Simulation of active region flux emergence, formation of δ-sunspots and the convective dynamo

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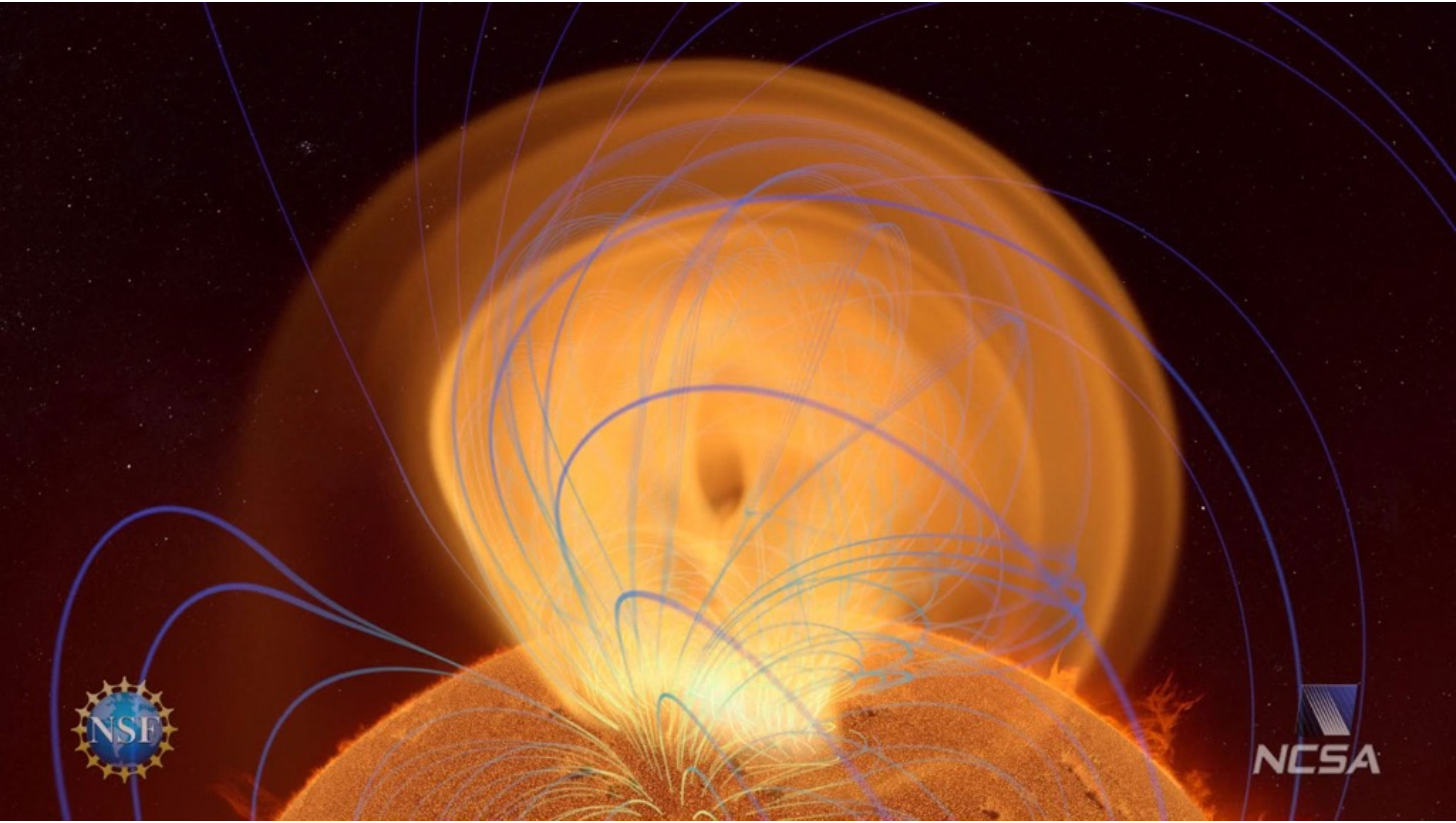
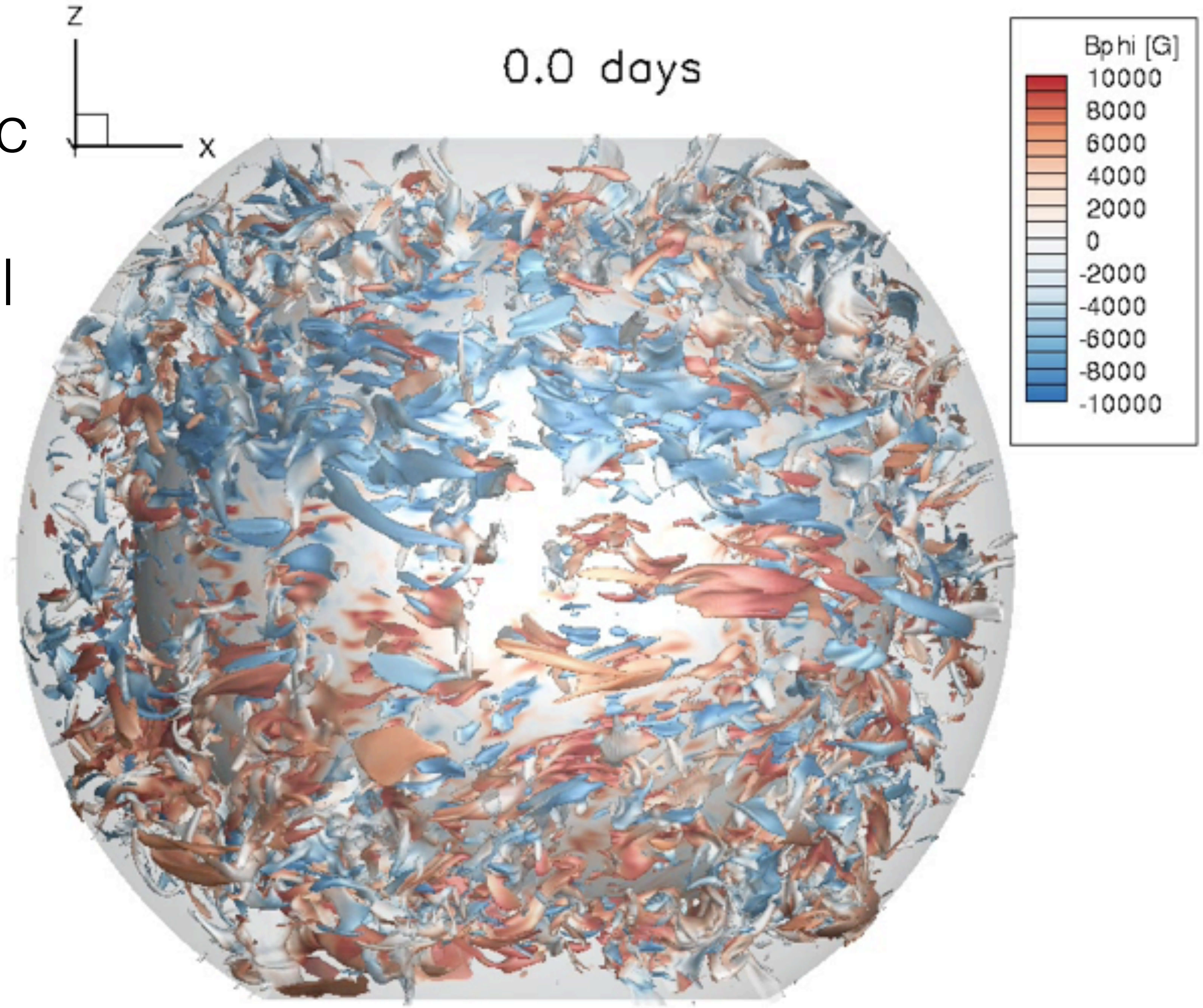
Solar Superstorms



Images from http://www.ncsa.illinois.edu/enabling/vis/cadens/documentary/solar_superstorms

Convective Dynamo in Global Simulations

We solve the MHD equations in the anelastic approximation in a rotating domain of partial spherical shell with solar luminosity forced across the shell.

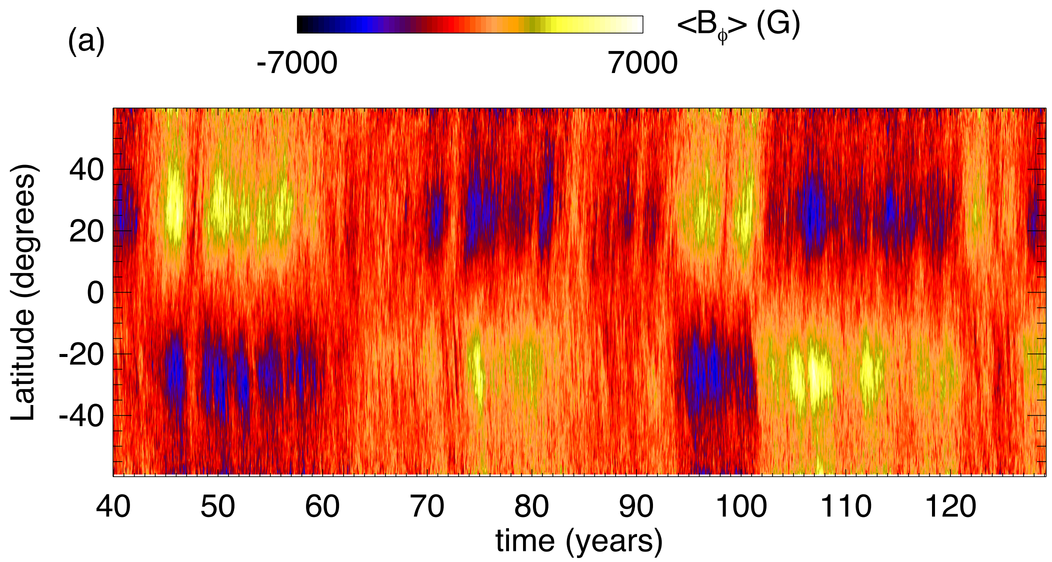


Emergence of super-equipartition magnetic fields

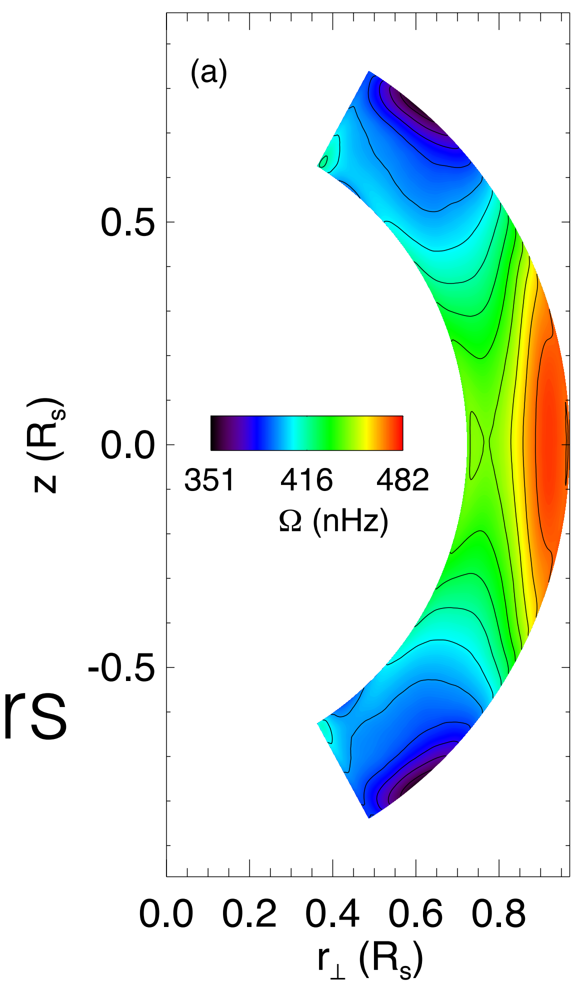
Fan & Fang, 2016

Large-scale Cyclic Magnetic Fields

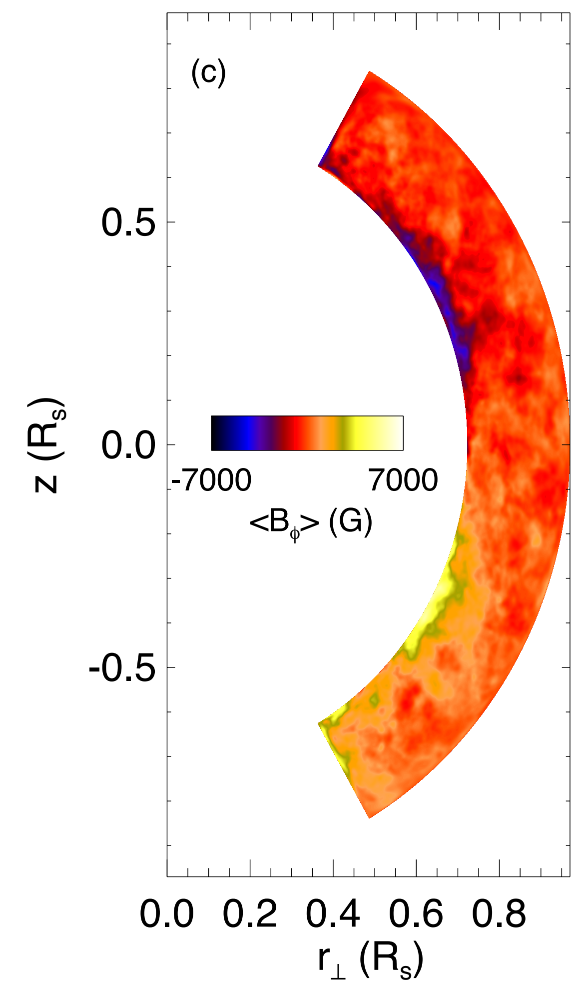
Lat-time diagram of mean toroidal field



Angular Rotation Rate

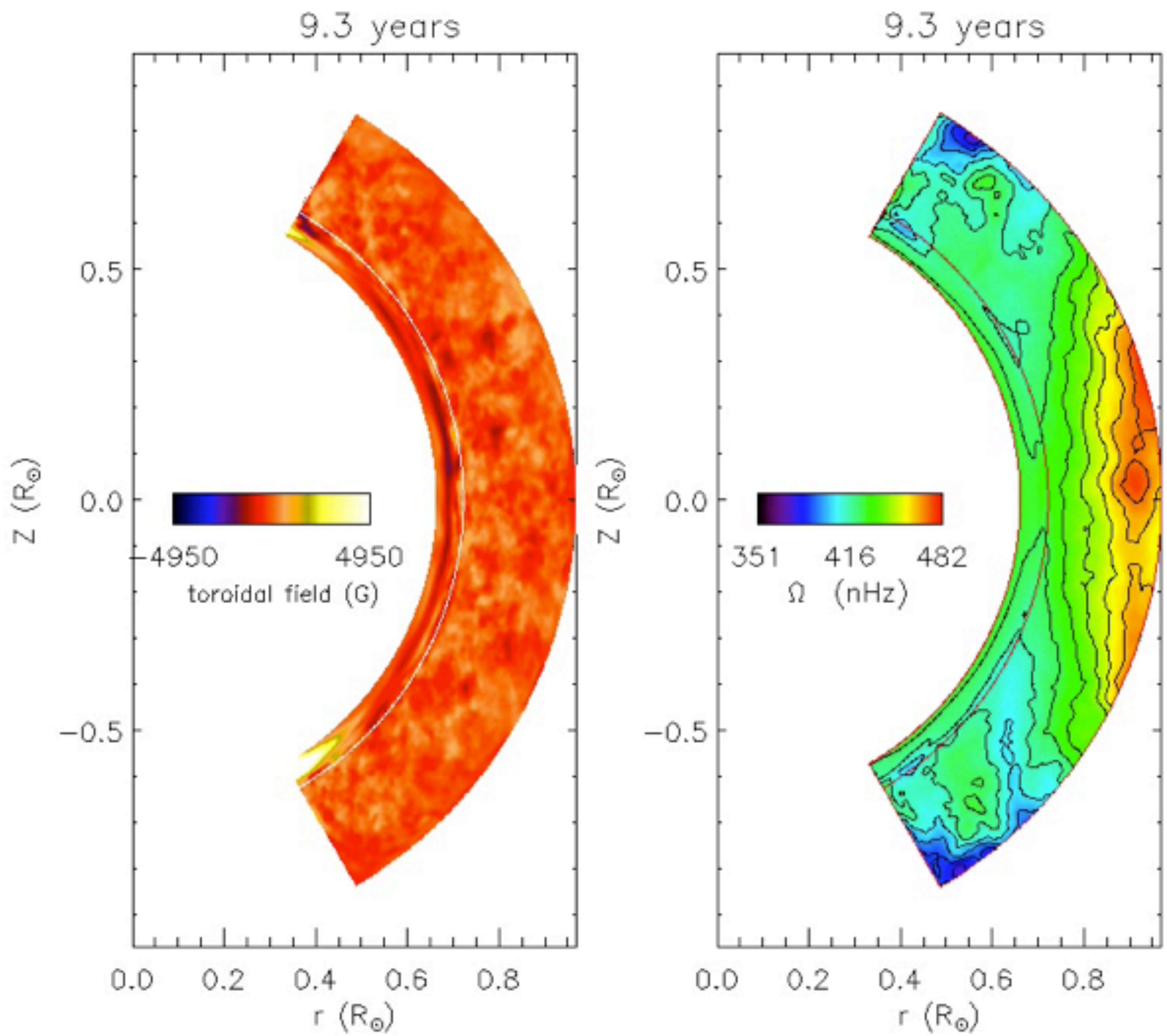


Toroidal Field



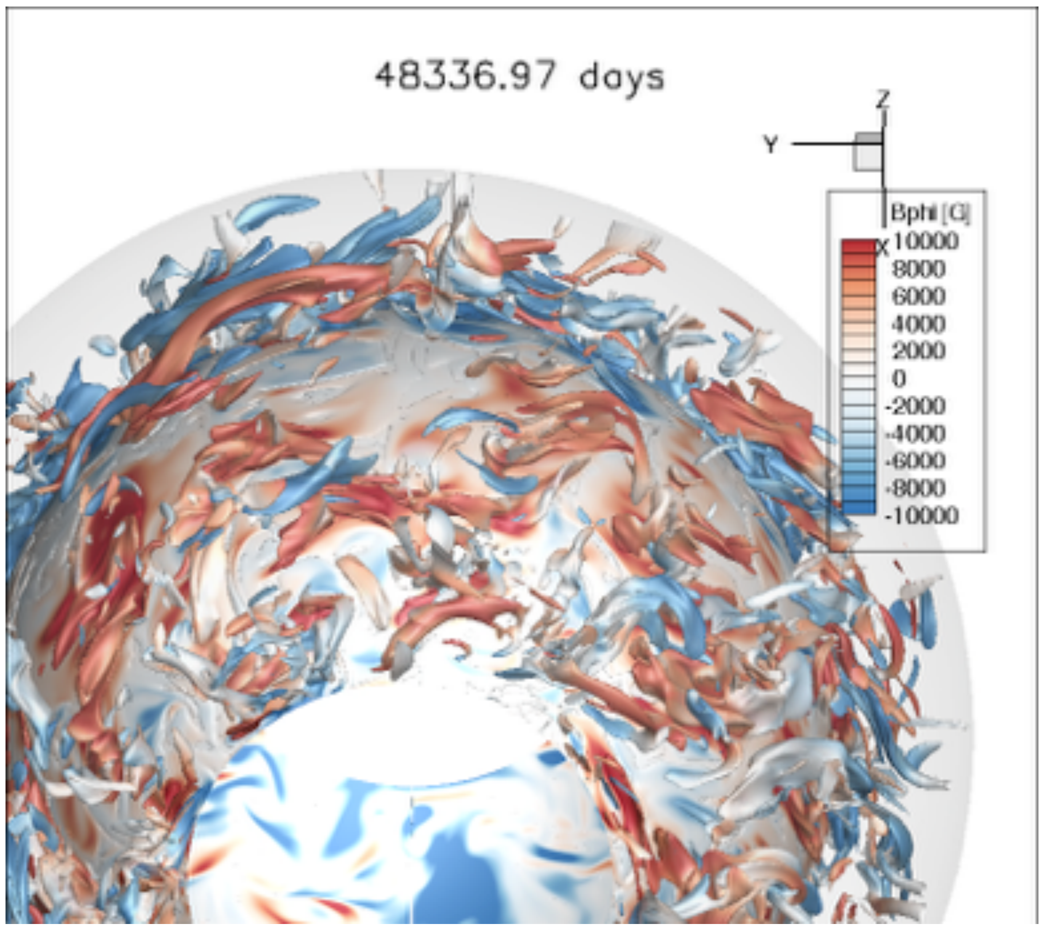
- Irregular cycles of 5-15 years
- Solar differential rotation
- Concentration of strong magnetic fields in the bottom of the convection zone

Storage of strong toroidal magnetic fields in the overshoot layer

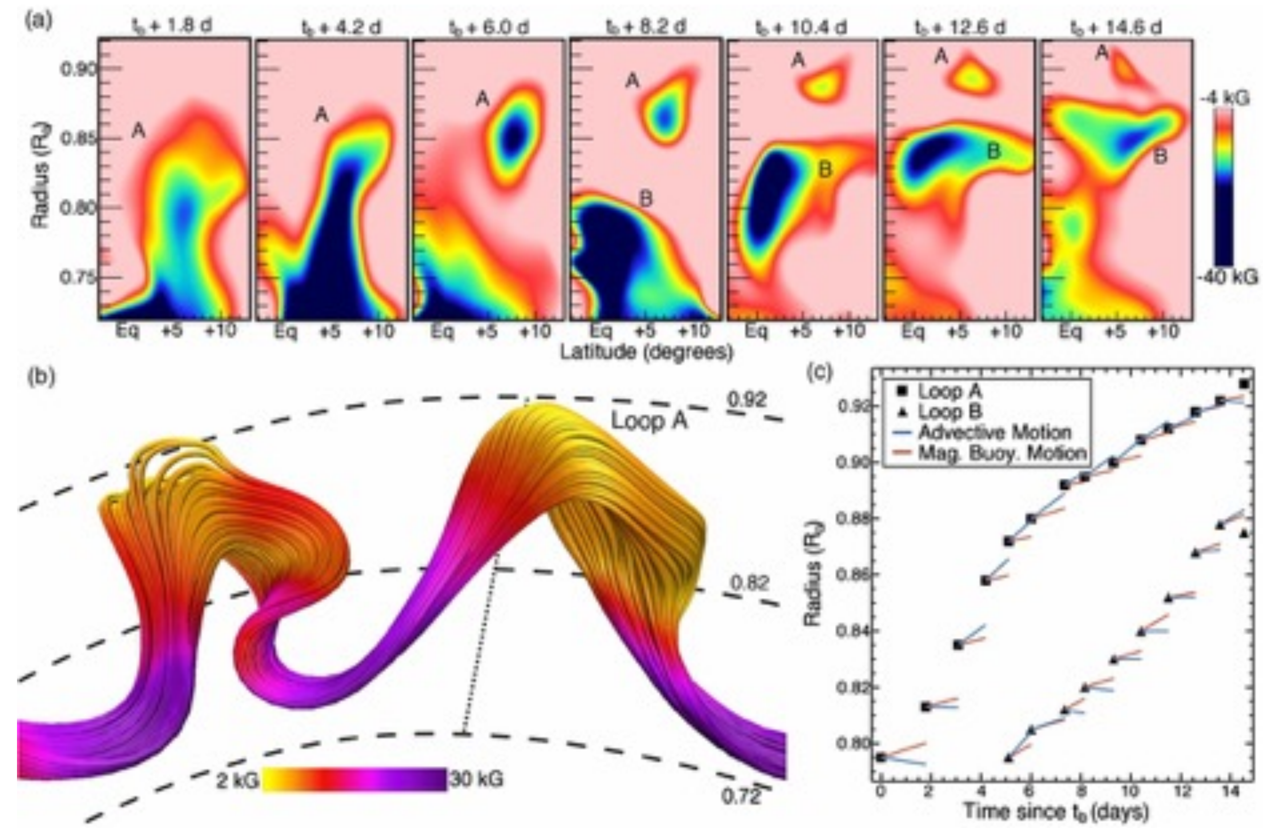


Magnetic tubes in dynamo simulations

Fan & Fang 2014

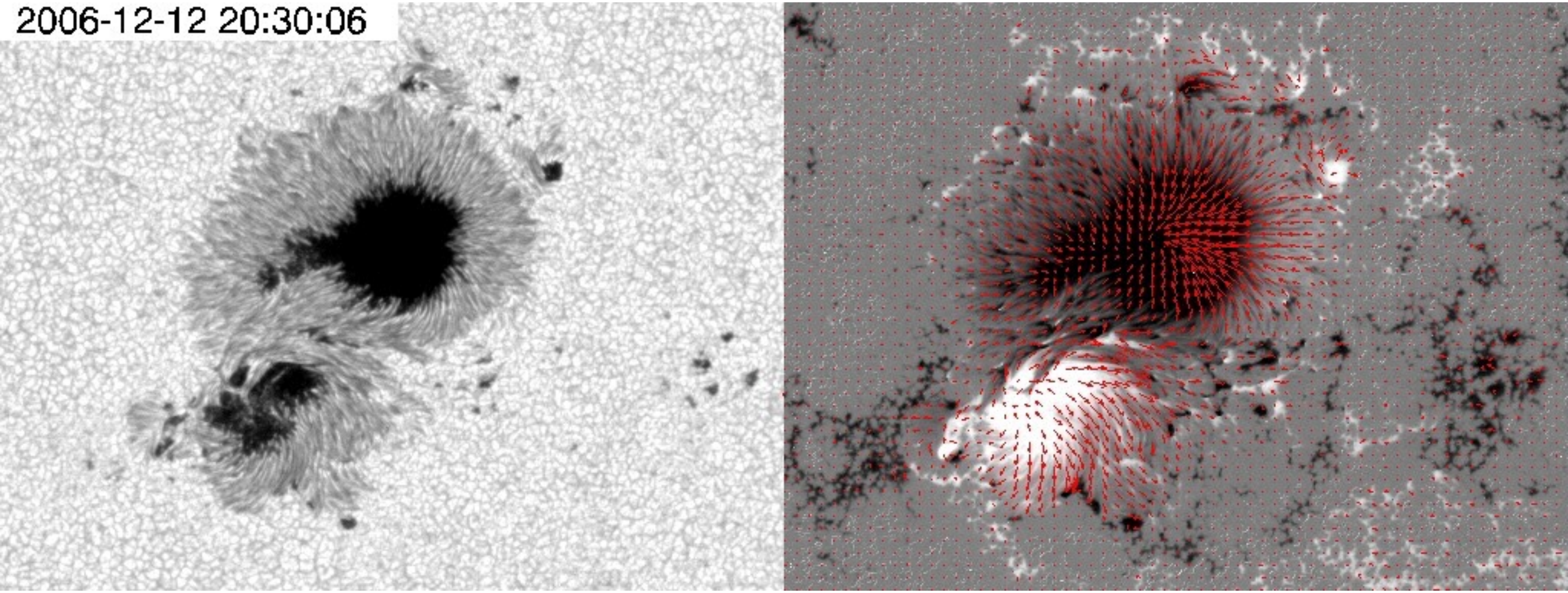


Buoyant magnetic loops in Nelson et al. (2011)



- In the midst of magneto-convection, super-equipartition toroidal flux bundles form and emerge near the surface, exhibiting properties that are similar to emerging solar active regions.

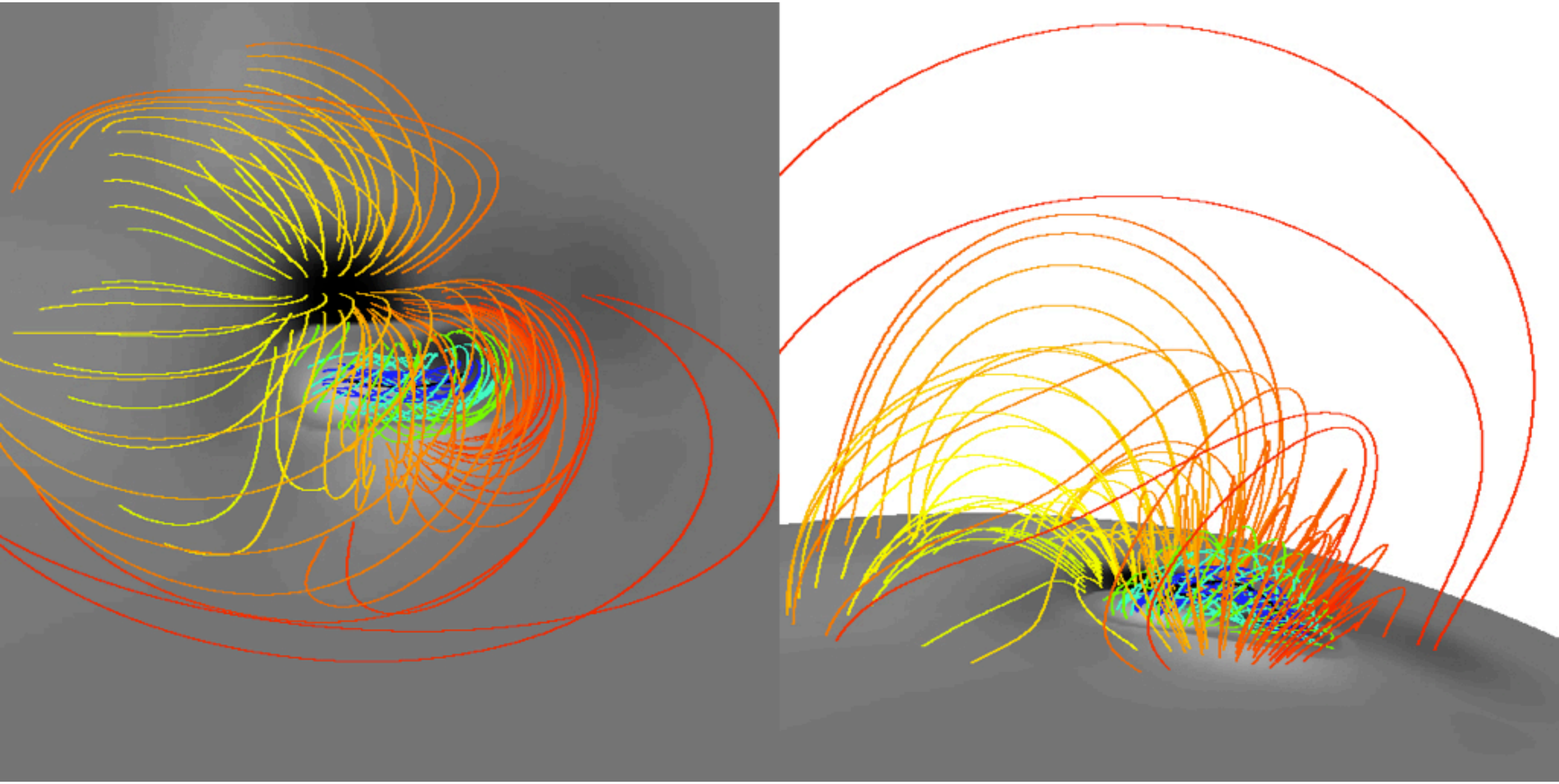
δ-spot Active Region



Courtesy of National Astronomical Observatory of Japan

- δ-spot: aggregated spots of opposite polarities sharing the same penumbra.

Coronal Eruptions from δ-spot

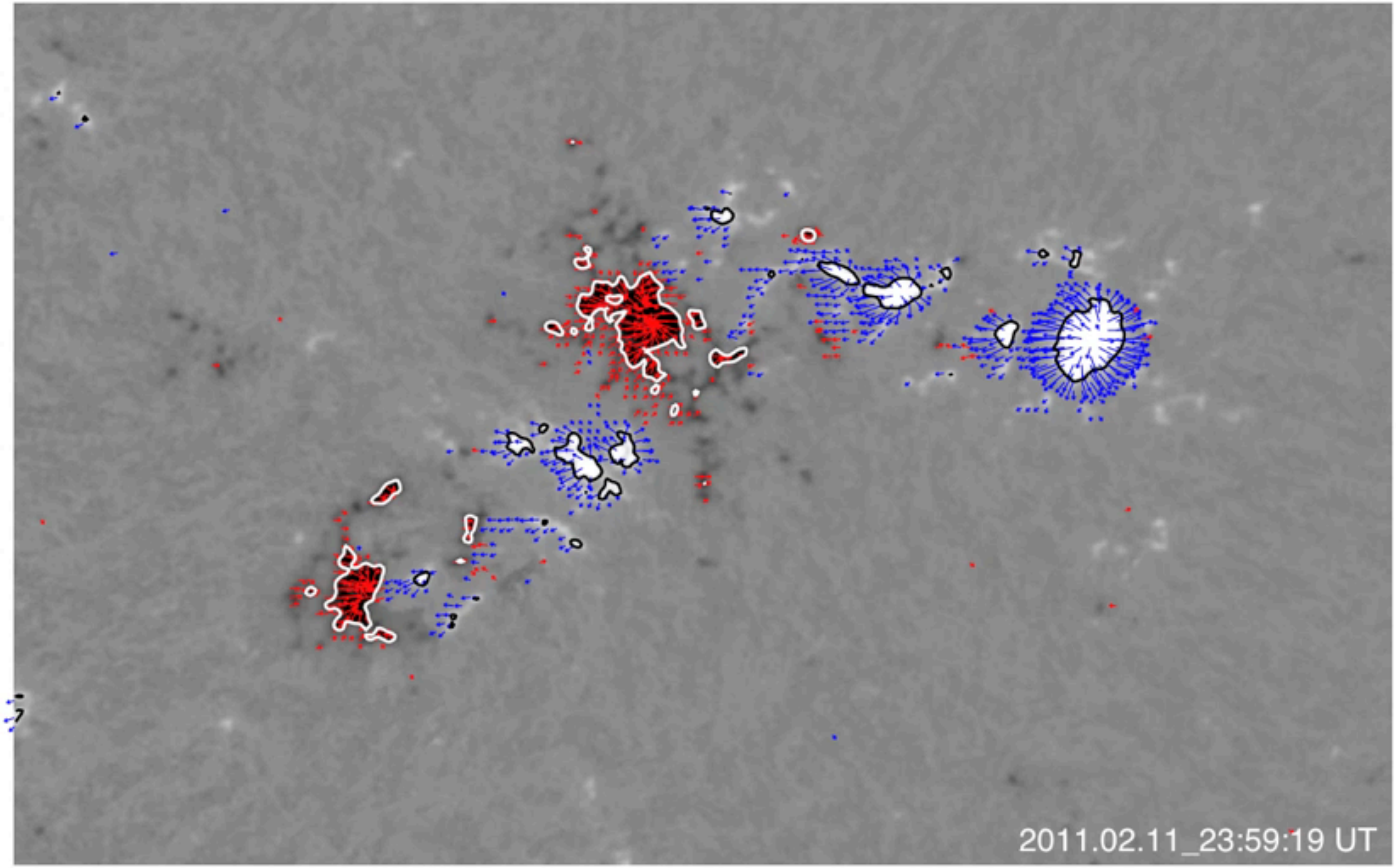


Fan 2011

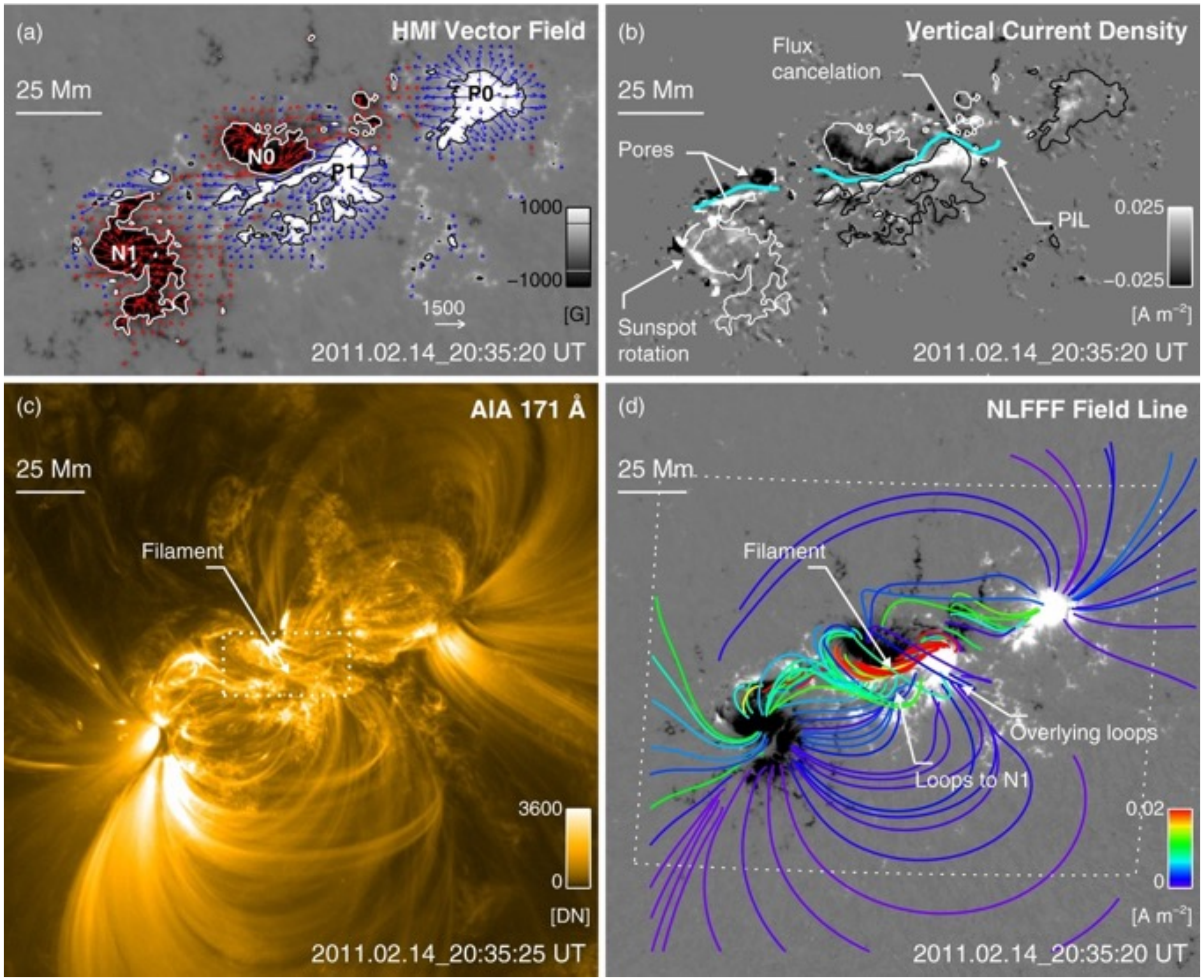
δ-spots: Observations and Theories

- High productivity in strong flares and CMEs (Hagyard et al. 1984; Tanaka 1991; Liu & Zhang 2001)
- Shearing motion and magnetic fields at the PIL (Tanaka 1979; Tang 1983, Lites et al. 1995)
- Tanaka (1991) and Leka et al. (1996): δ-sunspots can be formed by the emergence of highly twisted magnetic flux tubes from the convection zone.
- Linton et al. 1998, 1999; Fan et al. 1999: numerical simulations on helical kink instability of highly twisted rising flux tubes emerging from the interior.

Vector Magnetogram of AR 11158



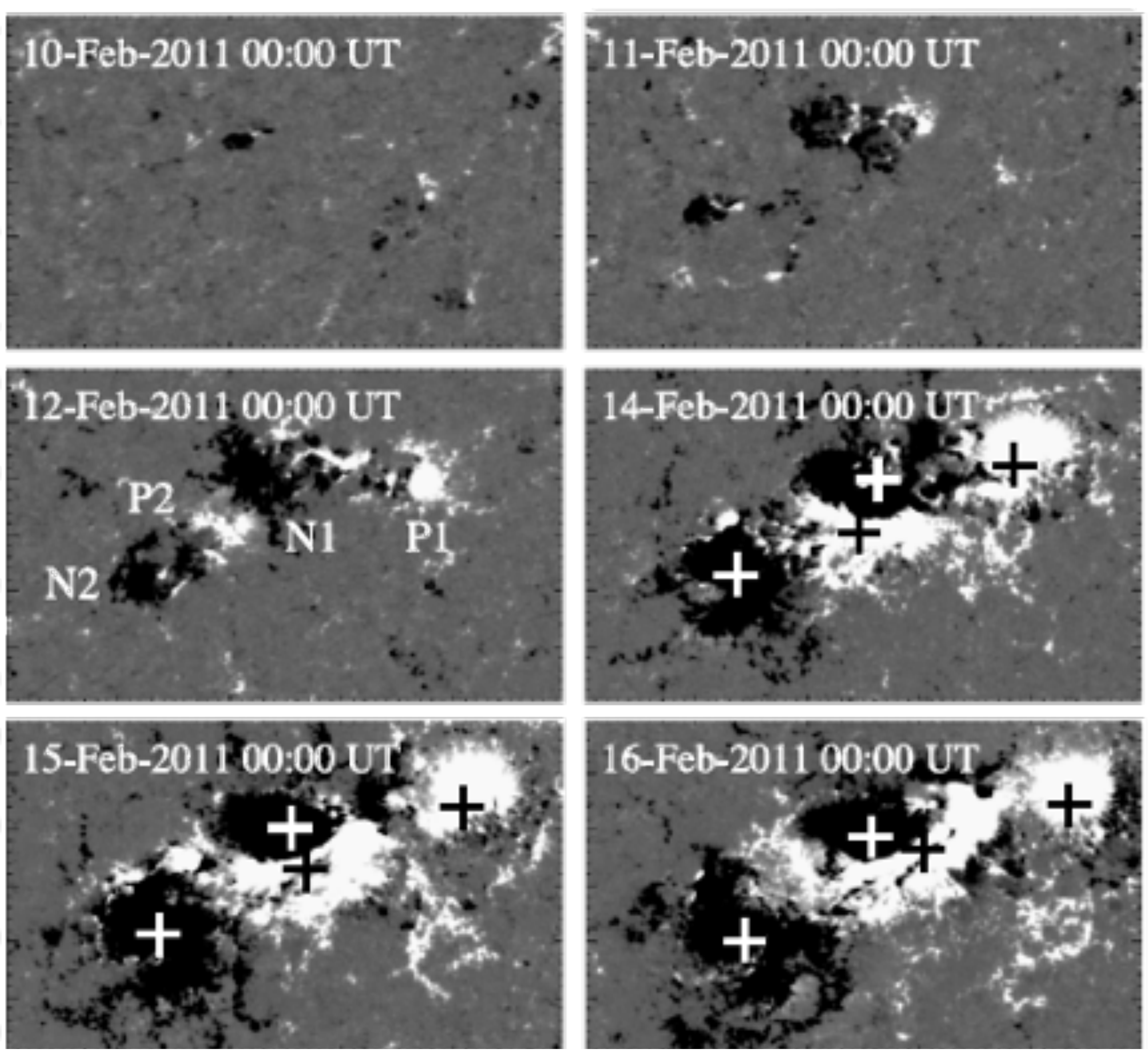
δ-spots: AR 11158

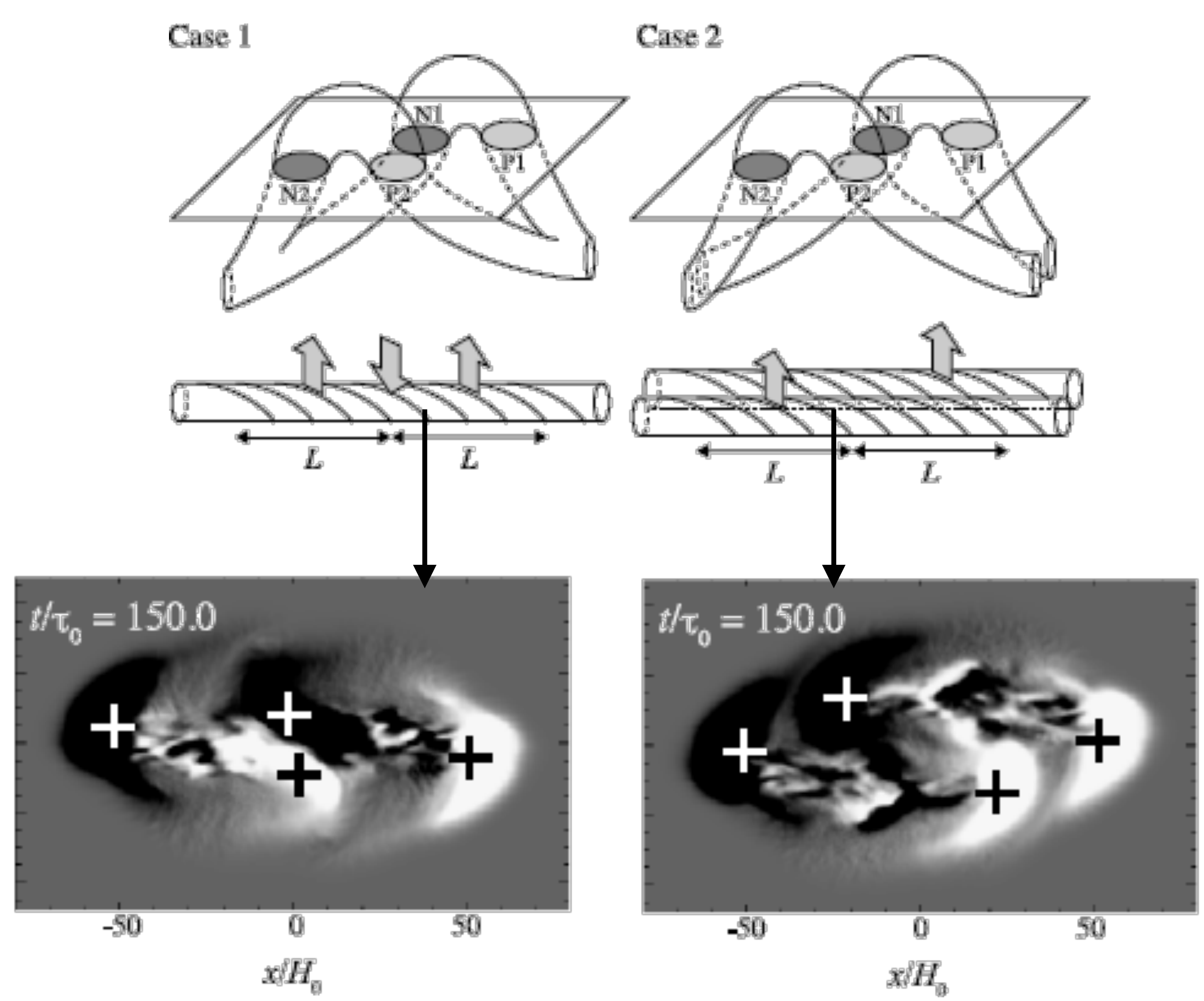


Sun et al. 2012

AR 11158: Simulations

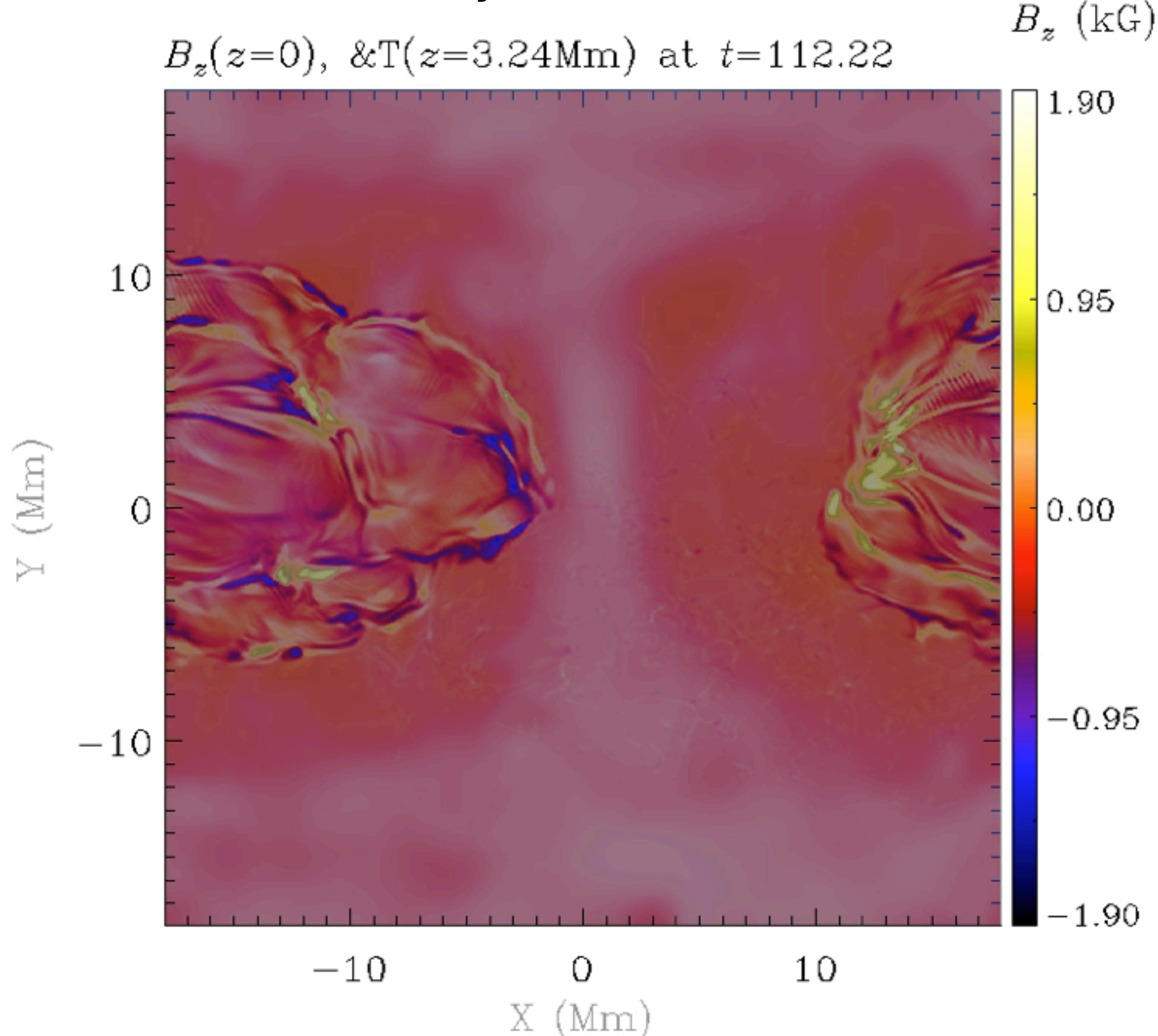
- Toriumi et al. 2014 compare two scenarios for the formation of AR 11158, with flux emergence from one and two flux ropes, respectively.





Toriumi et al. 2014

Chatterjee et al. 2016



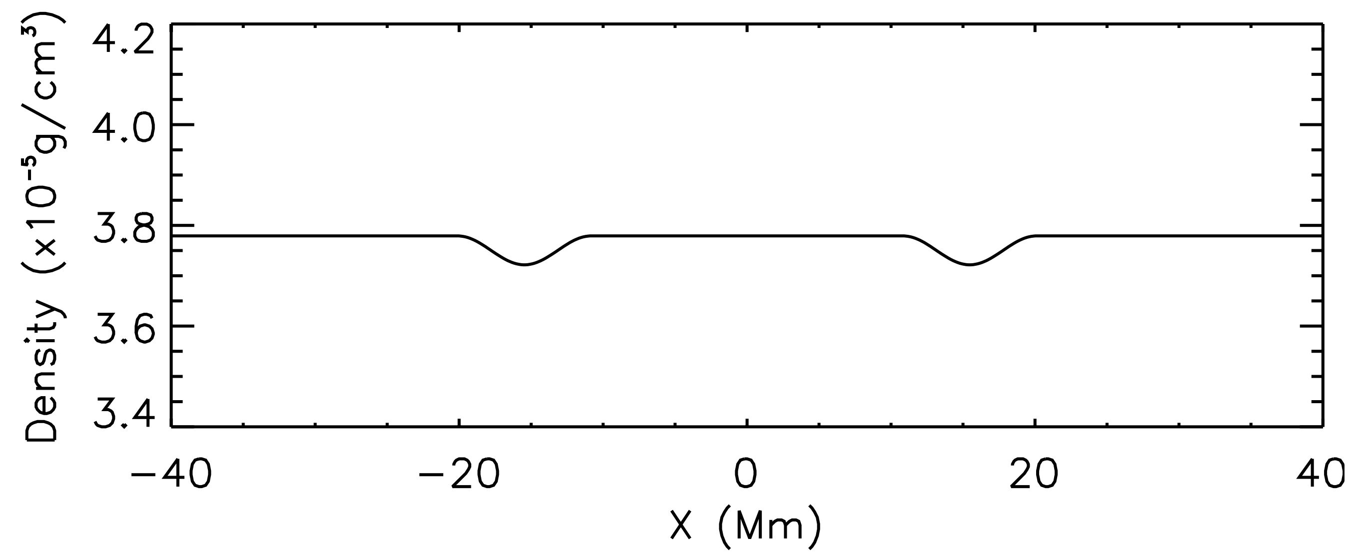
Experiment Setup

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0,$$

$$\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot \left[\rho \mathbf{u}\mathbf{u} + \left(p + \frac{\mathbf{B}\mathbf{B}}{8\pi} \right) \mathbf{I} - \frac{\mathbf{B}\mathbf{B}}{4\pi} \right] = \rho \mathbf{g},$$

$$\frac{\partial E}{\partial t} + \nabla \cdot \left[\left(E + p + \frac{\mathbf{B}\cdot\mathbf{B}}{8\pi} \right) \mathbf{u} - \frac{(\mathbf{u}\cdot\mathbf{B})\mathbf{B}}{4\pi} \right] = 0,$$

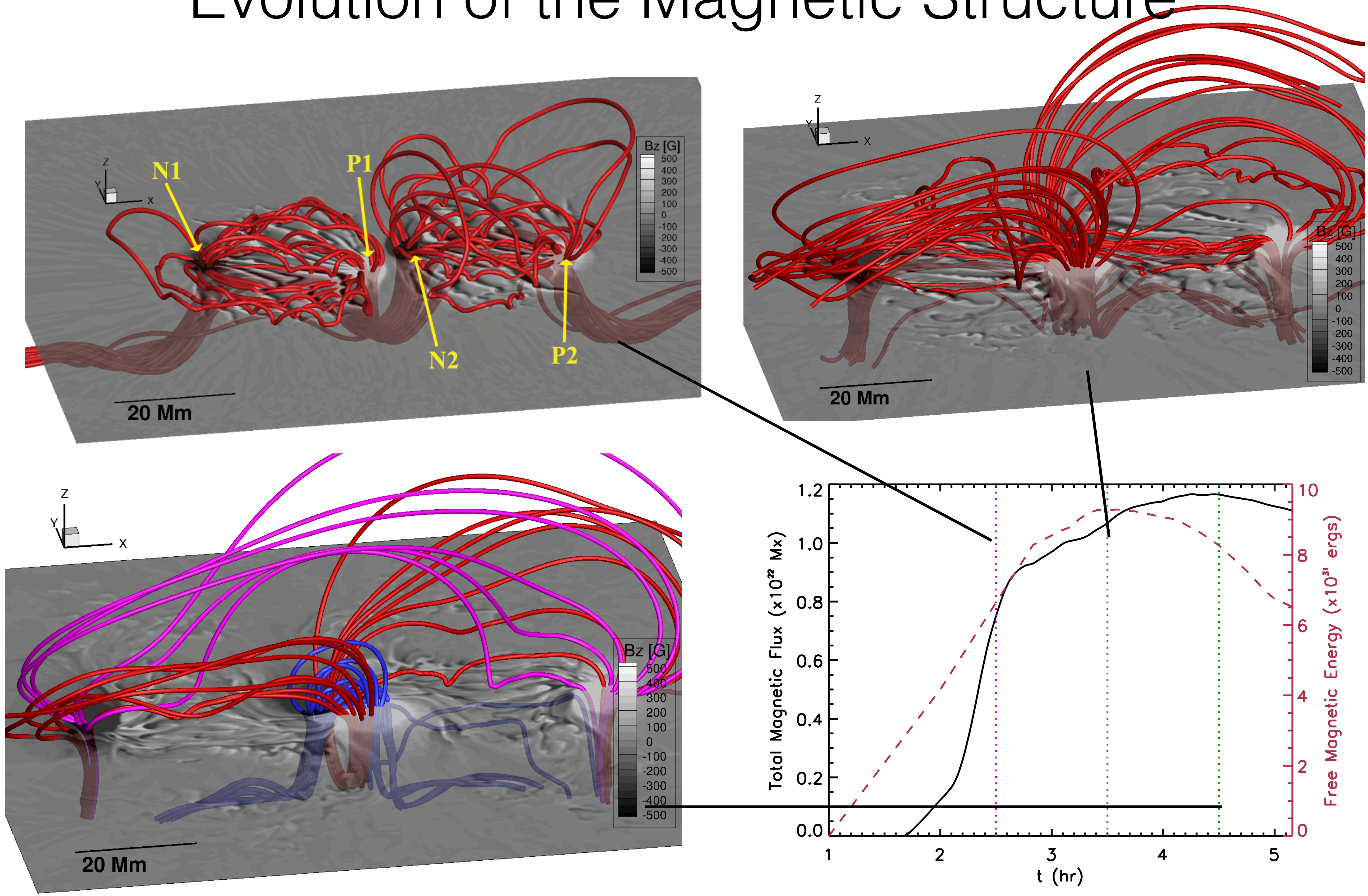
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}),$$



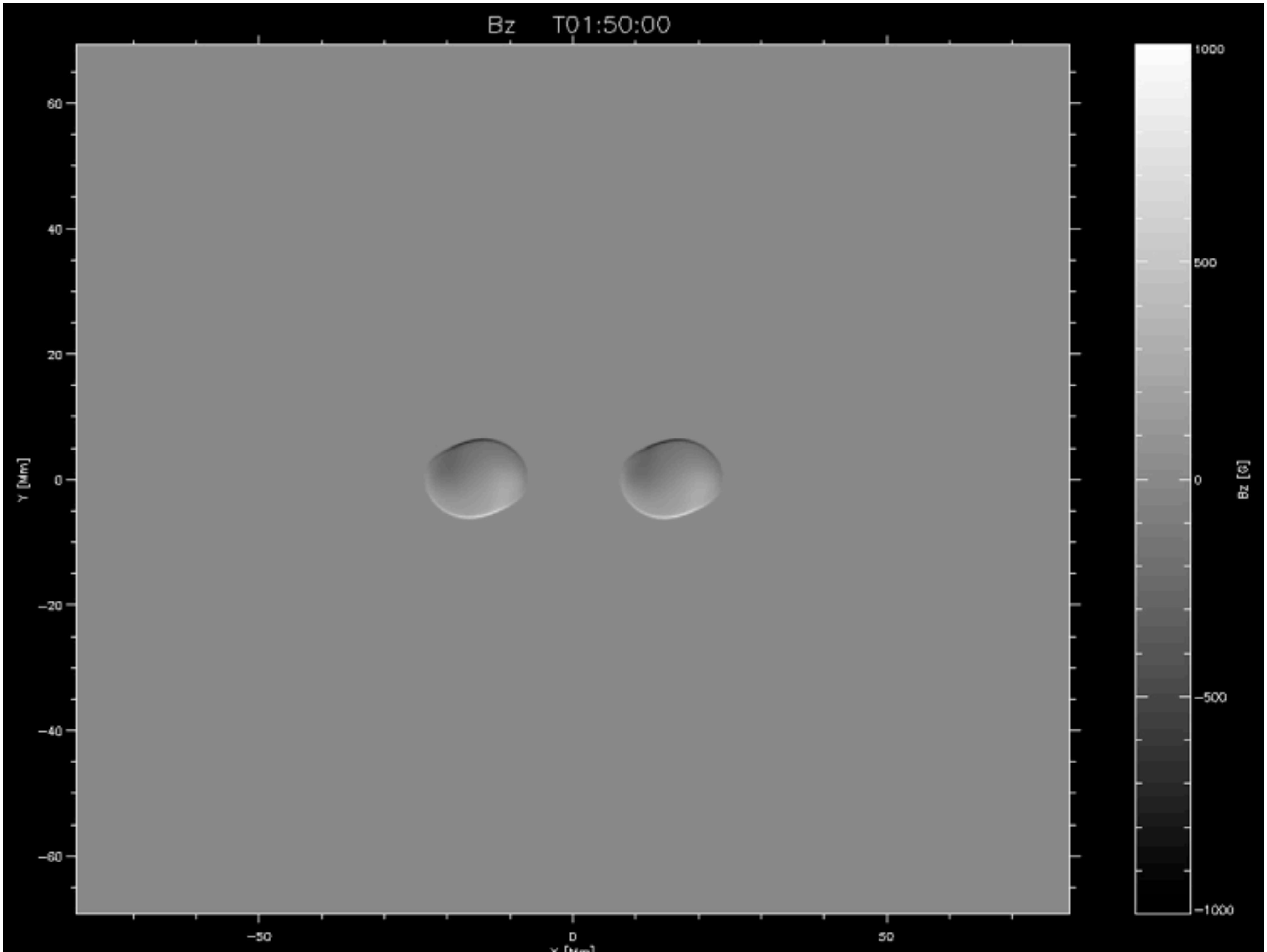
- 3D domain of 158×138×79 Mm^3 with 20 Mm of convection zone and 59 Mm of atmosphere
- Vertical cell size ranging from 38- 616 km
- Insert a buoyant twisted kink-stable magnetic flux rope into z = -10 Mm with $B_{central}$ = 12 kG, R = 3 Mm, $\Phi = 3.4\times10^{21}$ Mx, β = 66.

Fang & Fan, 2015

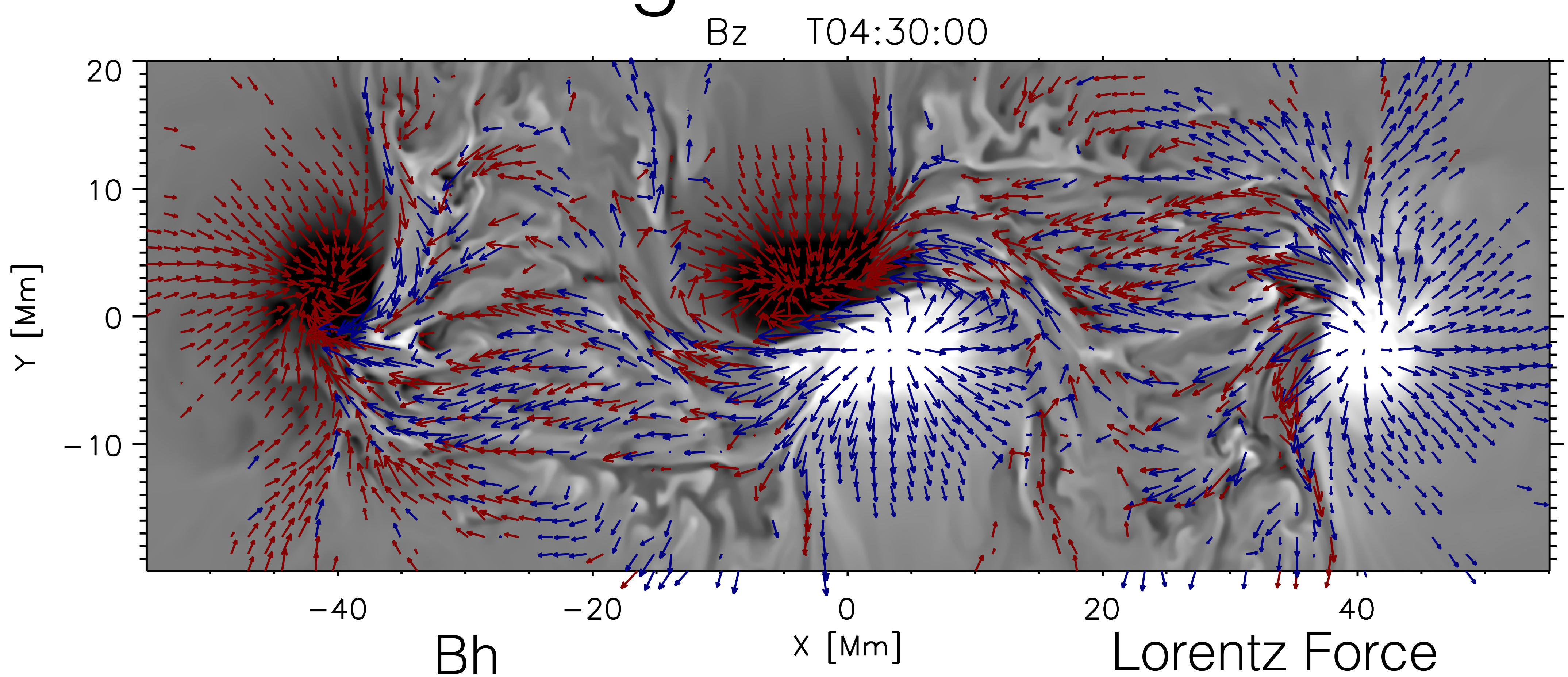
Evolution of the Magnetic Structure



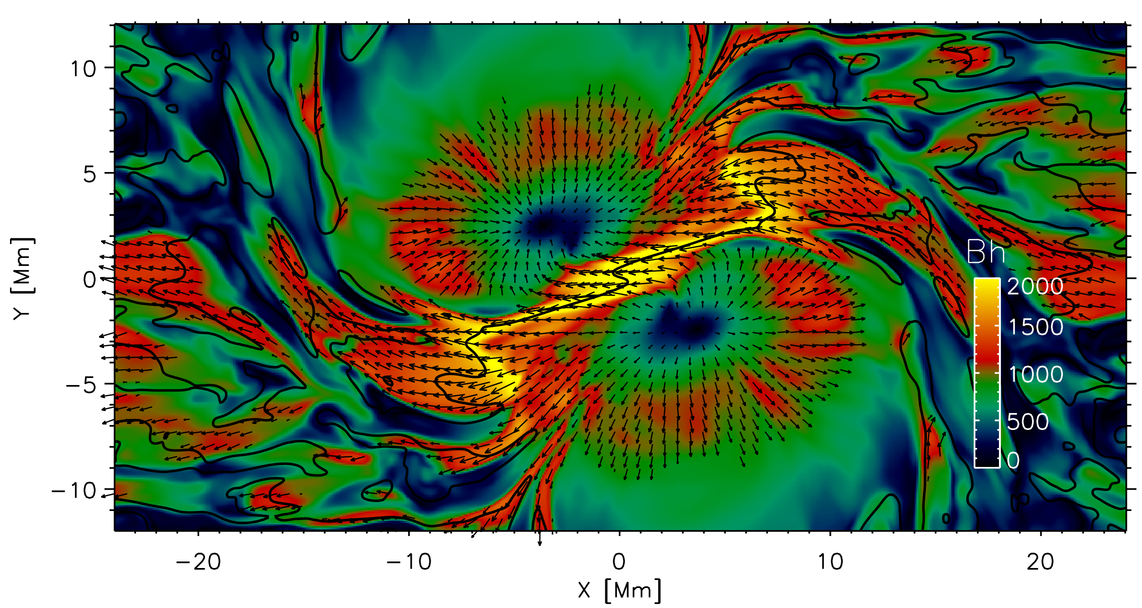
Flux Emergence on the Photosphere



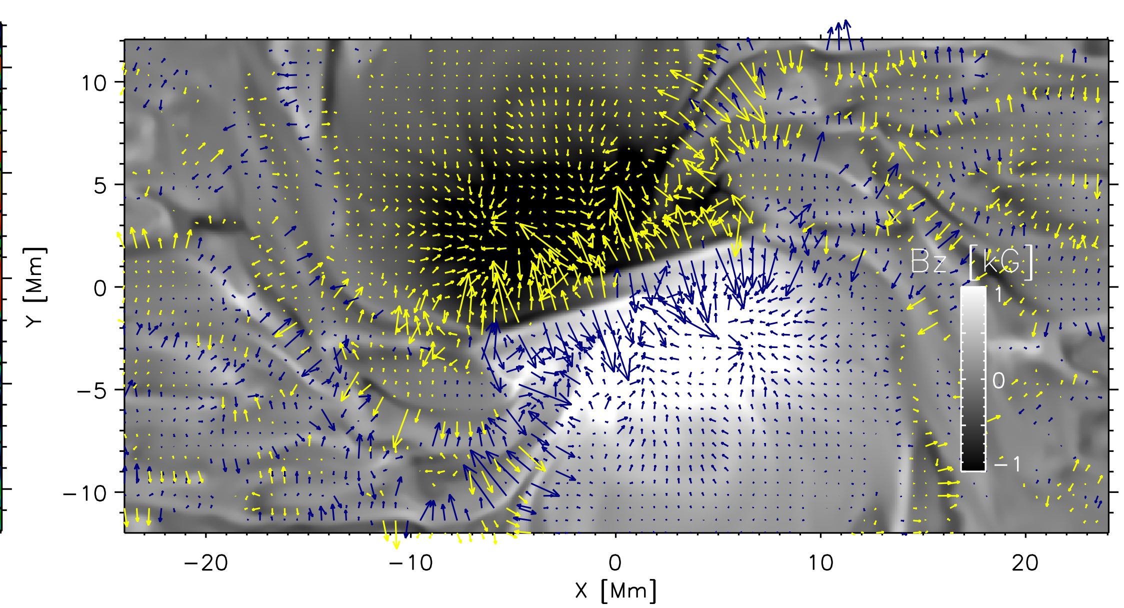
Magnetic Fields



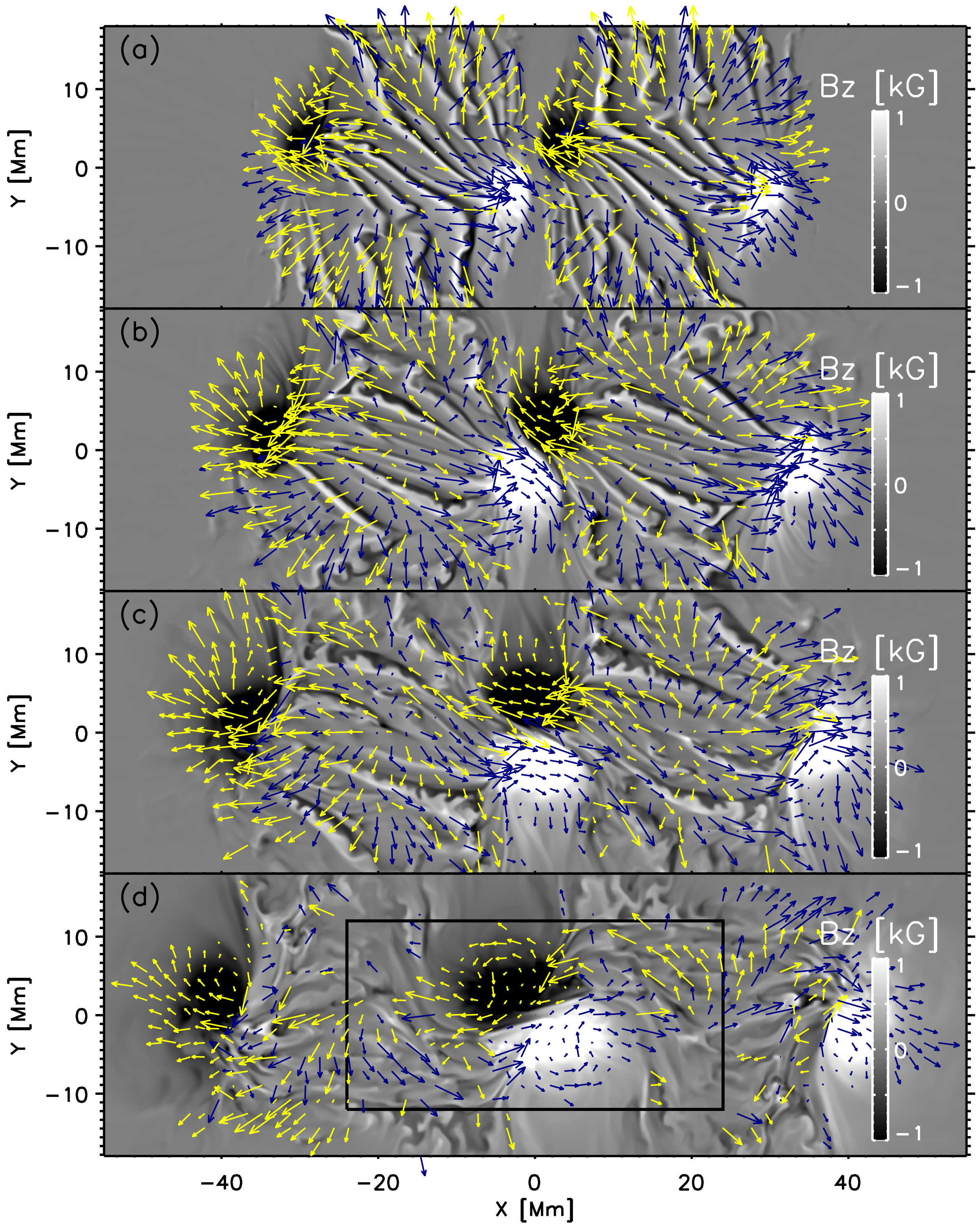
Bh



Lorentz Force

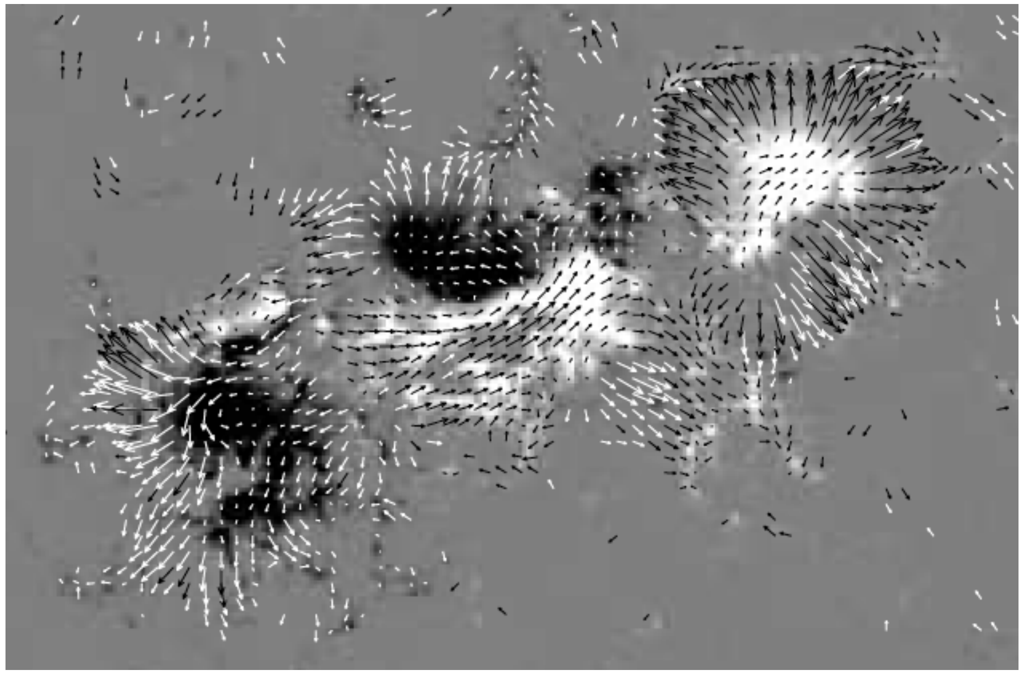


Photospheric Motions

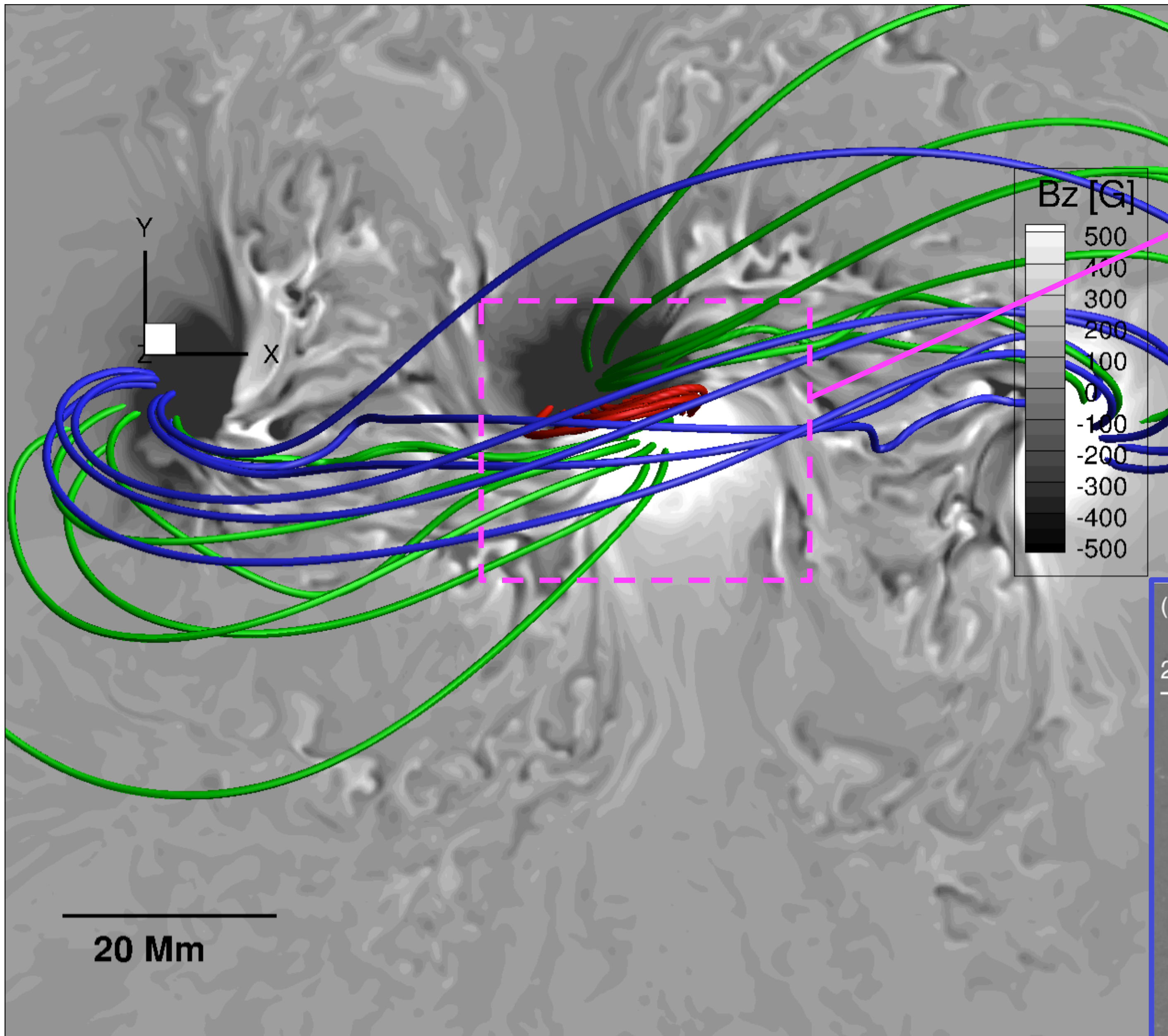


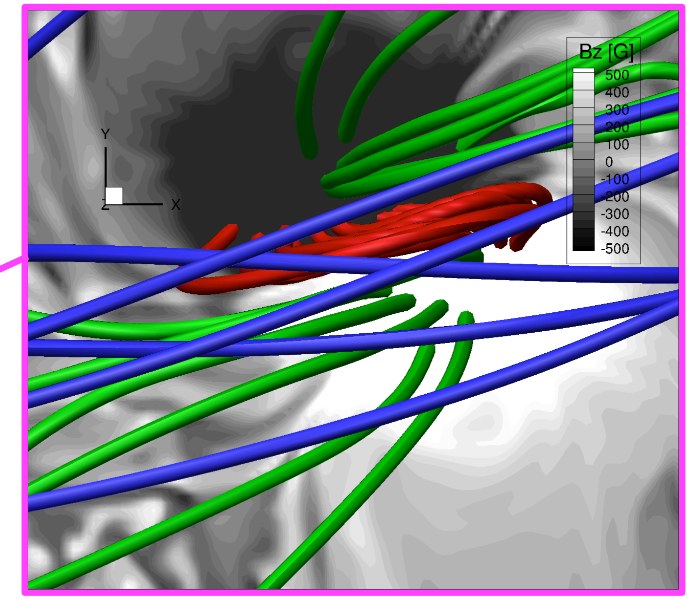
- Strong shearing motion at the PIL -- curvilinear path (Tang 1983)
- Rotation of the spots in the two ends
- Convergence at the periphery of the δ-spots

AR 11158 (Liu et al. 2012)

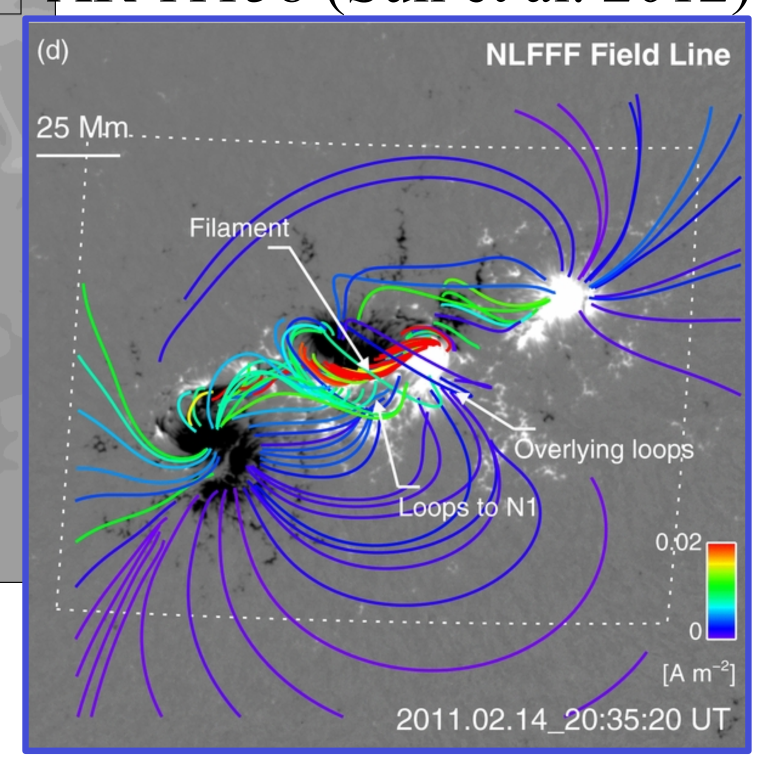


Coronal Magnetic Fields





AR 11158 (Sun et al. 2012)



Summary

- Simulations of global convective dynamo produce magnetic fields of super-equipartition strength.
- The overshoot layer may serve as a reservoir for strong large-scale magnetic fields.
- Near-surface simulations of flux emergence show the formation of a δ-spot active region by a pre-existing subsurface configuration.
- Collision of non-paired spots generates sharp PIL in the delta-spot with a reversed polarity to Hale's law.

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