3D Radiative MHD Modeling of Subsurface Dynamics and Atmosphere of the Sun and Links to Coronal Heating

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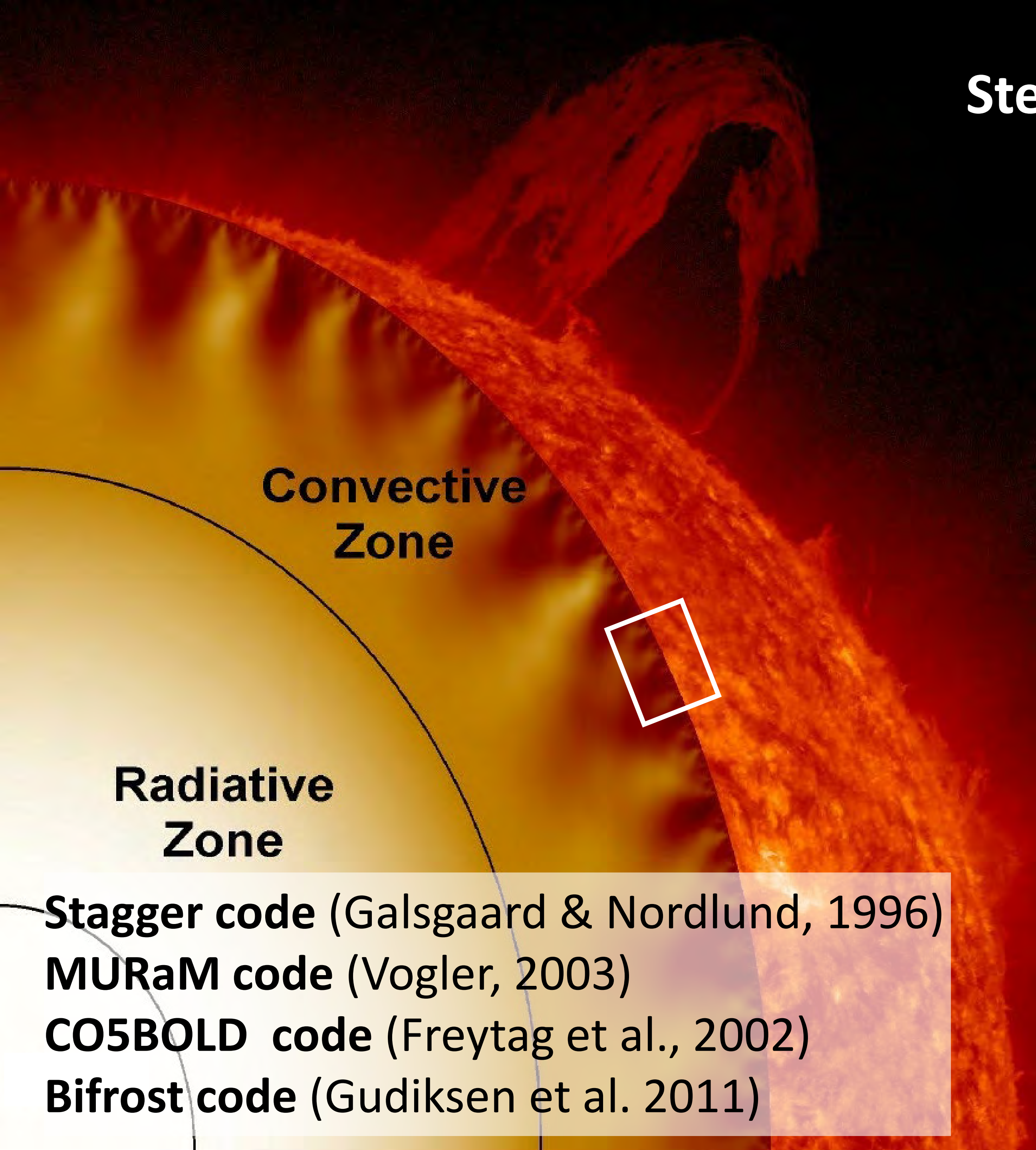
StellarBox code (Wray et al., 2015; 2018)

- Compressible plasma flows in a highly stratified medium
- 3D multi-group radiative energy transfer between fluid elements
- Real-gas equation of state
- Ionization and excitation of all abundant species
- Small-scale turbulence
  - LES: Smagorinsky model (including its dynamic form)
  - DNS + Hyperviscosity approach
  - MHD subgrid models
- Magnetic effects
- Rotation
- Internal structure
- Opacity tables



Stagger code (Galsgaard & Nordlund, 1996)
MURaM code (Vogler, 2003)
CO5BOLD code (Freytag et al., 2002)
Bifrost code (Gudiksen et al. 2011)

Numerical Model: Basic equations

The equations we solved are the grid-cell average conservation of mass:

$$\frac{\partial \rho}{\partial t} + (\rho u_i)_{,i} = 0$$

Conservation of momentum:

$$\frac{\partial \rho u_i}{\partial t} + \left(\rho u_i u_j + P_{ij}\right)_{,j} = -\rho \phi_{,i}$$

Conservation of energy:

Molecular and turbulent coefficients

$$\frac{\partial E}{\partial t} + \left(\begin{array}{l} E u_i + P_{ij} u_j - \kappa T_{,i} + \\ + \left(\frac{c}{4\pi}\right)^2 \frac{1}{\sigma} \left(B_{i,j} - B_{j,i}\right) B_j + F_i^{\mathrm{rad}} \end{array} \right)_{,i} = 0$$

with

$$P_{ij} = \left(p + \frac{2}{3}\mu u_{k,k} + \frac{1}{8\pi} B_k B_k\right)\delta_{ij} - \mu\left(u_{i,j} + u_{j,i}\right) - \frac{1}{4\pi} B_i B_j$$

$p(\rho,e)$

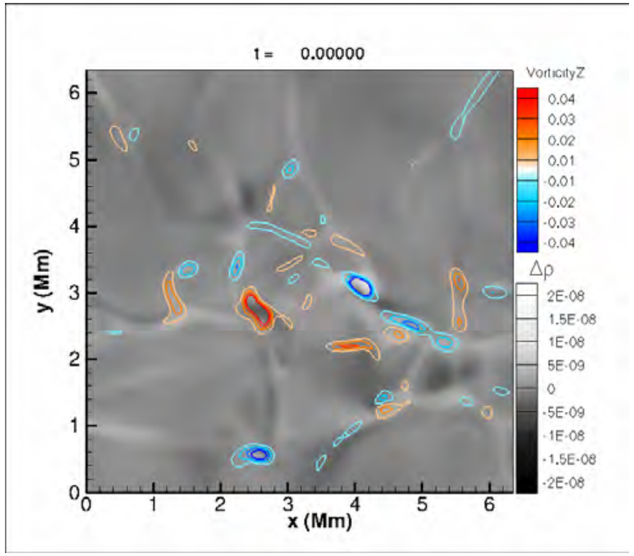
Conservation of magnetic flux:

$$\frac{\partial B_i}{\partial t} + \left(u_j B_i - u_i B_j - \frac{c^2}{4\pi\sigma}\left(B_{i,j} - B_{j,i}\right)\right)_{,j} = 0$$

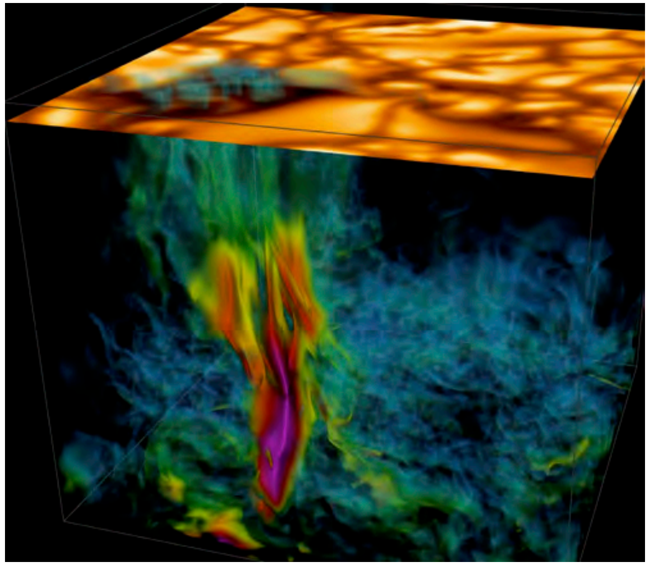
ρ denotes the average mass density, u_i, the Favre-averaged velocity

3D realistic modeling of the solar dynamics

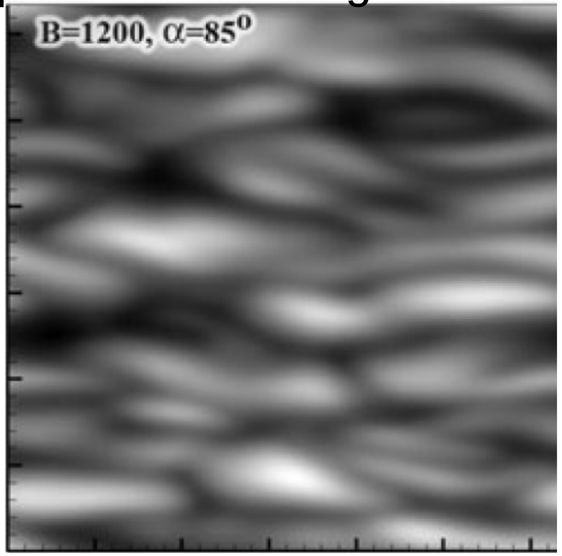
Acoustic waves excitation



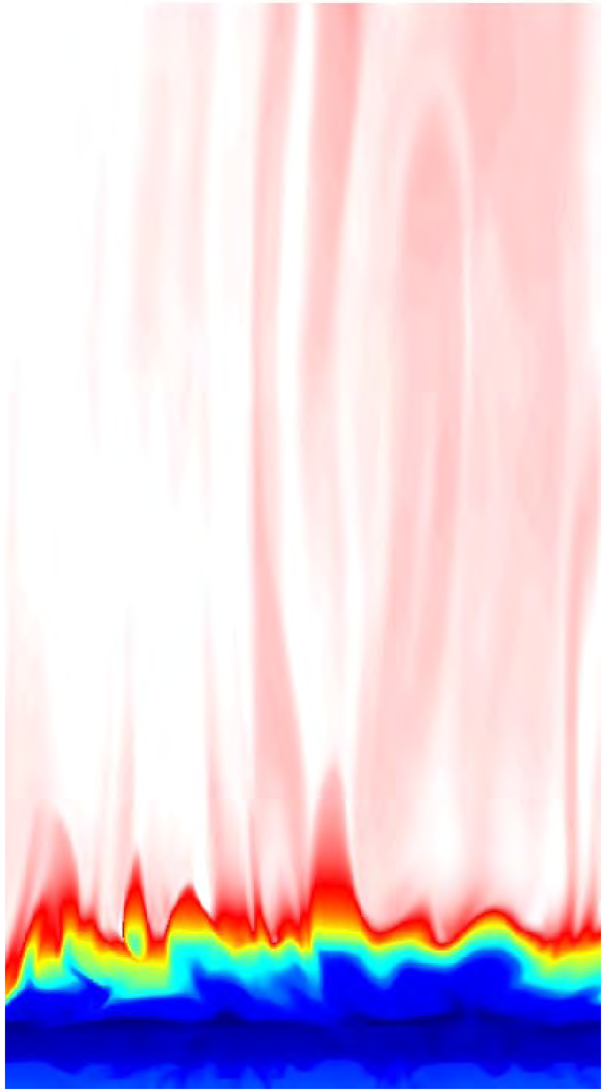
Magnetic structures formation



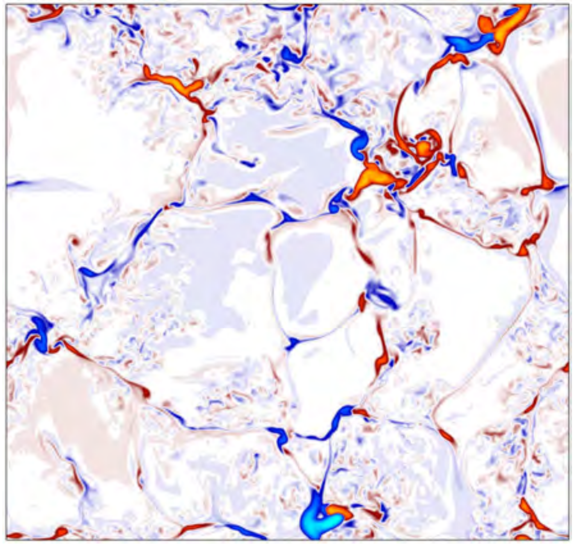
Self organization processes in magnetic field



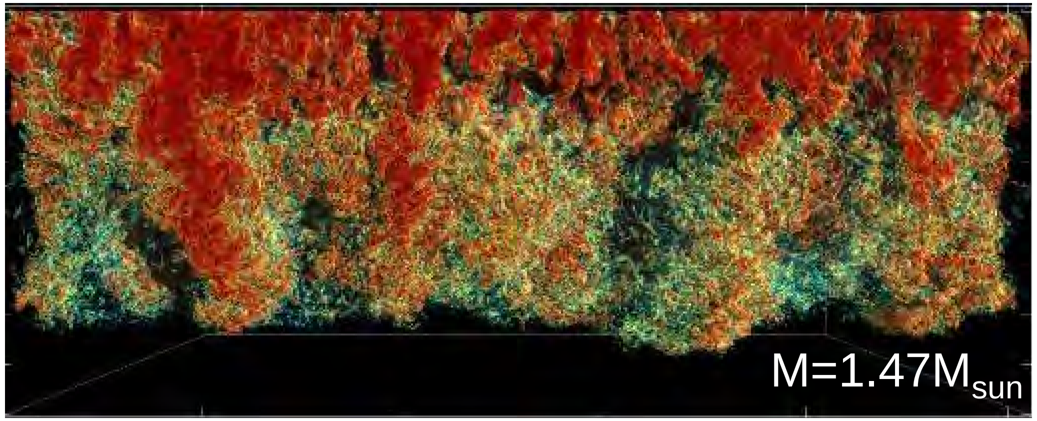
Solar corona structure and dynamics



Small-scale dynamo

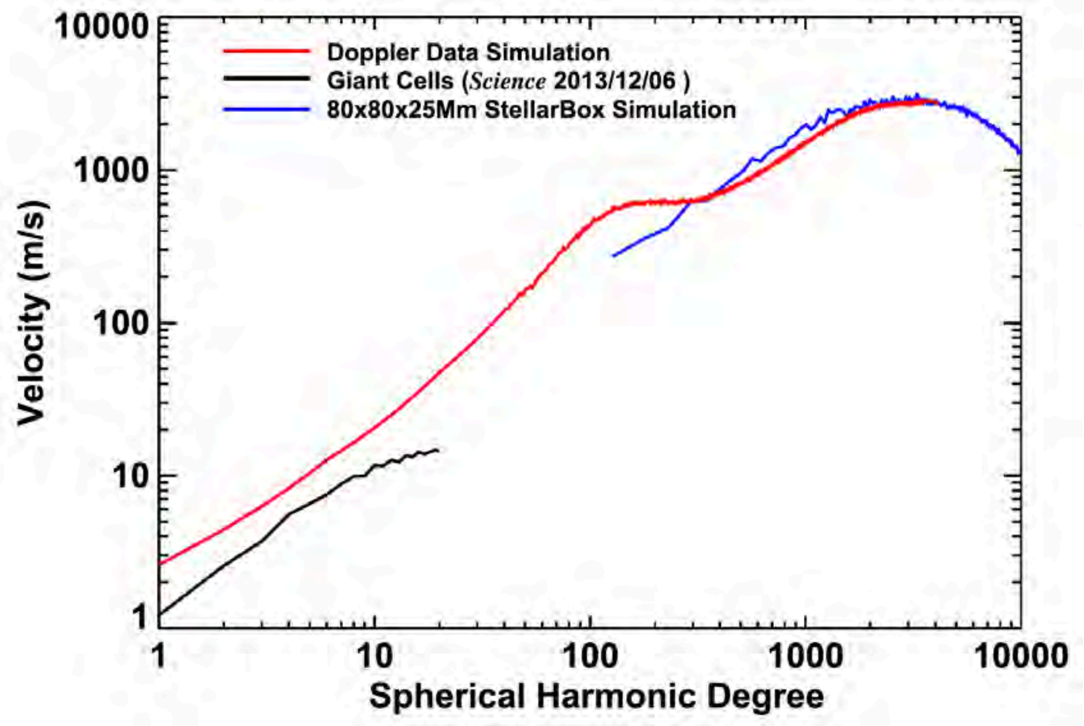


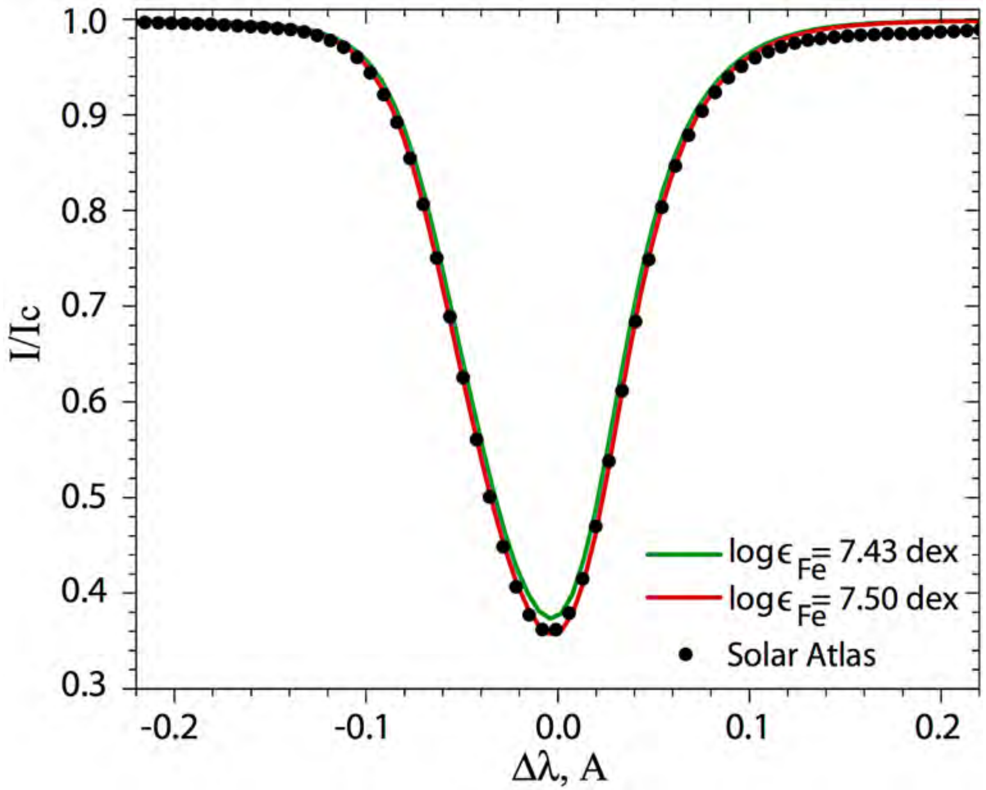
Stellar convection



Kitiashvili et al., 2009-2024

Comparison with observations

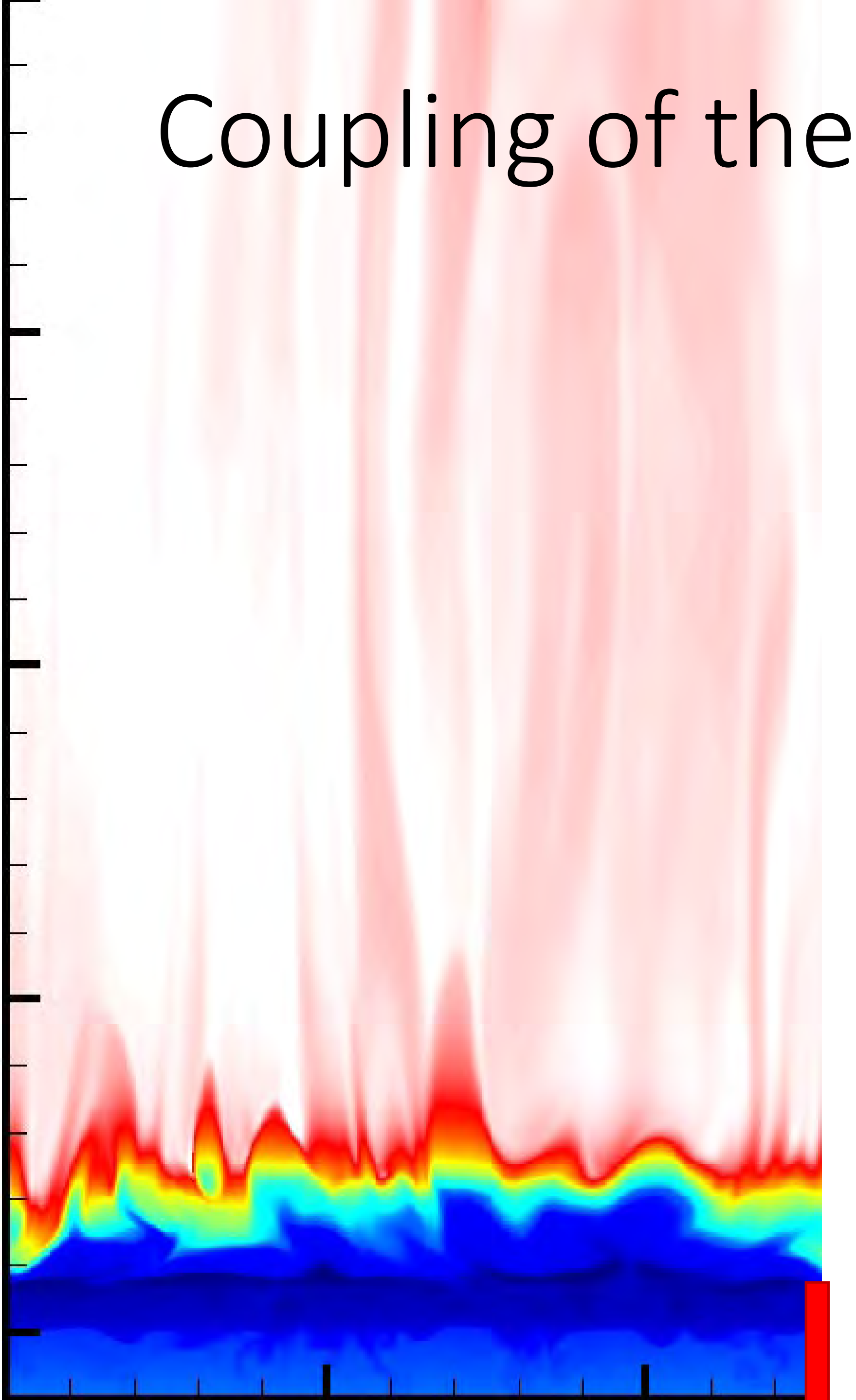




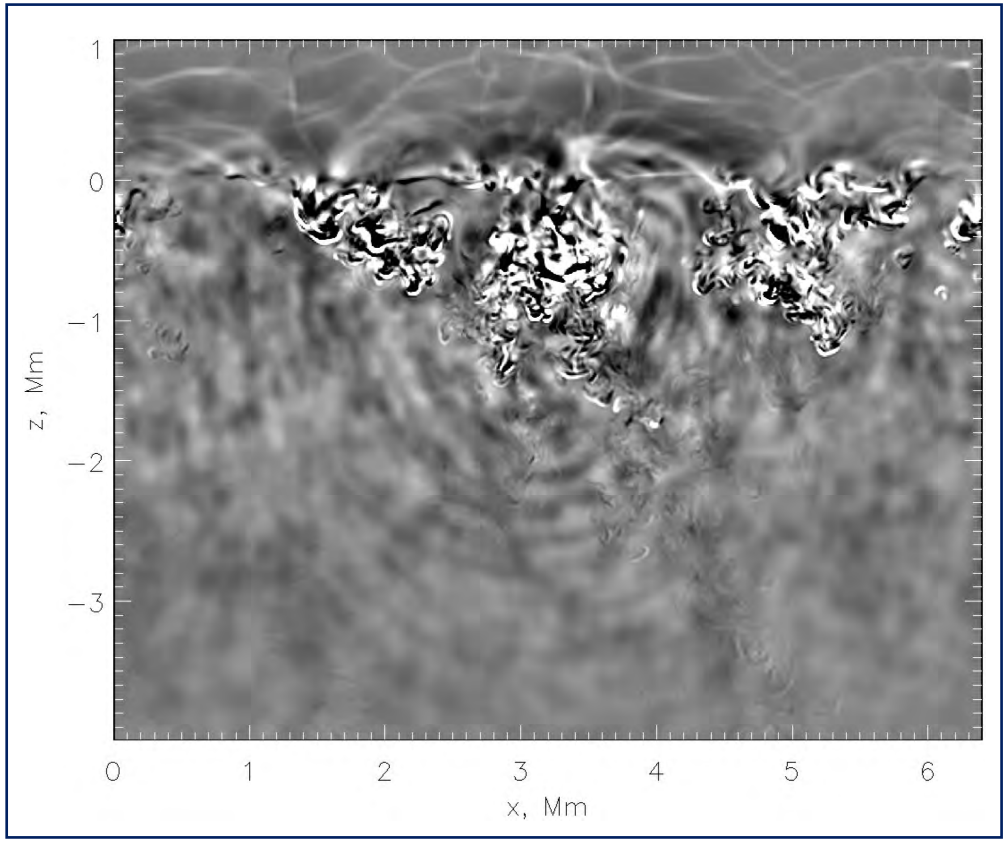
Comparison of radial velocity distribution as a function of the spherical harmonical degree from the StellarBox simulations and HMI data (Hathaway et al., 2015).

Comparison of the synthetic line profiles obtained from our simulations for two iron abundances: 7.43 and 7.50dex, and from the observations with Fourier Transform Spectrometer (FTS solar atlas) for the line 6173.3 A (Kitiashvili et al., 2015).

Coupling of the subsurface layers & atmosphere



Acoustic and shock waves

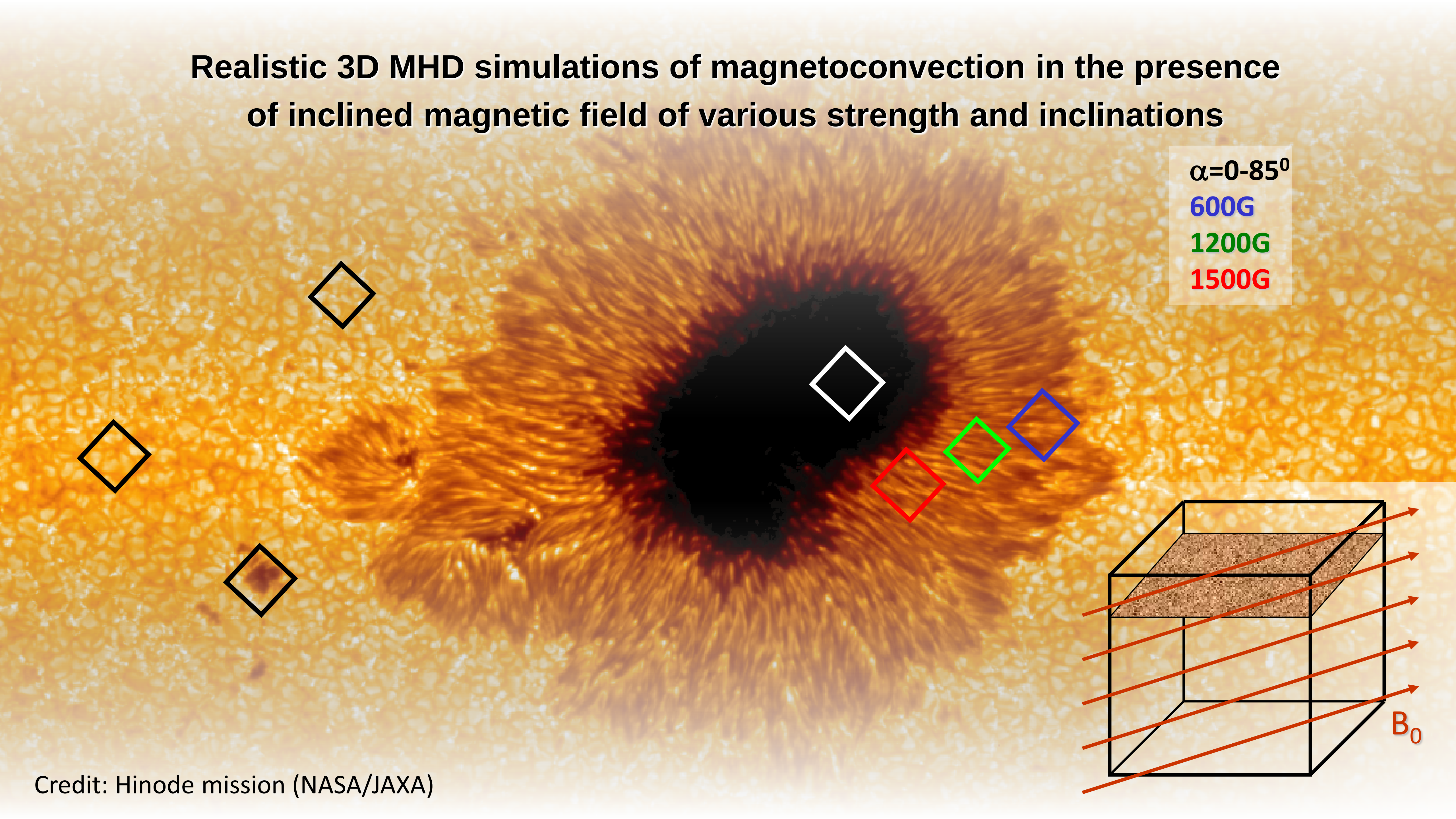


Acoustic waves

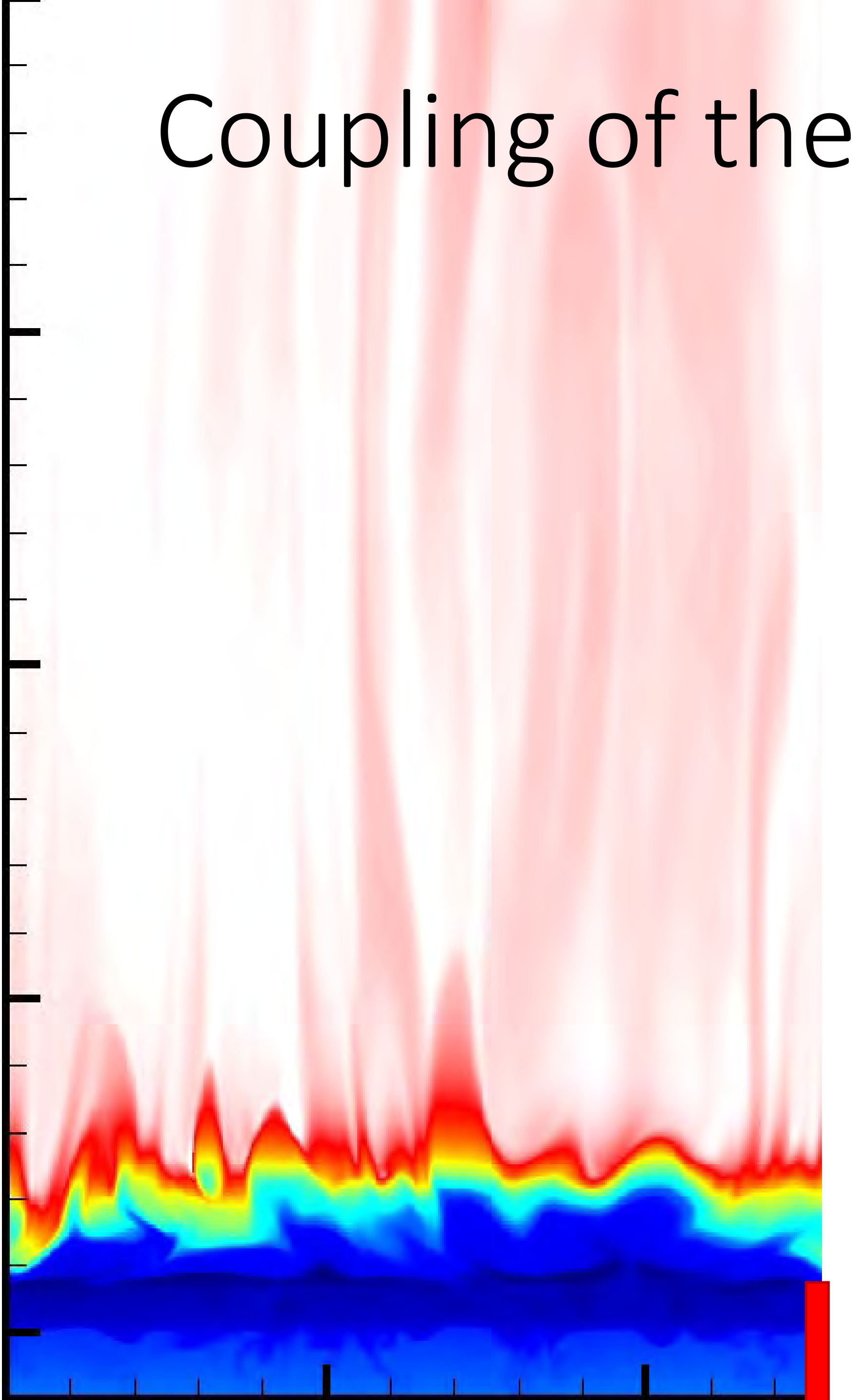
- Vortex tubes interaction
- Turbulent motions
- Granule collapse

Shock waves

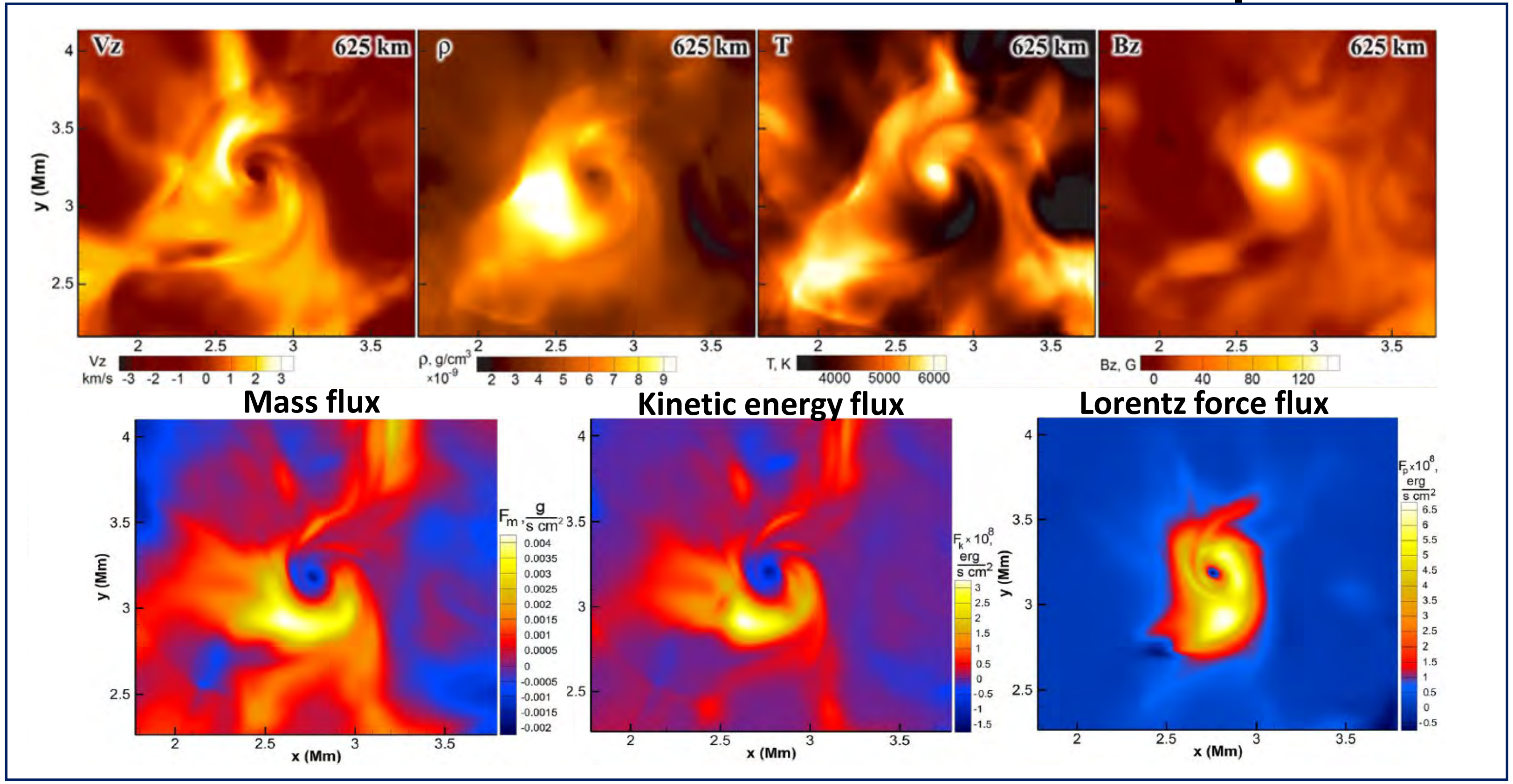
- Dynamics of the photosphere & granulation
- Acoustic noise
- Eruptive activity


Realistic 3D MHD simulations of magnetoconvection in the presence of inclined magnetic field of various strength and inclinations
α=0-85⁰
600G
1200G
1500G
B0
Credit: Hinode mission (NASA/JAXA)

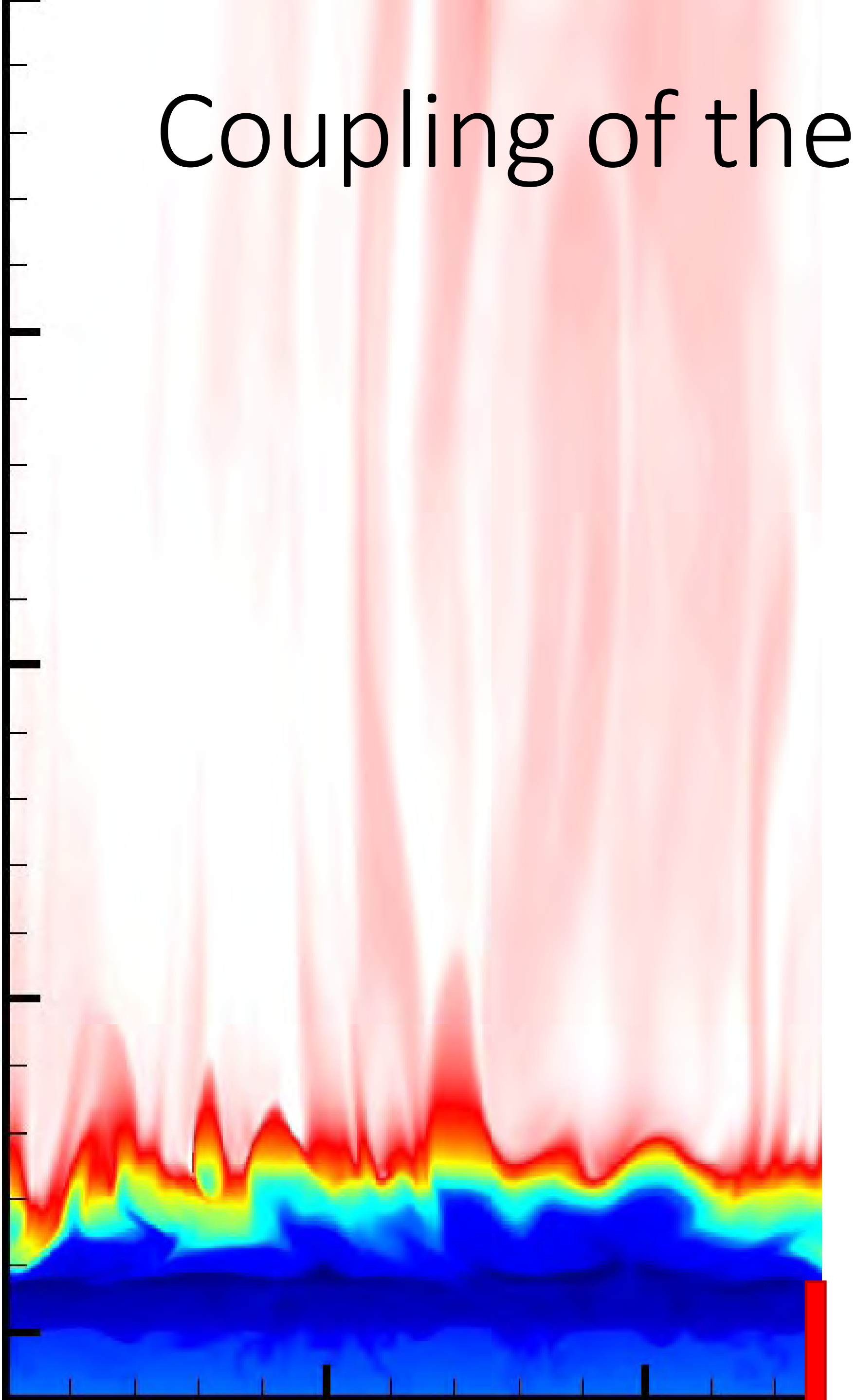
Coupling of the subsurface layers & atmosphere



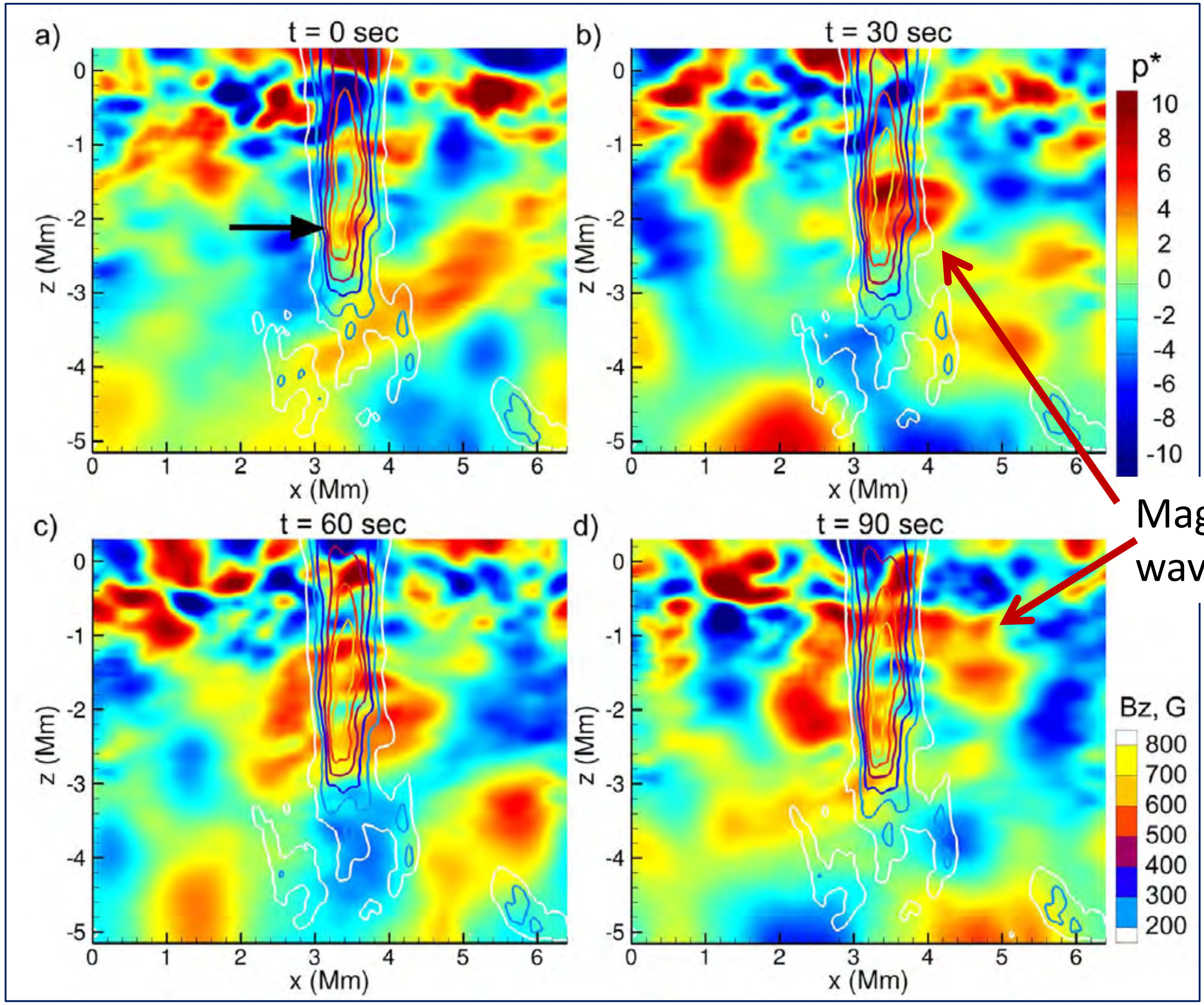
Vortex tube dynamics as a channel for energy exchange between the convection zone and solar atmosphere



Coupling of the subsurface layers & atmosphere

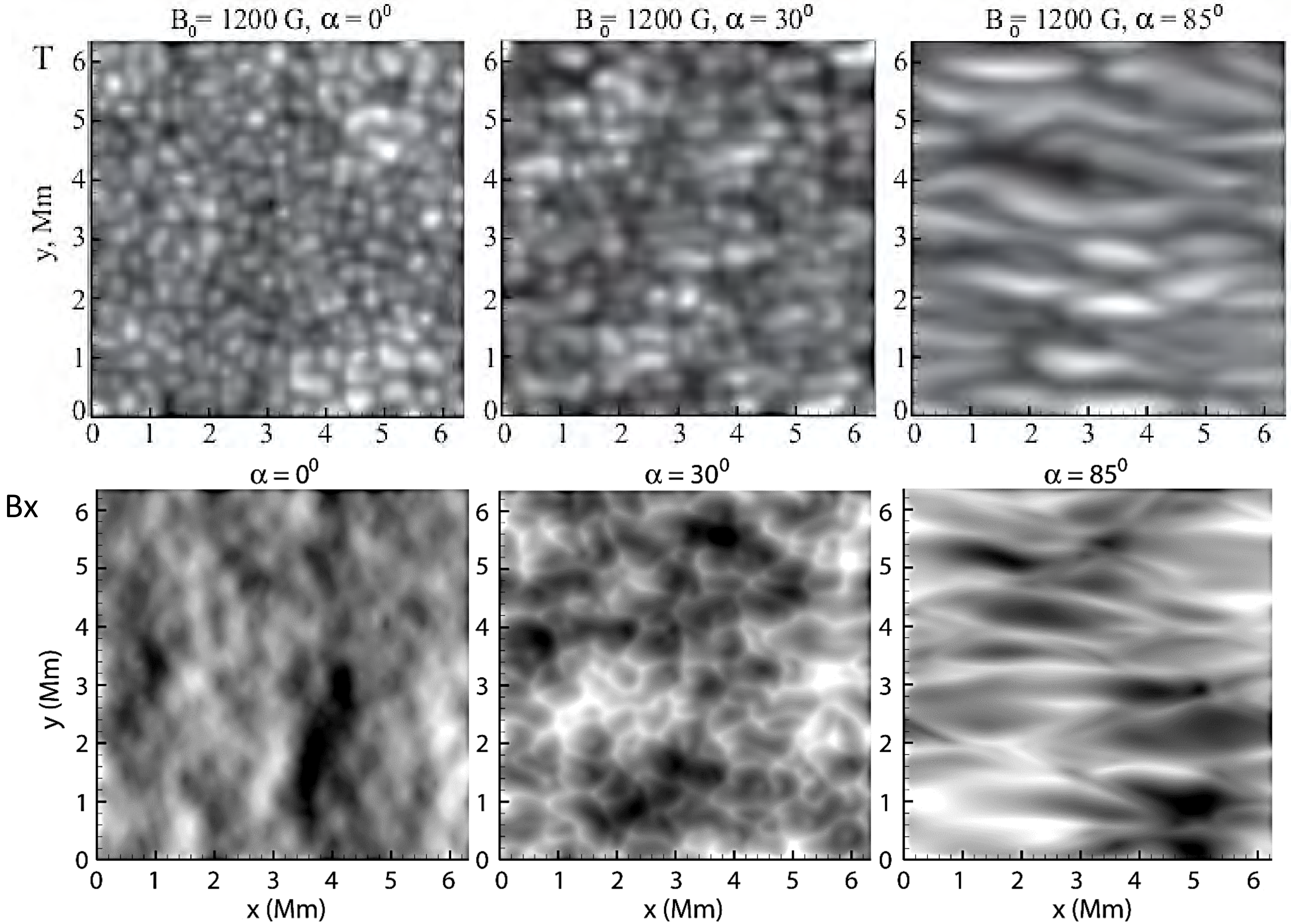


Presence of strong magnetic fields (e.g., pore-like structure)

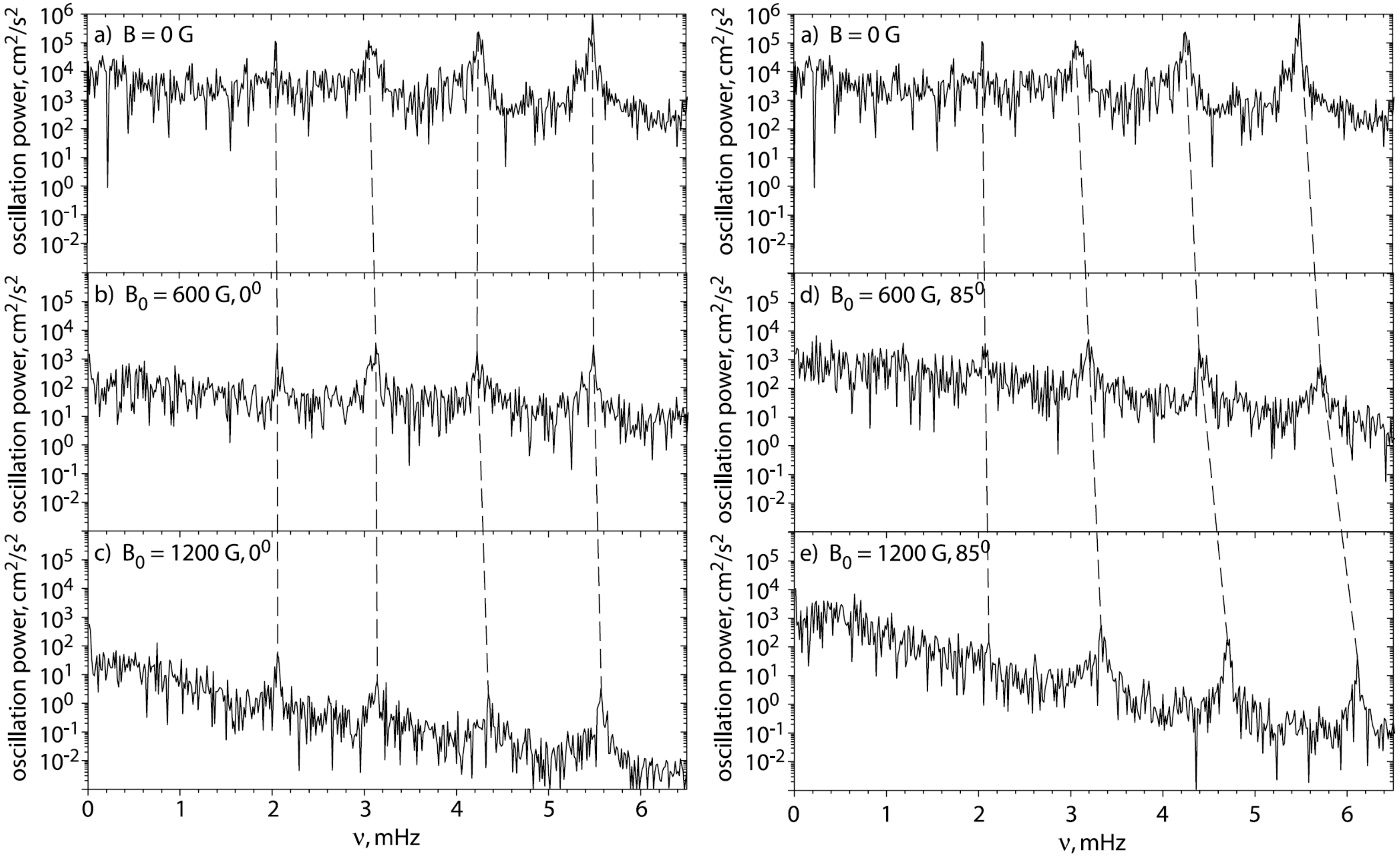


Magnetoacoustic waves

Evolution of the temperature and horizontal magnetic structure vs inclination



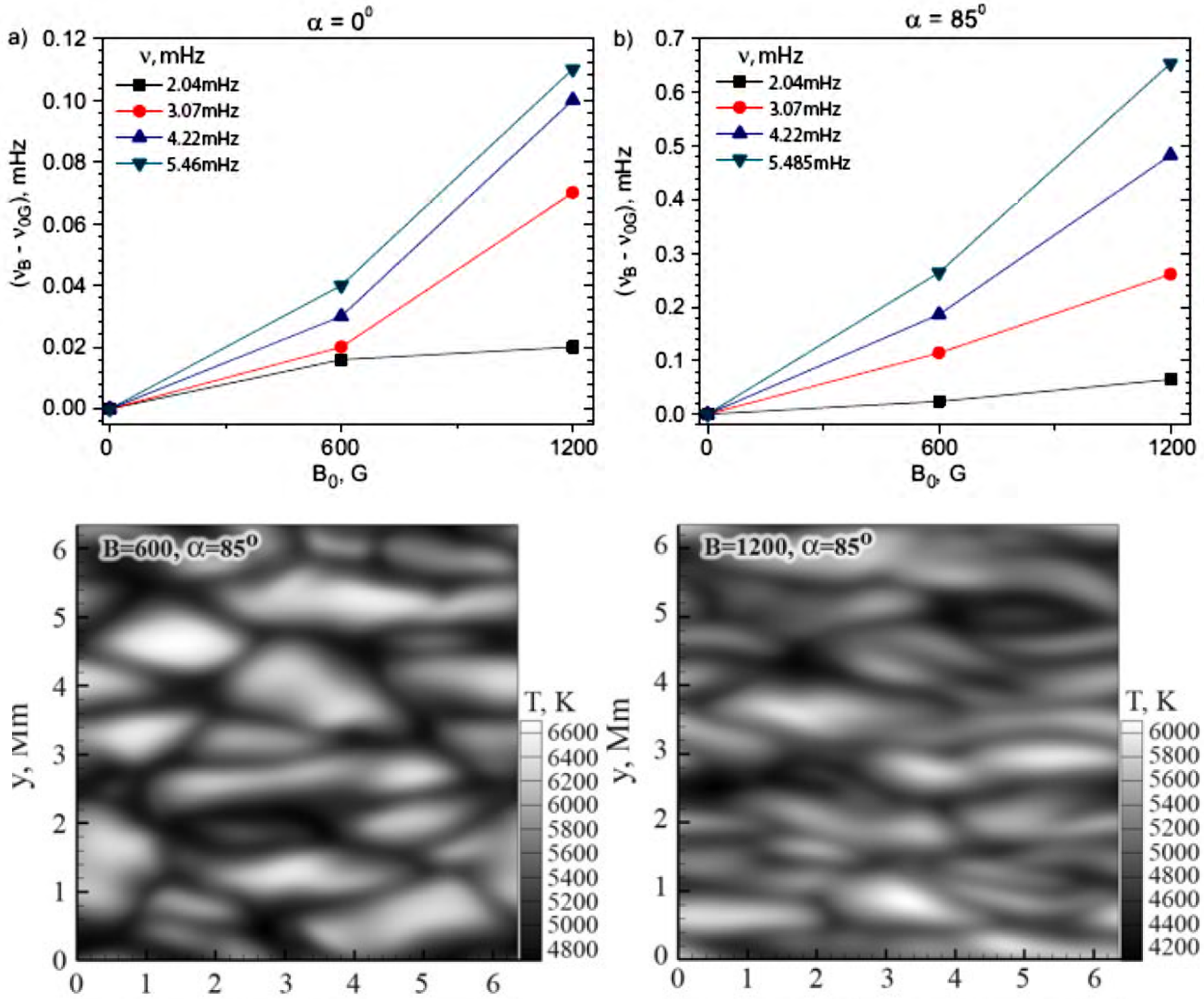
Oscillation power spectra of the mean vertical velocity (radial oscillations) in the vertical and inclined magnetic field regions



Oscillation power spectra of the vertical velocity for different magnetic field strengths and inclinations: a) B_0=0G; b) B_0=600G, $\alpha=0^0$; c) B_0=1200G, $\alpha=0^0$; d) B_0=600G, $\alpha=85^0$; and e) B_0=1200G, $\alpha=85^0$.

Kitiashvili et al., 2011

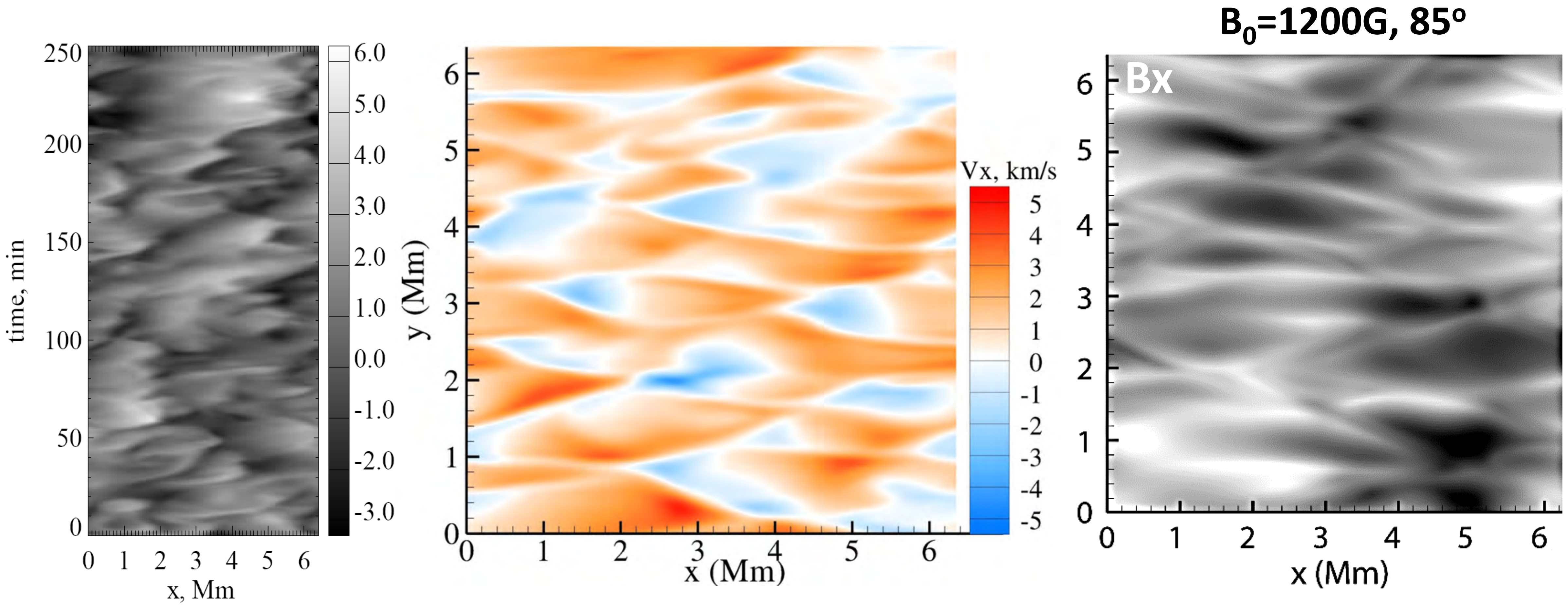
Effect of magnetic field inclination on surface oscillations



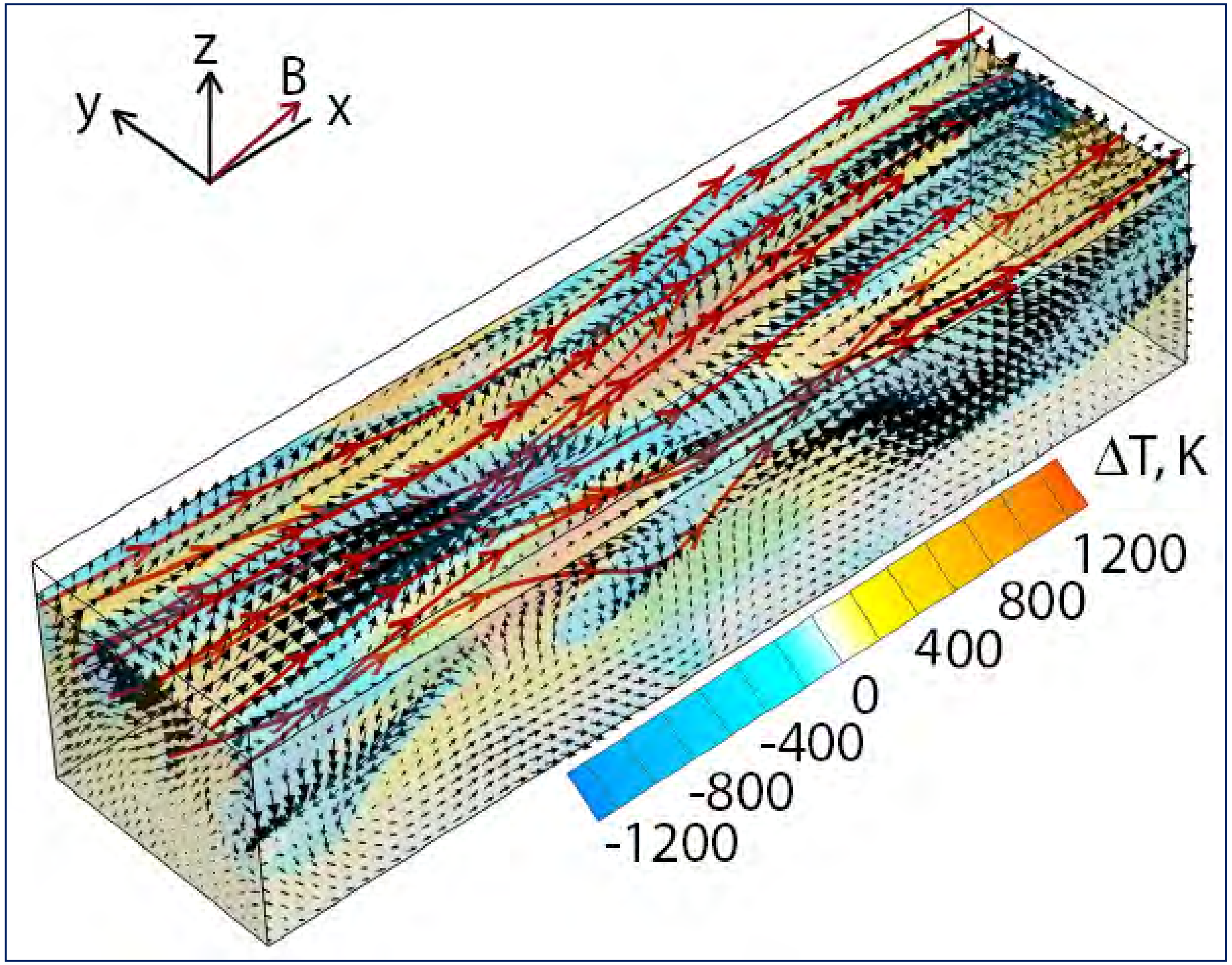
Frequency shifts of the oscillation modes (indicated by different colors) relative to the case of nonmagnetic convection for the vertical ($\alpha=0^0$, panel a) and almost horizontal ($\alpha=85^0$, panel b) magnetic fields.

Kitiashvili et al., 2010

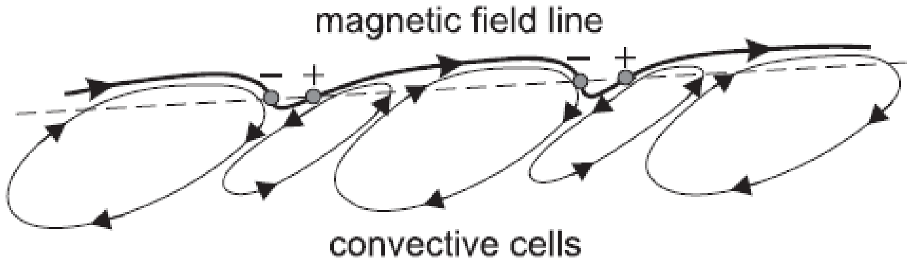
Horizontal velocity of flow along magnetic field inclination



Sea-serpent behavior in the penumbra simulations

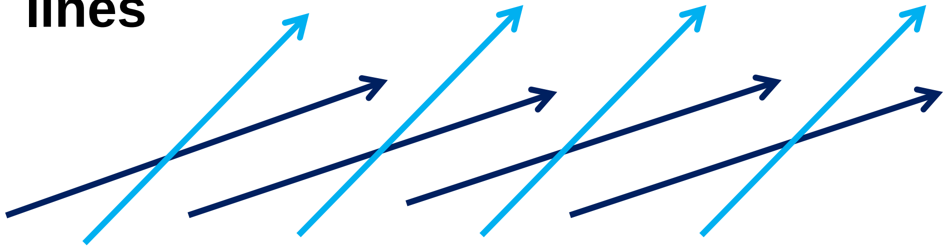


3D rendering of temperature variations, magnetic field lines (red curves) and flow field (arrows).



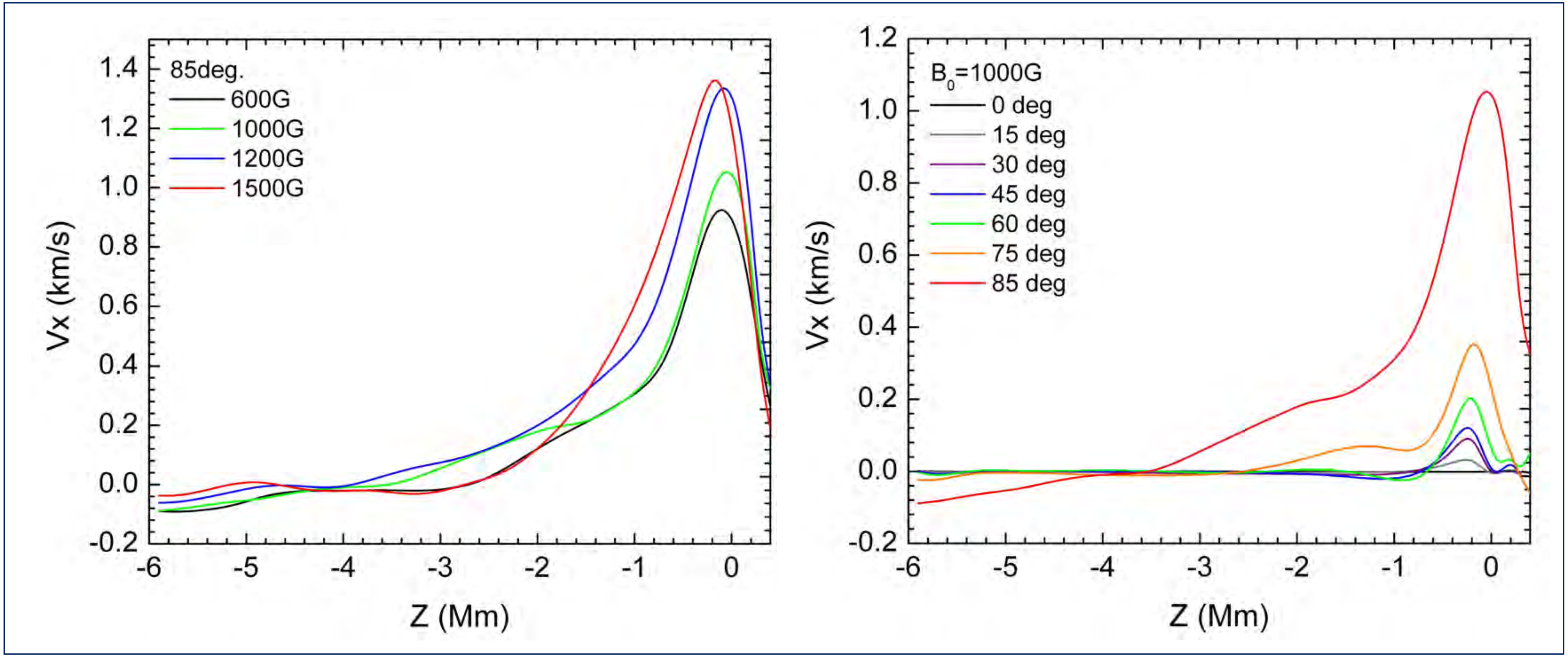
Thus, the numerical simulations connect the sea-serpent structure of the moving bipolar magnetic paths observed in the penumbra with the process of overturning magnetoconvection, traveling convective waves, and the Evershed flow.

Comb-like structure of magnetic field lines

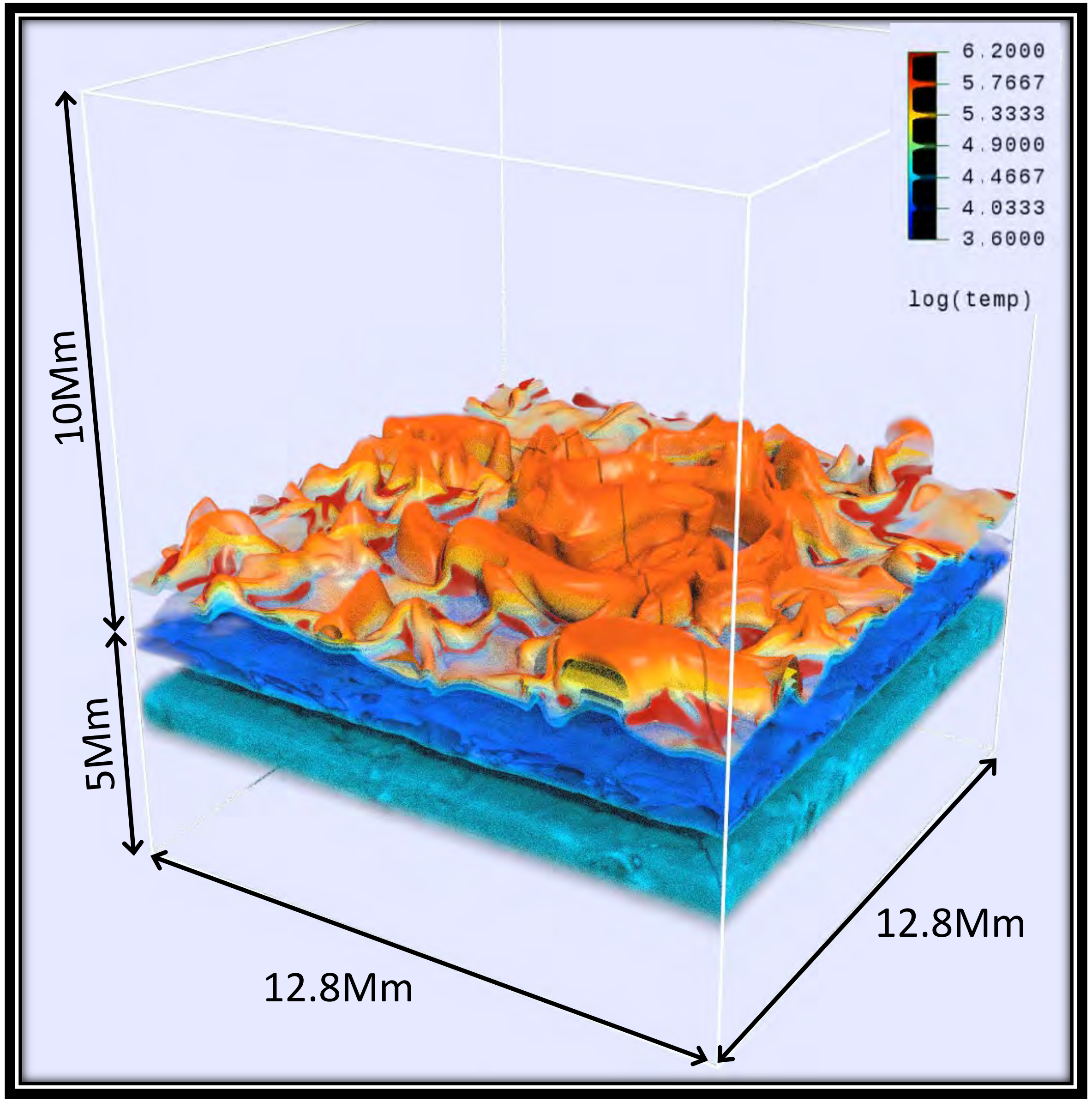


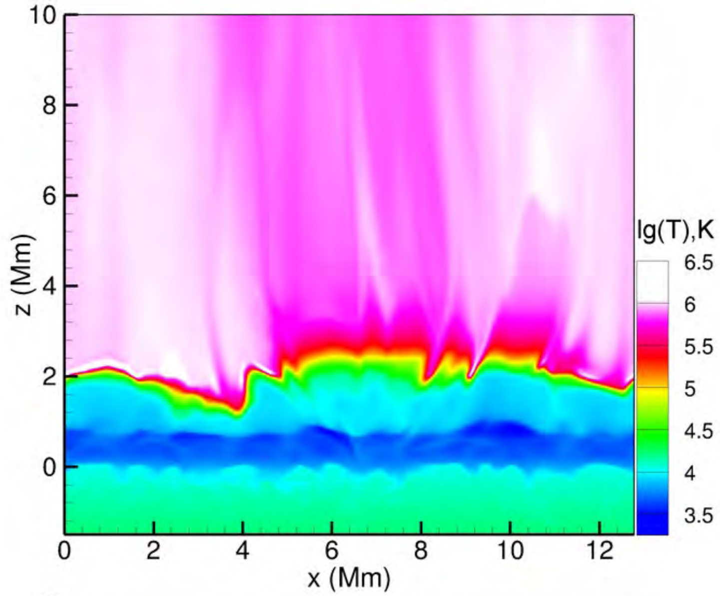
Kitiashvili et. al, 2010

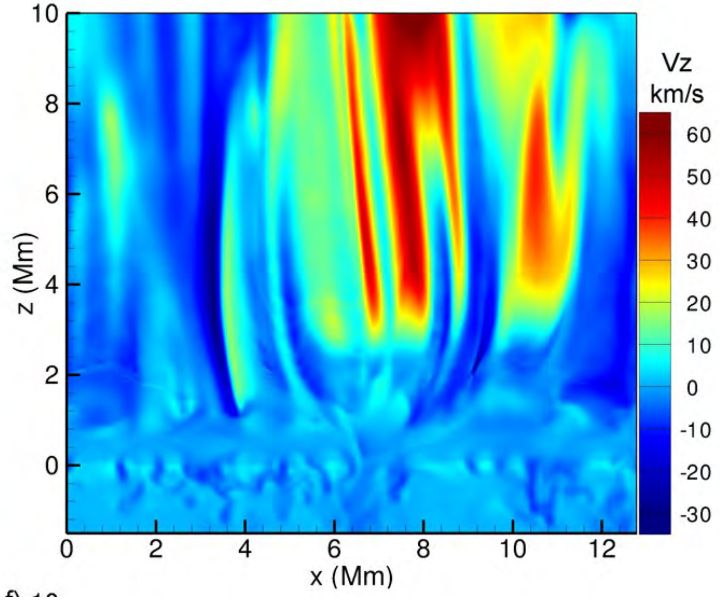
Distribution of plasma velocity with depth



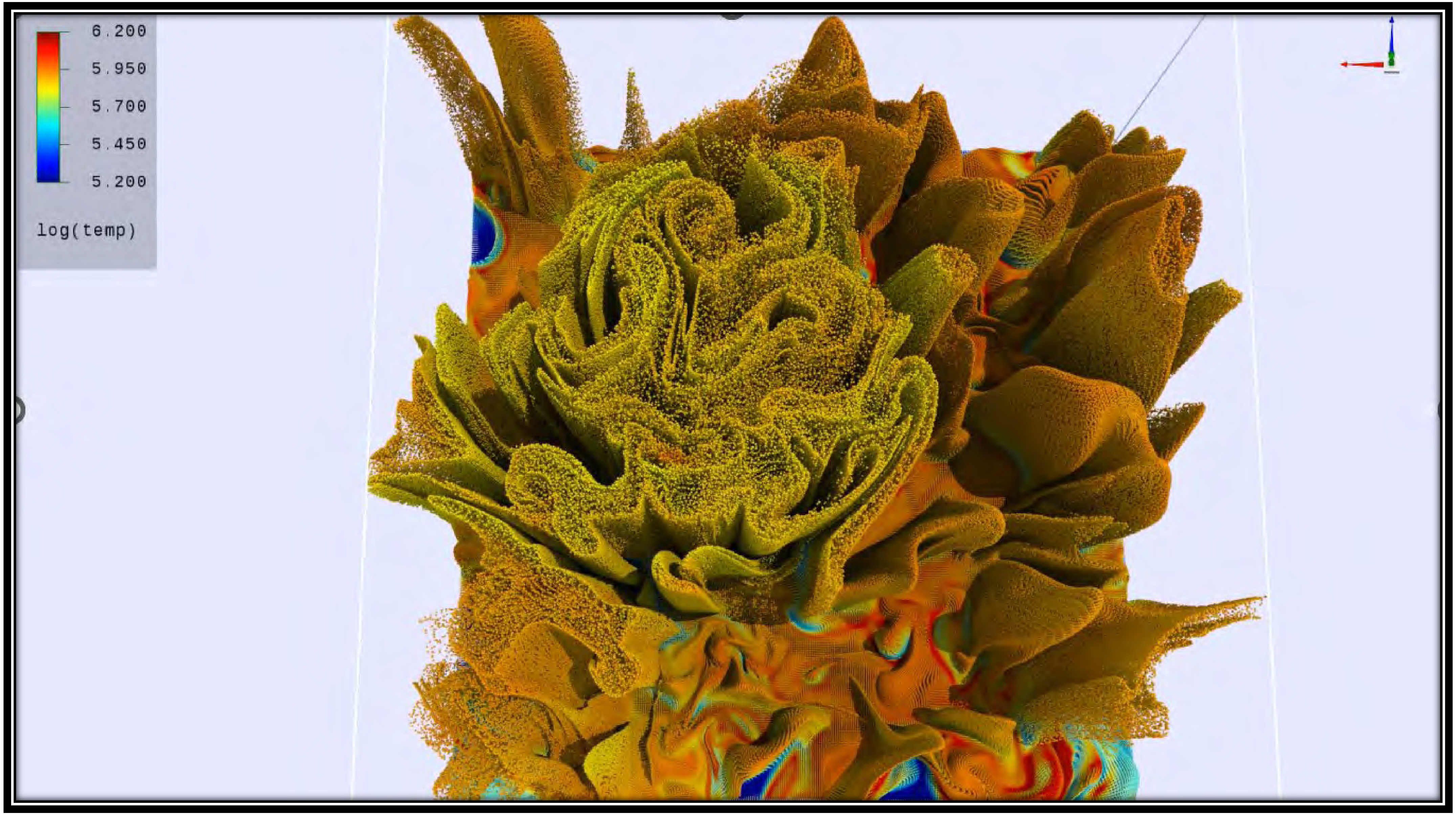
Heating in the transition zone



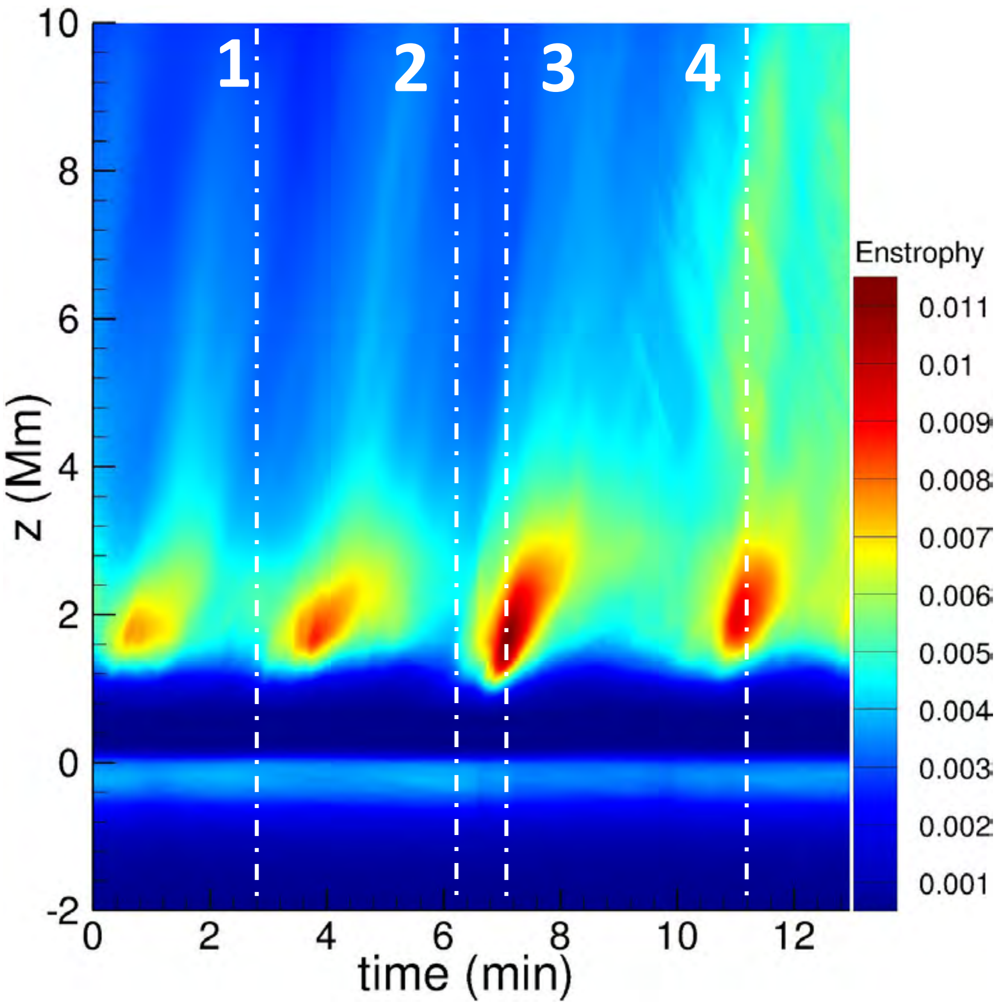


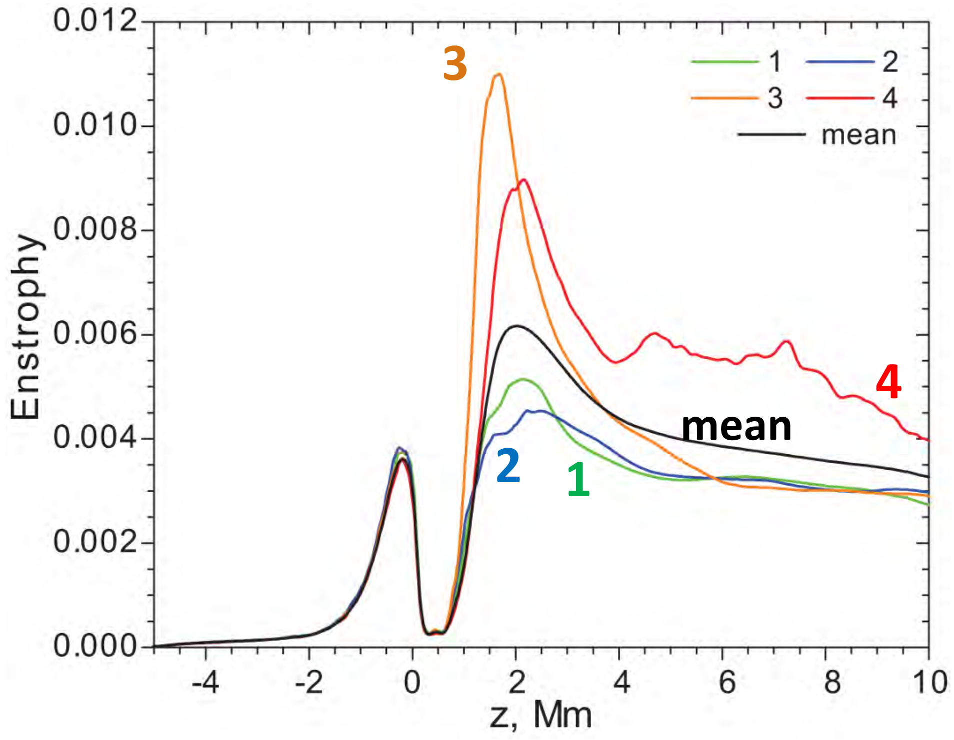


Self-formed magnetic structure in the solar atmosphere



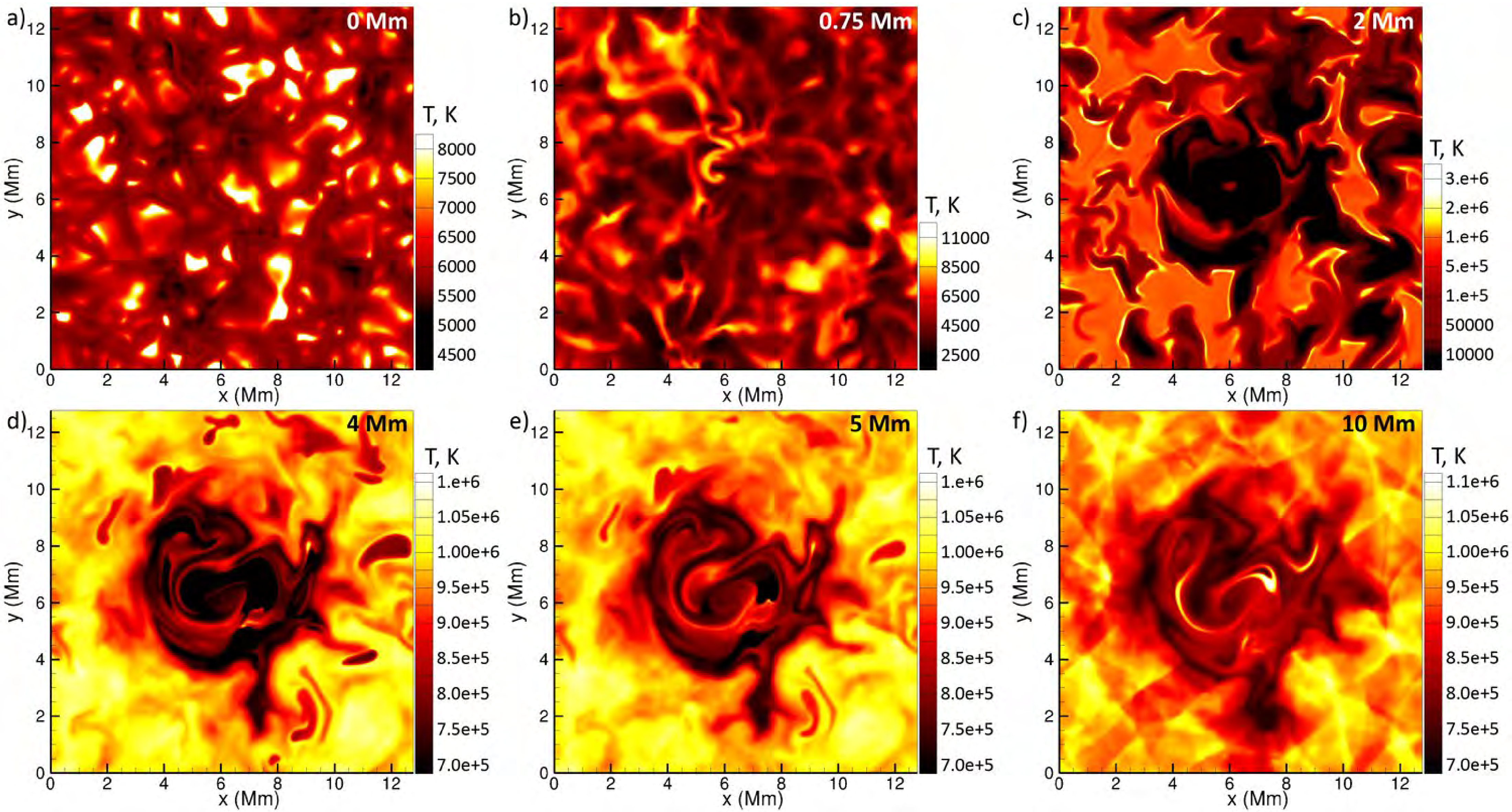
Enstrophy transport from the transition zone to the corona





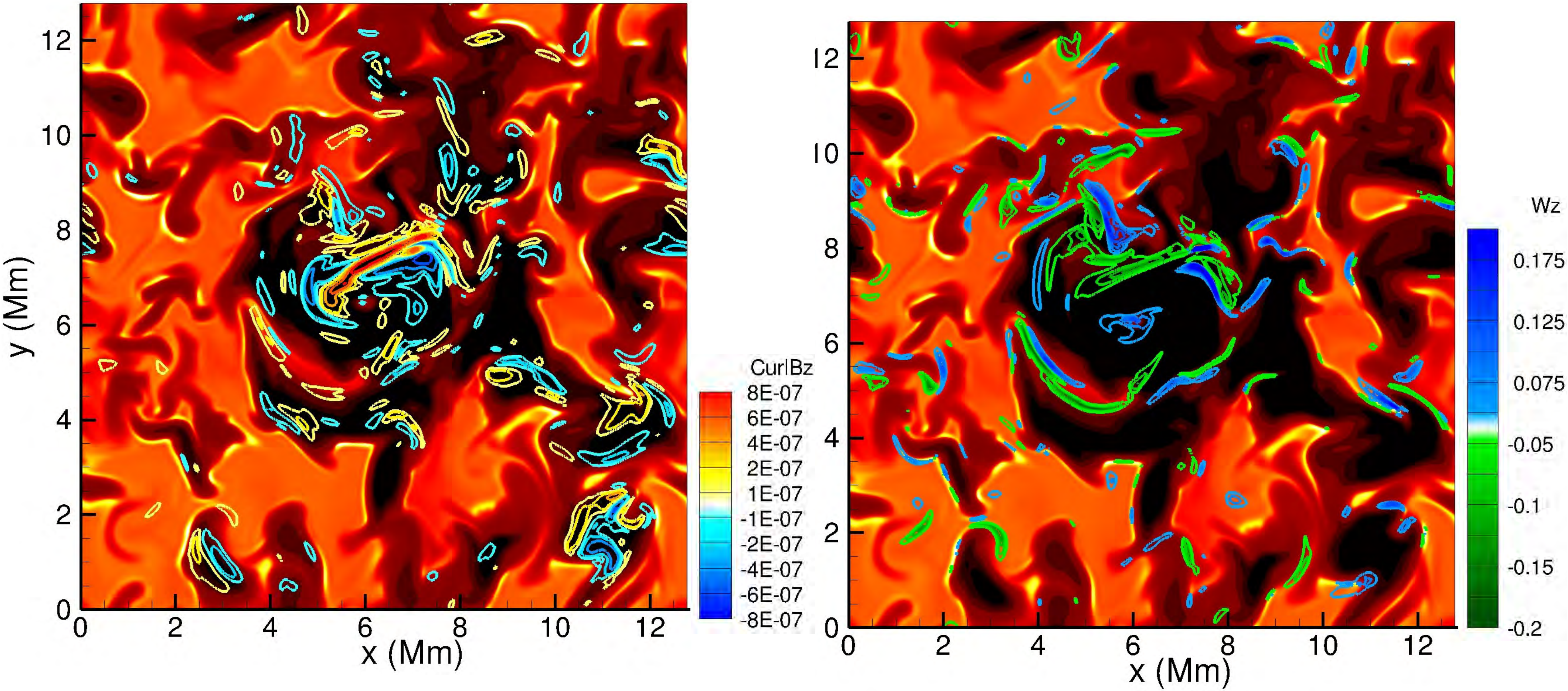
# Eruption	Enstrophy transport speed, km/s	
1	16	110
2	16	76
3	30	79
4	35	115

Temperature structure of the solar atmosphere

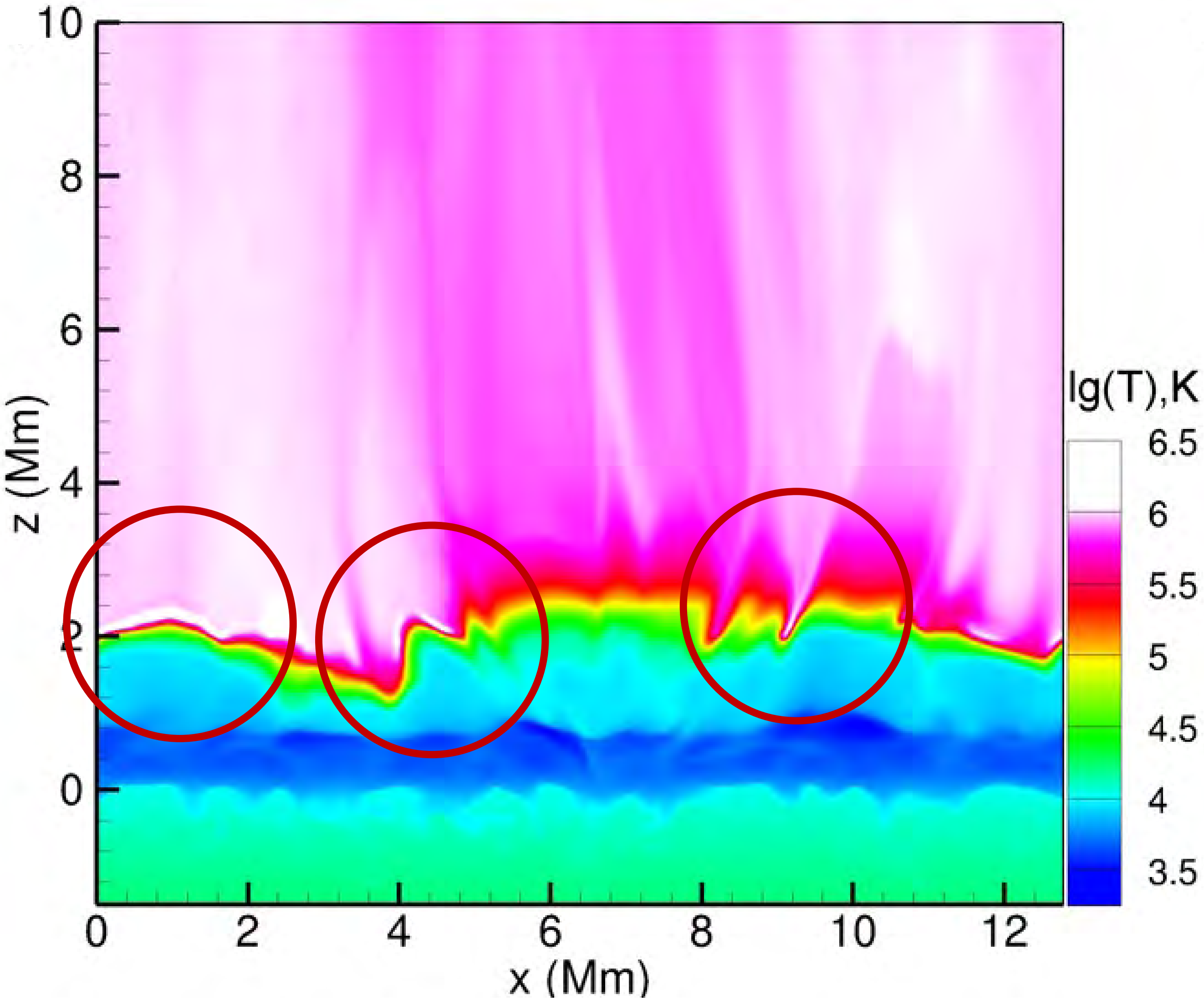


Heating events in the transition zone

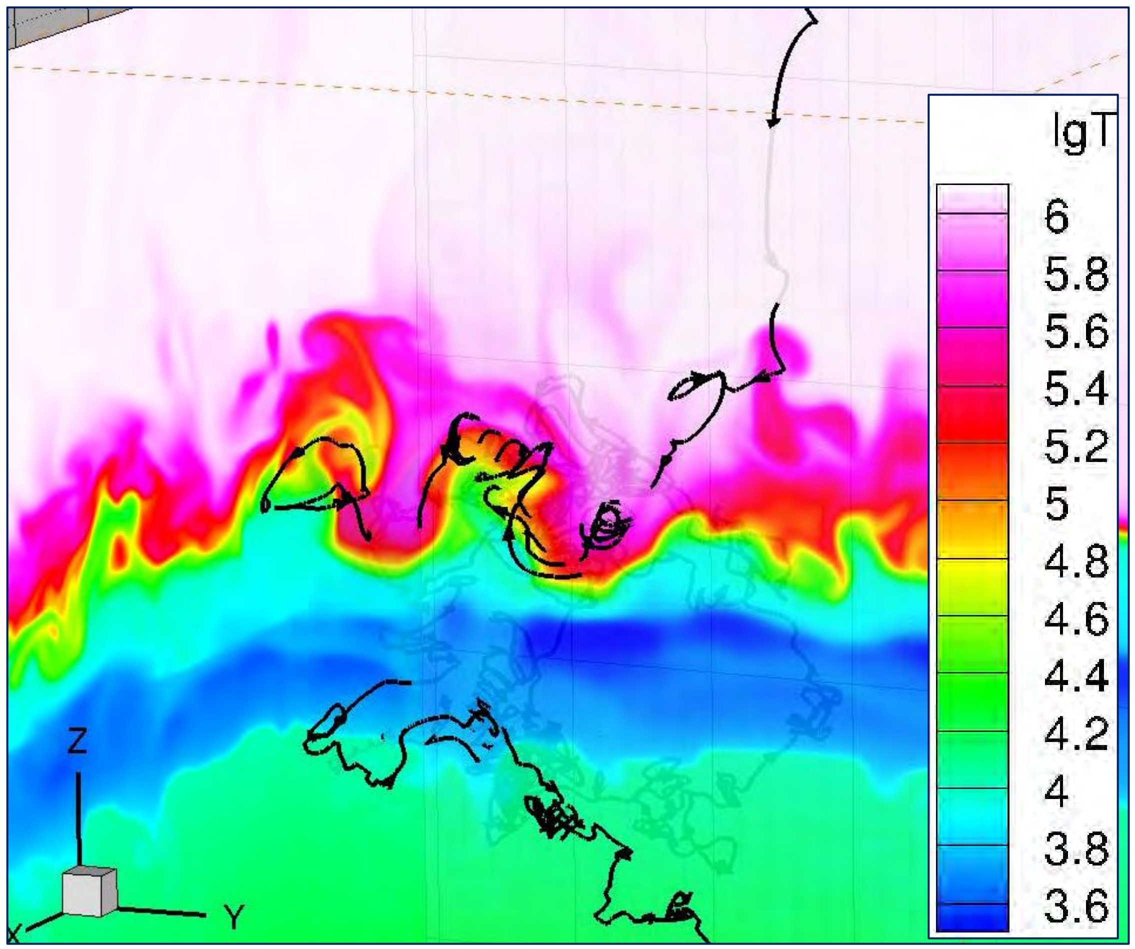
2Mm



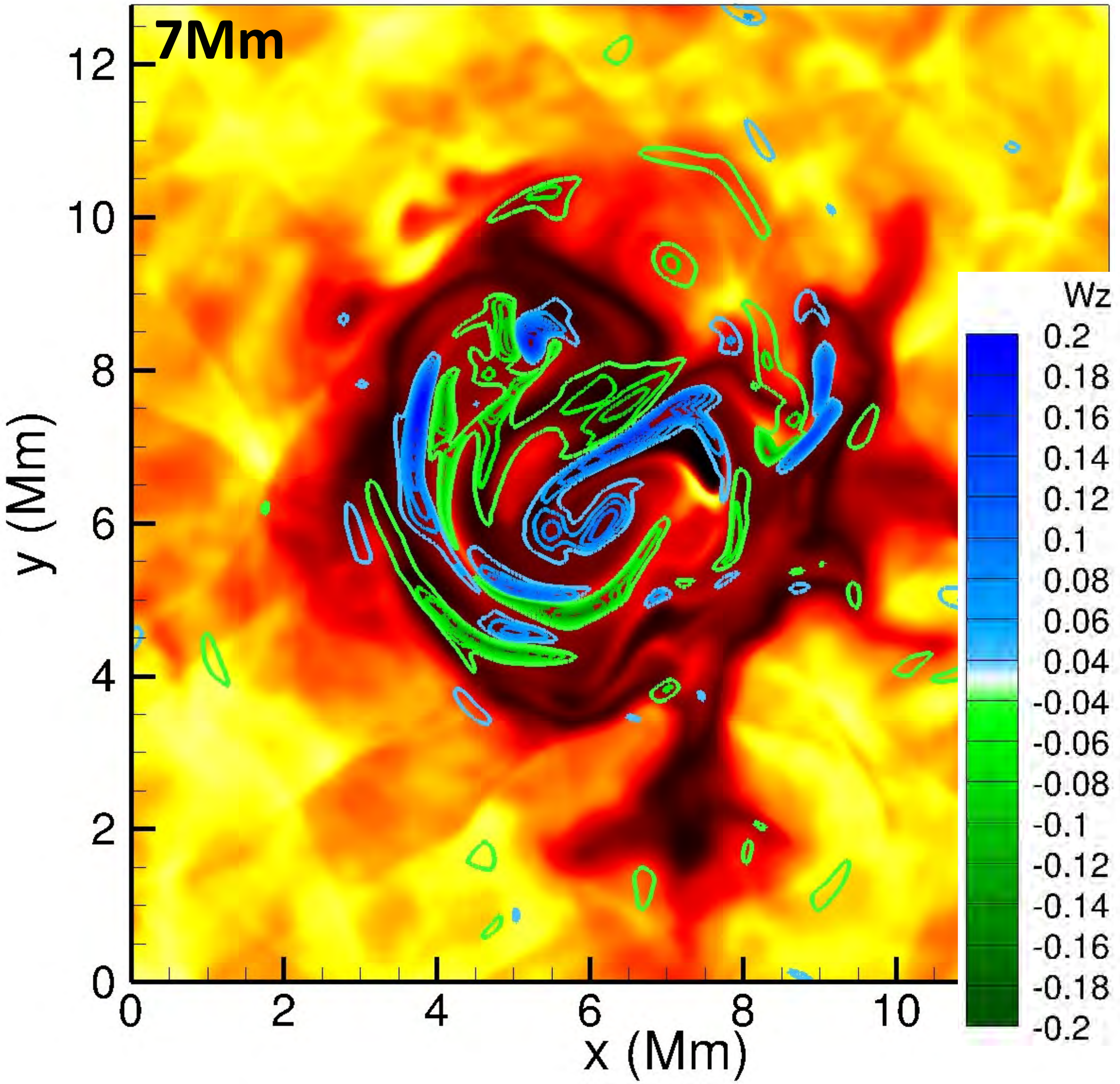
Heating in the transition zone

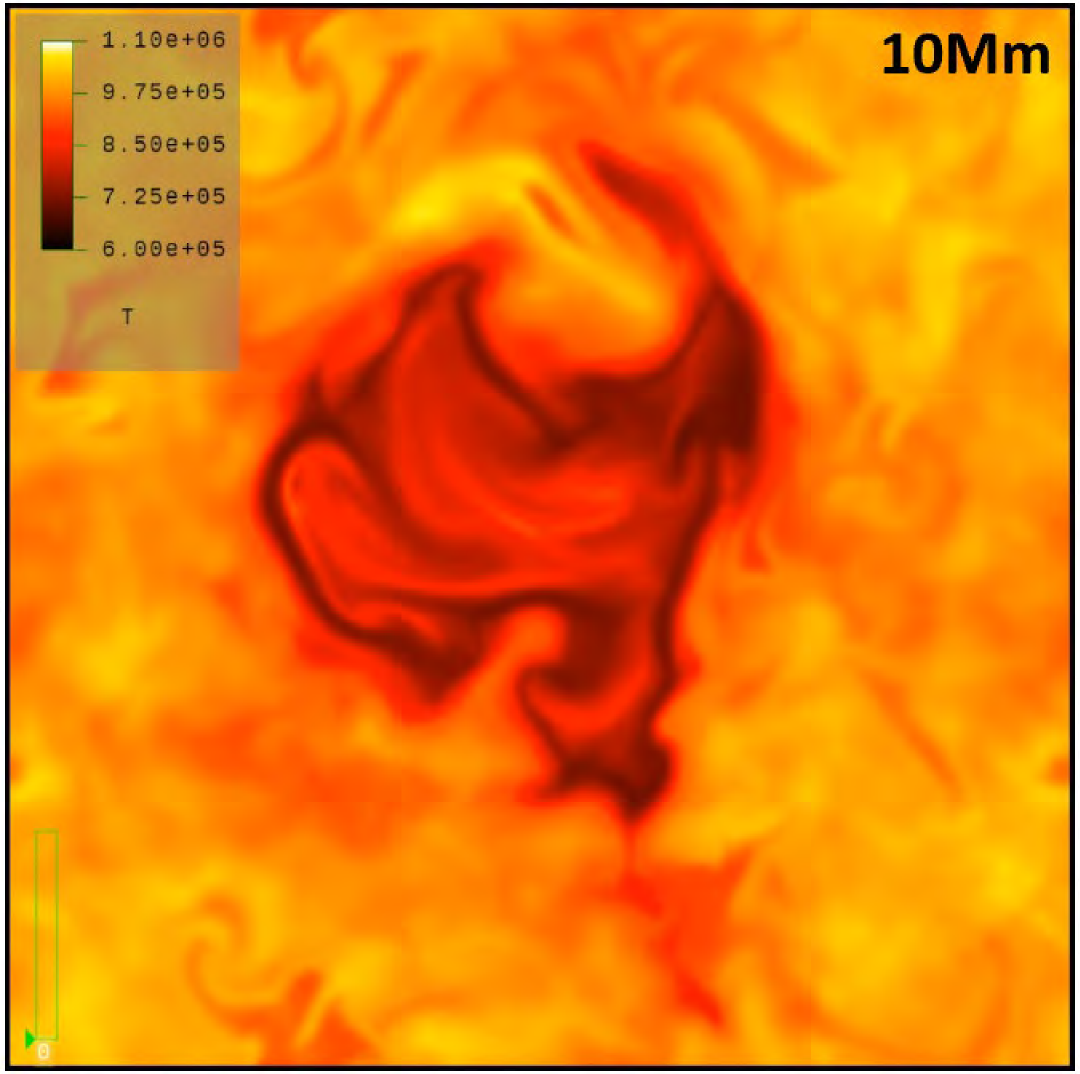


Electric currents in the transition zone

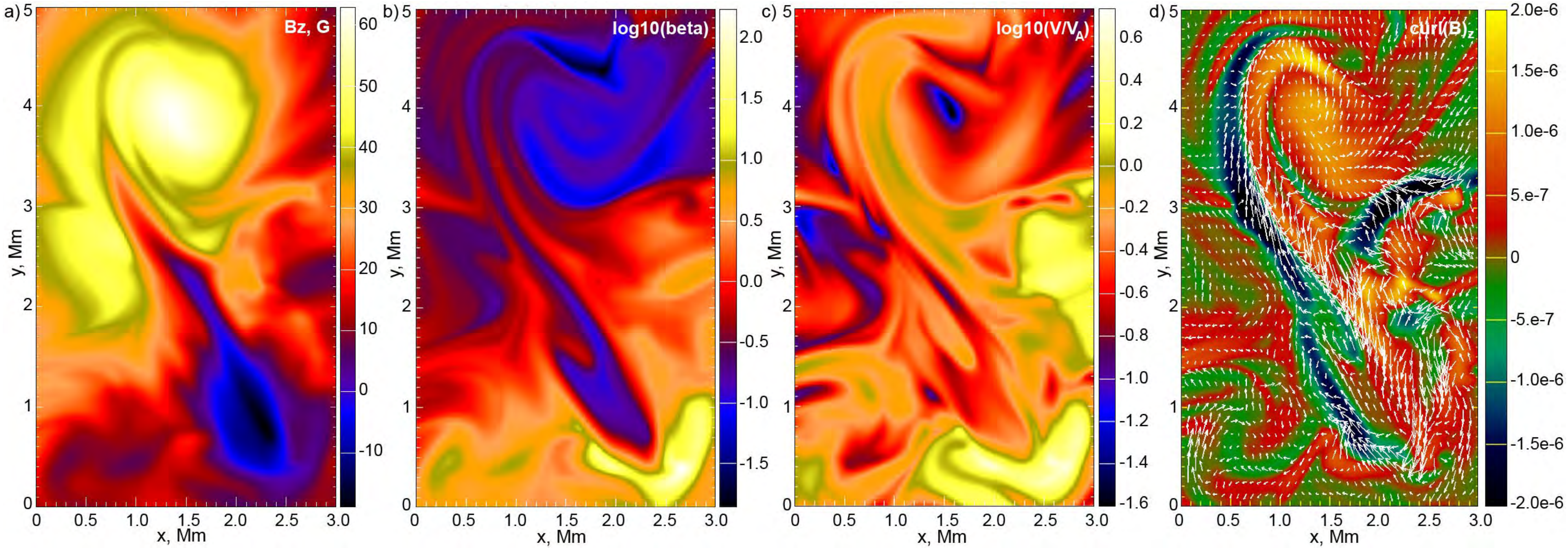


High-temperature bursts in a magnetic funnel-like structure



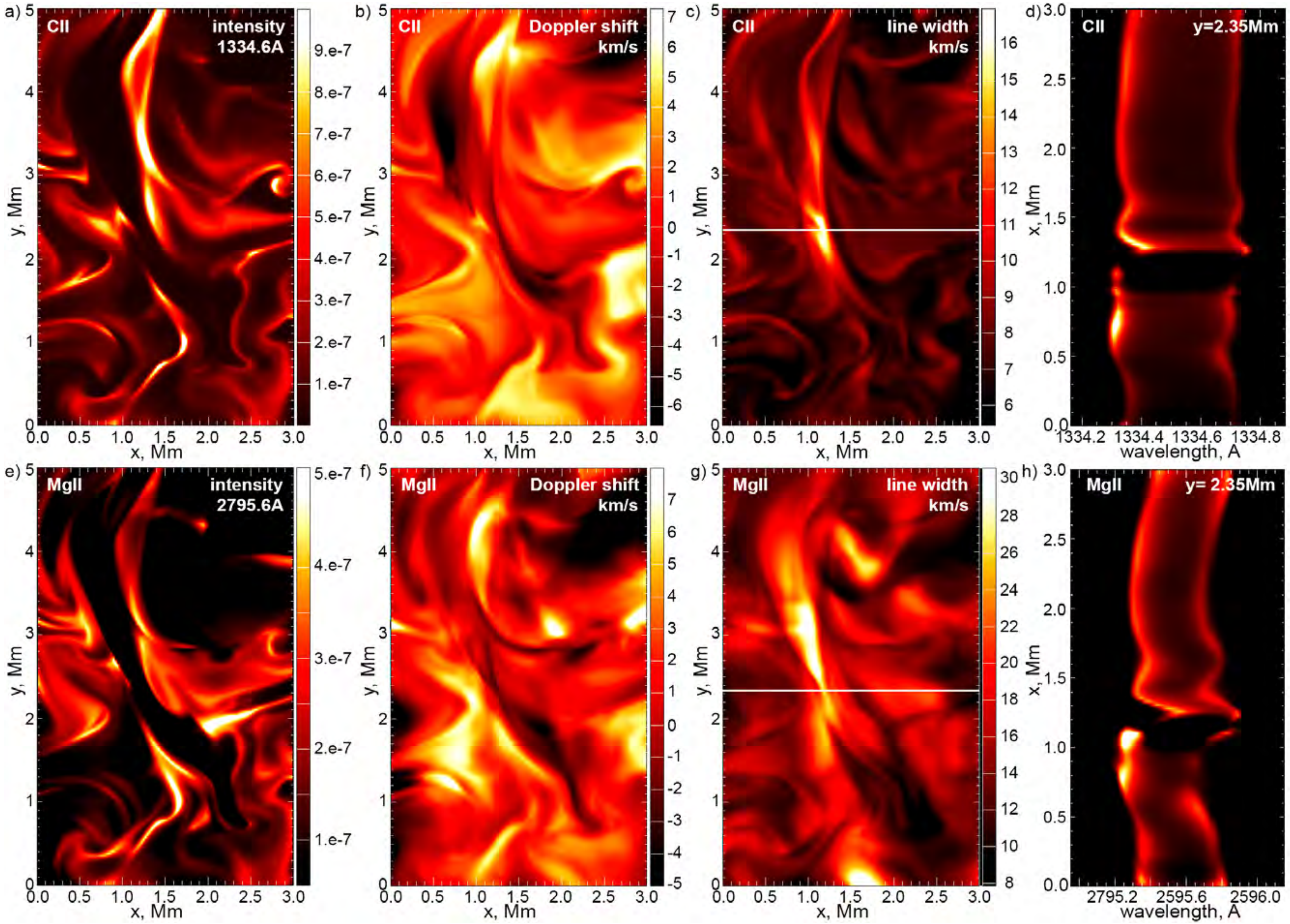


Self-Formation of a Current Sheet: Reconnection



A current sheet obtained by the MHD modeling: a) distribution of the vertical magnetic field; b) logarithm of plasma beta; c) the Alfven Mach number, and d) vertical component of the electric current, arrows show the horizontal current components revealing the current sheet and its interaction with turbulence.

Synthetic observables for the UV spectral lines observed by IRIS



Conclusion

The current computational capabilities allow us to perform 3D realistic RMHD modeling of different regimes of the turbulent solar plasma in the presence of magnetic fields from the upper layers of the convection zone to the corona. These studies enable physical understanding of observed phenomena and improve our capabilities to interpret actual observations.