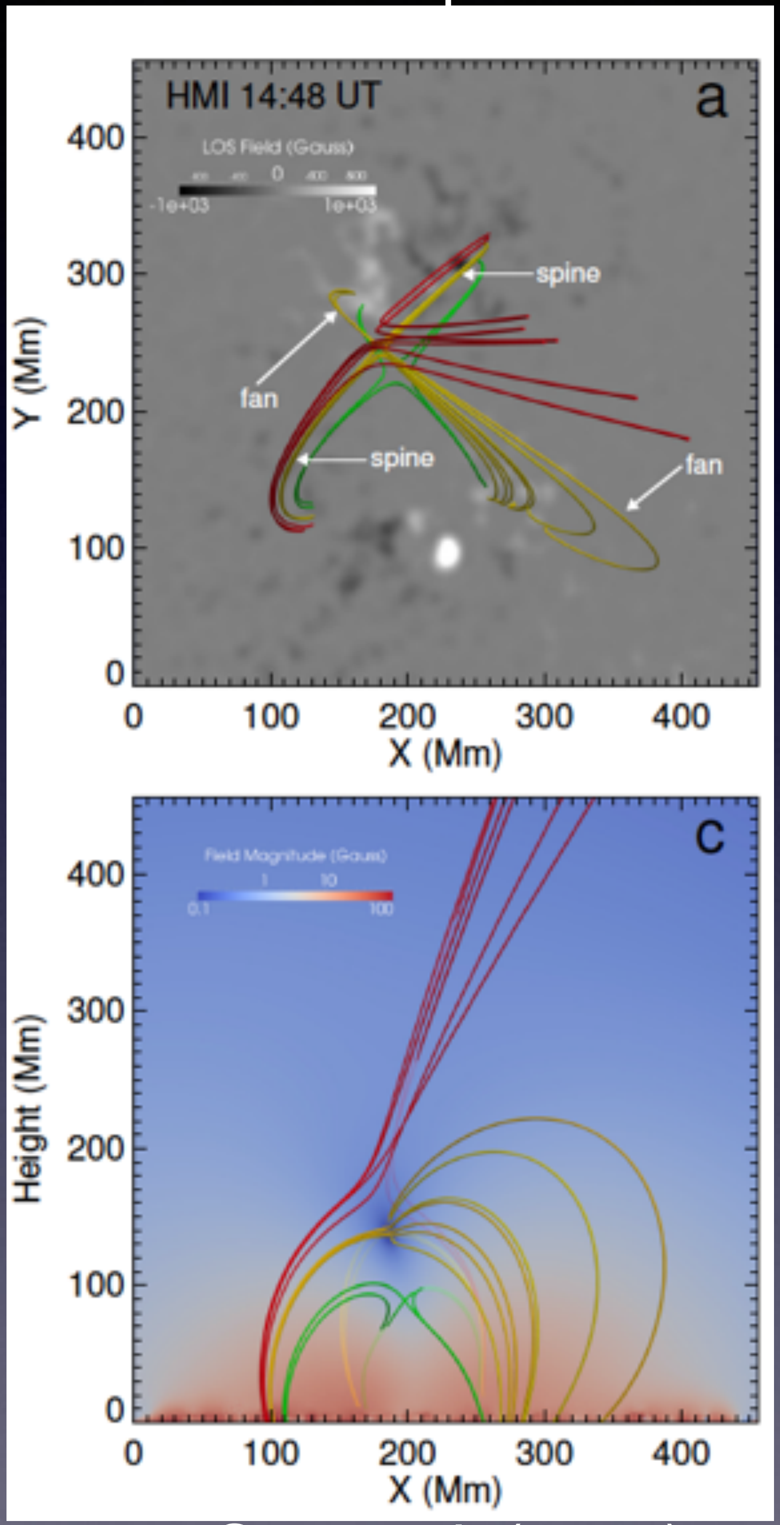
- Can the emergence of CZ flux tubes explain observed AR feature/motions?
    - Sunspot Rotation/Shearing Motions/Flux Cancellation - that lead to energization of the corona
- How do buoyant flux tubes emerge through the chromosphere and further into the corona? How do they interact with overlying field?
- How does flux emergence drive eruptions in ARs?
- How are coronal flux ropes formed if the CZ tubes do not bodily emerge?
- How are electric currents distributed in the corona?
- How is magnetic complexity (Helicity) injected into the corona?
- We can use idealized simulations to help answer these questions

Data driven and NLFFF modeling

- Why not just take observed magnetic fields and drive solar atmosphere models?
  - NLFFF extrapolations - assume equilibrium described by JxB=0, assumes low beta (force-free)
  - Peter at al. (2015) “Free energy estimates cannot be trusted with NLFFF extrap.s”
- Data-driven models - Must include lower atmosphere (cannot drive force-free corona with forced data)



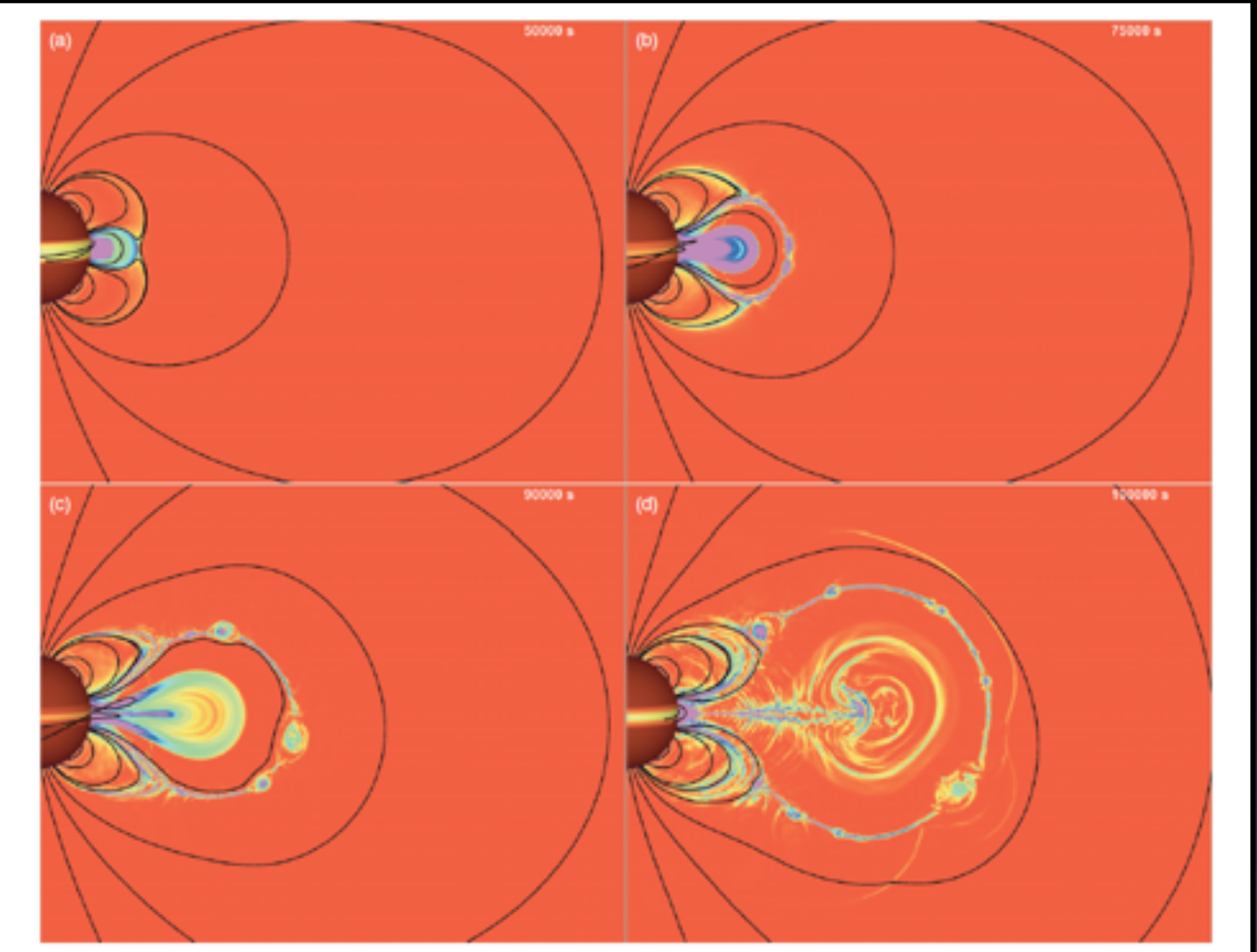
NLFFF extrapolations



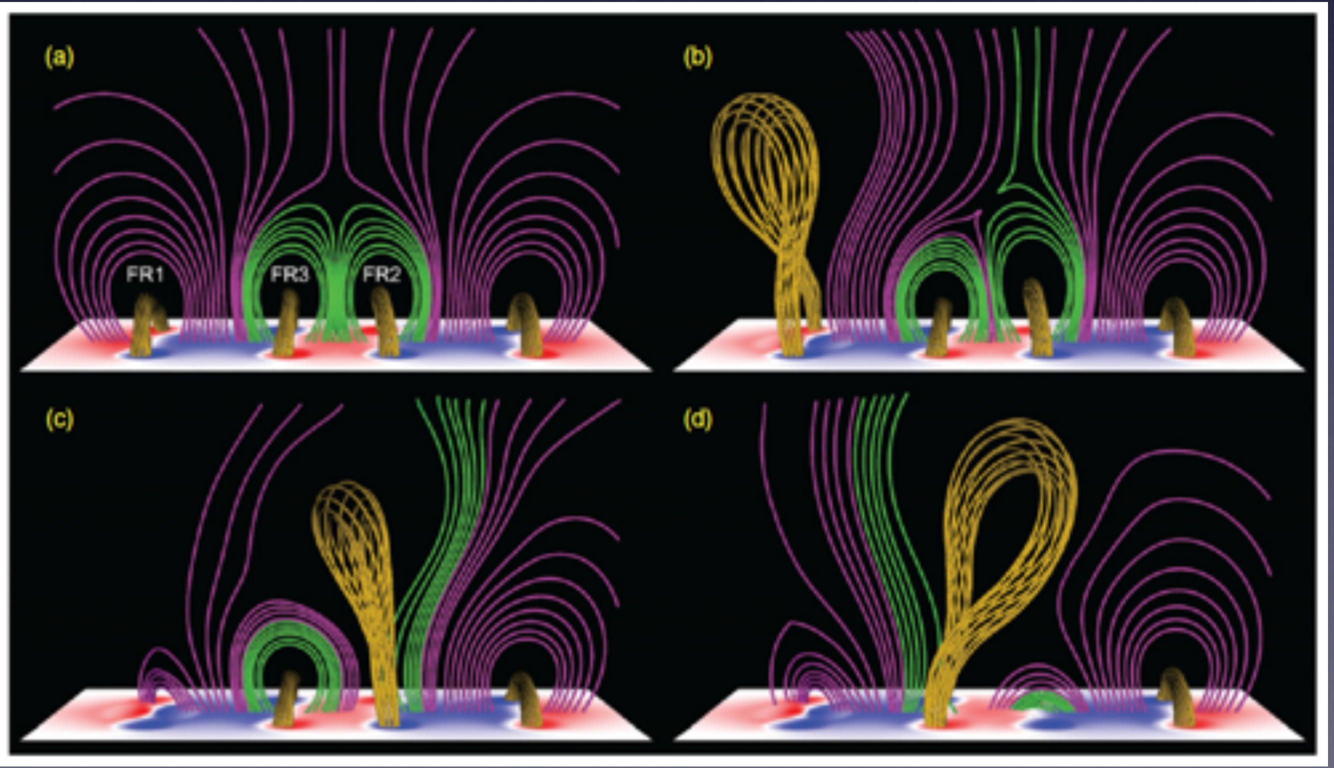
Sun et al. (2014)

Coronal Modeling

- Ignore the emergence process and model corona only
  - use signatures of emergence such as shearing and flux cancellation to
    - energize/destabilize coronal structures
  - Sunspot Rotation/Shearing Motions/Flux Cancellation - that lead to energization



Karpen et al., 2012.



Török et al.

What can we learn from emergence simulations to help with coronal modeling?

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MHD Modeling of the Sun

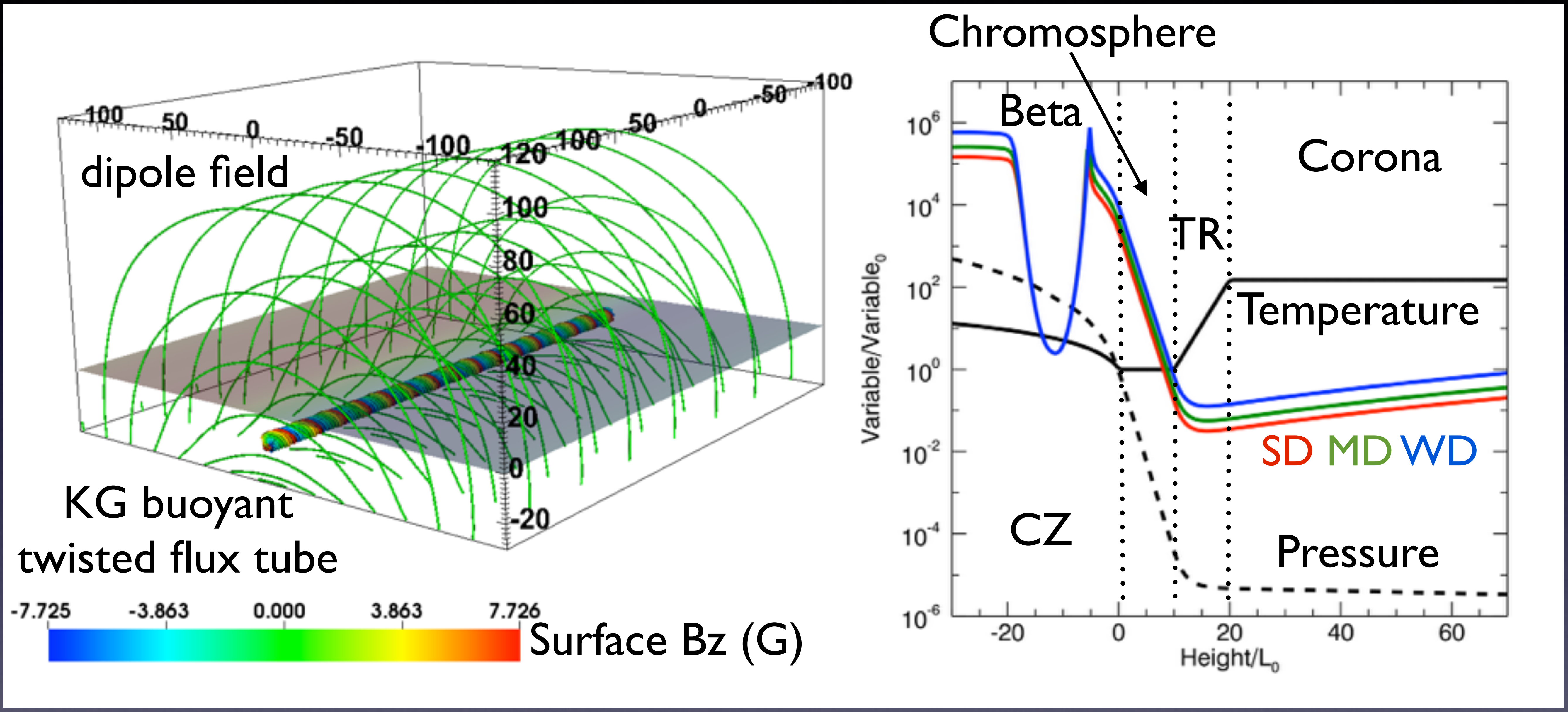
Box in the Sun: Cartesian Domain representing part of Sun, from upper CZ to lower corona (-20 Mm to ~100 Mm)

Solve equations of visco-resistive MHD

$$
\begin{aligned}
\frac{\partial}{\partial t}(\rho_T) + \nabla\cdot(\rho_T \mathbf{V}_T) &= 0 \\
\frac{\partial}{\partial t}(\rho_T \mathbf{V}_T) + \nabla\cdot(\rho_T \mathbf{V}_T \mathbf{V}_T) &= -\nabla\cdot\mathbb{P}_T + \mathbf{J}\times\mathbf{B} + \mathbf{F}_{ext} \\
\frac{\partial \epsilon_T}{\partial t} + \nabla\cdot(\epsilon \mathbf{V}_T)) &= -\nabla\cdot(\mathbf{h}_T) + \mathbb{P}_T : \nabla\mathbf{V}_T \\
&+ \mathbf{E}^{\mathbf{V}_T}\cdot\mathbf{J} + Q_{rad} + H
\end{aligned}
$$

$$
\boxed{\frac{\partial B}{\partial t} = \nabla\times(\mathbf{V}_T\times\mathbf{B}) - \nabla\times(\eta_{||}\mathbf{J}_{||}) - \nabla\times(\eta_{\perp}\mathbf{J}_{\perp})}
$$

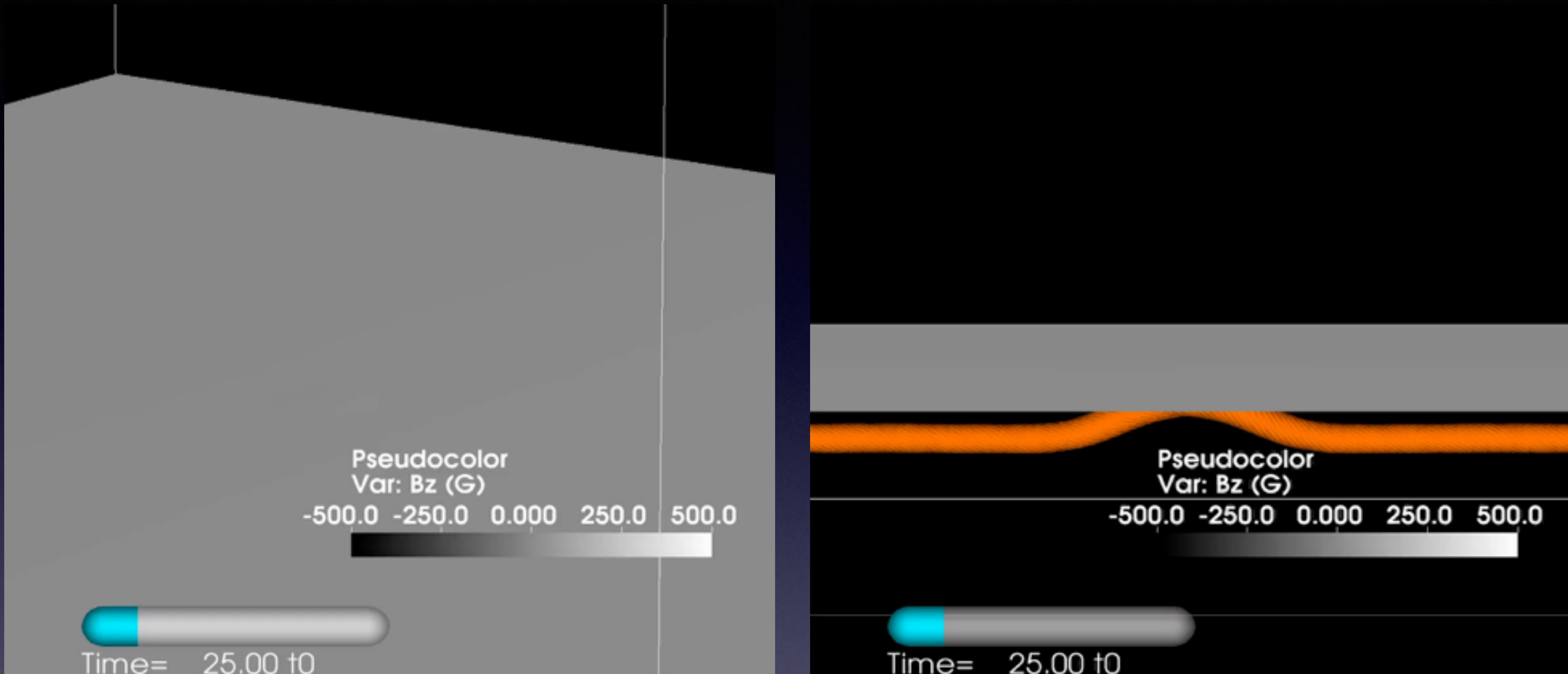
MHD Simulations



Leake et al. (2013,2014)

Vary dipole strength - Strong (SD) Medium (MD) and Weak (WD)
Vary relative orientation of emerging tube and dipole

Observed Magnetic Features in SImulations

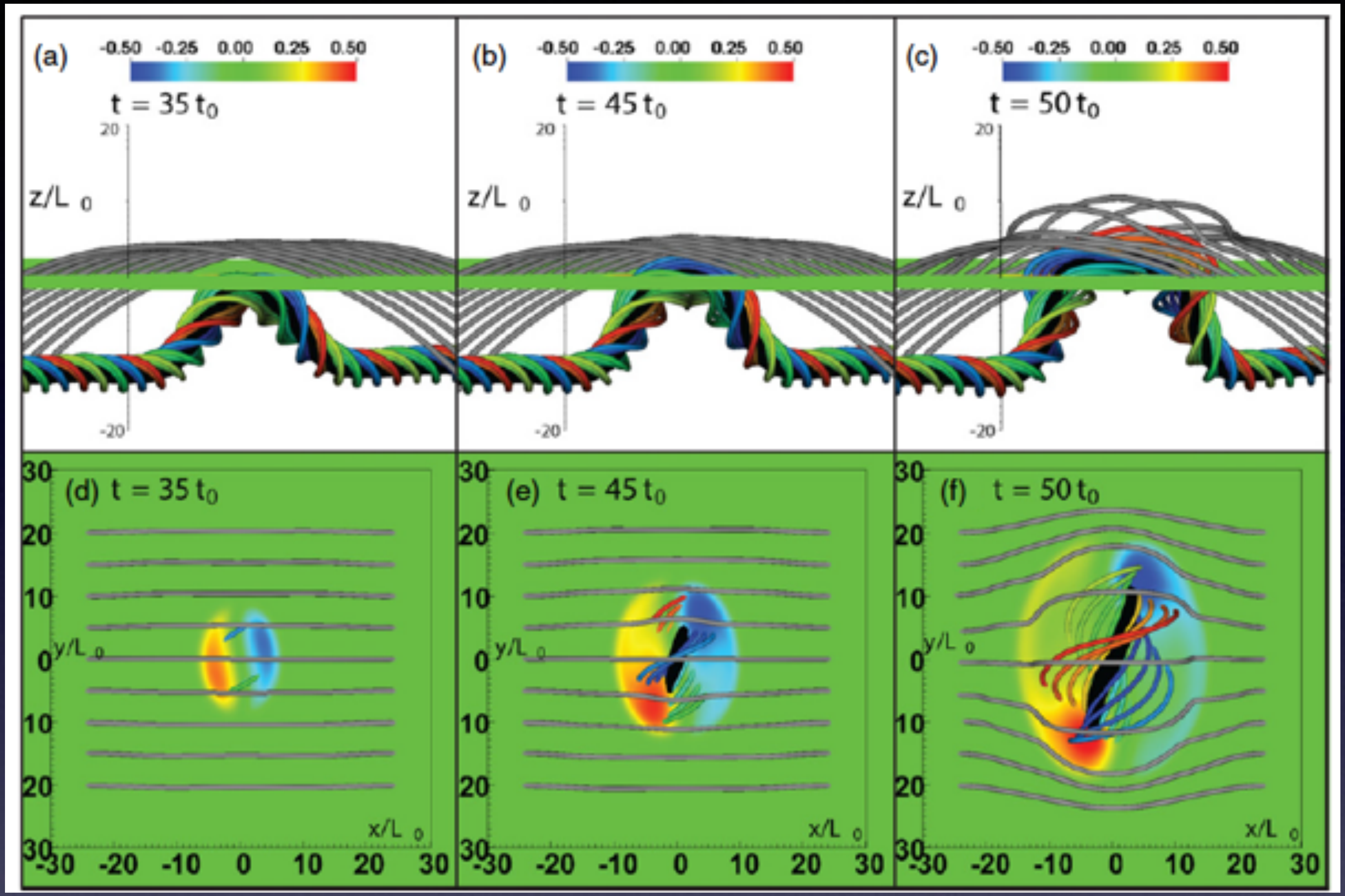


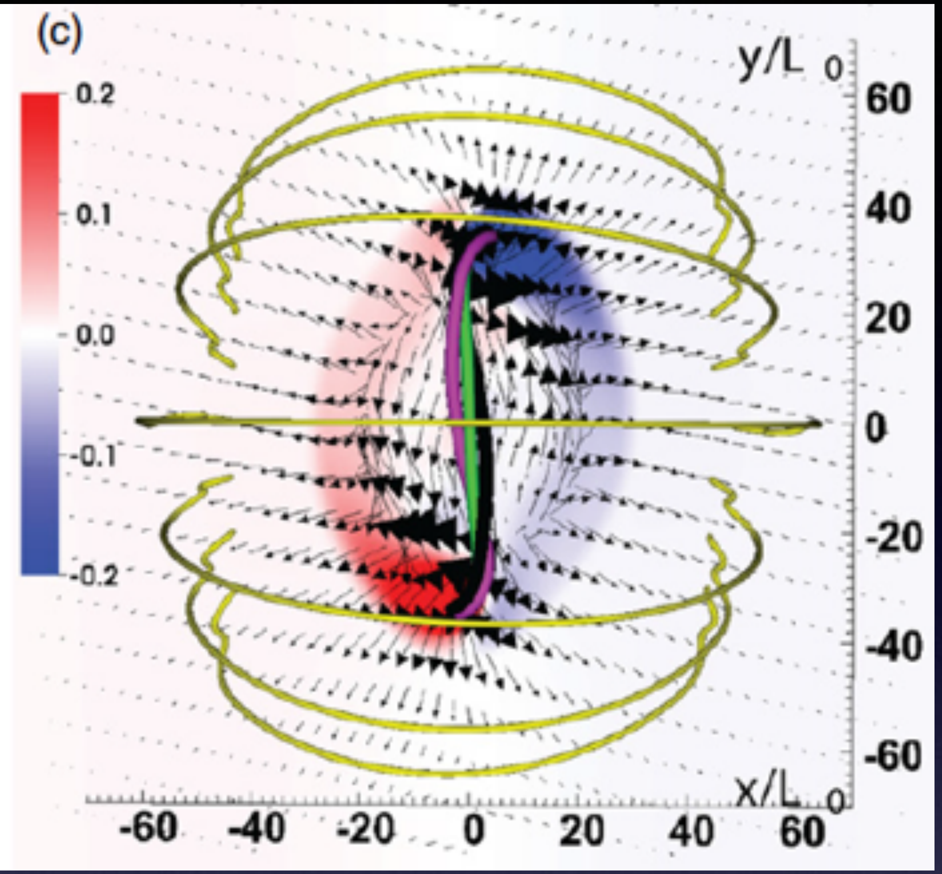
$t < 100\ t_0$: emerging flux tube has little interaction with dipole

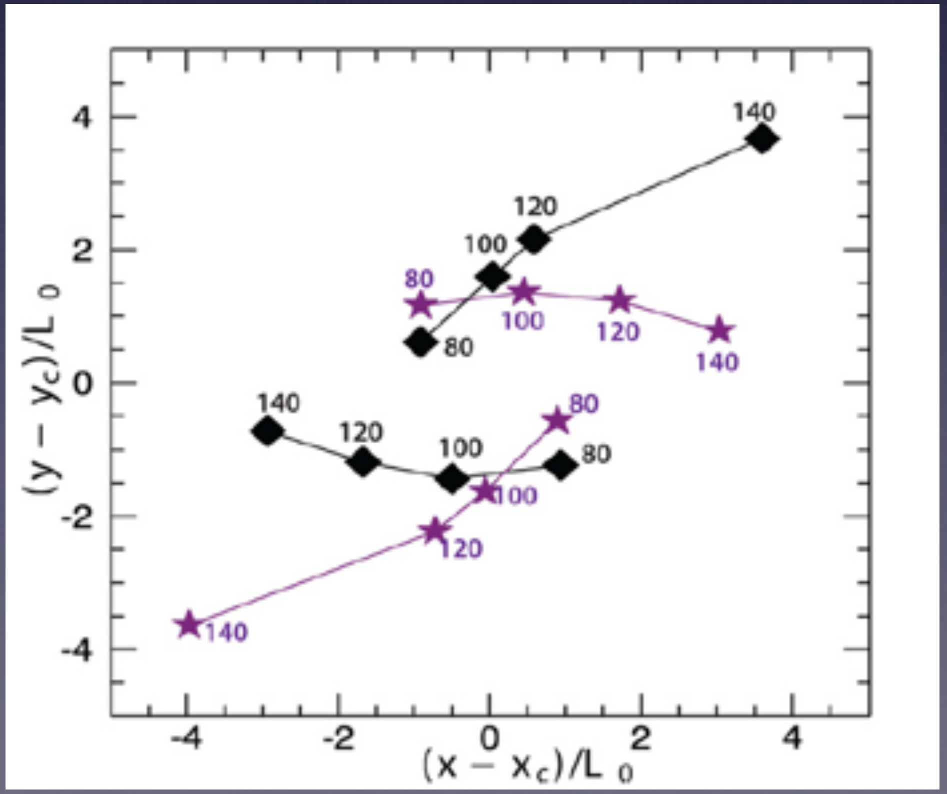
Partial flux tube emergence accompanied by shearing and rotational motions on surface (Manchester 2004, Fan 2009)

Further emergence ($>100\ t_0$) affected by overlying dipole field

Observed Magnetic Features in SImulations

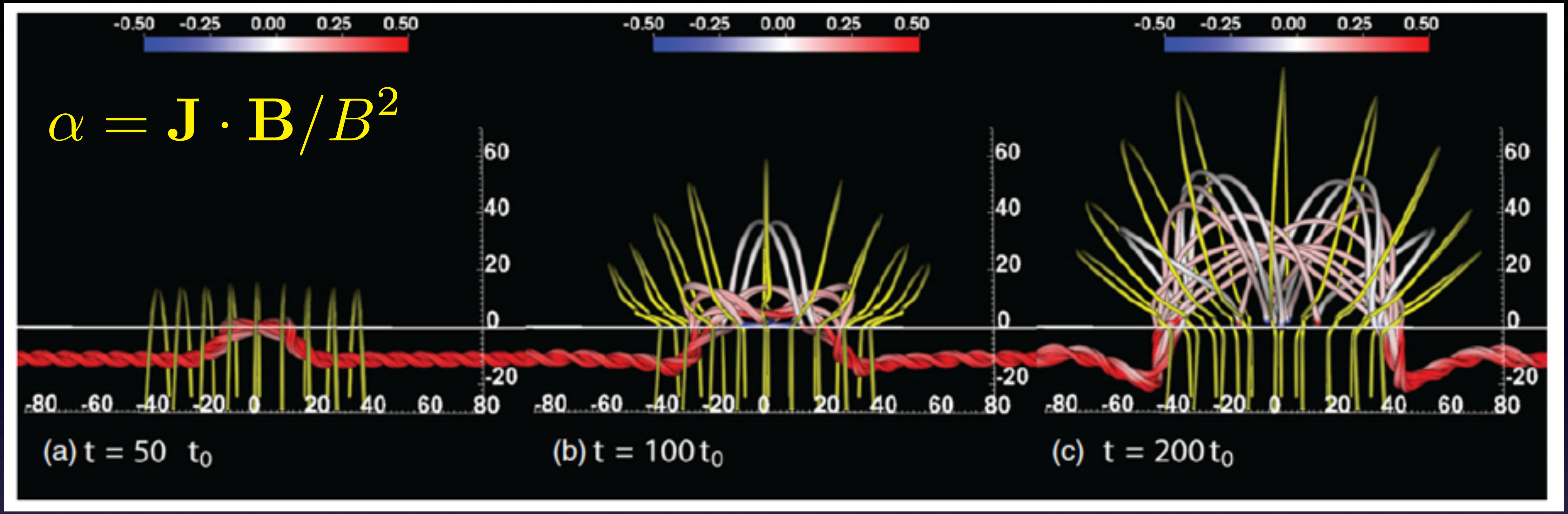




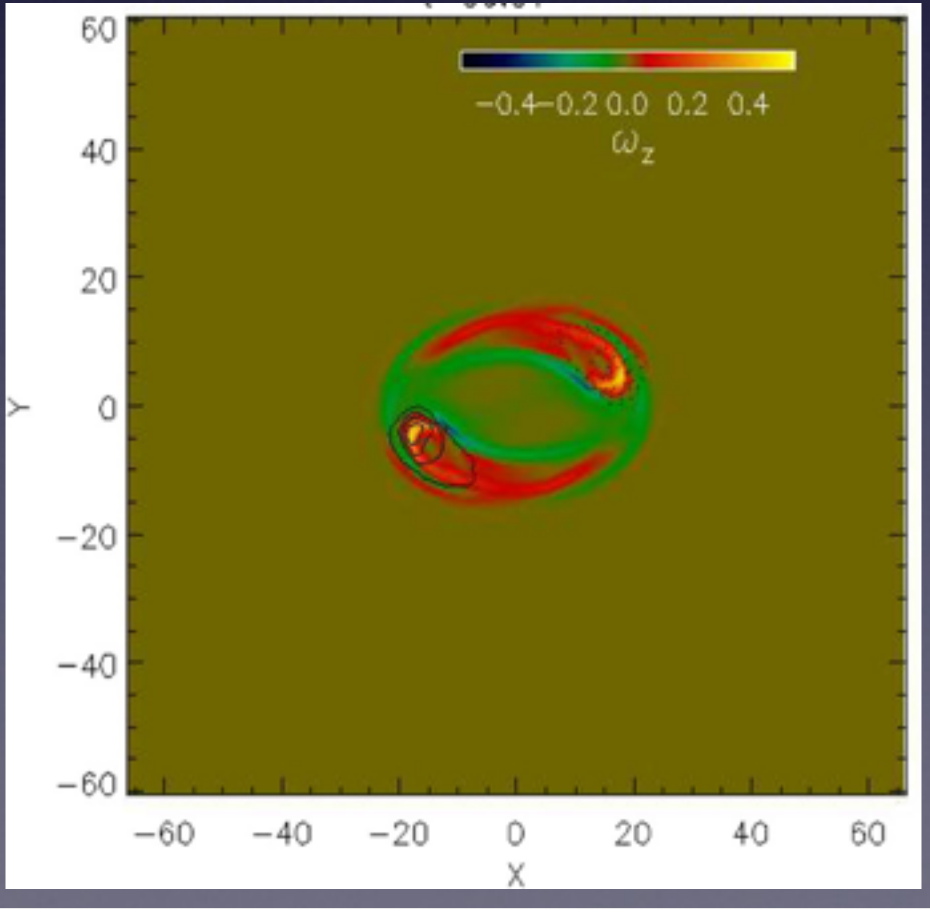


- Shearing caused by emergence of constant twist tube
- What is cause of rotational motion?

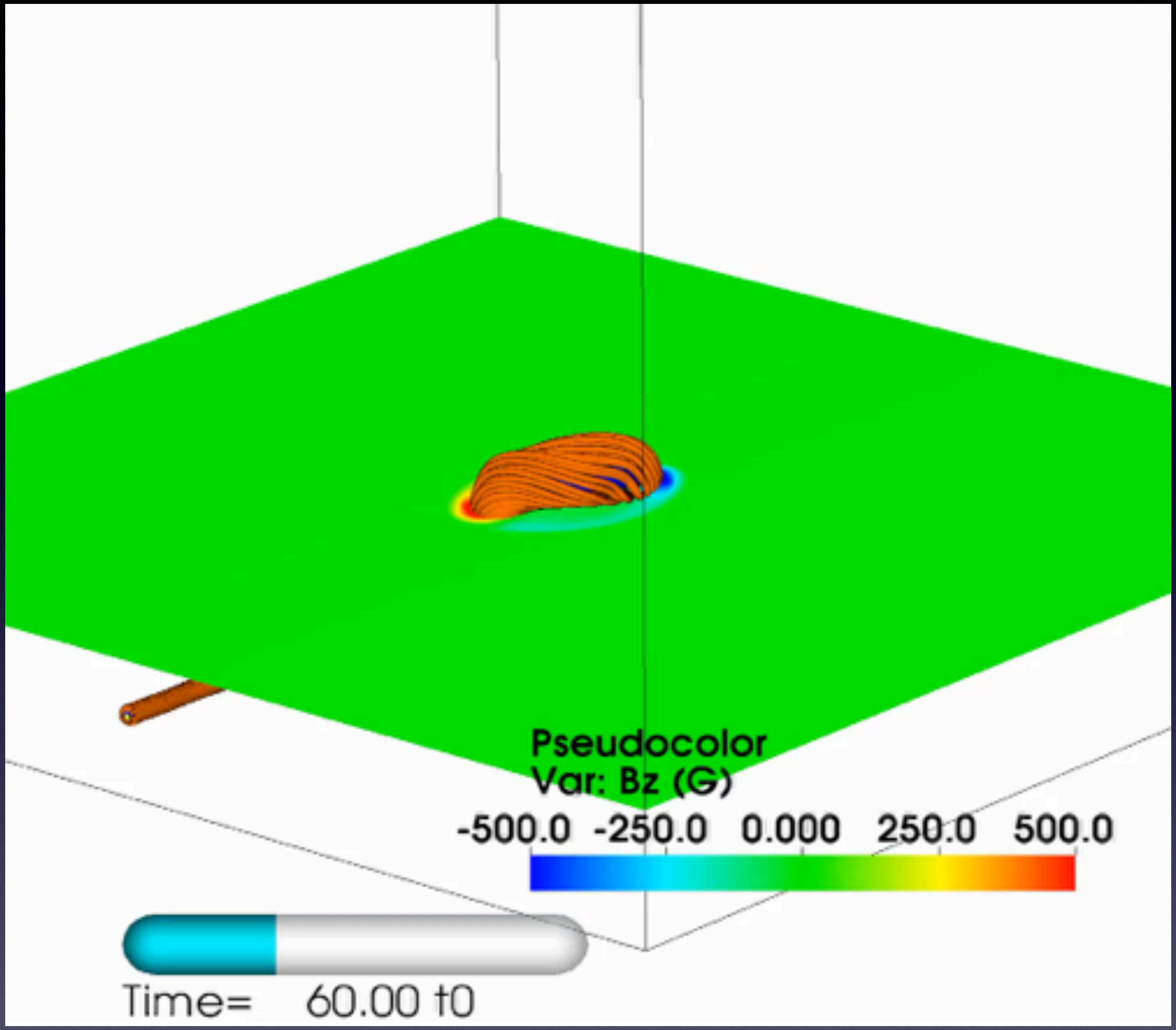
Cause of Rotations?

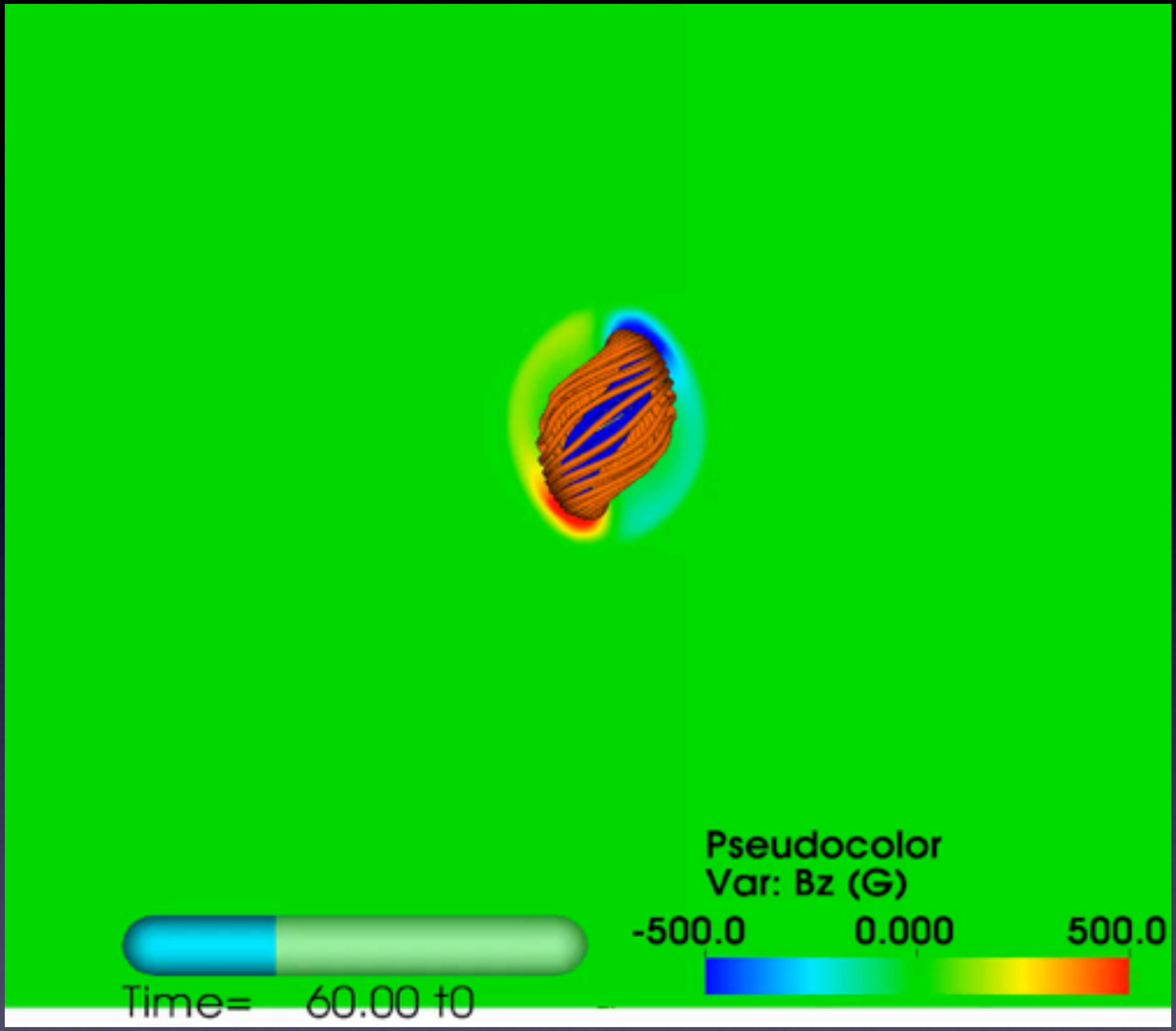


- As concave down part of fieldlines emerge into corona, they lengthen
- Twist/length (alpha) decreases in corona?
- Creates torque imbalance along fieldlines
- Equilibration creates torsional Alfven waves - manifest in rotations at surface



'Breakout' Reconnection with Overlying Field



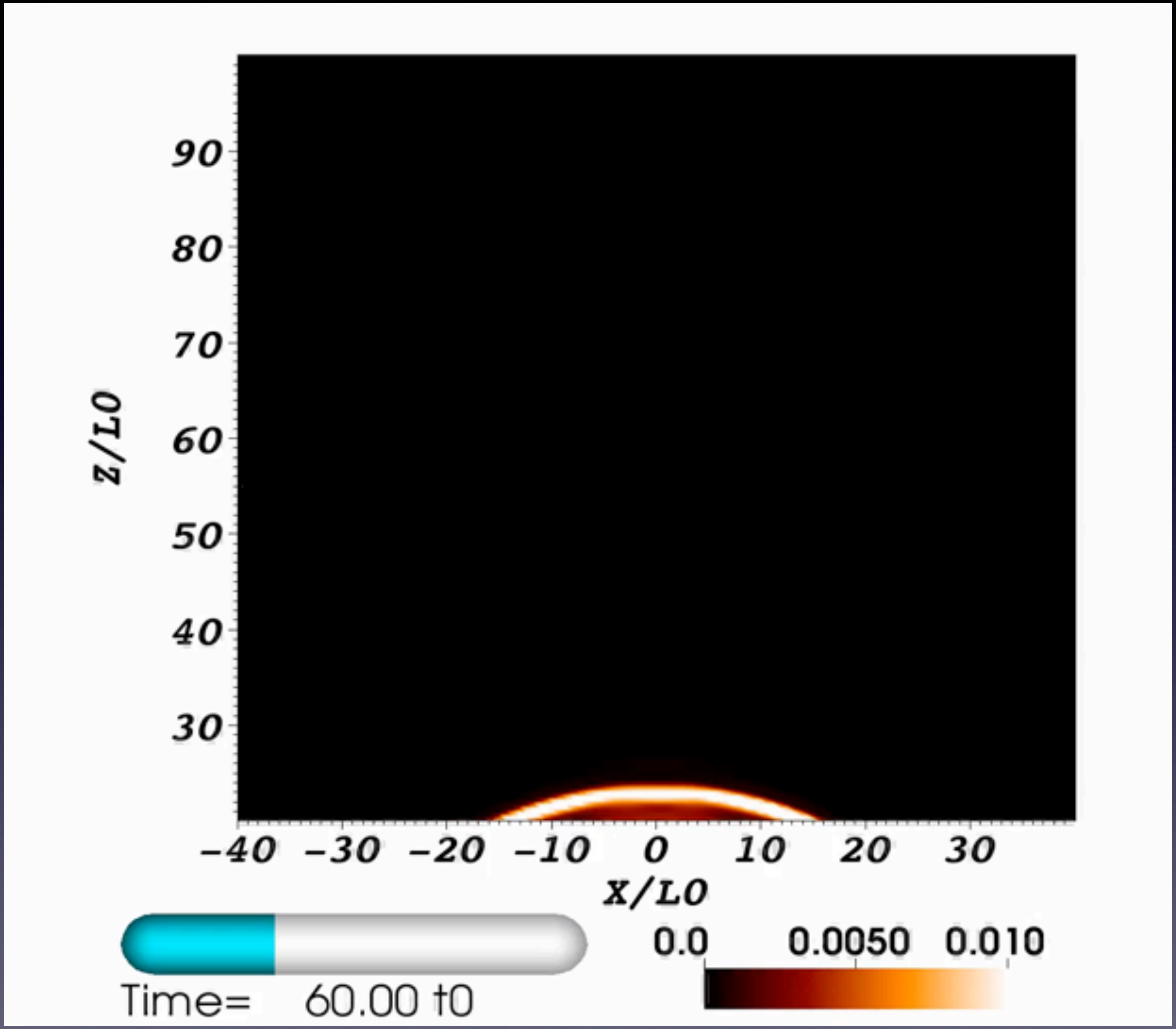


Overlying dipole not shown

Reconnection removes overlying magnetic field and allows central arcade to expand vertically

Quadrupolar structure formed

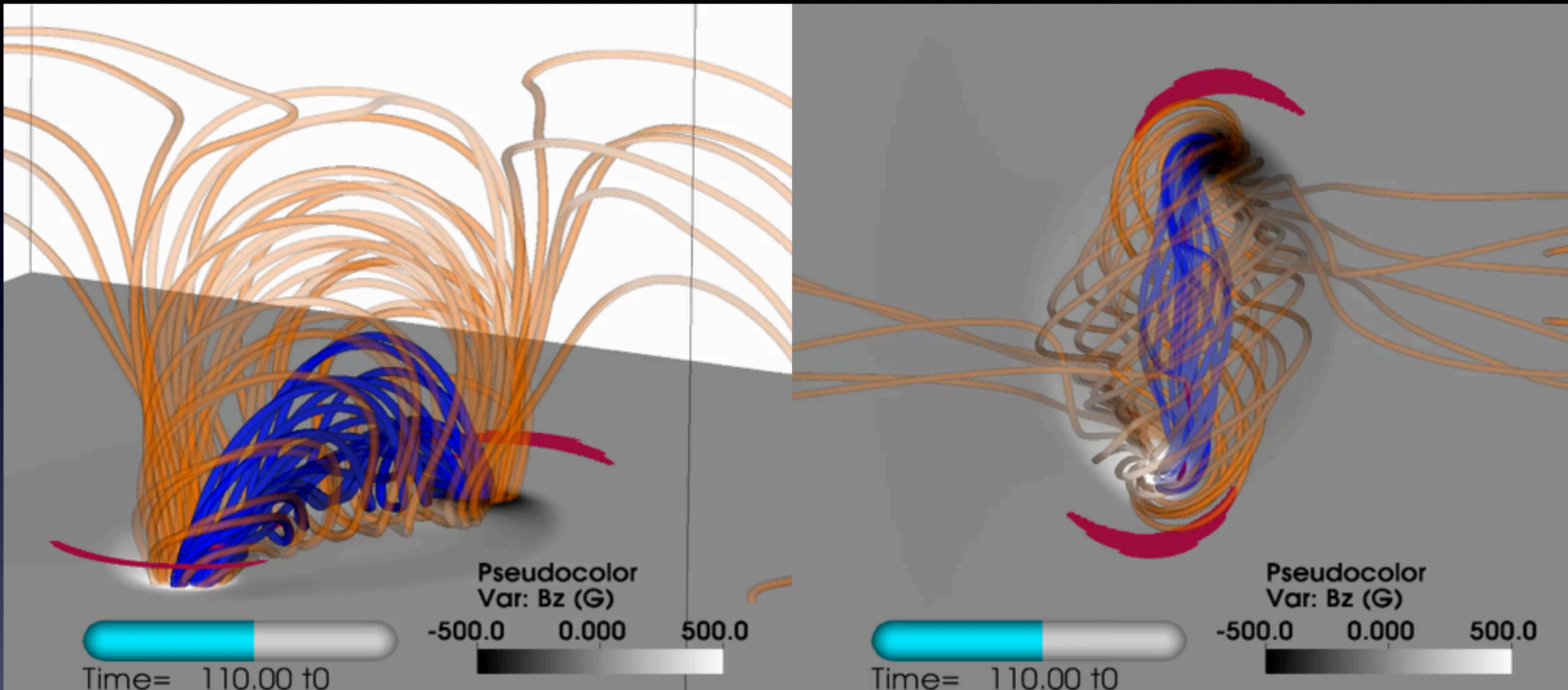
‘Breakout’ Reconnection



Separatrix between emerging field and dipole field
Current sheet, plasmoids - magnetic reconnection

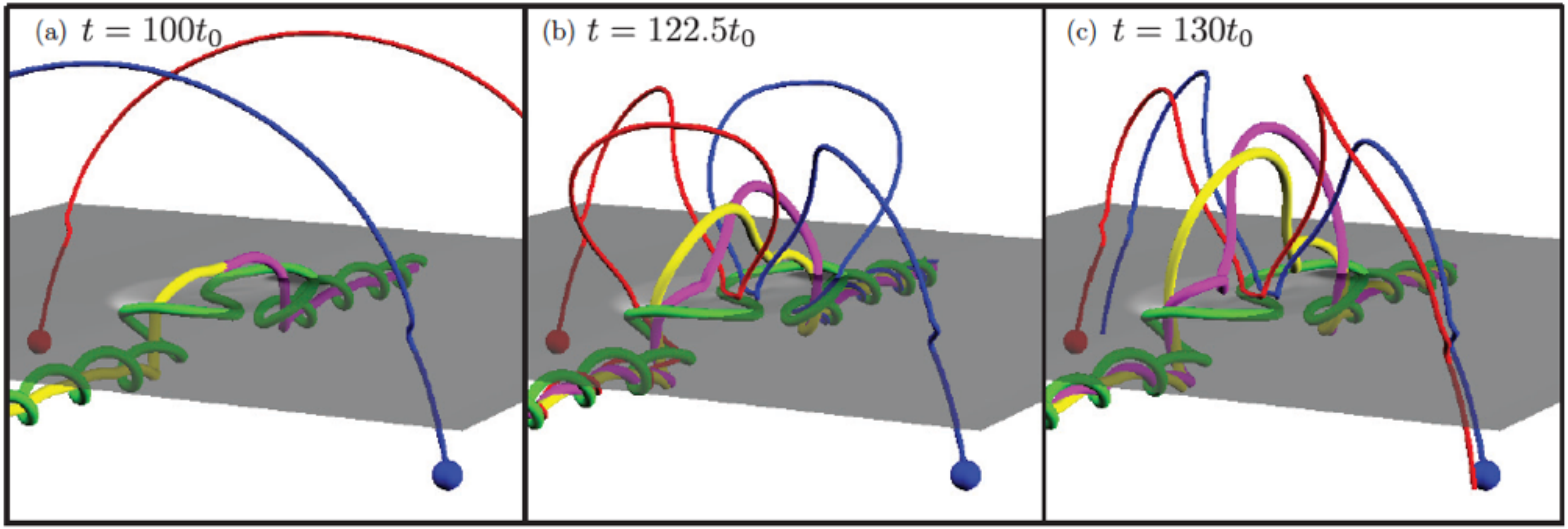
Leake at al., GMU Seminar, December, 2015

Flux Rope Formation



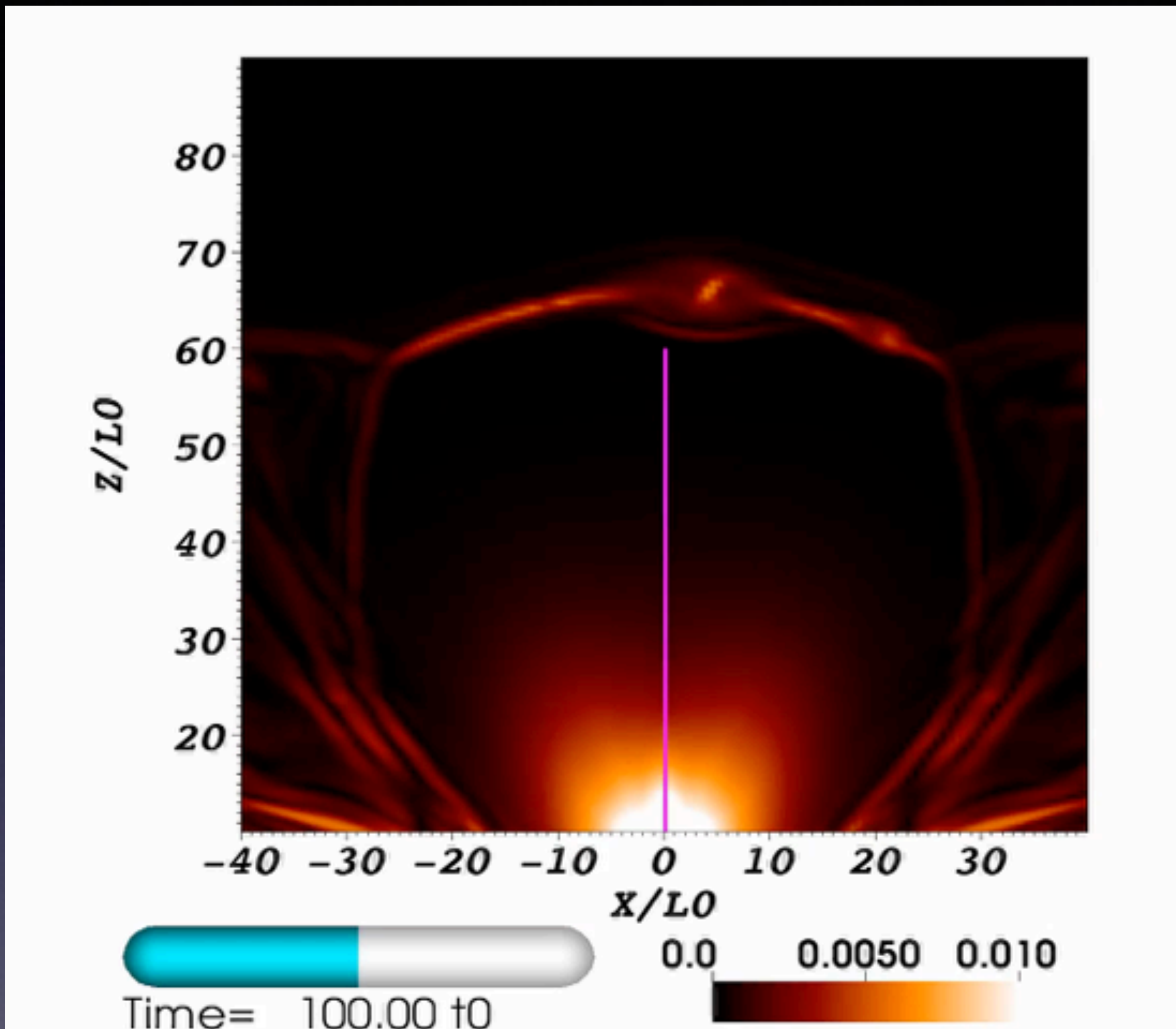
Vertical expansion of B field creates currents.
Current density ribbons
Two J-shapes become S-shapes - sigmoid
Internal reconnection of emerging arcade creates new flux rope

Flux Rope Formation

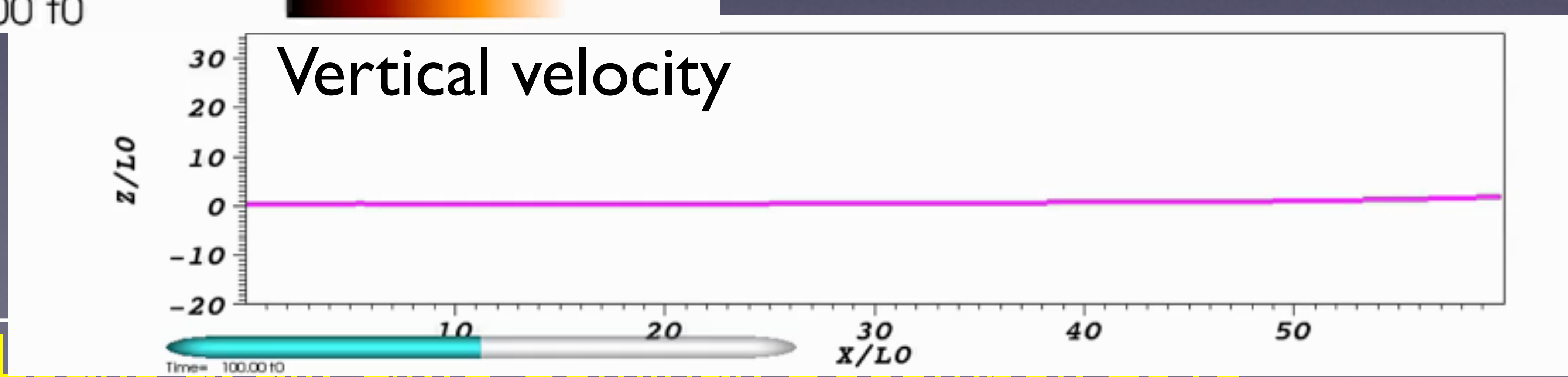


Look at connectivity of magnetic field during multiple reconnection events

‘Flare’ Reconnection

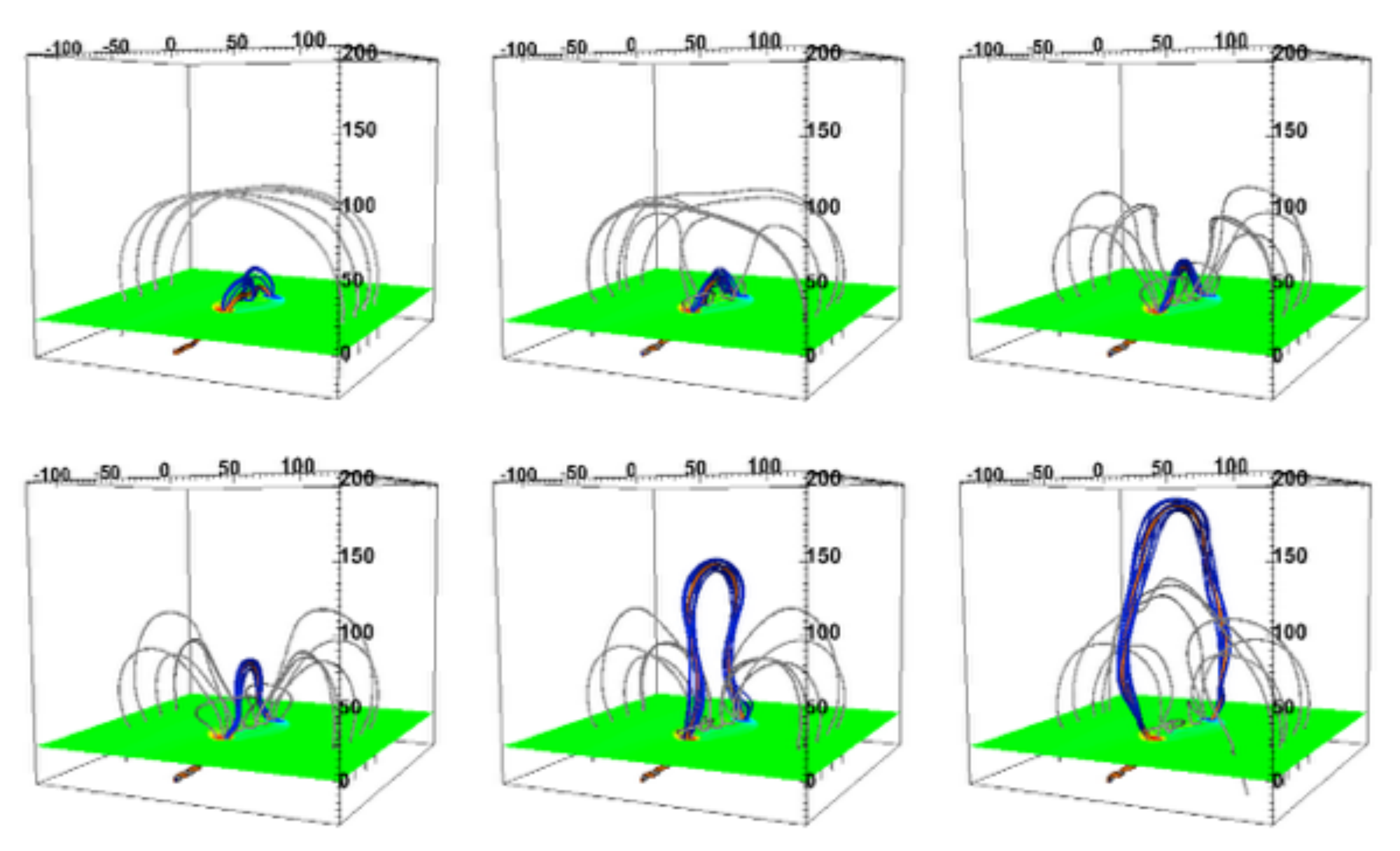


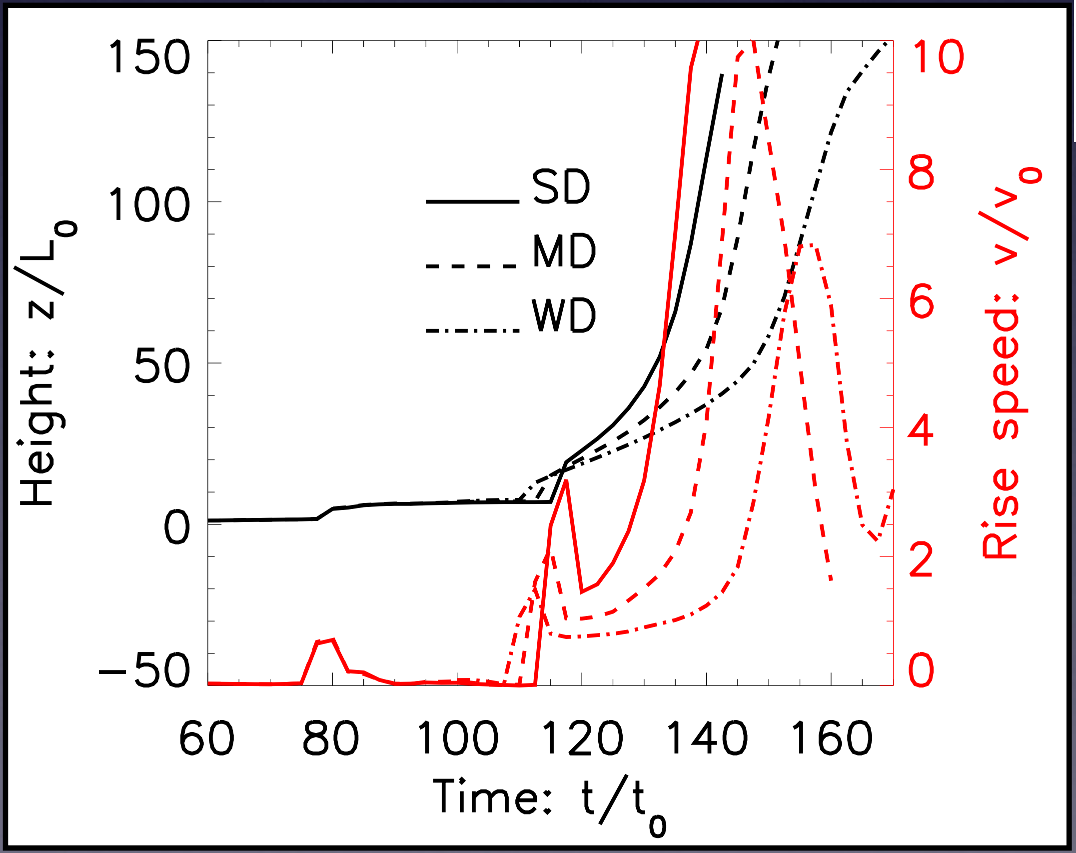
- Slow rise of flux rope
- ‘Horns’ beneath flux rope
- Current sheet beneath
- Fast rise of flux rope
- Reconnection
  - Bi-directional flows
  - Short post-flare loops



Flux Rope Eruption

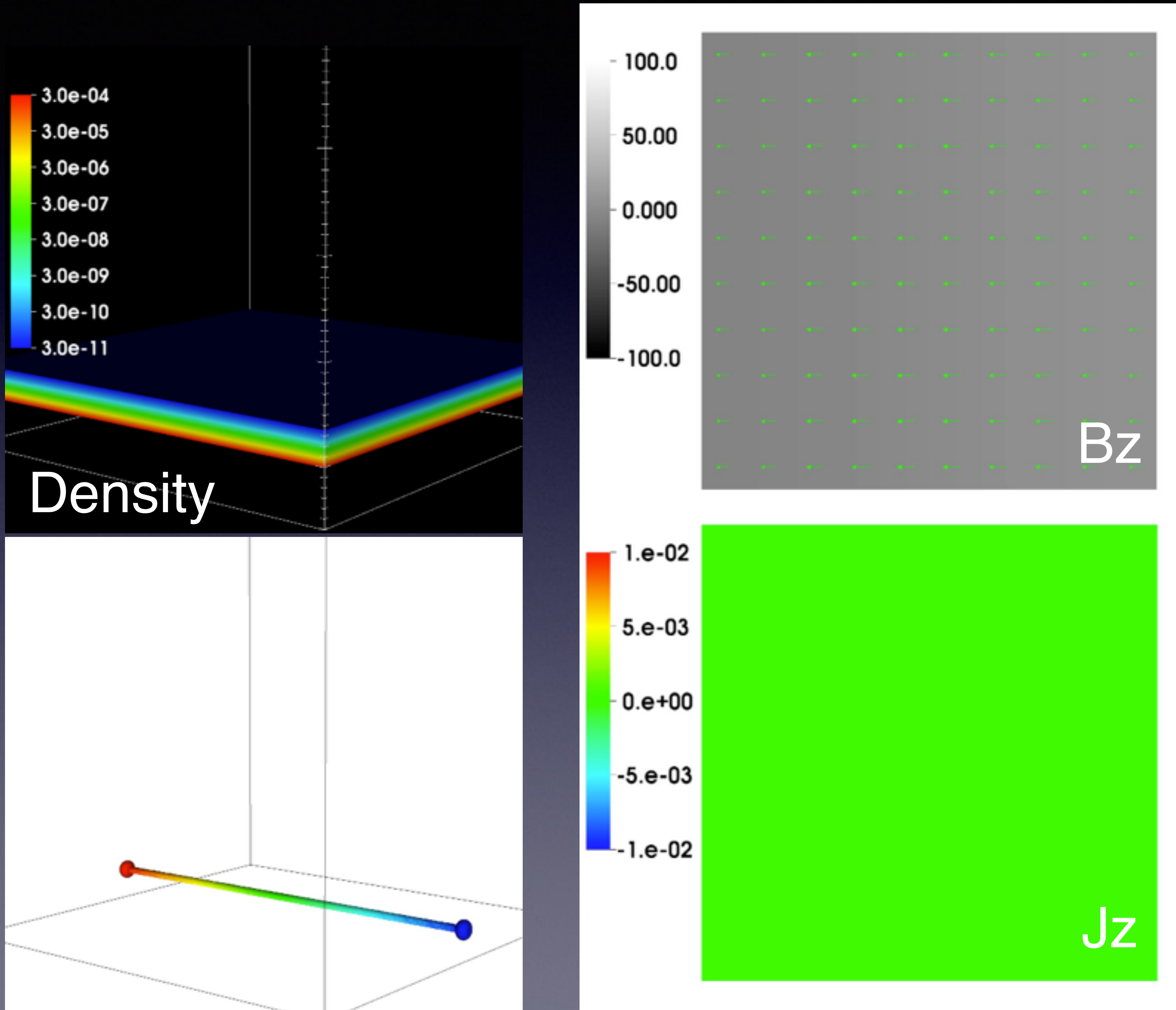
Eruption followed until rope hits top of simulation domain





- Eruption ~ 100 km/s (slow)
- These ARs have 10^19 Mx flux
- Does eruption speed scale with size of AR?

Flux Rope Eruption



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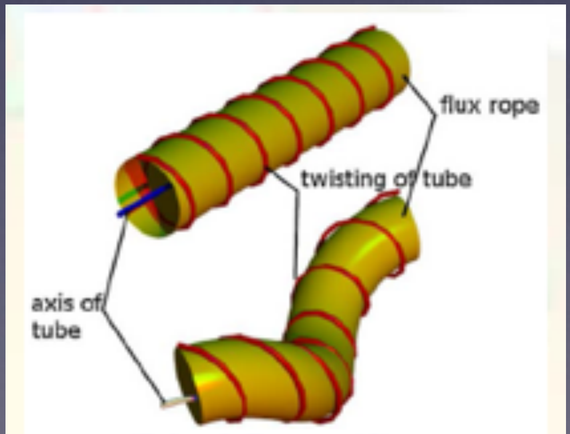
Helicity and Space Weather

- Helicity $H = \int_{\mathcal{V}} \vec{A} \cdot \vec{B} \, \mathrm{d}V \quad , \quad \vec{B} = \vec{\nabla} \times \vec{A}$ ← Magnetic vector potential
- Important quantity in terms of solar activity/CMEs
- Conserved in ideal MHD, in our sims ~3% loss
- For uniformly twisted tube $H = N \, \Phi_{ax}^2$
- Relative helicity may be important quantity for studying productivity of an AR

$$H_{\mathcal{V}} = \int_{\mathcal{V}} (\mathbf{A} + \mathbf{A}_{\mathrm{p}}) \cdot (\mathbf{B} - \mathbf{B}_{\mathrm{p}}) \; \mathrm{d}\mathcal{V}$$



(Prior & Berger 12)

Helicity Observations

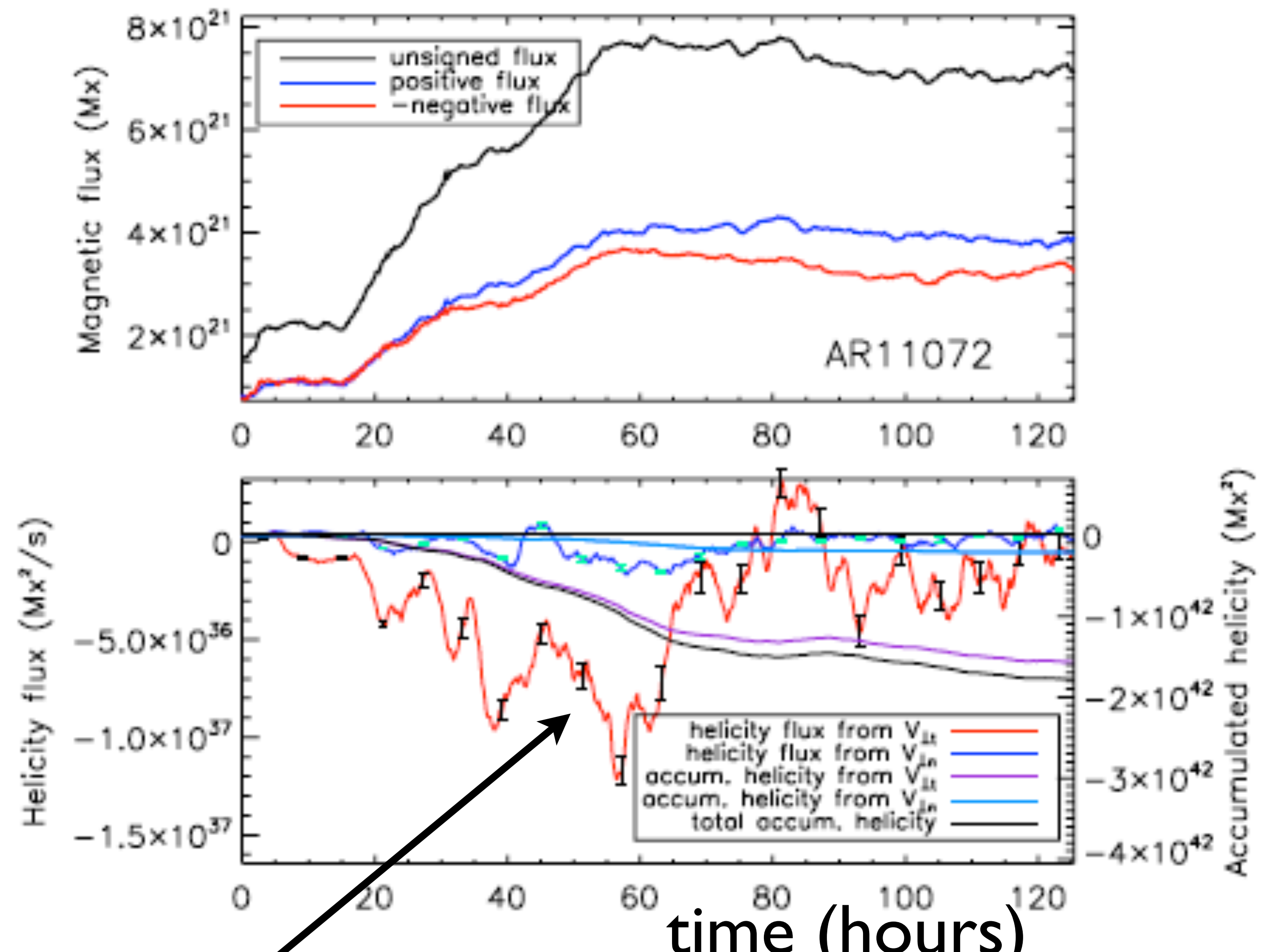
Relative magnetic helicity: Measure of complexity of field (twist, writhe)

$$\frac{dH}{dt} = -2\int_S (\mathbf{A}_p \cdot \mathbf{V}_h) B_z dS \quad \text{horiz. flows}$$

$$+2\int_S (\mathbf{A}_p \cdot \mathbf{B}_h) v_z dS \quad \text{vert. flows}$$

Pariat et al. 2005, Demoulin and Berger, 2003.

Liu and Schuck 2012, AR11072



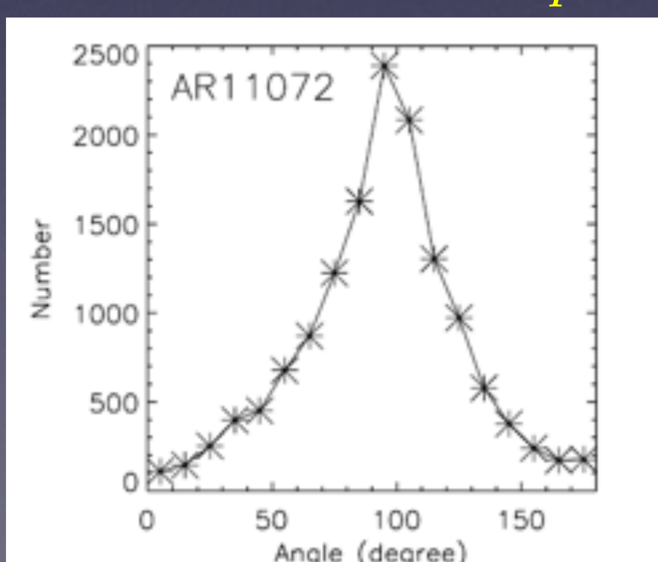
time (hours)

horizontal flow contribution dominates

Liu and Schuck 2012

$$2\int_S (\mathbf{A}_p \cdot \mathbf{B}_h) v_z dS \sim 0$$

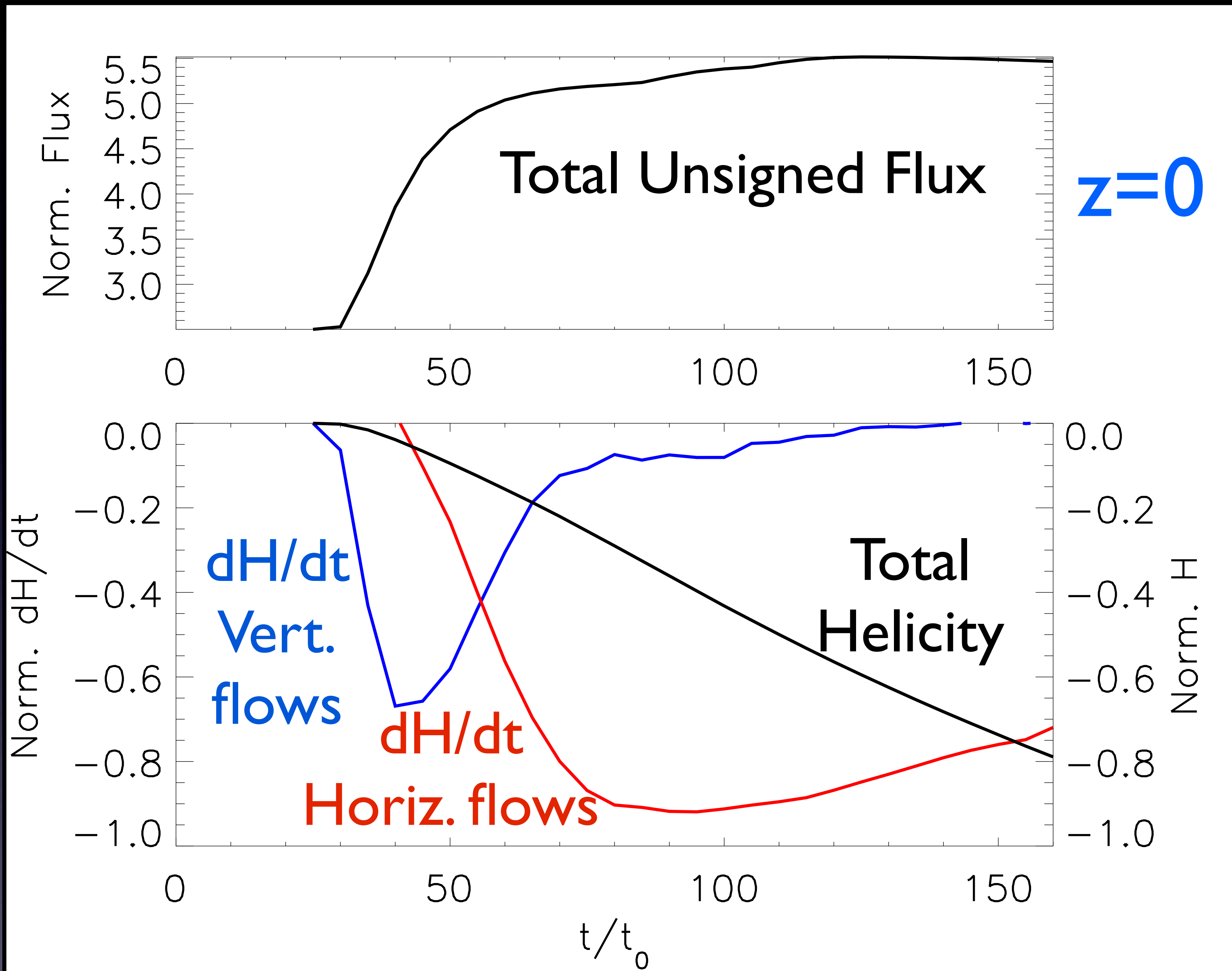
Potential field $\mathbf{A}_p \cdot \mathbf{B}_h \rightarrow 0$

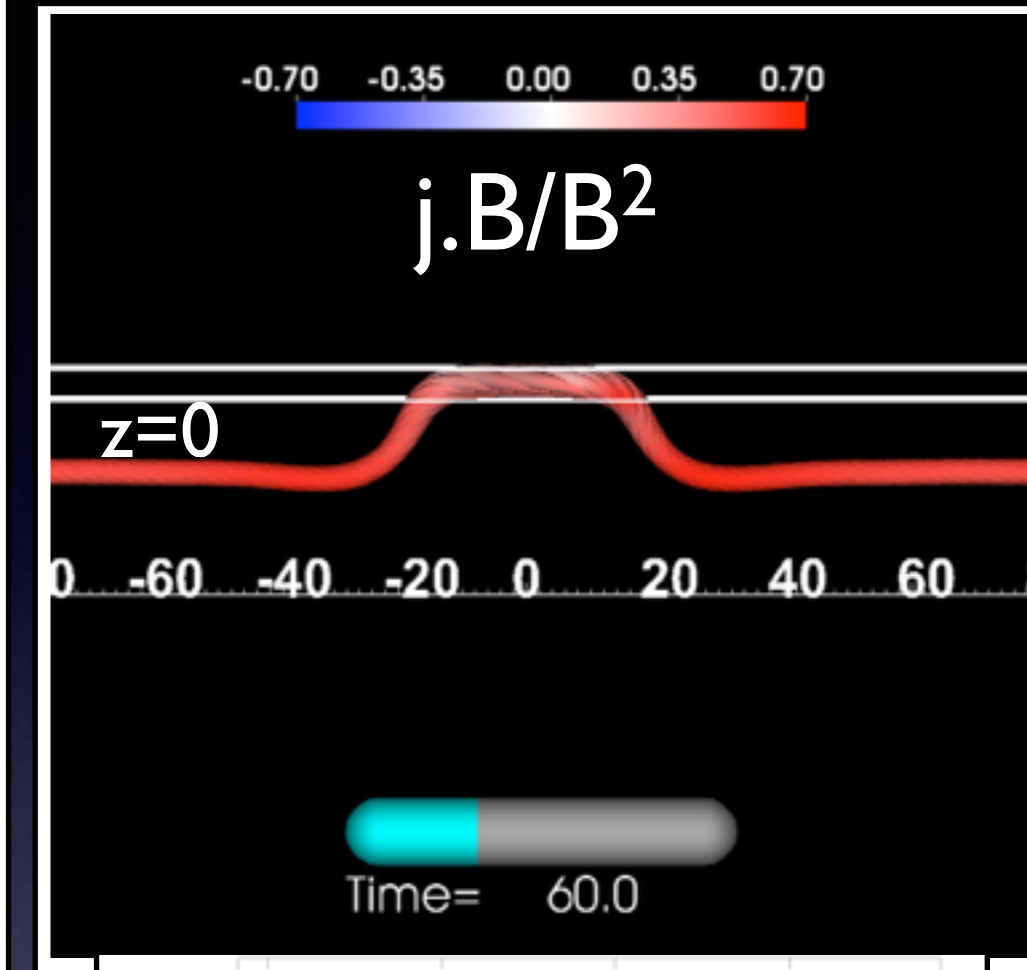


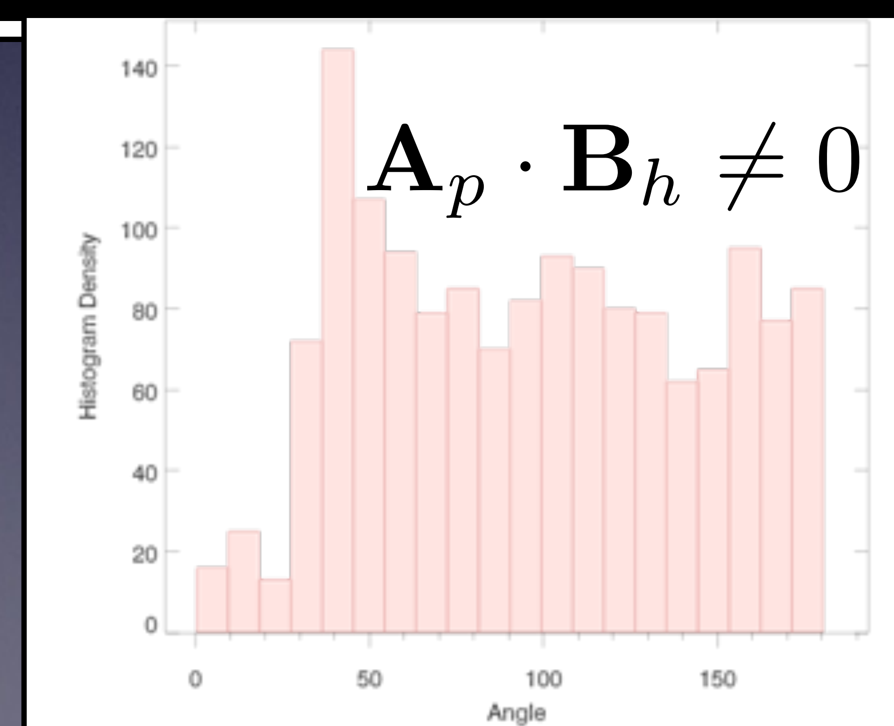
Helicity flux at surface dominated by horizontal flows mixing potential field?

Use sims. to help understand helicity injection

Helicity Injection in Simulations

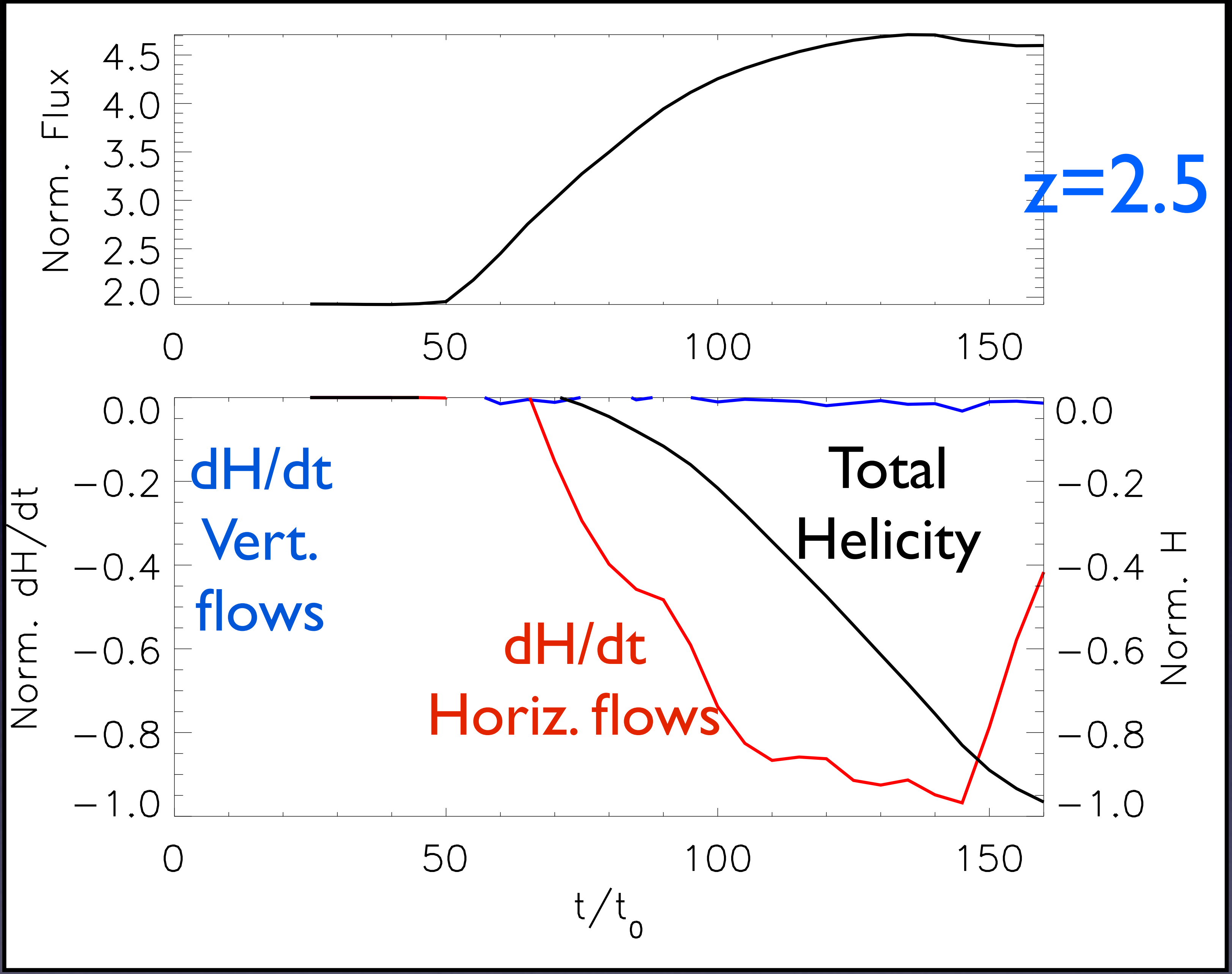


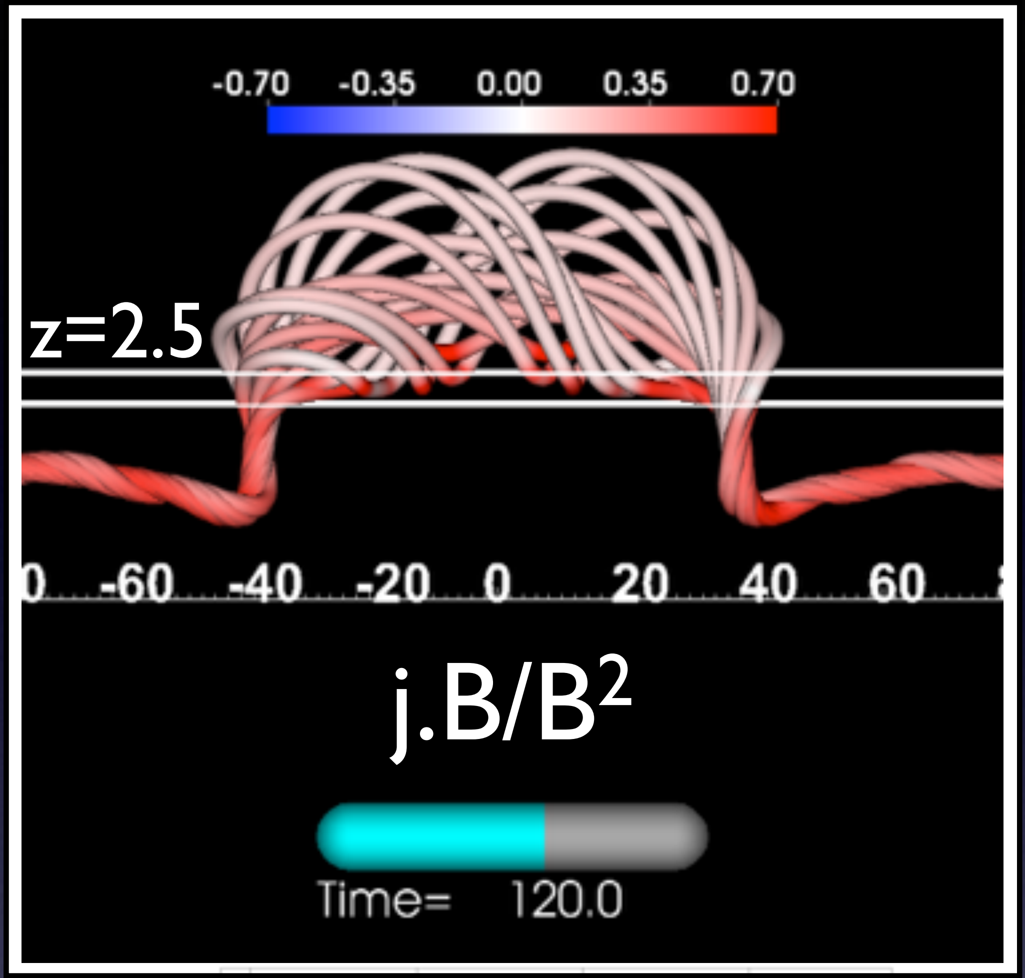


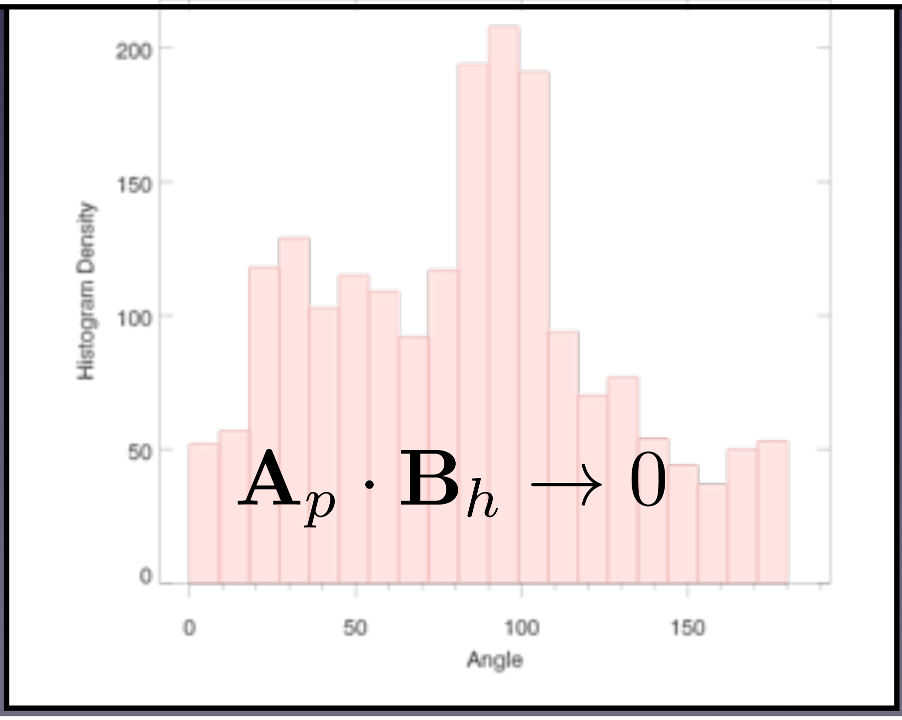


Twisted tube bodily emerges above z=0
Vertical flows initially dominate dH/dt
Horizontal flows dominate later

Helicity Injection in Simulations







No bodily emergence above z=2.5

Horizontal flows dominate (only potential field emerges?)

Need better decomposition of dH/dt

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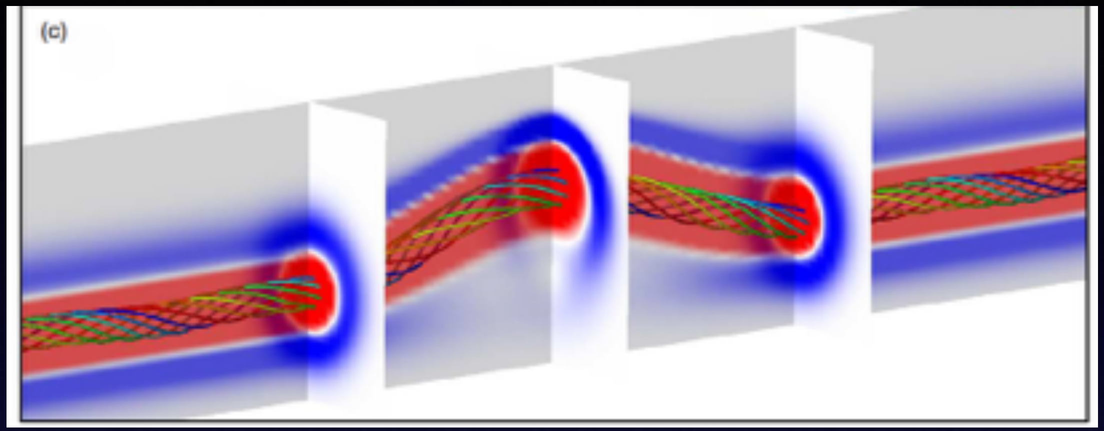
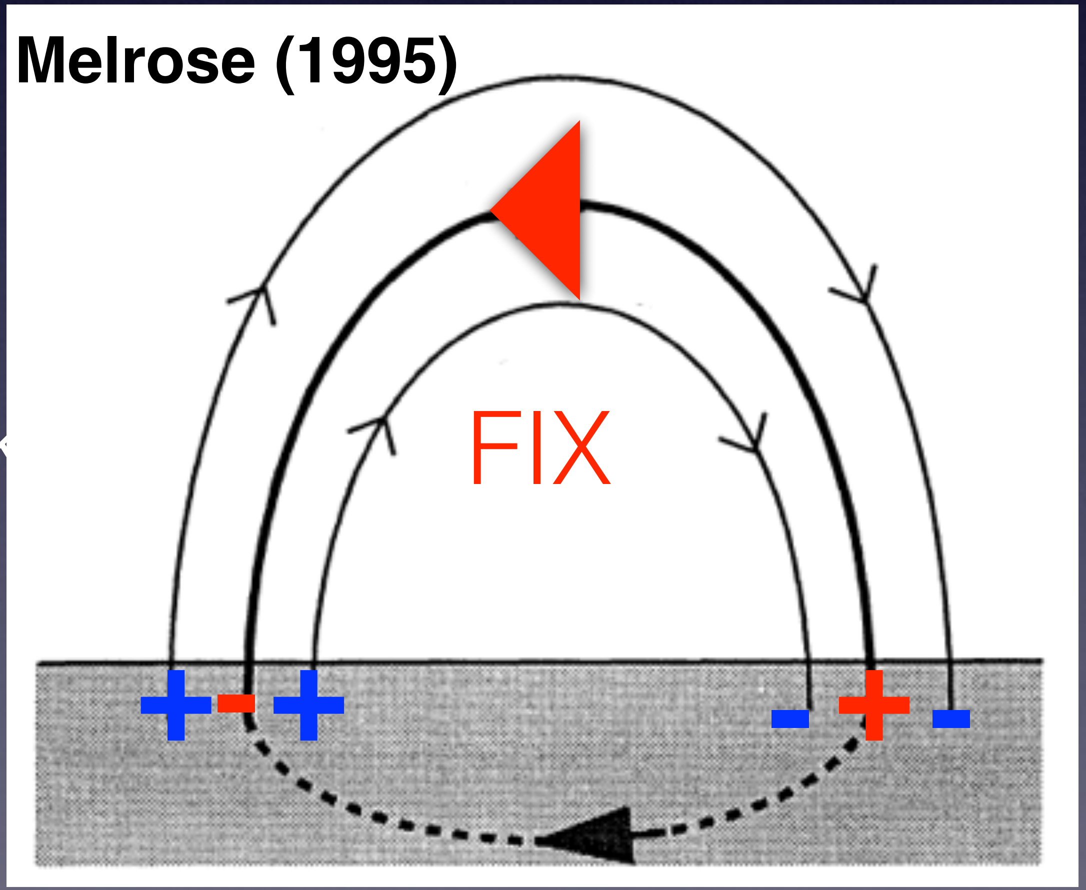
Motivation and Theoretical Considerations

- AR currents (J=curl(B)), the source of CME/flare energy, are believed to be created by
  - stressing of coronal magnetic field and/or emergence of current carrying flux from interior



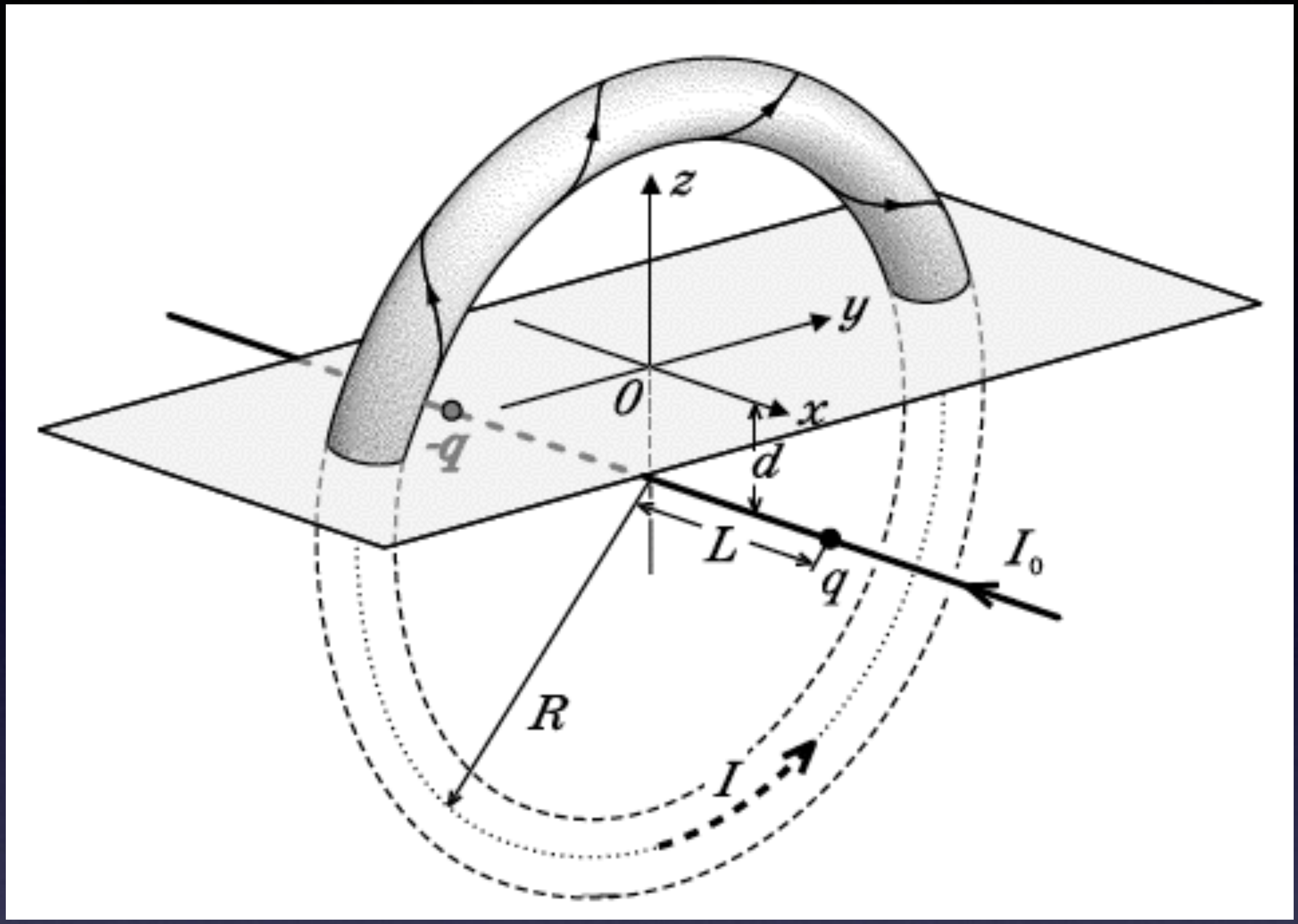
- Melrose argued that currents in corona cannot be generated by shearing motions, but must close in the interior
- Faraday's law requires that isolated flux tubes carry no net current
- If isolated, current neutralized, magn. flux tubes link into the corona, then would expect to observe balance direct and return current at footpoints

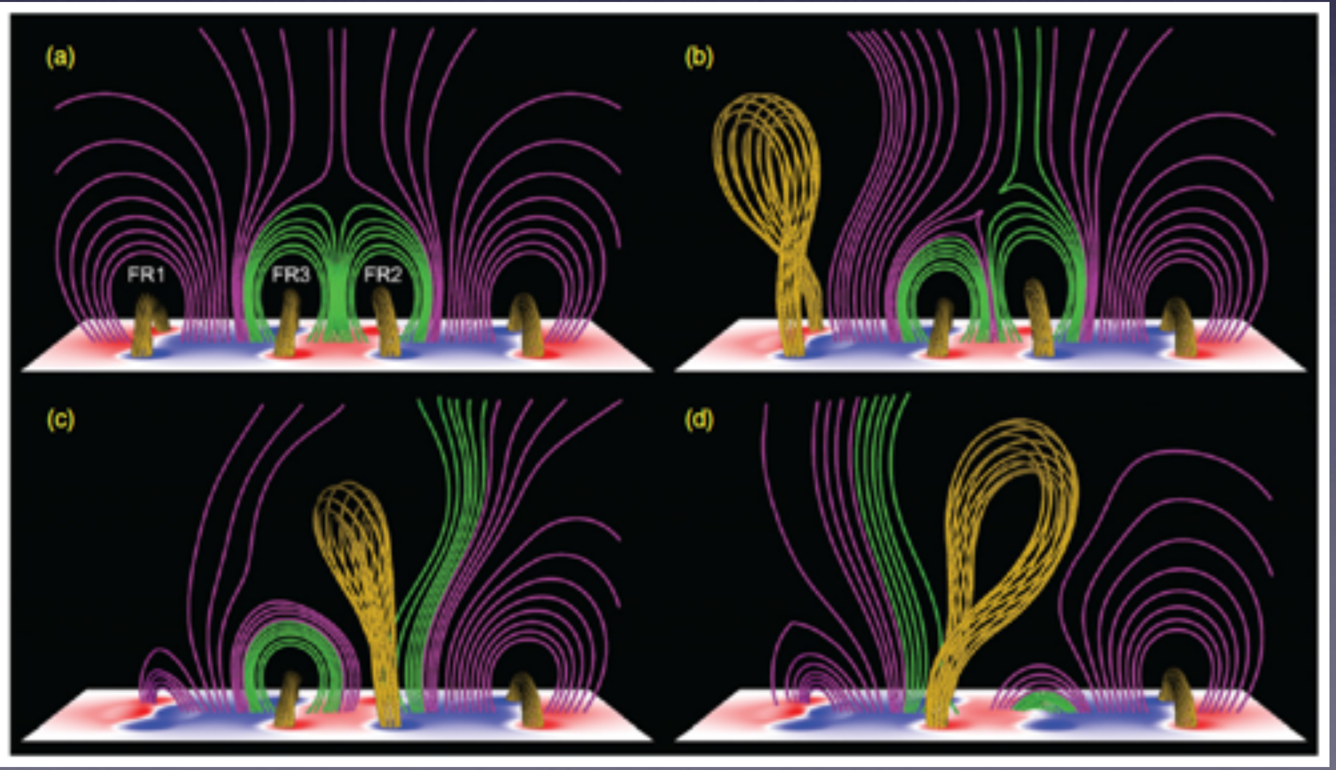


- Why should we care whether coronal currents are neutralized or not?
- Do we see these return currents in photospheric observations? Very little analysis so far.

Motivation and Theoretical Considerations

- Why should we care ?
  - The subject of electric current neutralization has lead to lively debate (not now) about:
    - the nature of coronal flare energy storage and energization
    - how to describe time-dependent coronal system (V,B vs E,J) - Leake et al. SSRv (2014)
  - Successful theoretical/numerical CME models use initial conditions based on non-neutralized current-carrying coronal flux ropes
    - Török and Kliem (2005), WIlliams et al. (2005), Schrijver et al. (2008), Kliem et al. (2010,2012,2013)

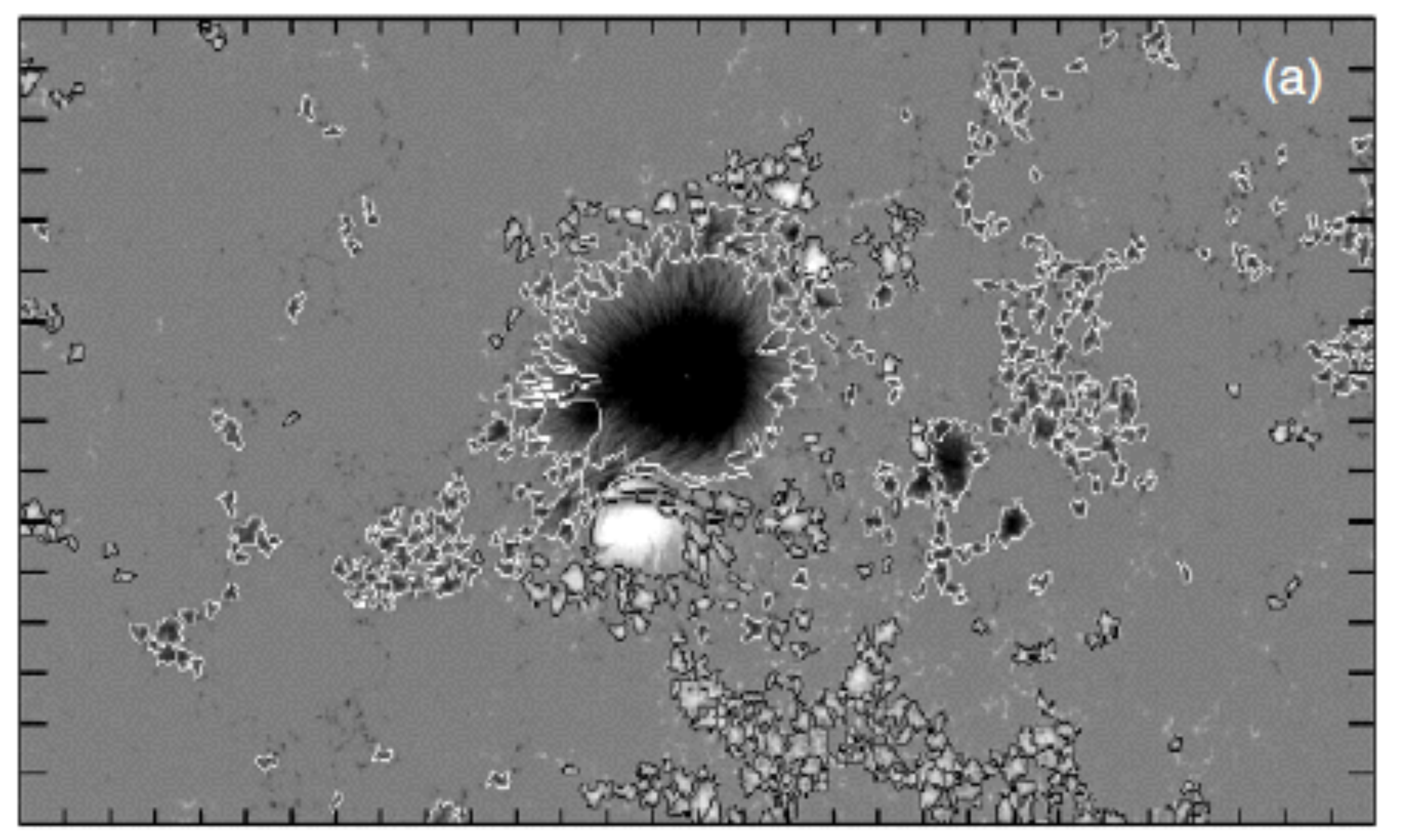


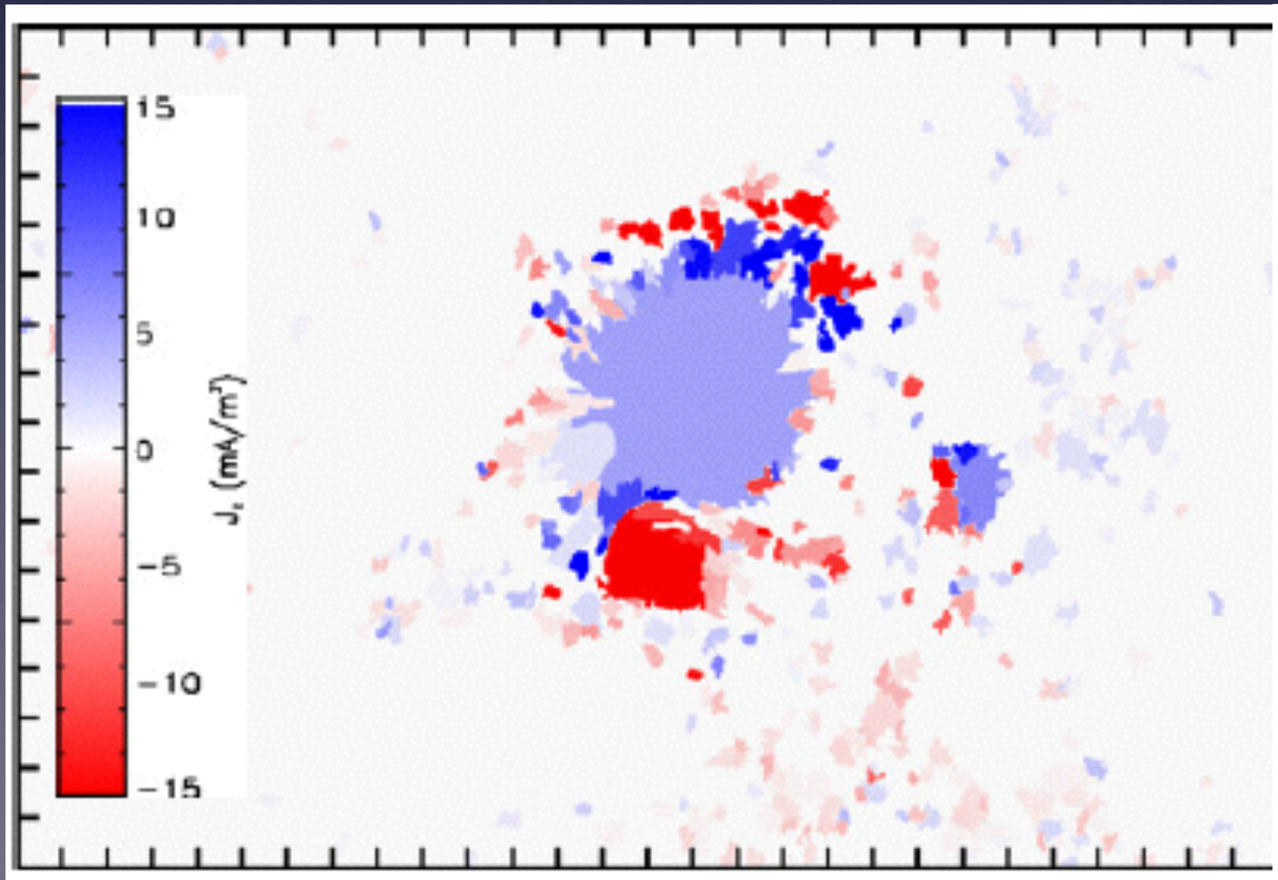


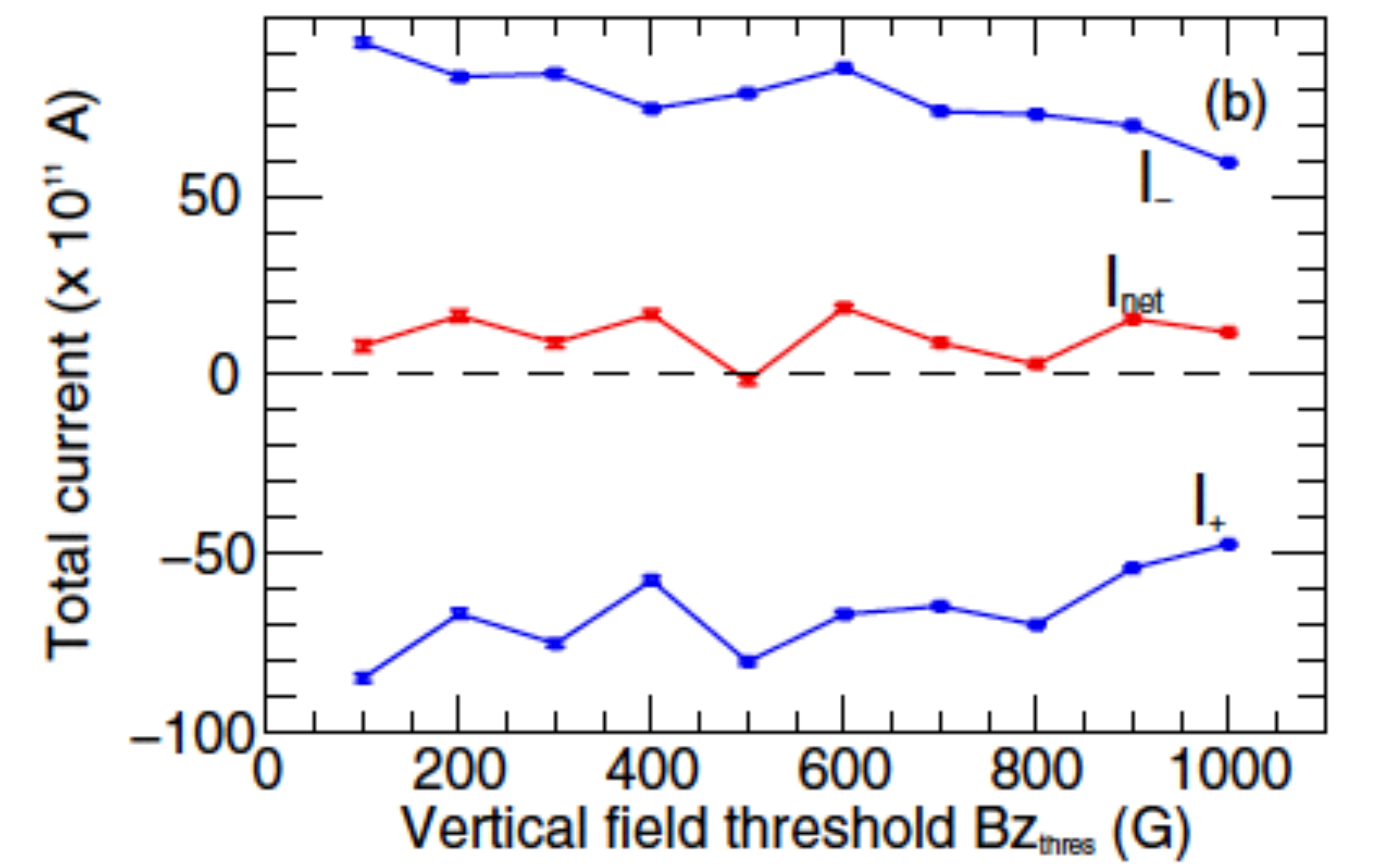
Observations: Flare region

Ravindra et al. (2011), Georgoulis et al. (2012)

- Flare-producing AR 10930
  - Find a net current in each polarity
- Onset of flares seems to depend on decrease in this net current
- Concluded that shear at PIL is important for net current

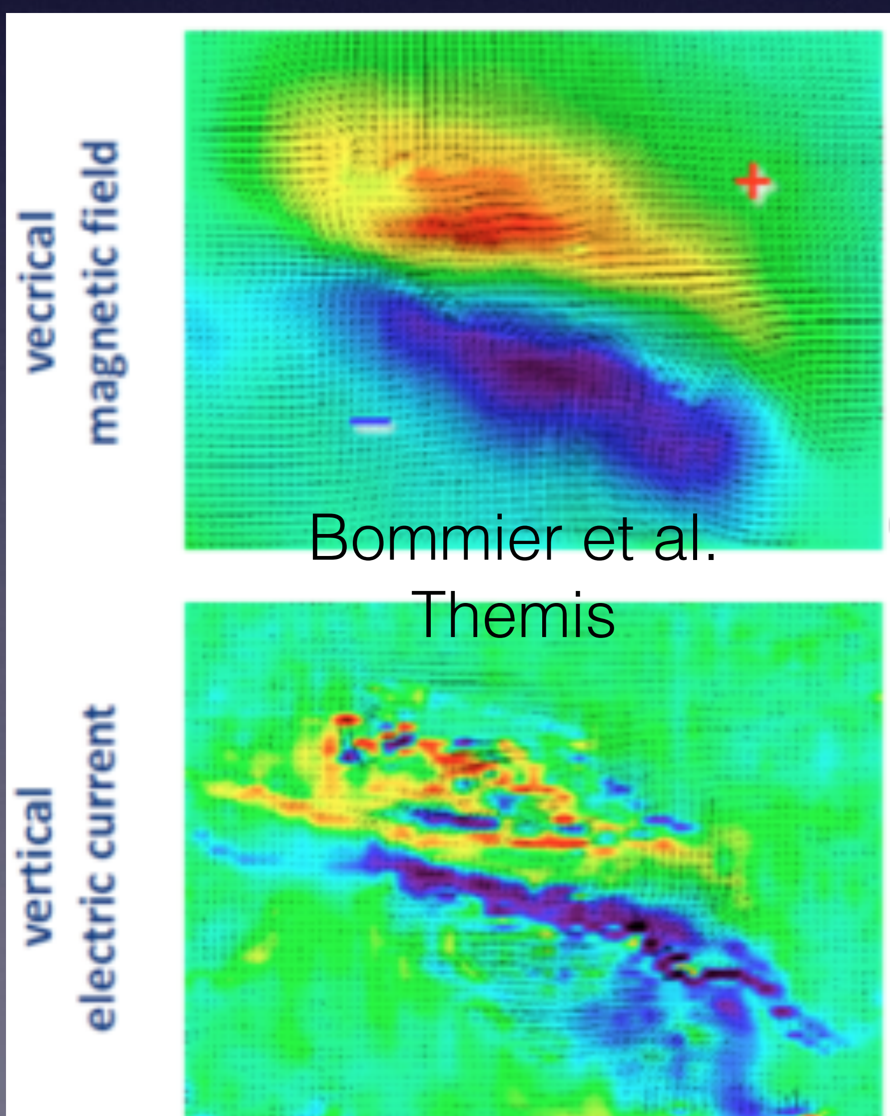




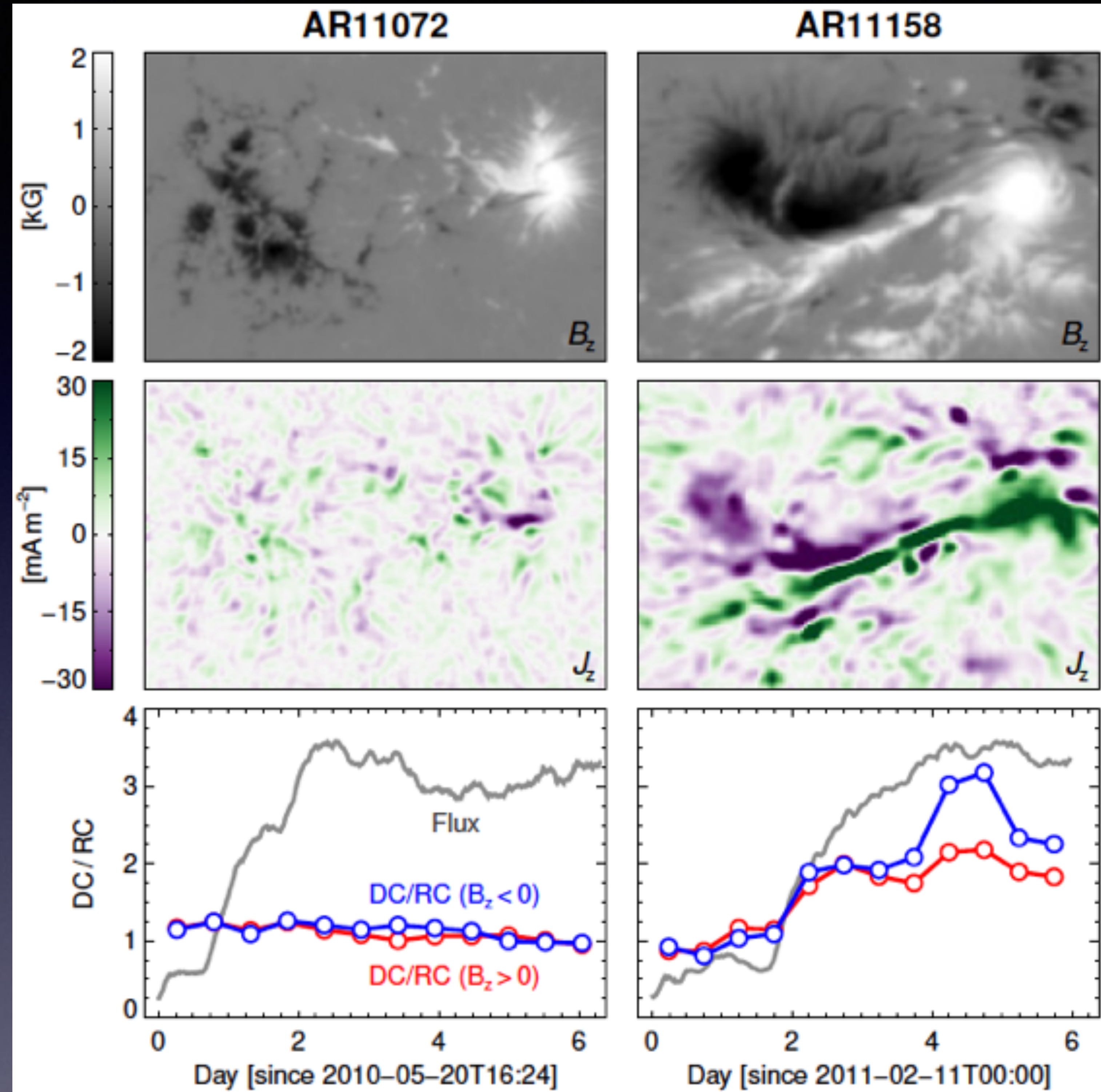


Observations: AR 11072 and 11158

- Courtesy Yang Liu
  - AR 11072/11158
    - 11158 highly sheared PIL and non-neutralized
- Is shear at PIL necessary for non-neutralization?



Bommier et al.
Themis

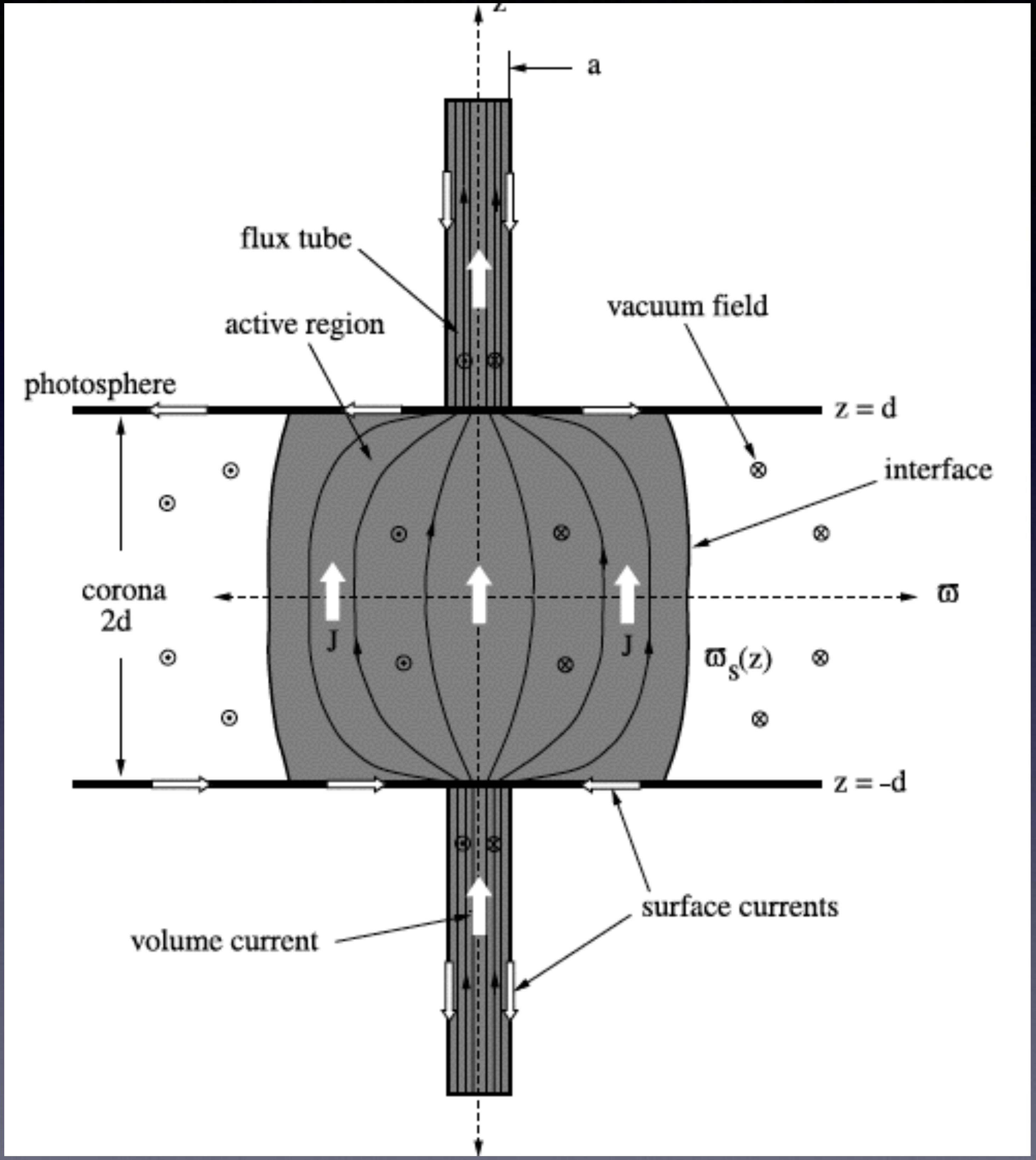


$$DC = \int J_z|_{(JzBz>0)} dA$$

$$RC = \int J_z|_{(JzBz<0)} dA$$

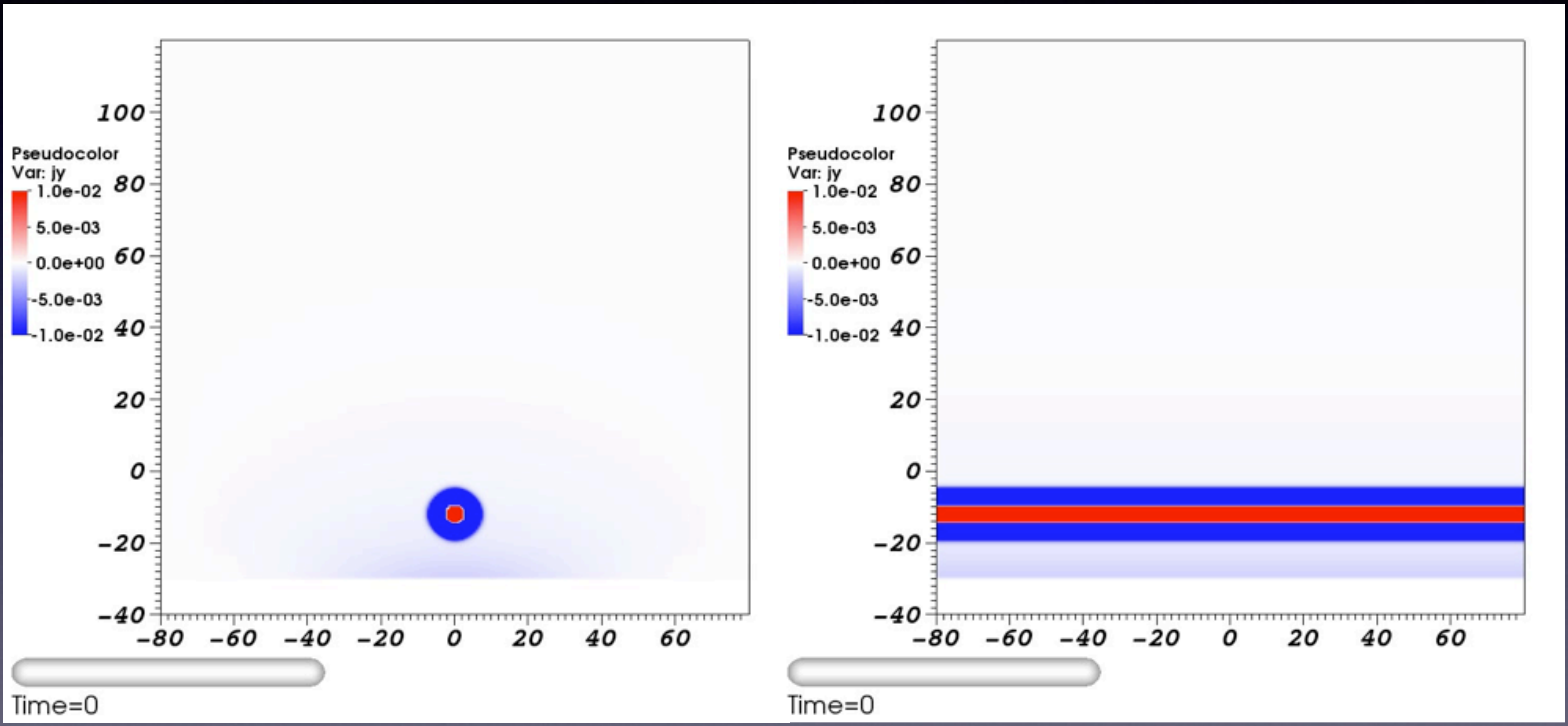
Early Model for flux tube emergence

- How can we get non-neutralized atmospheric currents from neutralized interior flux structures?
- Longcope and Welsch (2000)
  - Twisted flux tubes emerges into field-free corona
  - Initially, no twist emerges
  - Launches Torsional Alfven wave which twists up the coronal field
  - Return currents of the subsurface field are confined to the surface (why?)
- Let’s look at a dynamic simulation of flux emergence



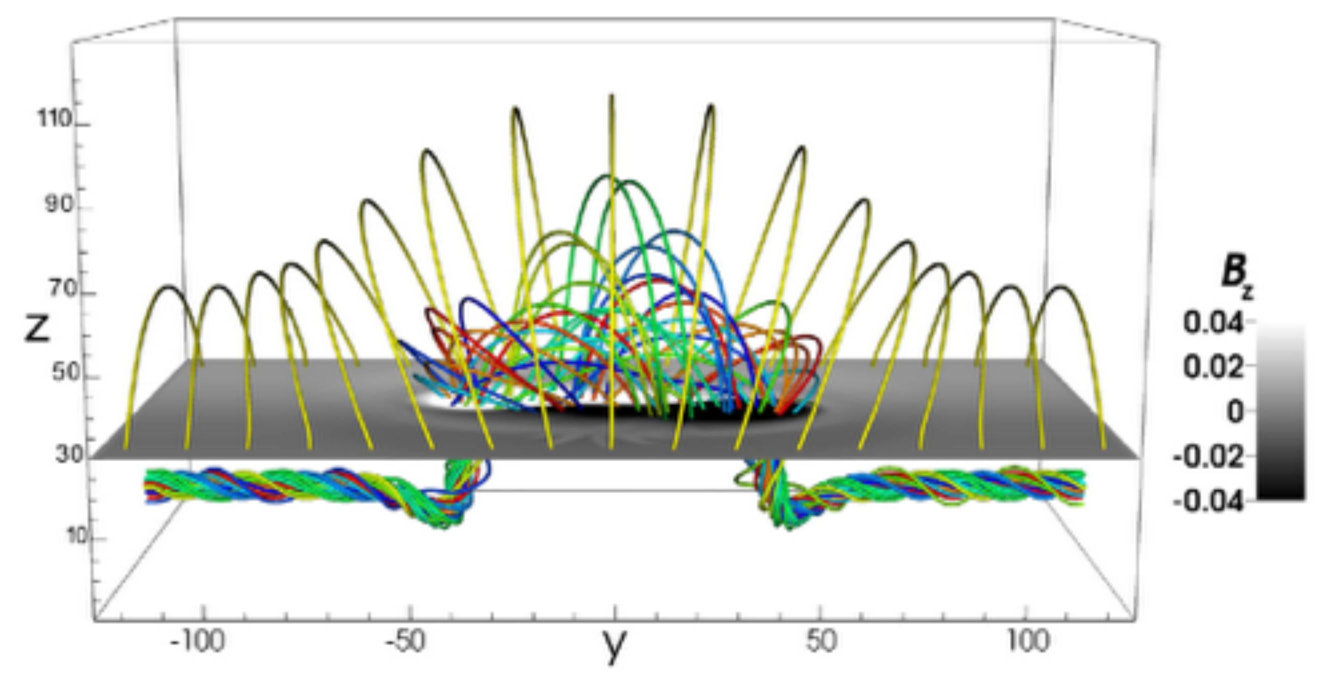
Simulations of flux tube emergence

Key feature is flux pile up near surface before emergence
Top of tube emerges first, later emergence builds up current in corona

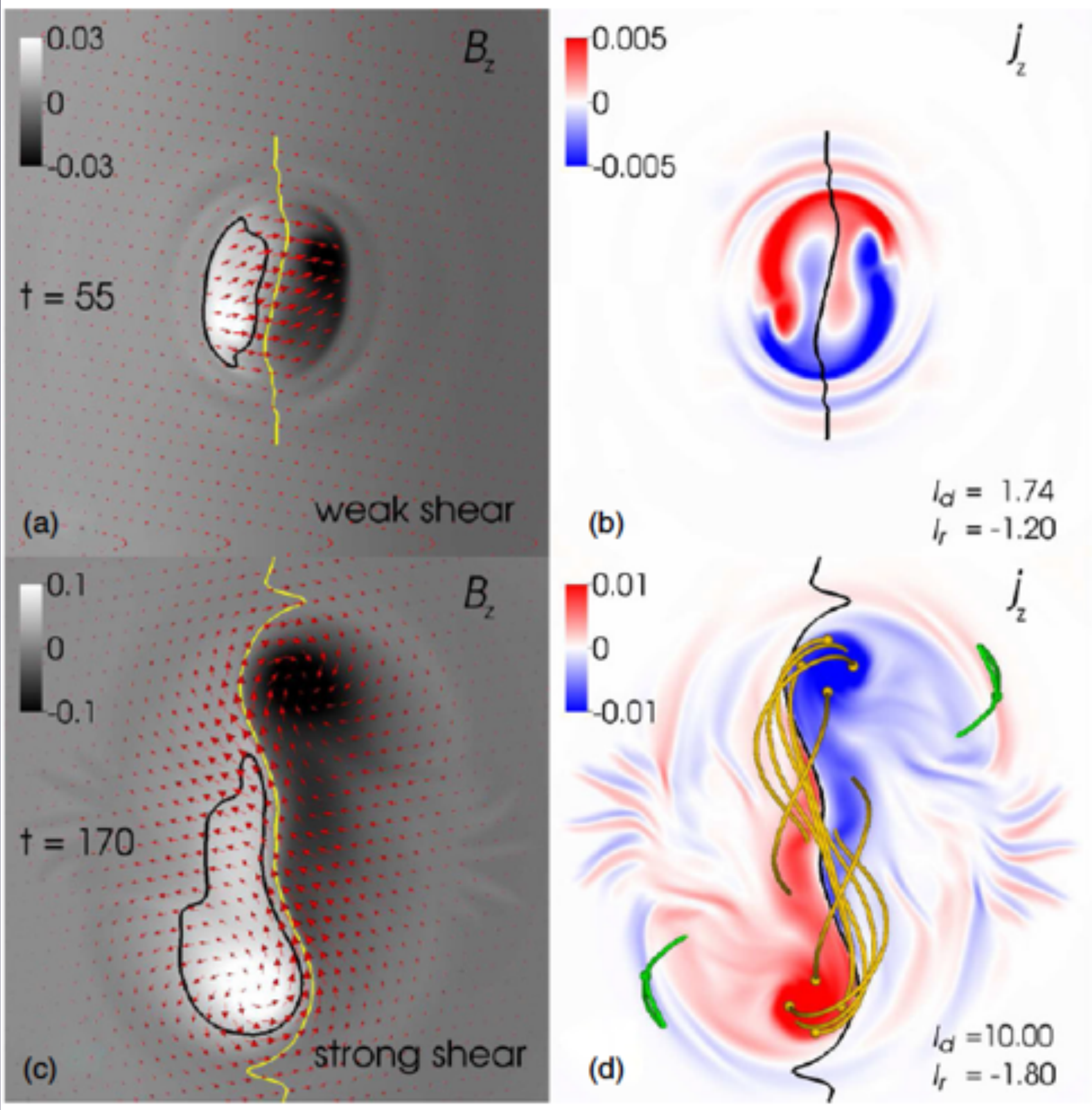


Where does the return current go?
Is there a net current in the atmosphere?

Initial results (Török et al. 2014)



Perform at two times, before and after significant shearing

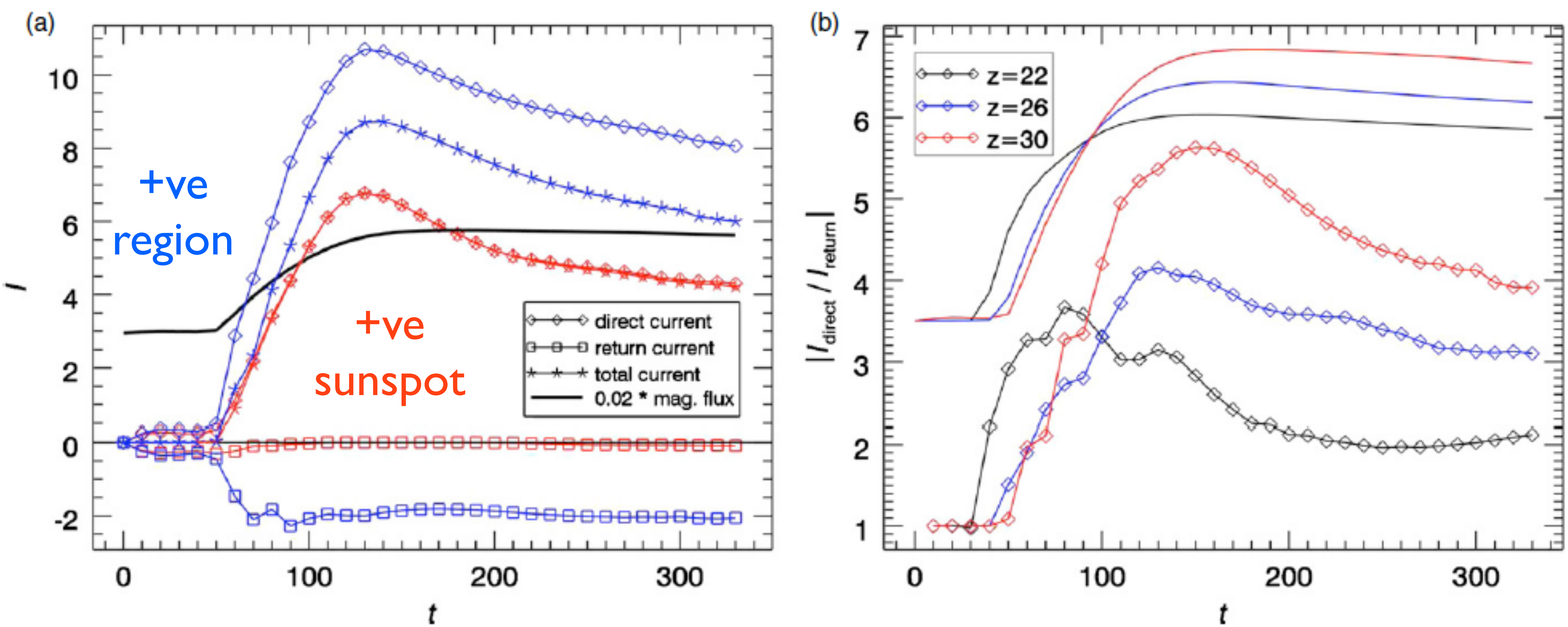


- Analyze direct and return currents in the atmosphere
- Do same surface integral as obs papers
  - +ve polarity and +ve region

$$DC = \int J_z|_{(JzBz>0)} dA$$

$$RC = \int J_z|_{(JzBz<0)} dA$$

Initial results (Török et al. 2014)



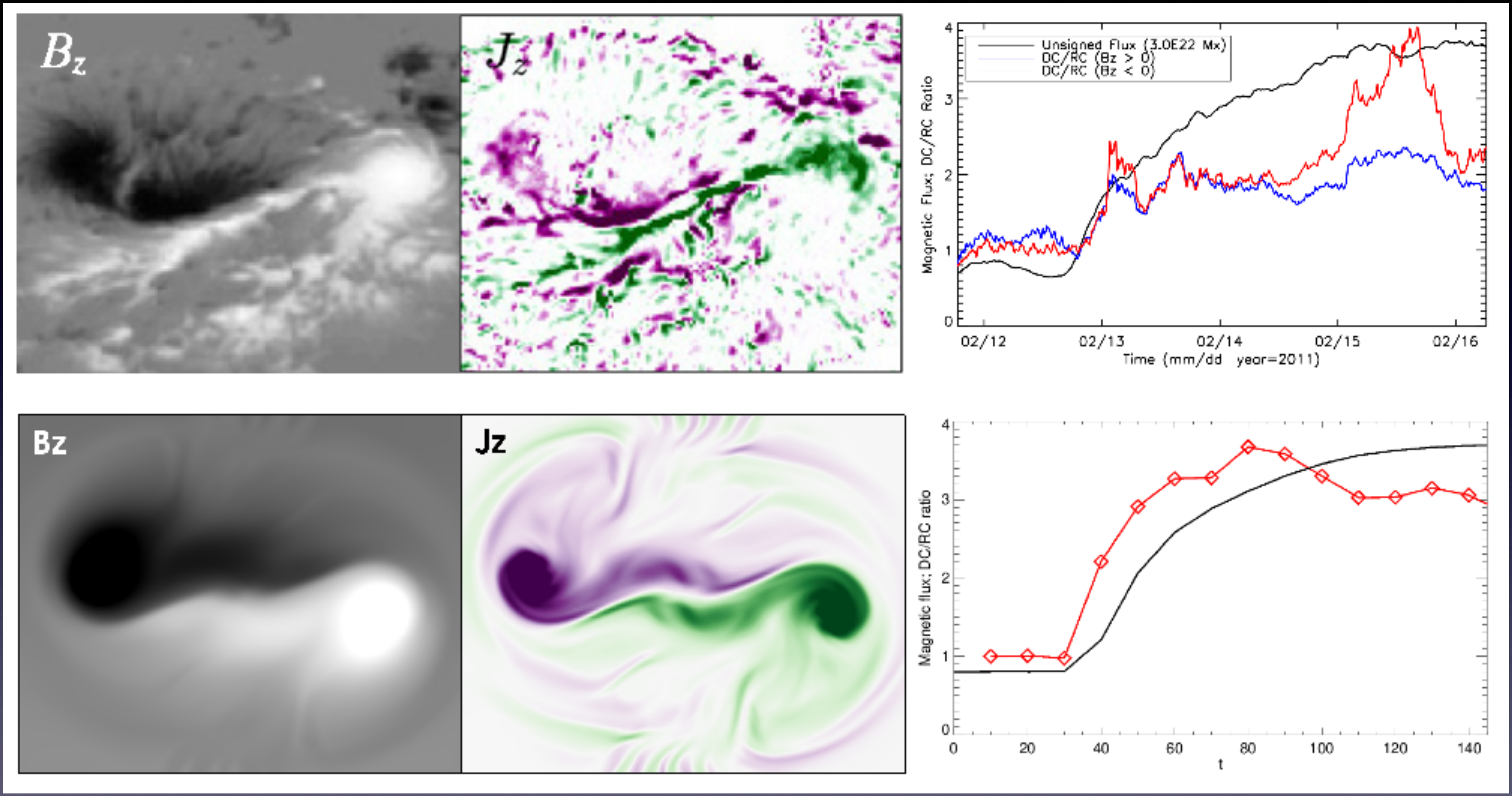
Current analysis

Direct: Jz*Bz>0 Return: Jz*Bz<0

Significant net current in these simulations

Strong shear at PIL

Comparison with center of AR11158



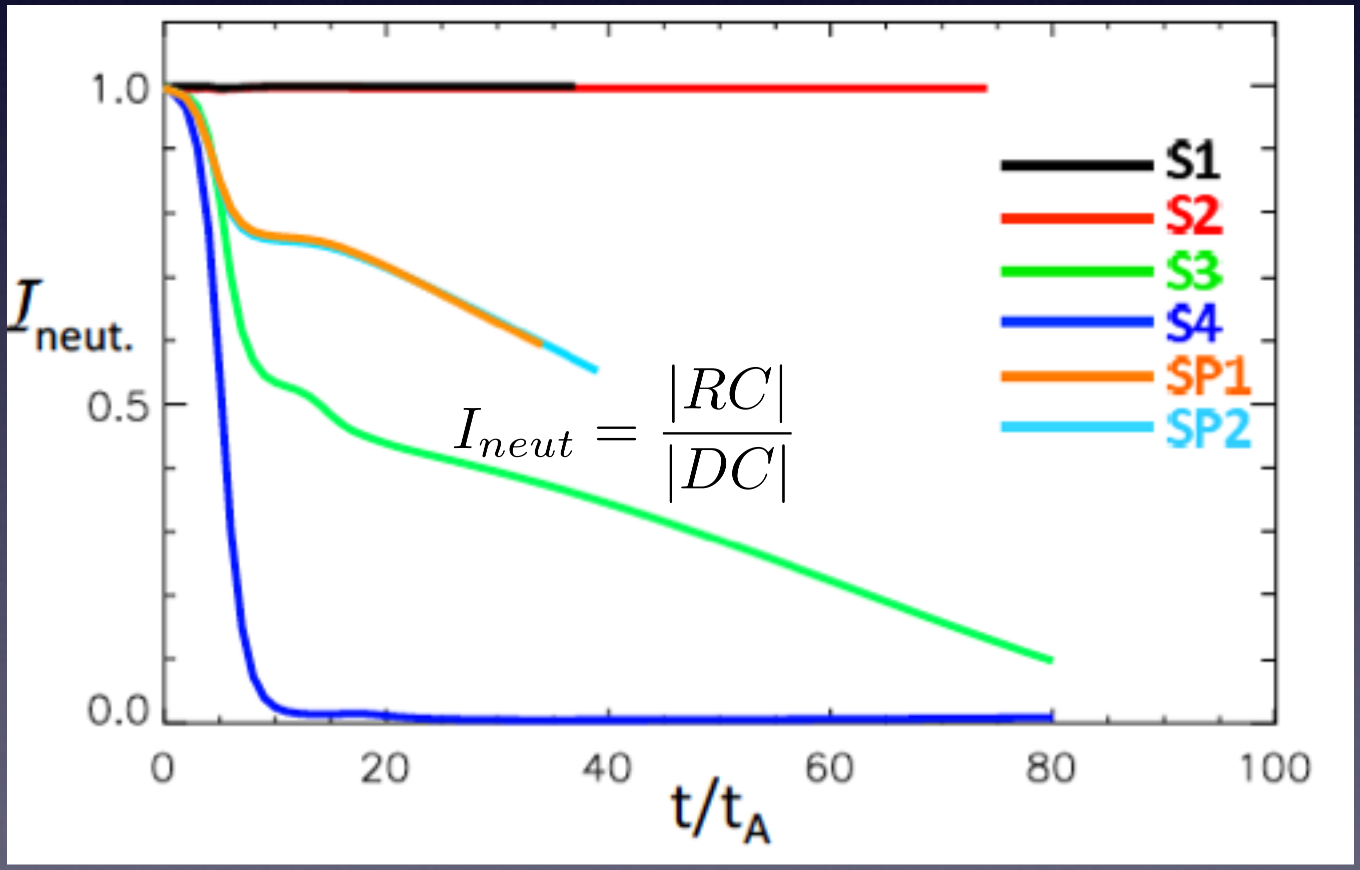
Significant net current in these simulations

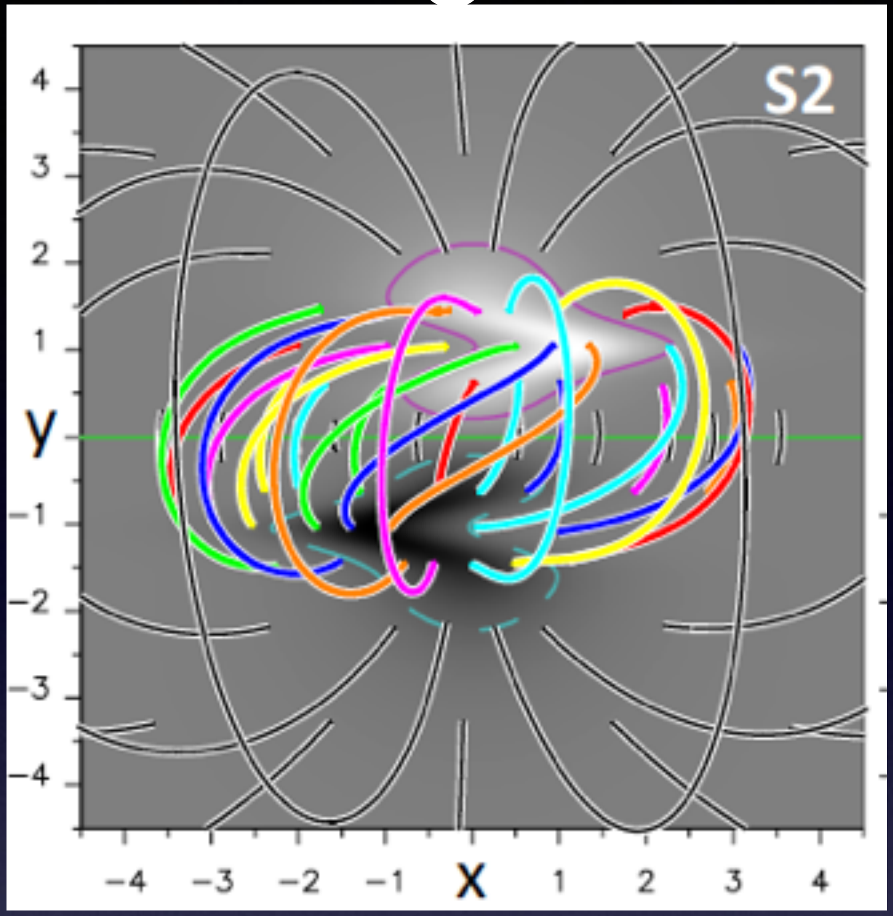
What is the role of magnetic shear?

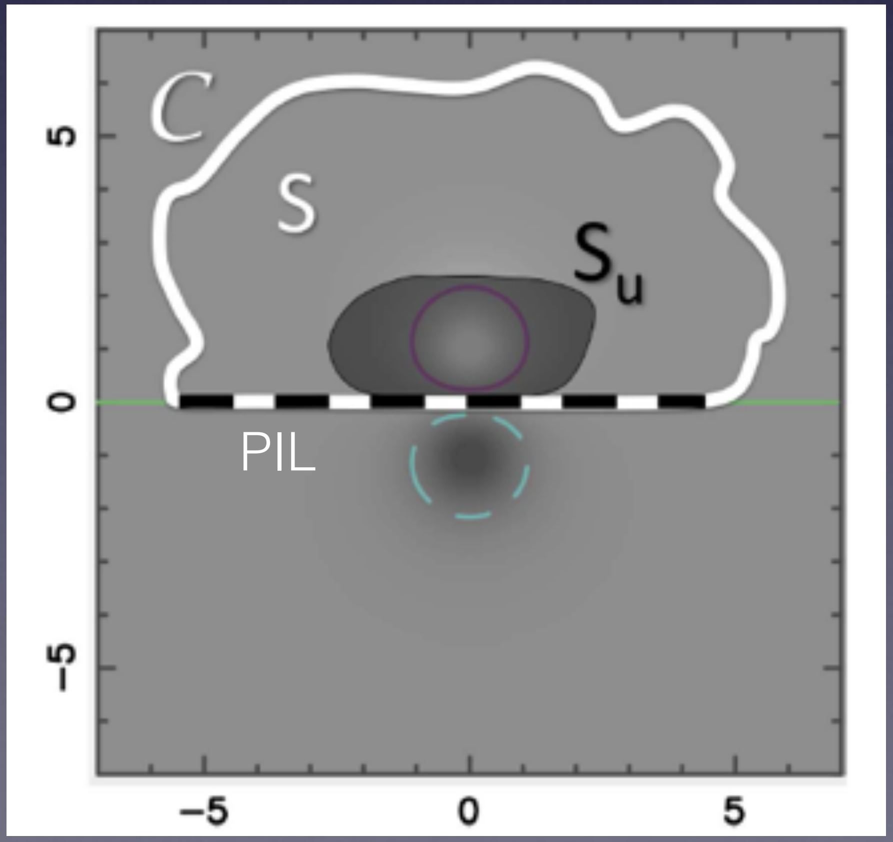
Where do the return currents go?

Insights from coronal modeling

- Dalmasse et al. (2015)
  - Apply various surface motions to generate current in a dipole field
  - More the PIL is sheared, the more non-neutralized the currents



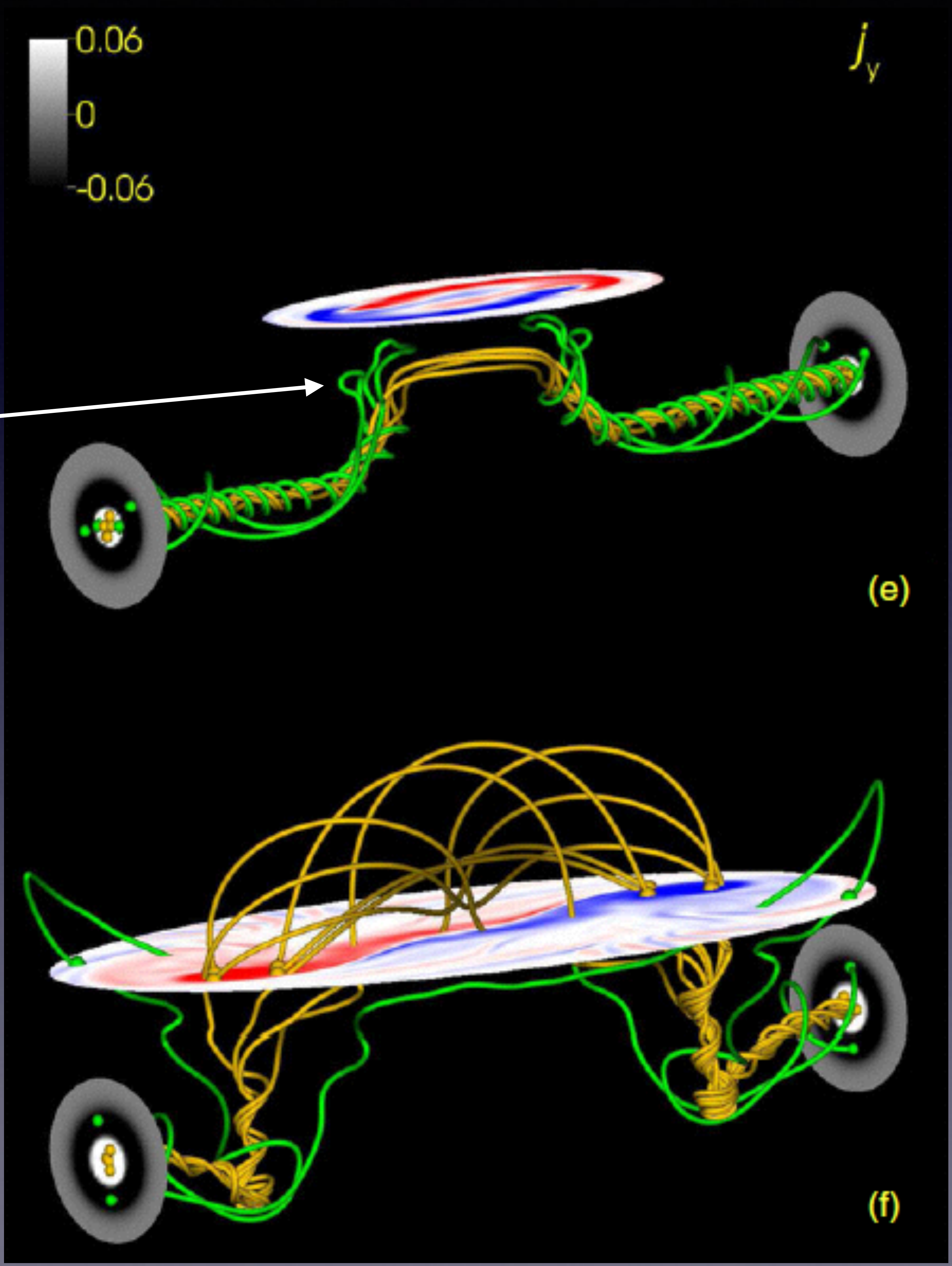




$$I_{total} = \frac{1}{\mu_0}\int_C \mathbf{B}_J \cdot \mathbf{dl} \approx \frac{1}{\mu_0}\int_{PIL} \mathbf{B}_J \cdot \mathbf{dl}$$

Current paths

- Look at connectivity of current fieldlines
- Selected fieldlines originating in regions of direct and return current in CZ
    - See ‘short-circuit’ of fieldlines
    - Direct current mainly follows simple path in and out of corona - thus contributing to direct current Jz calculation
    - Return current forms complicated paths at edge of emerging region
        - can enter and leave corona in same polarity - does not add to return current jz calculation



Contents

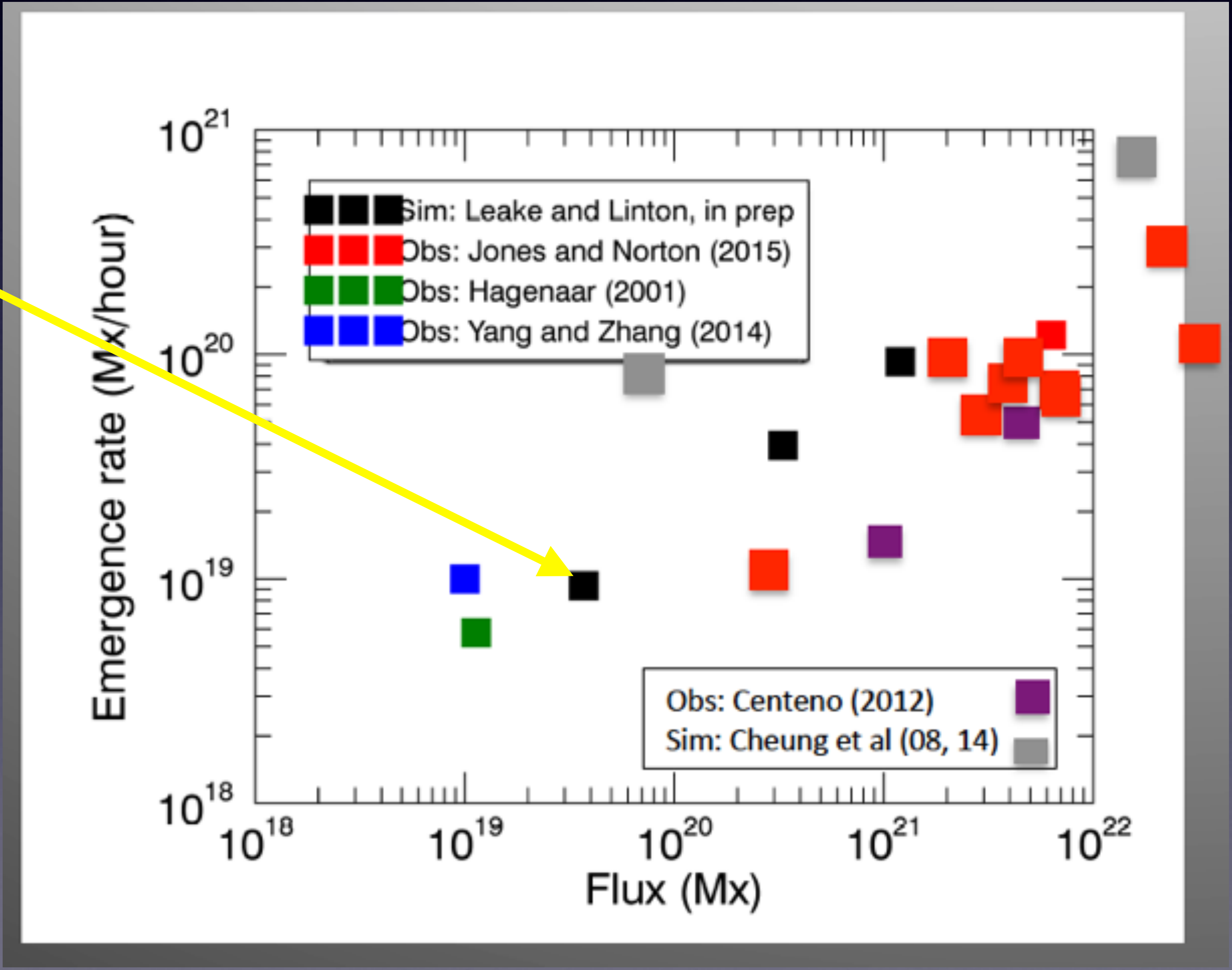
- Background
- MHD Simulations of Flux Rope Formation and Eruption
- Helicity Injection in the Solar Atmosphere
- Electrical Current Balance in the Corona (if time)
- What's next?

New Studies in Progress

- Do the flux rope formation and eruption mechanisms seen in small scale simulations occur on AR scales?

Sims shown today

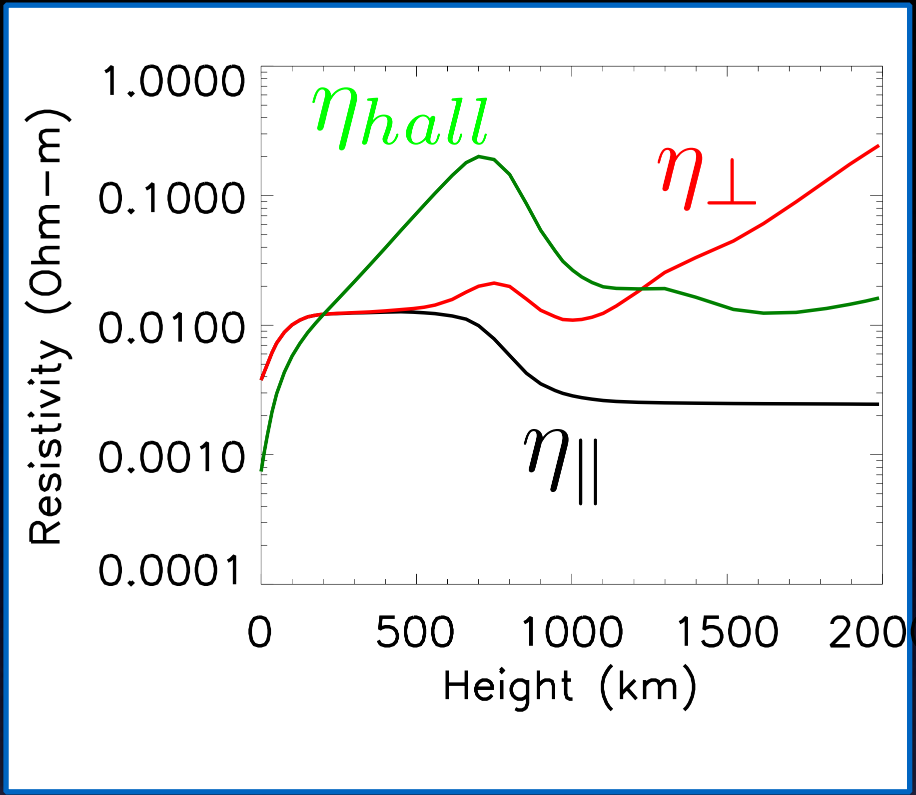
Vary free parameters in model to better match emergence rates, AR fluxes, AR twist

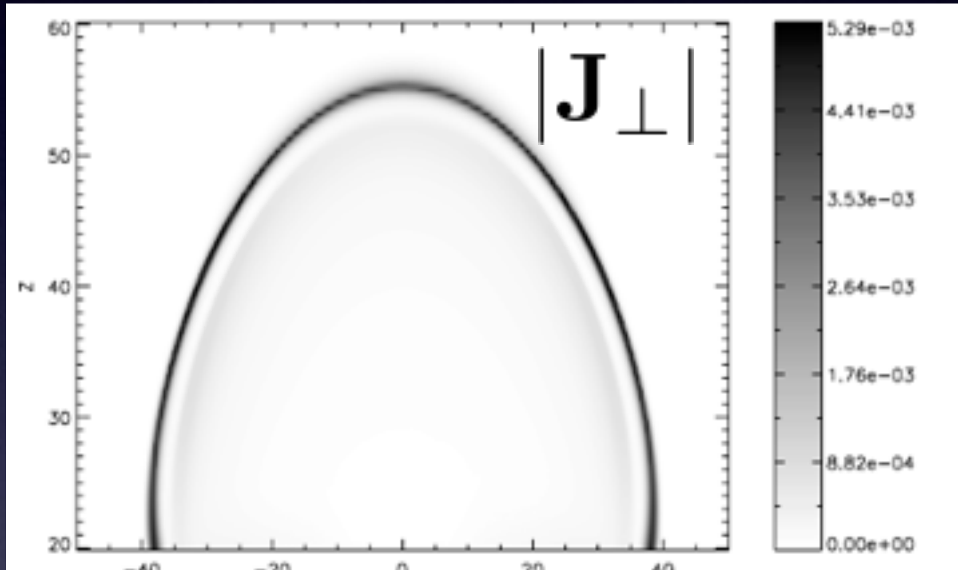


New Studies in Progress

- Chromospheric physics beyond a simple transition from CZ to corona

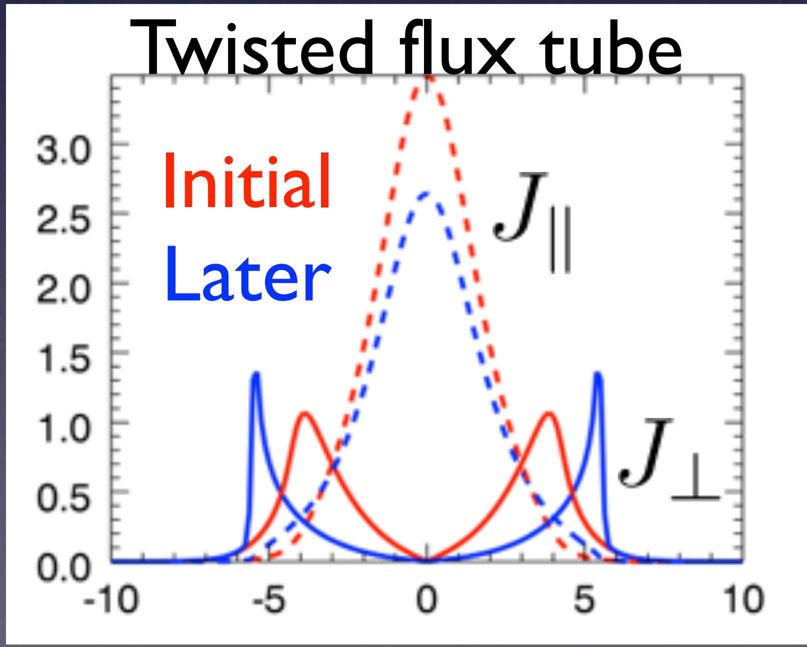
$$\frac{\partial B}{\partial t} = \nabla \times (\mathbf{V}_T \times \mathbf{B}) - \nabla \times (\eta_{\|}\mathbf{J}_{\|}) - \nabla \times (\eta_{\perp}\mathbf{J}_{\perp})$$





Leake at al. (2006, 2013)

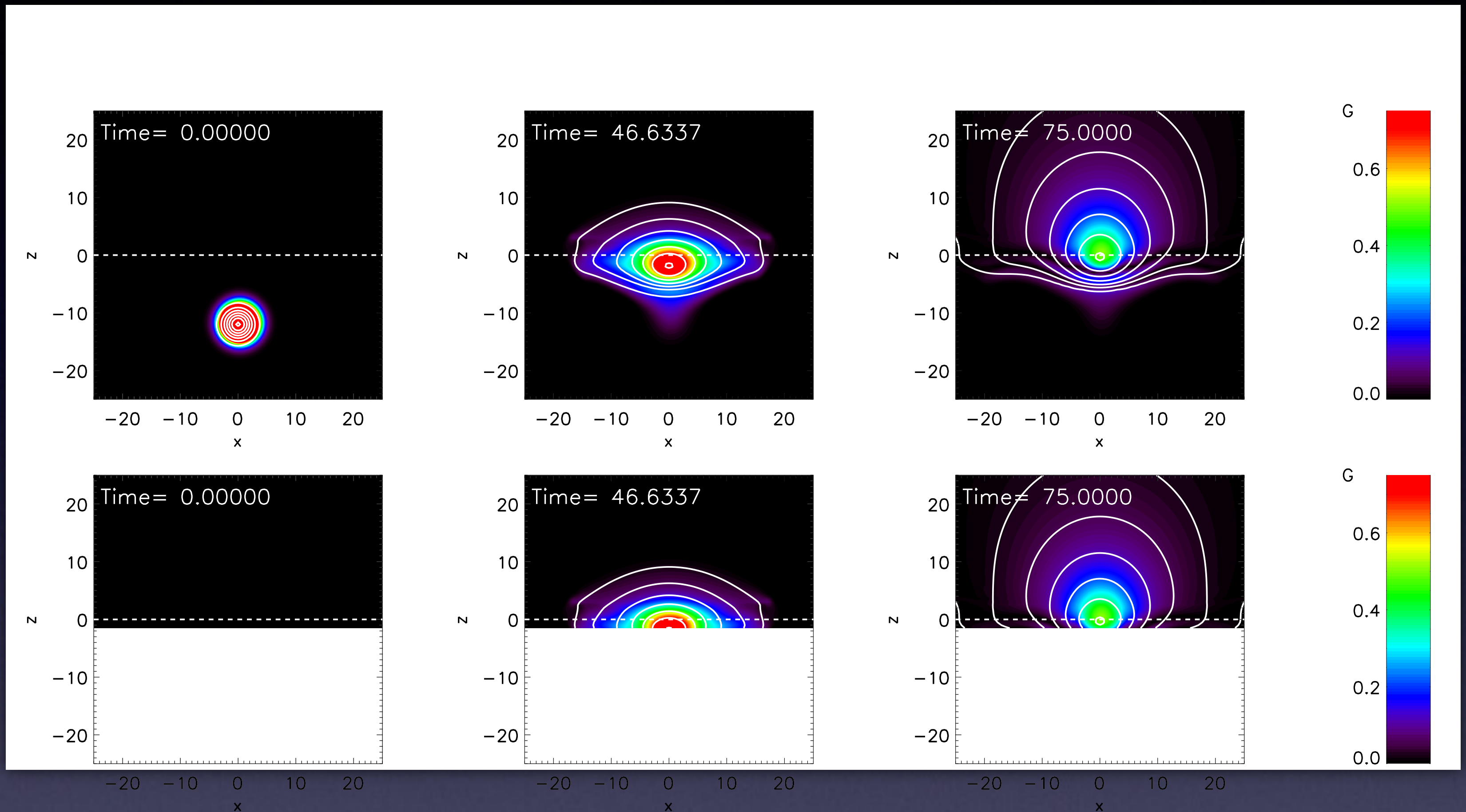
Dissipates cross-field currents



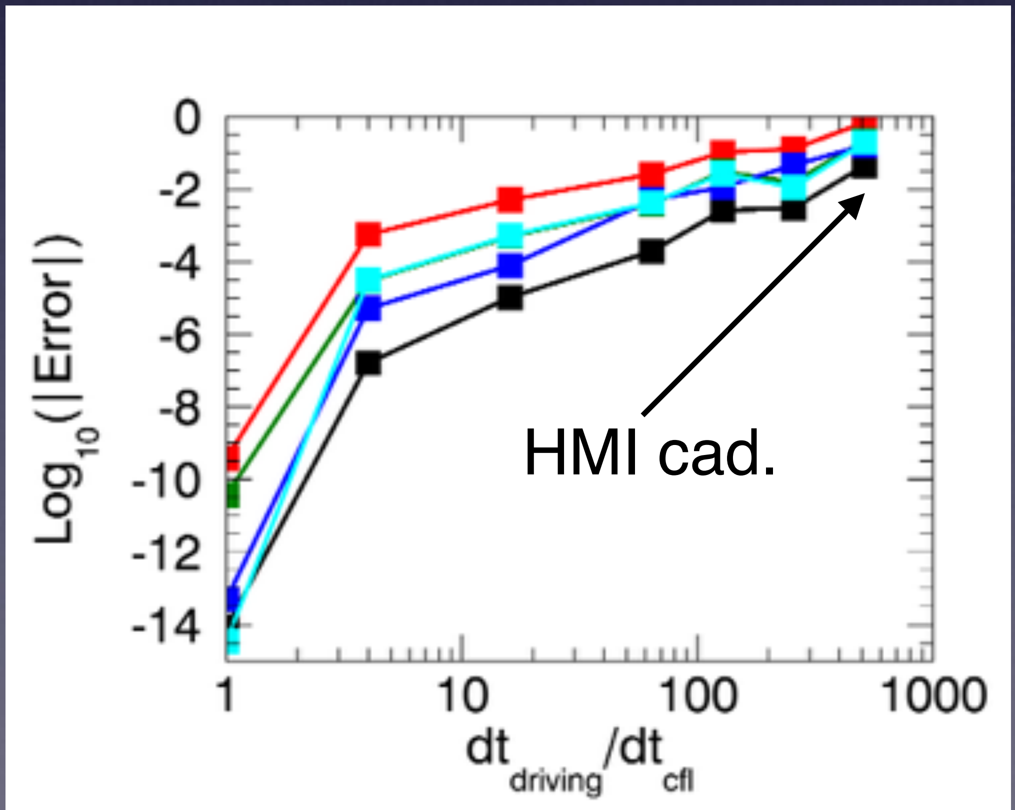
Partial Ionization model needs better treatment of thermodynamics

New Studies in Progress

- Currently have vector magnetic field data at surface from SDO/HMI on 12 min cadence - is it enough?



- Use emergence simulation as ground truth and drive atmosphere only model with surface data at varying cadence

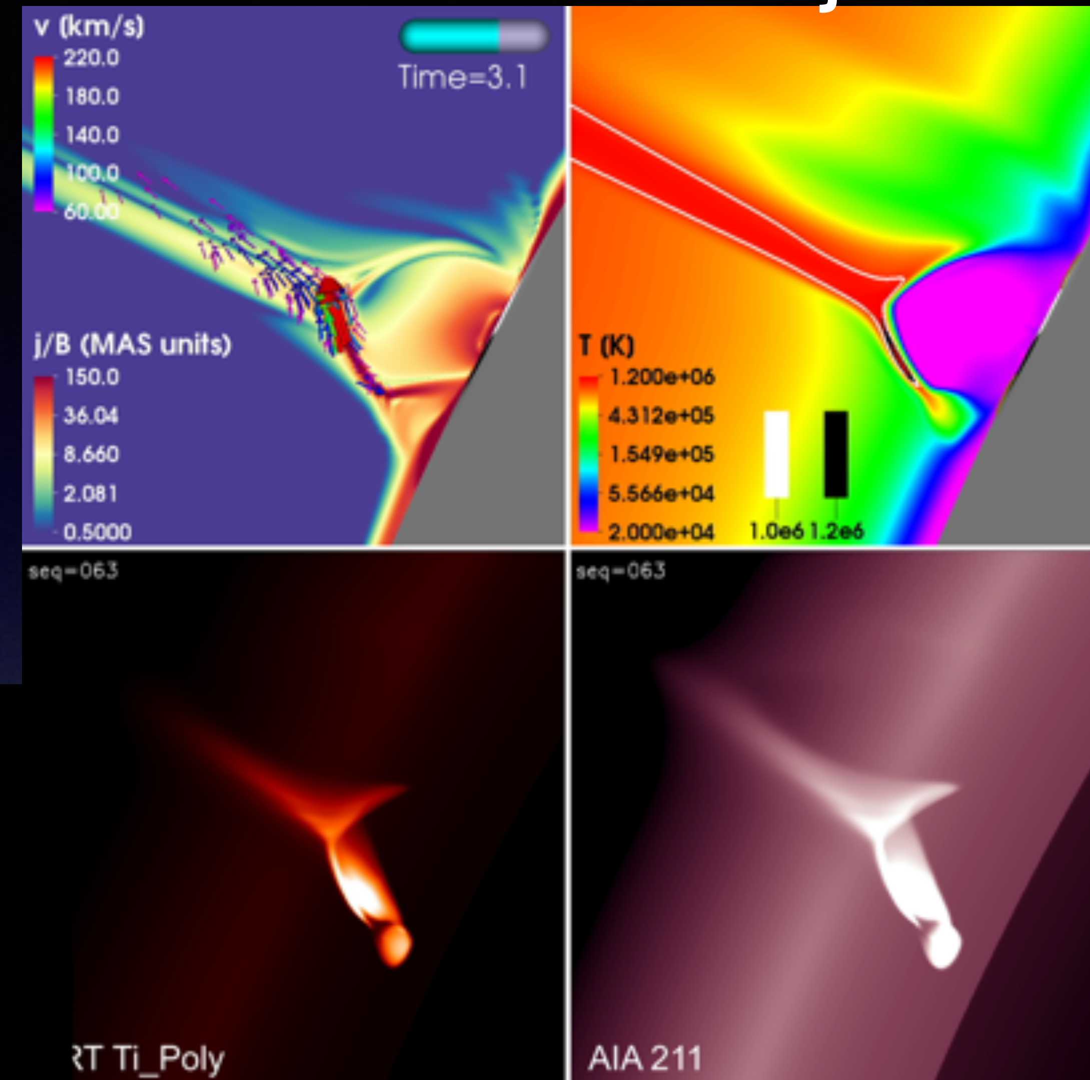


- Use volume integrated errors from Shrijver paper comparing NLFFF extraps
- Errors using HMI cadence can be ~10%
- Where are the errors - in free energy?

New Studies in Progress

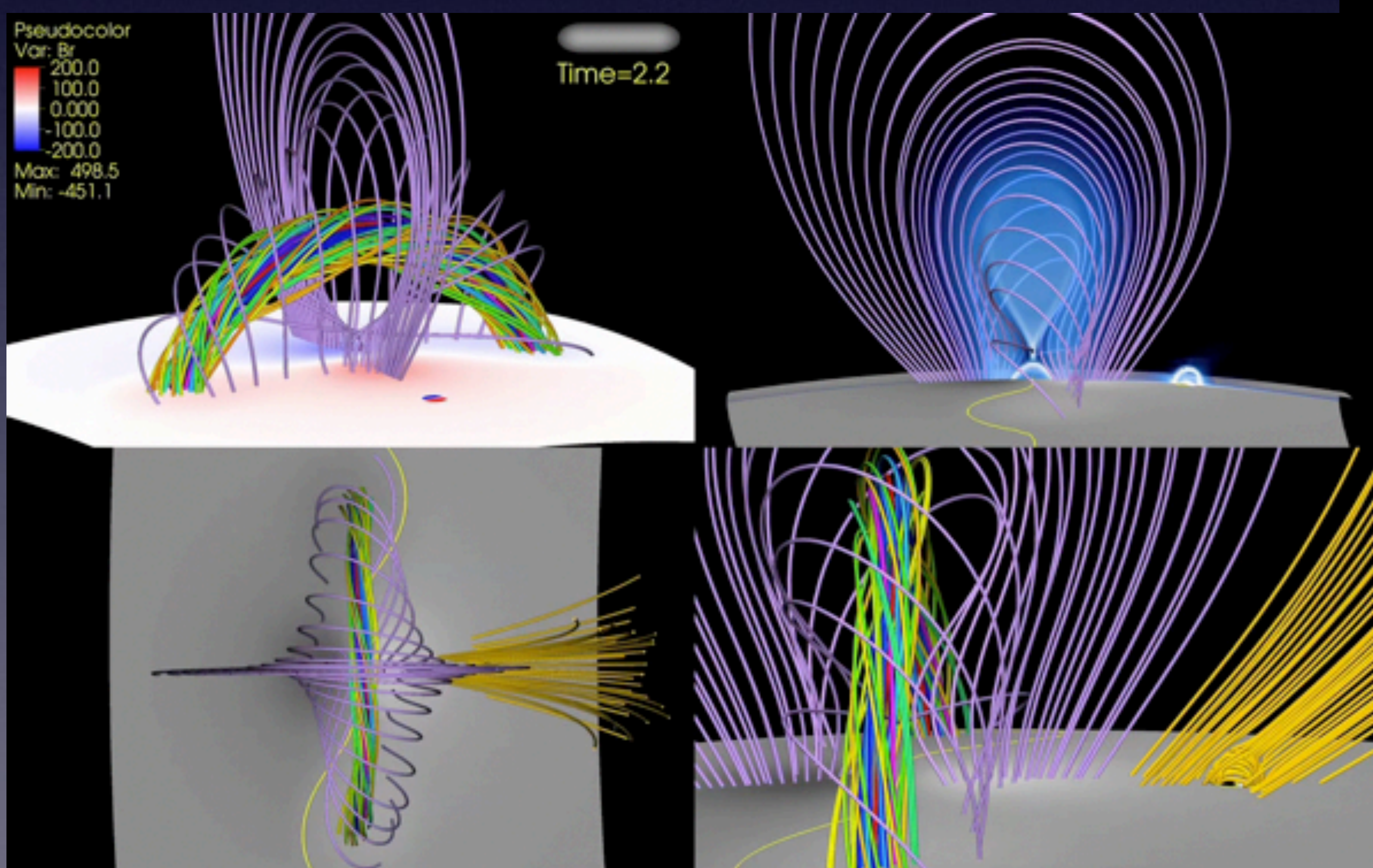
- Driving coronal models with data from our flux emergence simulations

jets



Török et al. in prep

CMEs



Summary

Though idealized, flux emergence simulations can help us learn a lot about the energization of the corona and how eruptions occur

Improving the realism (scales, chromospheric physics, thermodynamics) is necessary to fully utilize them to understand observations