Flux Emergence and Active Region Formation

Robert Stein – Michigan State Univ., USA

Åke Nordlund – Niels Bohr Inst., DK

This work is supported by NSF grants: OCI 1144506, AGS 1141921 and NASA grants: NNX12AH49G, NNX12AD05A

3D movies were made by Patrick Moran and Timothy Sandstrom of the NASA Ames Research Center visualization group, 2D movies were made by Bob Stein

Our goal: Understand how magnetic fields emerge through the upper convection zone?

Outline

1. Simulation setup
2. Flux emergence
3. Subsurface Spot Structure

Magneto-Hydrodynamic Equations

- Mass conservation

  $\partial\rho/\partial t = -\nabla \cdot (\rho \mathbf{u})$

- Momentum conservation

  $\partial(\rho\mathbf{u})/\partial t = -\nabla\cdot(\rho\mathbf{u}\mathbf{u}) - \nabla P - \rho\mathbf{g} + \mathbf{J}\times\mathbf{B} - 2\rho\boldsymbol{\Omega}\times\mathbf{u} - \nabla\cdot\tau_{visc}$

- Energy conservation

  $\partial e/\partial t = -\nabla\cdot(e\mathbf{u}) - P(\nabla\cdot\mathbf{u}) + Q_{rad} + Q_{visc} + \eta\mathbf{J}^2$

- Induction equation & Ohms law

  $\partial\mathbf{B}/\partial t = -\nabla \times \mathbf{E}, \quad \mathbf{E} = -\mathbf{u}\times\mathbf{B} + \eta\mathbf{J} + (1/en_e)(\mathbf{J}\times\mathbf{B} - \nabla P_e),$

6th order Finite Differences

$$f'_{i+1/2,j,k} = \frac{a}{\Delta x}(f_{i,j,k} - f_{i+1,j,k}) + \frac{b}{\Delta x}(f_{i-1,j,k} - f_{i+2,j,k}) + \frac{c}{\Delta x}(f_{i-2,j,k} - f_{i+3,j,k}) \ ,$$

where

$$c = 3/640, \ b = -1/24 - 5c, \ a = 1 - 3b + 5c \, .$$

5th order Interpolation

$$f_{i+\frac{1}{2},j,k} = a\left(f_{i,j,k} + f_{i+1,j,k}\right) + b\left(f_{i-1,j,k} + f_{i+2,j,k}\right) + c\left(f_{i-2,j,k} + f_{i+3,j,k}\right)$$

where

$$c = 3/256, \quad b = -25/256, \quad a = 0.5 - b - c$$

Numerical Method

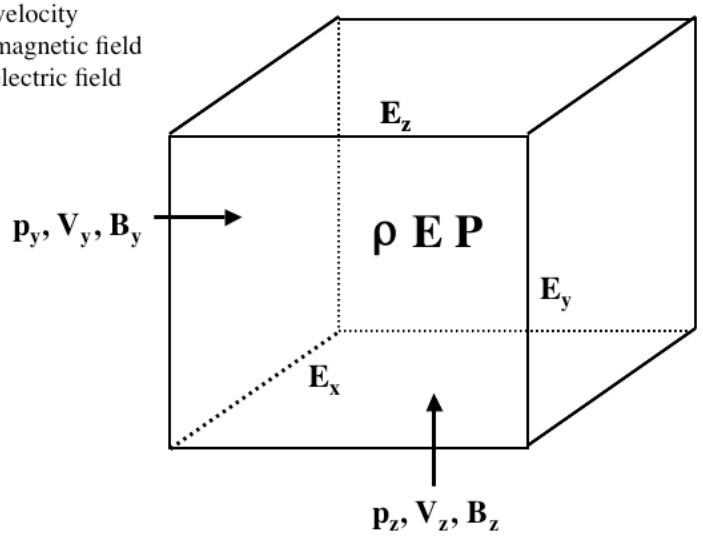
- Spatial differencing
  - 6th-order centered finite difference.
  - staggered
- Time advancement
  - 3rd order, low memory, Runga-Kutta
- Equation of state
  - tabular
  - including ionization
  - H, He + abundant elements
- Radiative transfer
  - 3D, LTE
  - 4 bin opacity distrib. Fctn.
- Diffusion

$$\left(\frac{\partial f}{\partial t}\right)_{diffisusion} = \left(\frac{\partial}{\partial x_i}\right)\left(\nu\alpha\left(\frac{\partial f}{\partial x_j}\right)\right)$$

$$\alpha = \Delta^3 / \max\left(\left|\Delta f\right|_{\{-2,-1,0,+1,+2\}}\right)$$

$$\nu_i = c_1(c_{sound}^2 + c_{Alfven}^2)^{1/2} + c_2\left|u_i\right| + c_3\left[(\Delta_3 u) < 0\right]\Delta x_i$$

ρ =density
E=energy
P=pressure
p_x=momentum
V_x=velocity
B_x=magnetic field
E_x=electric field

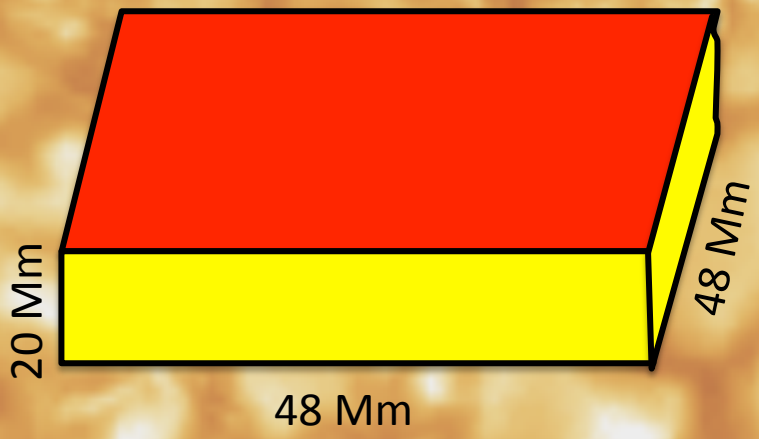


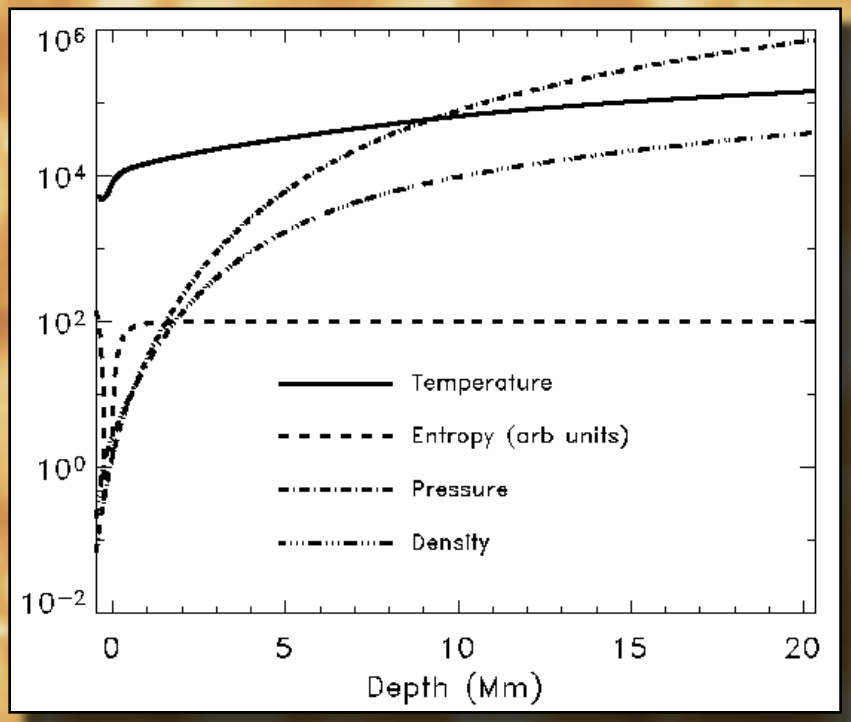
Variables used in solving the governing equations and their staggering.

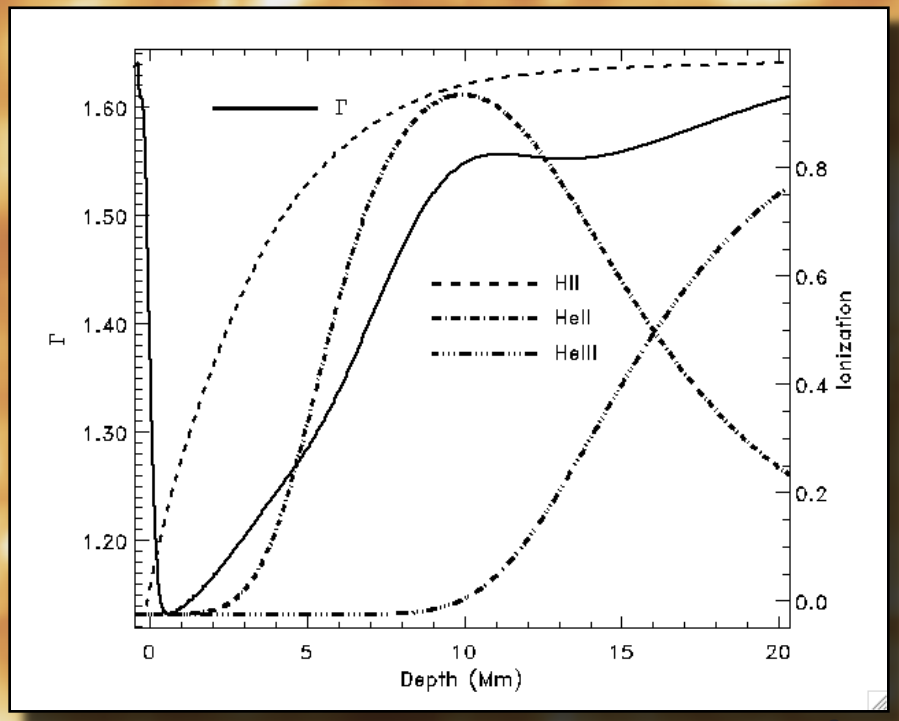
Simulation

Domain: 48 Mm wide, 20 Mm deep
Temperature minimum – 20 Mm depth
10 % geometric depth, 2/3 scale heights of convection zone

Resolution: 24 km horizontal, 12-80 km vertical







Boundary Conditions

- Vertical:
  - Density: Top extrapolate lnρ. Bottom-inflows fix rho, -outflows rho➔<rho>.
  - Velocity -> constant @ top, zero derivative @ bottom;
  - energy/mass Top: ➔ average value, Bottom: extrapolate <E>;
- B tends to potential field @ top,

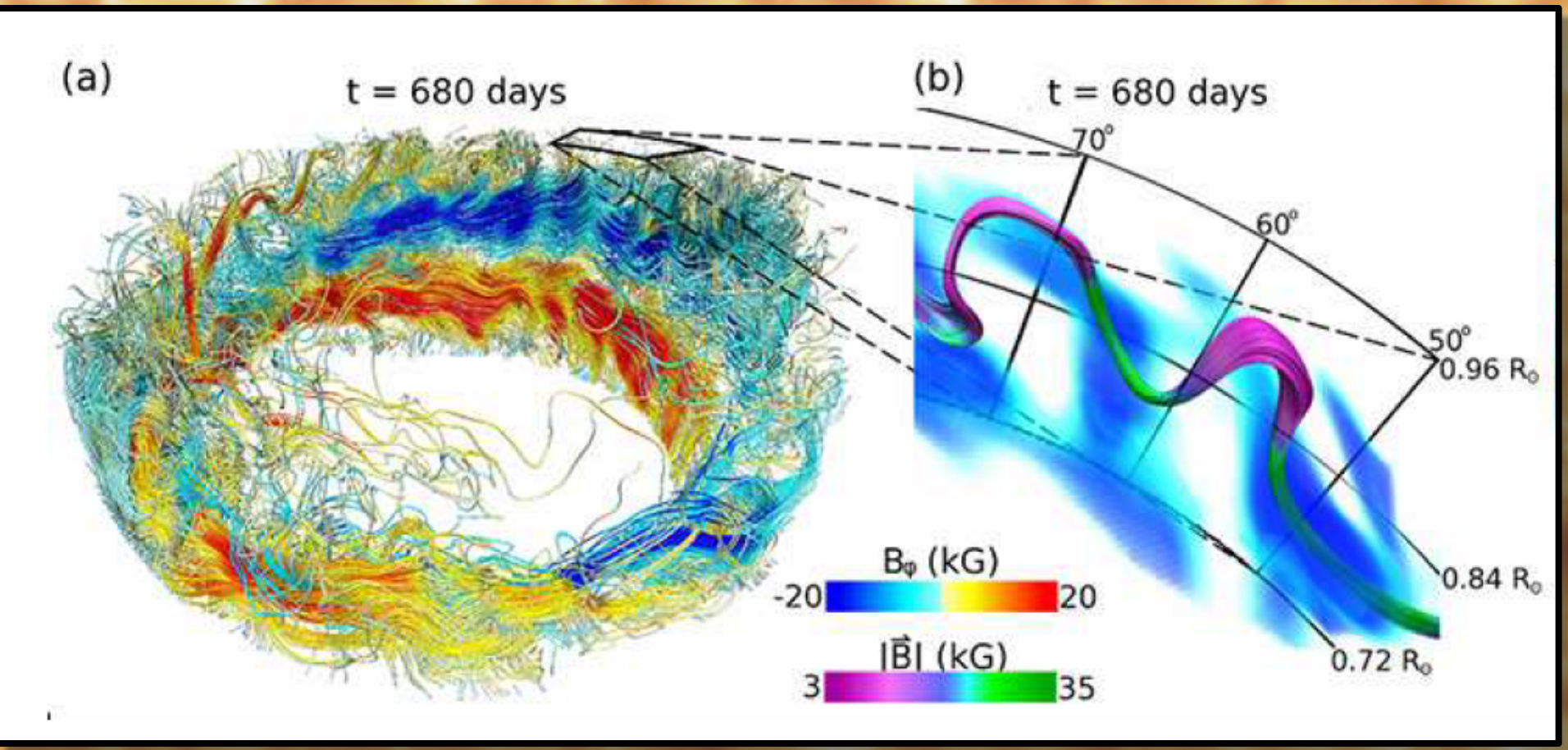
  B advected by Inflows @ bottom (20 Mm) --

  Weak (1 kG) or Strong (5 kG), minimally structured (horizontal, uniform, untwisted) magnetic field .
  Represents top of larger, rising flux concentration.

Source of Magnetic Flux: Dynamo

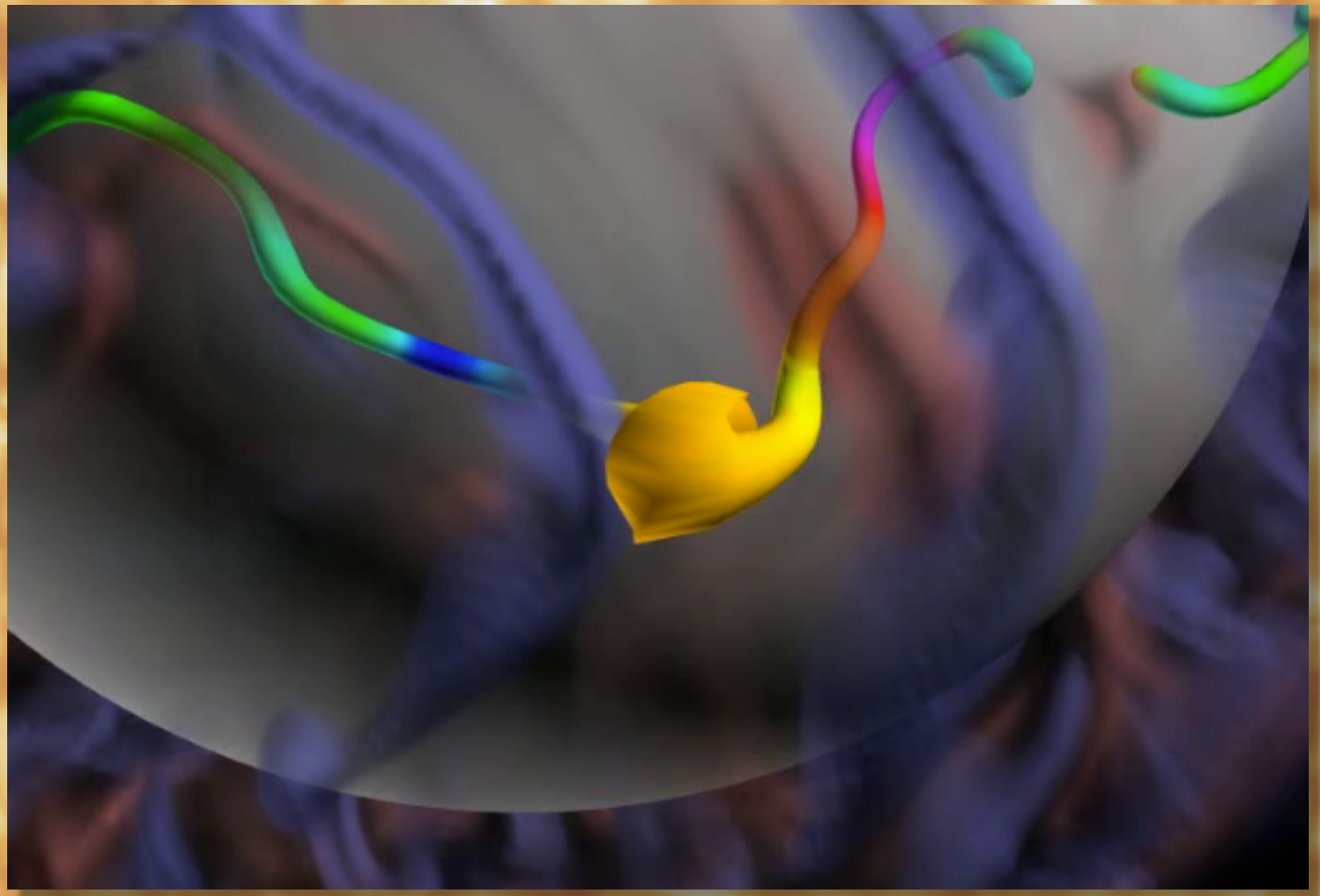
courtesy Nelson 2013

Where dynamo field is strong, buoyant loops form. Convective advection and buoyancy bring loops to the surface. Giant cell downflows hold down legs. Loops have scale of convection where they form. Model rise of these large-scale loops as horizontal field incident at bottom of surface computational domain.



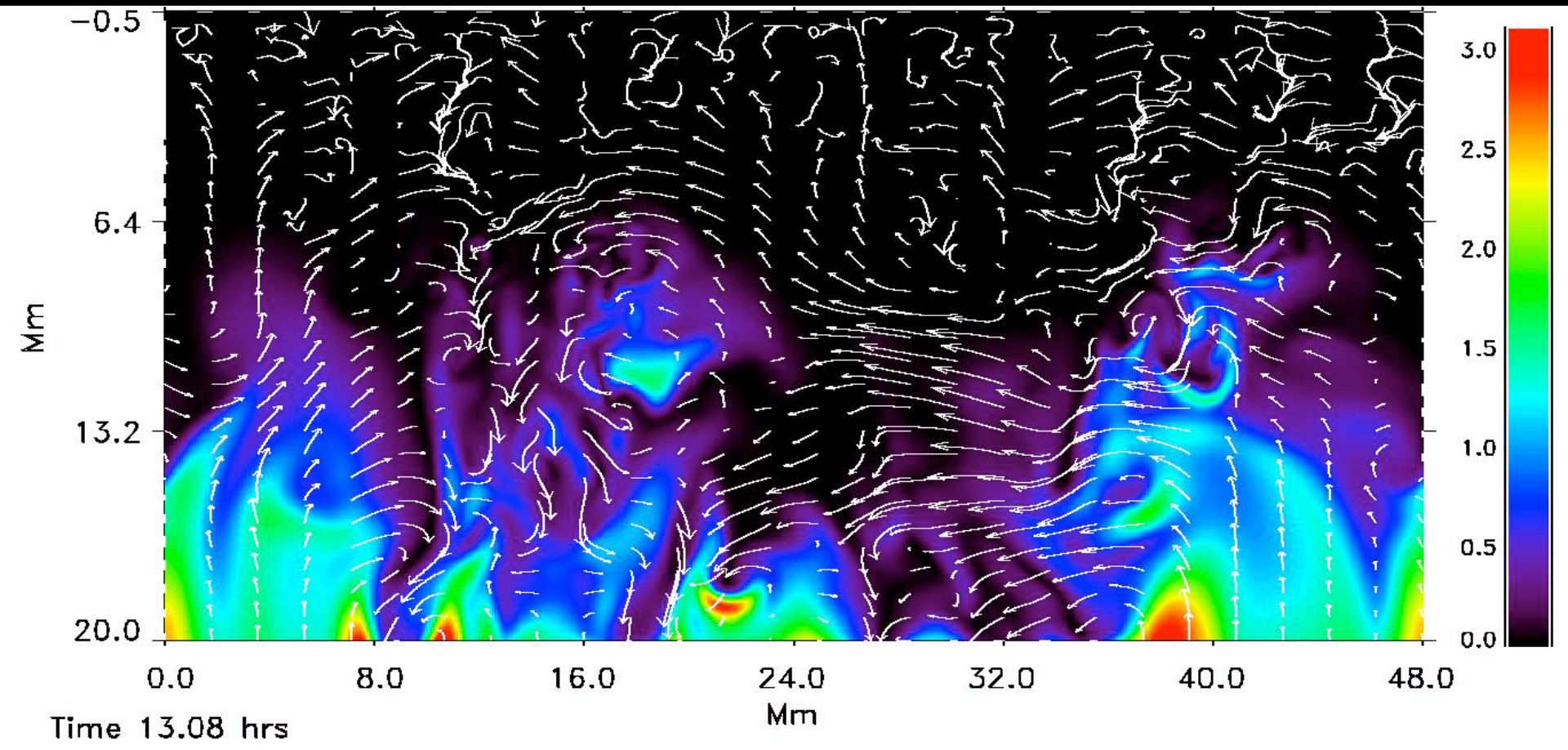
Even if flux tube rises from tachocline, tops of loops approaching the surface can be represented by horizontal field.

(from calculation of Maria Weber)



B.C. Horizontal, Uniform, Untwisted **B** advected into domain.

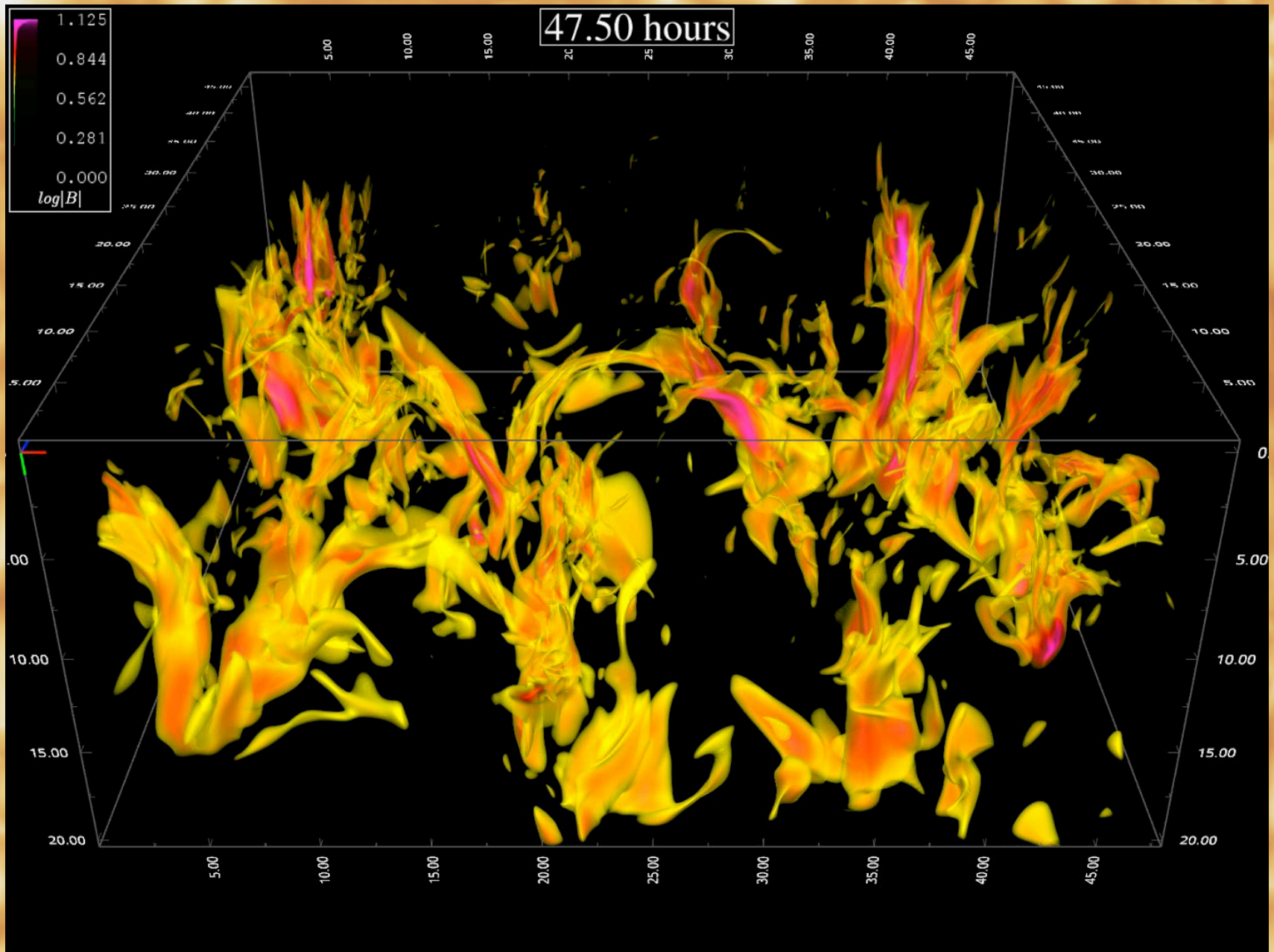
Upflows carry field toward surface, downflows push it down, producing loops.



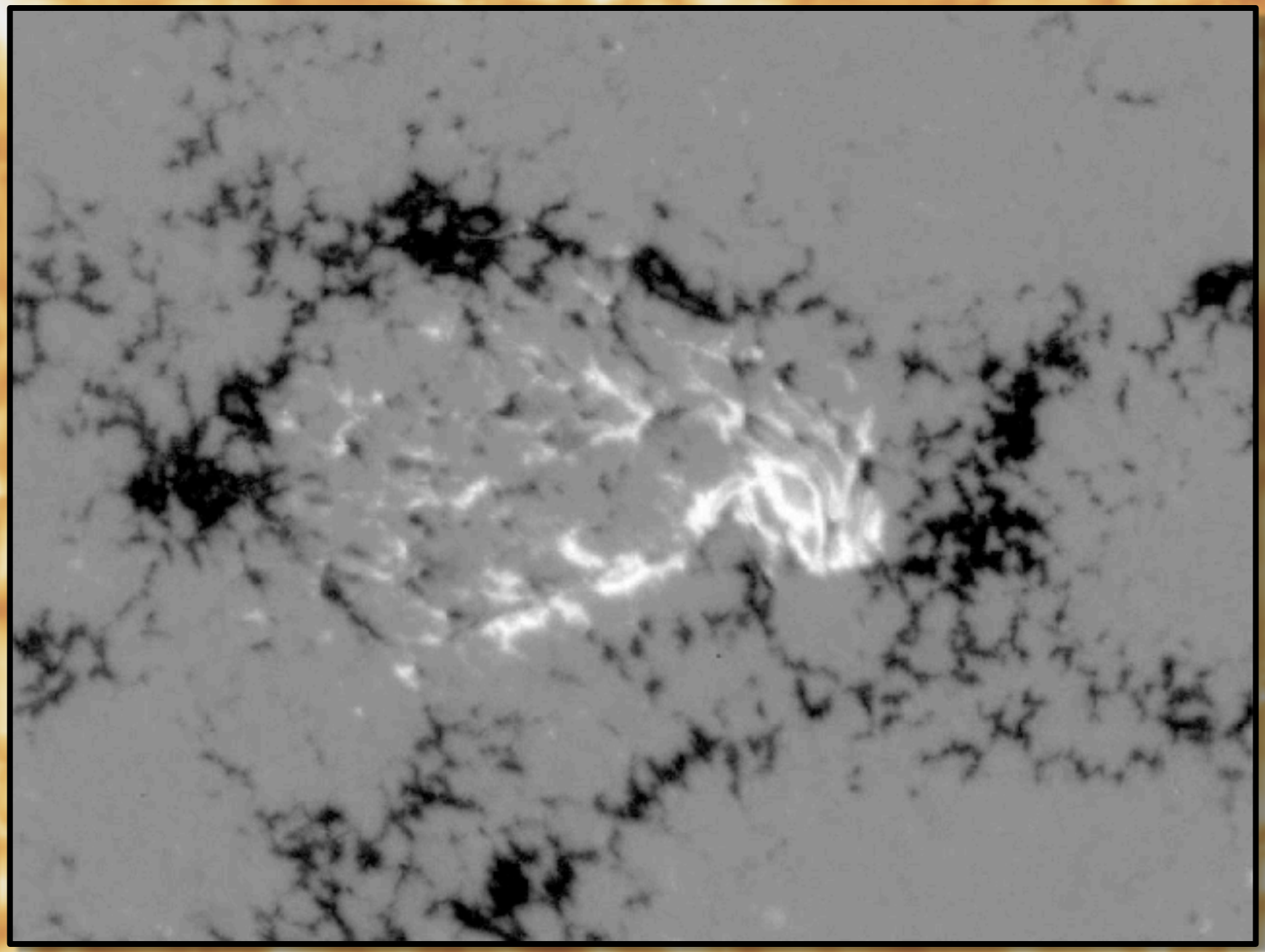
Vertical slice: |B| image, V arrows

Scale in kG

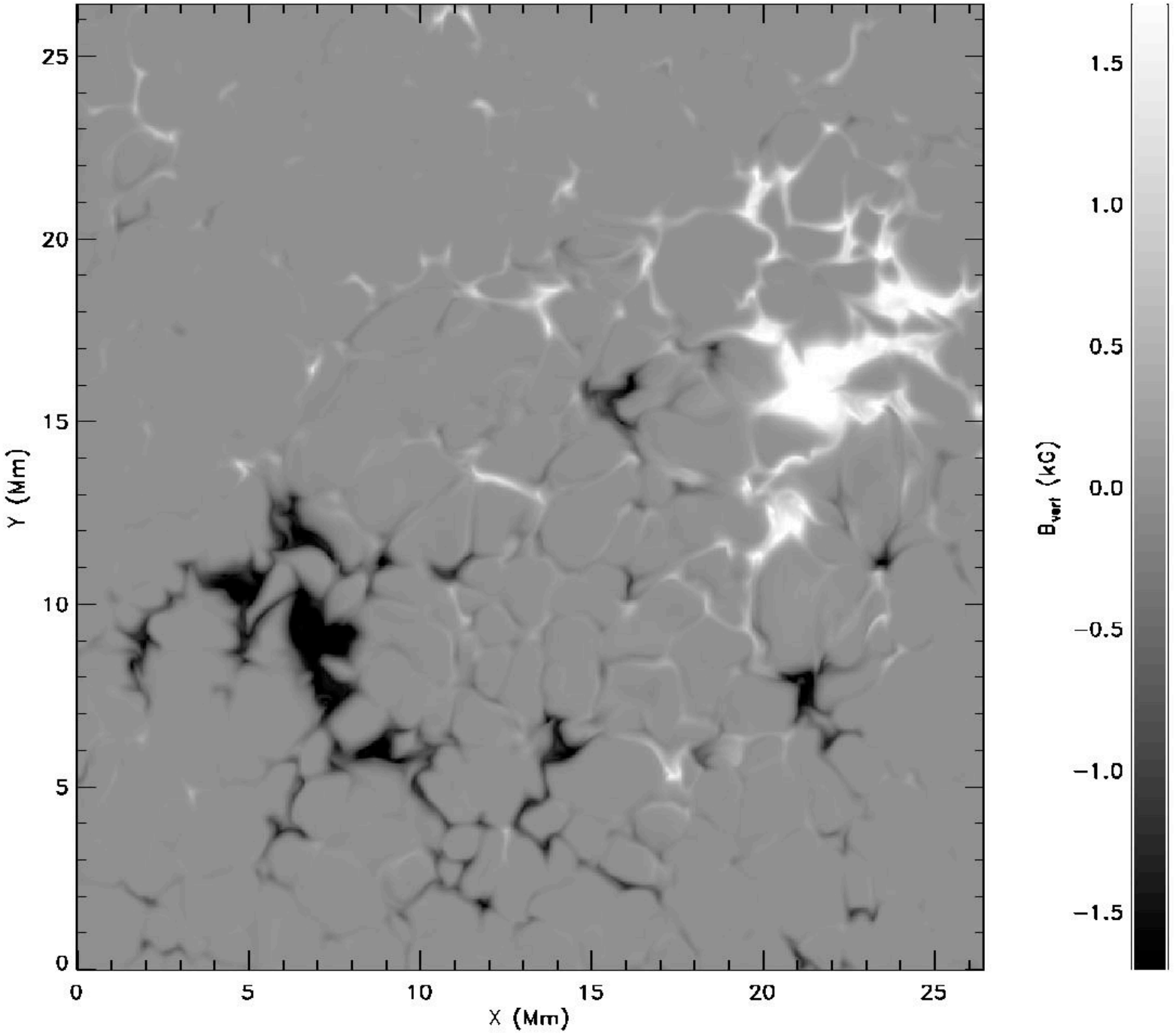
Convection advects flux toward surface & depth



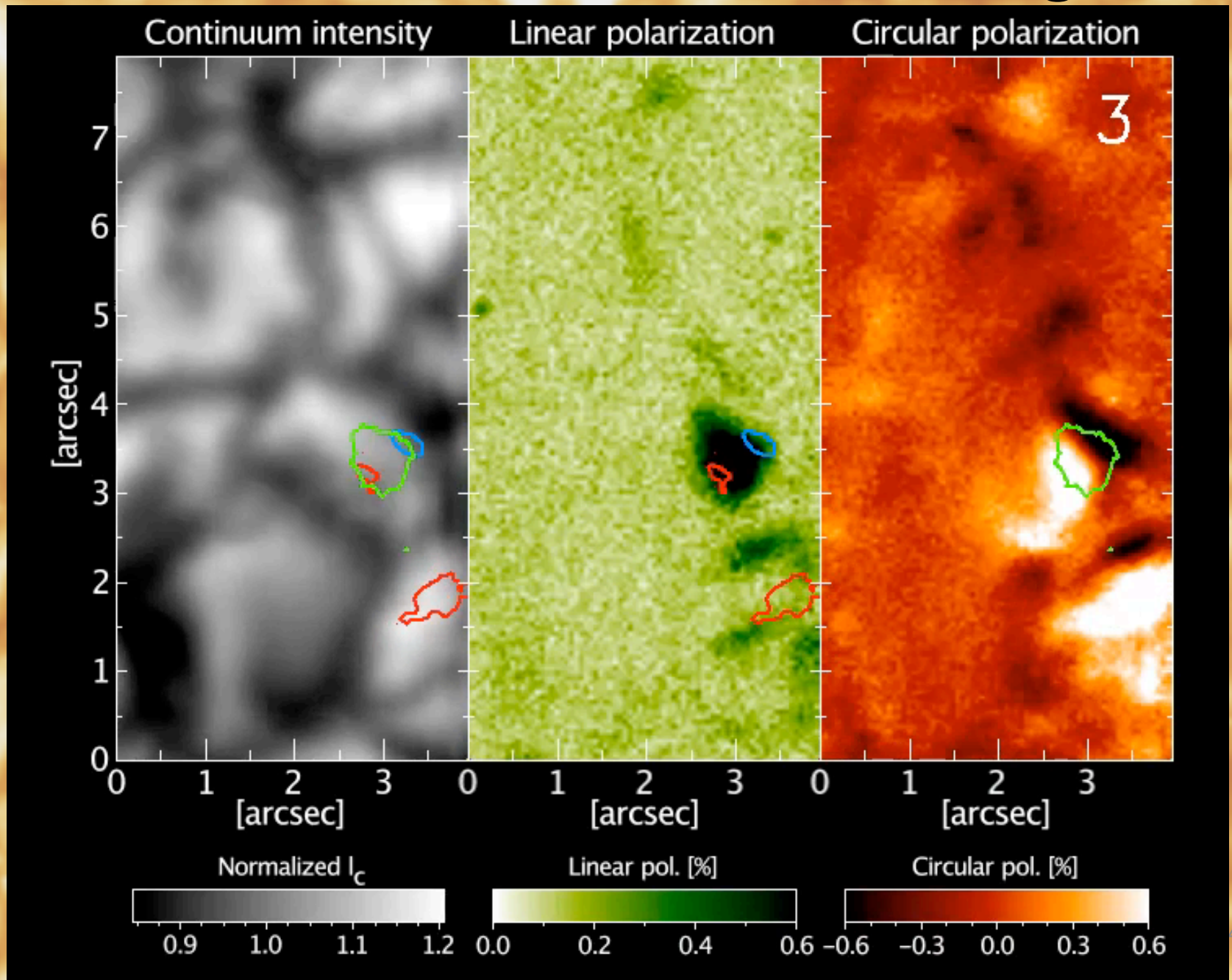
AR Flux Emergence (Hagenaar)



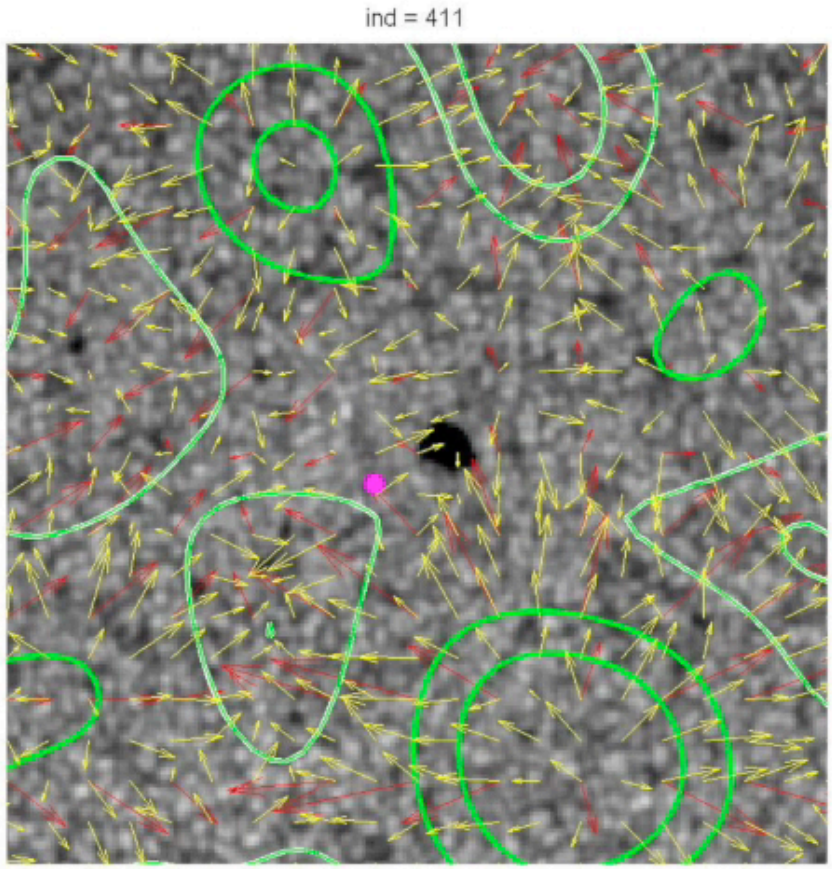
Magnetogram (Vertical B)

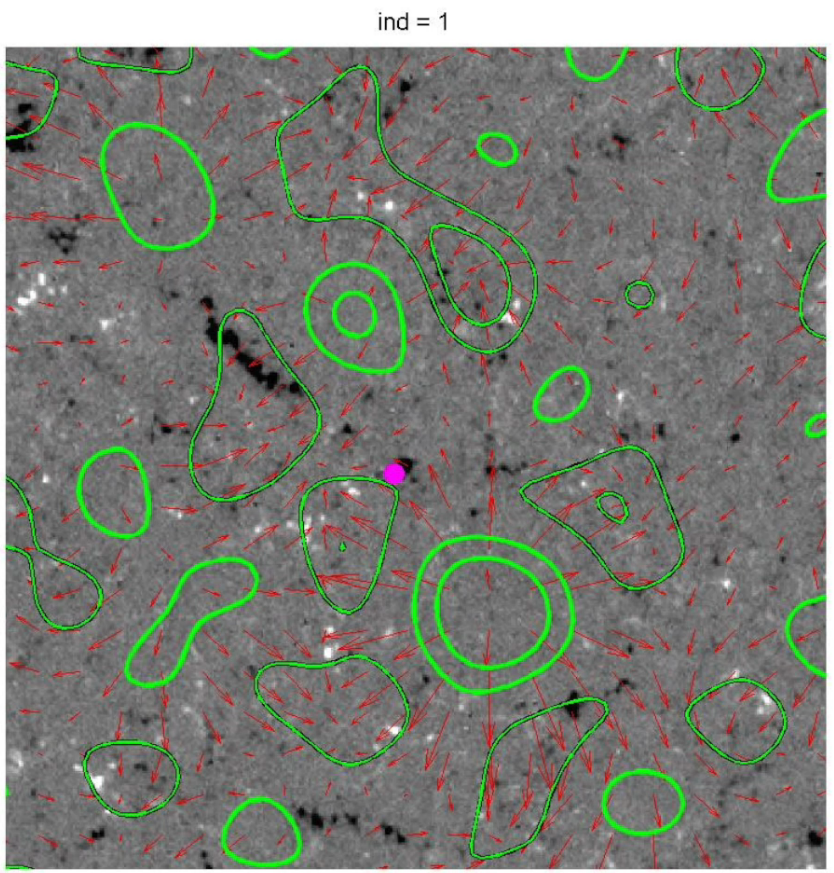


Sunrise observation of flux emergence



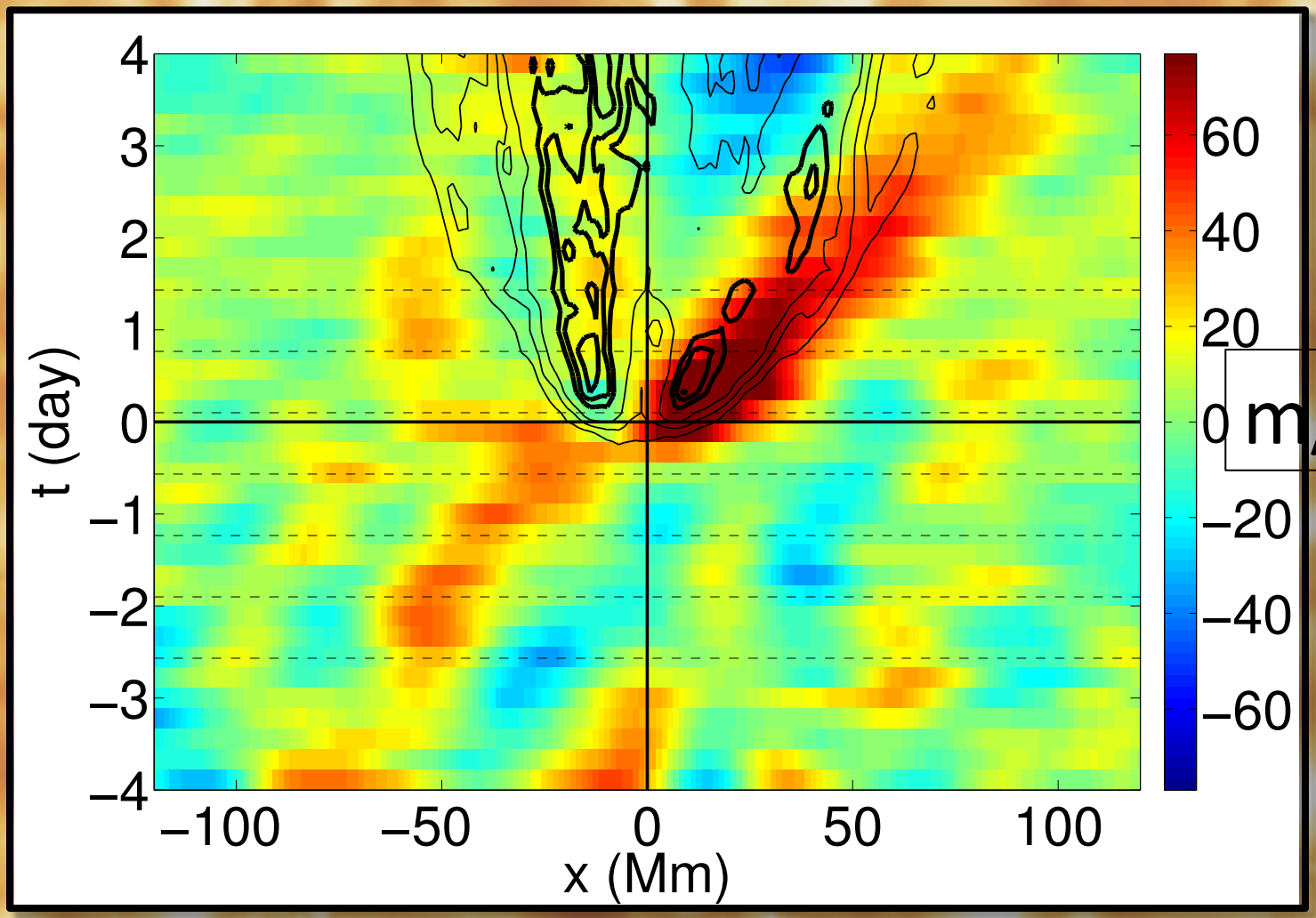
AR emerge in converging region at edge of supergranules





From Aaron Birch & Hannah Schunker

Strong fields first appear on a scale larger than granules but smaller than supergranules.



EW velocity and Magnetic field strength as a function of time since emrgence, average of 60 AR.

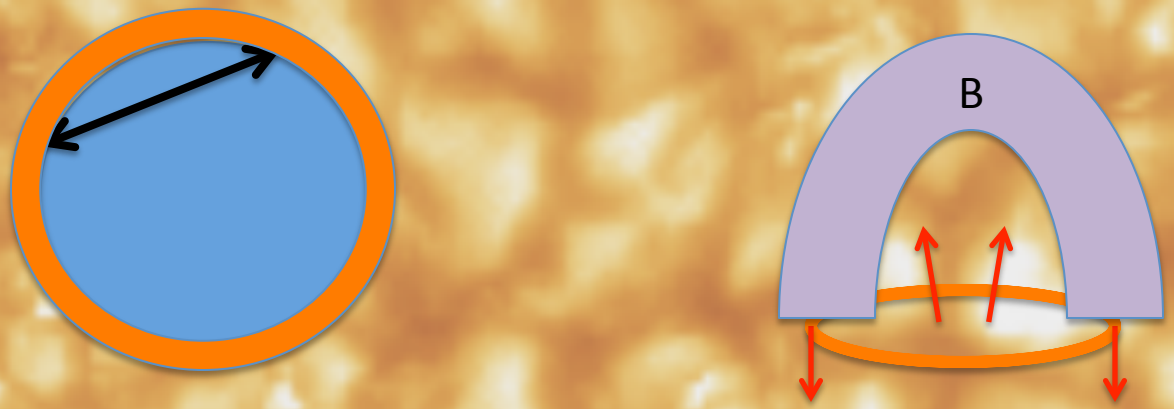
30 m/s feature
Noise ~ 10 m/s

Lowest B contour 40 G
Heavy contour 120 G

From Aaron Birch & Hannah Schunker

Speculation

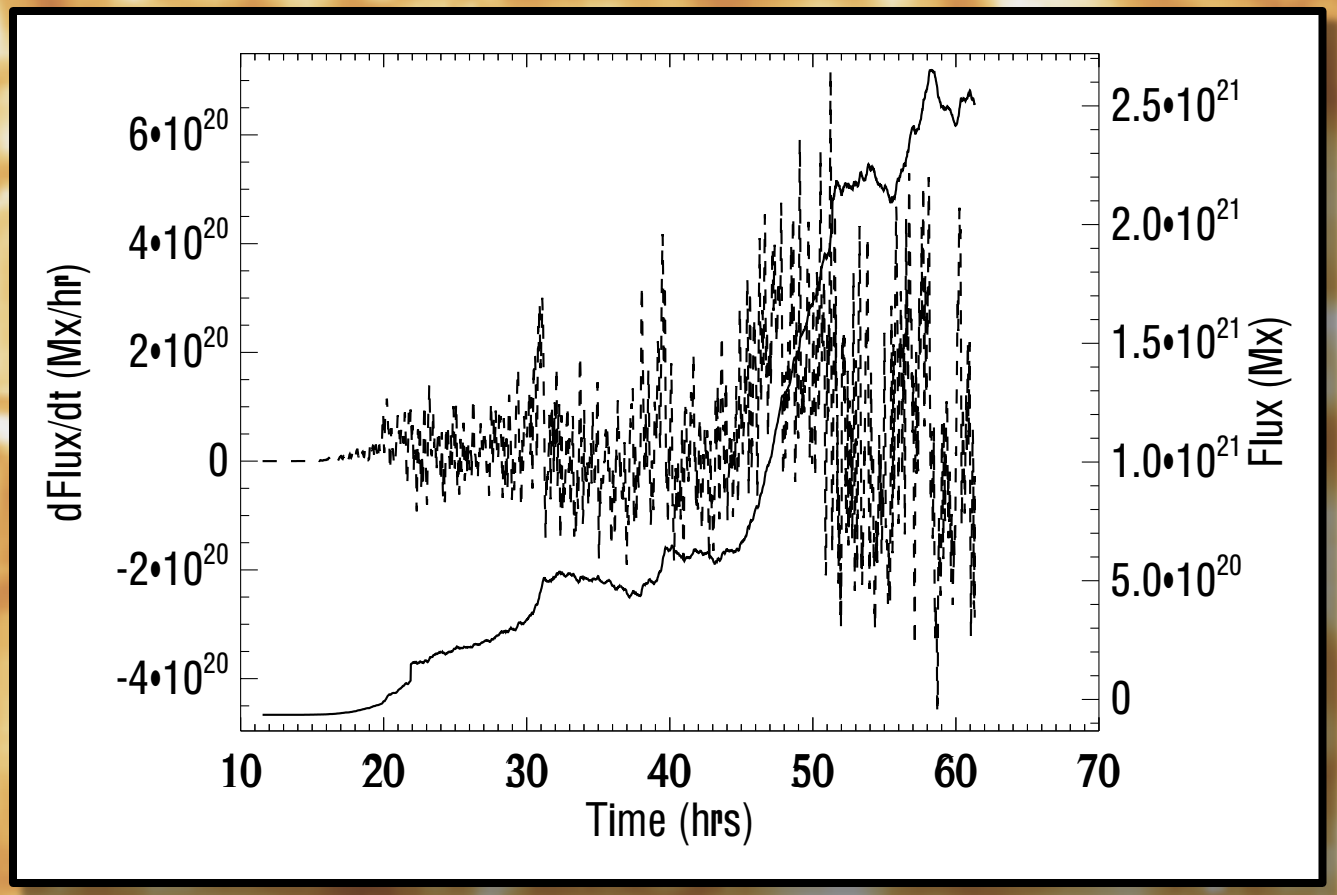
- AR form from a flux concentrations emerging over part of a supergranule or larger cell.

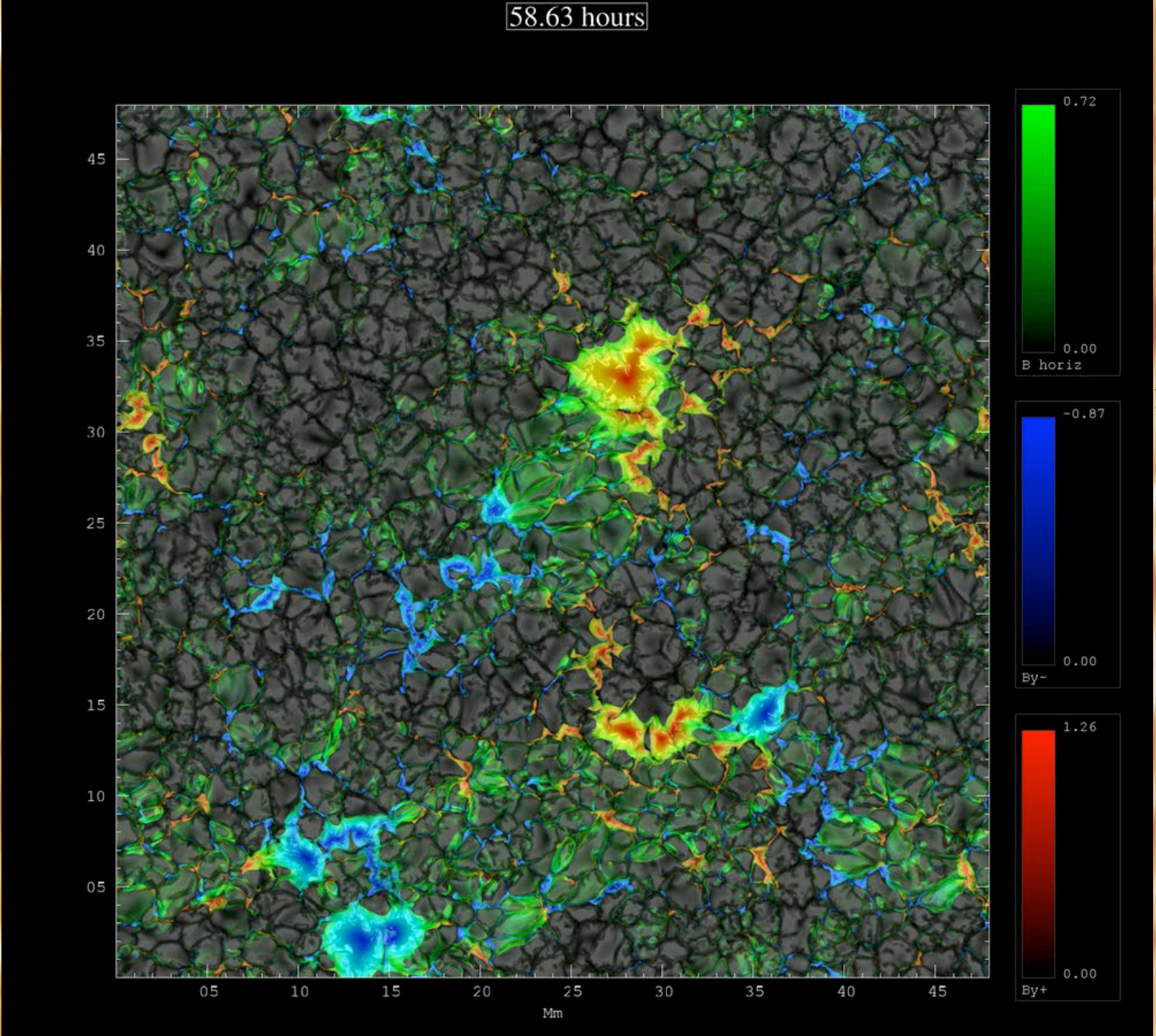


- The legs of an active region are rooted in some large convective cell. The largest separation observed should indicate the minimum size of the convective cell where the legs are rooted and hence a minimum depth where the spots are rooted.

Weak, Non-buoyant, Field

Total Unsigned Vertical Flux

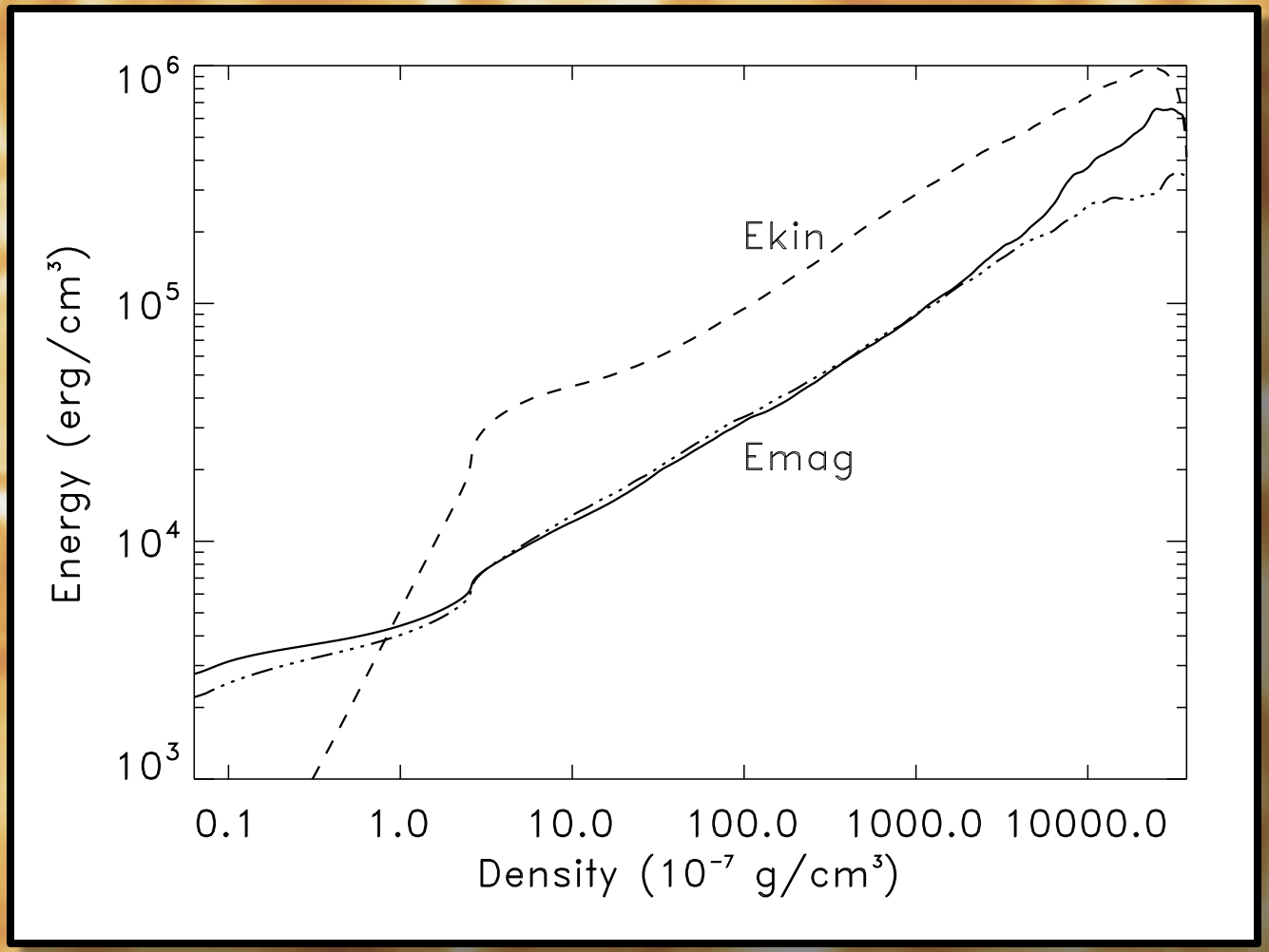




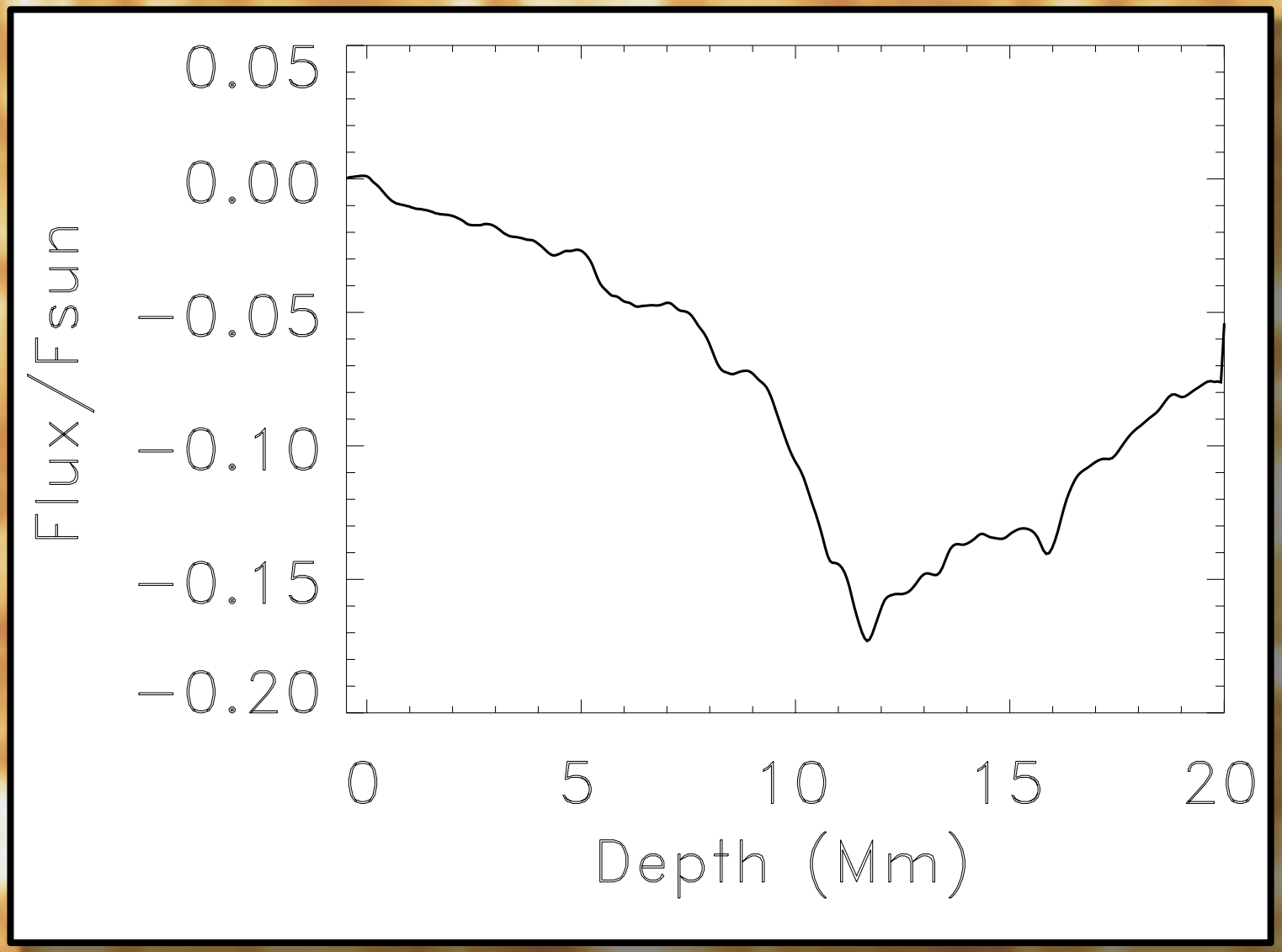
B_V: red,blue
B_H: green

B emerges in localized patches. B_H emerges over granules, B_V at ends in lanes

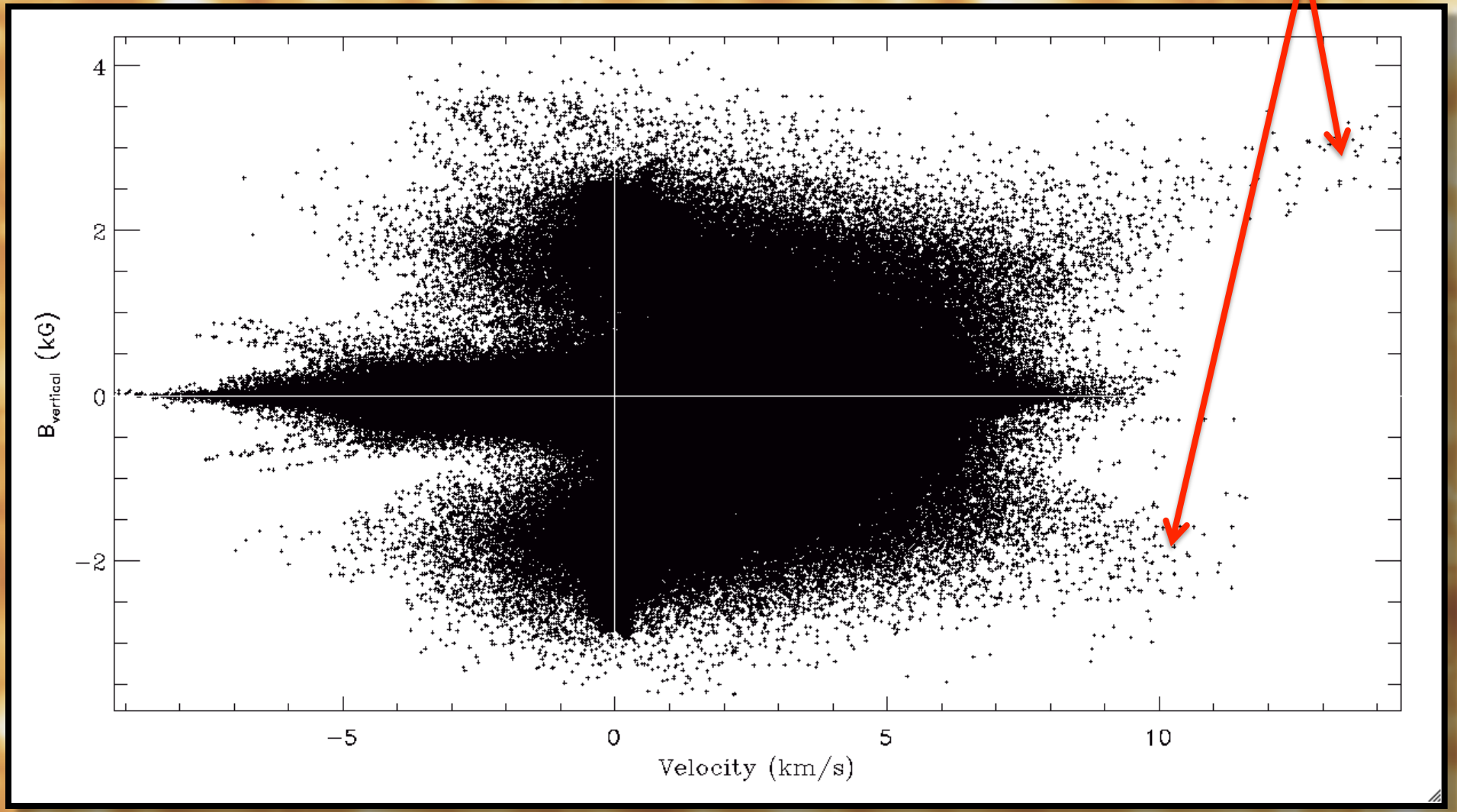
Field is power law in density



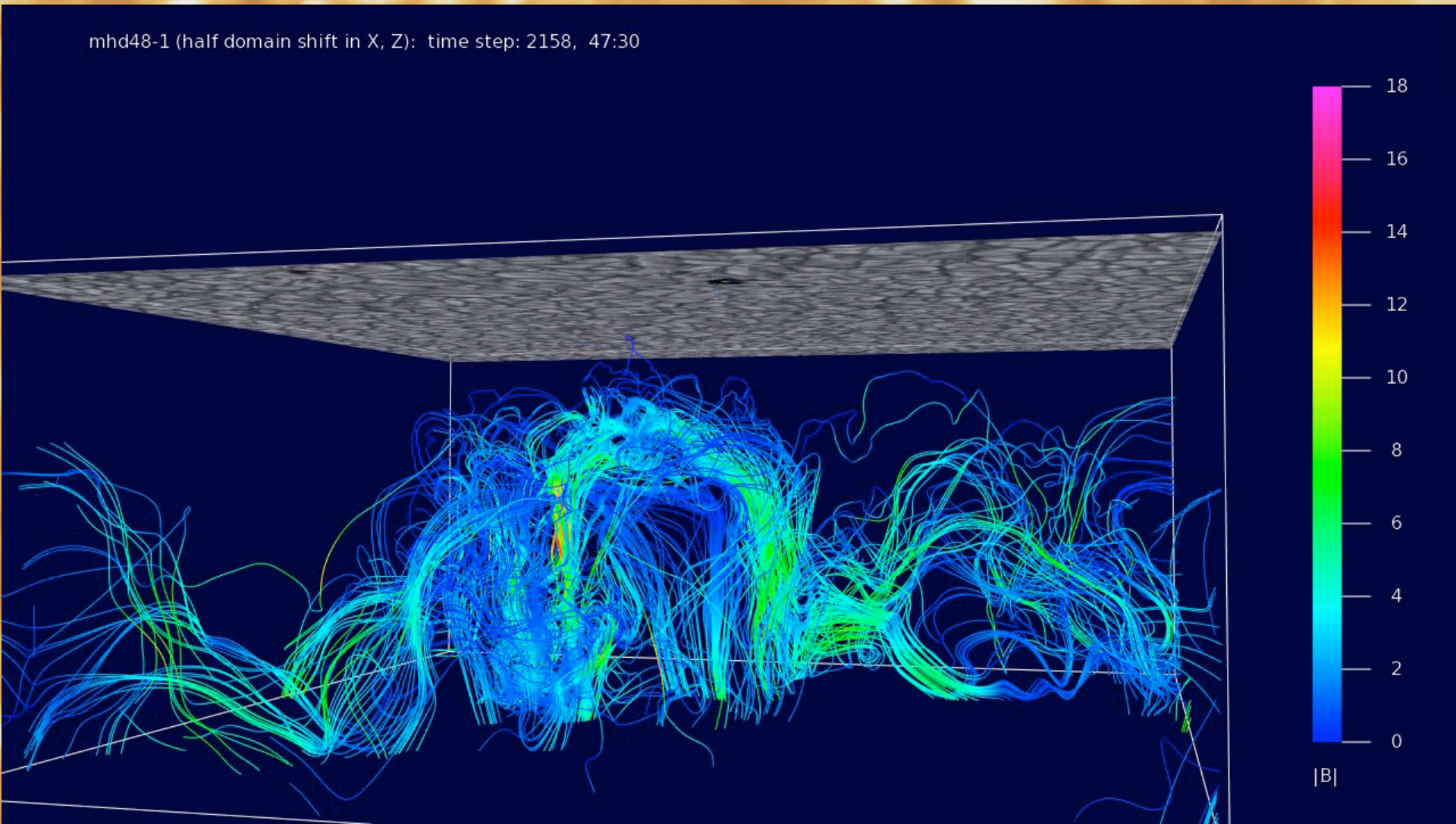
Poynting Flux is Downward



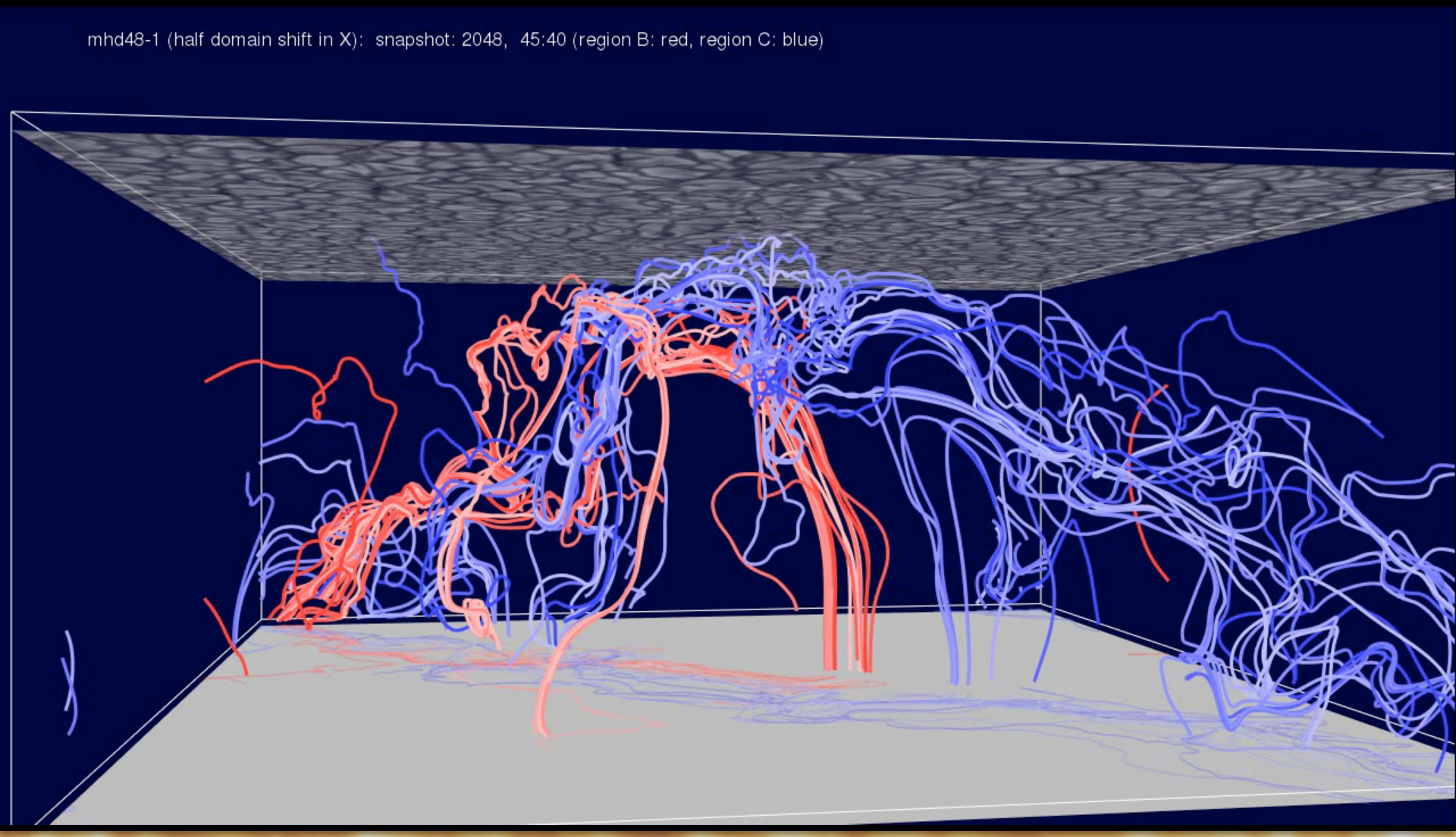
Strong B mostly in Downflows
Strong B suppresses flows
Supersonic evacuation of B concentrations



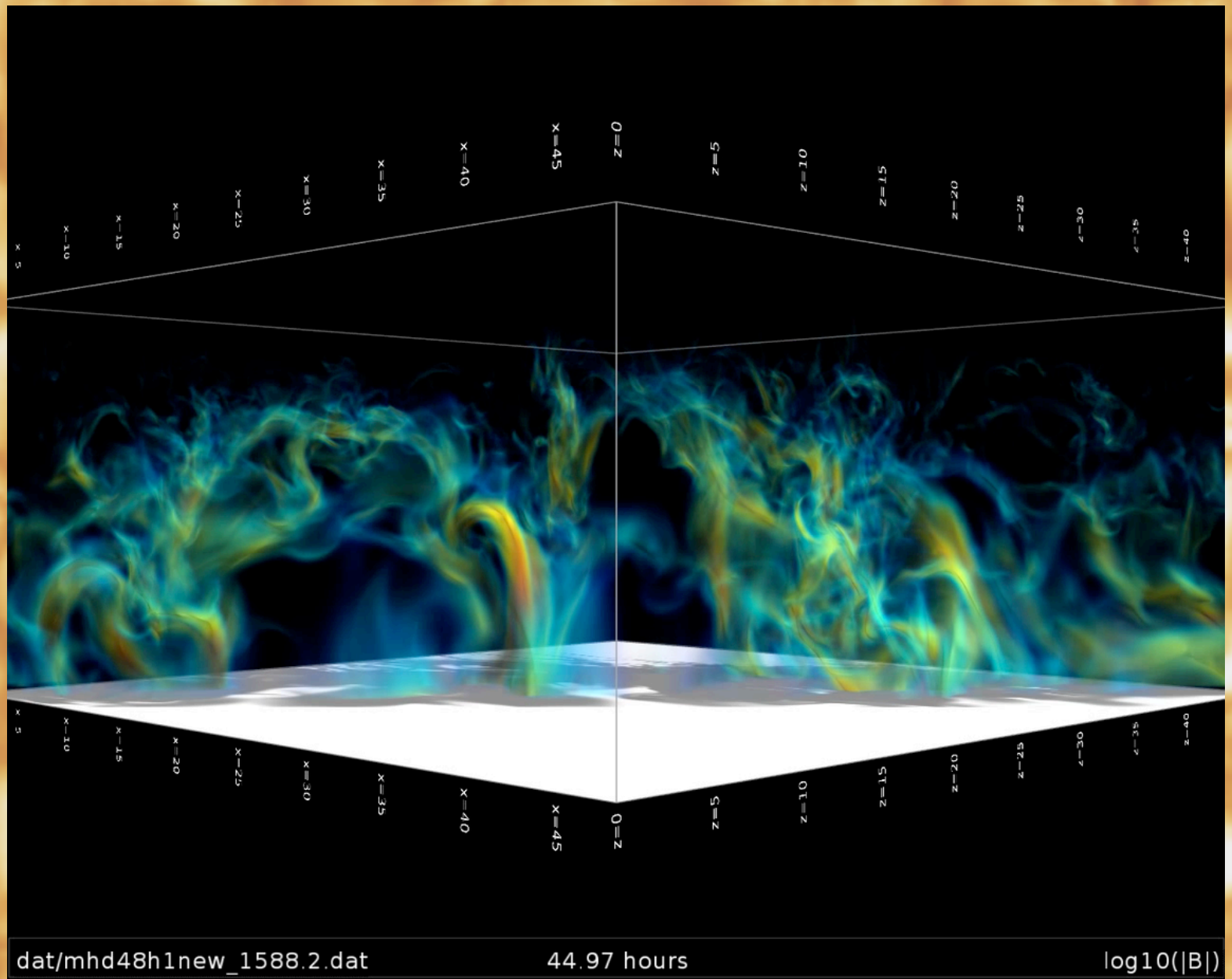
Magnetic Loop Emerging through Surface – forms mini Active Region from legs of large loop. Convection advects, fragments & confines loop.

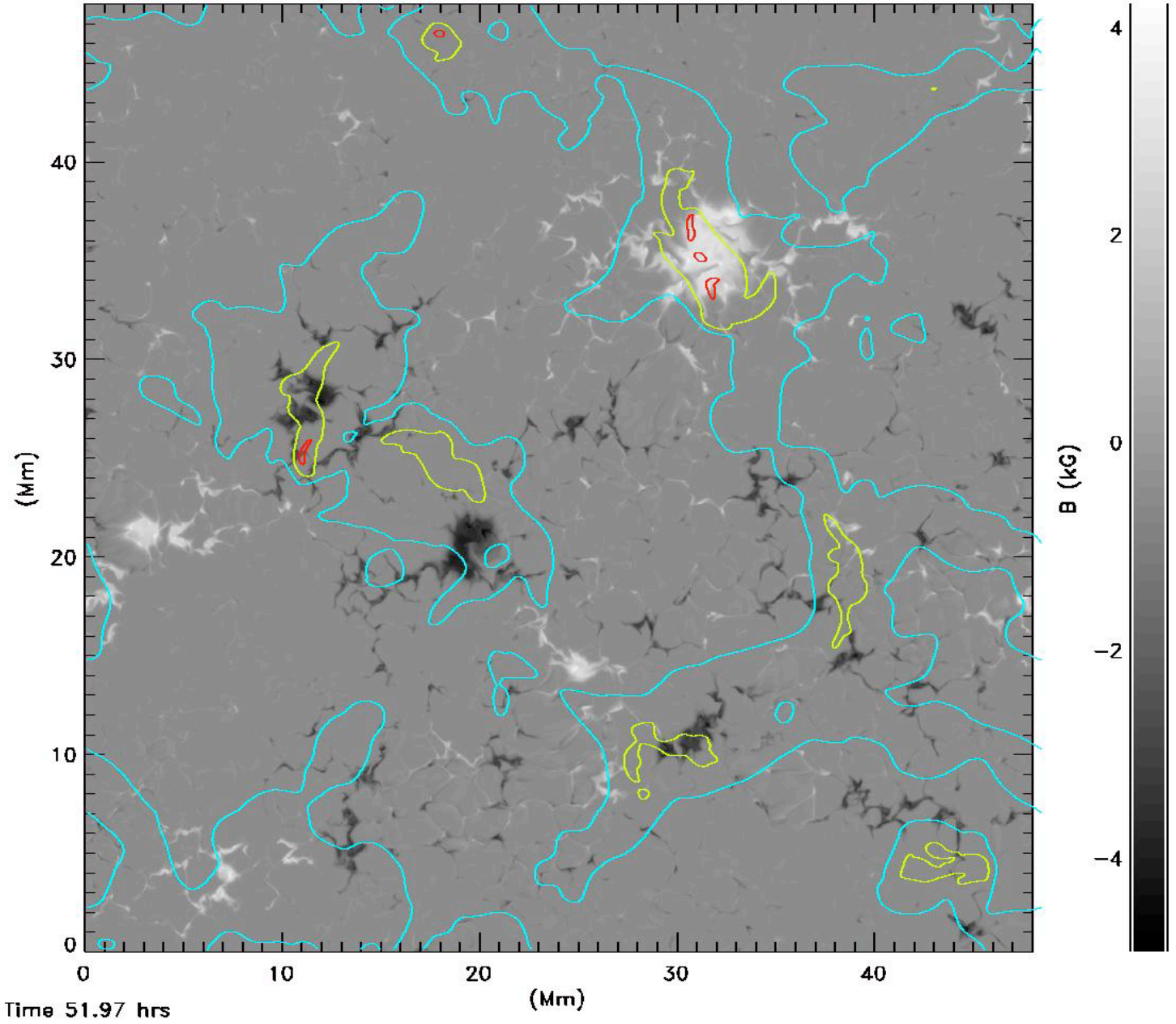


Another example: more complex serpentine loop structure



Complex, serpentine loop system





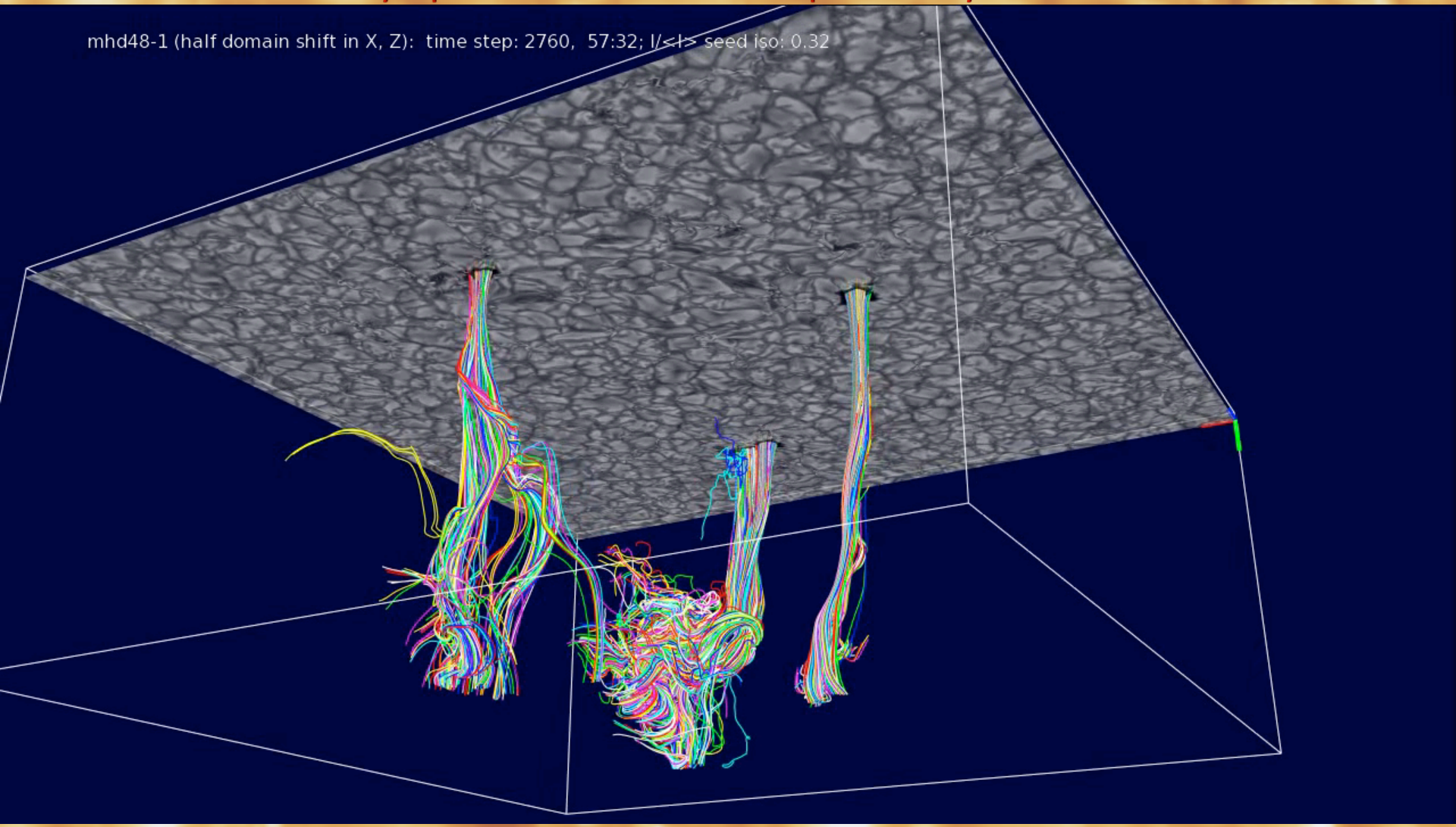
Upflows raise B, supergranule downflows pin down loop legs.

B_{vert} surface image, V_{vert} bottom contours (blue = 0 velocity)

Bipole controlled by large convective structures with little magnetic influence & little spreading.

Subsurface Spot Structures

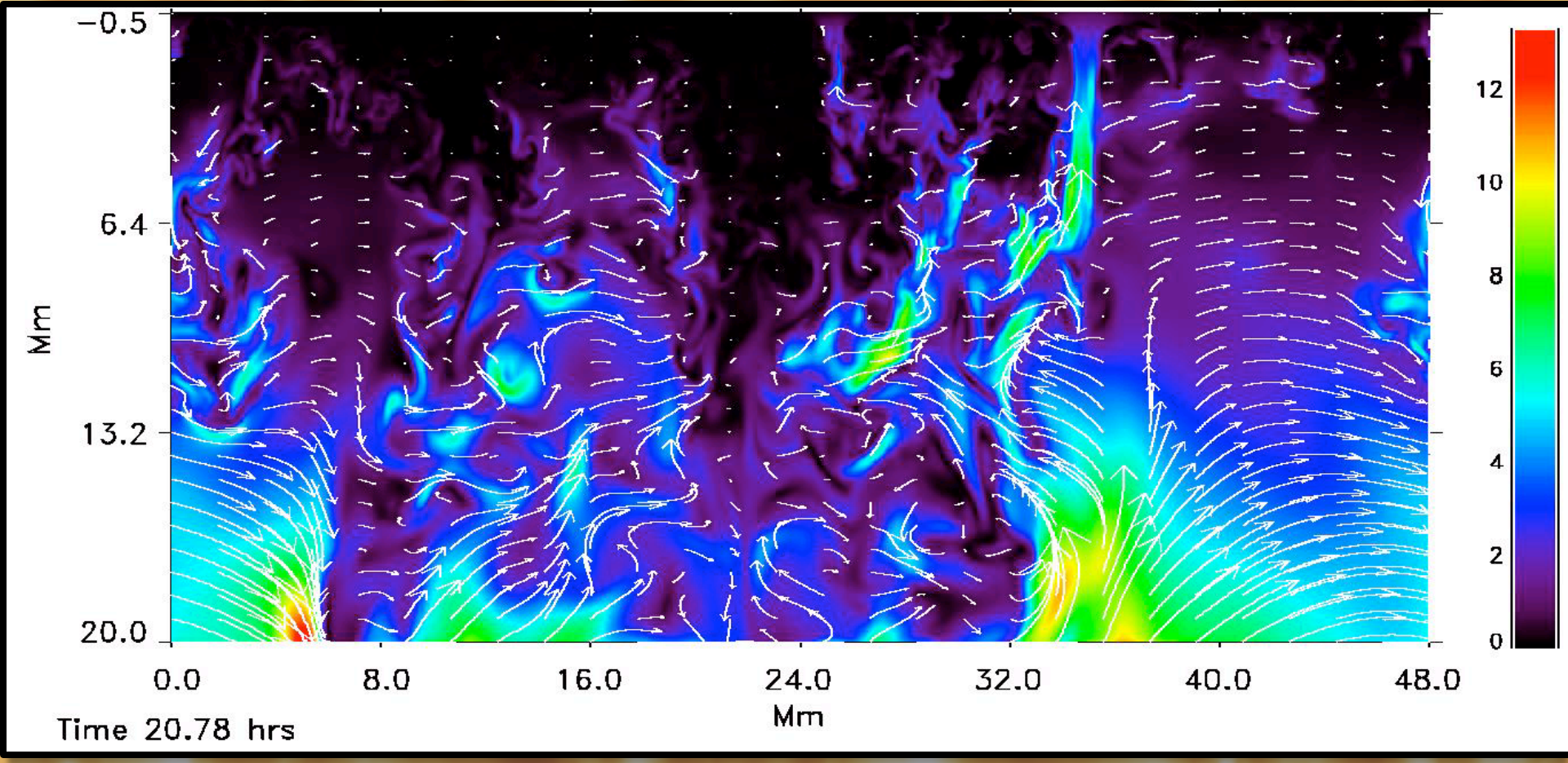
Every spot model made is probably correct!!



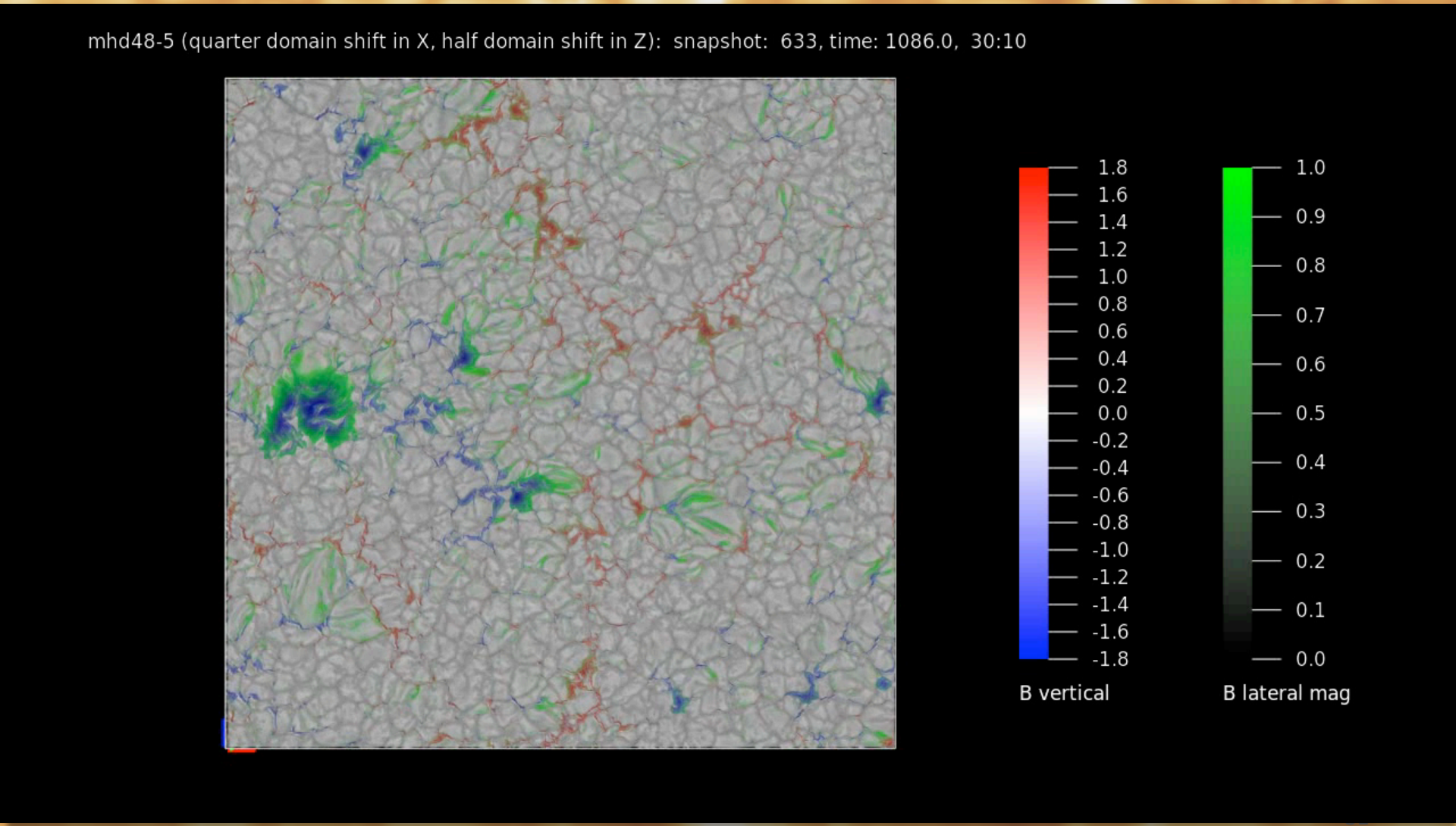
Movie shows magnetic field lines on contours of increasing emergent intensity

Strong, Buoyant Field

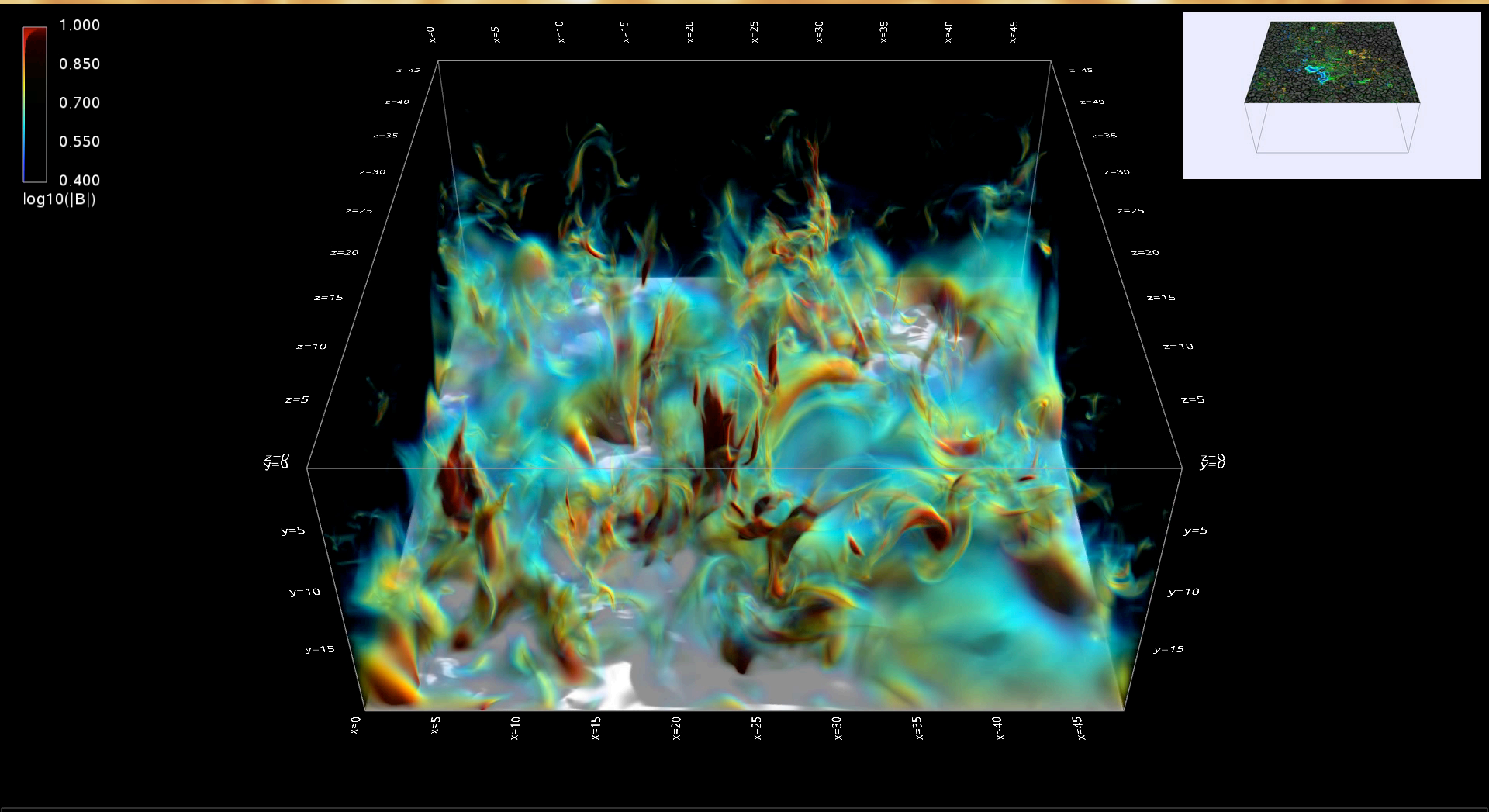
Flux concentration emerges from end of loop

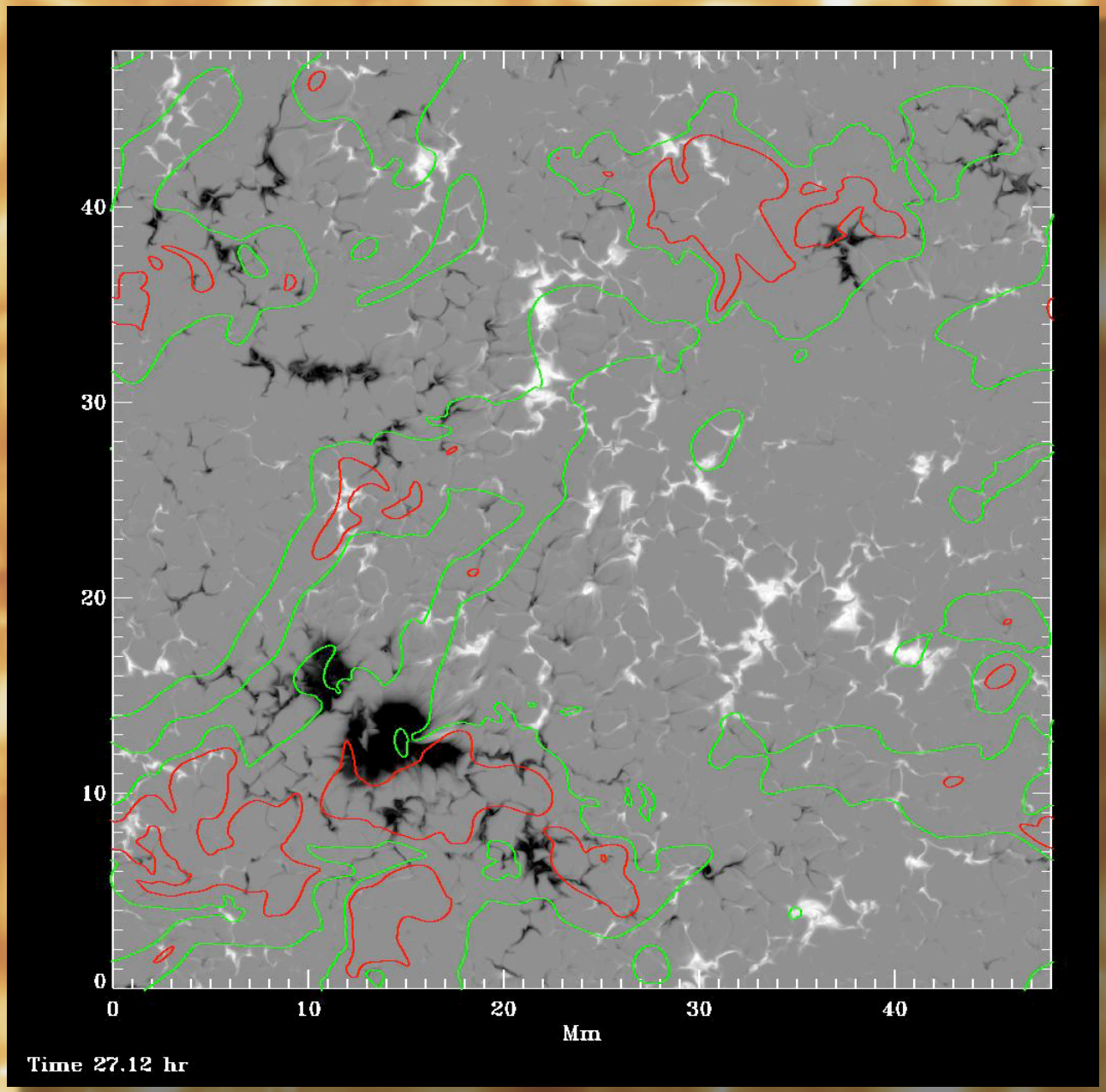


Again, field first emerges in mixed polarity with horizontal fields over granules and vertical legs in inergranular lanes. The opposite polarity components then counter stream into the legs of the underlying, large loop. The opposite polarites spread apart in this case and strong horizontal fields surround vertical flux concentration.



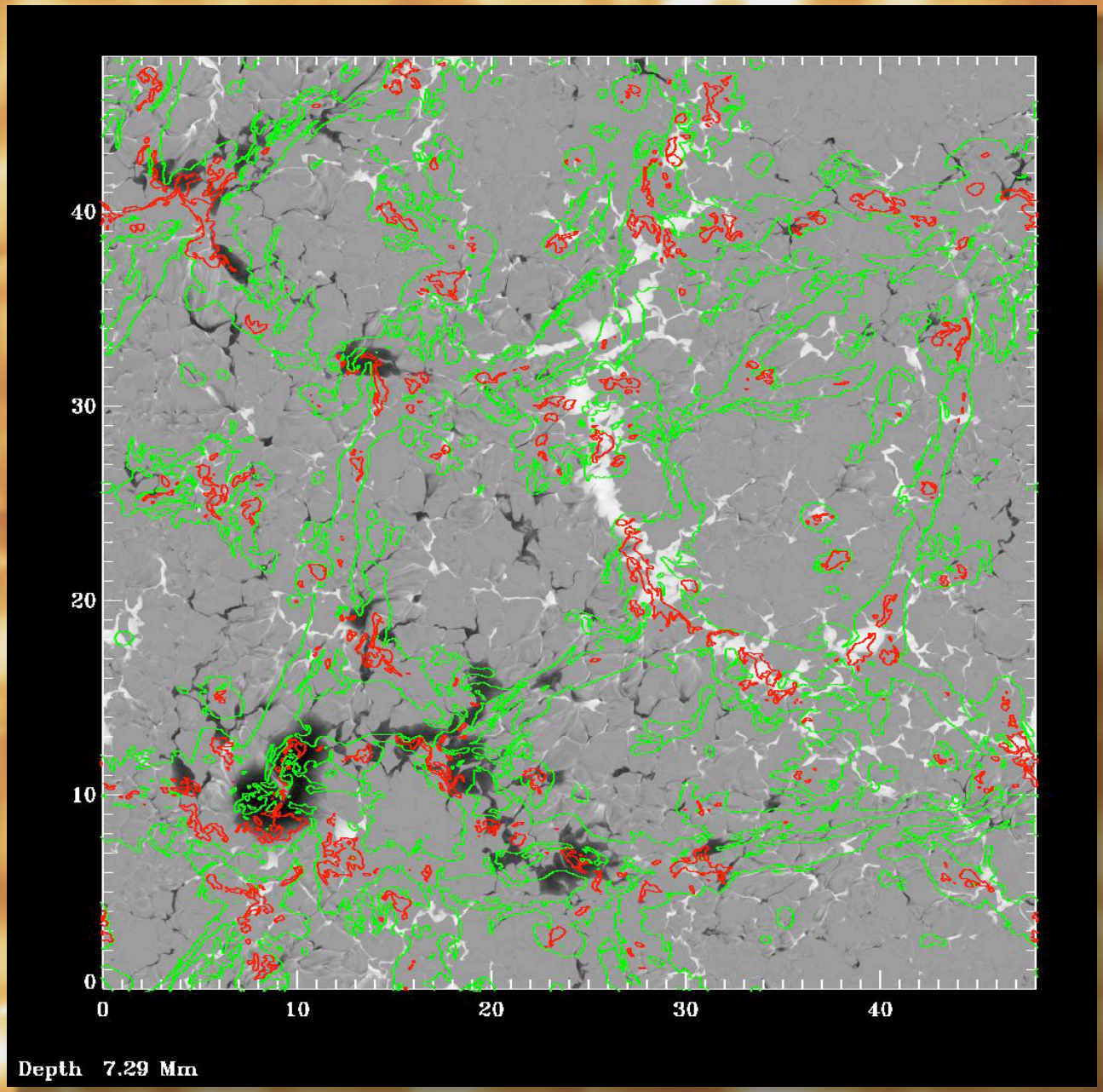
Log(B) showing loop structures & emergent flux concentration.





Buoyant flux emerges over SG center. Coherent leg forms in SG downflow. Magnetic field elongates SGs. Makes bipole spread.

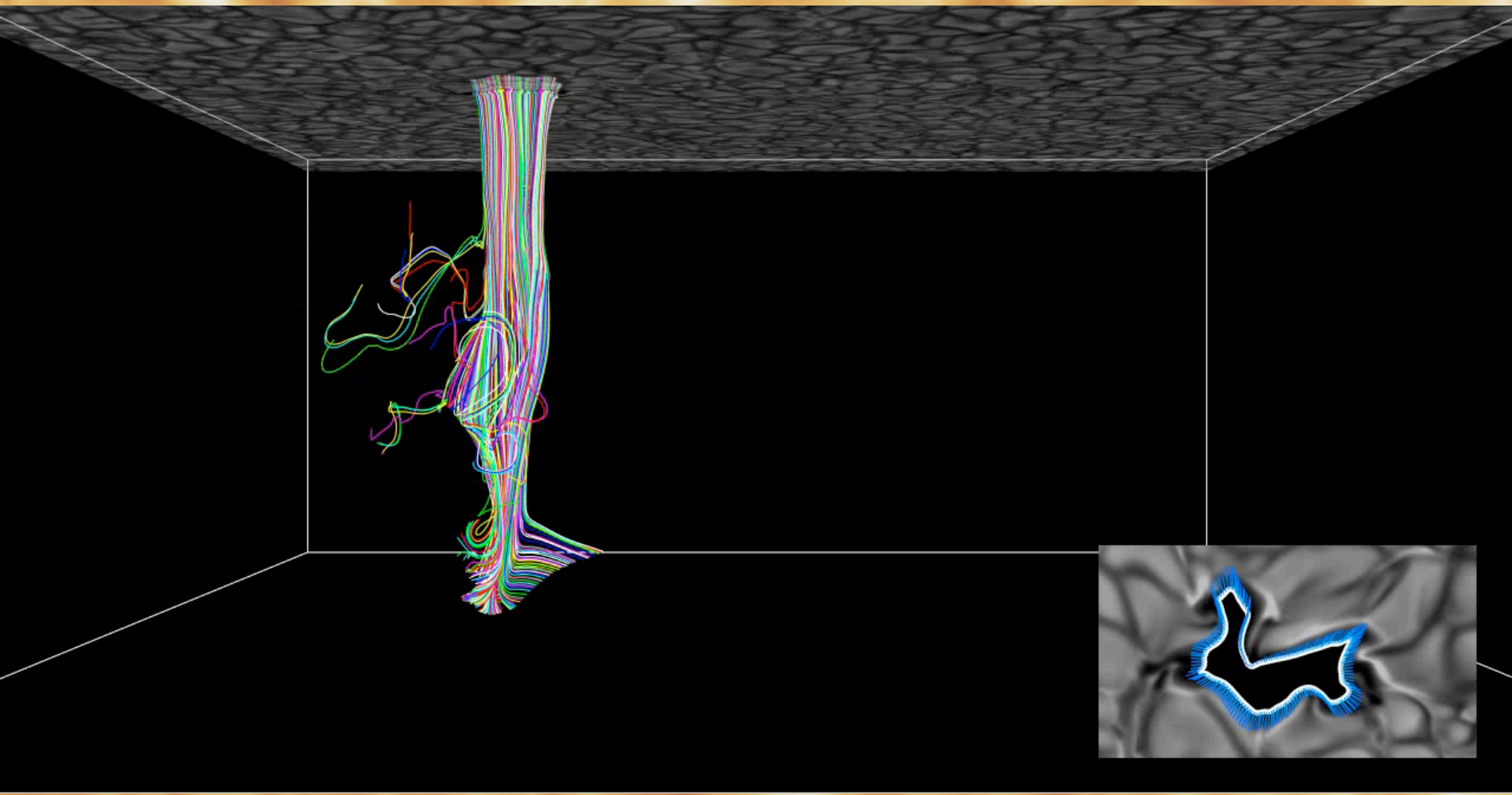
Surface vertical field image &bottom vertical velocity contours (green=0, red=strong downflow).



Surface Field (BW image) & Velocity Cells (contours) vs. Depth

Subsurface Structure of Pore/Spot

Field lines in core extend to bottom, are twisted about each other & remain coherent. Field lines in periphery connect to their surroundings.



Summary: Flux Emergence

Magneto-convection upflows & downflows produce undulating, serpentine flux ropes and loops.

Although most magnetic structures are advected downward, upflows and buoyancy bring some field to the surface.

Convective flows shred the flux ropes into bundles of adjacent field lines, which appear at the surface in a mixed polarity, "pepper & salt" pattern.

Where magnetic flux approaches the surface granules get elongated.

Underlying, large-scale, magnetic structures cause the surface field to collect into unipolar (active) regions, as the flux rope legs emerge.

Data & Movies @ http://steinr.pa.msu.edu/~bob/research.html