Small-Scale Plasma Eruptions Driven by Vortex Tubes

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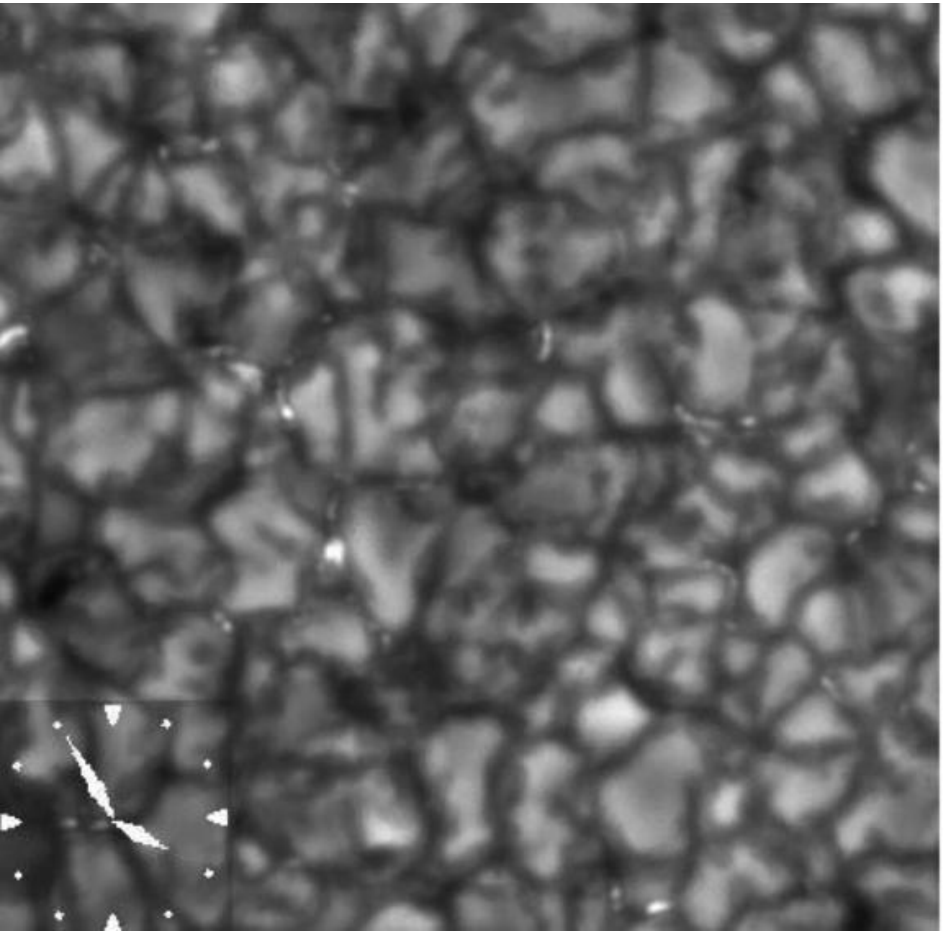
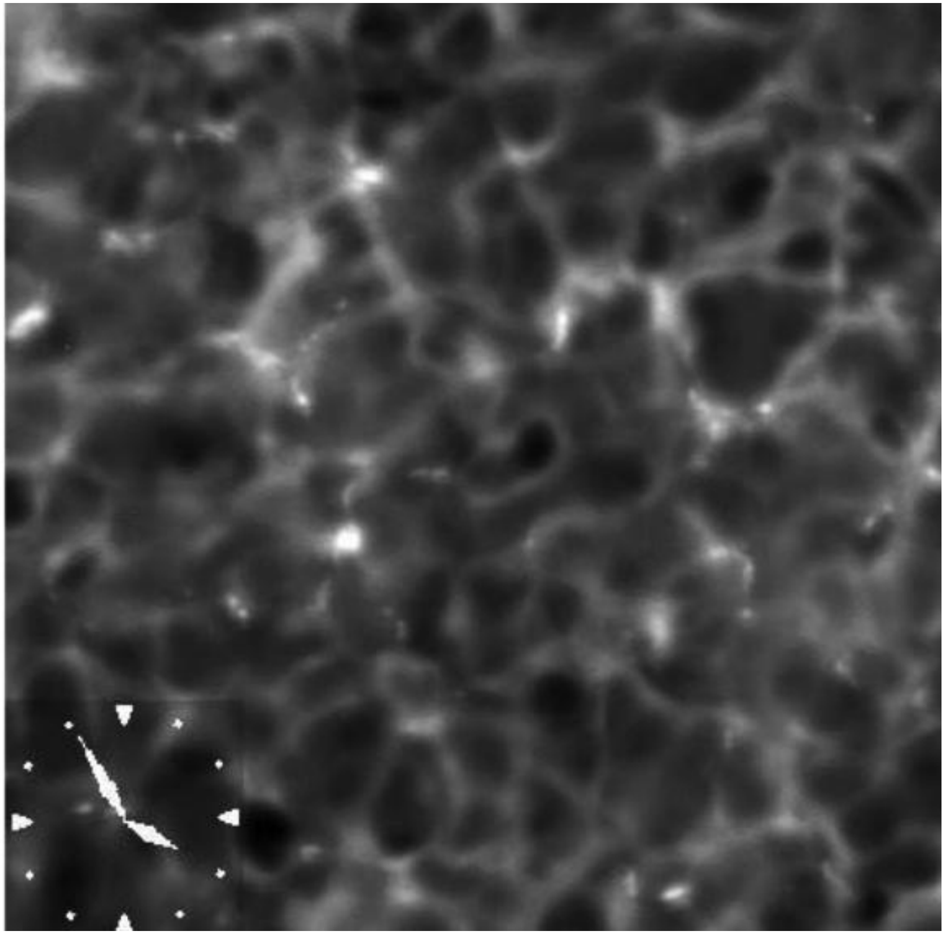
Quiet Sun Region





Hinode: G-band, CaIIH

Identification of vortex tubes in observations

THE ASTROPHYSICAL JOURNAL, 447:419–427, 1995 July 1

VORTICITY AND DIVERGENCE IN THE SOLAR PHOTOSPHERE

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ABSTRACT

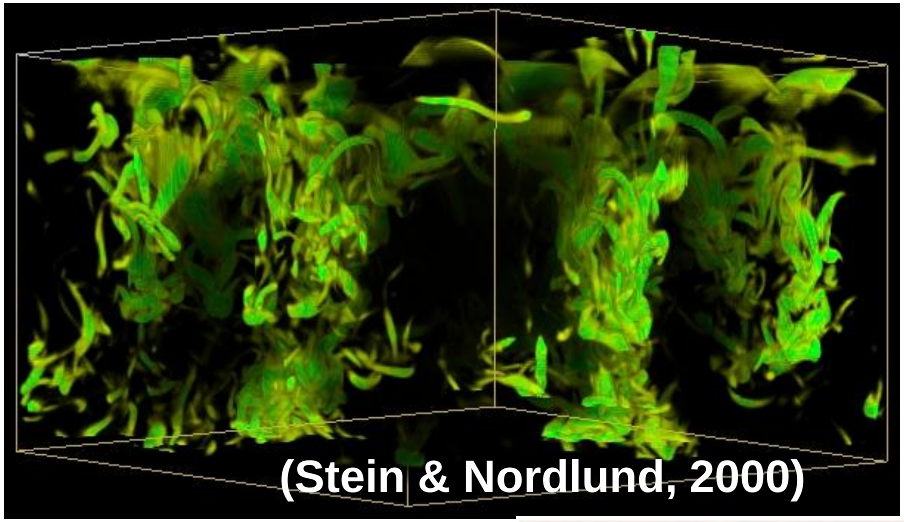
We have studied an outstanding sequence of continuum images of the solar granulation from Pic du Midi Observatory. We have calculated the horizontal vector flow field using a correlation tracking algorithm, and from this determined three scalar fields: the vertical component of the curl, the horizontal divergence, and the horizontal flow speed. The divergence field has substantially longer coherence time and more power than does the curl field. Statistically, curl is better correlated with regions of negative divergence—that is, the vertical vorticity is higher in downflow regions, suggesting excess vorticity in intergranular lanes. The average value of the divergence is largest (i.e., outflow is largest) where the horizontal speed is large; we associate these regions with exploding granules. A numerical simulation of general convection also shows similar statistical differences between curl and divergence. Some individual small bright points in the granulation pattern show large local vorticities.

Bonet et. al, 2008, 2010

Wedemeyer-Böhm & Rouppe van der Voort, 2009

Wedemeyer-Bohm et al., 2012

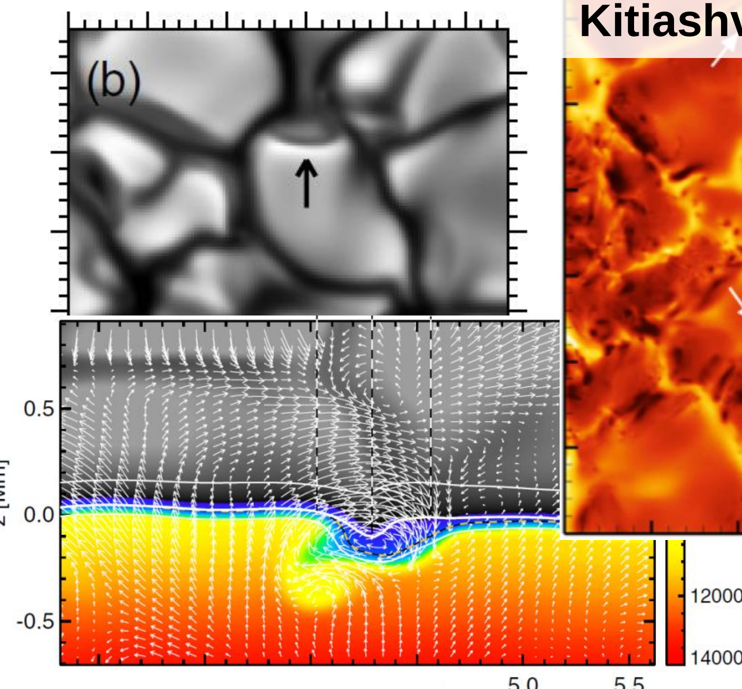
Vortex tubes in simulations


(Stein & Nordlund, 2000)

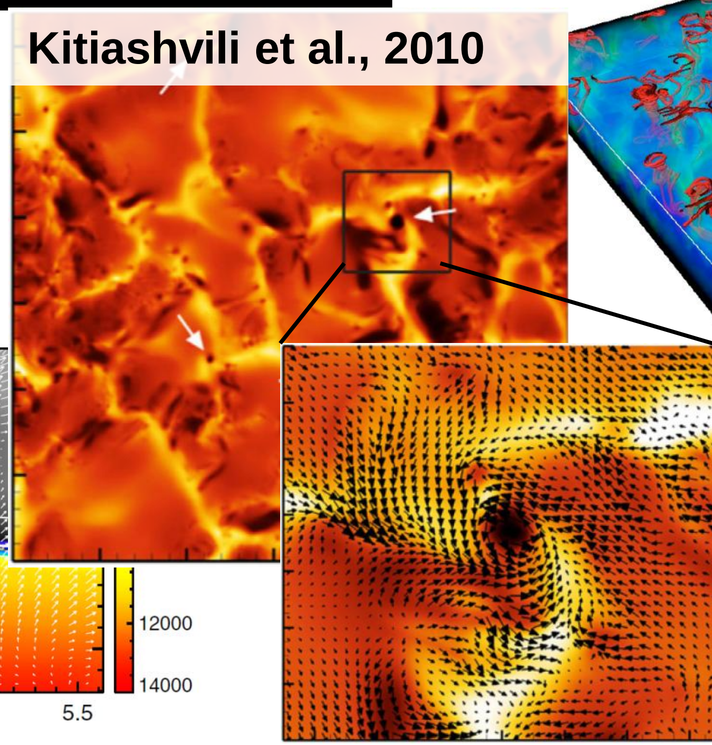
Magnetic structures in a dynamo simulation

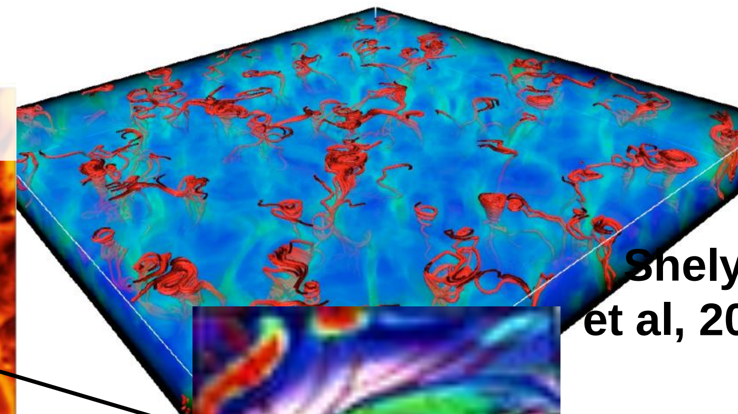
Brandenburg, A., Jennings, R. L., Nordlund, Å., Rieutord, M., Stein, R. F., Tuominen, I.

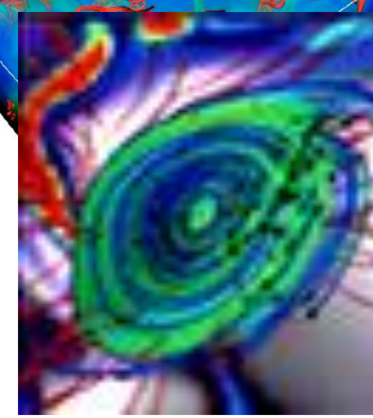
Journal of Fluid Mechanics, vol. 306, 325



Steiner et al., 2010


Kitiashvili et al., 2010


Shelyag et al, 2011


Wedemeyer-Bohm et al, 2012

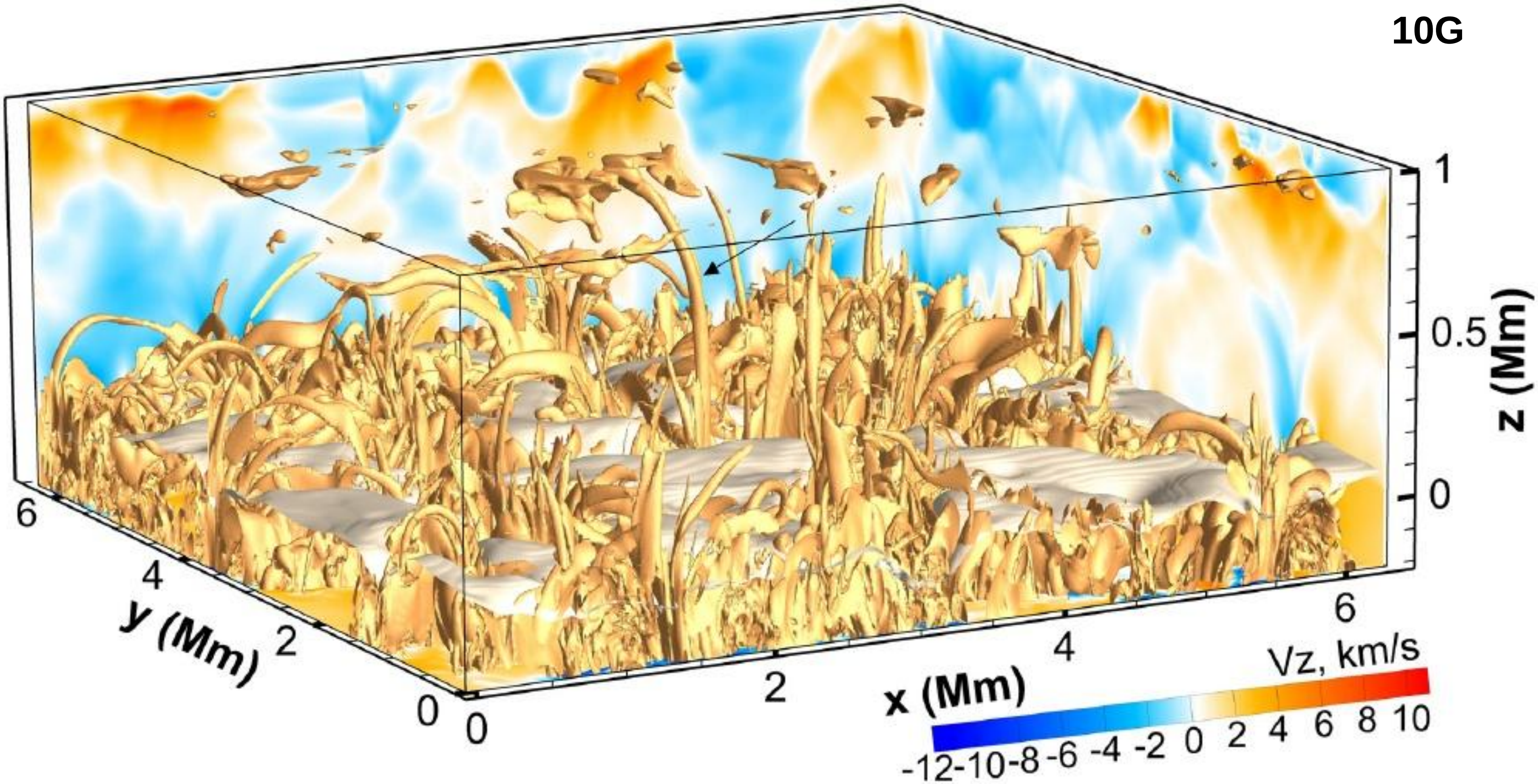
Numerical Model: Basic characteristic of the code

"SolarBox"

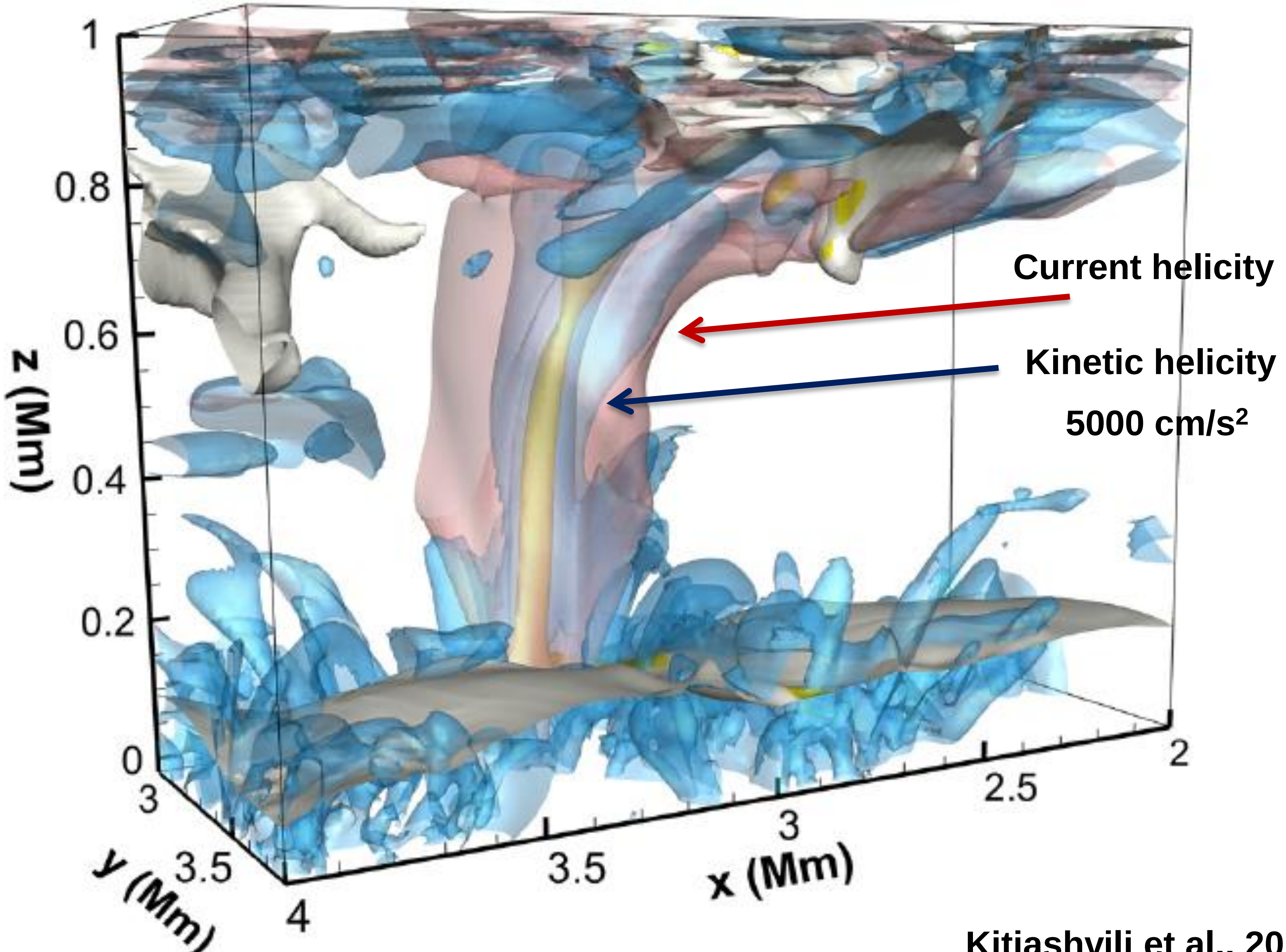
- ✓ 3d rectangular geometry
- ✓ Fully conservative compressible
- ✓ Fully coupled radiation solver:
  - – LTE using 4 opacity-distribution-function bins
  - – Ray-tracing transport by Feautrier method
  - – 14 ray (2 vertical, 4 horizontal, 8 slanted) angular quadrature
- ✓ Non-ideal (tabular) EOS
- ✓ 4th order Padé spatial derivatives
- ✓ 4th order Runge-Kutta in time
- ✓ Different Turbulence models
  - - LES: Smagorinsky model (and its dynamic procedure)
  - - DNS + Hyperviscosity approach

We use a 3D non-linear radiative MHD code developed for simulating the upper solar convection zone and lower atmosphere. This code takes into account several physical phenomena: compressible fluid flow in a highly stratified medium, 3D multi-group radiative energy transfer between the fluid elements, a real-gas equation of state, ionization and excitation of all abundant species, and magnetic effects. A unique feature of this code is implementation of various subgrid scale turbulence models. We adopted the most widely used subgrid-scale Smagorinsky model (Smagorinsky,1963) in the compressible formulation (Germano et al.,1991).

Vortices in the low atmosphere

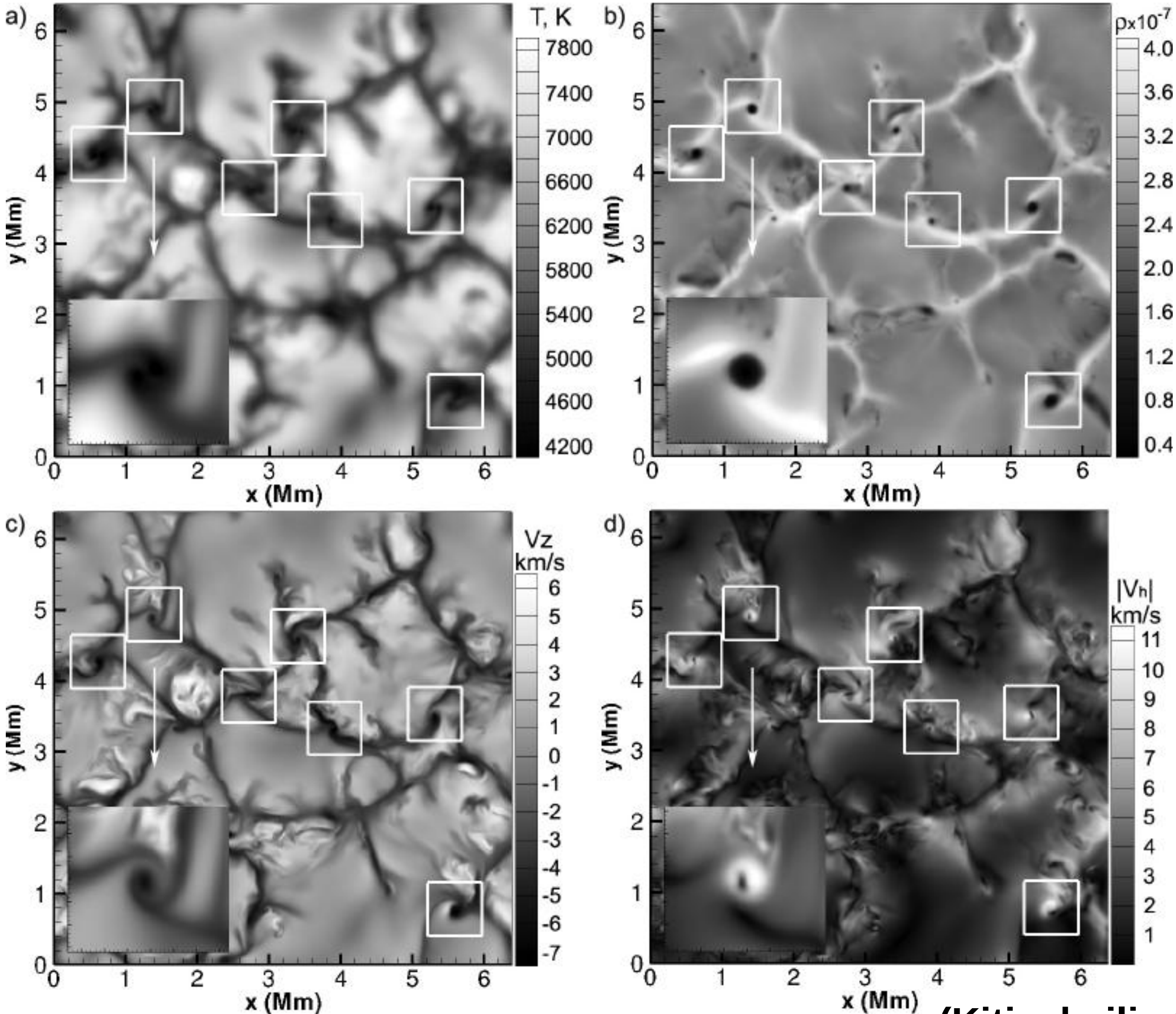


Vortex tube structure above the solar surface



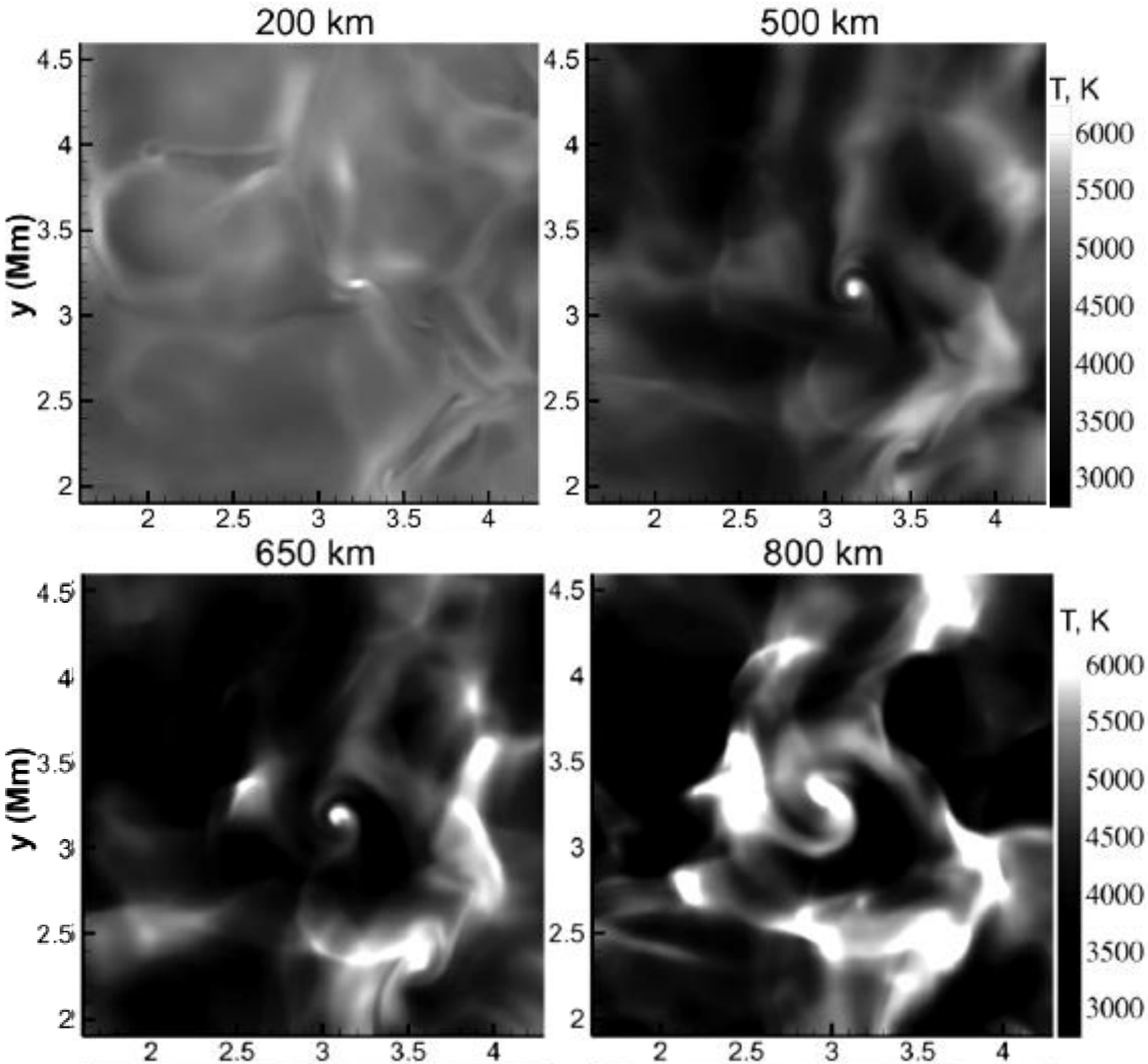
Kitiashvili et al., 2012

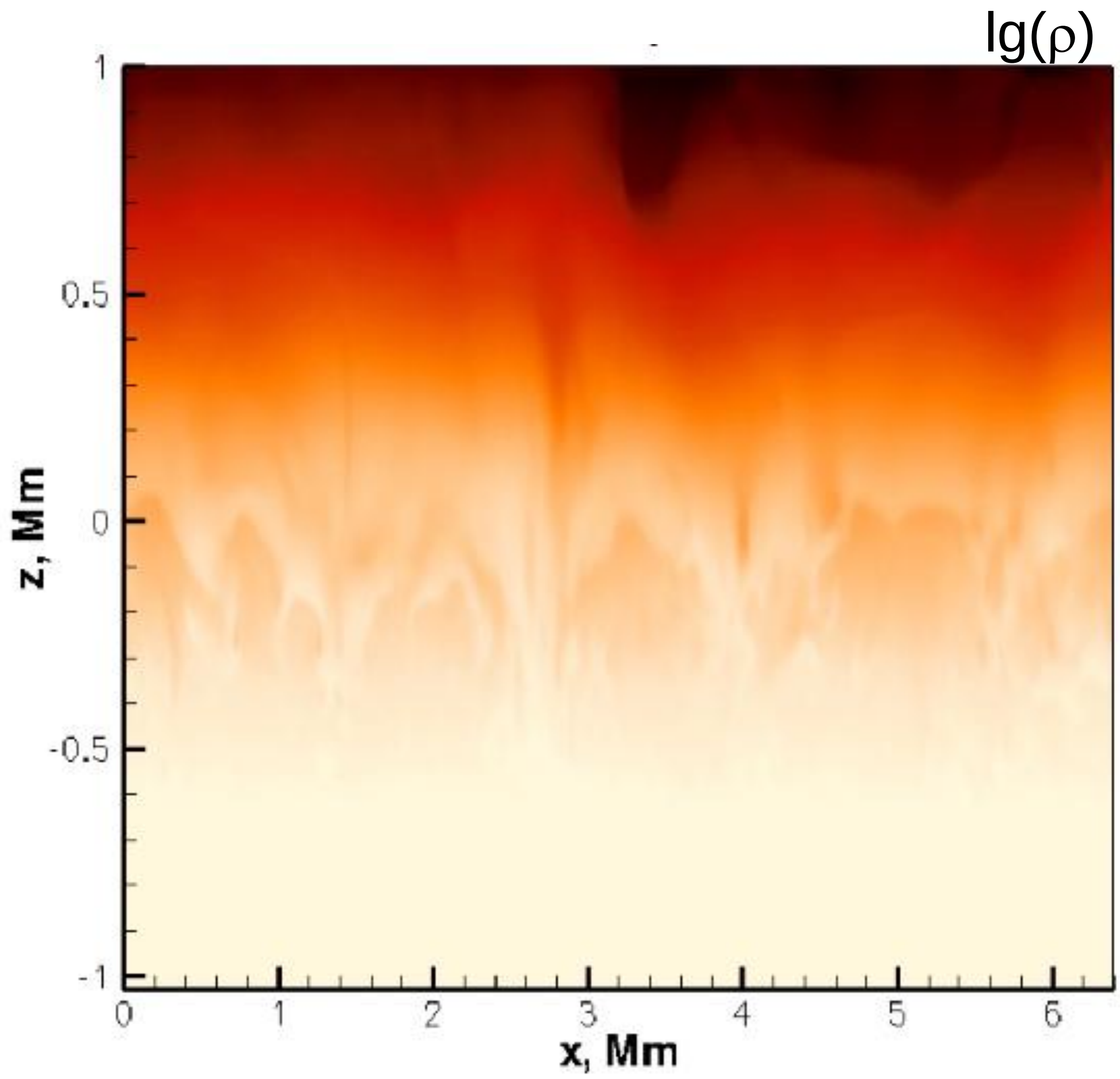
Quiet Sun Region



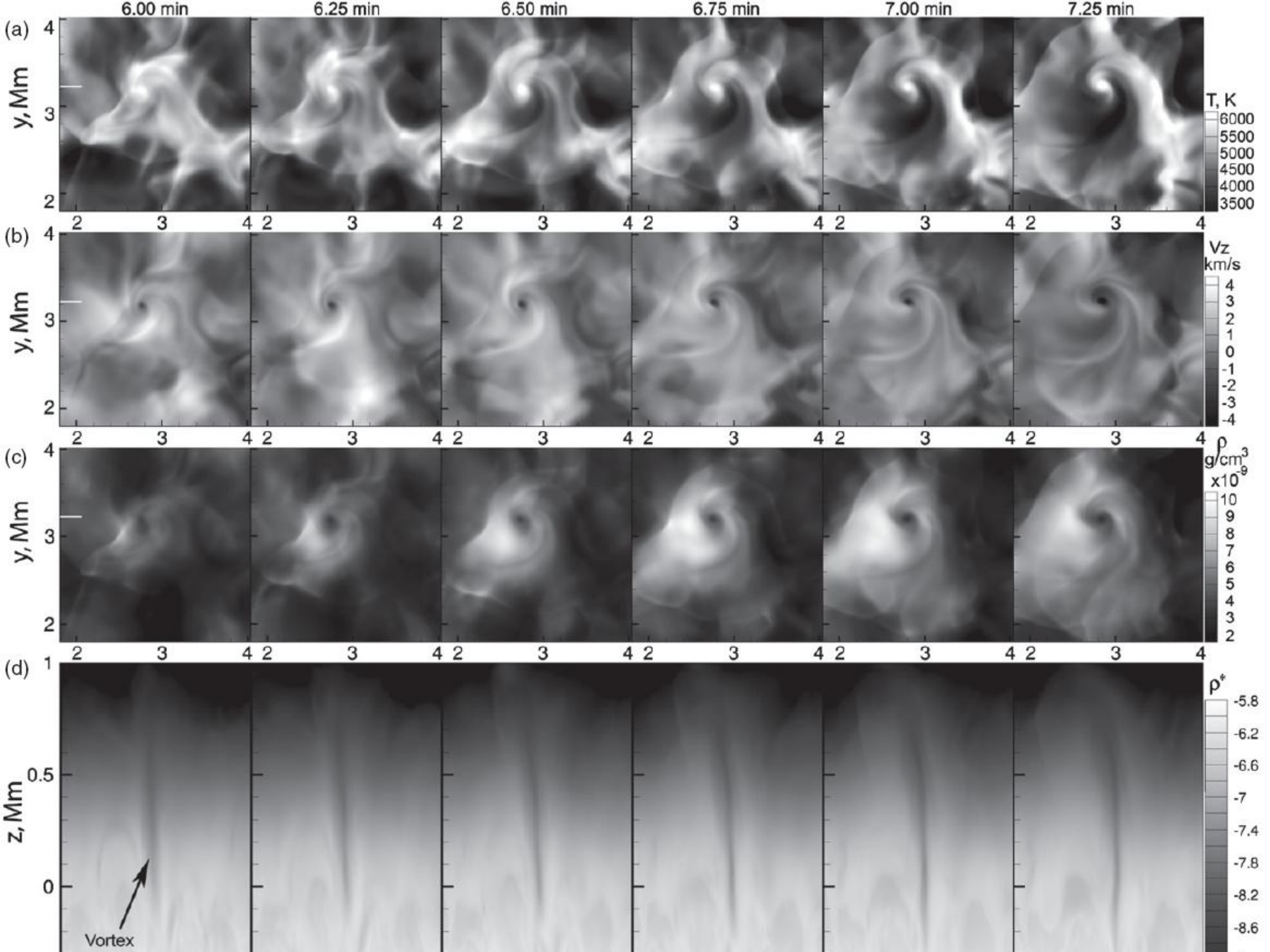
(Kitiashvili et al., 2011)

Vortex tube structure above the solar surface

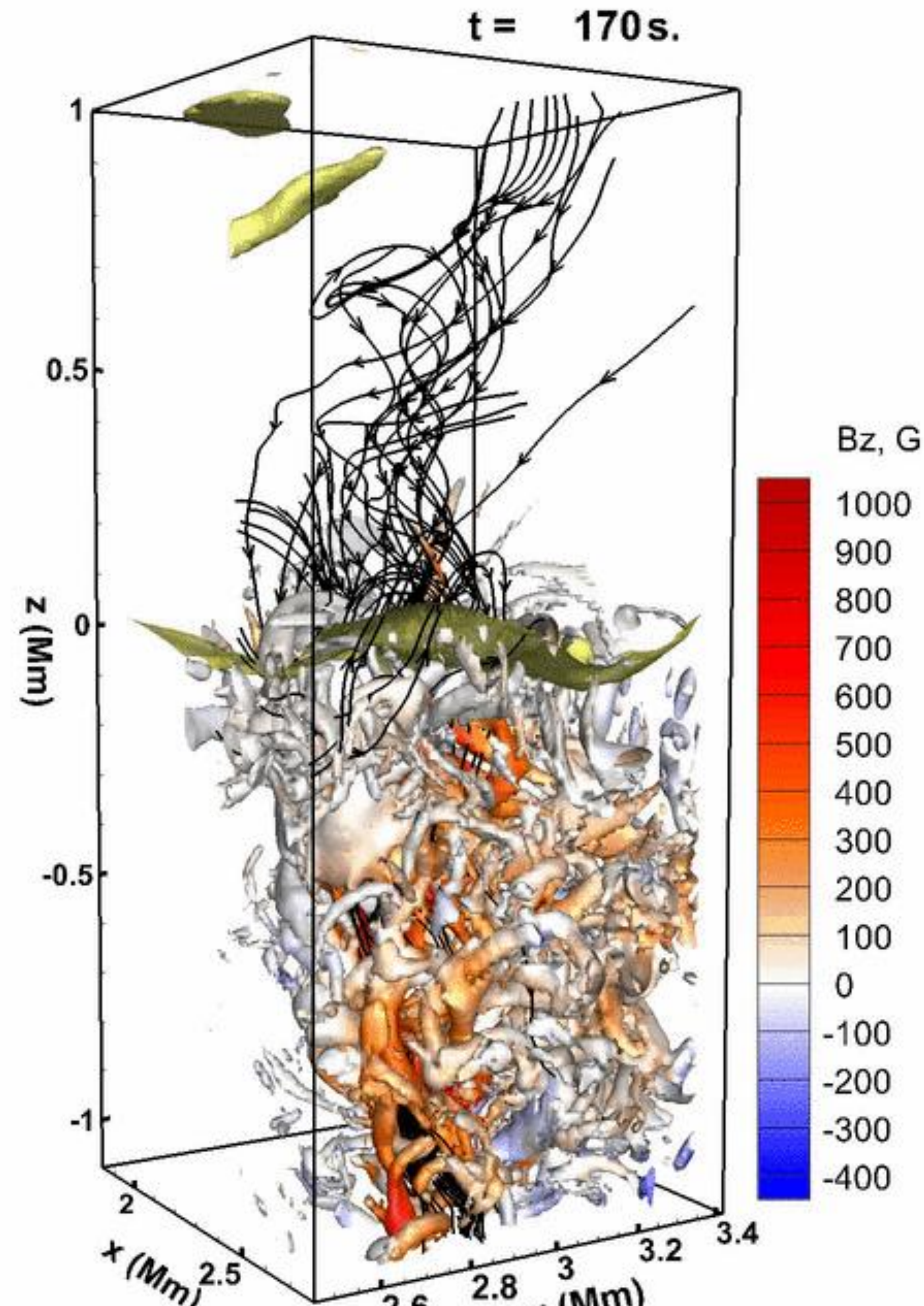




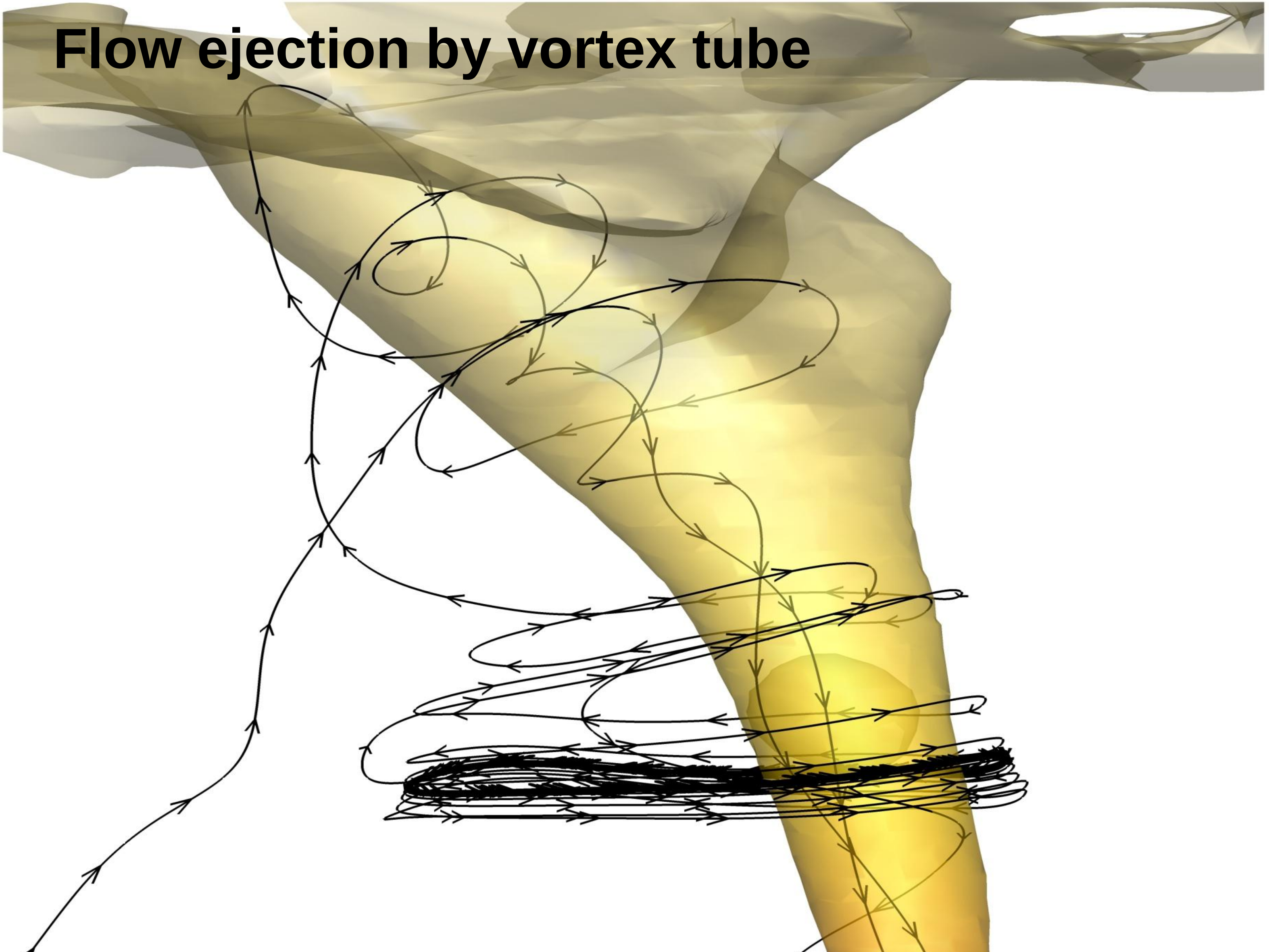
(Kitiashvili et al., 2013)



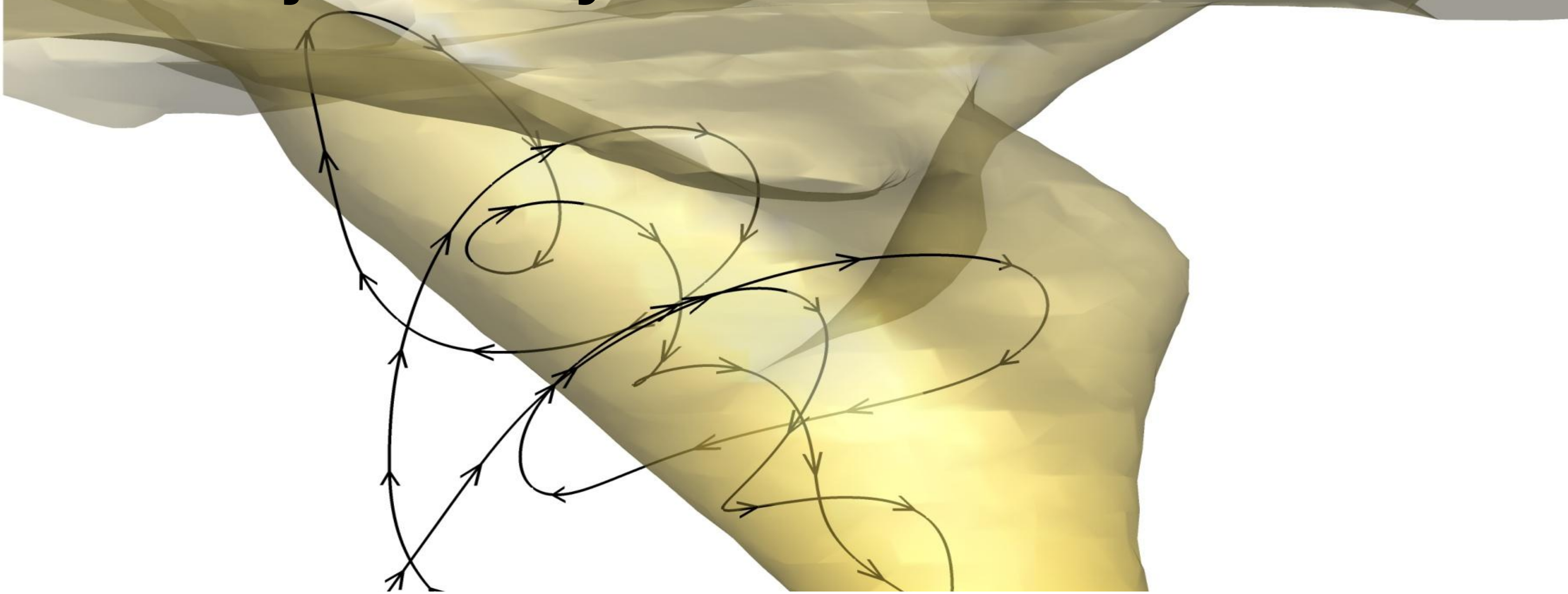
6.00 min
6.25 min
6.50 min
6.75 min
7.00 min
7.25 min
(a)
(b)
(c)
(d)
y, Mm
z, Mm
T, K
Vz km/s
ρ g/cm3 x10-9
ρ*
Vortex


t = 170 s.
Bz, G
1000
900
800
700
600
500
400
300
200
100
0
-100
-200
-300
-400
z (Mm)
1
0.5
0
-0.5
-1
x (Mm)
2
2.5
y (Mm)
2.6
2.8
3
3.2
3.4

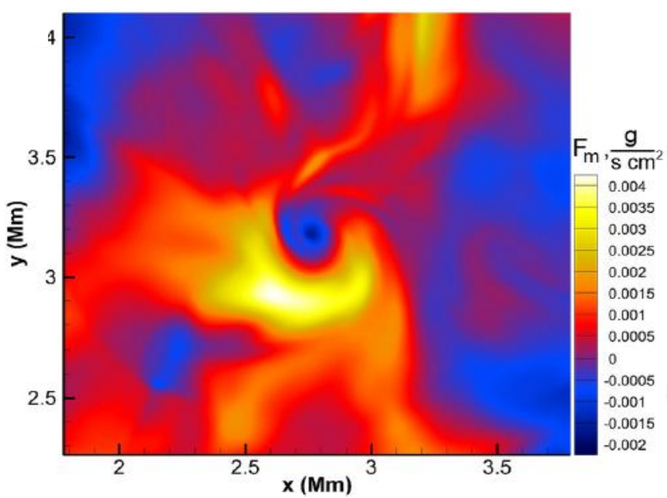
Flow ejection by vortex tube



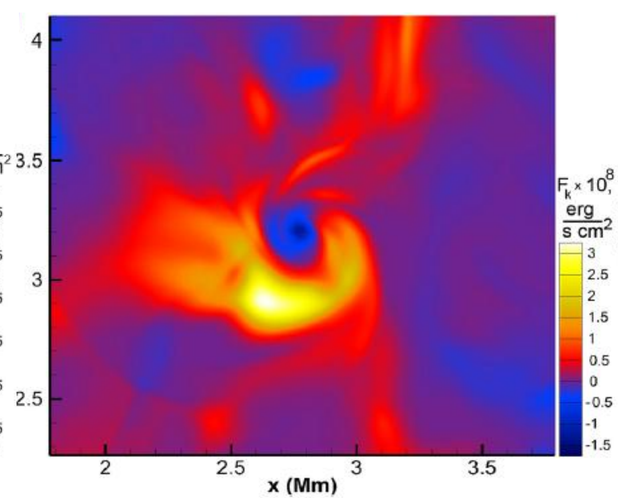
Flow ejection by vortex tube



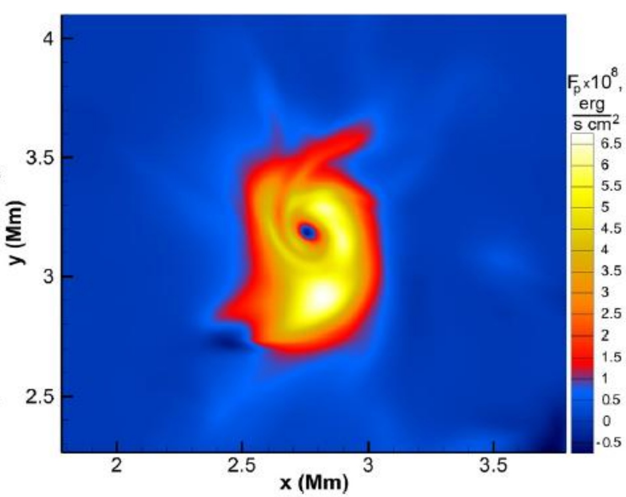
Mass flux (0.65 Mm)



Kinetic energy flux

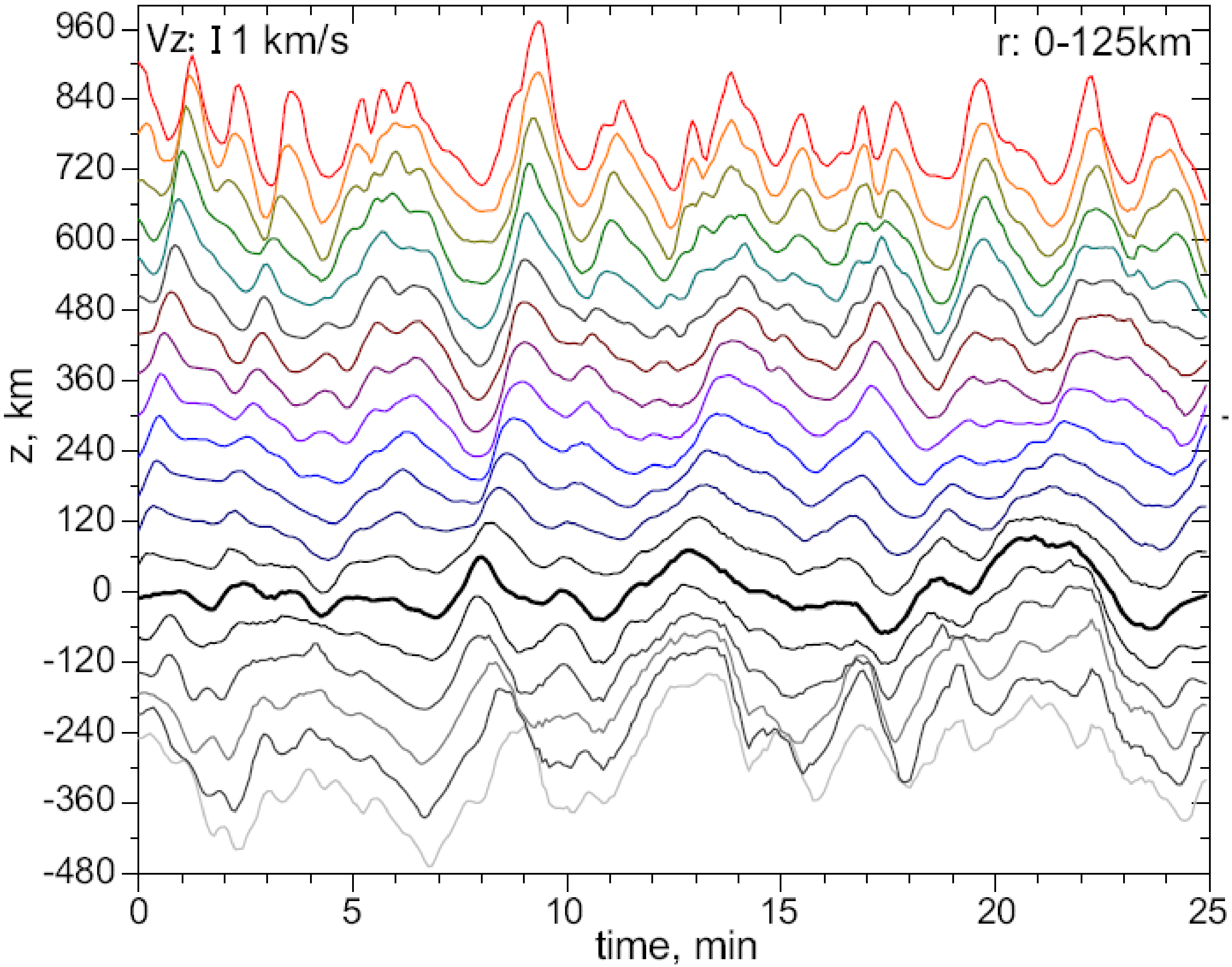


Poynting flux



Flow ejection: vertical velocity

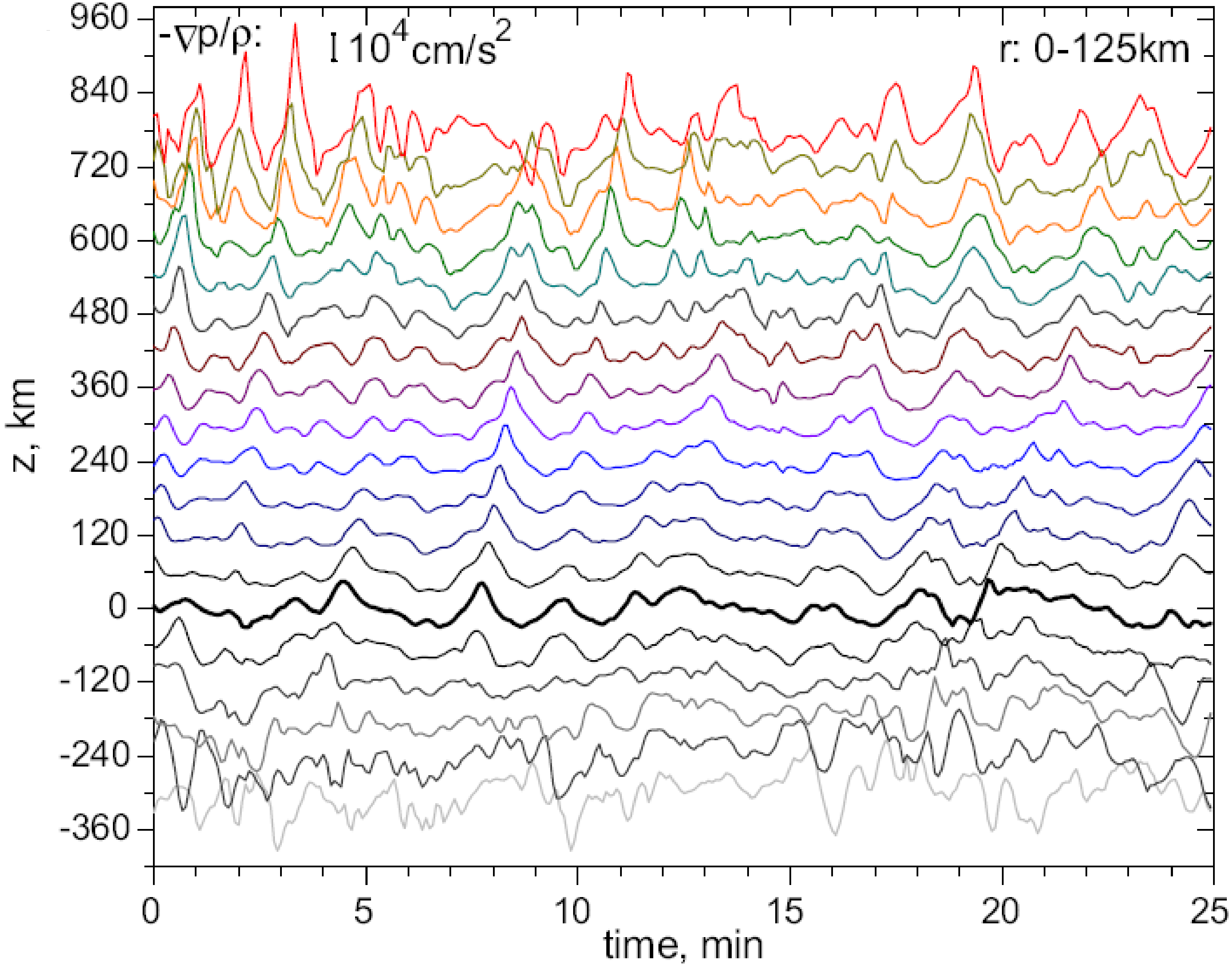
$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} = \frac{\mathbf{J} \times \mathbf{B}}{c\rho} - \frac{\nabla p}{\rho} - g$$



Kitiashvili et al., 2013

Flow ejection: pressure gradient

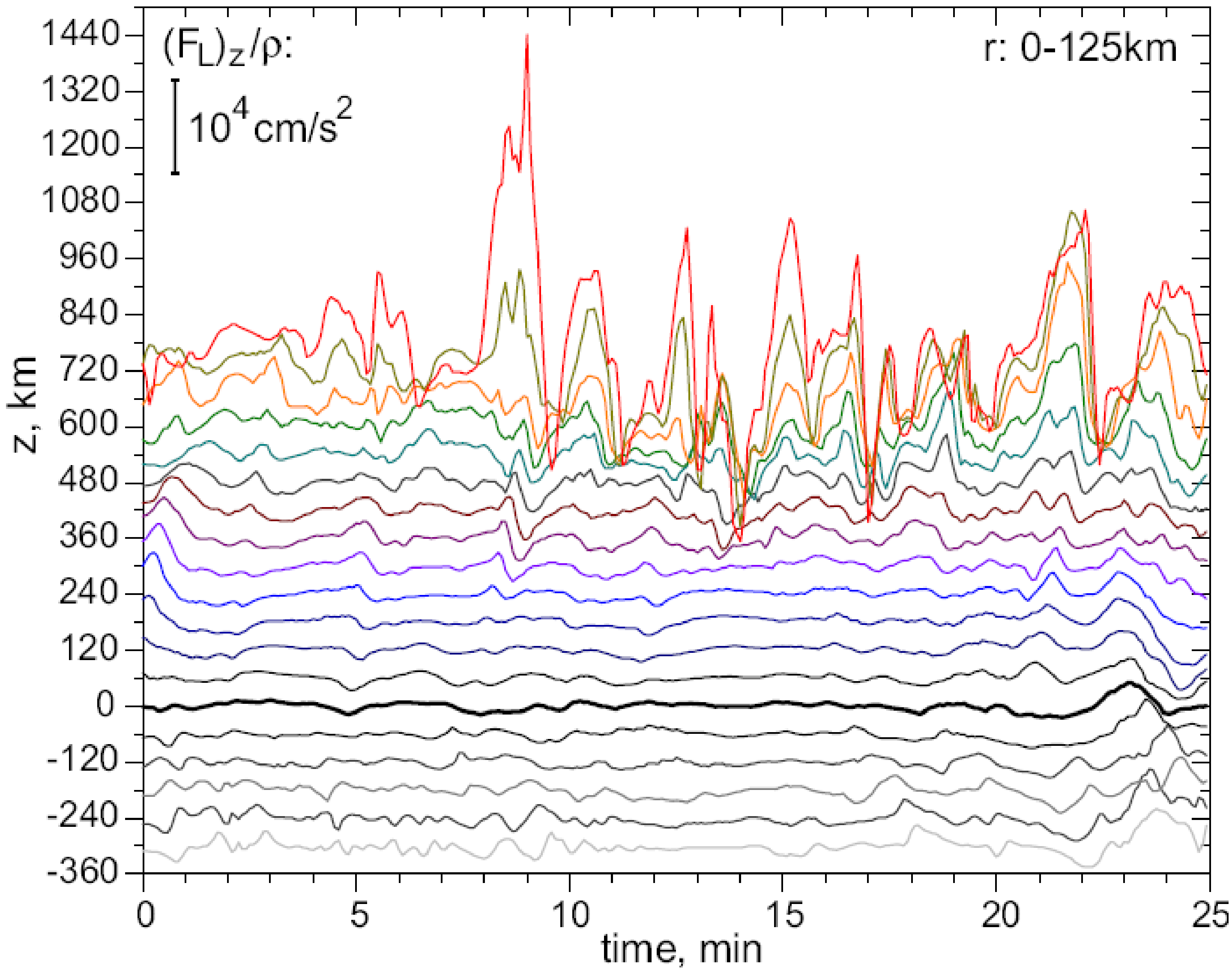
$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} = \frac{\mathbf{J} \times \mathbf{B}}{c\rho} - \frac{\nabla p}{\rho} - g$$



Kitiashvili et al., 2013

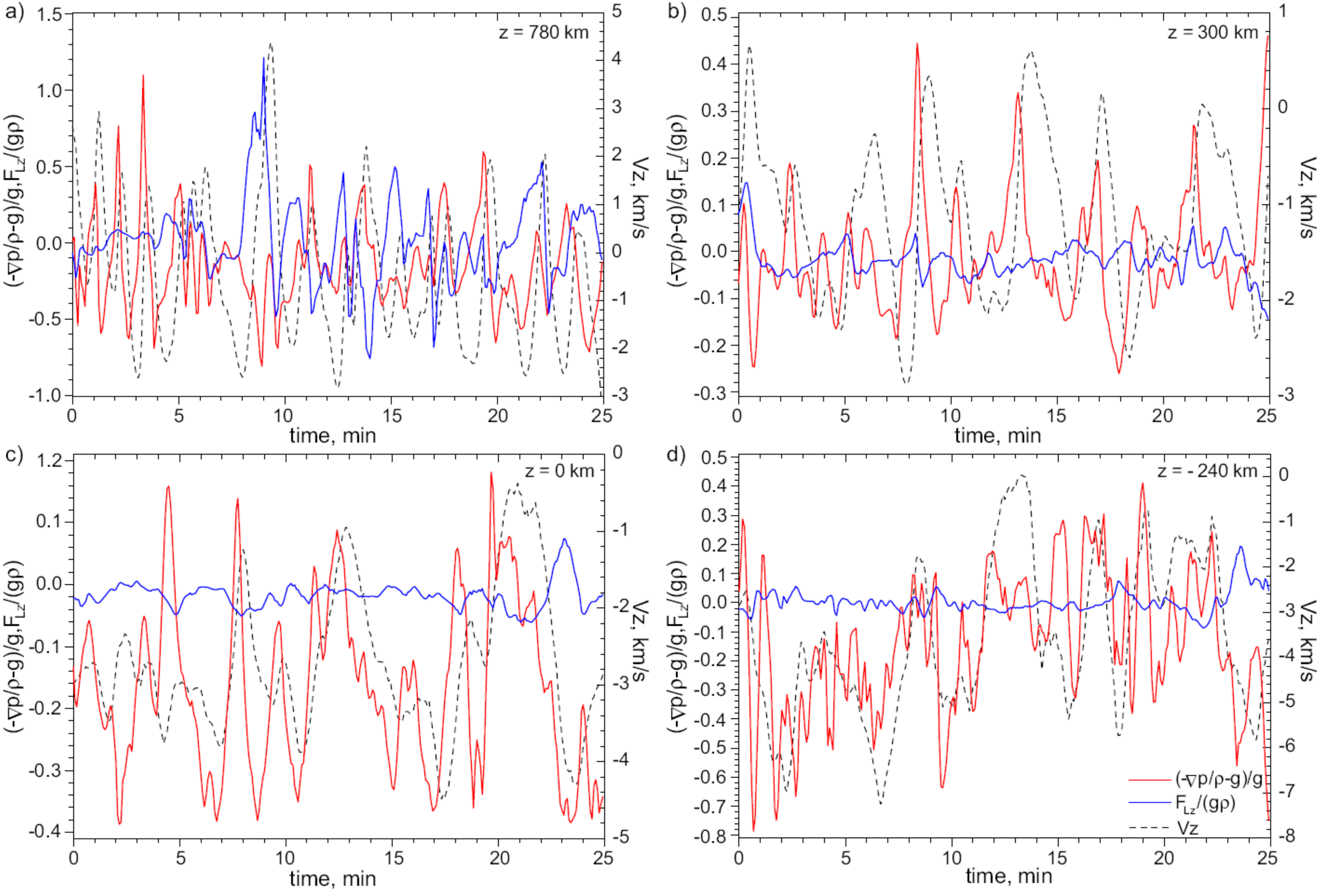
Flow ejection: Lorentz force

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} = \boxed{\frac{\mathbf{J} \times \mathbf{B}}{c\rho}} - \frac{\nabla p}{\rho} - g$$

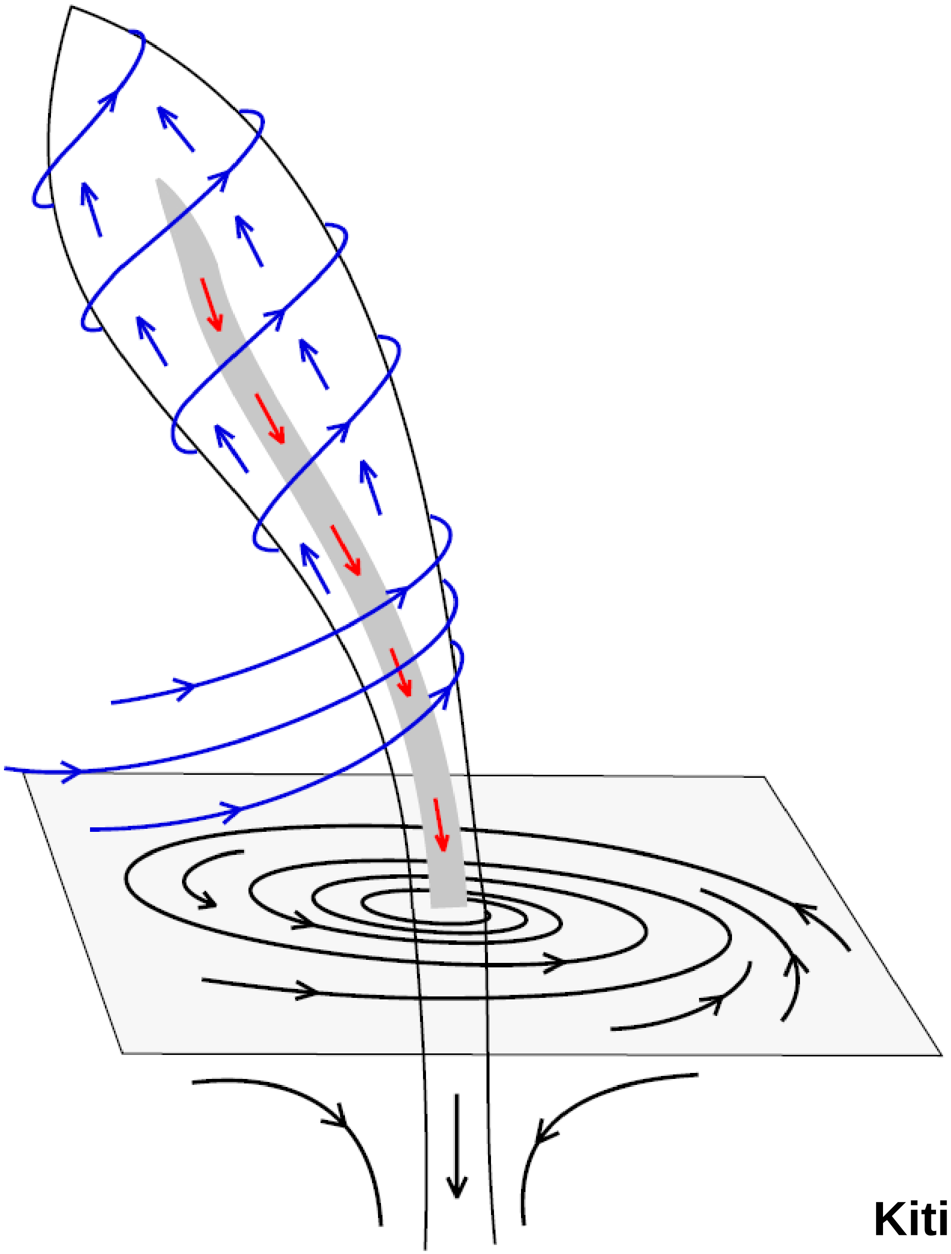


Kitiashvili et al., 2013

Flow ejection: hydrodynamic vs magnetic forces



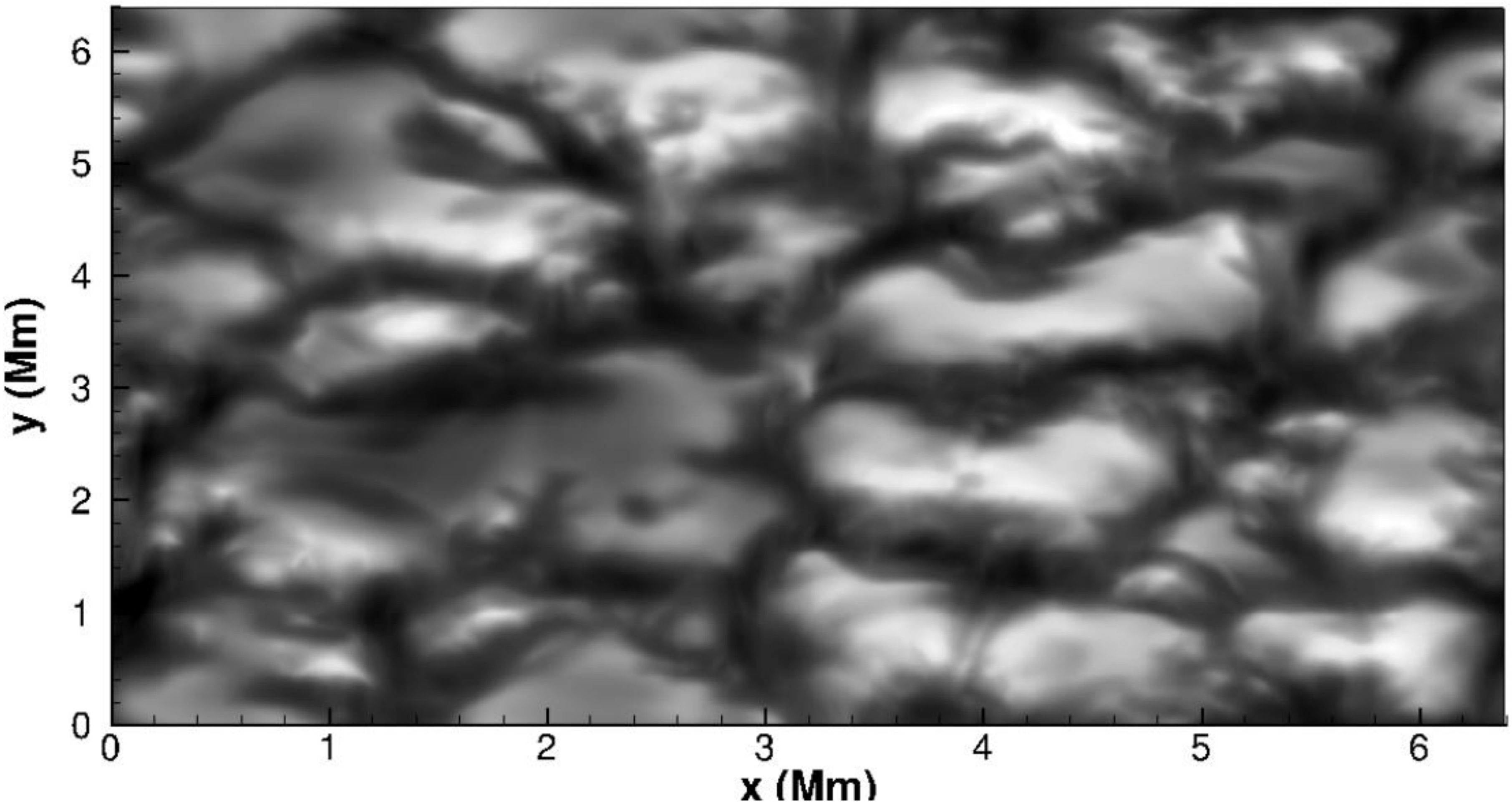
Mechanism of spontaneous flow ejections



Kitiashvili et al., 2013

Continuum intensity at 6302A

10G, 60deg



Conclusions

- The results of our simulations of the quiet Sun with weak mean magnetic field reveal strong interacting vortices in the top layers of the convection zone. The vortices are often characterized by supersonic horizontal flows and strong downflows in the vortex cores. They are numerous and interact with each other.
- The simulations reveal penetration of the vortex tubes from the photosphere into the chromosphere in both cases, without magnetic field and with initially weak distributed magnetic field.
- The vortex tube penetration causes significant qualitative changes of the atmospheric dynamics, causing strong variations into thermodynamic structure, magnetic field lines topology, local heating, and twisted upflows in the solar atmosphere.
- The vortex tubes capture and amplify background magnetic field, and generate ubiquitous small-scale eruptions resembling spicules. The simulations show that the eruptions are initiated just below the surface by pressure gradients, and accelerated by the Lorentz force in the mid chromosphere.