The non-neutralization of electric currents in active regions: Insights from numerical simulations

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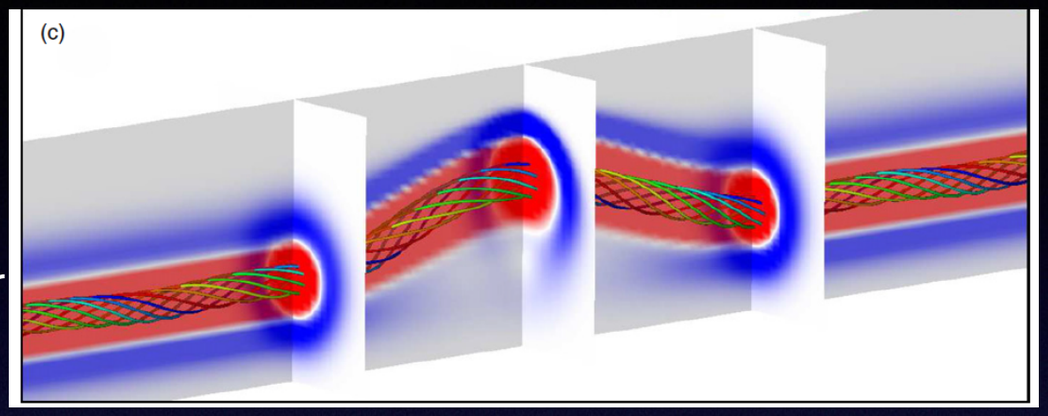
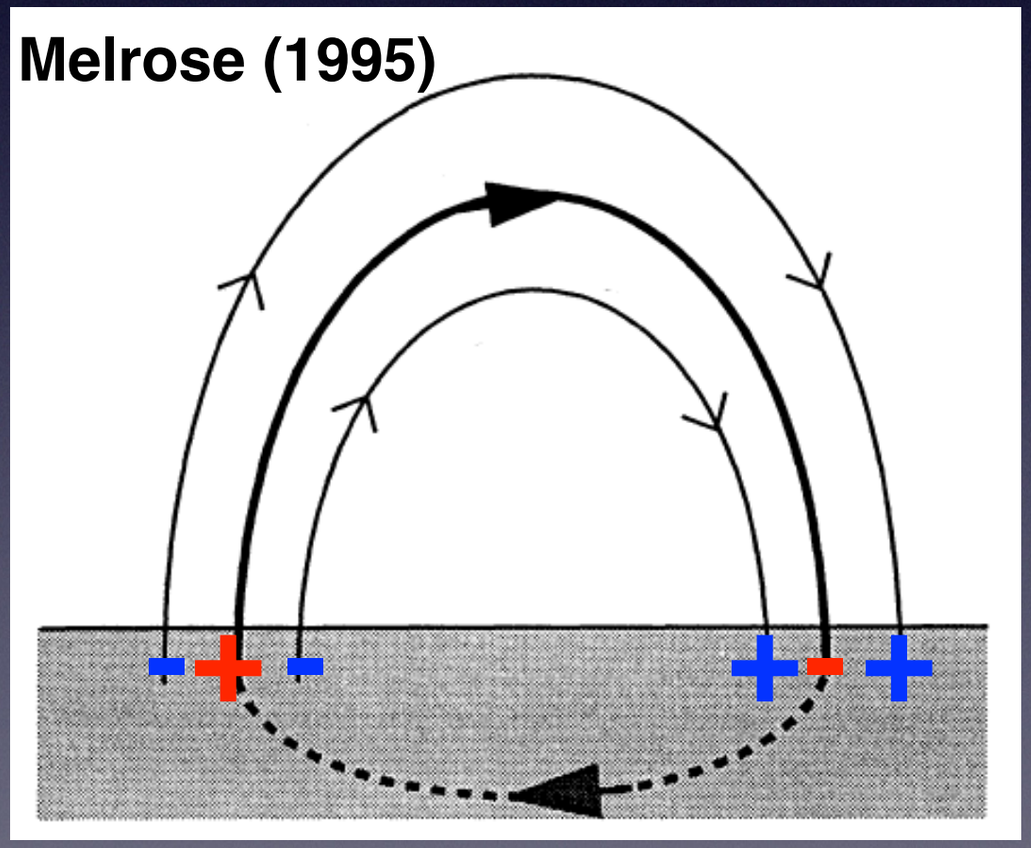
Motivation and Theoretical Considerations

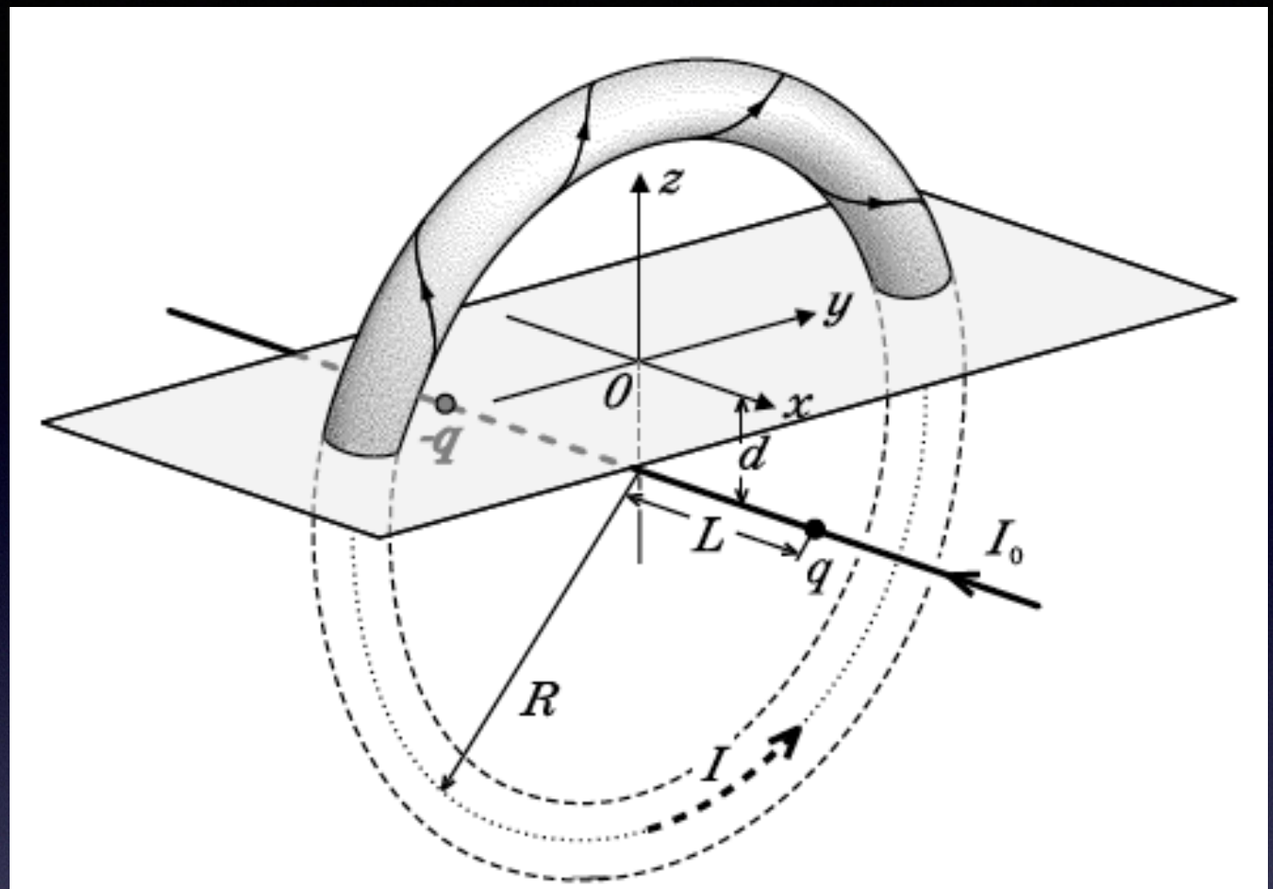
- AR currents (J=curl(B)), the source of CME/flare energy, are believed to be created by
  - stressing of coronal magnetic field
  - emergence of current carrying flux from interior
- Melrose argued that currents in corona cannot be generated by shearing motions, but must close in the interior
- Faraday's 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.

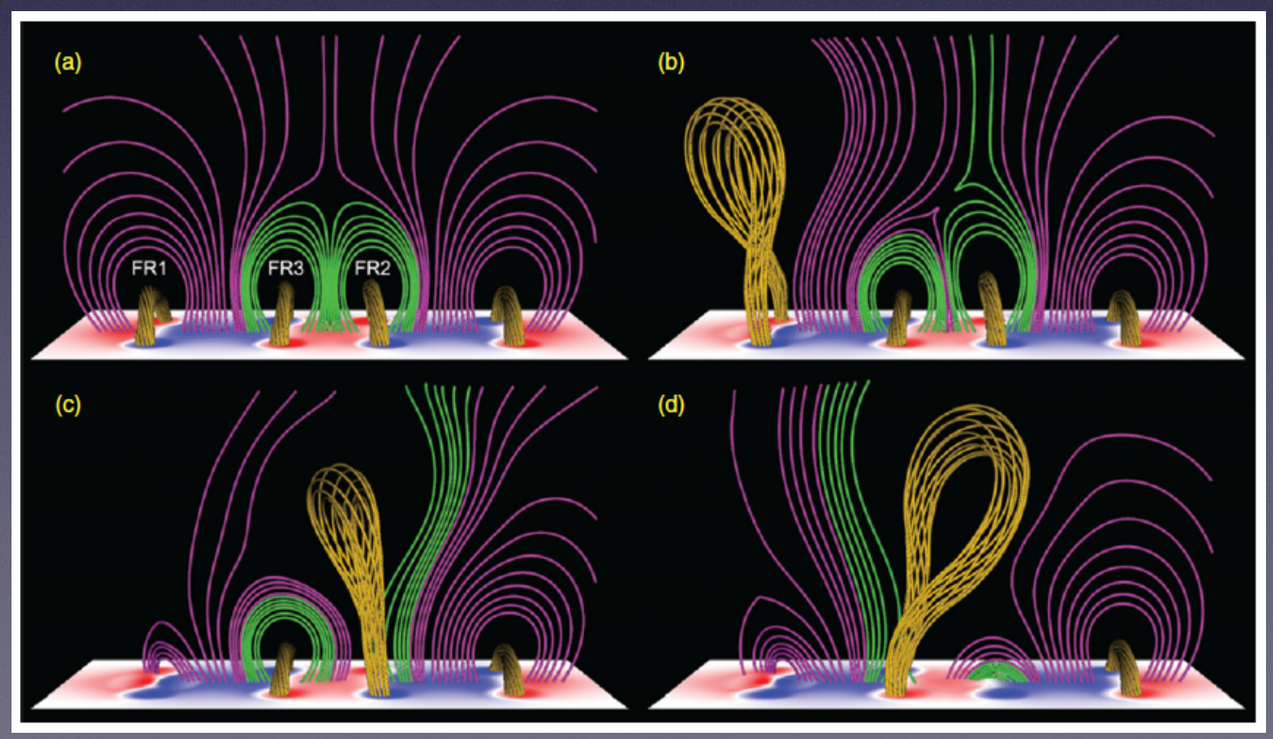




Motivation and Theoretical Considerations

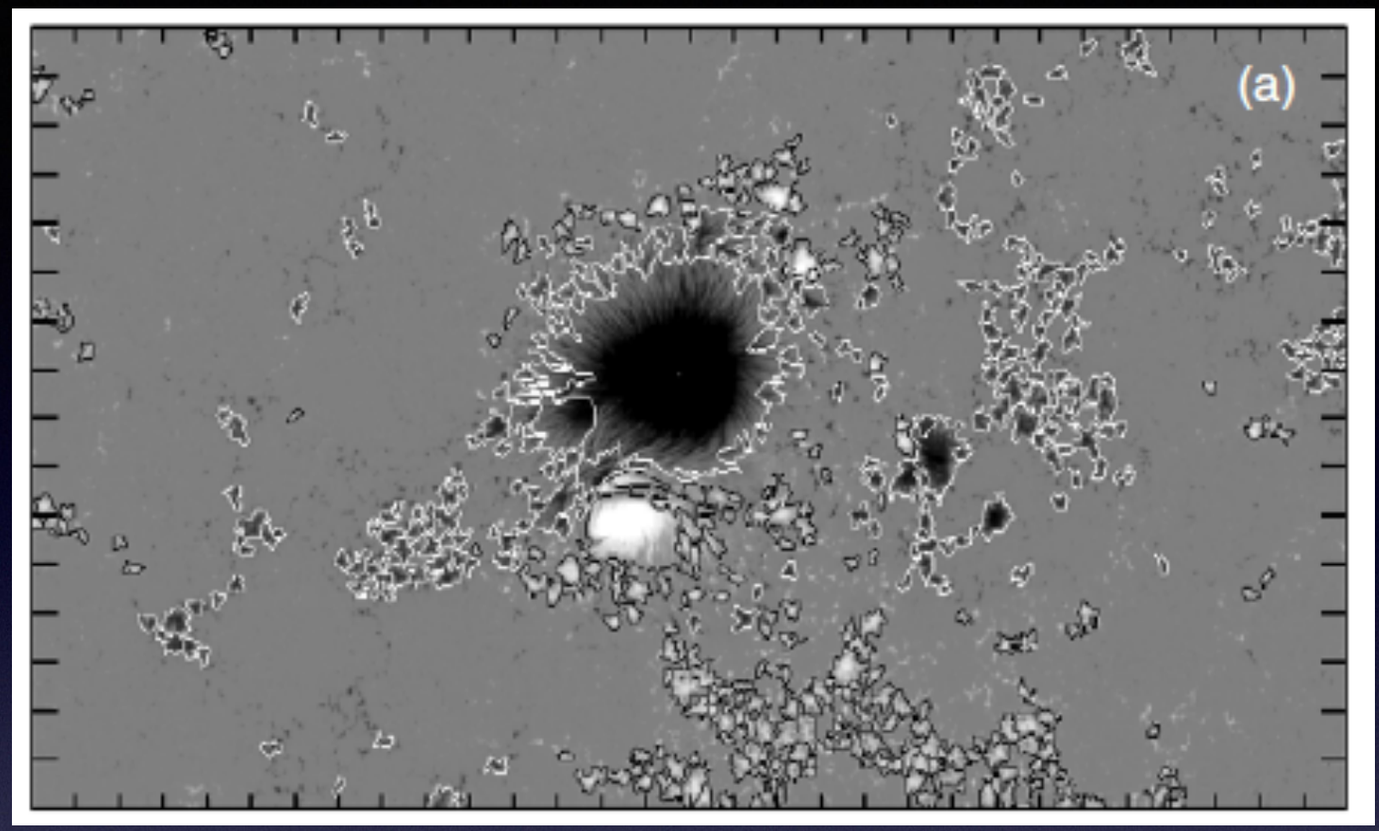
- Why should we care ?
  - The subject of electric current neutralization has lead to lively debate (not now) about:
    - the nature of coronal flare energy storage and energization
    - how to describe time-dependent coronal system (V,B vs E,J) - Leake et al. SSRv (2014)
  - Successful theoretical/numerical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

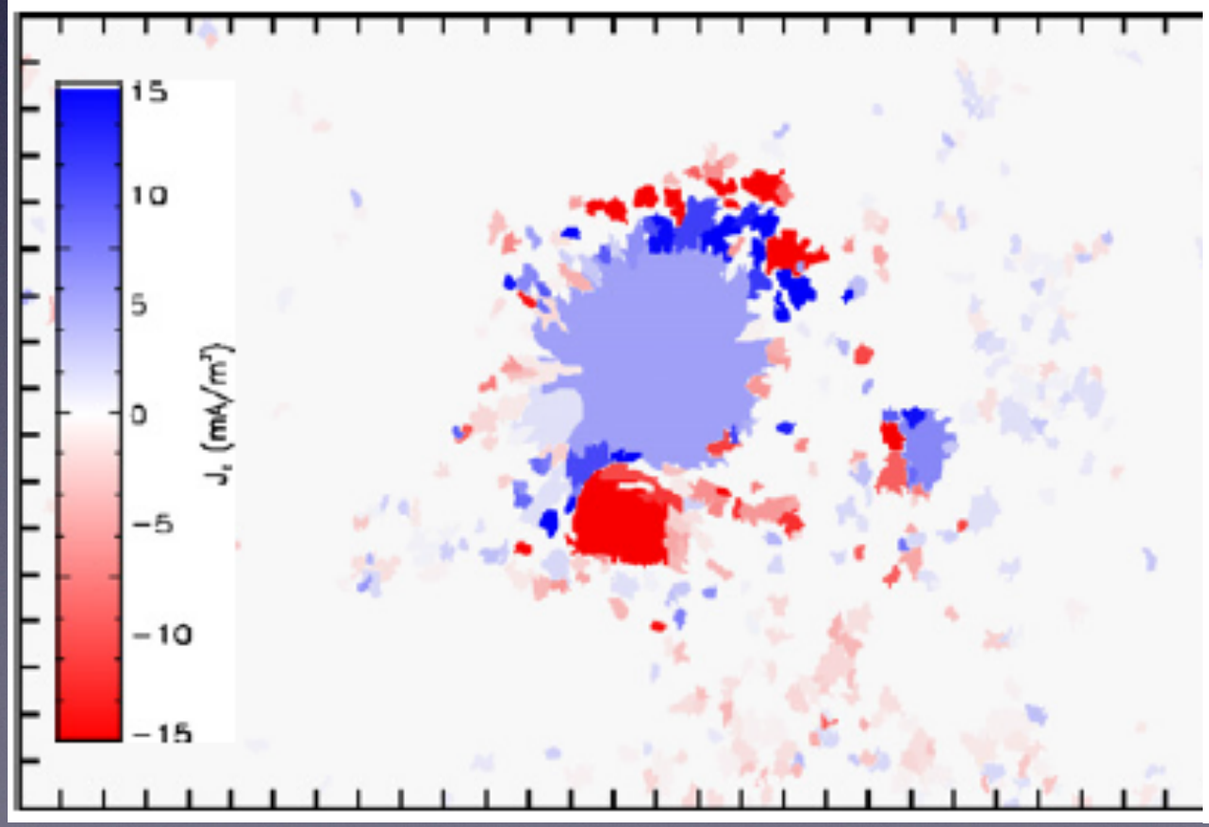


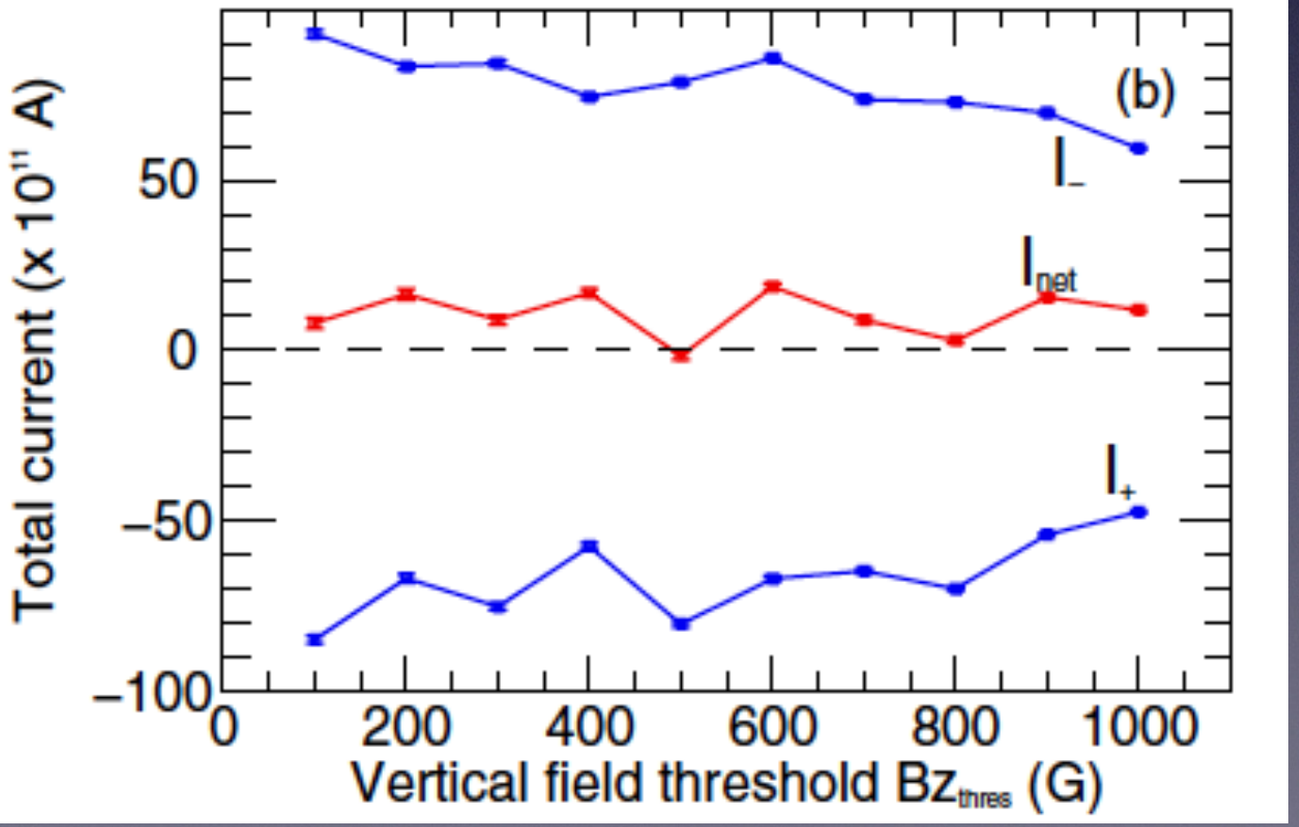


Observations: Flare region

- 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

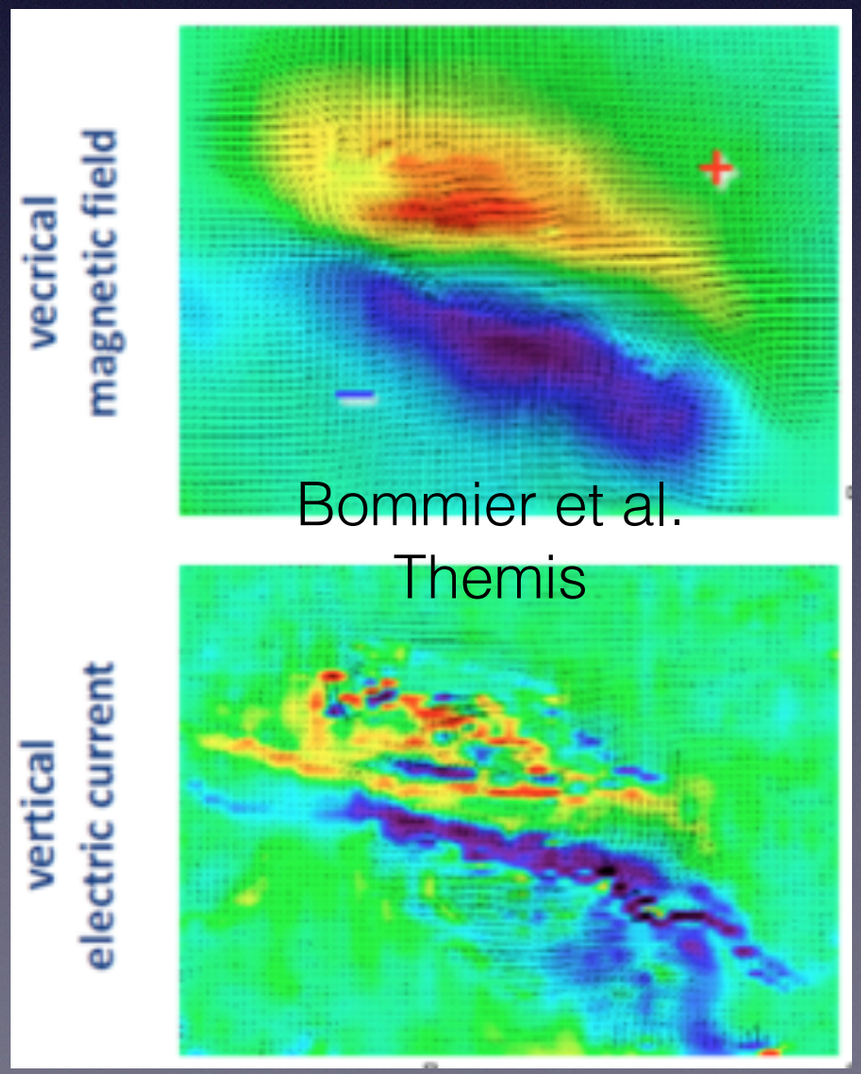




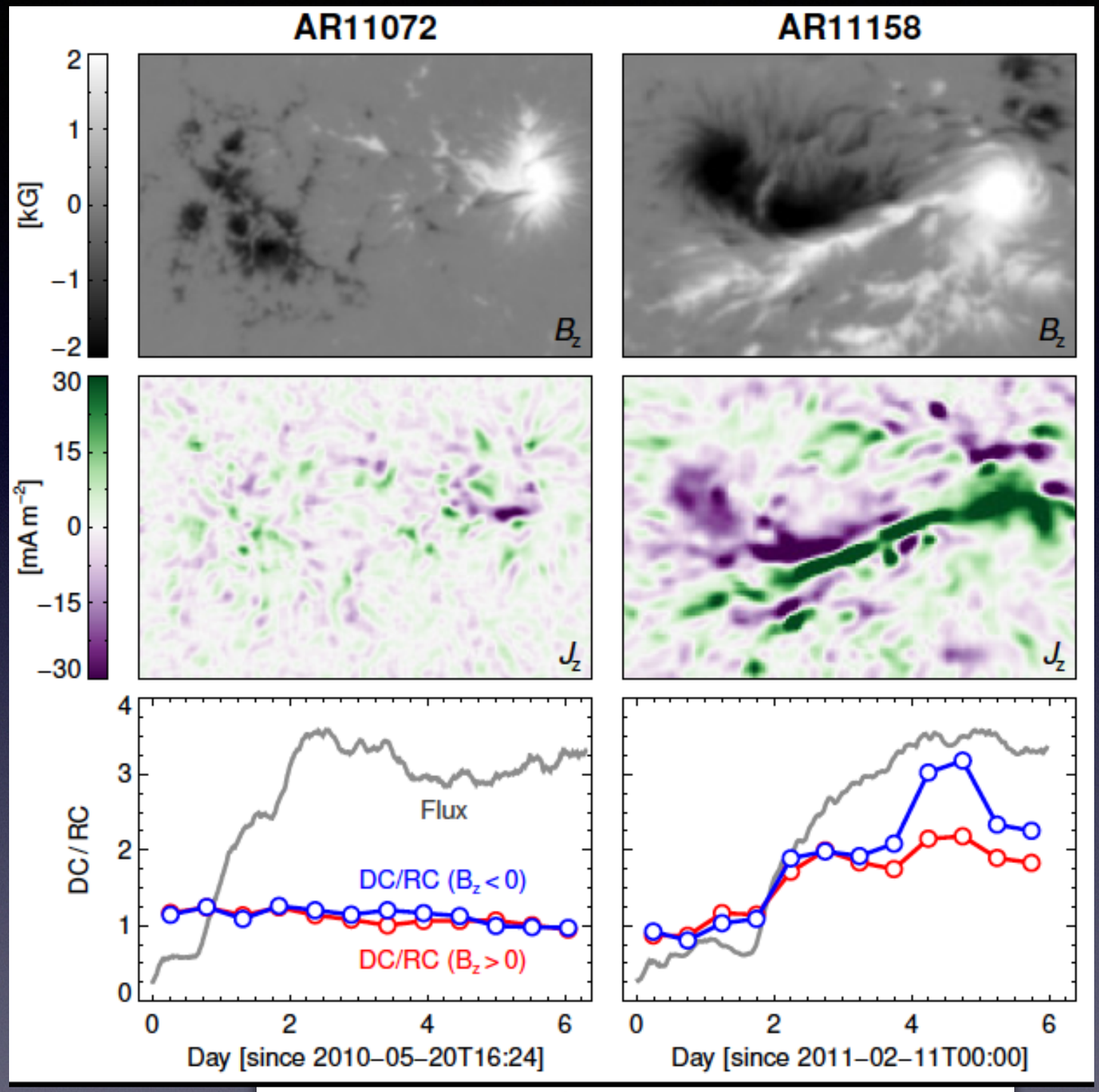


Observations: AR 11072 and 11158

- 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

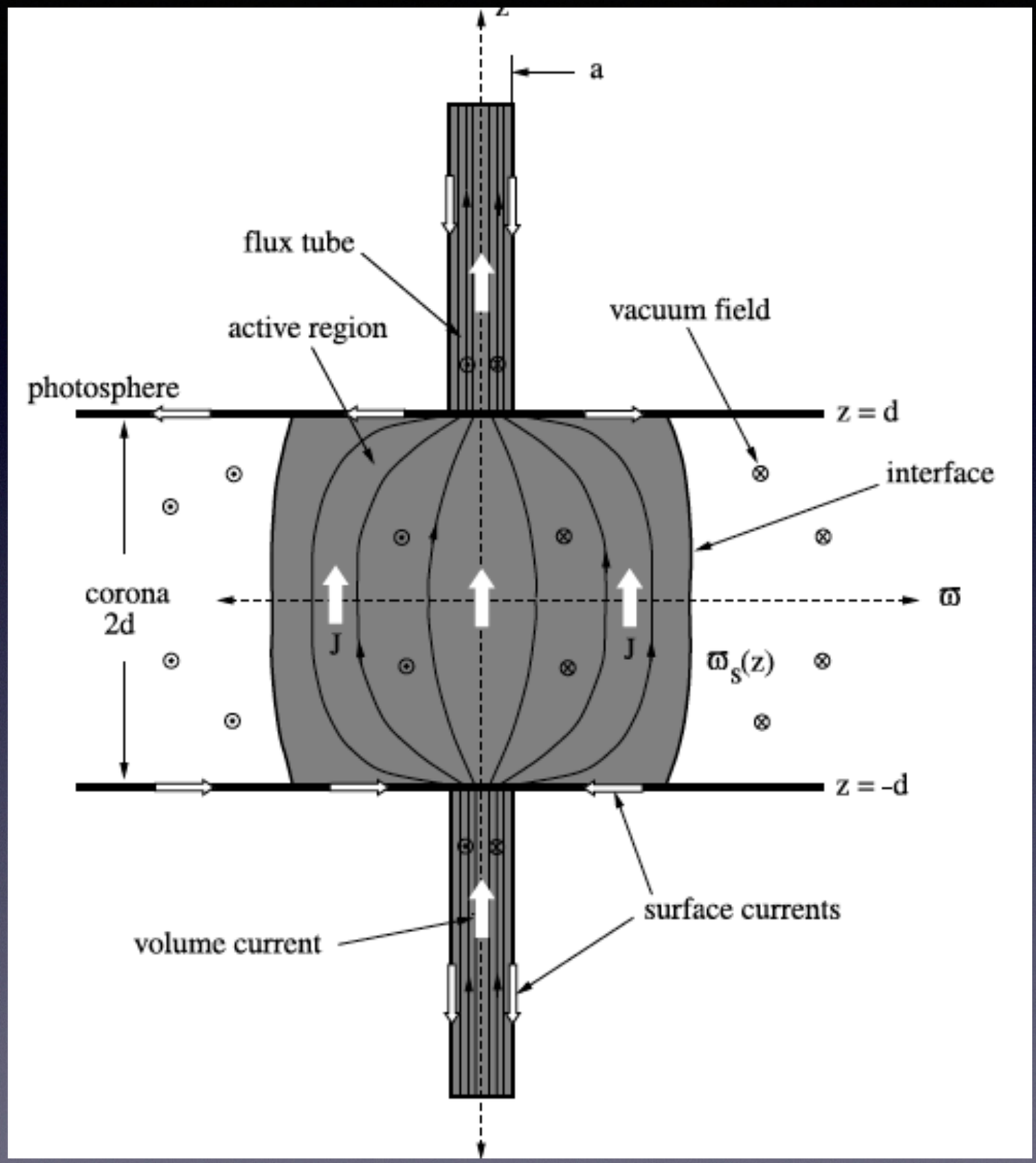


$$DC = \int J_z|_{(JzBz>0)} dA$$

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

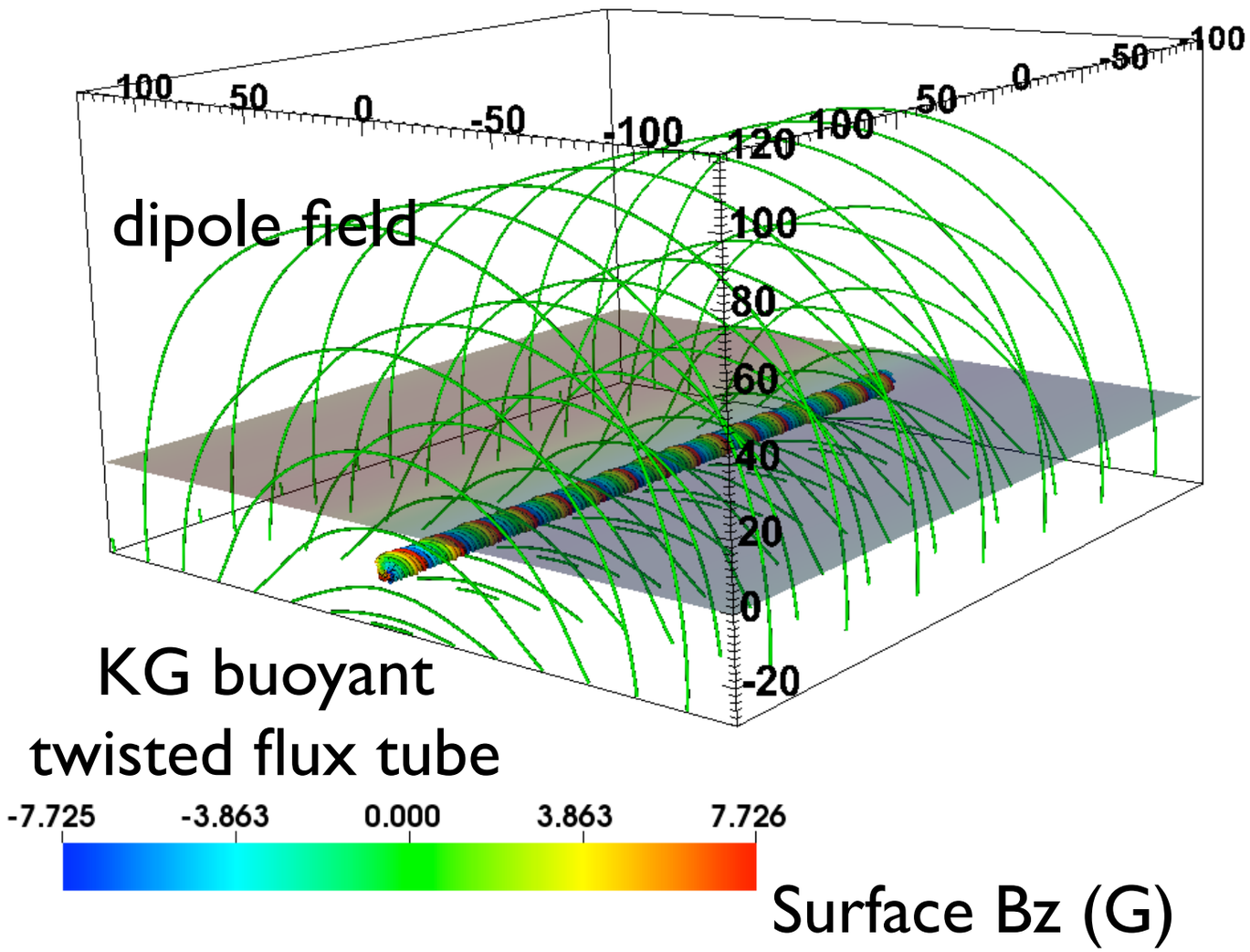
Early Model for flux tube emergence

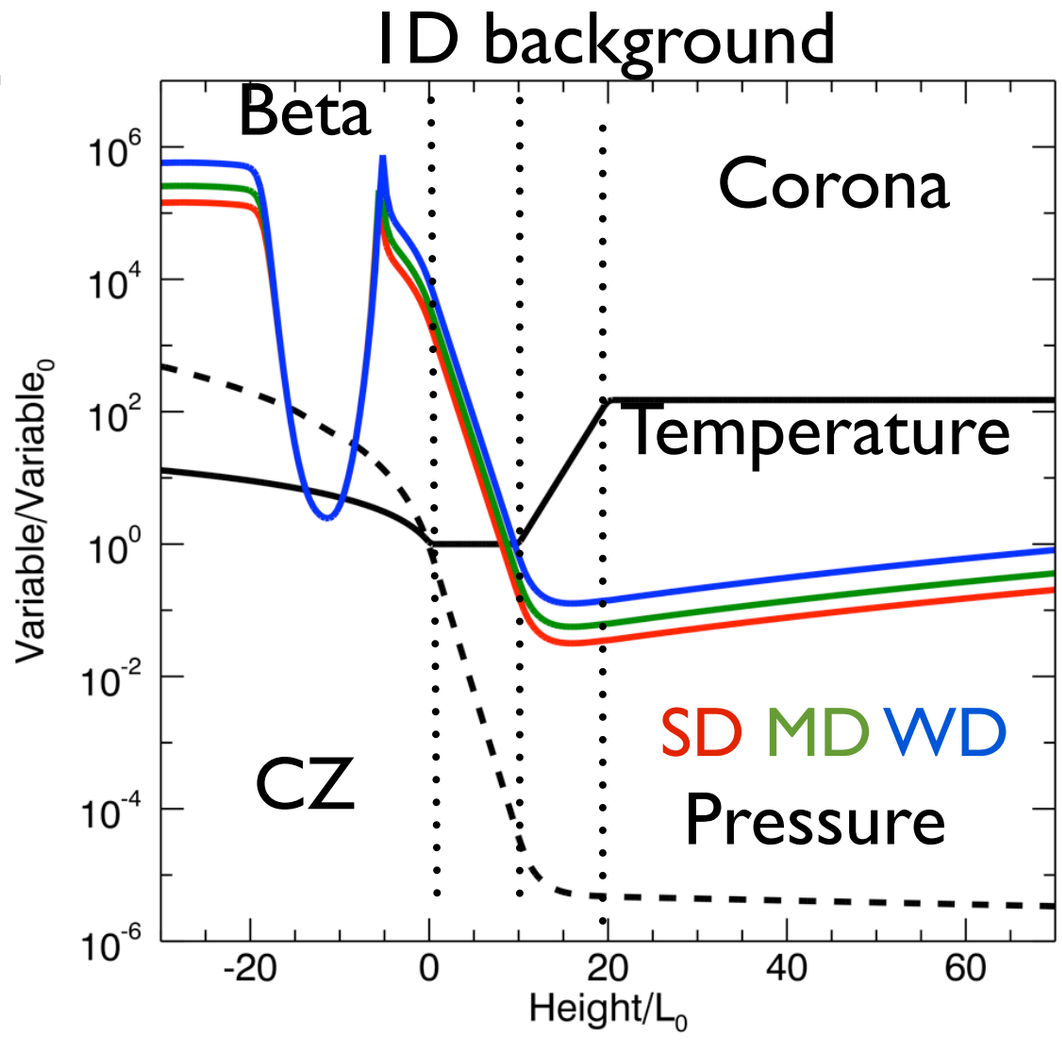
- How can we get non-neutralized atmospheric currents from neutralized interior flux structures?
- Longcope and Welsch (2000)
  - Twisted flux tubes emerges into field-free corona
  - Initially, no twist emerges
  - Launches Torsional Alfven wave which twists up the coronal field
  - Return currents 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

Leake at al. (2013,2014)

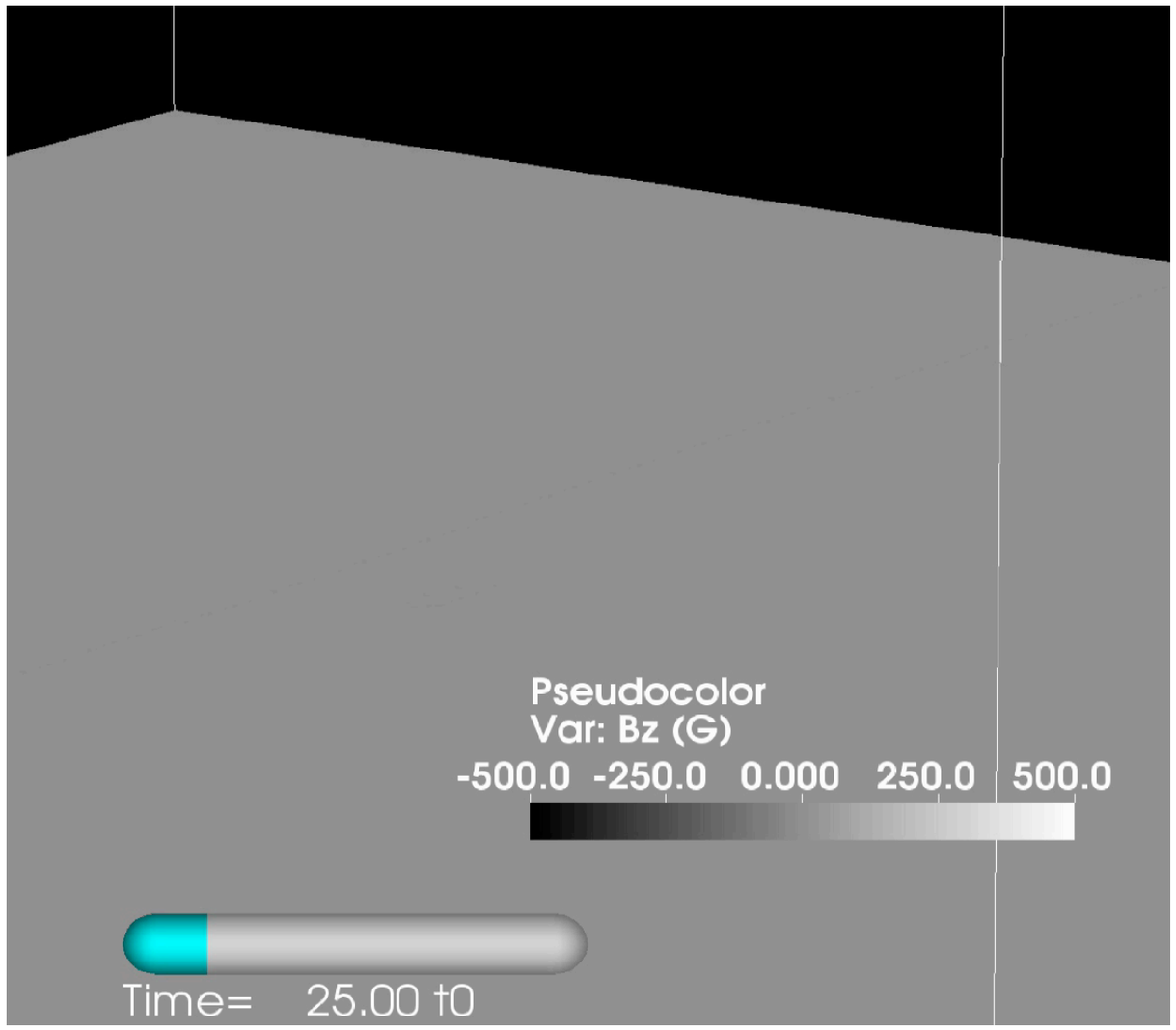


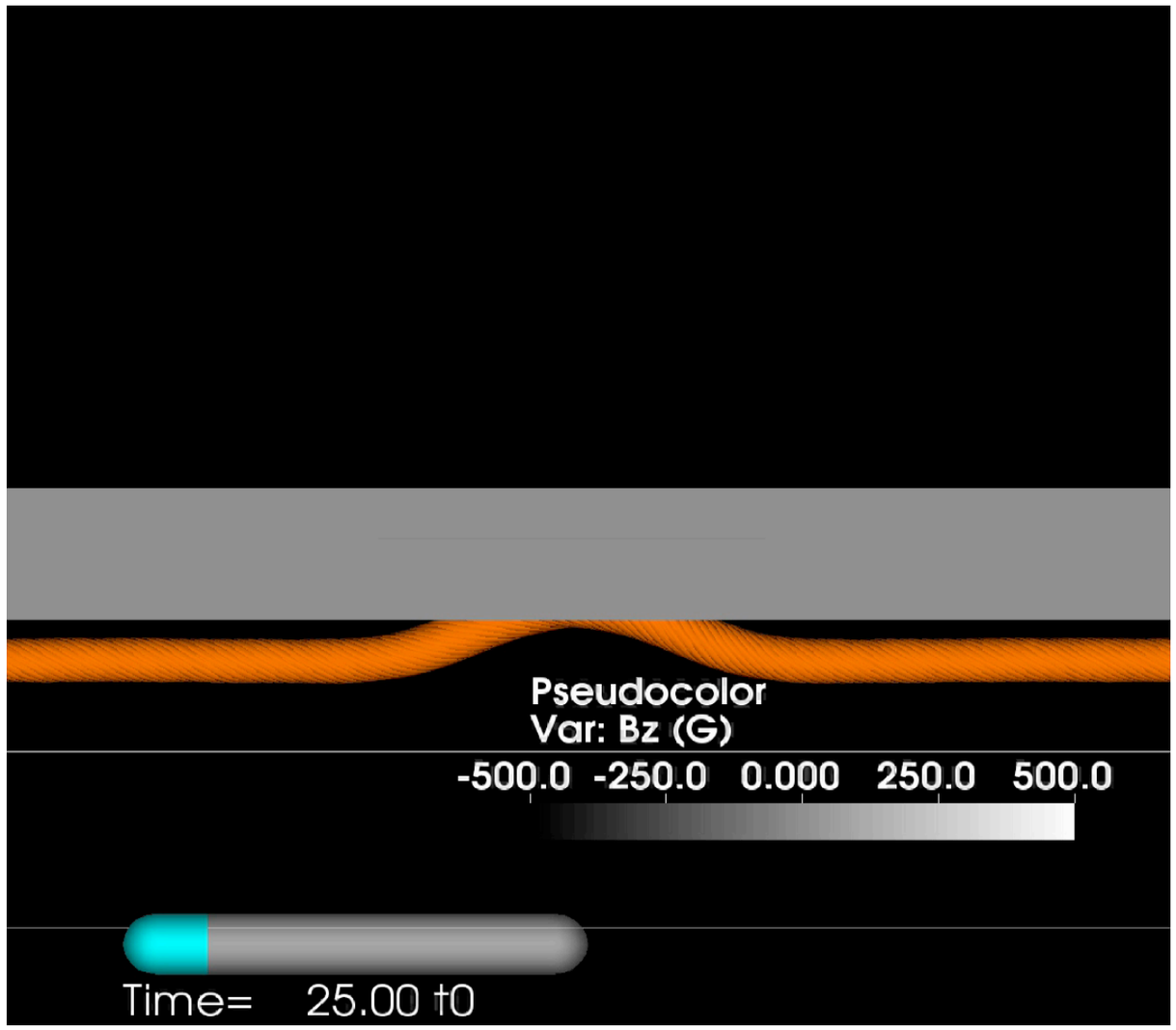


Magara 2003, 2006, Manchester 2004, Archontis et al. 2004, 2012, Fan 2001,2009, Fang 2010

Vary dipole strength - Strong (SD) Medium (MD) and Weak (WD)
Vary dipole orientation

Simulations of flux tube emergence





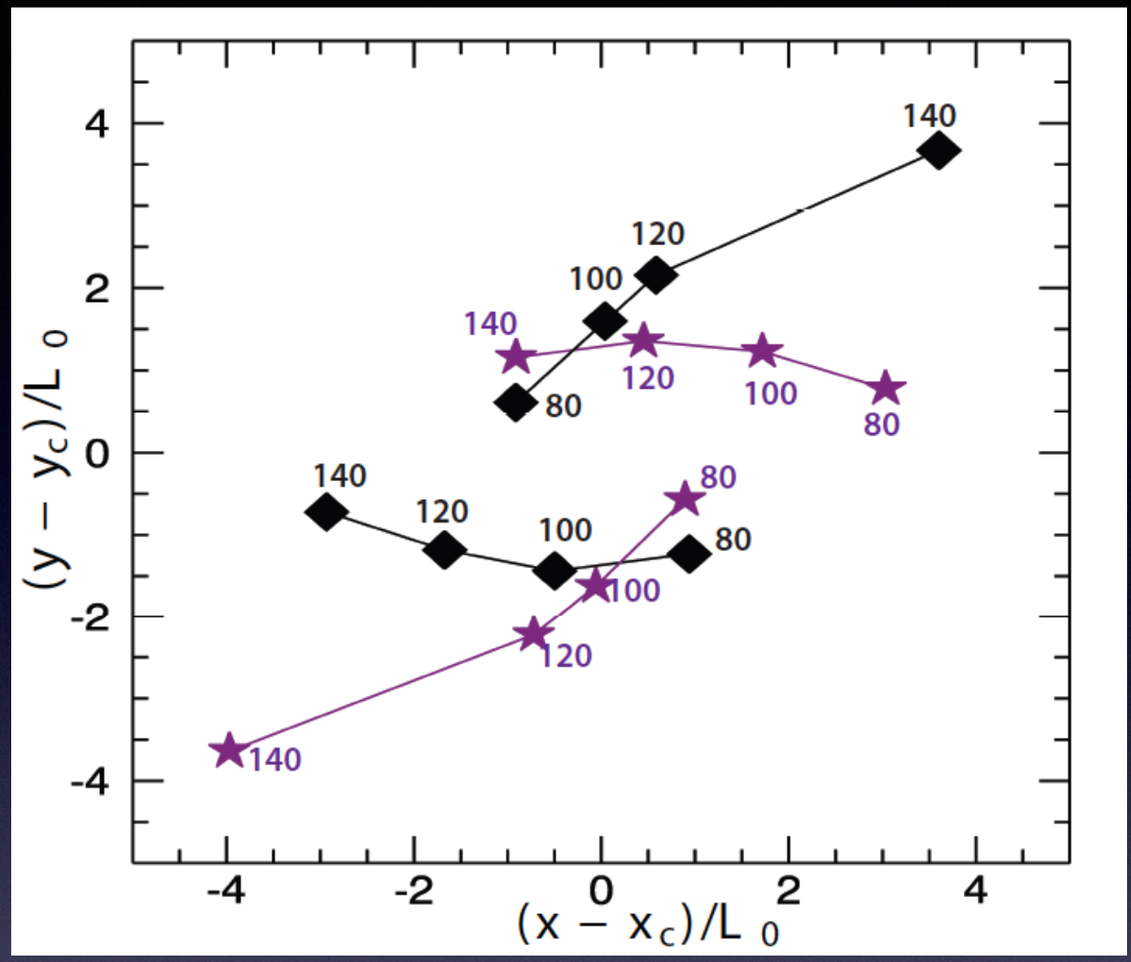
$t<100\ t_0$: emerging flux tube has little interaction with dipole

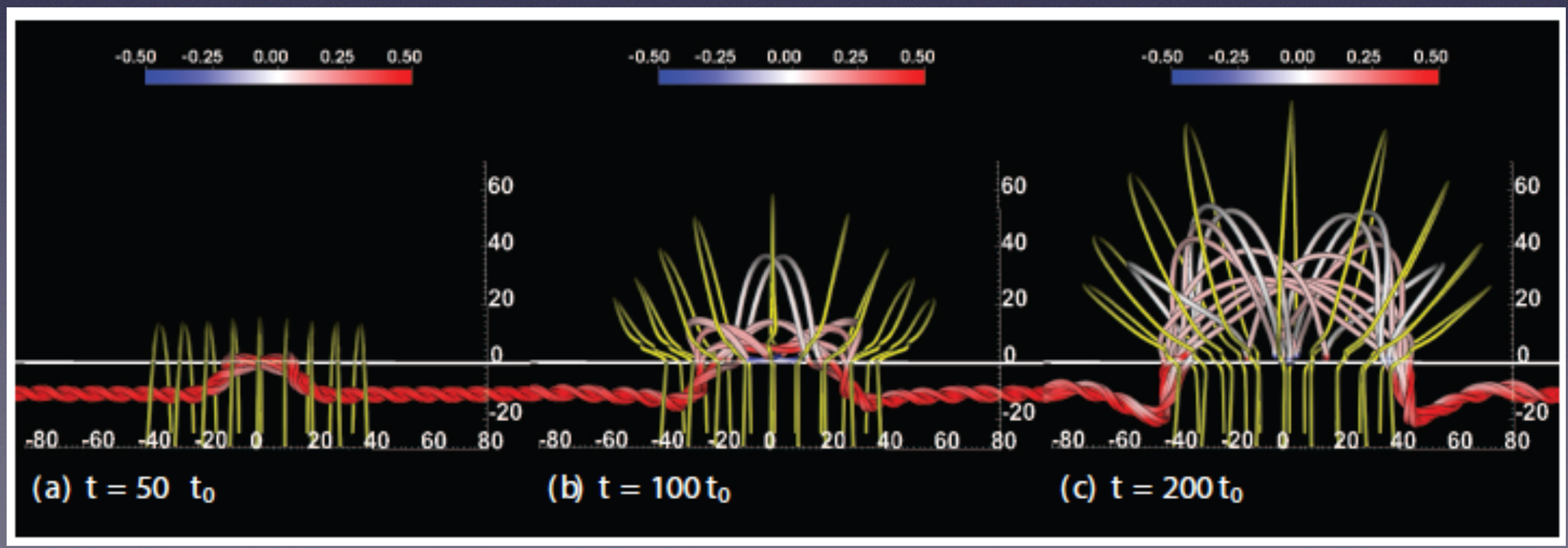
Partial flux tube emergence accompanied by shearing and rotational motions on surface (Manchester 2004, Fan 2009)

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

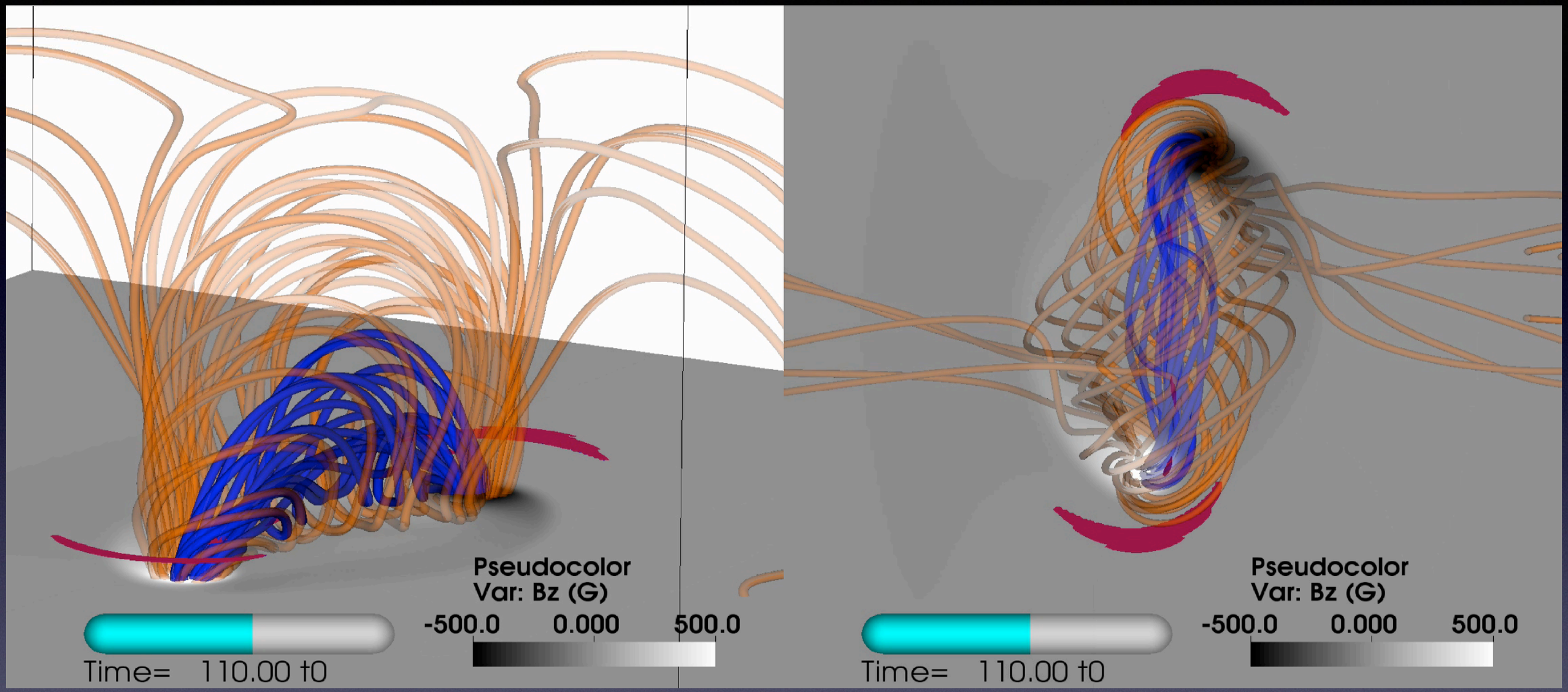
Simulations of flux tube emergence

Source of rotation: propagation of twist into corona - Sturrock's talk at this meeting, Fan (2009), Manchester (2004), Longcope and Welsch)





Simulations of flux tube emergence



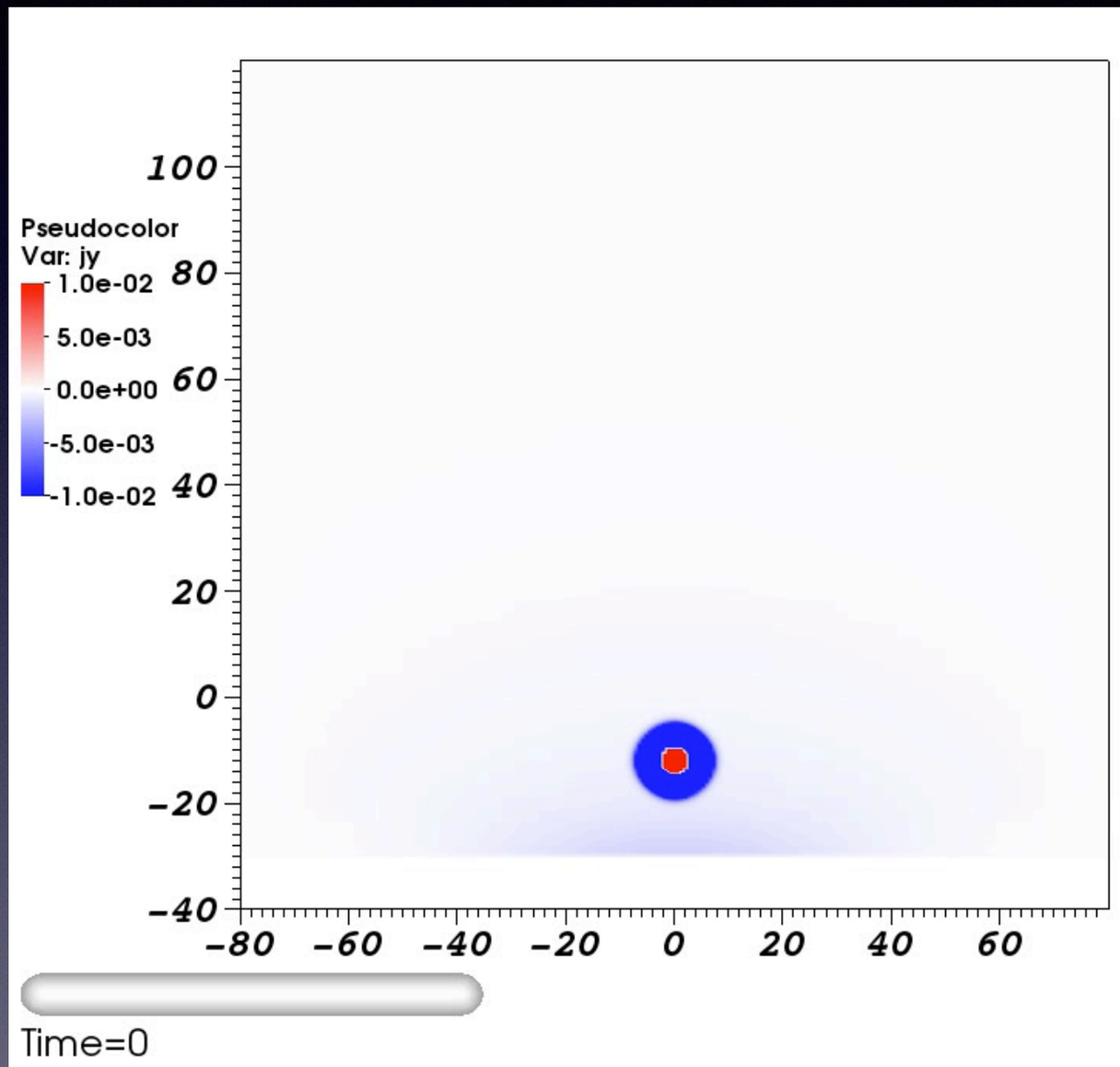
Vertical expansion of B field (aided by reconnection above) creates vertical currents.

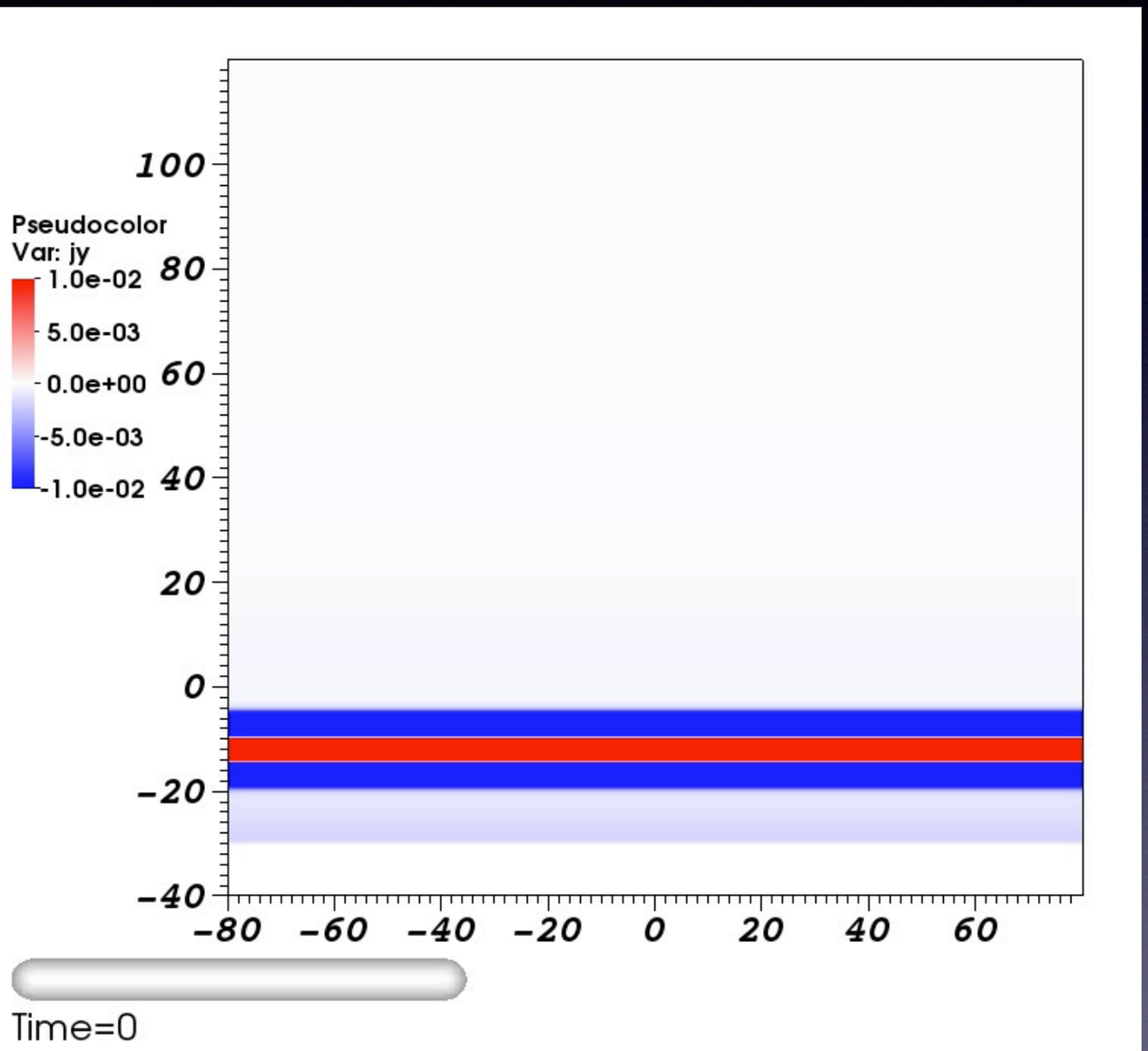
Current density ribbons. Two J-shapes become S-shapes - sigmoid

Internal reconnection of emerging arcade creates new distinct flux rope in the corona (Archontis, Fan, Manchester, Mactaggart, Hood)

Simulations of flux tube emergence

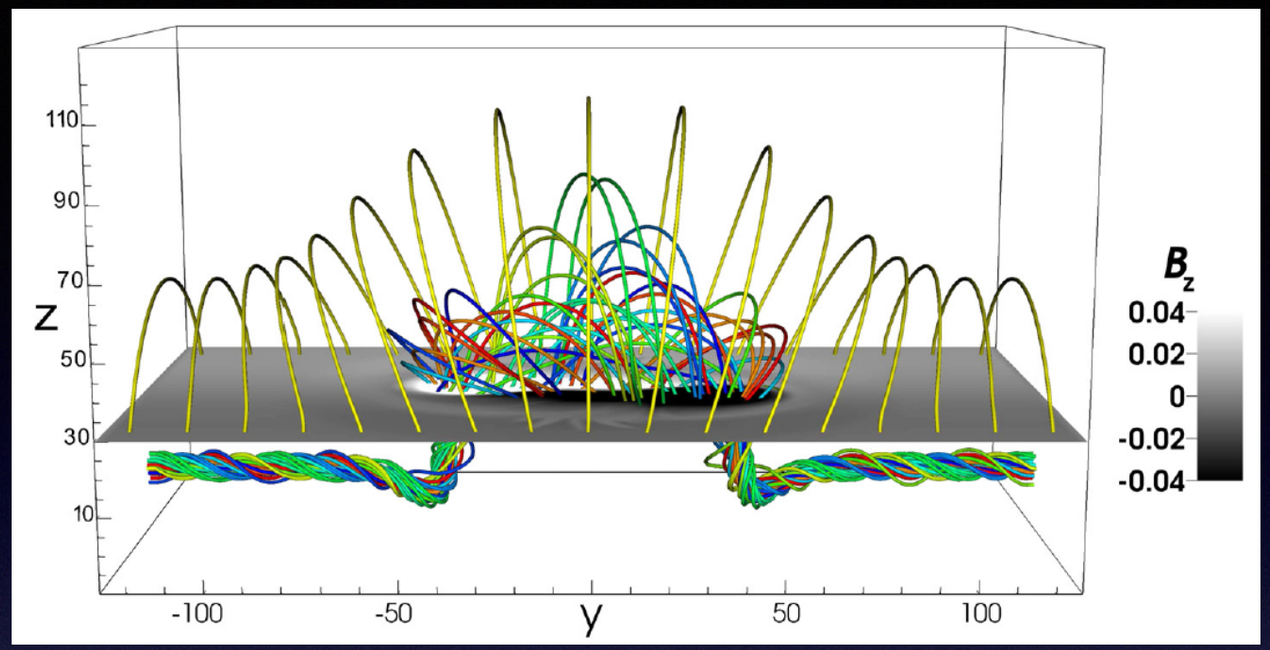
Key feature is flux pile up near surface before emergence
Top of tube emerges first, later emergence builds up current in corona





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

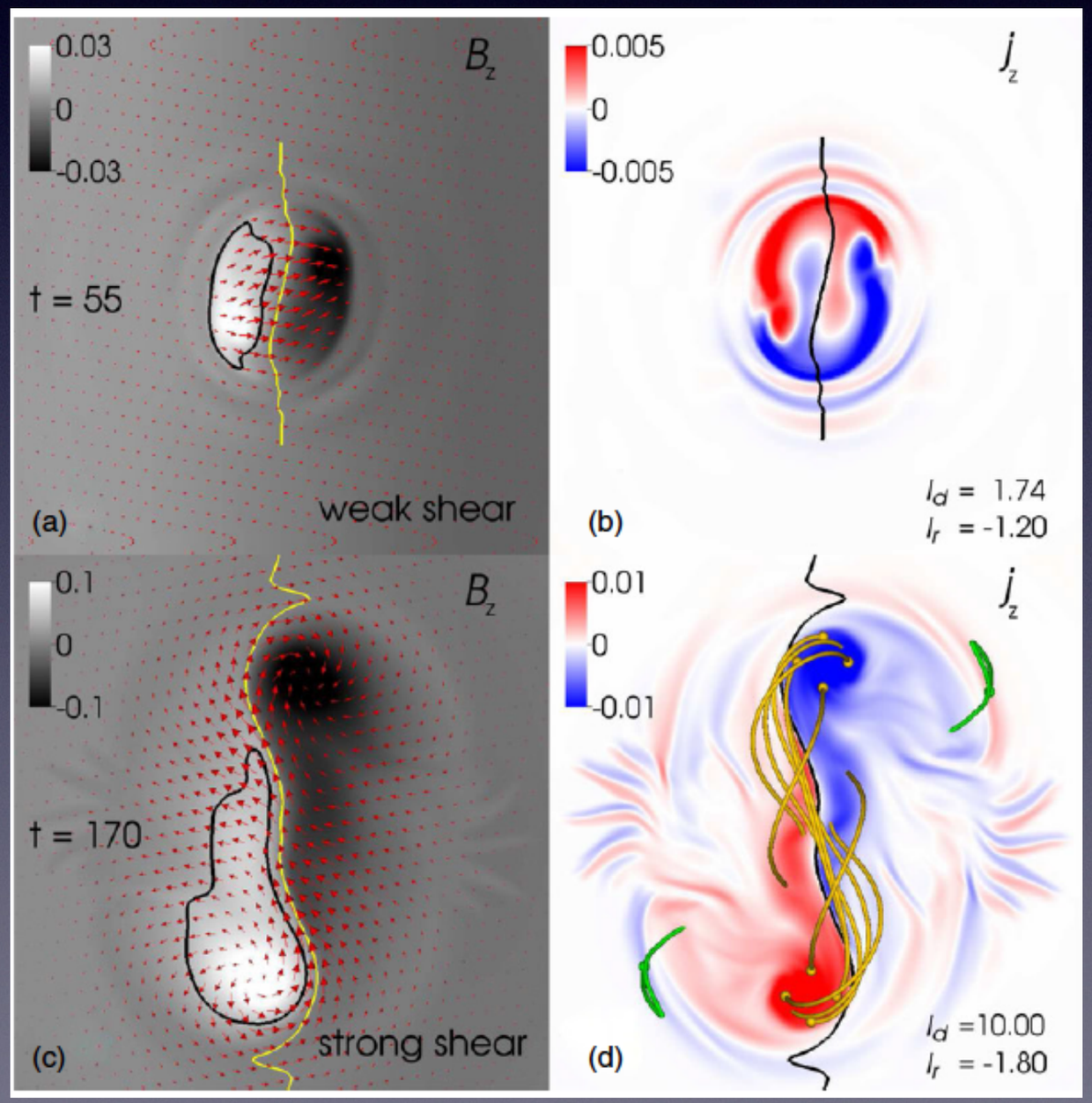
Initial results (Török et al. 2014)



- Analyze direct and return currents in the atmosphere

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

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



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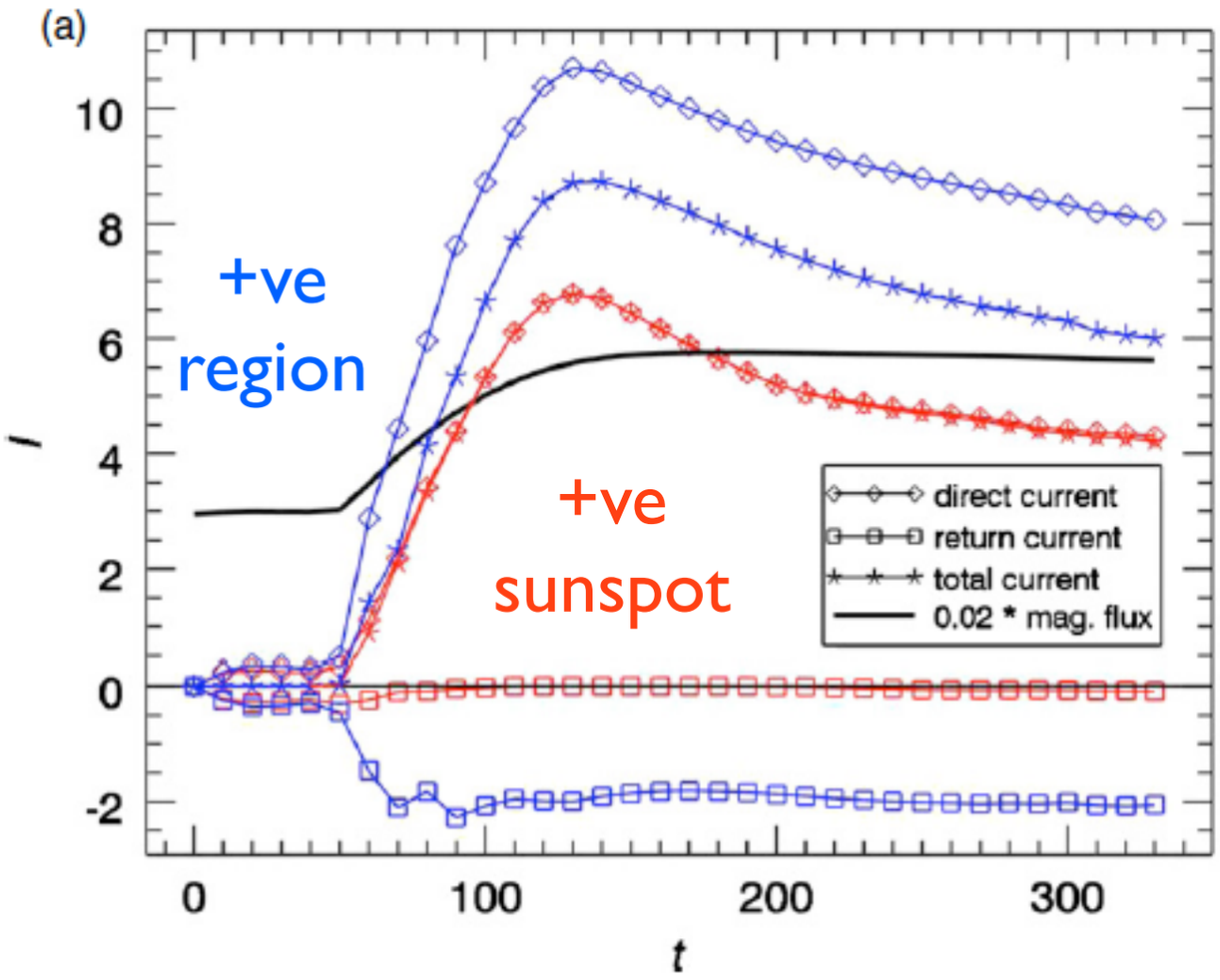
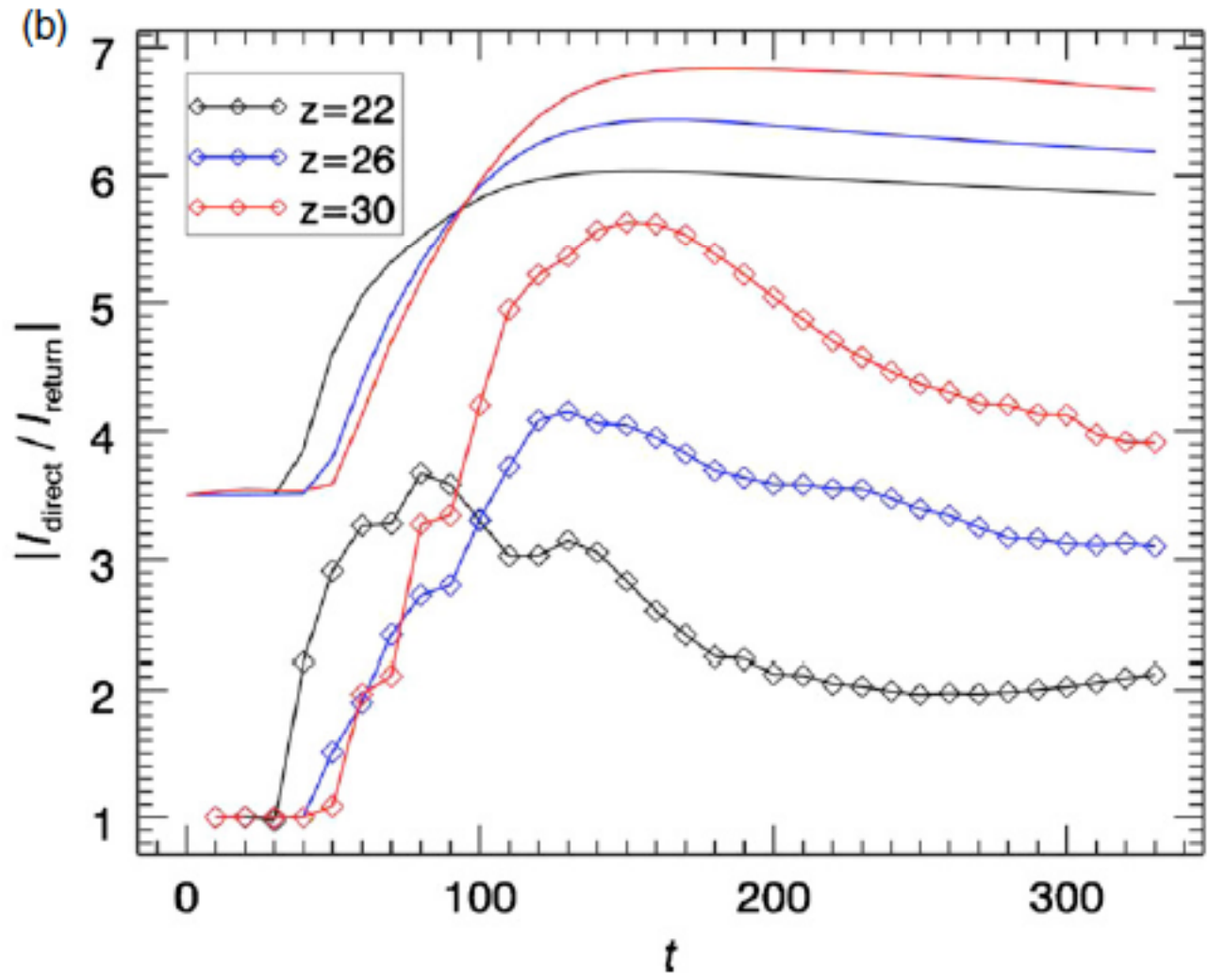




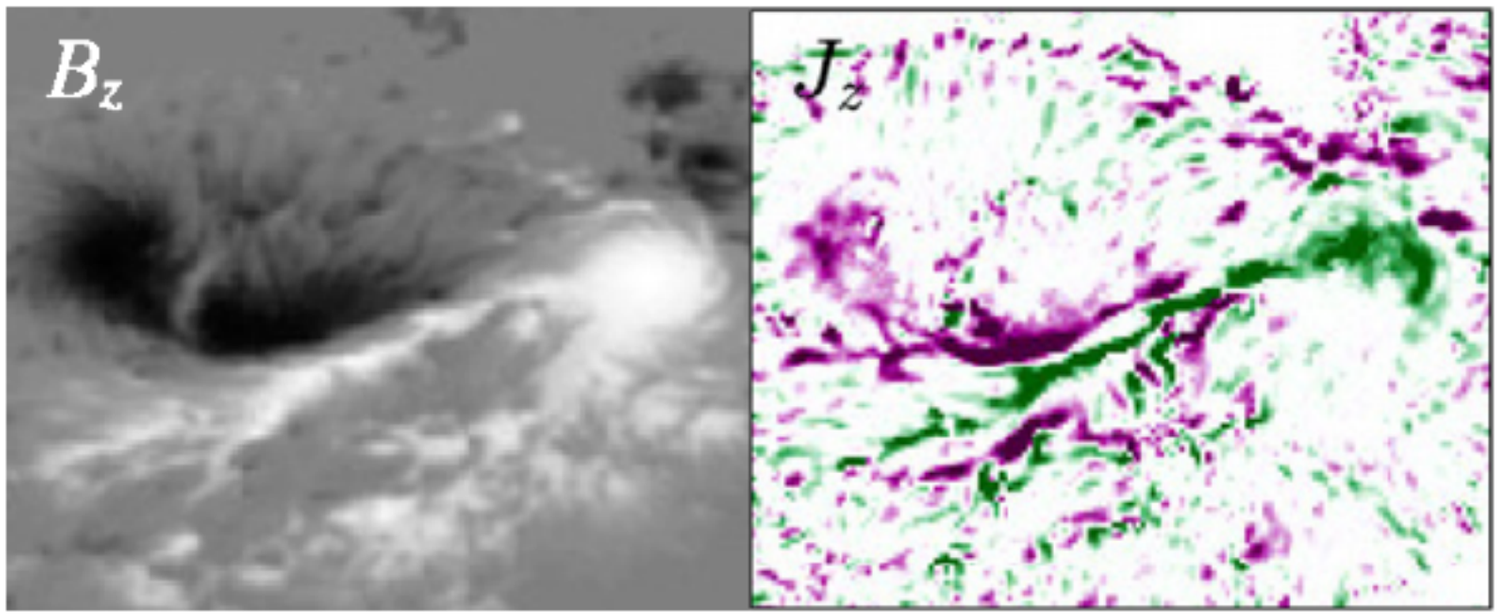
Current analysis

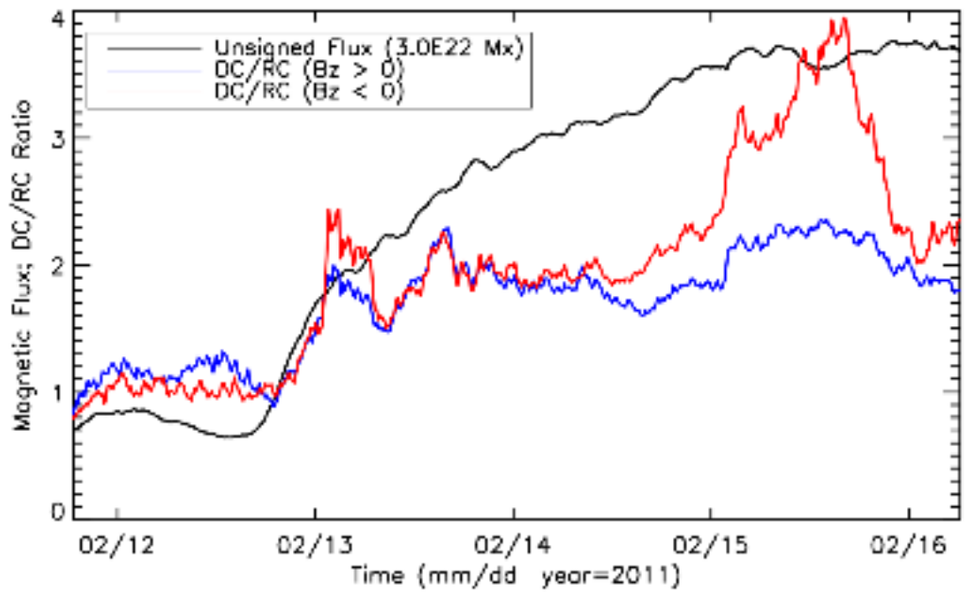
Direct: Jz*Bz>0 Return: Jz*Bz<0

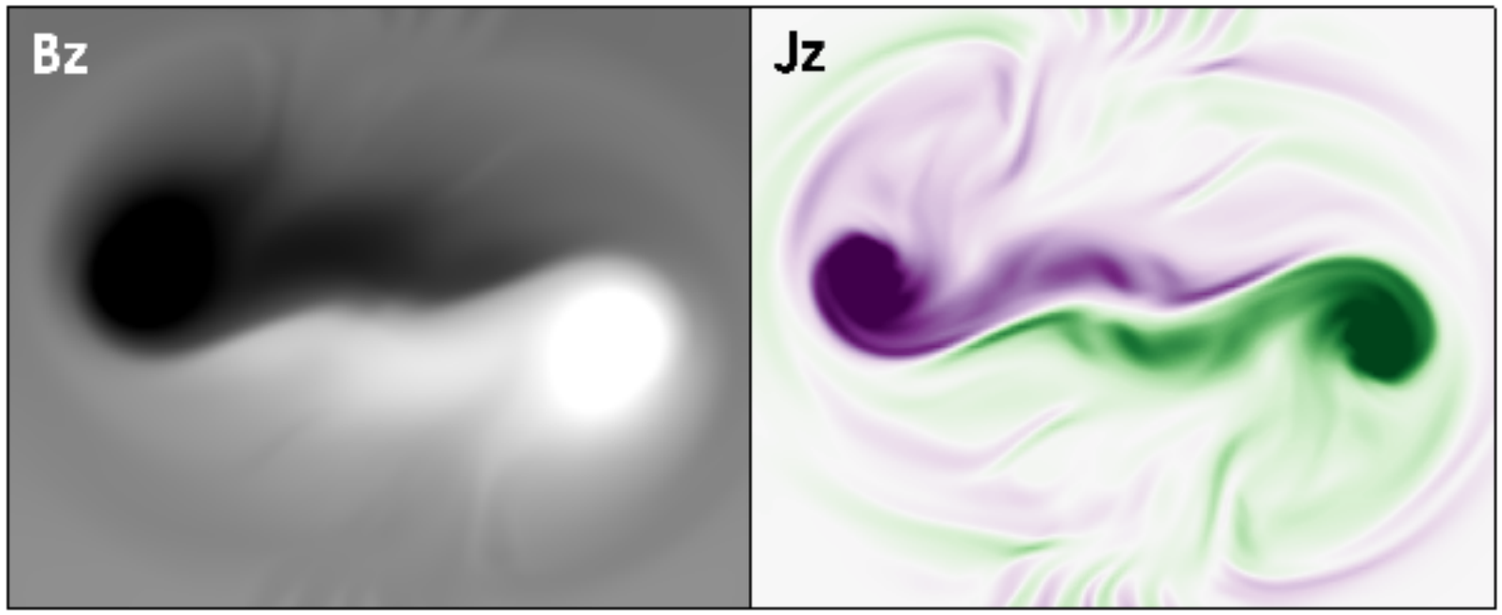
Significant net current in these simulations

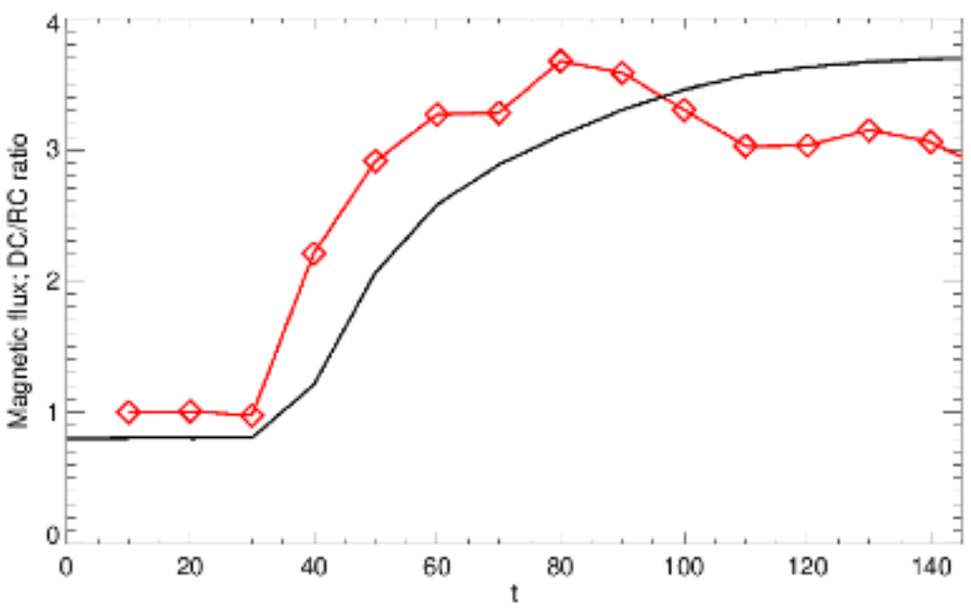
Strong shear at PIL

Comparison with center of AR11158









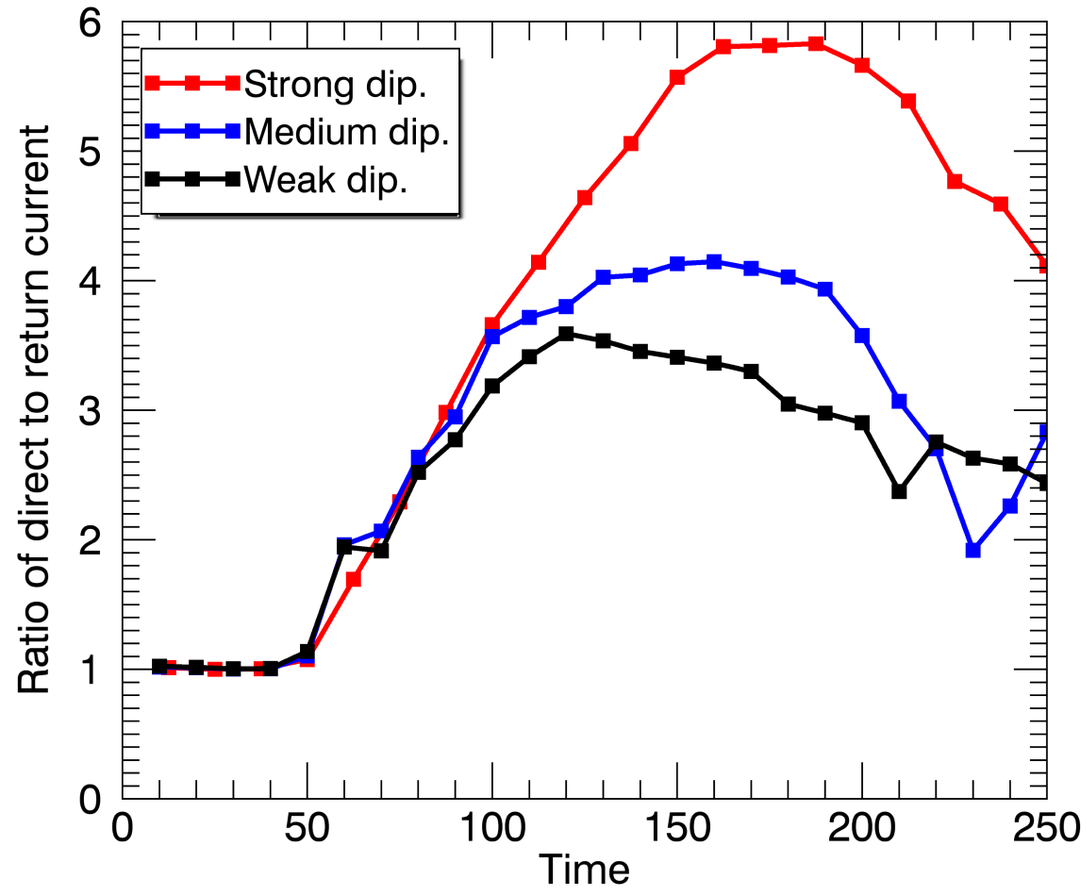
Significant net current in these simulations

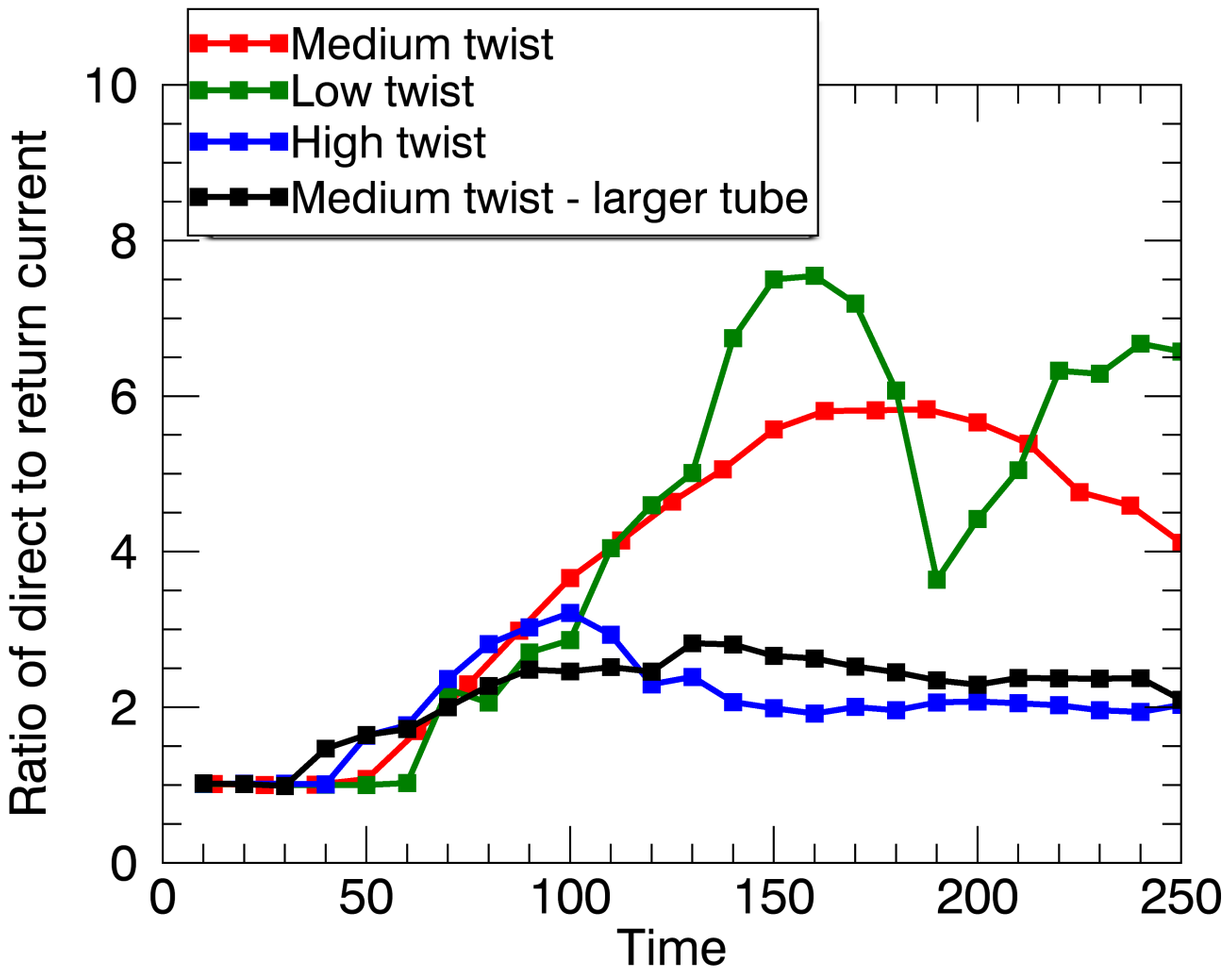
What is the role of magnetic shear?

Where do the return currents go?

Varying dipole field strength and tube twist

Stronger dipole - more confined emerging region - less neutralization

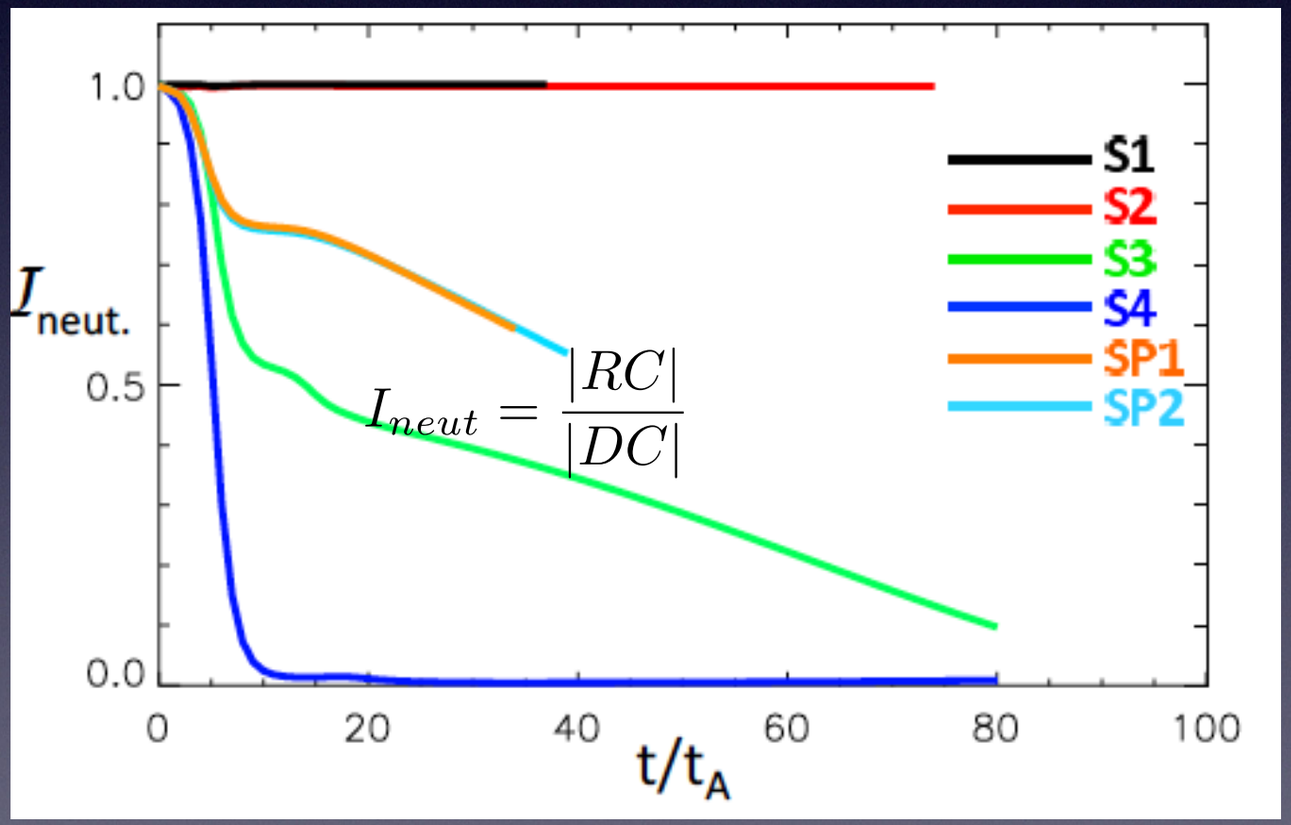


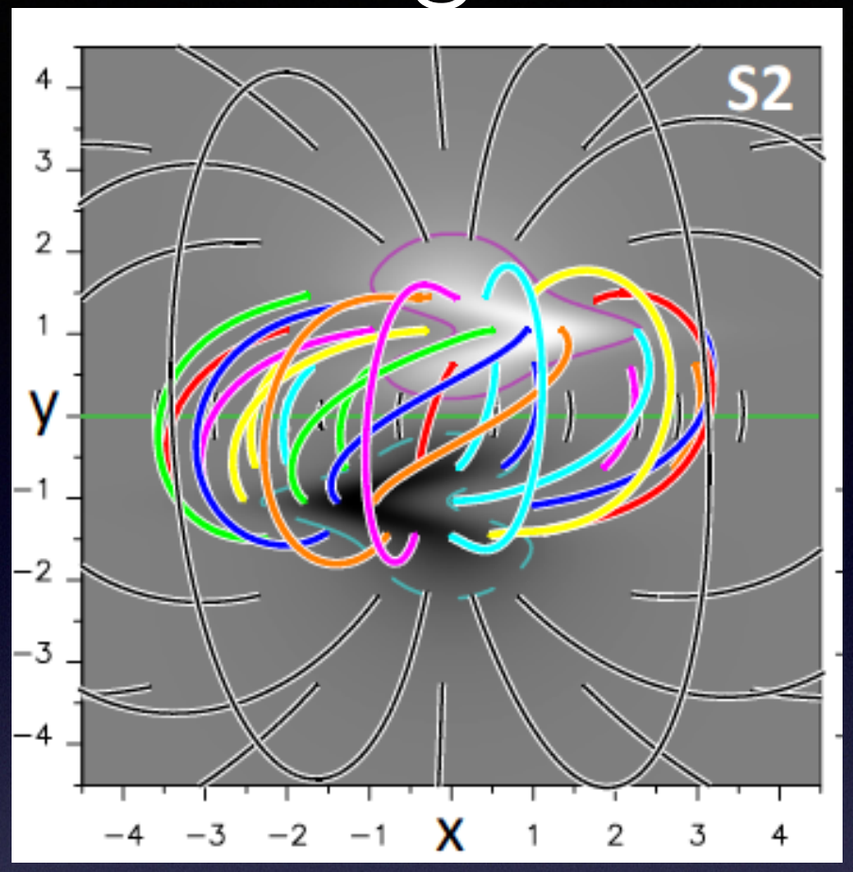


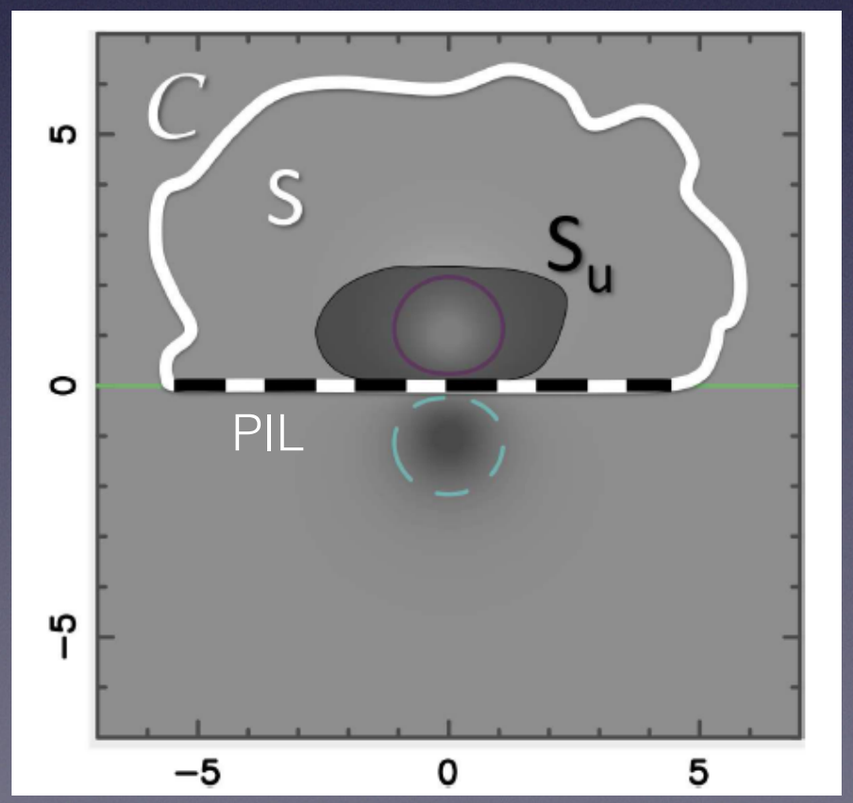
Less twist - more shear - less neutralization

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



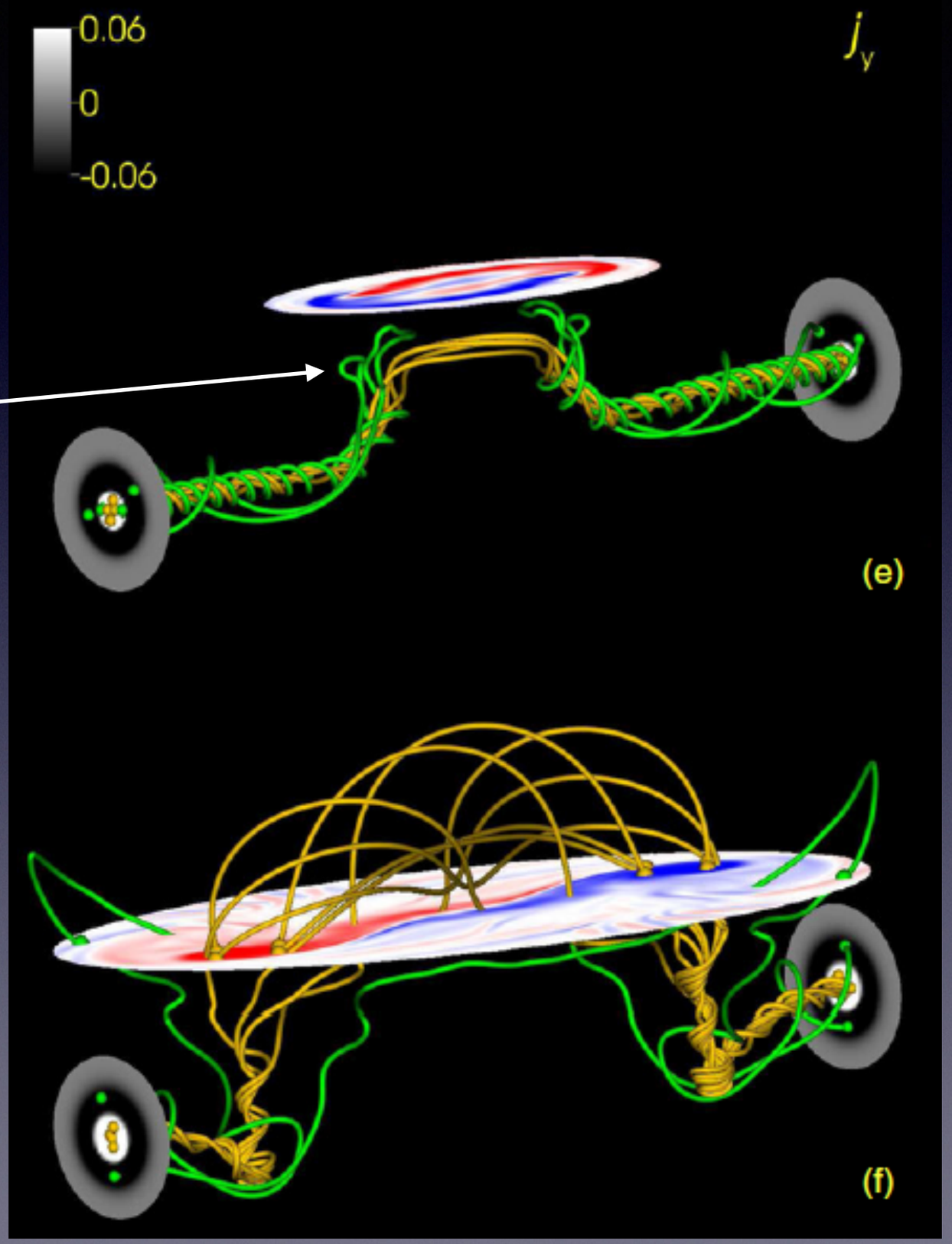




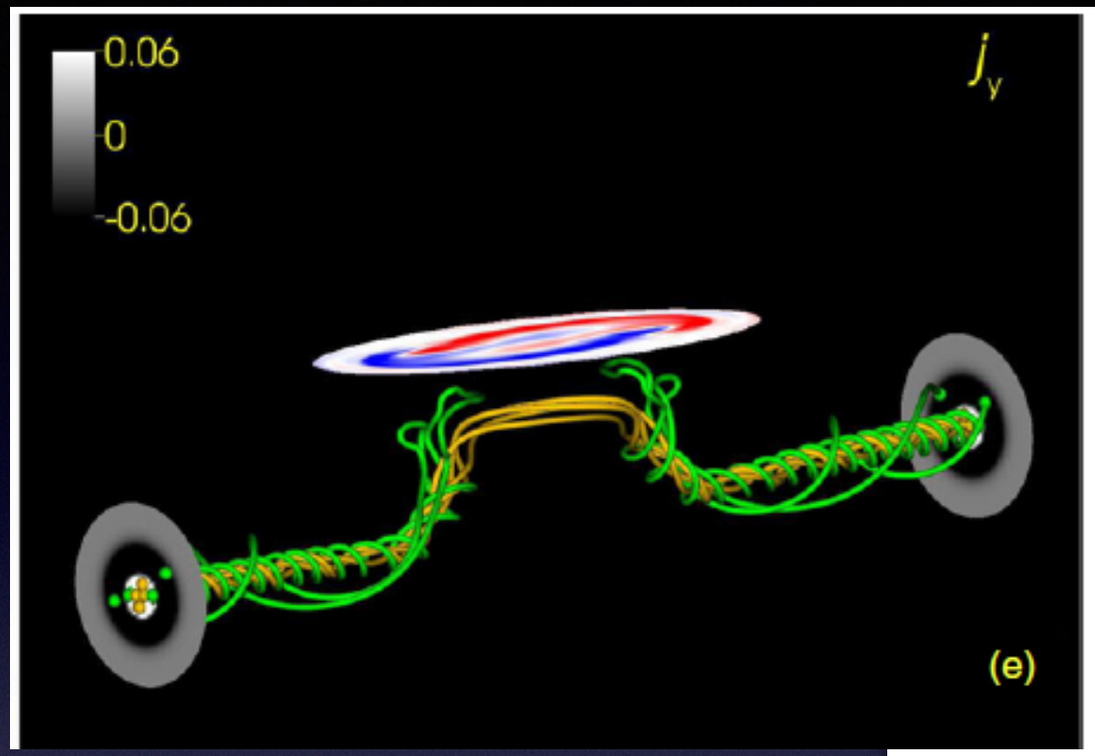
$$I_{total} = \frac{1}{\mu_0}\int_C \mathbf{B}_J \cdot \mathbf{dl} \approx \frac{1}{\mu_0}\int_{PIL} \mathbf{B}_J \cdot \mathbf{dl}$$

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



Cause of short-circuiting

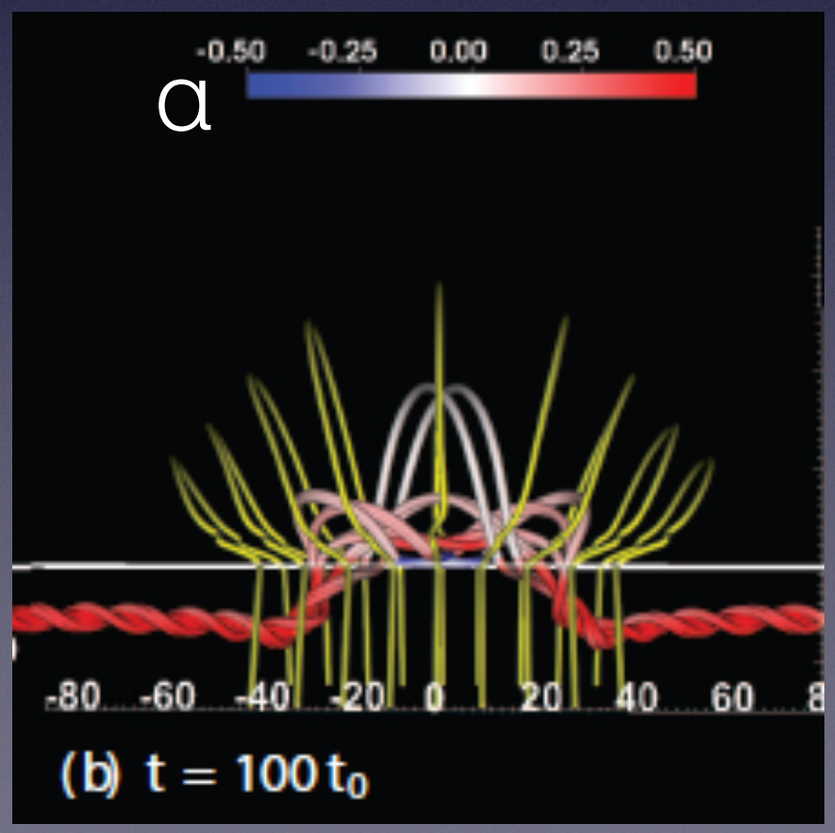


- Short-circuiting
  - current fieldline ‘turns-around and returns to same plane, but with opposite sign

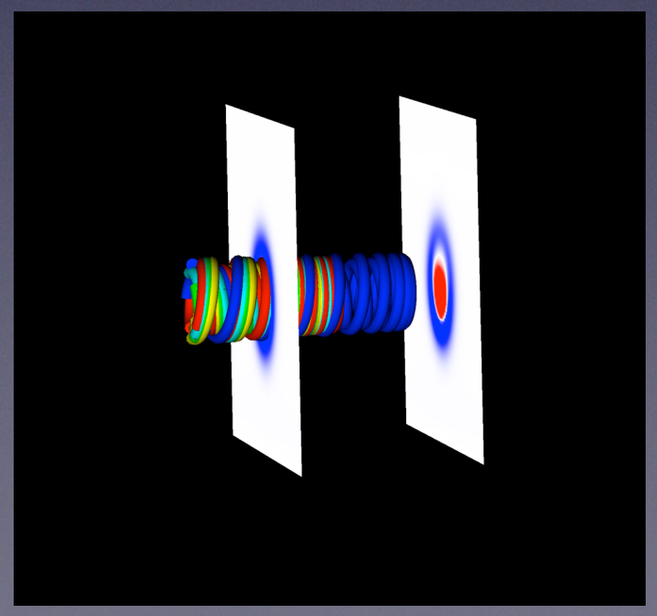
$$B_y = B_0 e^{-r^2/a^2}, B_\theta = qrB_y$$

$$\Phi_{j_y>0} \equiv \int_0^a j_y r dr \sim qB_0 a^2 \sim q$$

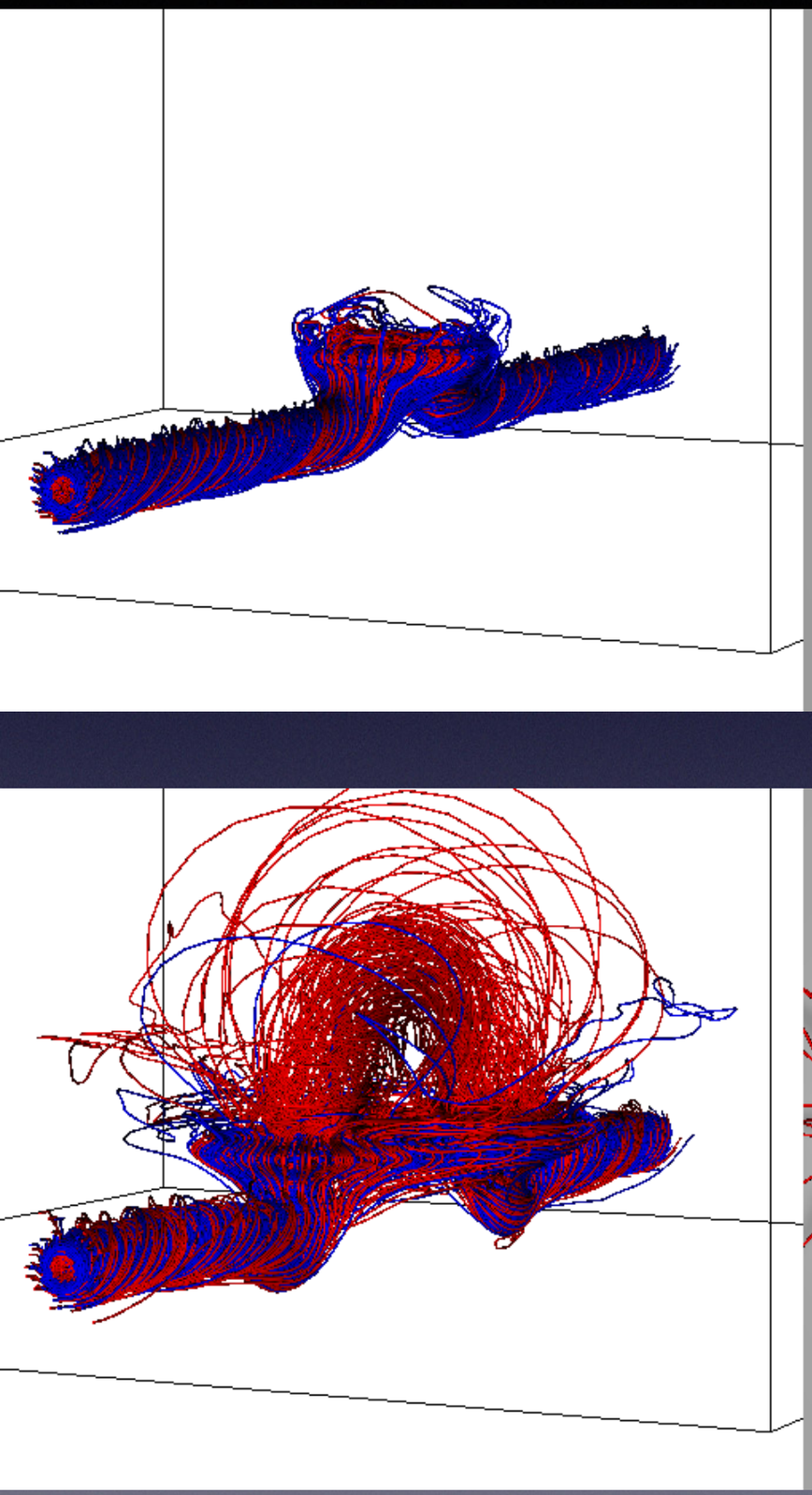
If q (or α) changes along axis (y), then get divergence in flux and J_y changes sign

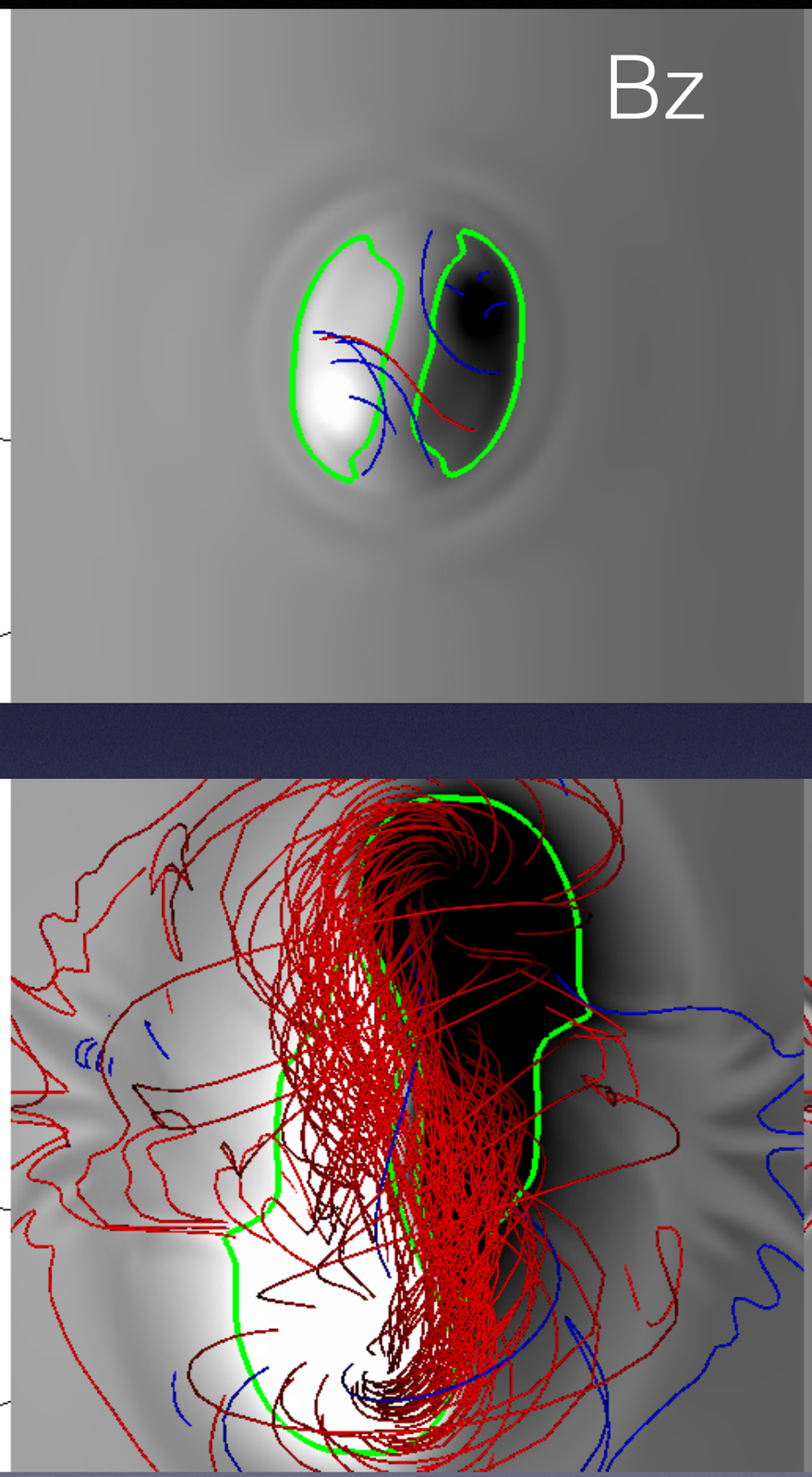


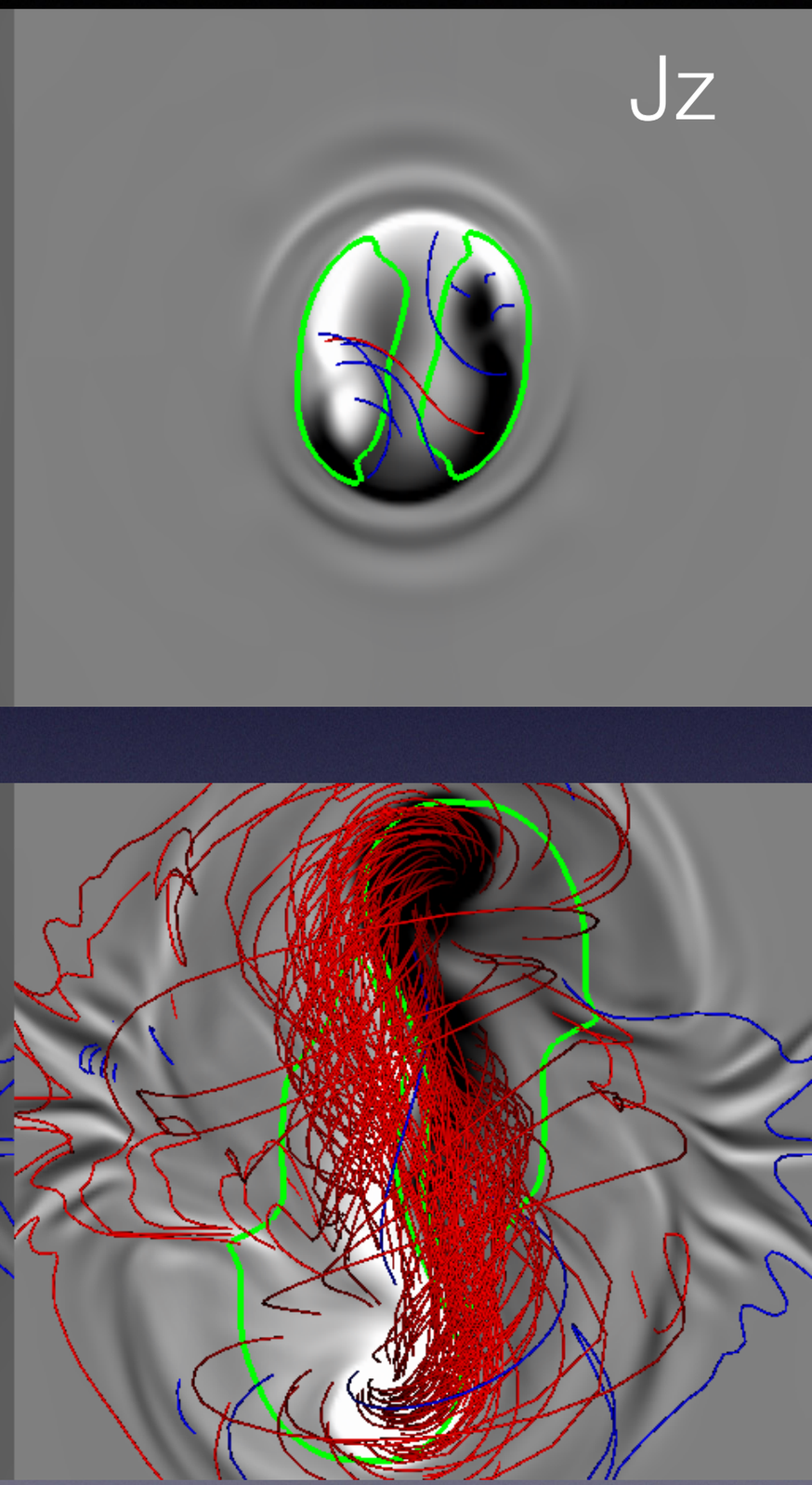
Example: straight tube with q varying along it’s axis



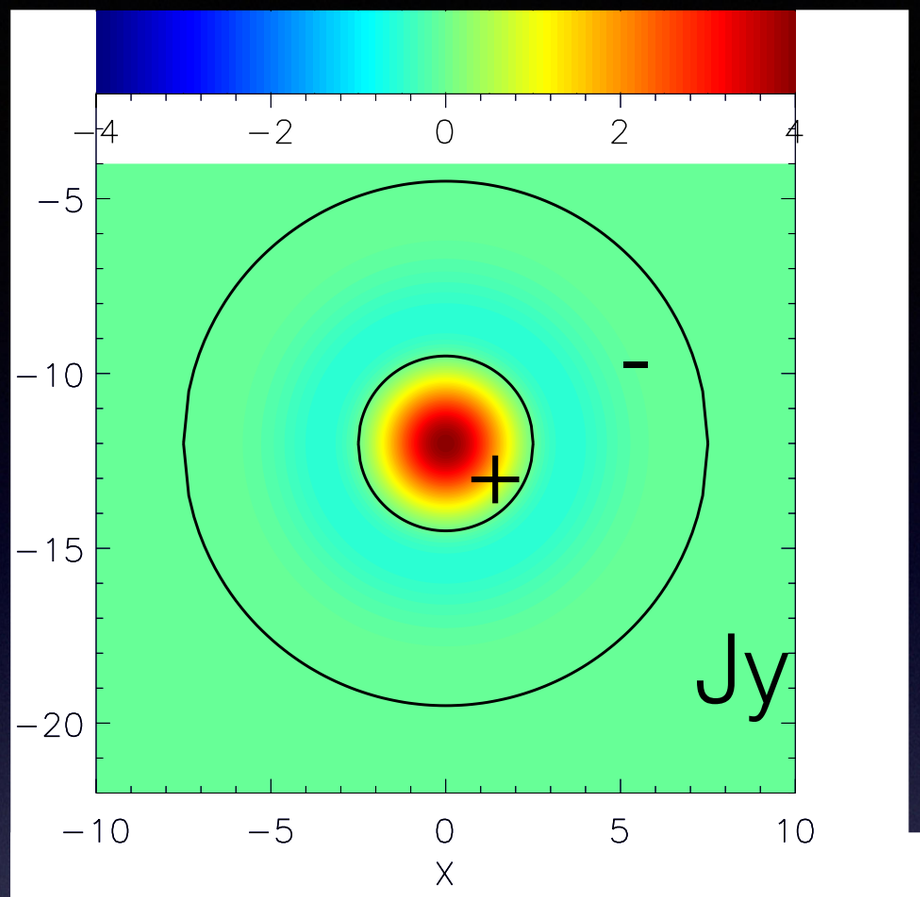
Following direct/return currents



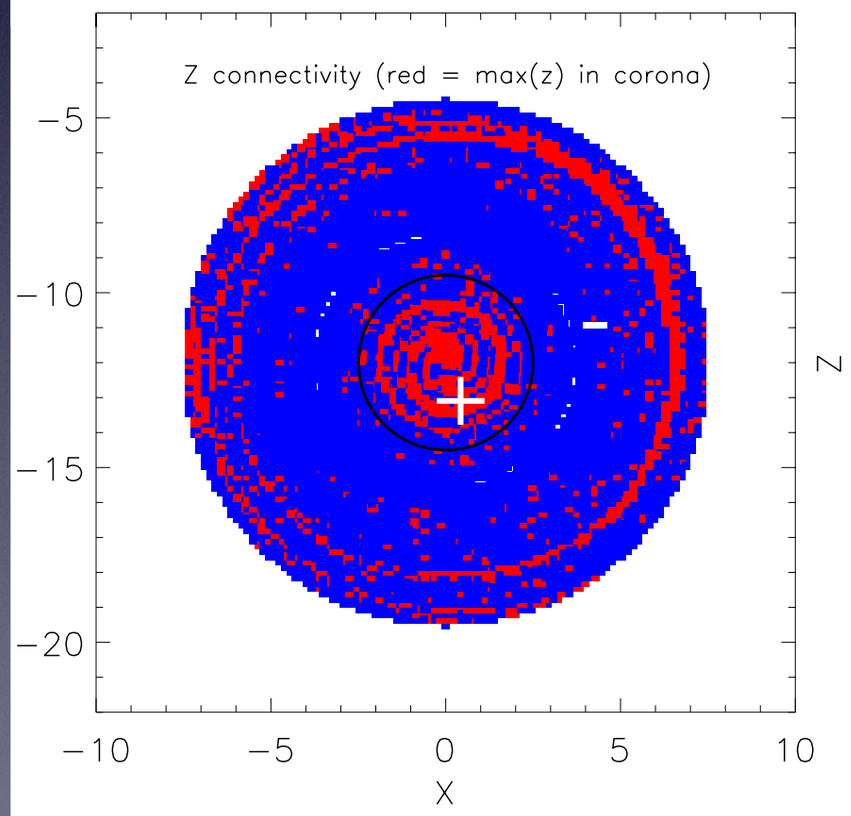


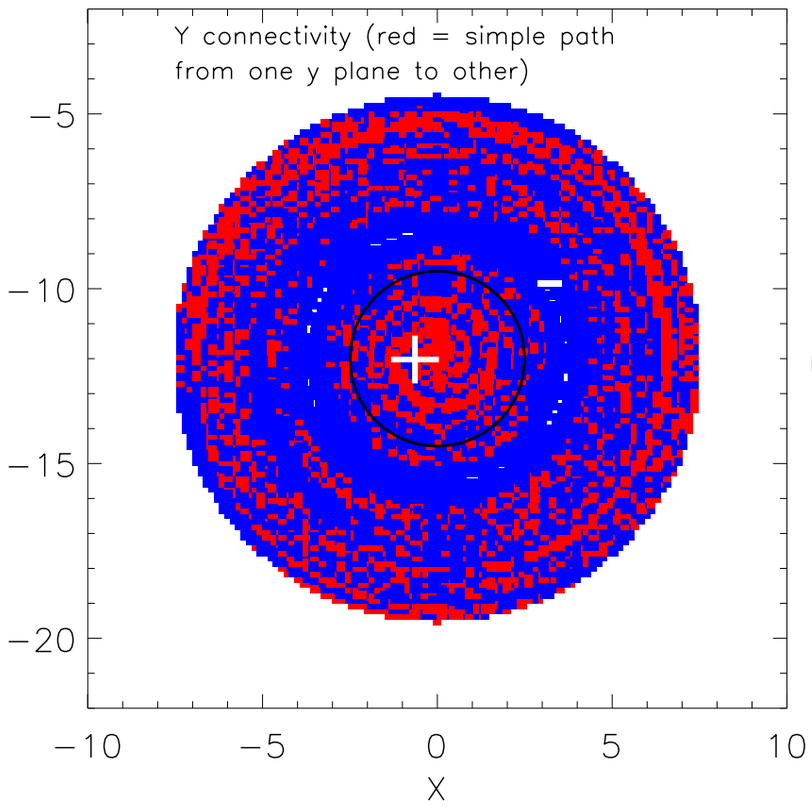


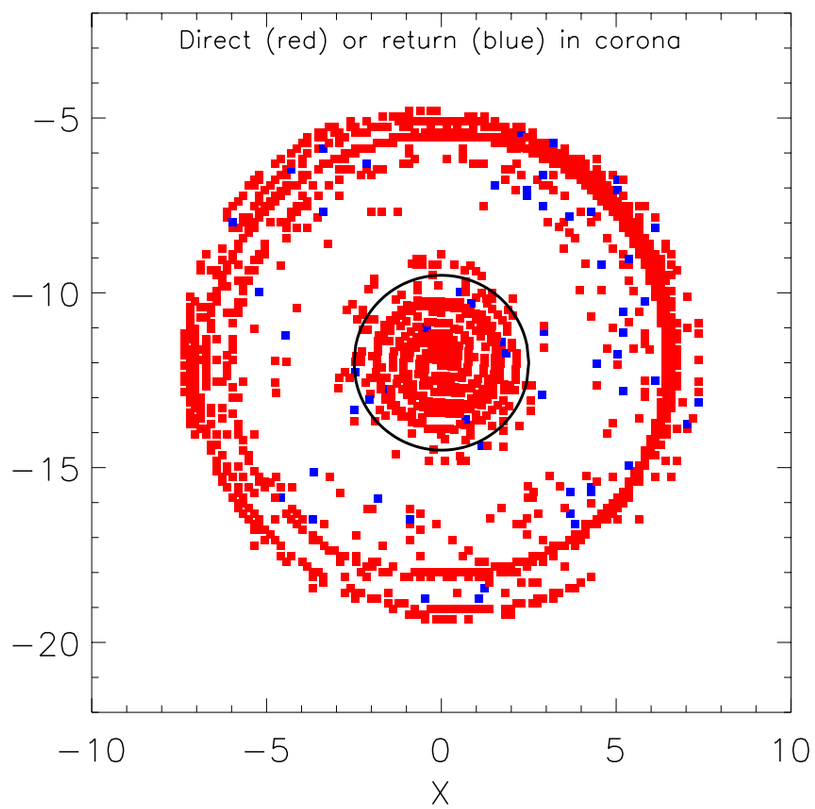
Current “fieldline” connectivity



- Seed current fieldlines from side boundary
- Axial current - inner compact direct current surrounded by diffuse return current
- Originate fieldlines from either “direct” (+ve Jy) or “return” (-ve Jy current)
- Small percentage of original return current fieldlines extend into corona as direct current
- Most of return current does not emerge!





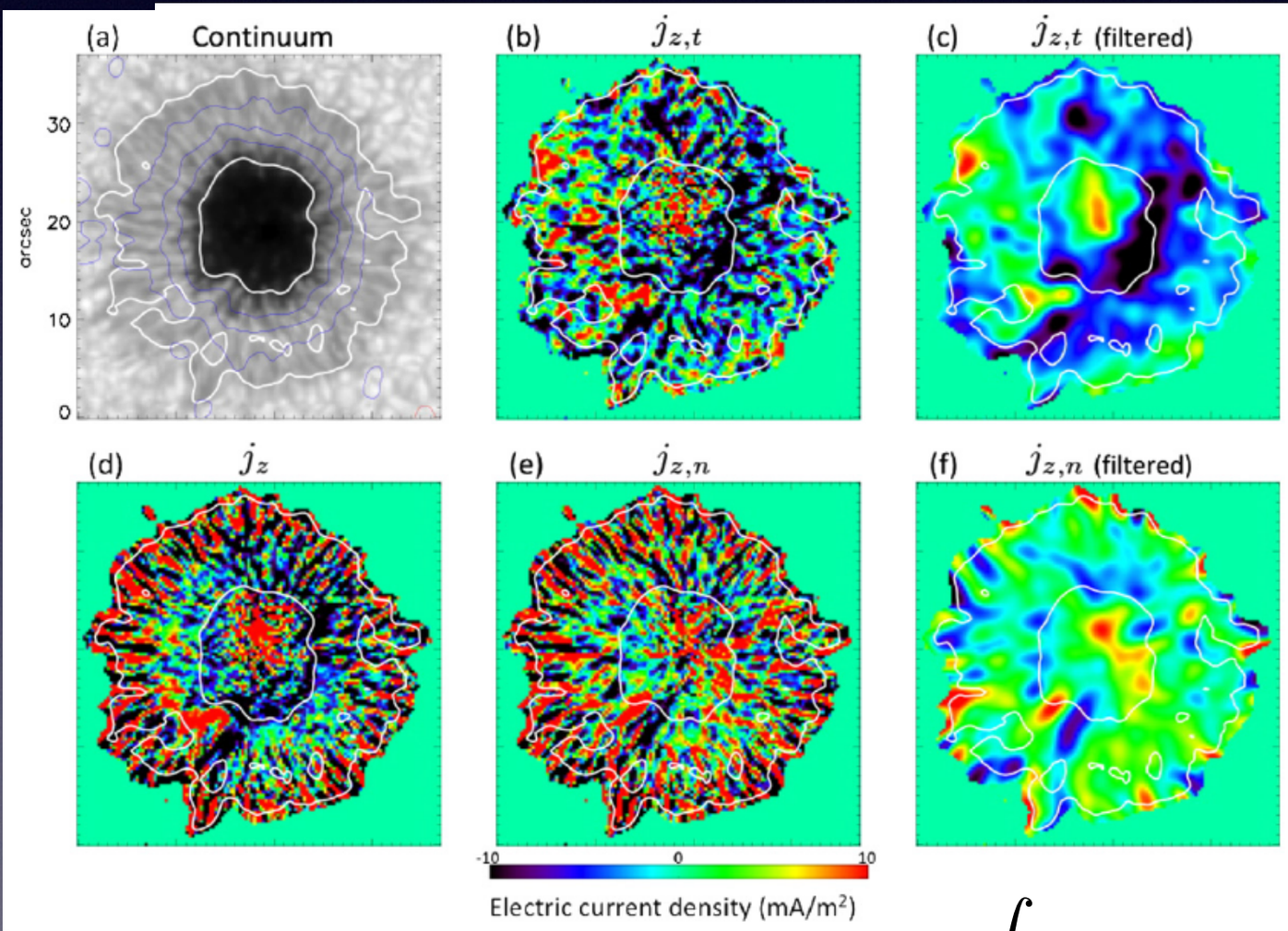


Results and open questions

- Our simulations suggest that neutralized CZ tubes create non-neutralized coronal currents upon emergence
    - return currents remain near surface, as predicted in Longcope and Welsch - but why?
- Coronal simulations show that amount shear at PIL determines net-neutralization
- Can we nail down where the return currents of the flux tube actually go?
    - connectivity of J fieldlines
    - Integral methods
- Relationship between twist, shear and neutralization?
- Does result hold for other initial (less idealized) profiles of magnetic field in the CZ?
- More, careful observational analysis

Observations: Sunspots

- Venkatakrishnan et al. (2009), Gosain (2014)
  - Looked at isolated sunspots with Hinode/SOT - effect of Fibril fields
  - Find sunspots are well neutralized (as predicted by Parker)



$$I_{net} = \int_{Bz>B_0} J_z dA$$