



Small-scale emergence of magnetic flux in the quiet Sun

F. Moreno-Insertis

J. Martinez Sykora, Viggo Hansteen

Emergence of magnetic loops within granules

Martinez Gonzalez & Bellot Rubio, 2009

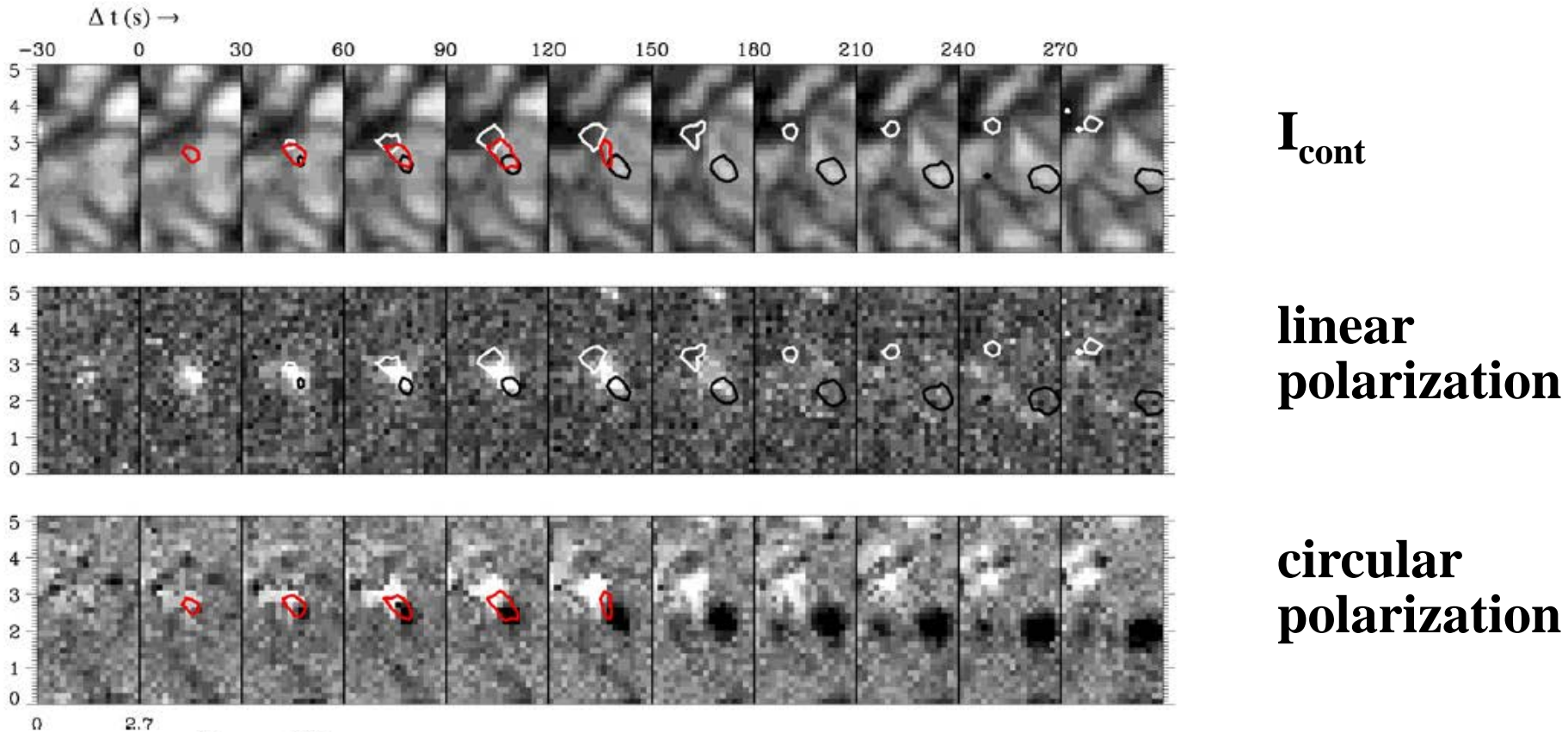
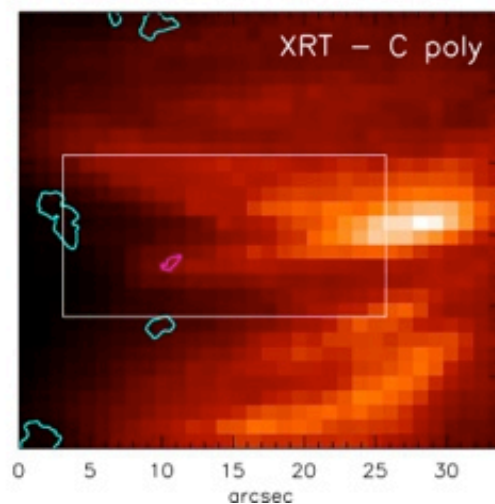
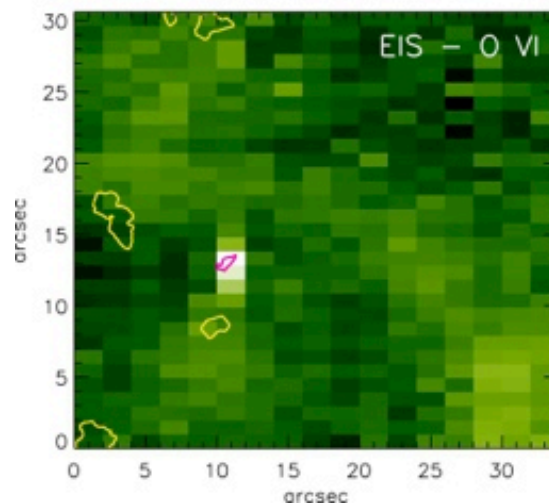
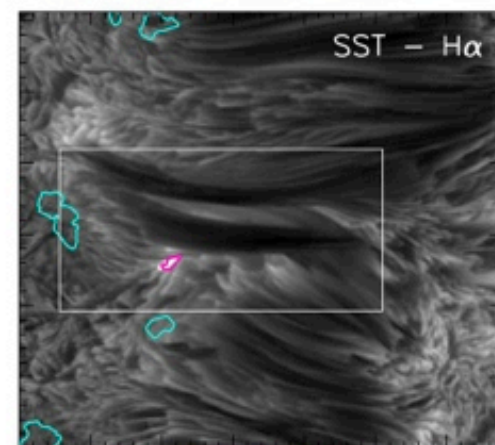
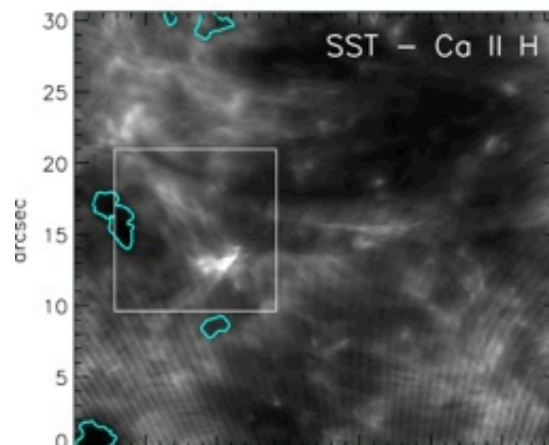
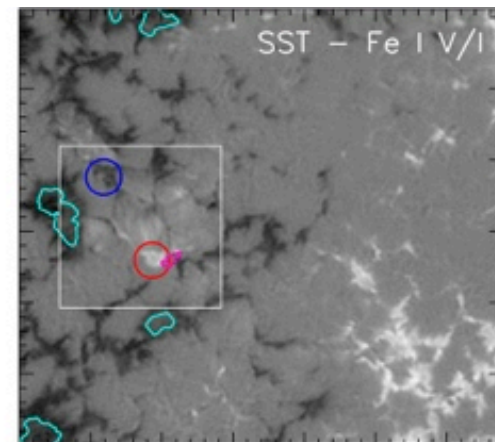
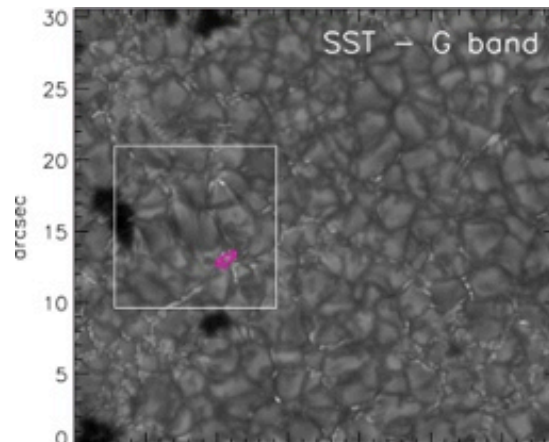


Figure 2. Emergence of a small-scale magnetic loop in the quiet solar photosphere. Time runs from left to right. Top: maps of continuum intensity at 630 nm. Middle: total linear polarization in the 630.25 nm line, saturated at 0.3 pm. Bottom: total circular polarization in the 630.25 nm line. The signals are clipped at ± 0.1 pm. Red contours represent linear polarization larger than 0.22 pm. Black and white contours indicate circular polarization signals stronger than ± 0.1 pm. Both x- and y-axis are in arcsec.

Flux emergence across photosphere, chromosphere and corona



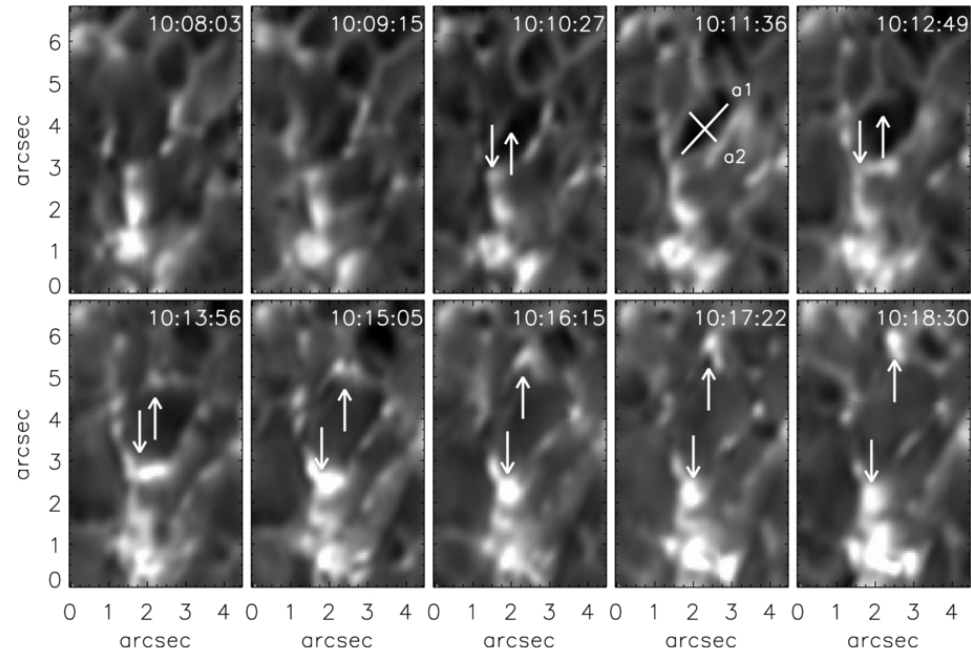
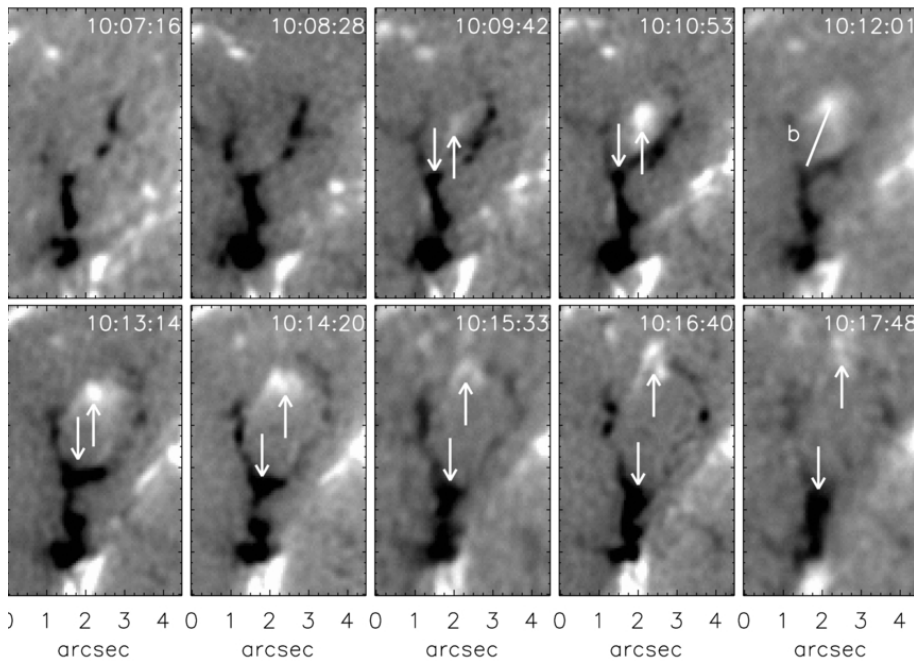
Guglielmino et al 2010

Emergence of bubble-shaped magnetized plasma at granular level

Ortiz et al 2014

FeI 6302, Circular polarization

CaI 8542-0.8 Å



THEORY

**3D numerical experiments
and simulations**

Flux emergence across the low atmosphere

Dynamics

- **Huge expansion** in the lowermost few Mm of the atmosphere
- **Transition from $\beta > 1$ to low- β regime.**
- Emergence typically occurs after the development of **magnetic buoyancy instabilities in the photosphere.**

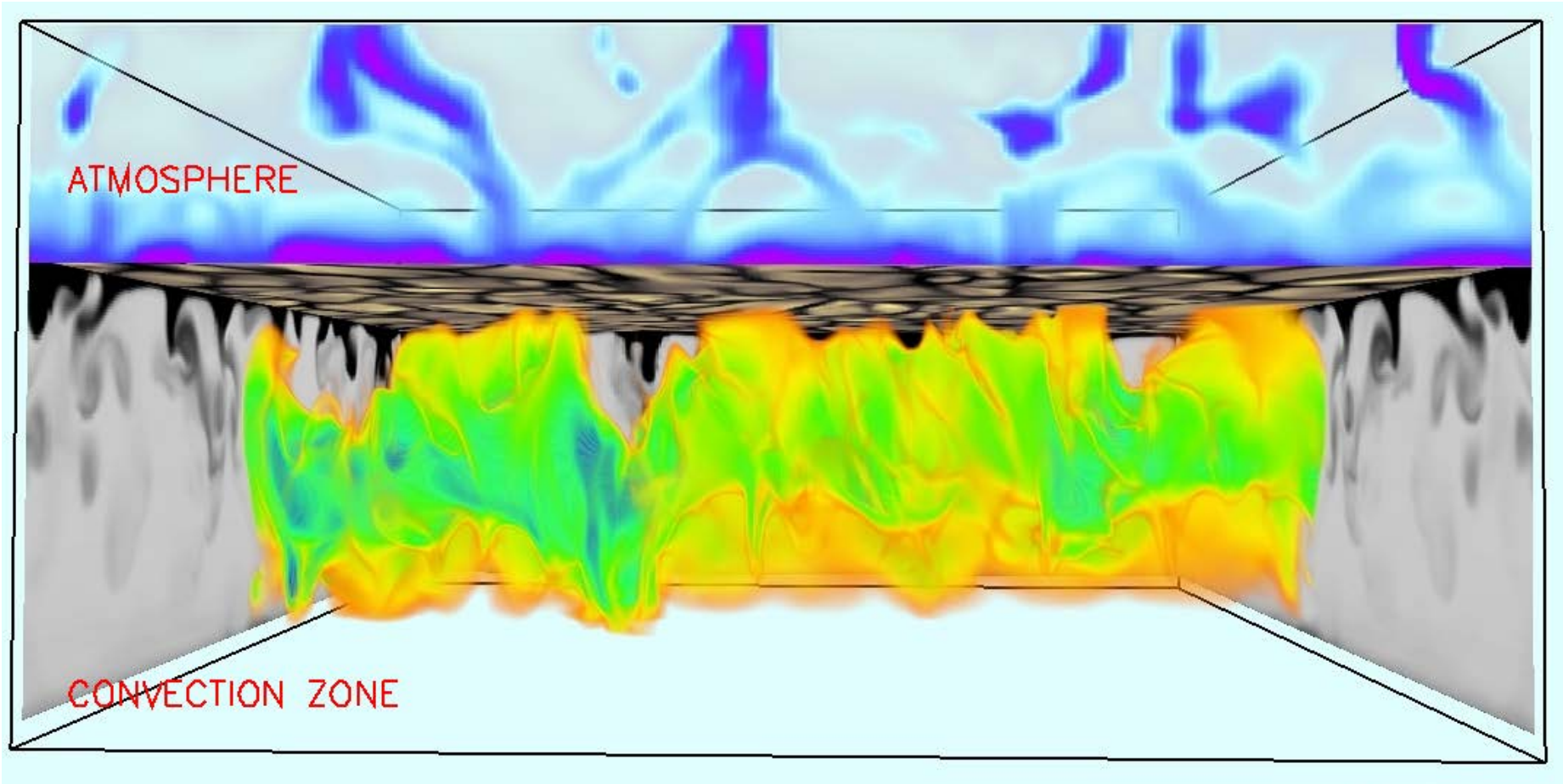
Thermodynamics / Radiation

- **Detailed EOS necessary** (e.g.: to avoid catastrophic drop of T in the low atmosphere)
- **Radiation-matter interaction:** LTE RT (photosphere) but NLTE effects (chromosphere)
- **Entropy sources:** Joule heating /// Heat conduction // **Optically thin cooling necessary**

Convection zone – to – atmosphere flux emergence *radiation-MHD* models

- **Cheung et al 2007, 2008, 2010** → MuRAM // up to the mid photosphere
- **Tortosa-Andreu + M.-Inertis 2009** → MuRAM, up to mid chromosphere
- **Martinez Sykora et al 2008, 2009** → Oslo SC, including the corona
- **See also:** Steiner et al 2012, Fang et al. 2013, Martinez Sykora et al 2011, 12

Flux emergence below the surface



Flux emergence in the QS: 3D simulation

M.-Insertis, M. Sykora, Hansteen, 2015

Box size: 10 Mm x 10 Mm x 12.5 Mm

Resolution: Horizontal: 20 km

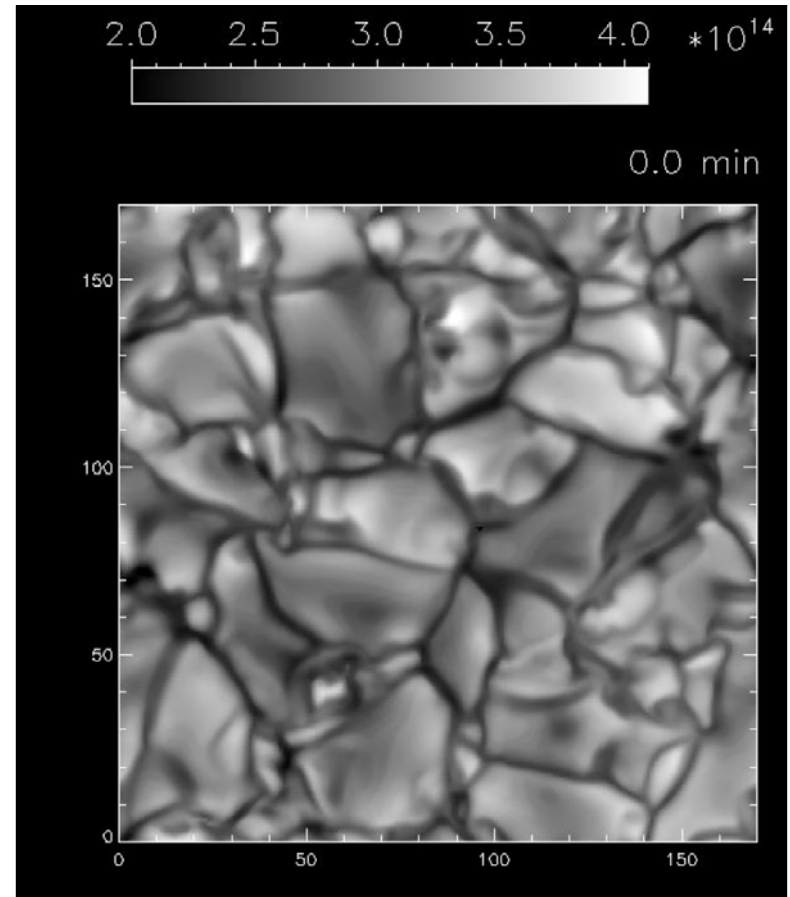
Vertical: 16 km (photosphere)

32 km (corona)

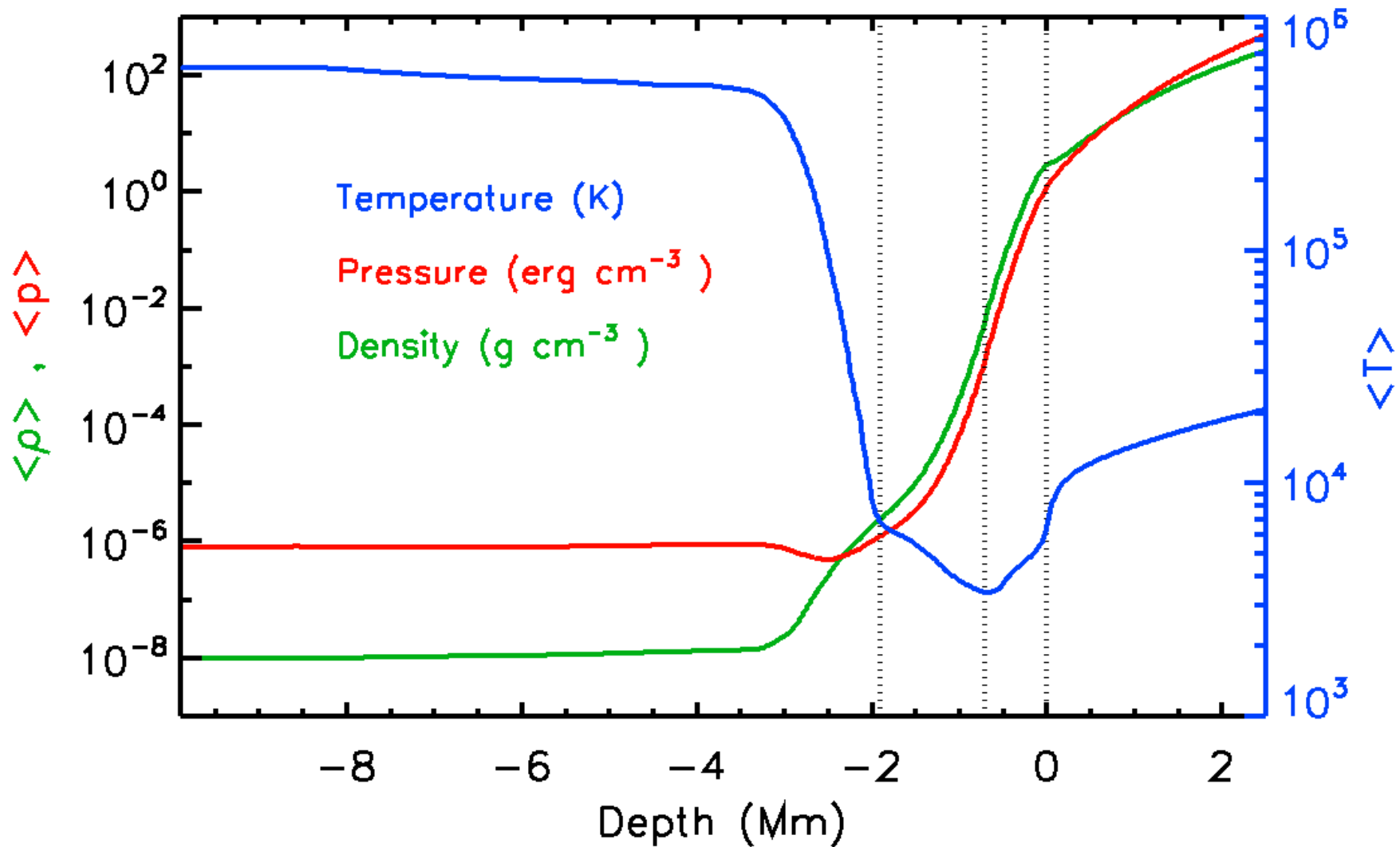
Corona: ≈ 1 Gauss average ambient magnetic field

Flux injection through the bottom boundary:

flux-tube shaped domain of $9 \cdot 10^{18}$ Mx with radius 0.2 Mm



Stratification: horizontal averages

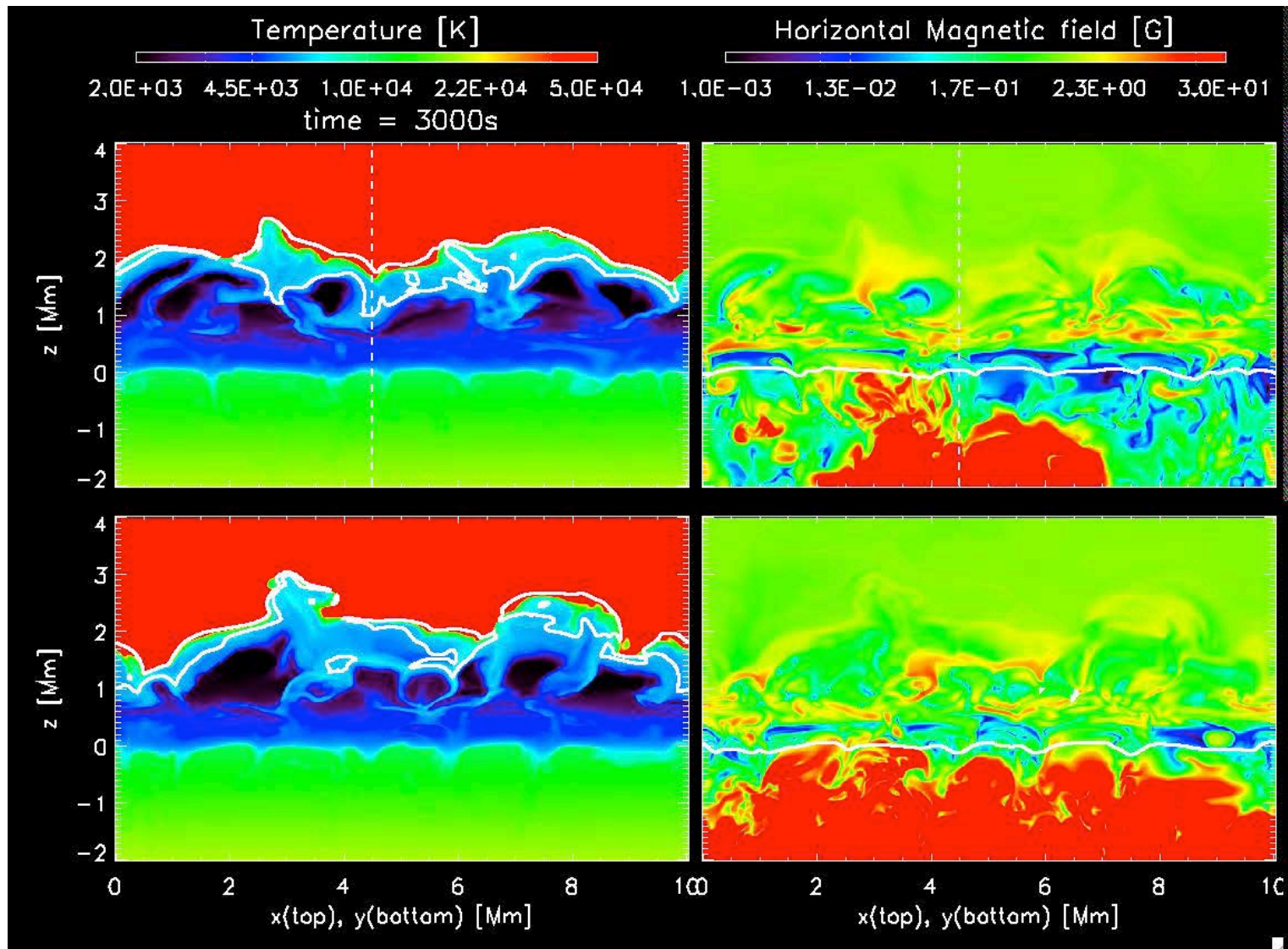


Calculations carried out with the BIFROST code

Gudiksen et al 2011

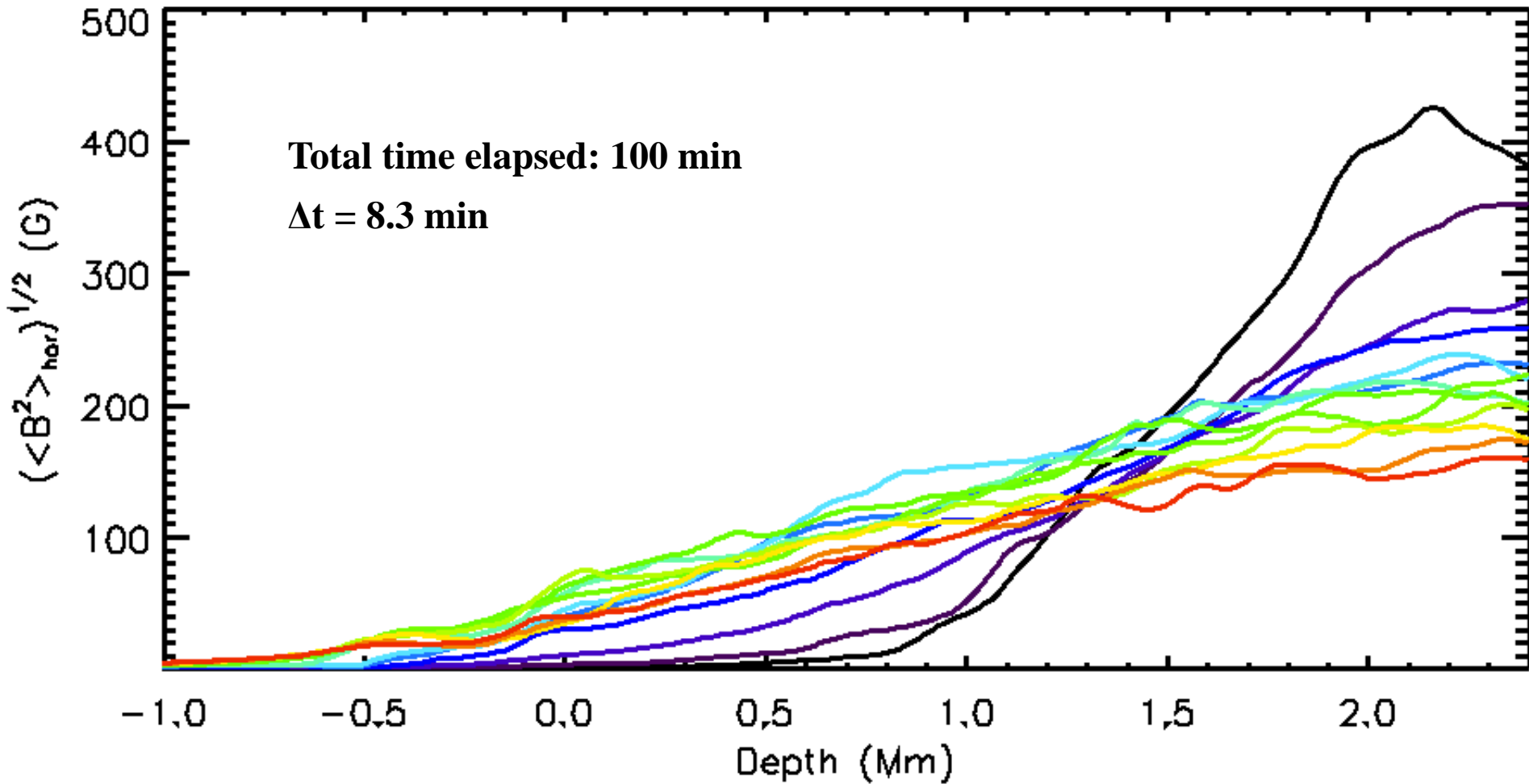
- **Realistic EOS**
- **Radiative transfer (photosphere, chromosphere)**
- **Heat conduction**
- **Optically thin cooling in the corona**

Magn flux entering the atmosphere



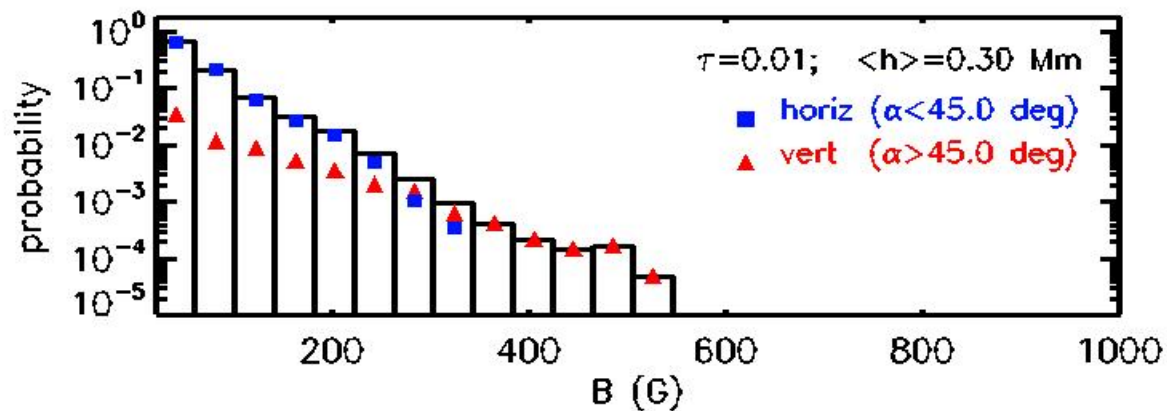
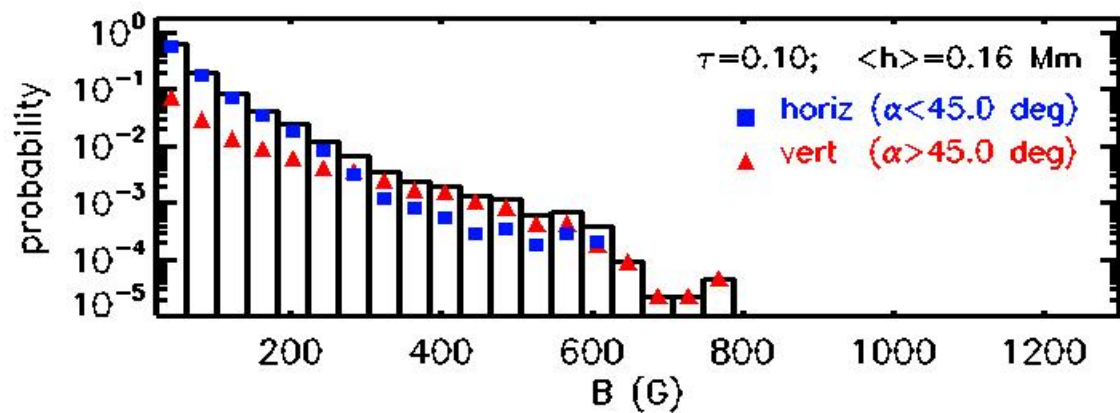
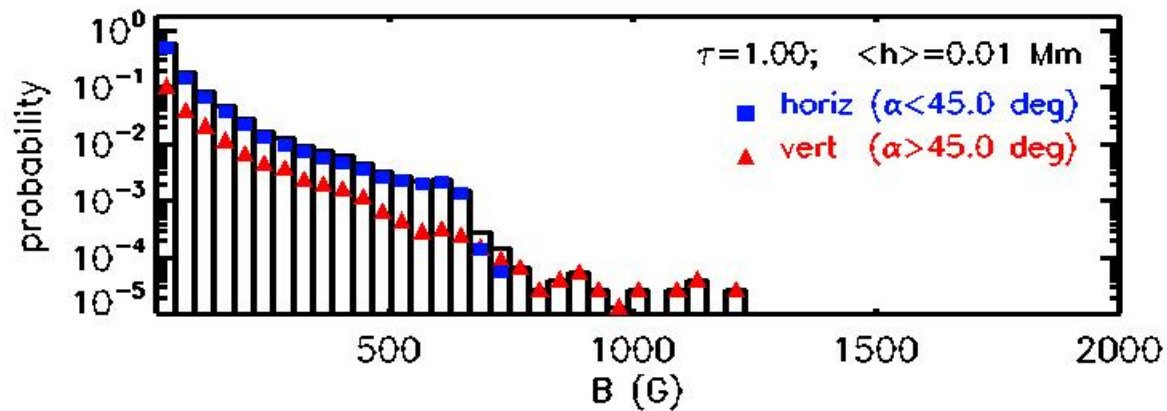
Time evolution of B_{rms}

Equivalent diffusion rate due to convection



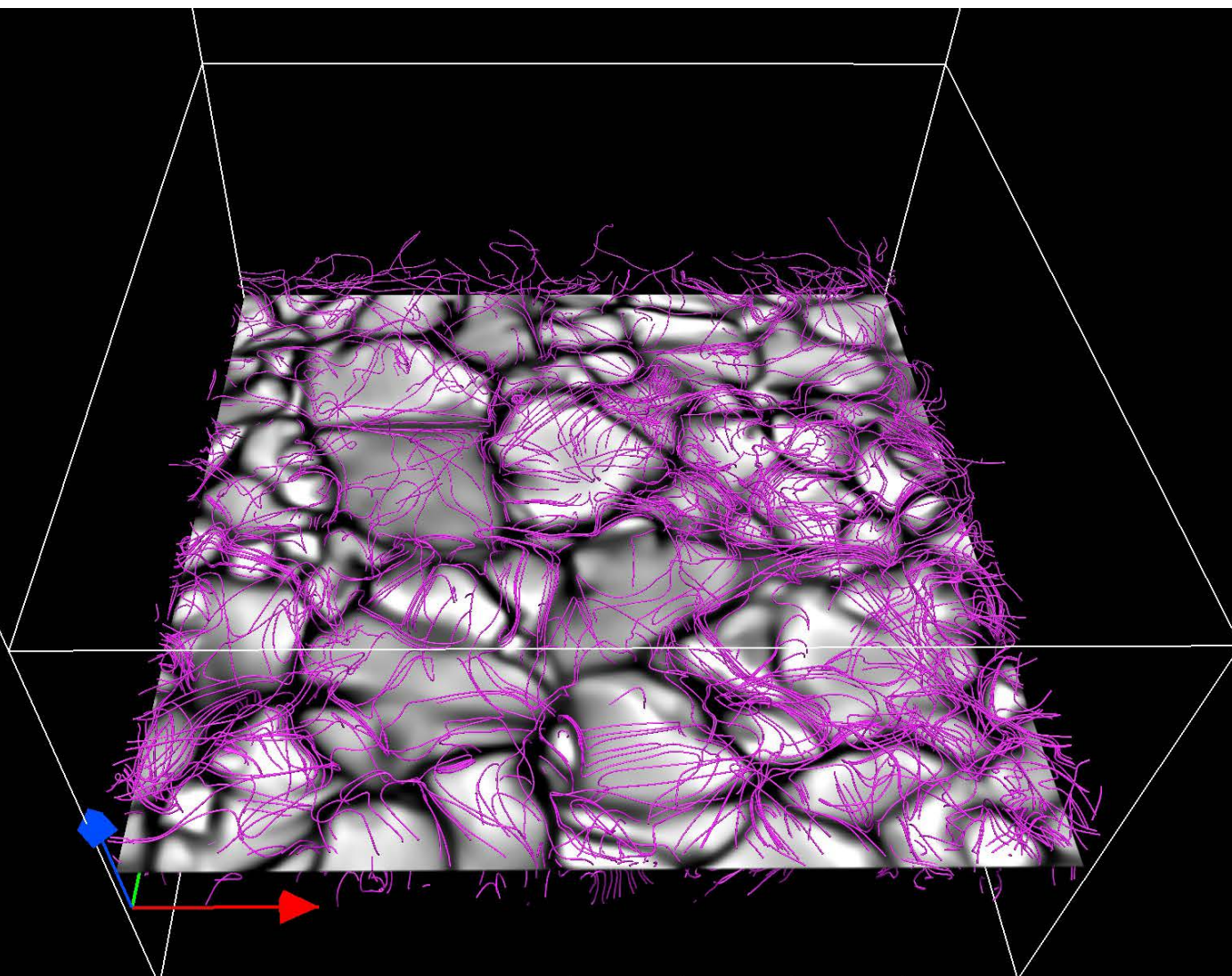
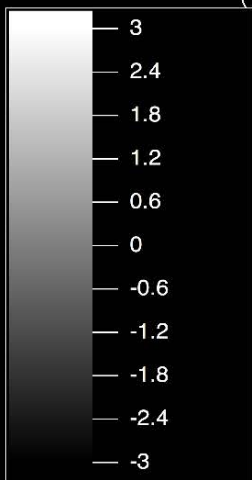
$$\eta_{\text{equiv}} = 1.4 \cdot 10^{-4} \text{ Mm}^2 / \text{s}$$

time=115.0 min

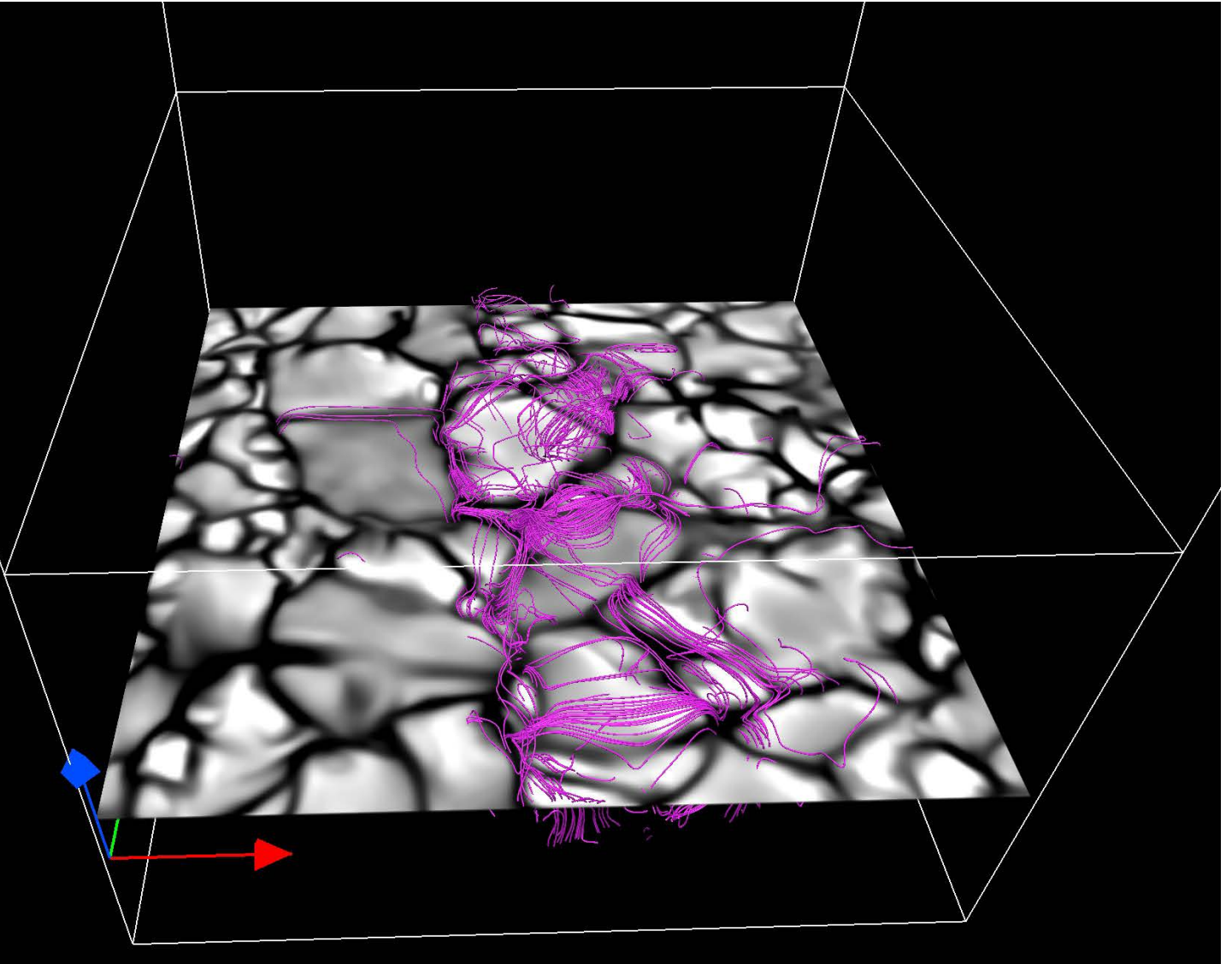
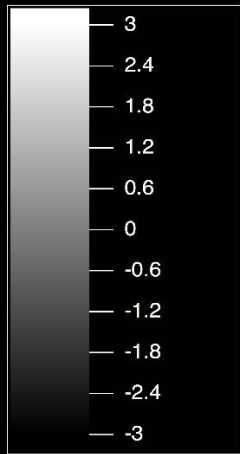


**Field line tracing:
the linkage to the higher levels
in the atmosphere**

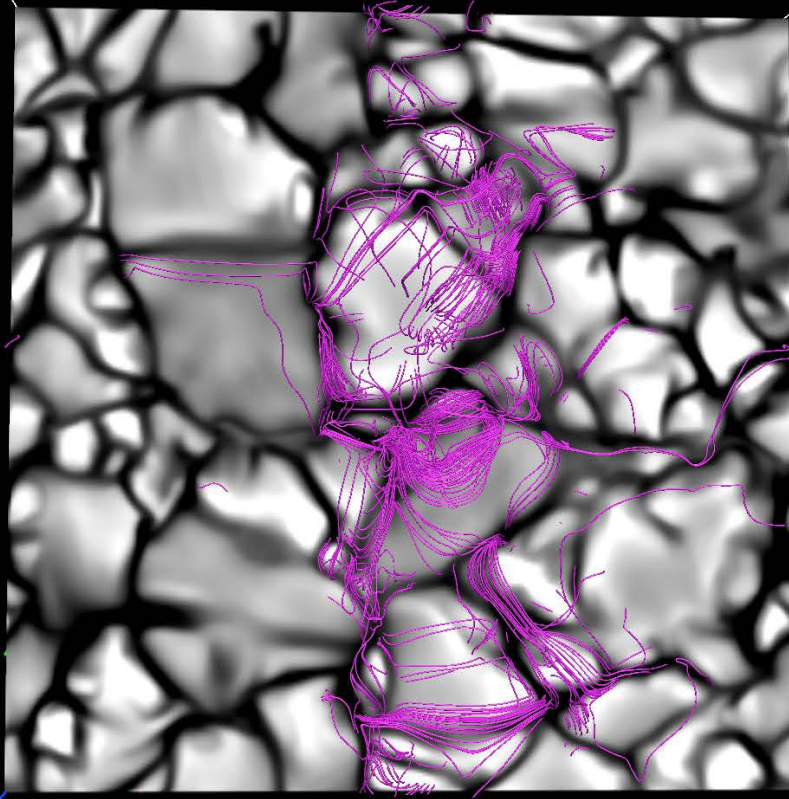
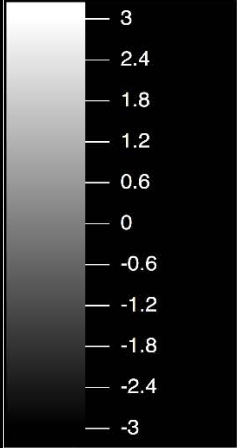
TimeStep: 490



TimeStep: 490



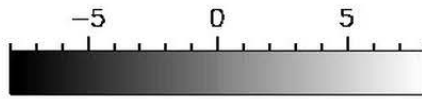
TimeStep: 490



The appearance of emerging-flux domains

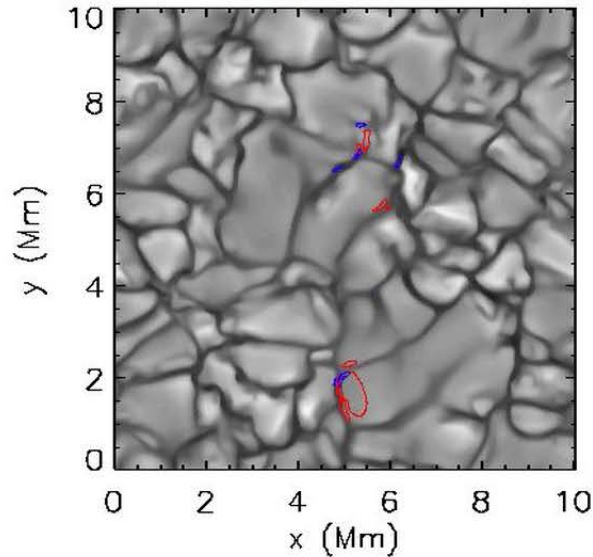
- Coherent patches of horizontal field become flanked by patches of vertical field → **flux rope or flux sheet** appearance
- Most often the rising patch appears to fill the granule interior (as in the bubbles observed by Ortiz et al 2014)
- and lead to strong concentrations (800 – 1000 G) in granular lanes and at vertices
- But the vast majority of the pixels at photospheric levels are weakly magnetized (< 100 G)

An instance of emergence of a magnetic sheet in a granular cell

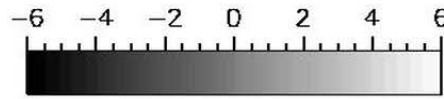


UPFLOW (km sec⁻¹)

Contours (G):
bhor 150. 800.
bz -800. 800.

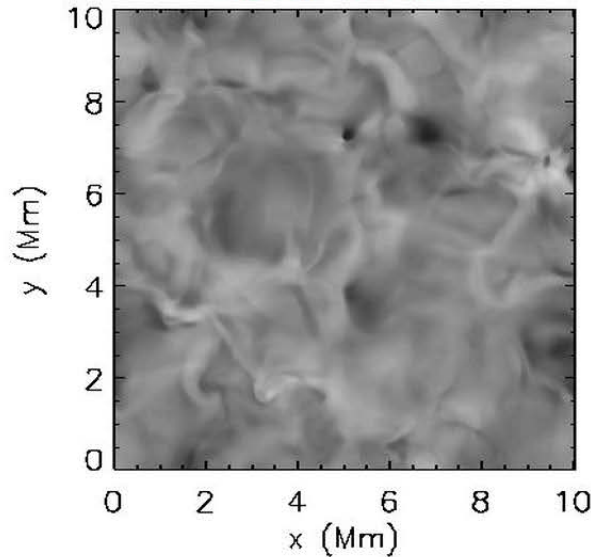


z = 0 km

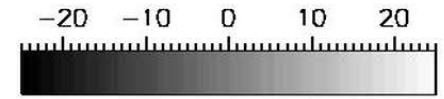


UPFLOW (km sec⁻¹)

Contours (G):
snapshot=400
time=66.67 min
bz -200. 200.

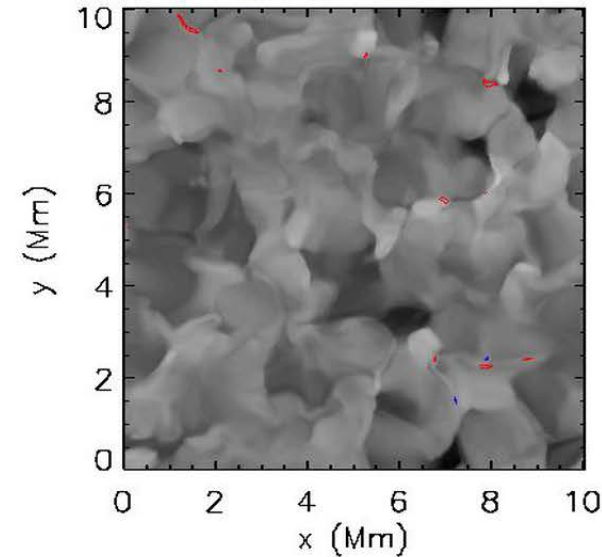


z = 500 km



UPFLOW (km sec⁻¹)

Contours (G):
bhor 10. 50.
bz -50. 50.



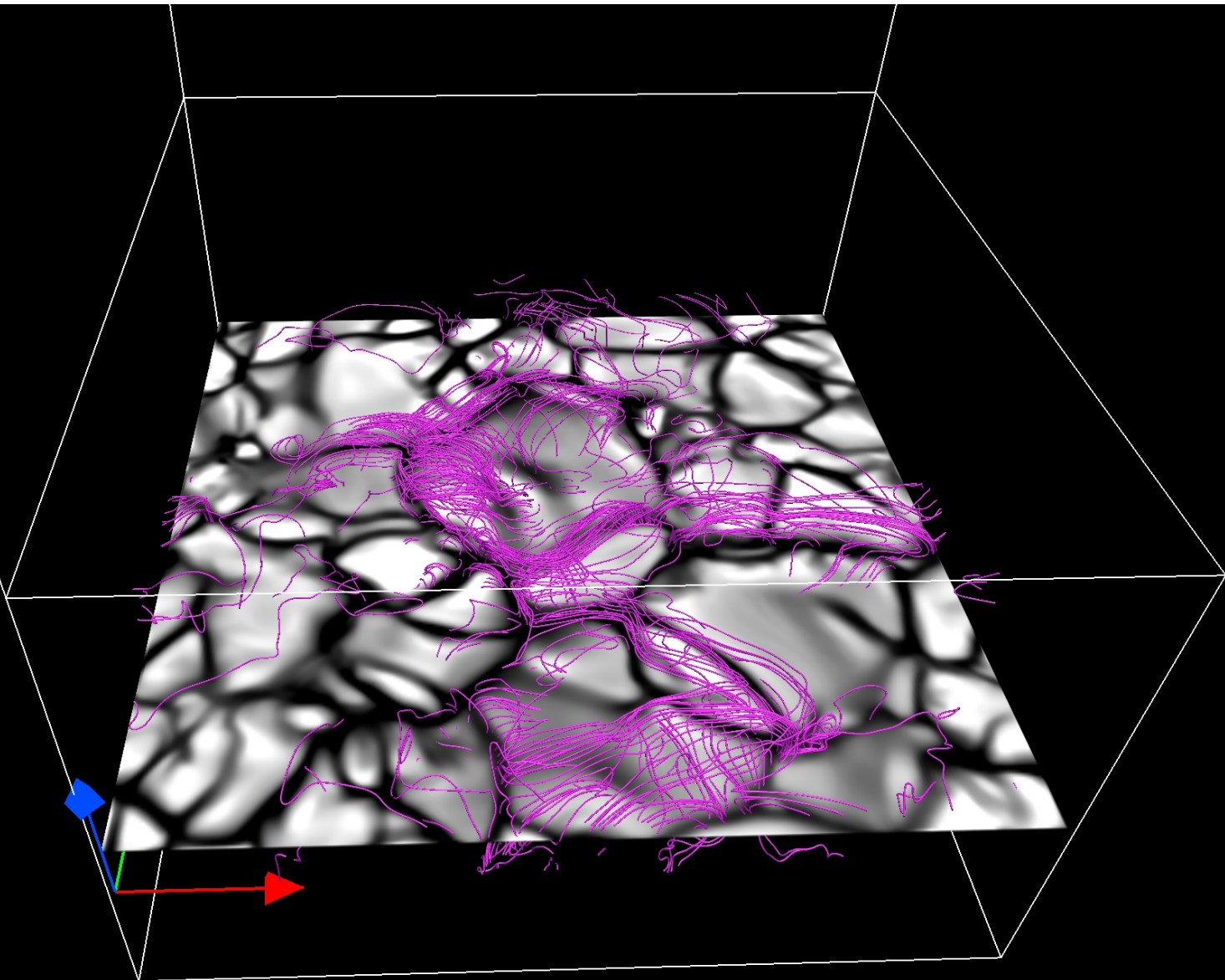
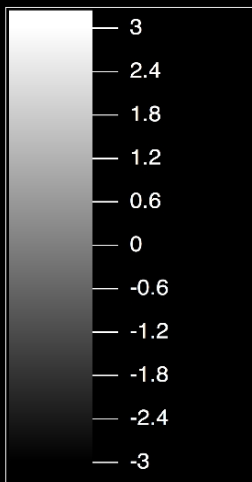
z = 1000 km

**The linkage of the emerging field
to the coronal field**

The initial stages

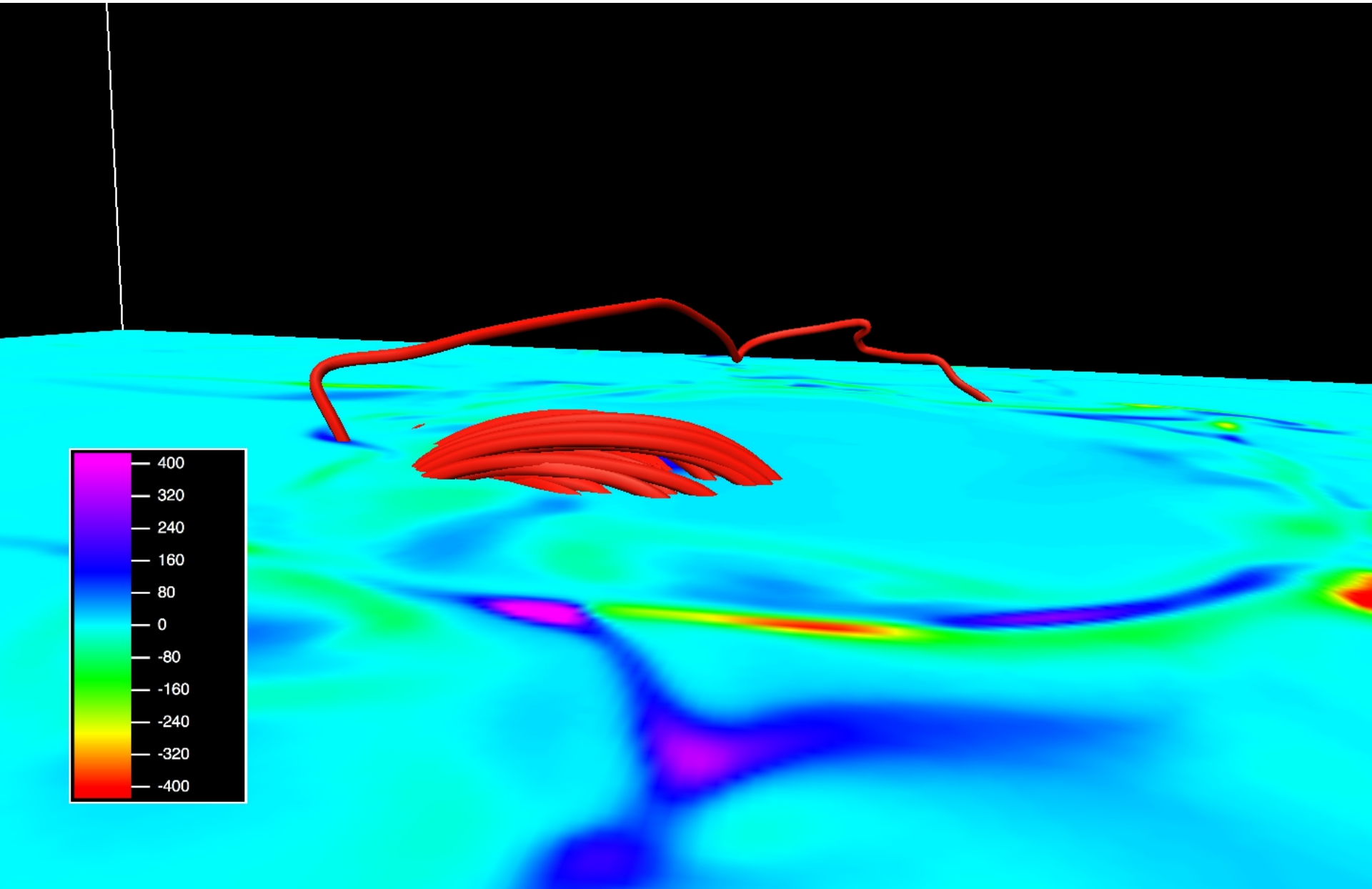
- **Arrival of flux sheet at the photosphere**
- **Linkage to preexisting fields does not reach above 500 km**

TimeStep: 535



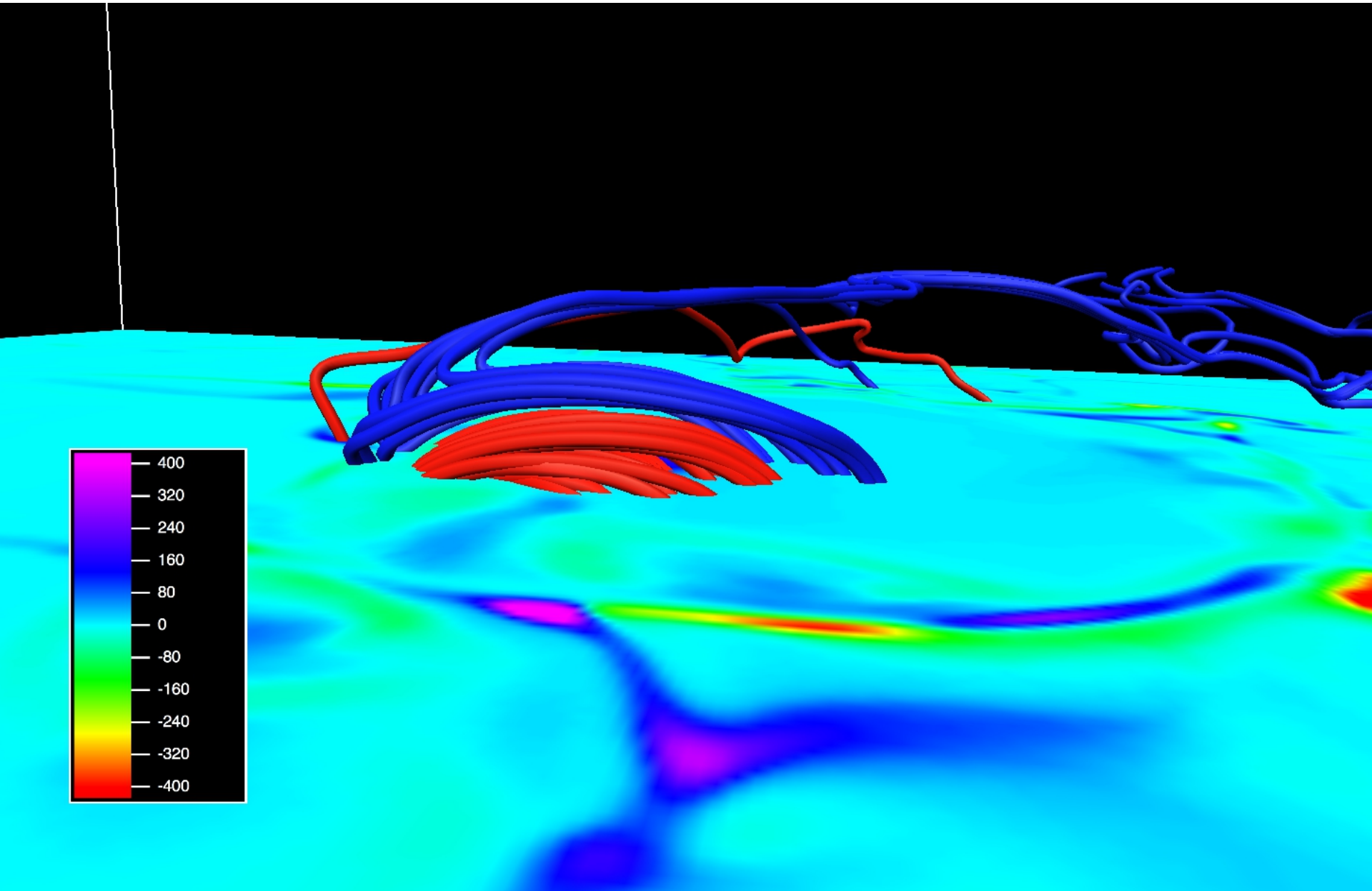
$t = 84 \text{ min}$

Red field lines: traced from the photosphere



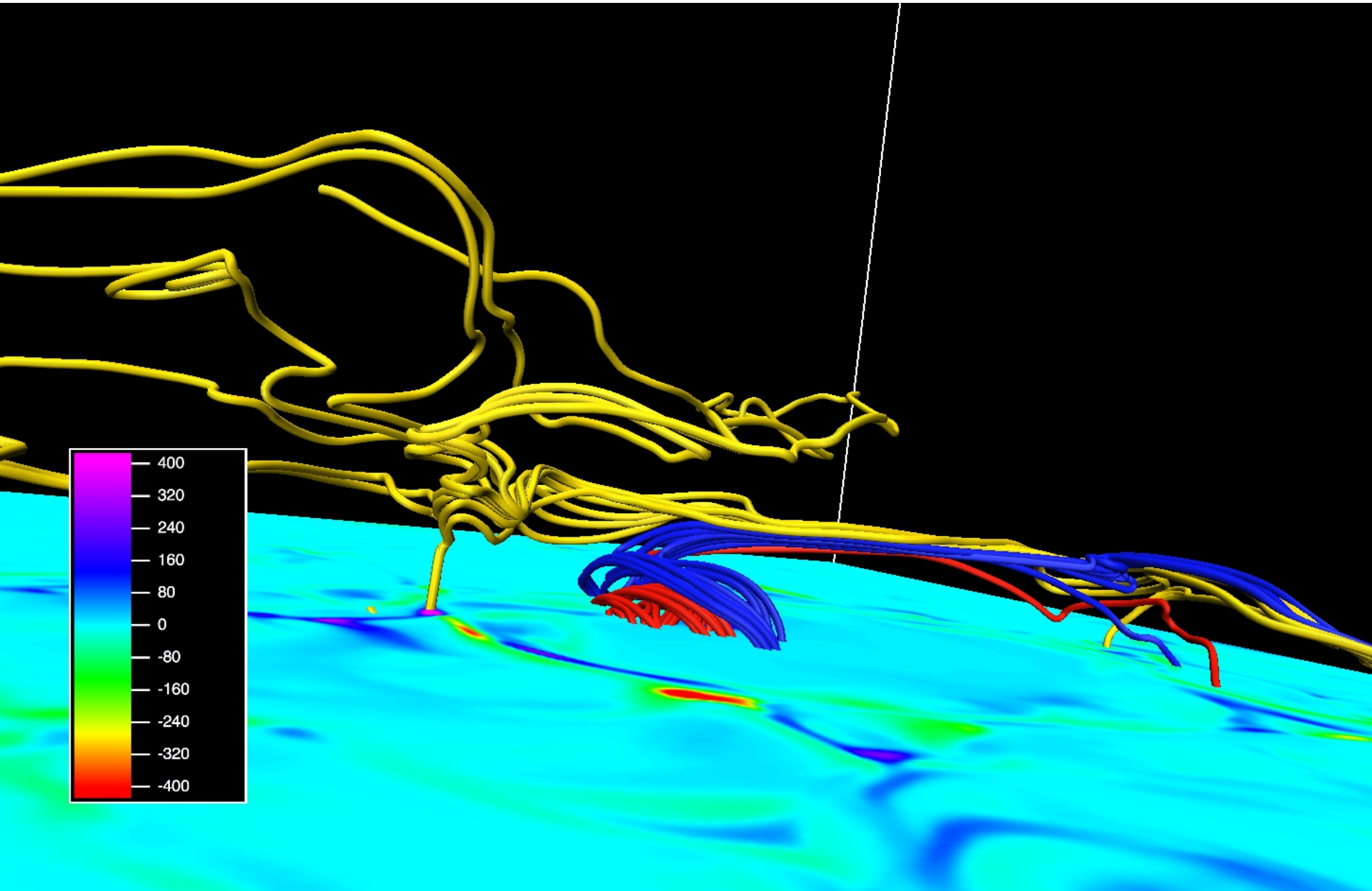
$t = 84 \text{ min}$

Blue field lines: traced from 250 km height



$t = 84 \text{ min}$

Yellow field lines: traced from 500 km height



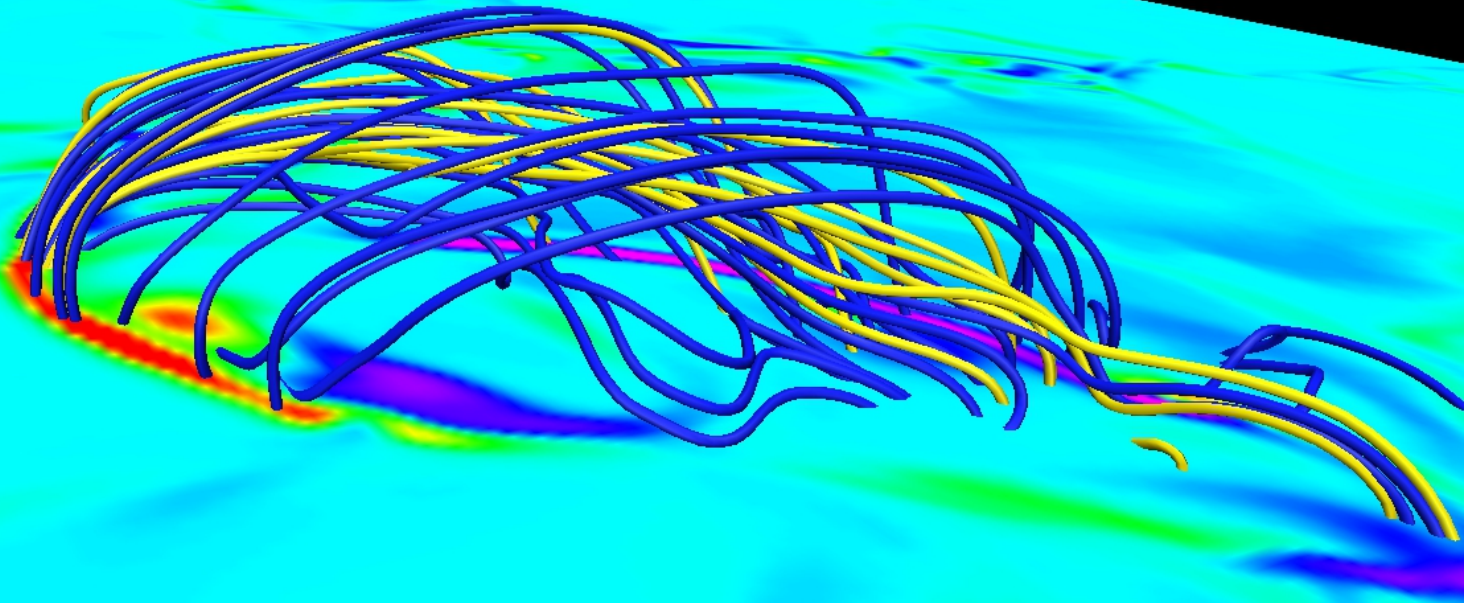
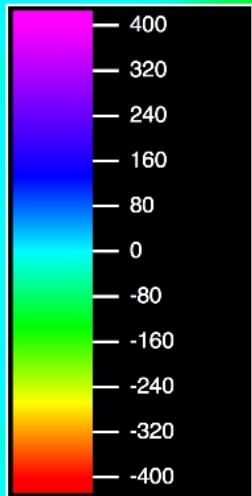
The intermediate stage:

- **Arrival at the chromosphere**
- **The corona has very few (preexisting) links to the photospheric system**

$t = 92 \text{ min}$

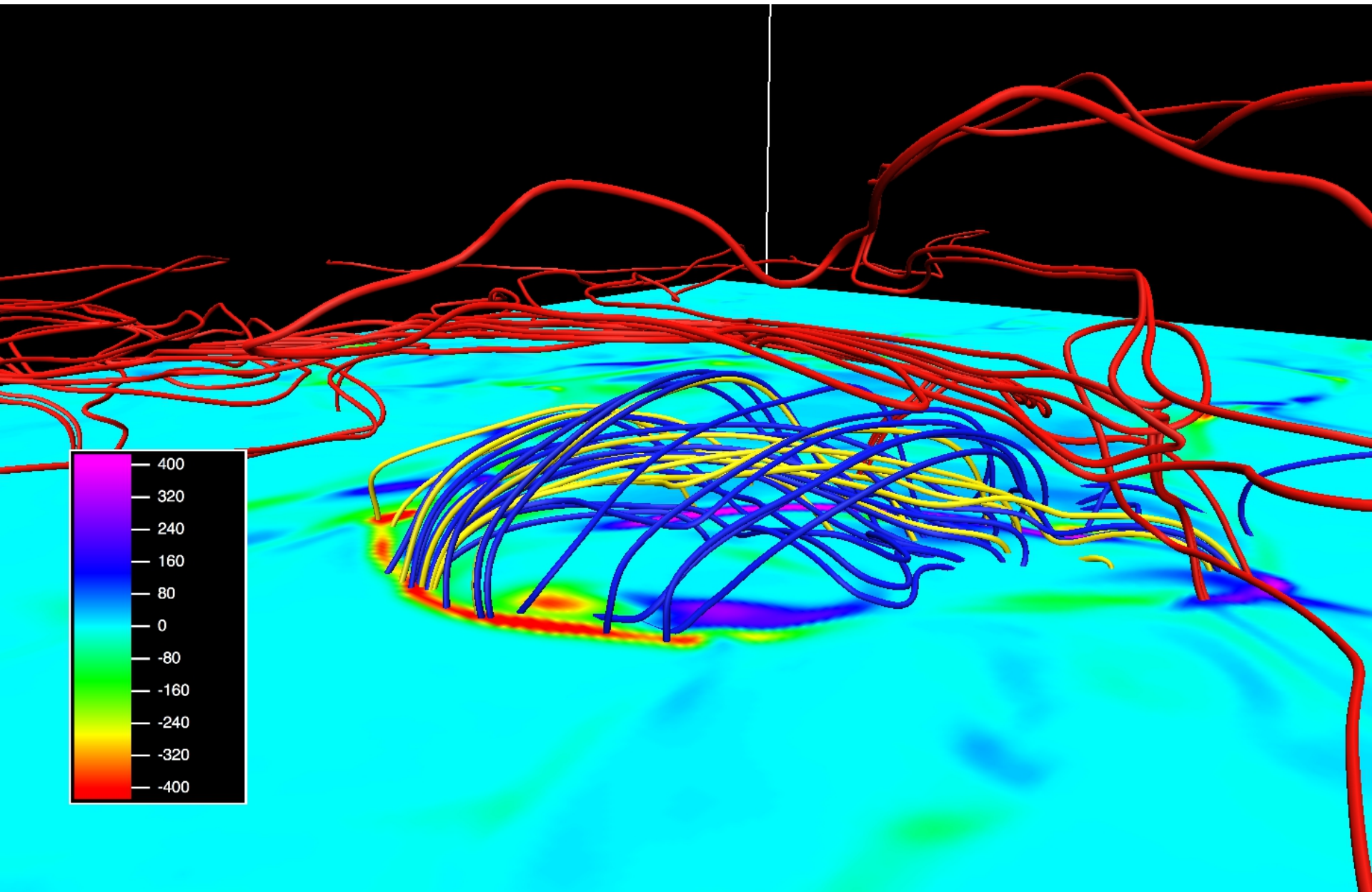
Blue field lines: traced from 500 km height

Yellow field lines: traced from $z=0$



$t = 92 \text{ min}$

Red field lines: traced from 900 km height

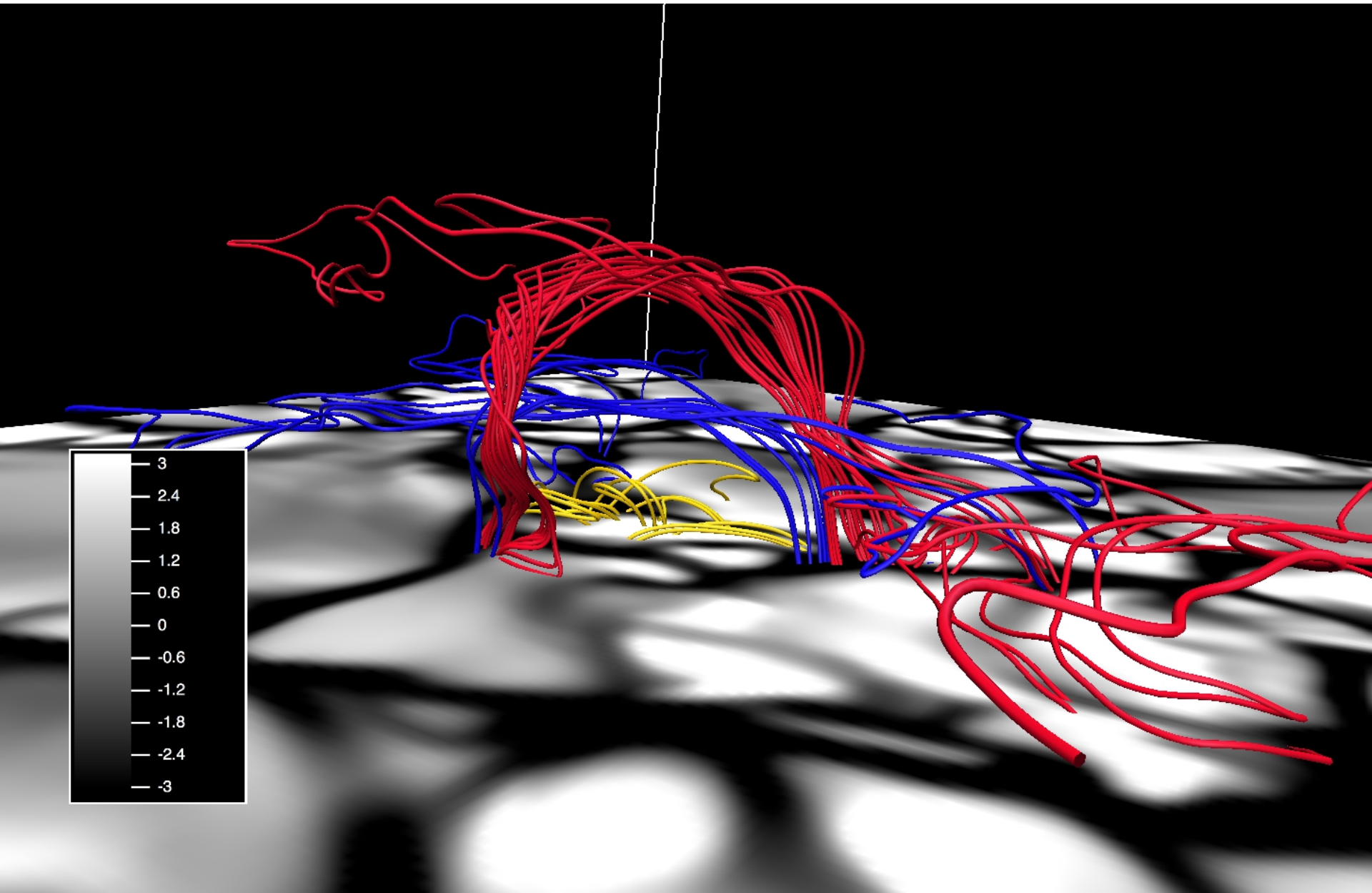


The advanced stage:

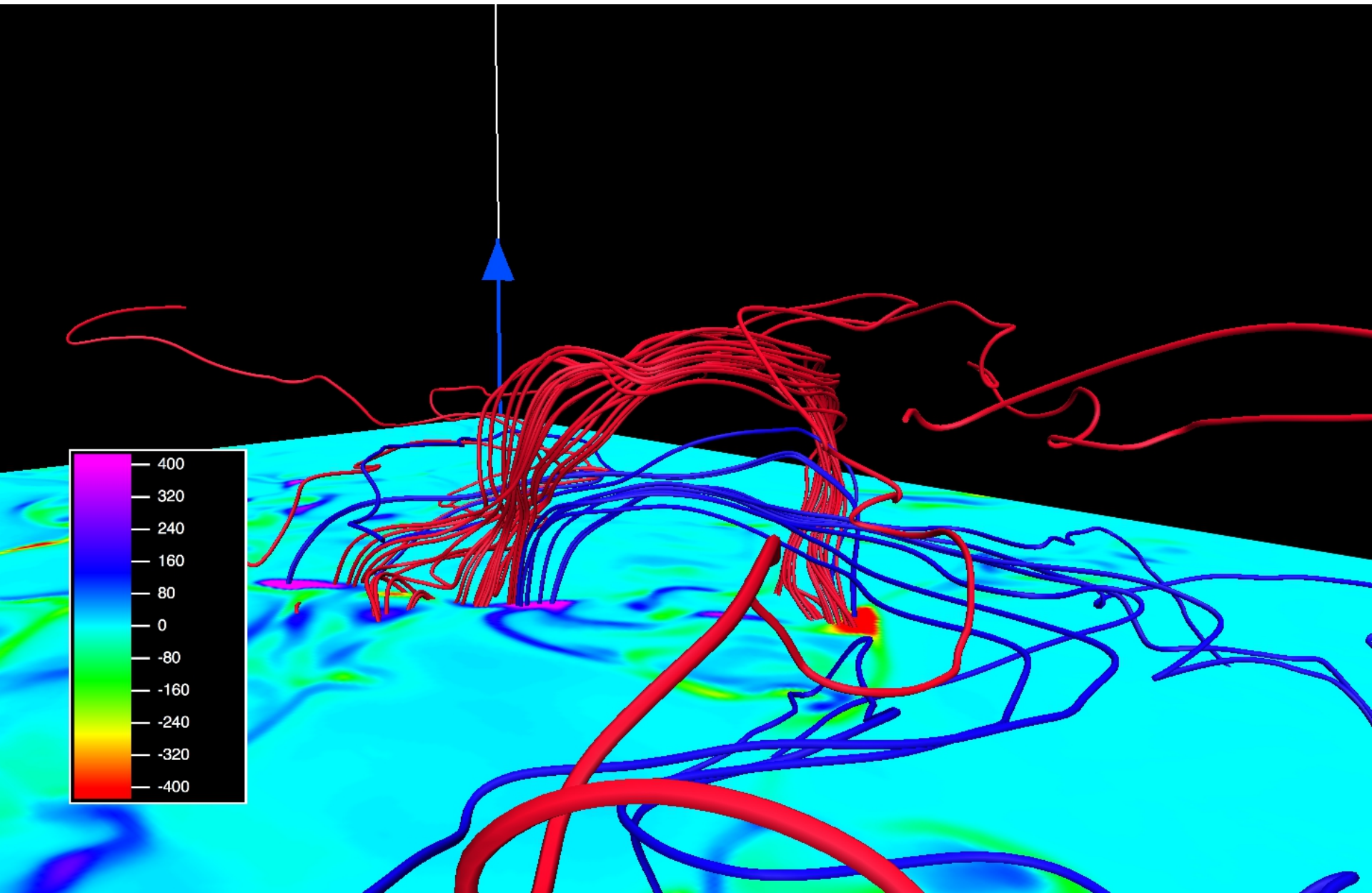
- **Large coronal flux rope straddling a few granules**
- **Regular granulation pattern at the photosphere**

$t = 99 \text{ min}$

Red: 1000 km; Blue: 500 km; Yellow: 0km

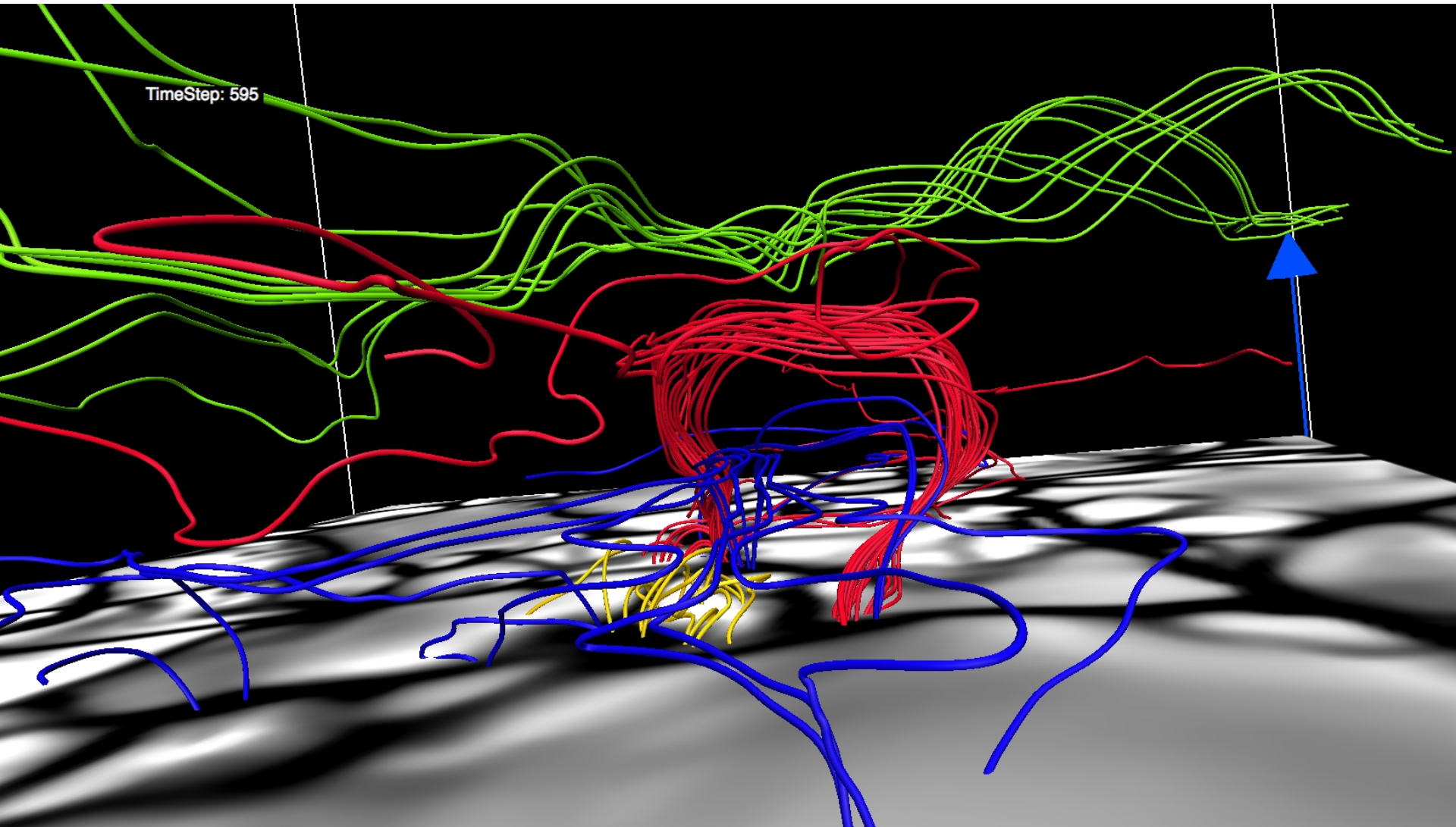


$t = 99 \text{ min}$

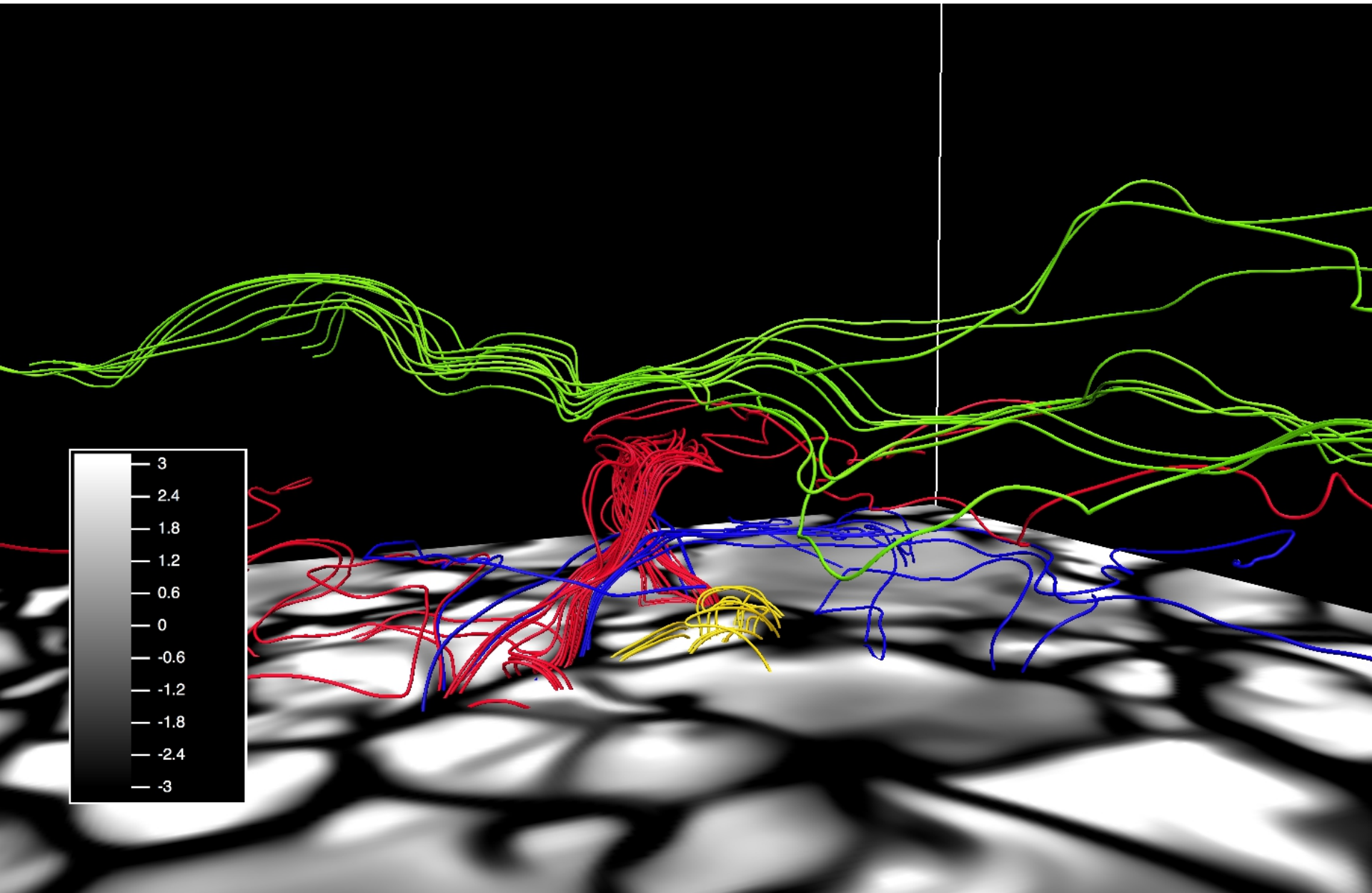


$t = 99 \text{ min}$

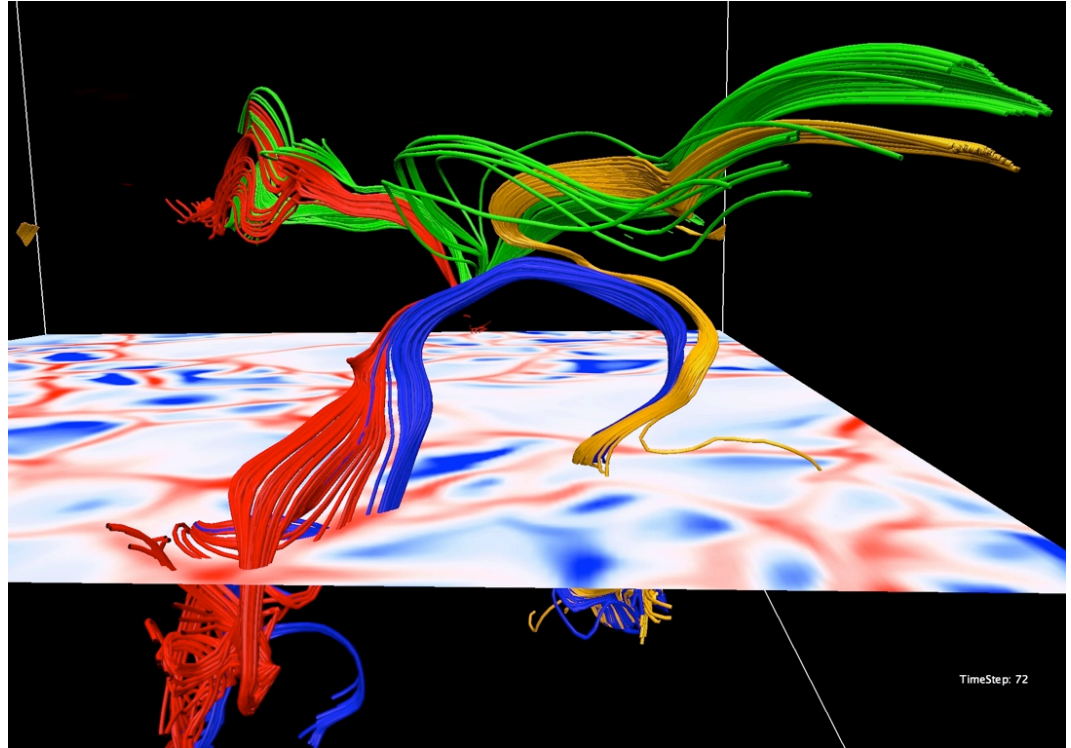
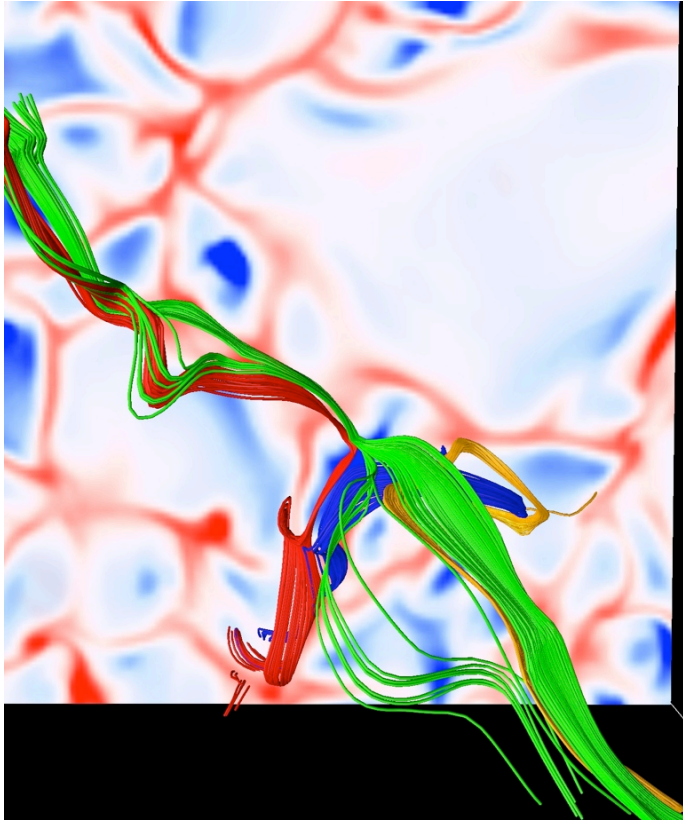
Green: 1600 km



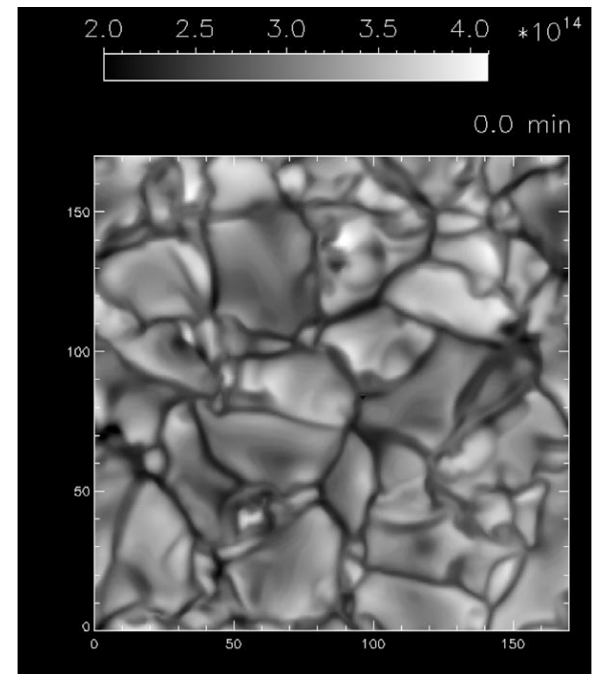
$t = 99 \text{ min}$



**Reconnection
of the emerging bipole
with the ambient coronal field**



Synthetic observations in the visible range from the 3D simulations

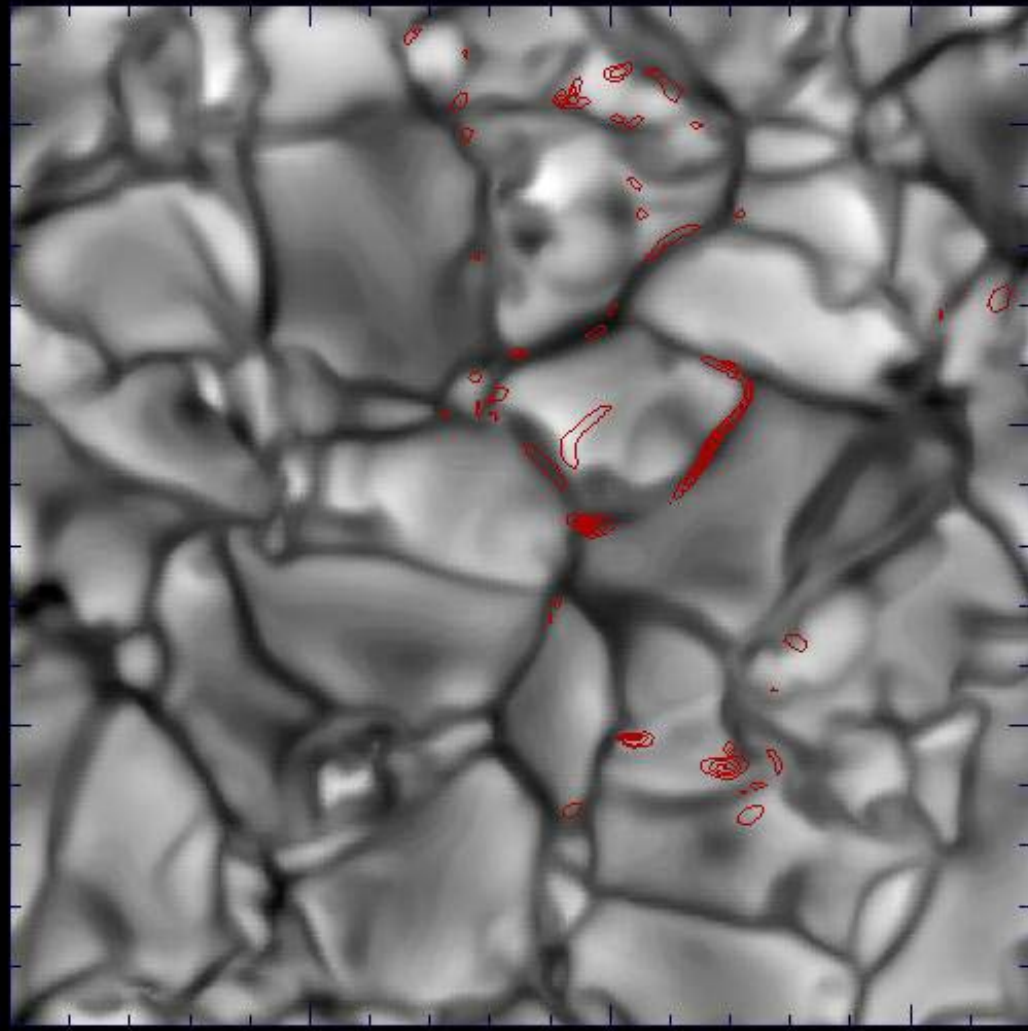


- **We synthesize the emerging Stokes parameters, I, Q, U, V in different spectral lines from the plasma in the computational box**
- **Movie:**
 - **Continuum intensity background map (grey scale)**
 - **Contours of λ -integrated $|V|$, and λ -integrated $(U^2 + Q^2)$ for FeI 630.2nm**
- **Synthesis carried out with the NICOLE program (H. Socas et al 2013, 2014)**

2.0 2.5 3.0 3.5 4.0 $\times 10^{14}$



0.0 min



Some final thoughts

- **Exciting observations** thanks to very high-resolution at different heights
- **Modeling capabilities** are in a position to
 - **Explain some observed features** and
 - **predict** further ones
- Complicated physics necessary for understanding the global evolution → slow progress