Simulations of flux emergence events I

Daniel Nóbrega-Siverio[1,2,3,4]

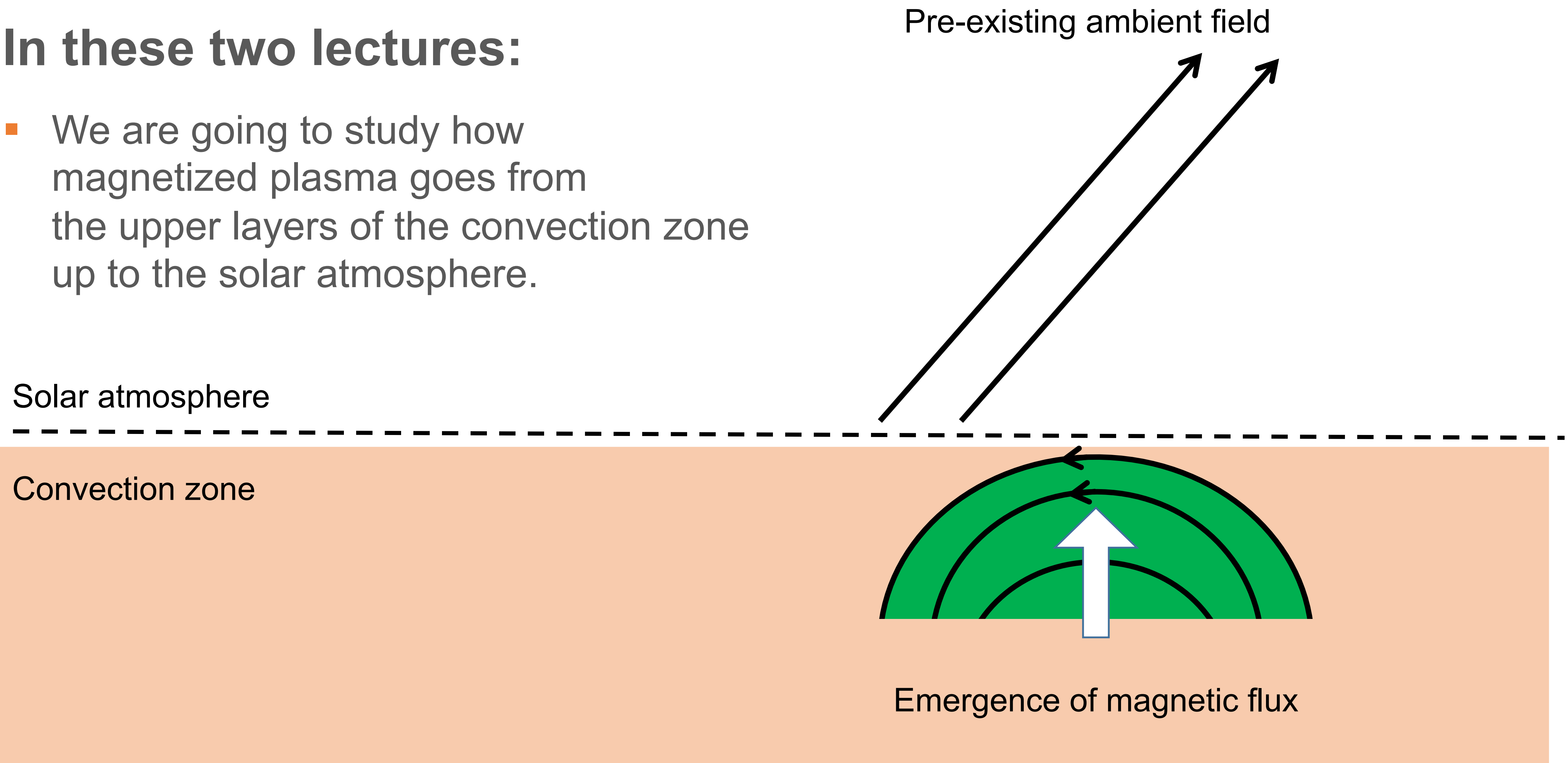
1. Instituto de Astrofísica de Canarias, E-38205 La Laguna, Tenerife, Spain.
2. Universidad de La Laguna, Dept. Astrofísica, E-38206 La Laguna, Tenerife, Spain
3. Rosseland Centre for Solar Physics, University of Oslo, PO Box 1029 Blindern, 0315 Oslo, Norway.
4. Institute of Theoretical Astrophysics, University of Oslo, PO Box 1029 Blindern, 0315 Oslo, Norway.

Email: dnobrega@iac.es

Introduction

In these two lectures:

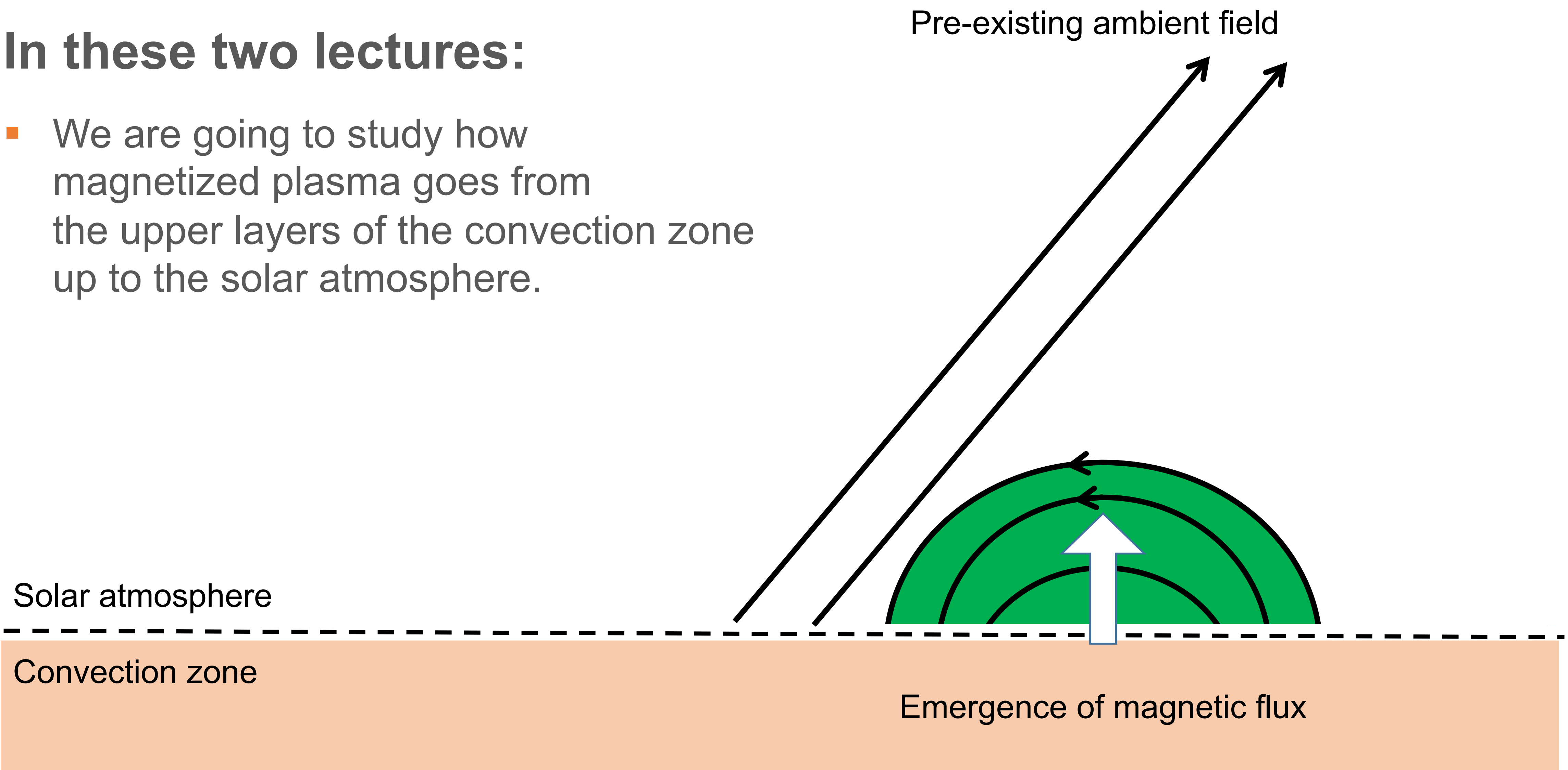
- We are going to study how magnetized plasma goes from the upper layers of the convection zone up to the solar atmosphere.



Introduction

In these two lectures:

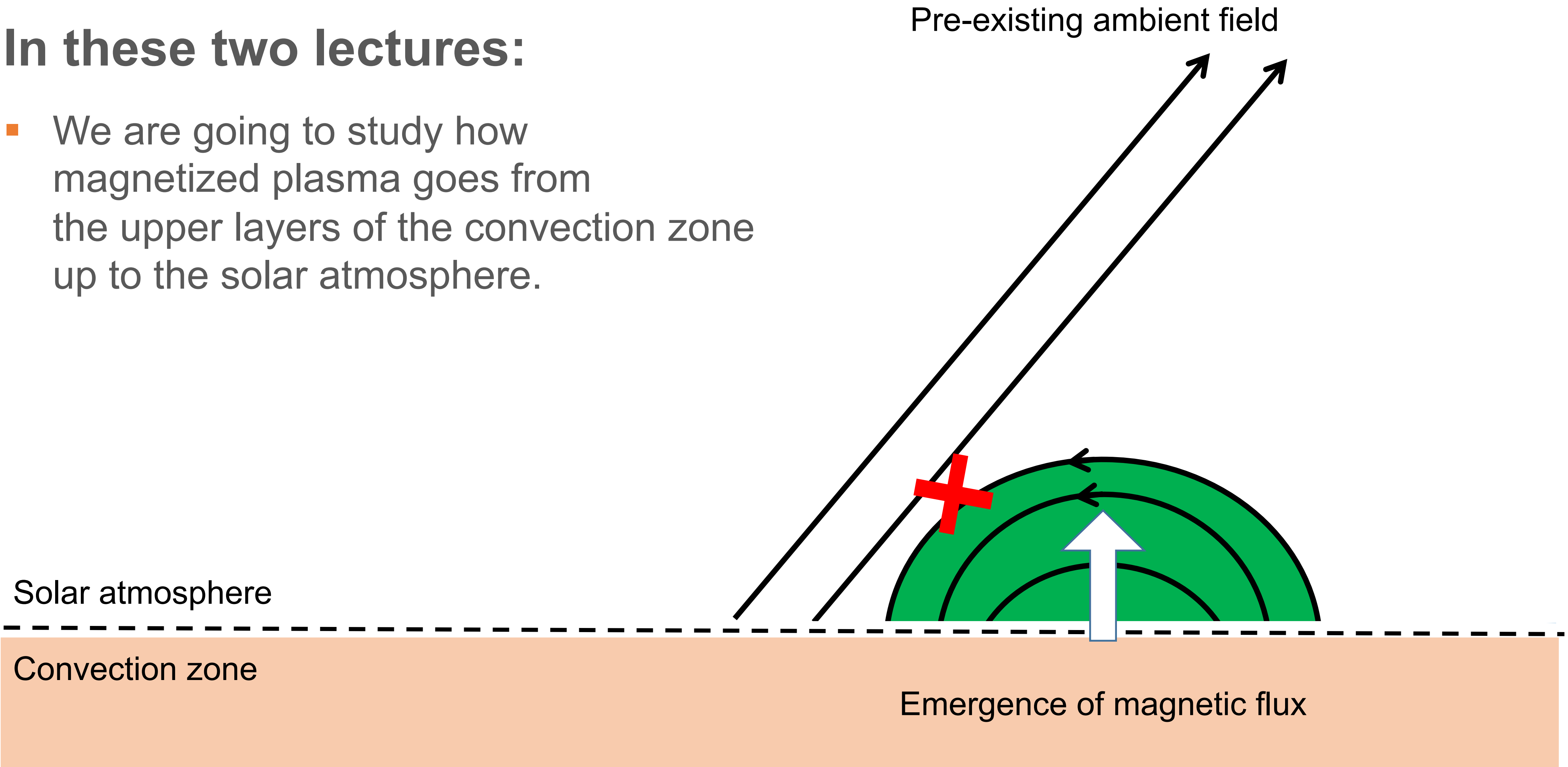
- We are going to study how magnetized plasma goes from the upper layers of the convection zone up to the solar atmosphere.



Introduction

In these two lectures:

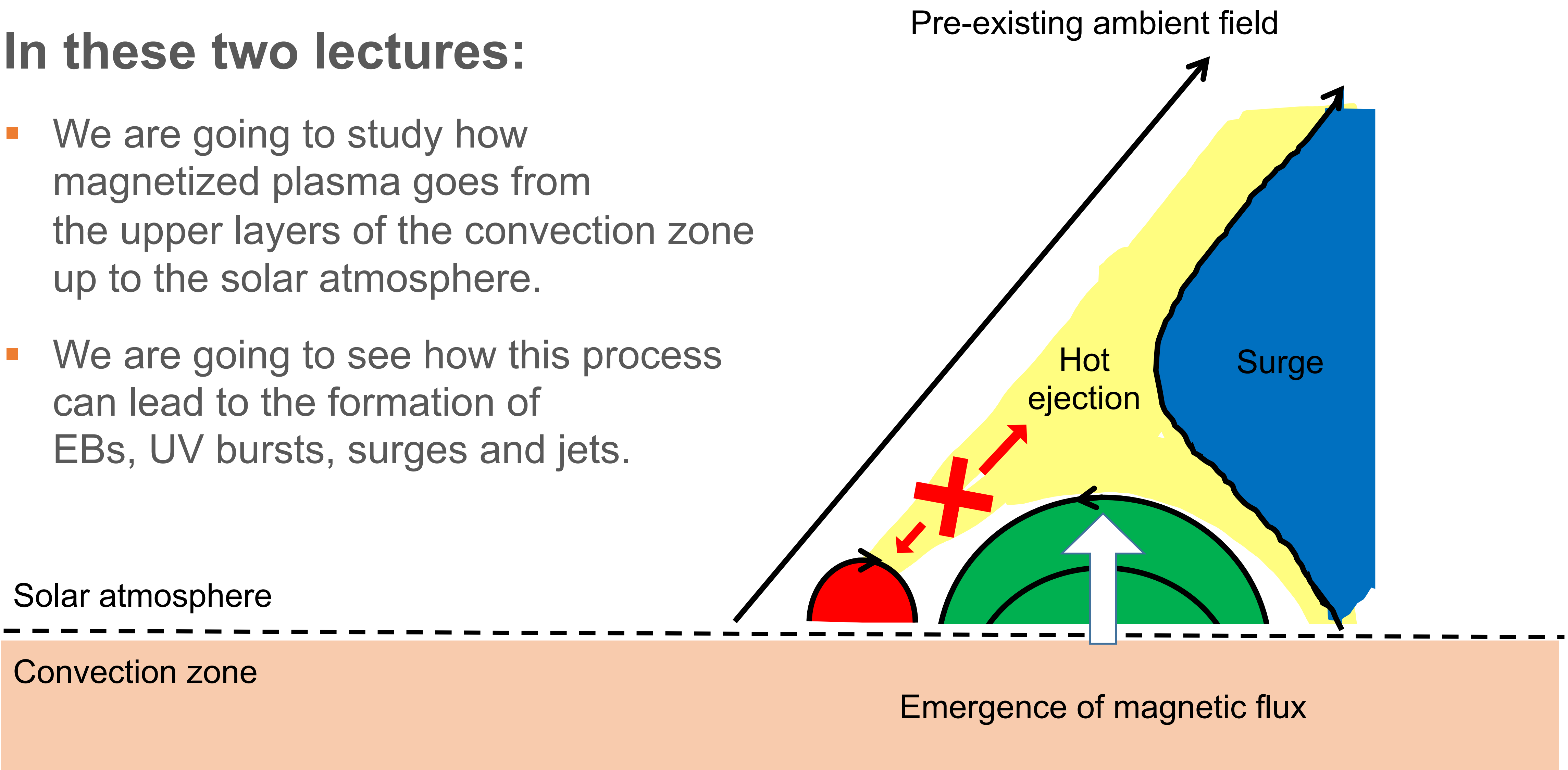
- We are going to study how magnetized plasma goes from the upper layers of the convection zone up to the solar atmosphere.



Introduction

In these two lectures:

- We are going to study how magnetized plasma goes from the upper layers of the convection zone up to the solar atmosphere.
- We are going to see how this process can lead to the formation of EBs, UV bursts, surges and jets.



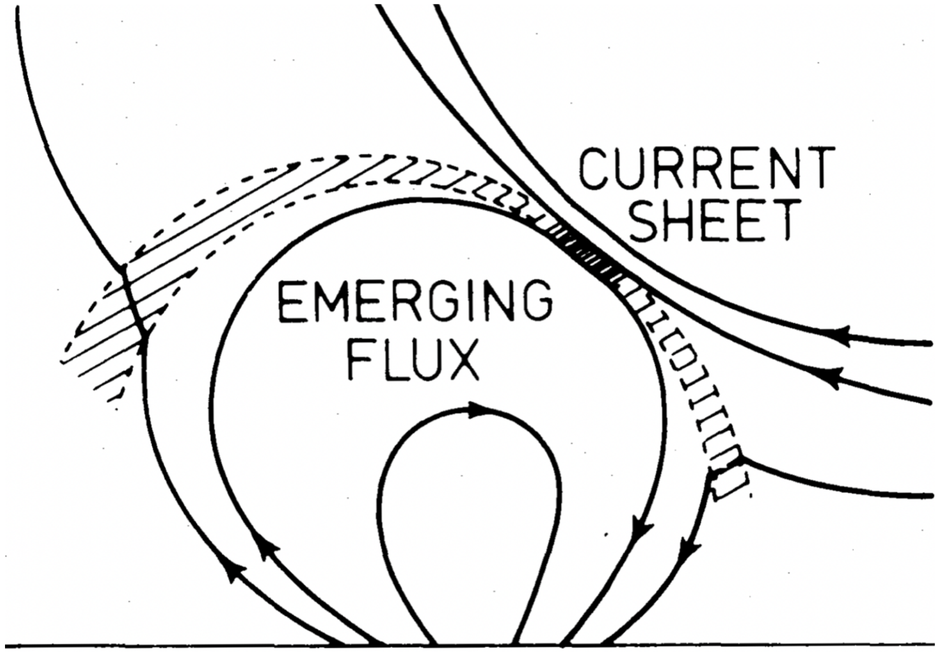
Introduction

Flux emergence models:

- The first theoretical explanation came in the 70s by Heyvaerts et al. 1977:
  solar flares could be produced
  by magnetic reconnection between
  the emerging flux and the pre-existing field.

- Numerous numerical experiments have shown that **magnetic reconnection and flux emergence** are key physical mechanisms to explain eruptive/ejective events in the solar atmosphere

  (e.g., Forbes & Priest 1984, Shibata et al. 1992, Yokoyama & Shibata 1995, 1996, Fan 2001, Miyagoshi & Yokoyama 2004, Archontis et al. 2004, 2005, 2007, Leake & Arber 2006, Cheung et al. 2007, 2008, Nishizuka et al. 2008, Moreno-Insertis et al. 2008, Martínez-Sykora et al. 2008, 2009, Murray et al. 2009, Archontis et al. 2010, Takasao et al. 2013, Archontis et al. 2013a,b, Moreno-Insertis & Galsgaard 2013, Fang et al. 2014, Toriumi et al. 2015, MacTaggart et al. 2015, Nóbrega-Siverio et al. 2016, 2017, 2018, Hansteen et al. 2019, Yang et al. 2018, Nóbrega-Sverio, et al. 2020, among many others)



Heyvaerts et al. 1977

Check the reviews by
Cheung & Isobe 2014, Fan 2021

Layout

The layout of the lectures is as follows:

- Interaction of magnetized plasma in the upper layers of the convection zone.
- Arrival at the solar surface: anomalous granulation.
- Rise and expansion of the magnetized plasma through the solar atmosphere.
- First stages of the reconnection between emerging and pre-existing field.
- Ellerman bombs, UV bursts, surges and jets.

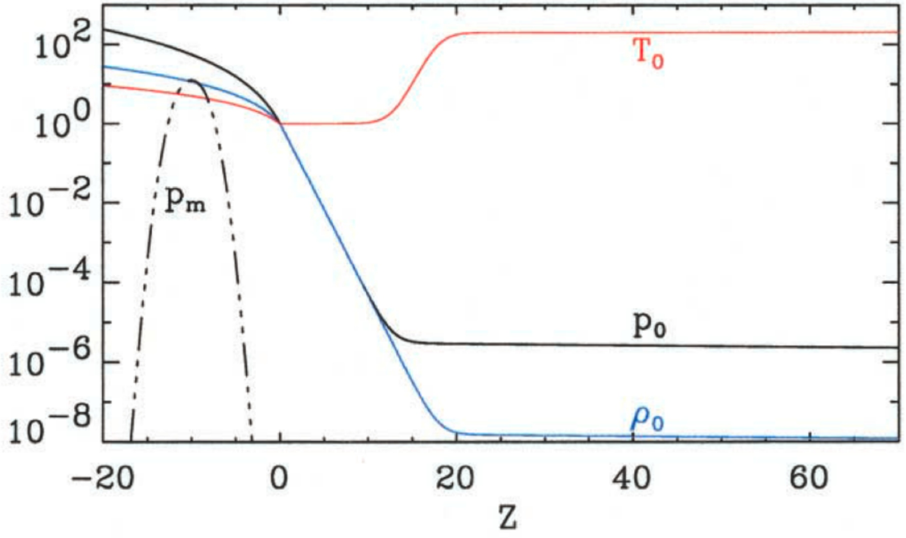
MHD modeling

Rosseland Centre for Solar Physics

Initial condition (not including convective motions): :

Plane-parallel atmosphere in hydrostatic Eq.:

- An adiabatically stratified polytropic layer (convection zone).
- An isothermal layer (photosphere and the chromosphere).
- An increasing temperature layer (transition region).
- Another isothermal layer (corona).



Fan 2001

$$T(z) = \begin{cases} 1 - \frac{\gamma-1}{\gamma} z, & z < 0, \\ 1, & 0 \le z \le 10, \\ T_{\rm cor}^{[(z-10)/10]}, & 10 < z < 20, \\ T_{\rm cor}, & z \ge 20, \end{cases}$$

McTaggart et al. 2015

MHD modeling

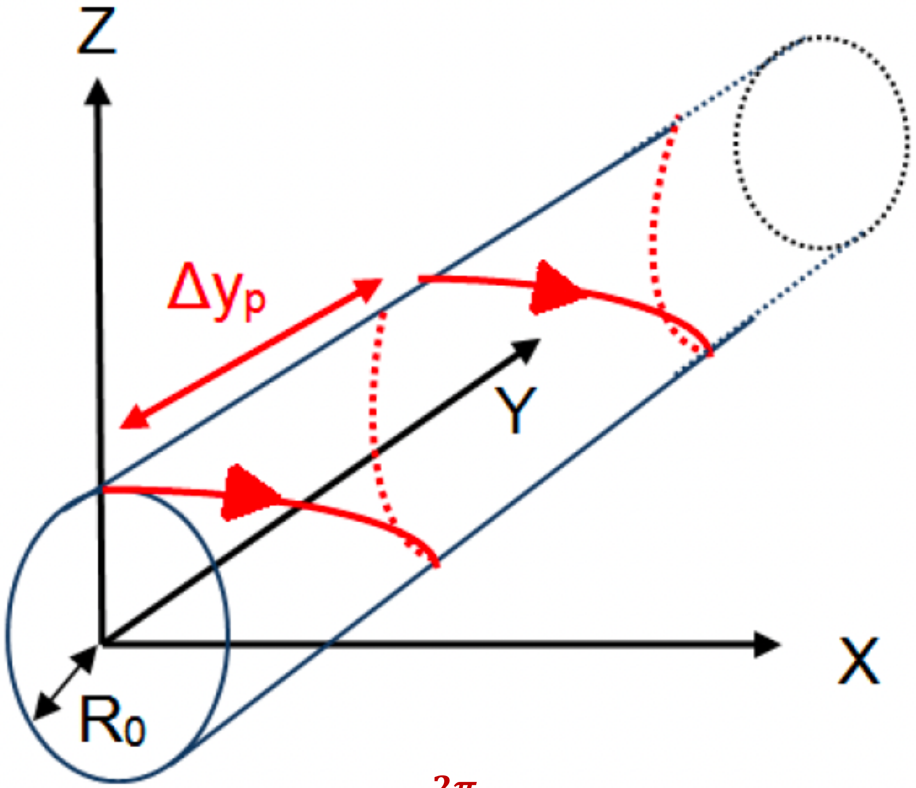
Twisted magnetic tube:

- Canonical way of having flux emergence. Field components are given by:

$$B_y = B_0 \exp\left(-\frac{r^2}{R_0^2}\right),$$

$$B_\theta = q\; r\; B_y,$$

where ***r*** and ***θ*** are the radial and azimuthal coordinates relative to the tube axis,
R_0 is the the radius of the tube,
q is a twist parameter, and
B_0 is the magnetic field in the tube axis.



$$\Delta y_p = \frac{2\pi}{q} \equiv Pitch$$

(e.g Fan 2001, Archontis et al. 2004, 2005, 2007, Cheung et al. 2007, 2008, Moreno-Insertis et al. 2008, Martínez-Sykora et al. 2008, 2009, Murray et al. 2009, Archontis et al. 2010, Archontis et al. 2013a,b, Moreno-Insertis & Galsgaard 2013, Fang et al. 2014, Toriumi et al. 2015, MacTaggart et al. 2015, Nóbrega-Siverio et al. 2016, 2017, 2018, 2020, among many others)

MHD modeling

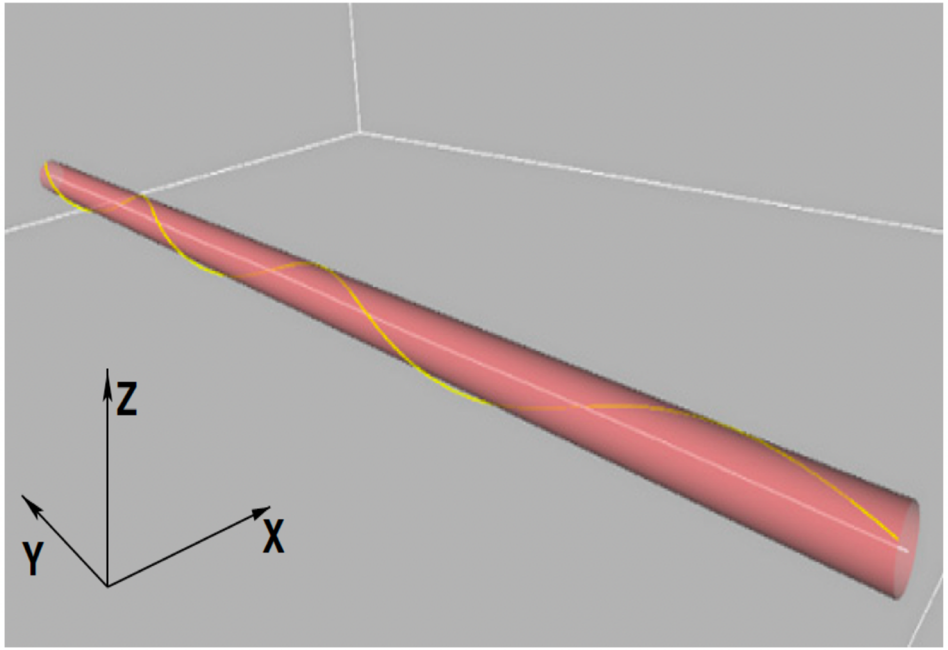
Twisted magnetic tube:

- Canonical way of having flux emergence. Field components are given by:

$$B_y = B_0 \exp\left(-\frac{r^2}{R_0^2}\right),$$

$$B_\theta = q\ r\ B_y,$$

where ***r*** and ***θ*** are the radial and azimuthal coordinates relative to the tube axis,
R_0 is the the radius of the tube,
q is a twist parameter, and
B_0 is the magnetic field in the tube axis.



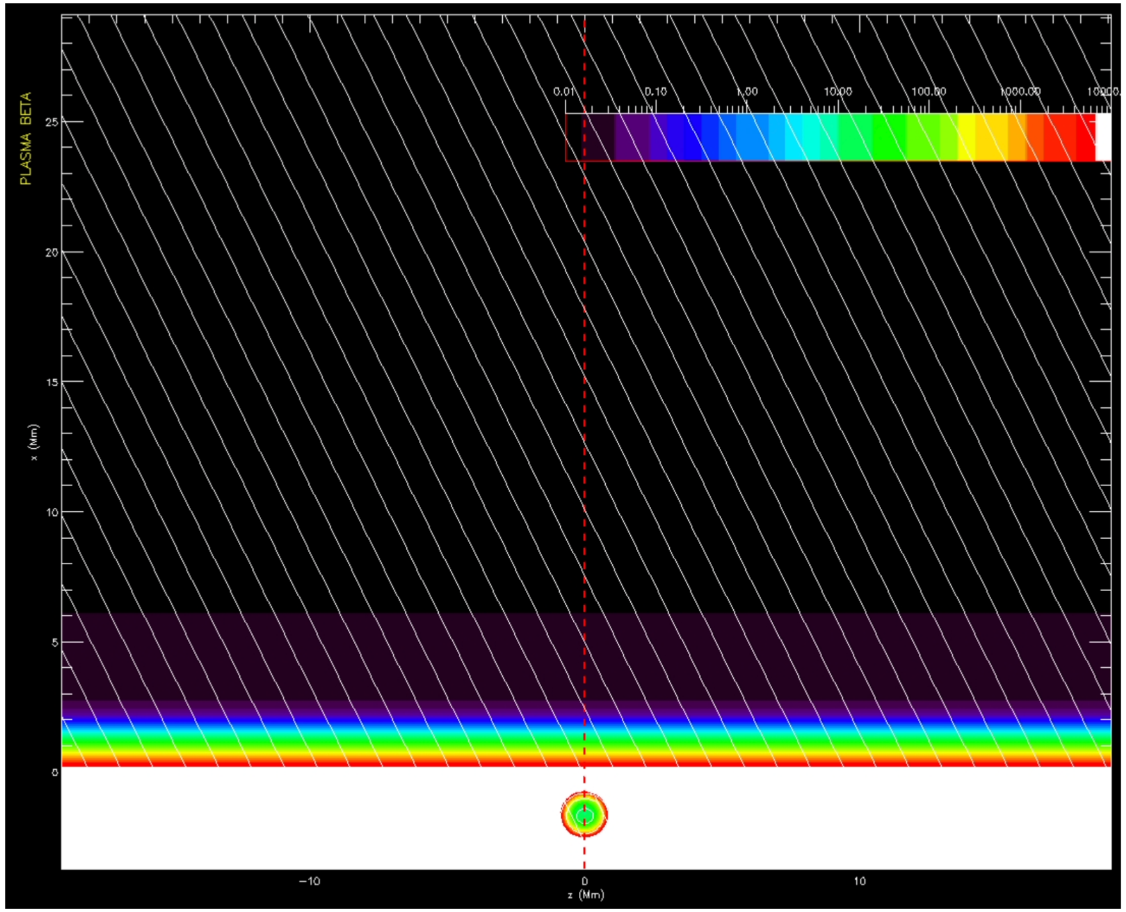
Archontis et al. 2013

Autores	z_0 (Mm)	R_0 (Mm)	q (Mm^{-1})	B_0 (kG)
Moreno-Insertis & Galsgaard (2013)	−1.70	0.430	2.4	3.8
Tortosa-Andreu & Moreno-Insertis (2009)	−1.80	0.400	0.6	7.5
Cheung et al. (2008)	−3.90	0.600	0.4	14.0
Martínez-Sykora et al. (2008)	−2.60	0.450	0.6	4.5
Cheung et al. (2007)	−1.35	0.200	2.6	8.5

MHD modeling

Twisted magnetic tube:

- To restore mechanical equilibrium, the gas pressure distribution within the tube is decreased typically via a density deficit.
- This implies that the tube is going to be buoyant, so it can goes up through the convection zone.



Moreno-Insertis & Galsgaard 2013

MHD modeling

Rise of the tube:

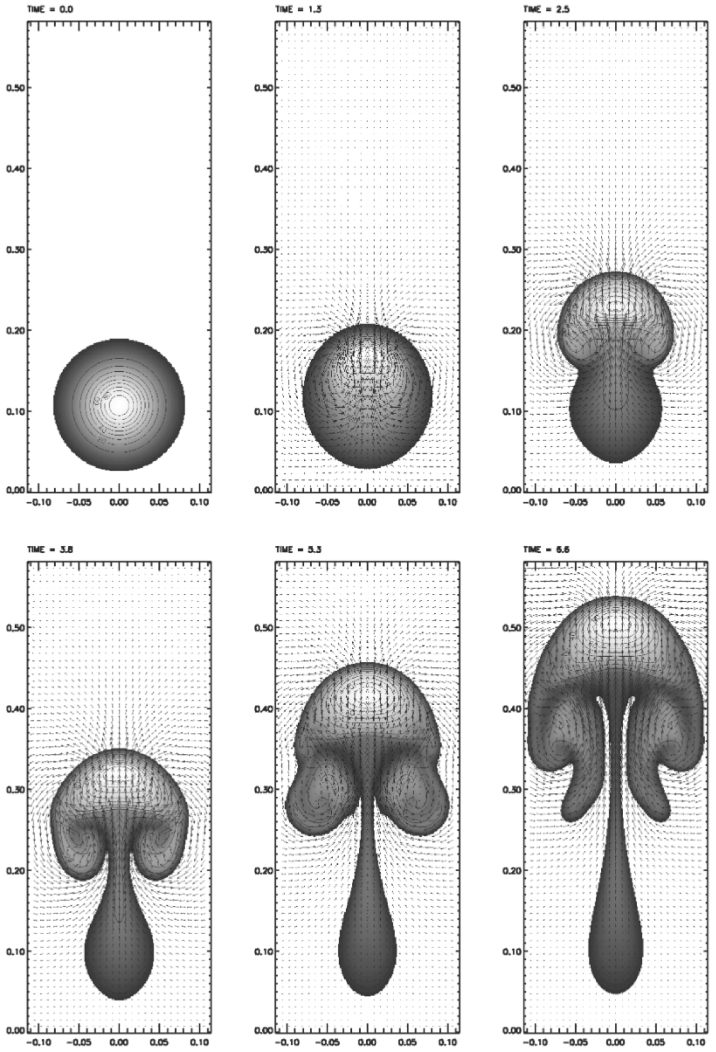
- In a stratified environment without convective motions,

  - the tube tends to split into counter-rotating vortex rolls (dumbbell shapes).

  - the tube can retain coherence because of its transverse component counteracts the horizontal pressure gradient.

  - due to the diminishing scale heights, the tube flattens into a pancake-like structure.

(e.g Schüssler 1979, Spruit et al. 1987, Moreno-Insertis & Emonet 1996, Longcope et al. 1996, Toriumi & Yokoyaa 2001, Archontis et al. 2004, among others)



Emonet & Moreno-Insertis 1998

MHD modeling

Rise of the tube:

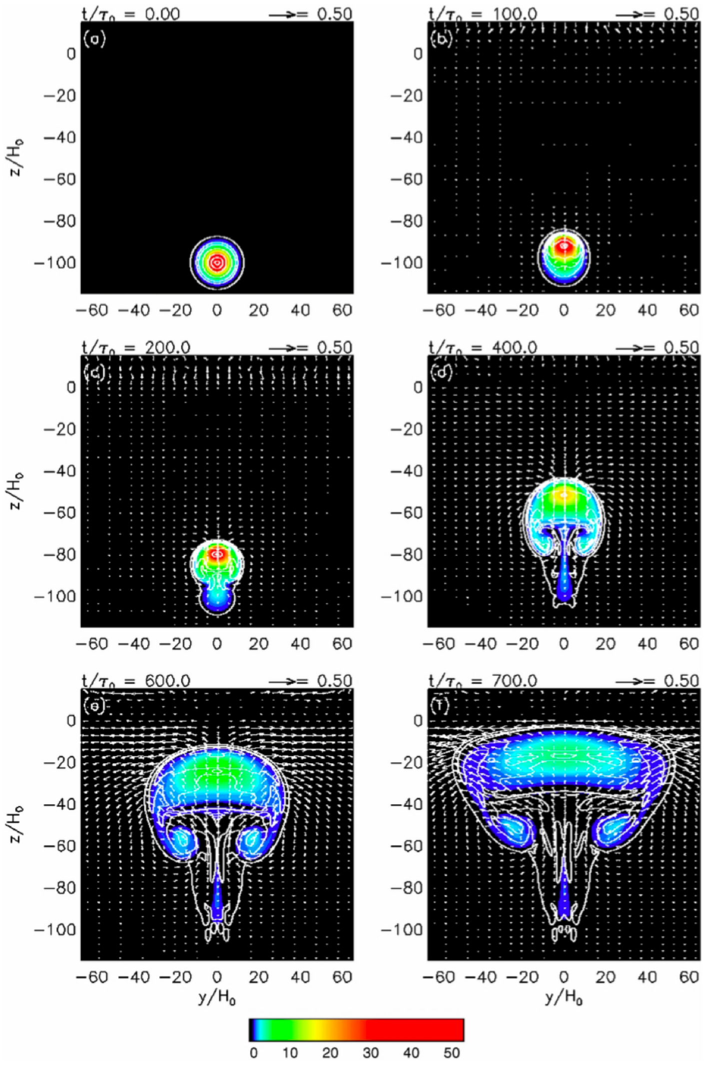
- In a stratified environment without convective motions,

  - the tube tends to split into counter-rotating vortex rolls (dumbbell shapes).

  - the tube can retain coherence because of its transverse component counteracts the horizontal pressure gradient.

  - due to the diminishing scale heights, the tube flattens into a pancake-like structure.

(e.g Schüssler 1979, Spruit et al. 1987, Moreno-Insertis & Emonet 1996, Longcope et al. 1996, Toriumi & Yokoyaa 2001, Archontis et al. 2004, among others)



Toriumi & Yokoyama 2001

MHD modeling

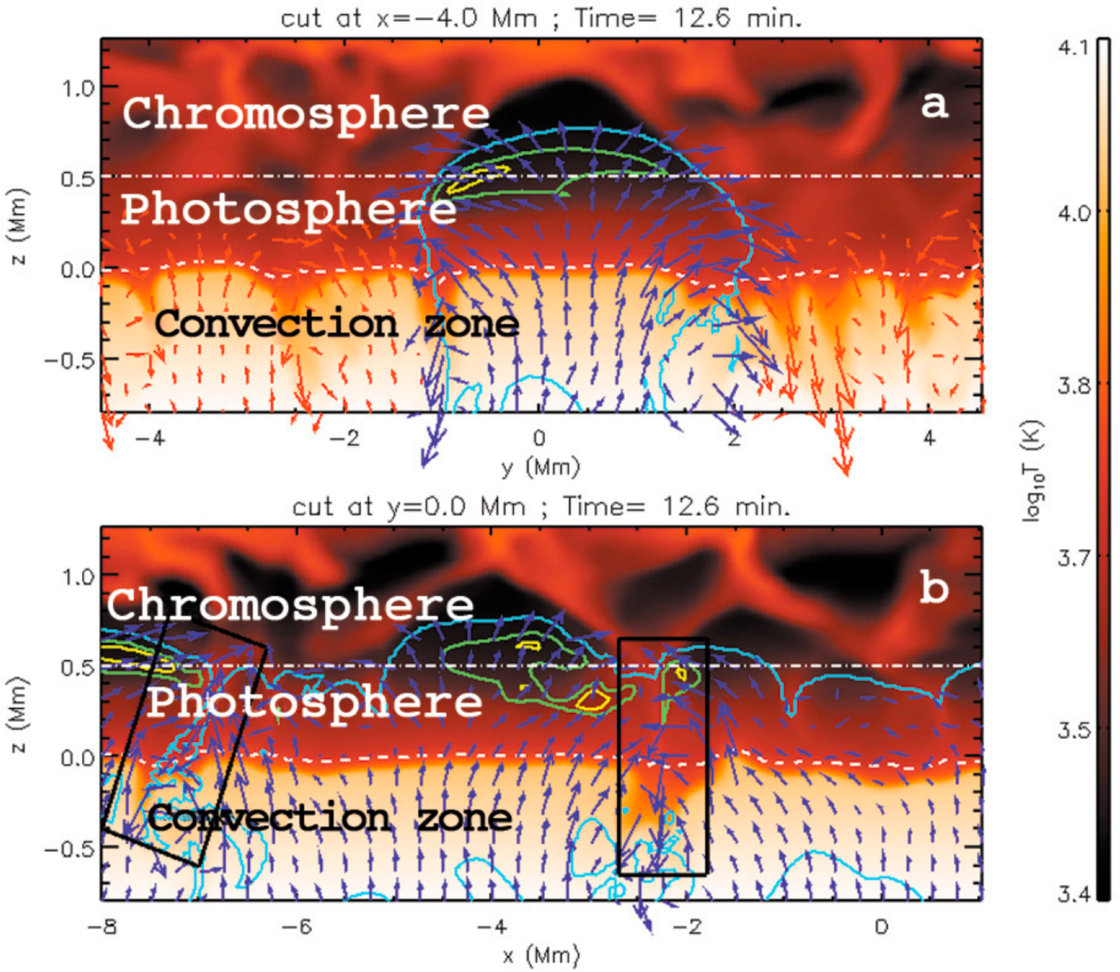
Rosseland
Centre
for Solar
Physics

Initial condition (including convective motions):

Statistically Stationary Eq.

- Radiation transfer adequate to the photosphere to get self-consistent convection zone with granulation.

Example using the MURaM code (Vögler et al. 2005)



Tortosa-Andreu & Moreno-Insertis et al. 2009

MHD modeling

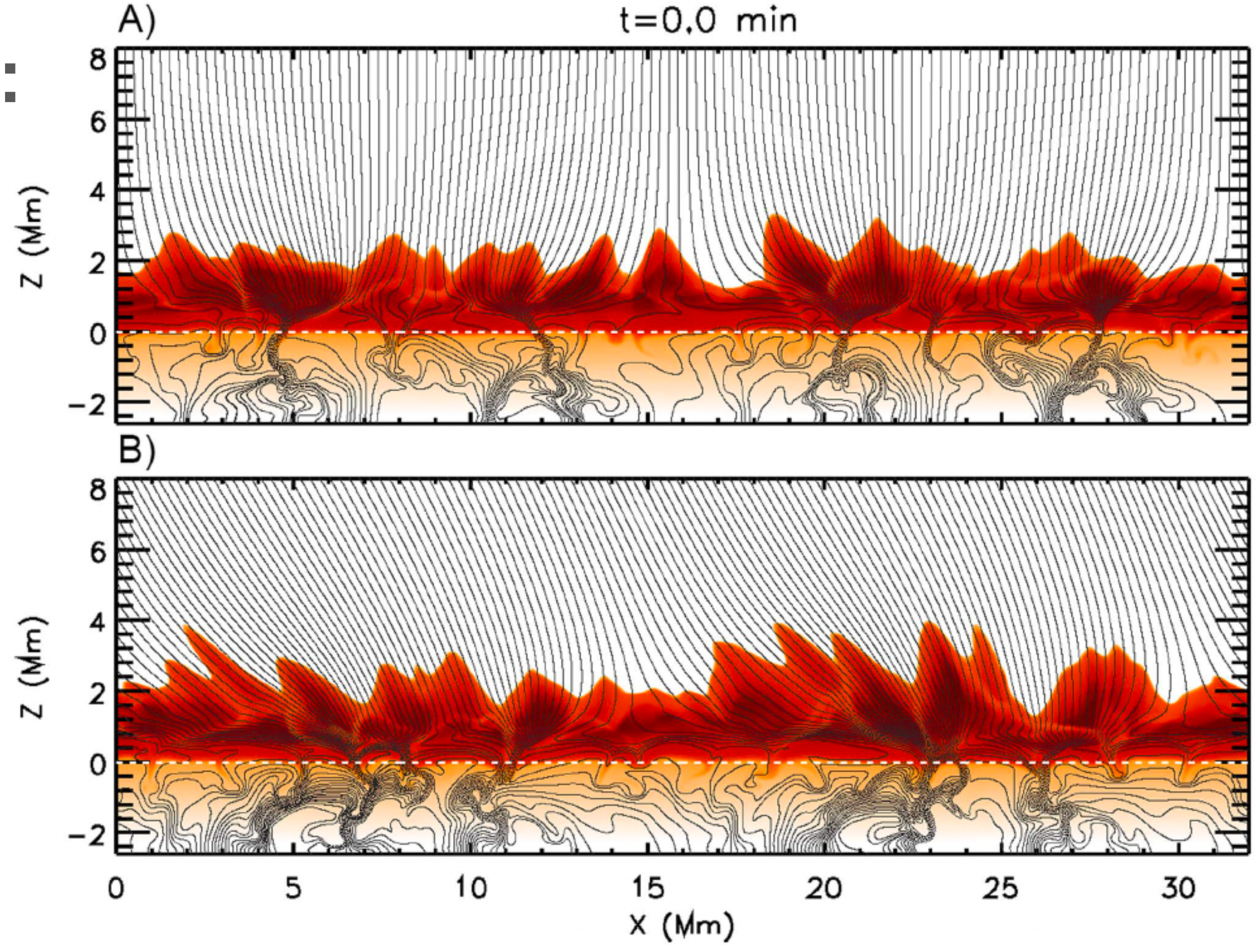
Rosseland
Centre
for Solar
Physics

Initial condition (including convective motions):

Statistically Stationary Eq.

- Radiation transfer adequate to the photosphere to get self-consistent convection zone with granulation.

Example using the Bifrost code (Gudiksen et al. 2011)



Nóbrega-Siverio et al. 2018

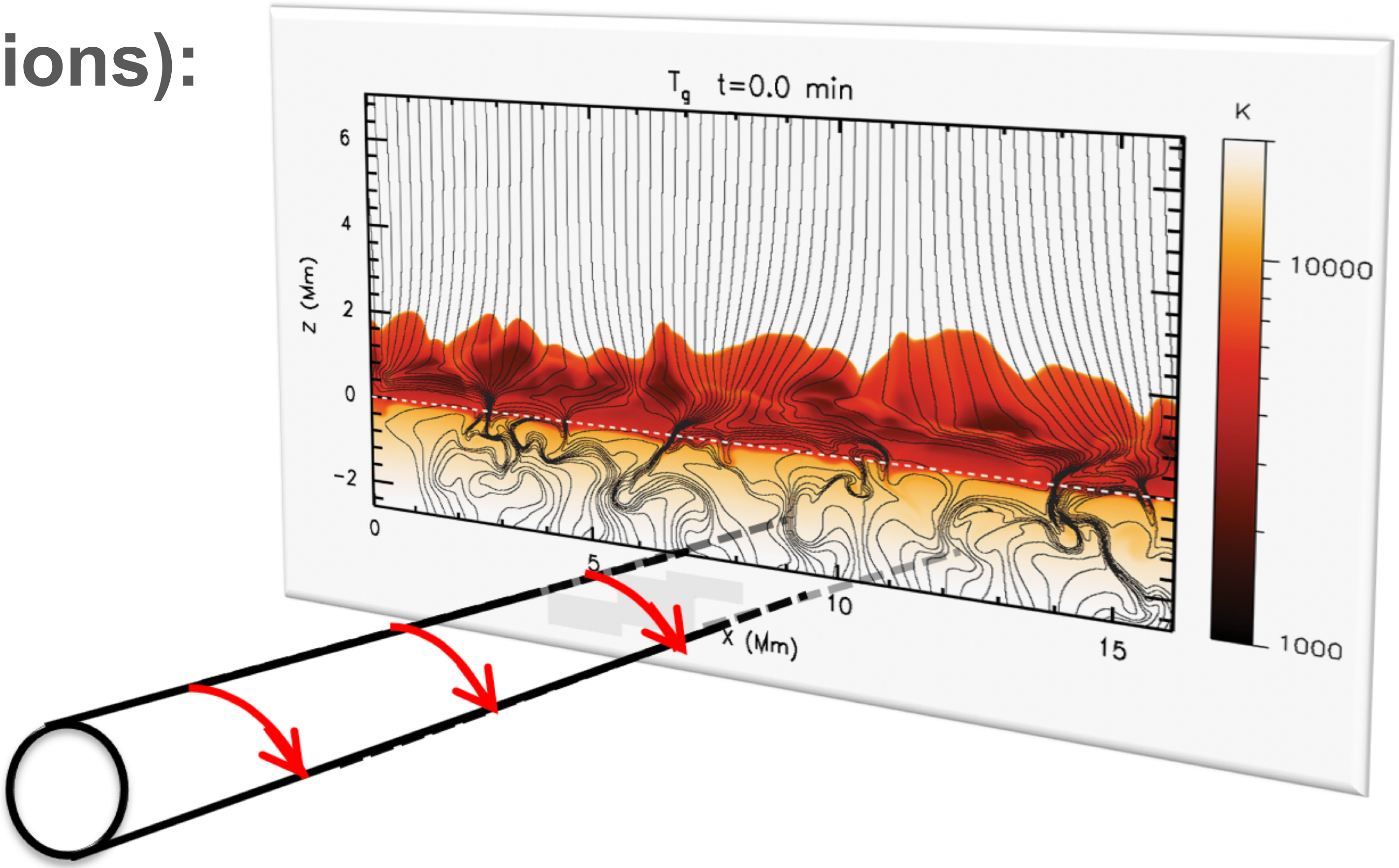
MHD modeling

Initial condition (including convective motions):

Statistically Stationary Eq.

- Radiation transfer adequate to the photosphere to get self-consistent convection zone with granulation.
- Magnetic flux emergence through the injection of a twisted magnetic tube →

Example using the Bifrost code (Gudiksen et al. 2011)



Nóbrega-Siverio et al. 2016

MHD modeling

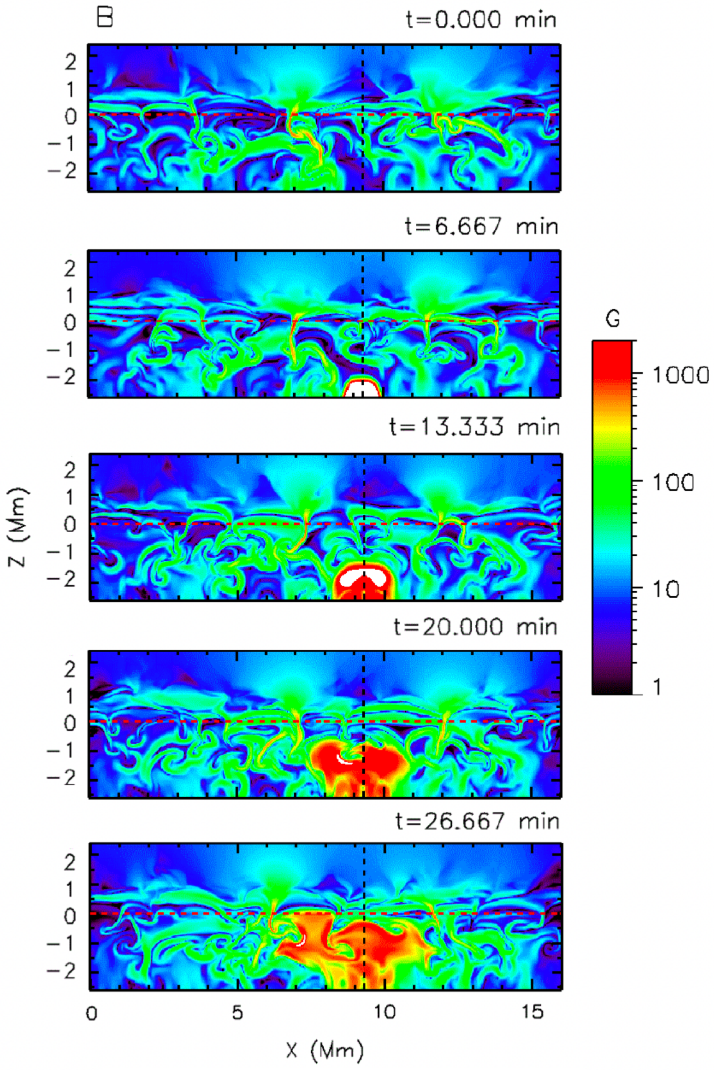
Rosseland
Centre
for Solar
Physics

Rise of the tube:

- In a stratified environment **with** convective motions,

  - similar characteristics as we saw before due to the stratification (e.g., vortex rolls),

  - the granulation perturbs the evolution of the twisted magnetic tube,



Nóbrega-Siverio's Master Thesis

MHD modeling

Rise of the tube:

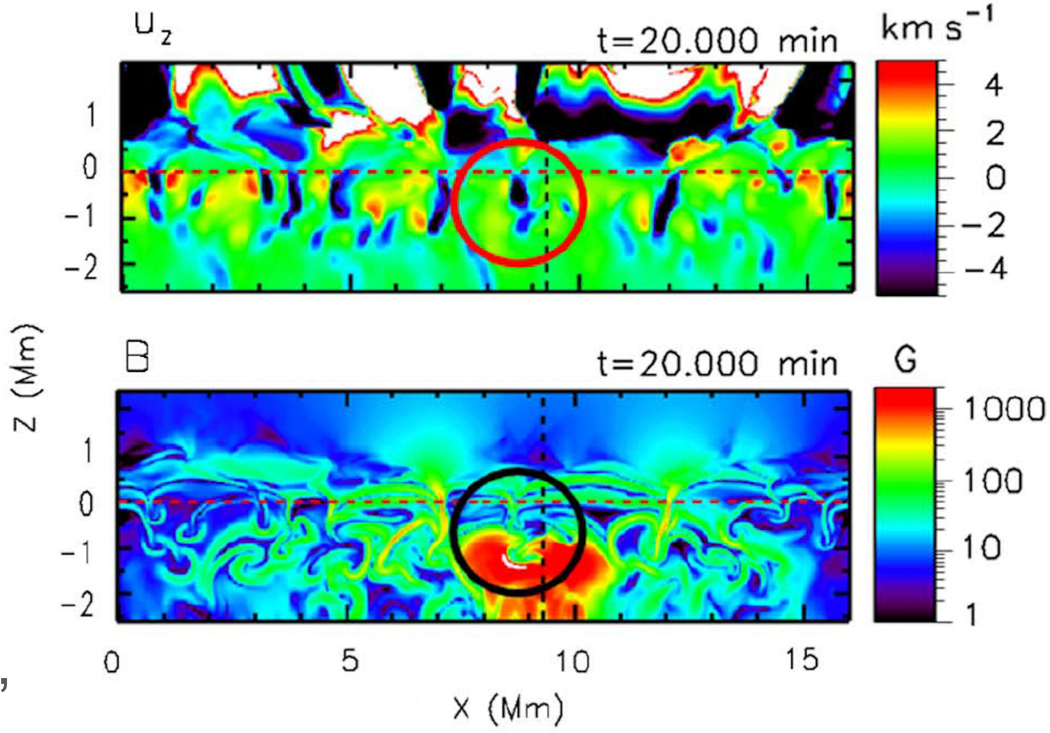
- In a stratified environment **with** convective motions,

  - similar characteristics as we saw before due to the stratification (e.g., vortex rolls),

  - the granulation perturbs the evolution of the twisted magnetic tube,

  in particular,
  convection flows deform and break the tube into smaller fragments in the regions of strong shear, typically where the downflows hit the tube.

(e.g Cheung et al. 2007, 2008, Tortosa-Andreu & Moreno-Insertis 2009, Martínez-Sykora et al. 2008, 2009, Nóbrega-Siverio et al. 2016, Hansteen 2017, 2019, among others)

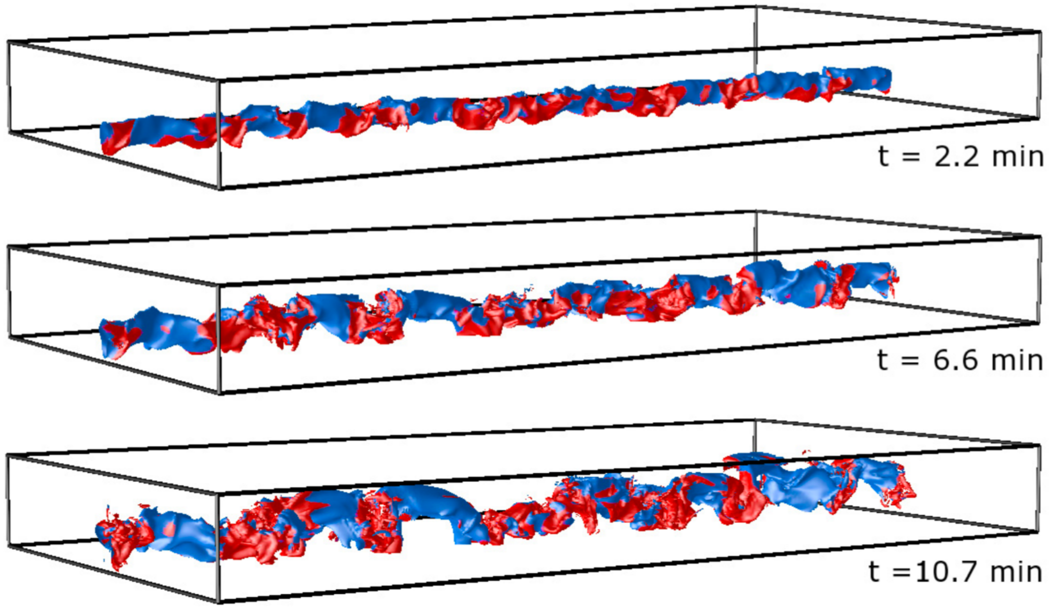


Nóbrega-Siverio's Master Thesis

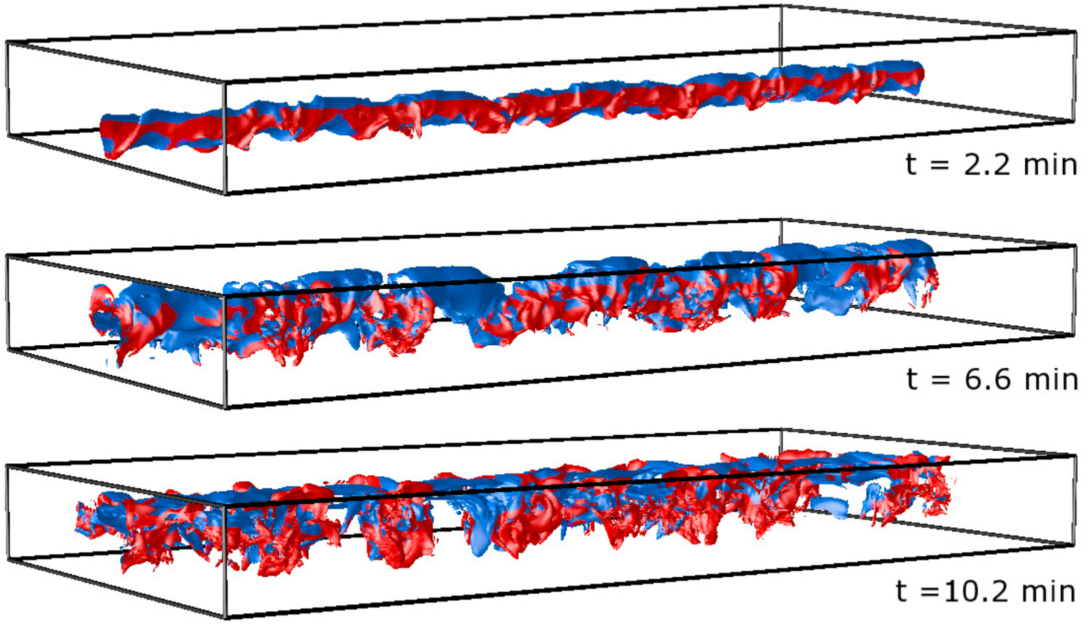
MHD modeling

Rise of the tube:

- In a stratified environment **with** convective motions,



weak magnetic flux tube (B_0 = 2500 G)



strong magnetic flux tube (B_0 = 8500 G)

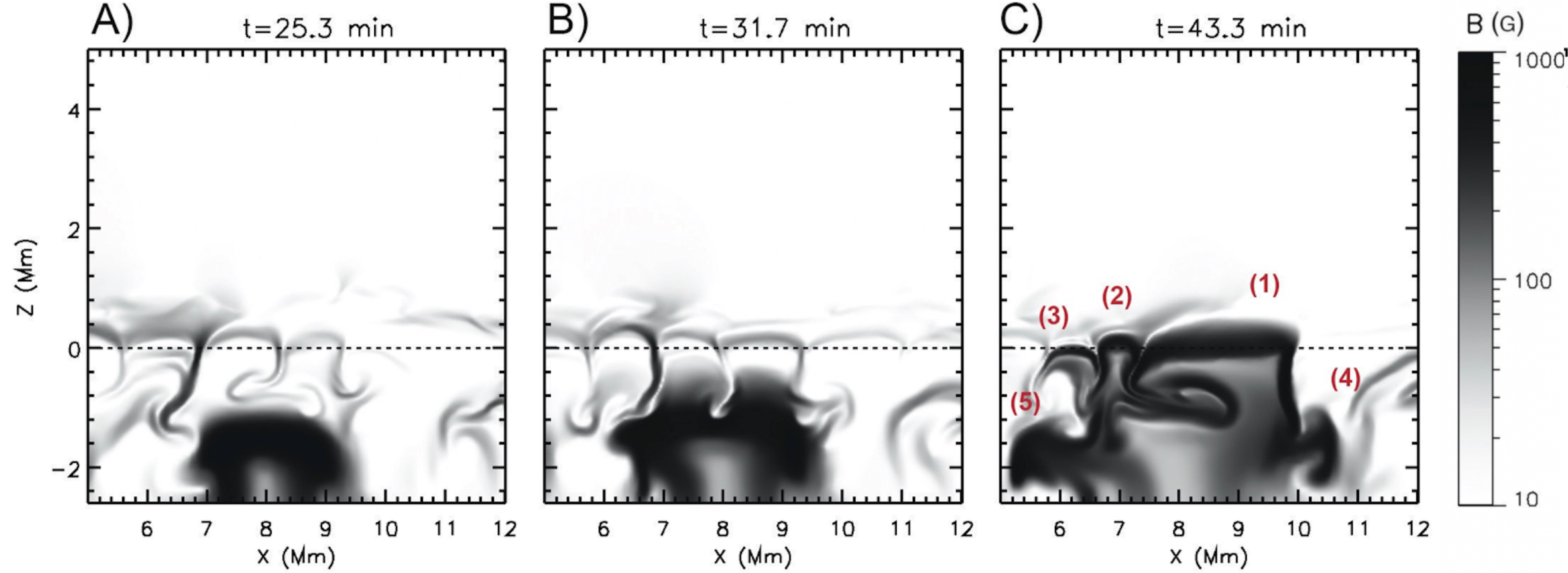
Cheung et al. 2007

MHD modeling

Rosseland
Centre
for Solar
Physics

Arrival at the surface:

- Not all the parts of the fragmented tube reach the surface.

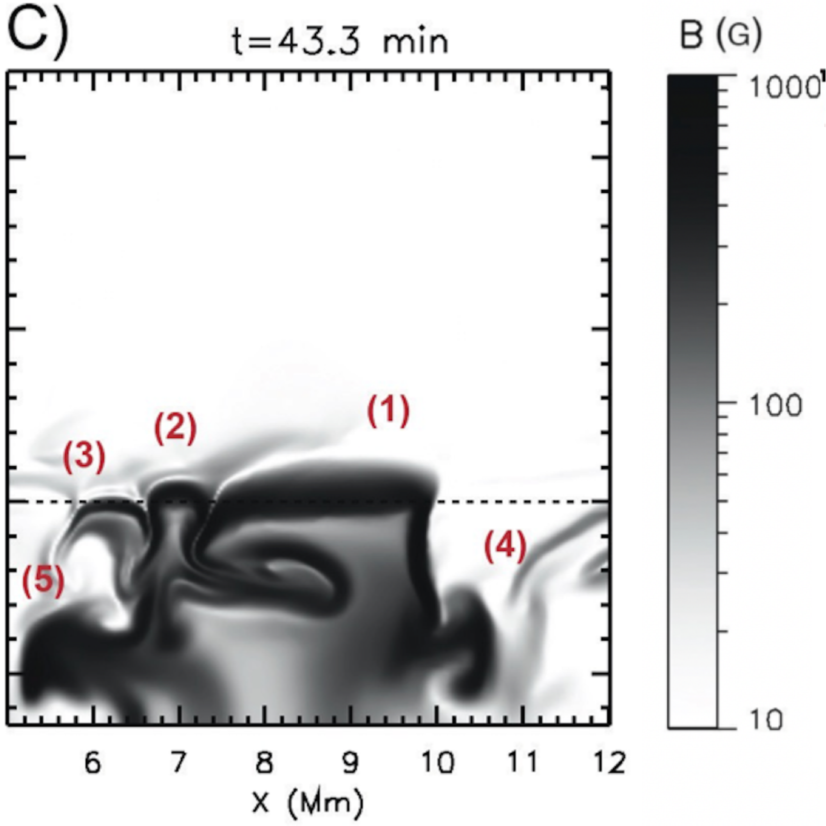


Nóbrega-Siverio et al. 2016

MHD modeling

Arrival at the surface:

- In the photosphere, there is transition between super- and sub-adiabatically stratified regions.
- This implies that an emerging fluid element enters a stably stratified region that is difficult to penetrate.
- As a consequence, the magnetized plasma starts to pile up, increasing the magnetic pressure.
- The enhanced pressure produces a sideways growth of the emerging fragments, leading to anomalous granules.

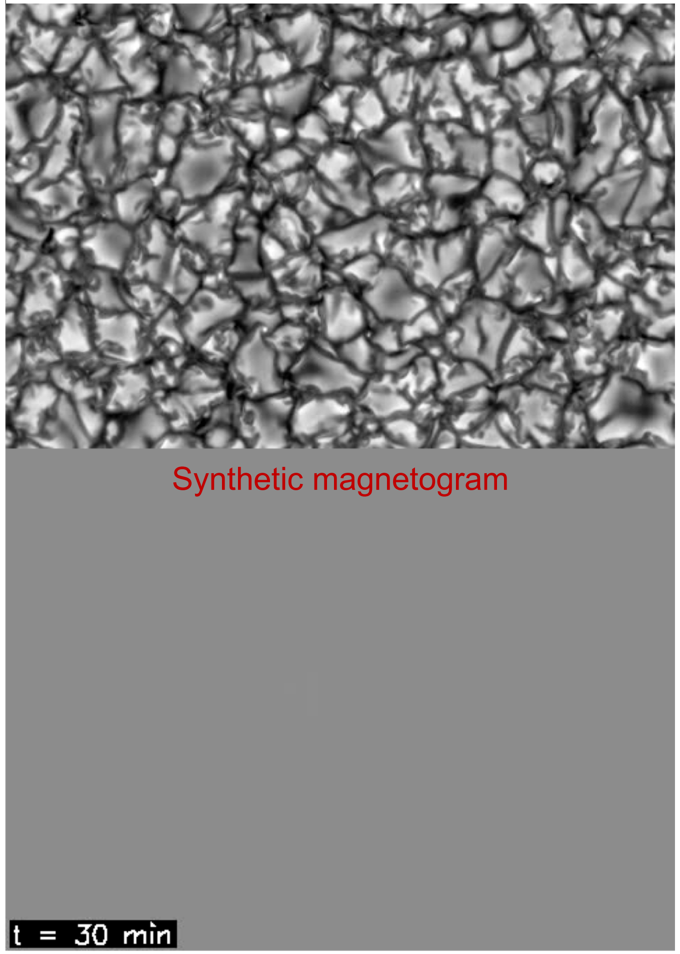


Nóbrega-Siverio et al. 2016

MHD modeling

Arrival at the surface:

- In the photosphere, there is transition between super- and sub-adiabatically stratified regions.
- This implies that an emerging fluid element enters a stably stratified region that is difficult to penetrate.
- As a consequence, the magnetized plasma starts to pile up, increasing the magnetic pressure.
- The enhanced pressure produces a sideways growth of the emerging fragments, leading to anomalous granules.


Continuum intensity images (at 500 nm)

Synthetic magnetogram

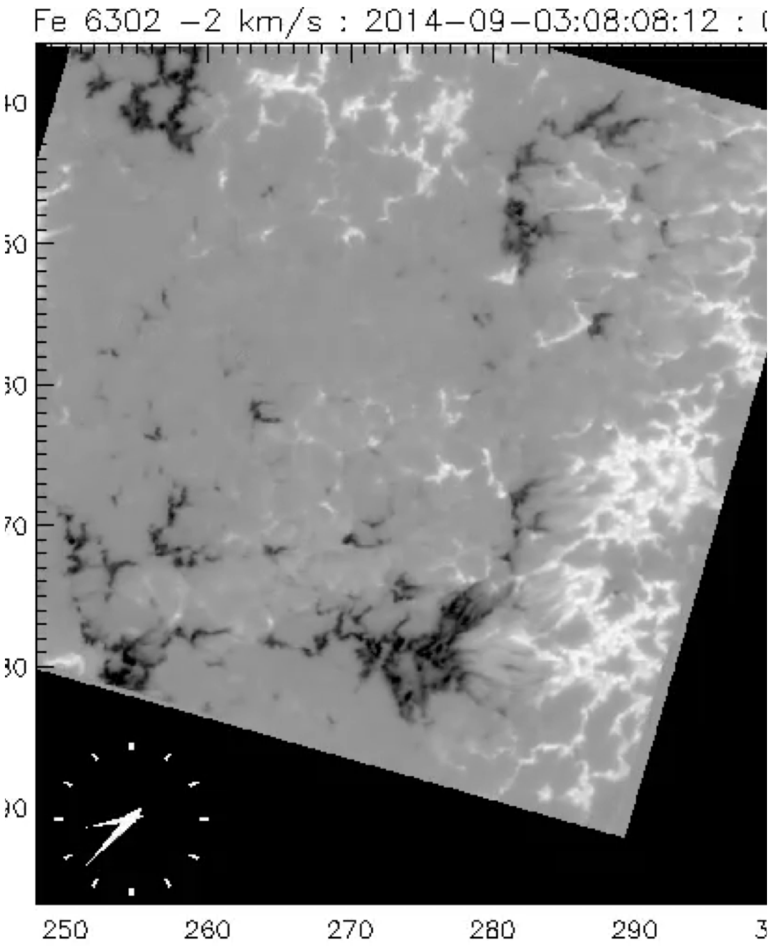
Cheung et al. 2008

Comparison with observations

Arrival at the surface:

- In the photosphere, there is transition between super- and sub-adiabatically stratified regions.
- This implies that an emerging fluid element enters a stably stratified region that is difficult to penetrate.
- As a consequence, the magnetized plasma starts to pile up, increasing the magnetic pressure.
- The enhanced pressure produces a sideways growth of the emerging fragments, leading to anomalous granules.

(observational examples of anomalous granulation: Orozco Suárez et al. 2008, Guglielmino et al. 2010, Ortiz et al. 2014, among many others)



SST Observation courtesy of
Luc Rouppe van der Voort

MHD modeling

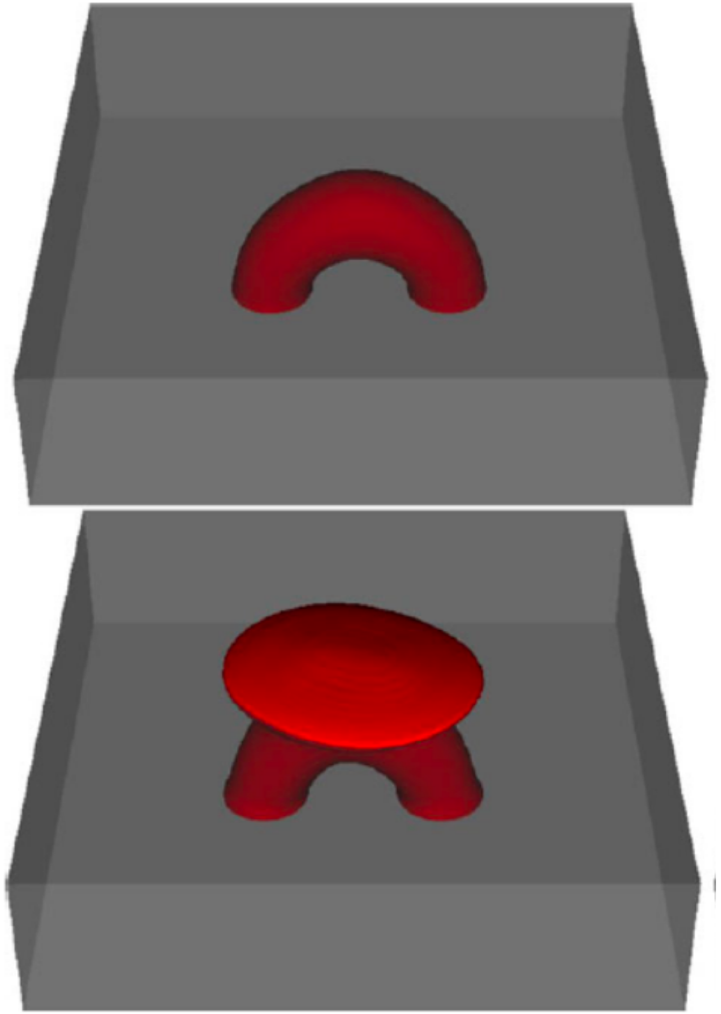
Buoyancy instability:

- The later evolution occurs
  in the frame of the buoyancy instability:
- This instability occurs when the vertical gradient of the magnetic field is large enough to overcome the sub-adiabatic stabilizing term.

$$-H_p \frac{\partial}{\partial z}(\log B) > -\frac{\gamma}{2}\,\beta\delta + (k_{\|} H_p)^2 \left(1 + \frac{k_\perp^2}{k_z^2}\right) \quad ,$$

- If the field does not get strong enough, no emergence will ensue.

(for details about the buoyancy instability, check
Newcomb 1961, Yu 1965, Thomas & Nye 1975, Acheson 1979, among others)



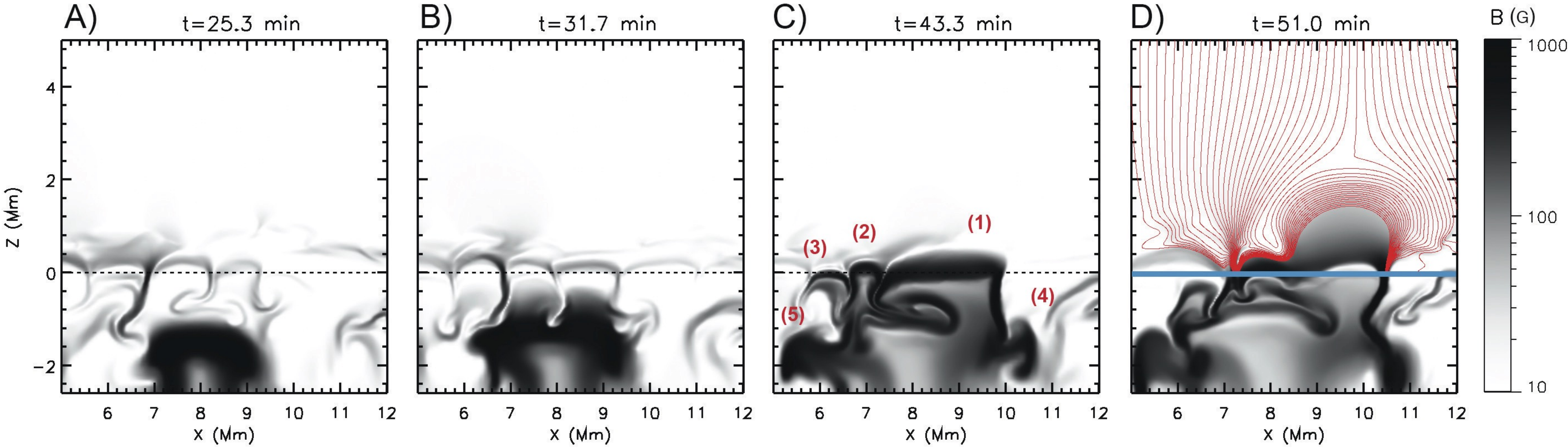
Hood et al. 2012

MHD modeling

Buoyancy instability:

- If the field gets strong enough…
  this instability will allow the magnetized fluid
  to go through the solar atmosphere!

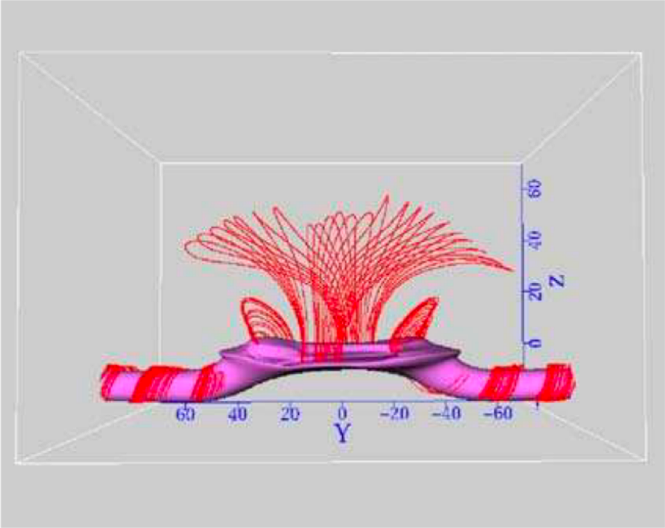
Nóbrega-Siverio et al. 2016

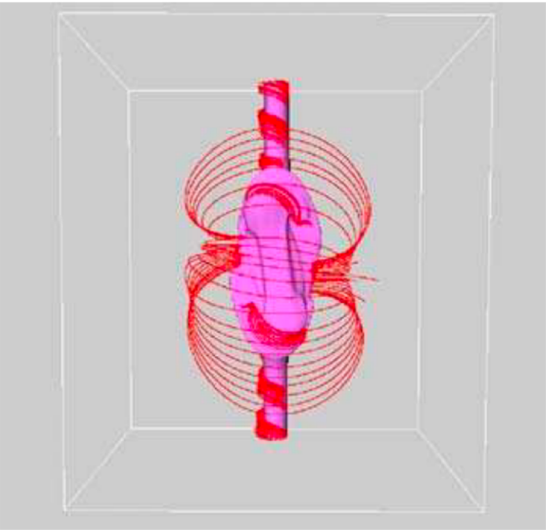


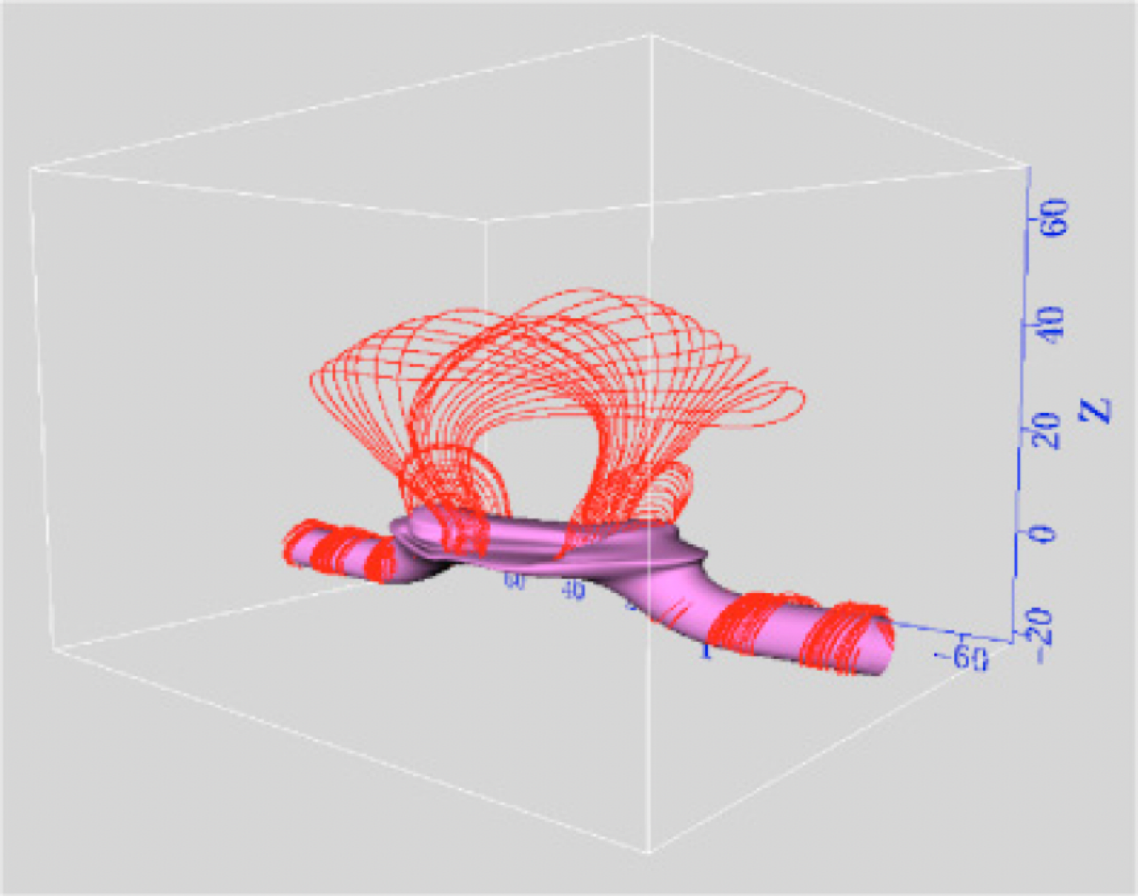
MHD modeling

Buoyancy instability:

- If the field gets strong enough…
  this instability will allow the magnetized fluid to go through the solar atmosphere!





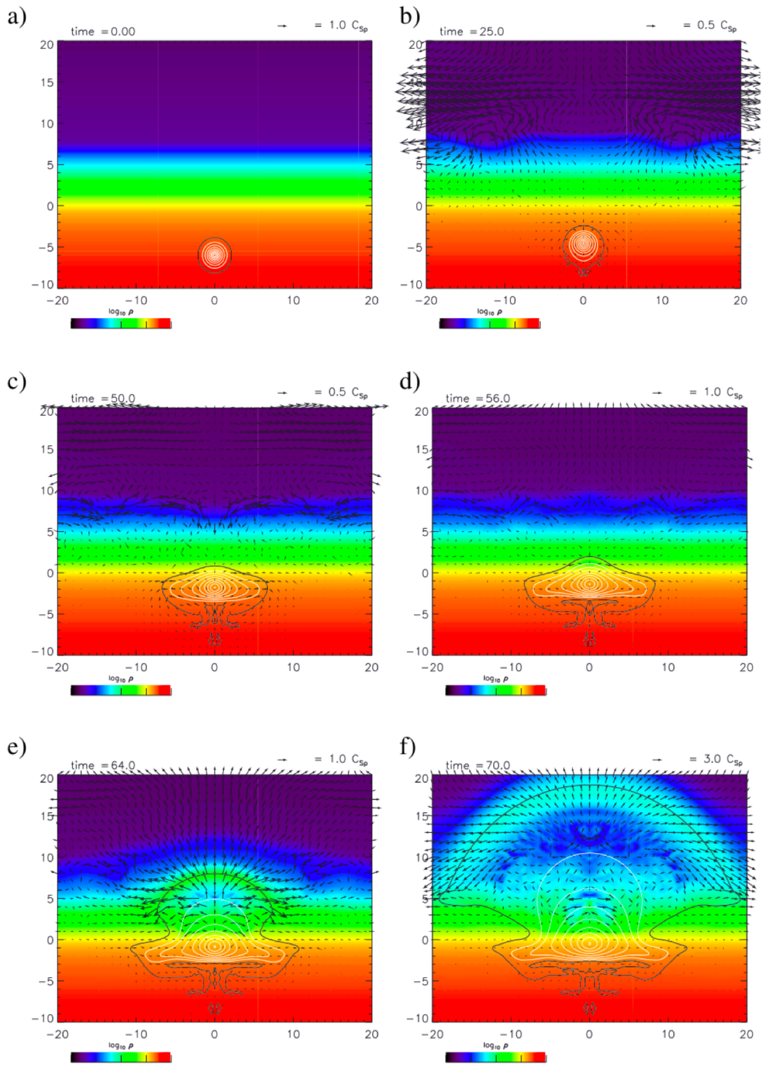


Archontis et al. 2004

MHD modeling

Expansion into the atmosphere:

- The expansion occurs in all directions, but the horizontal components of the velocity are larger than the vertical components.
- This expansion leads to a dome-like structure.
- The expansion is rapid and it decreases local values of temperature and density.
- The dome interior suffers a draining process owing to the gravitational flows that take place along the loop-like magnetic field lines.

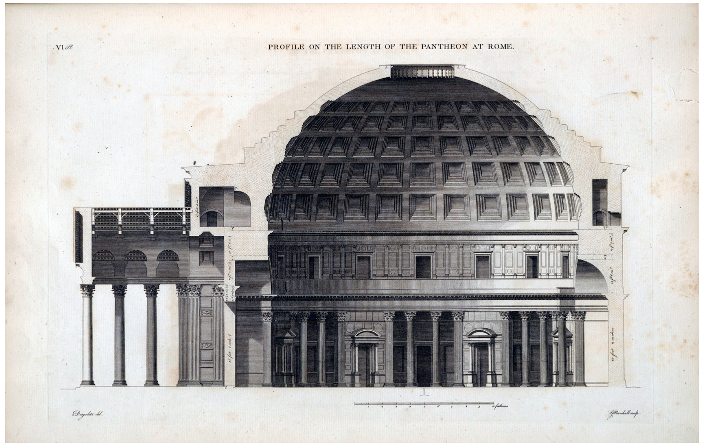


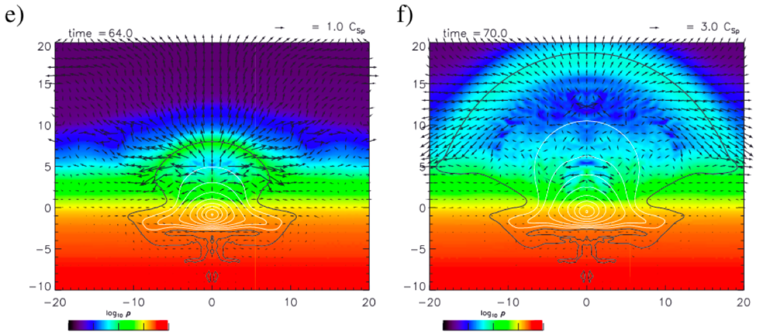
Magara 2001

MHD modeling

Expansion into the atmosphere:

- The expansion occurs in all directions, but the horizontal components of the velocity are larger than the vertical components.
- This expansion leads to a dome-like structure.
- The expansion is rapid and it decreases local values of temperature and density.
- The dome interior suffers a draining process owing to the gravitational flows that take place along the loop-like magnetic field lines.



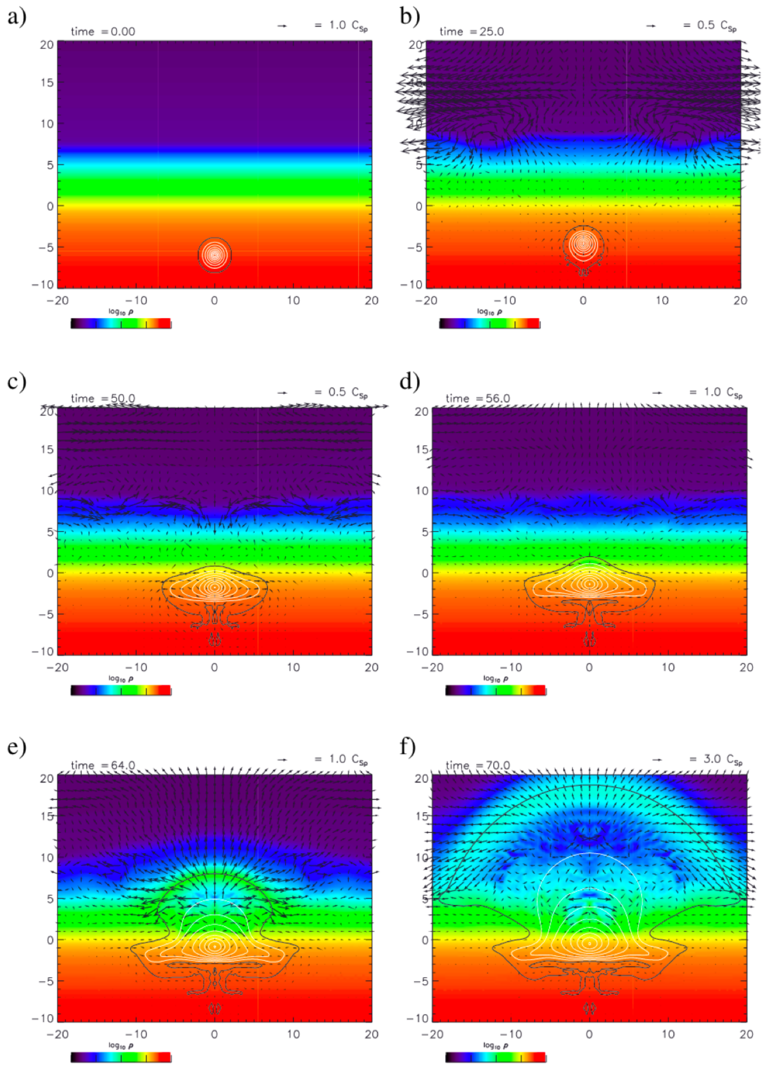


Magara 2001

MHD modeling

Expansion into the atmosphere:

- The expansion occurs in all directions, but the horizontal components of the velocity are larger than the vertical components.
- This expansion leads to a dome-like structure.
- The expansion is rapid and it decreases local values of temperature and density.
- The dome interior suffers a draining process owing to the gravitational flows that take place along the loop-like magnetic field lines.

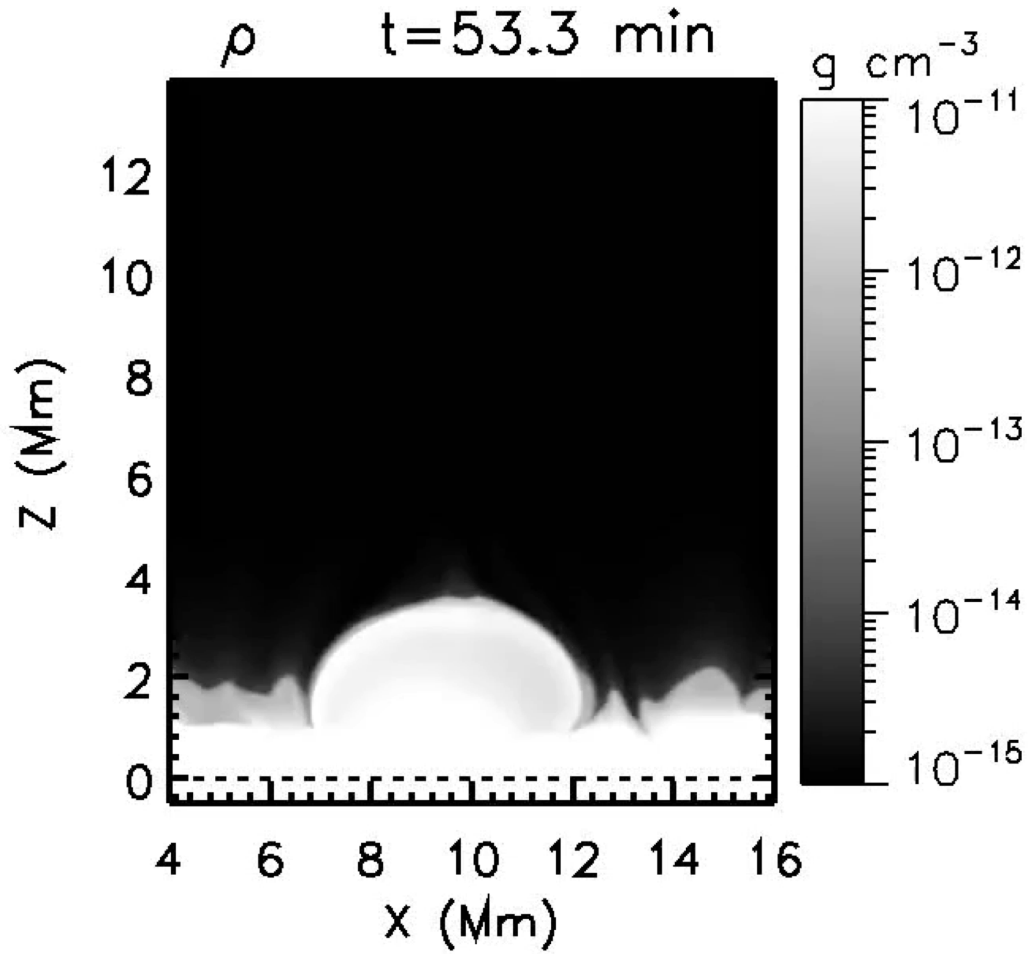


Magara 2001

MHD modeling

Expansion into the atmosphere:

- The expansion occurs in all directions, but the horizontal components of the velocity are larger than the vertical components.
- This expansion leads to a dome-like structure.
- The expansion is rapid and it decreases local values of temperature and density.
- The dome interior suffers a draining process owing to the gravitational flows that take place along the loop-like magnetic field lines.

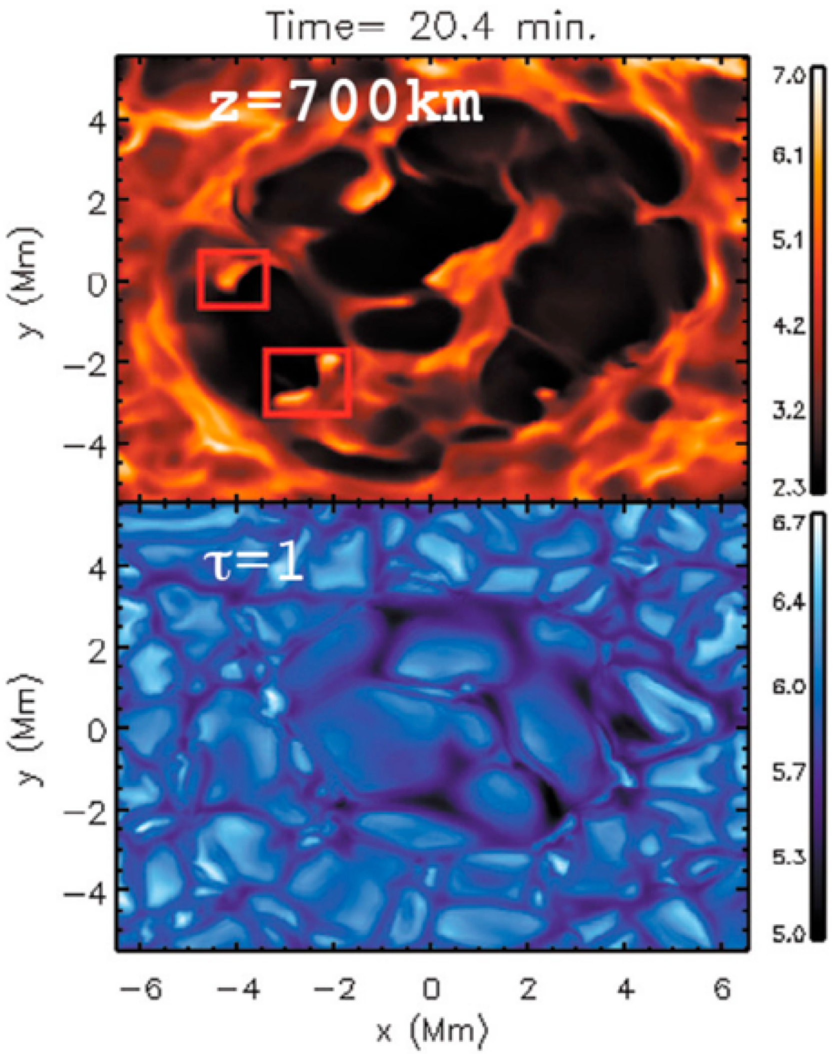


Nóbrega-Siverio et al. 2016

MHD modeling

Expansion into the atmosphere:

- The expansion occurs in all directions, but the horizontal components of the velocity are larger than the vertical components.
- This expansion leads to a dome-like structure.
- The expansion is rapid and it decreases local values of temperature and density.
- The dome interior suffers a draining process owing to the gravitational flows that take place along the loop-like magnetic field lines.



Tortosa-Andreu and Moreno-Insertis 2009

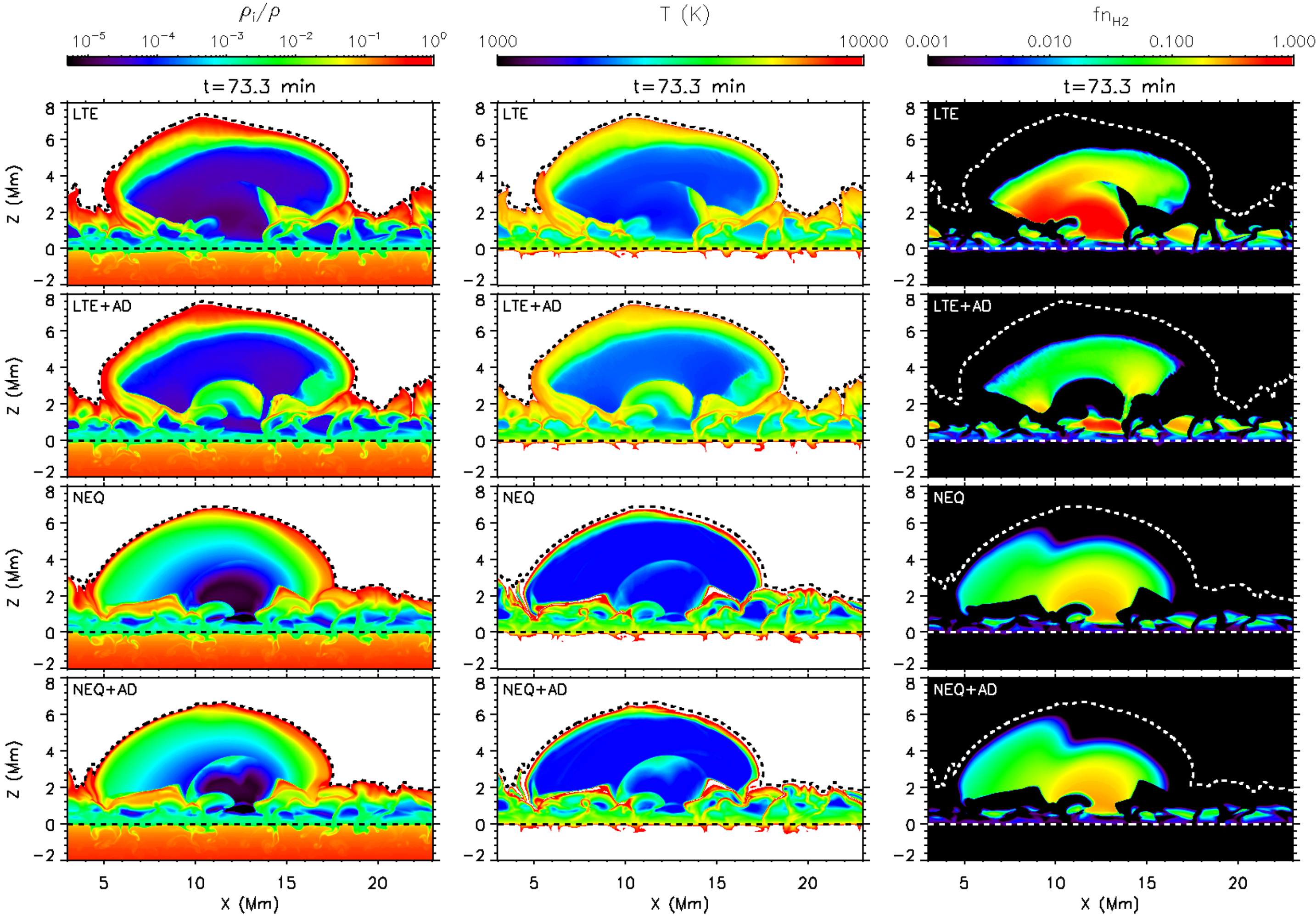
MHD modeling

Rosseland Centre for Solar Physics

Expansion into the atmosphere:

- The thermodynamics of the emerged dome are one of the main open questions.
- Studying the physical properties is difficult both from the theoretical point of view and from observations.

Nóbrega-Siverio et al. 2020

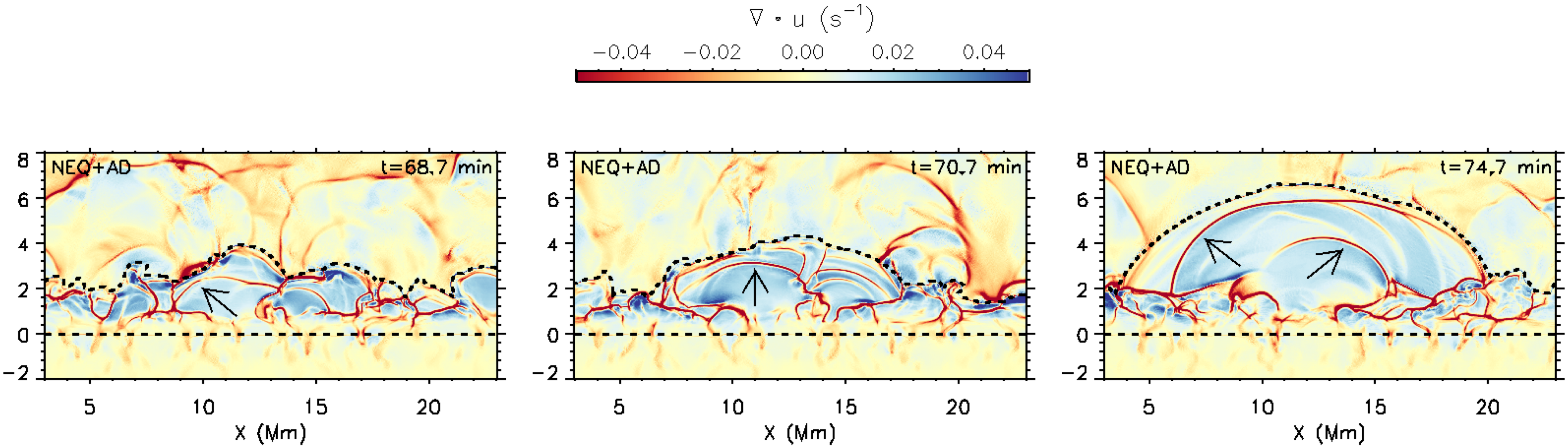


MHD modeling

Rosseland
Centre
for Solar
Physics

Expansion into the atmosphere:

- Important departures from LTE, and other physical mechanisms such as shocks, molecule formation, ambipolar diffusion… may play an important role.

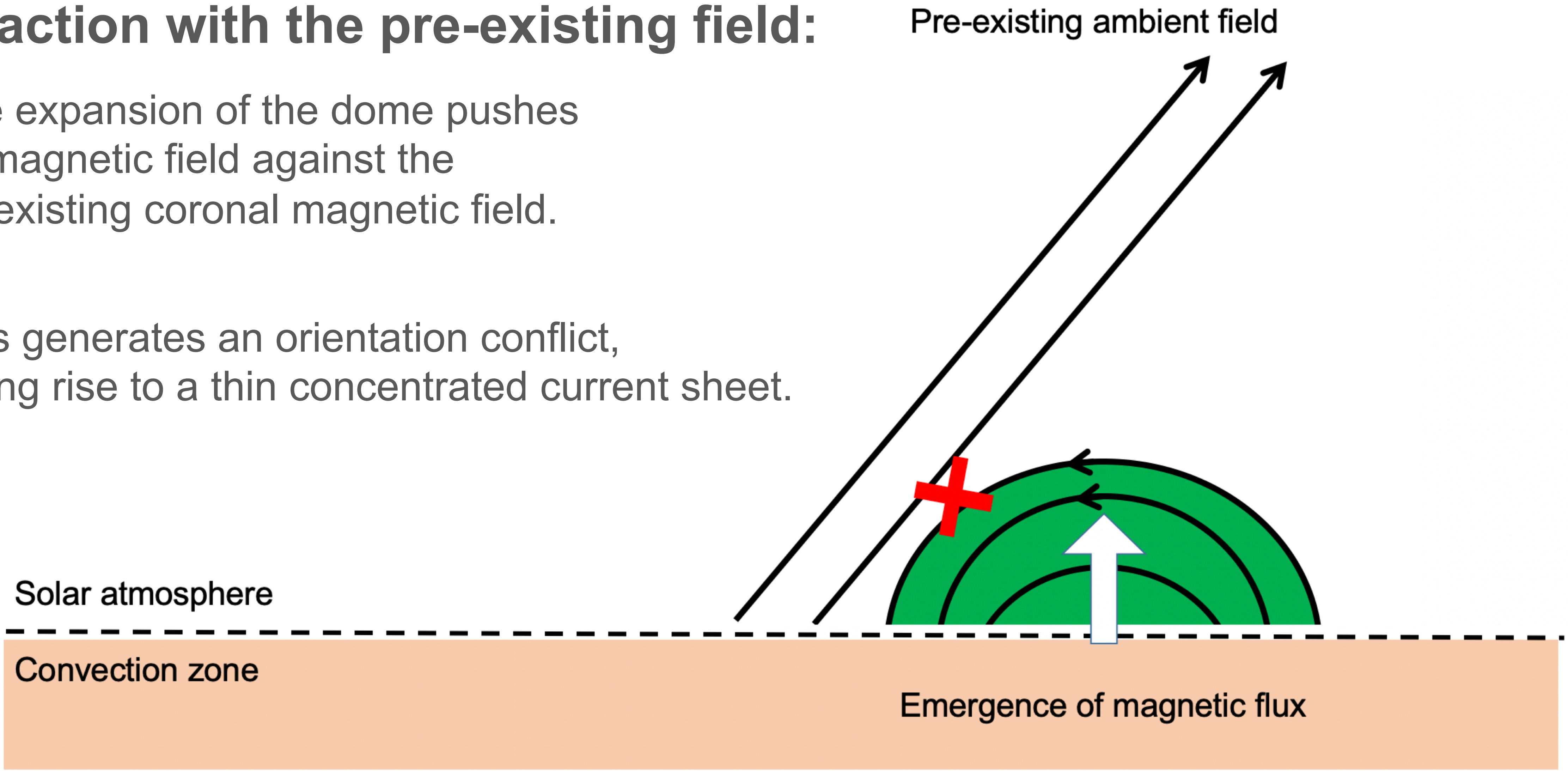


Nóbrega-Siverio et al. 2020

MHD modeling

Interaction with the pre-existing field:

- The expansion of the dome pushes its magnetic field against the preexisting coronal magnetic field.
- This generates an orientation conflict, giving rise to a thin concentrated current sheet.



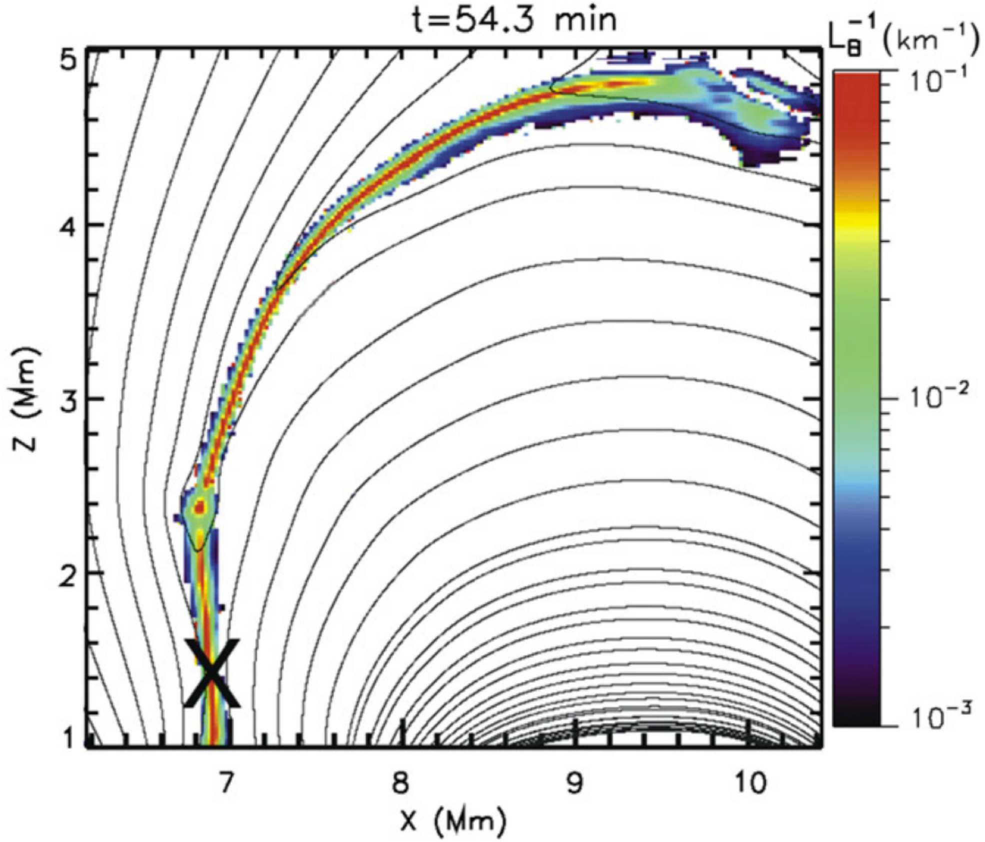
MHD modeling

Rosseland
Centre
for Solar
Physics

Interaction with the pre-existing field:

- The expansion of the dome pushes its magnetic field against the preexisting coronal magnetic field.
- This generates an orientation conflict, giving rise to a thin concentrated current sheet.
- This is the ideal scenario for magnetic reconnection.

$$L_B^{-1} = \frac{|\nabla \times \boldsymbol{B}|}{|\boldsymbol{B}|}.$$



Nóbrega-Siverio et al. 2016

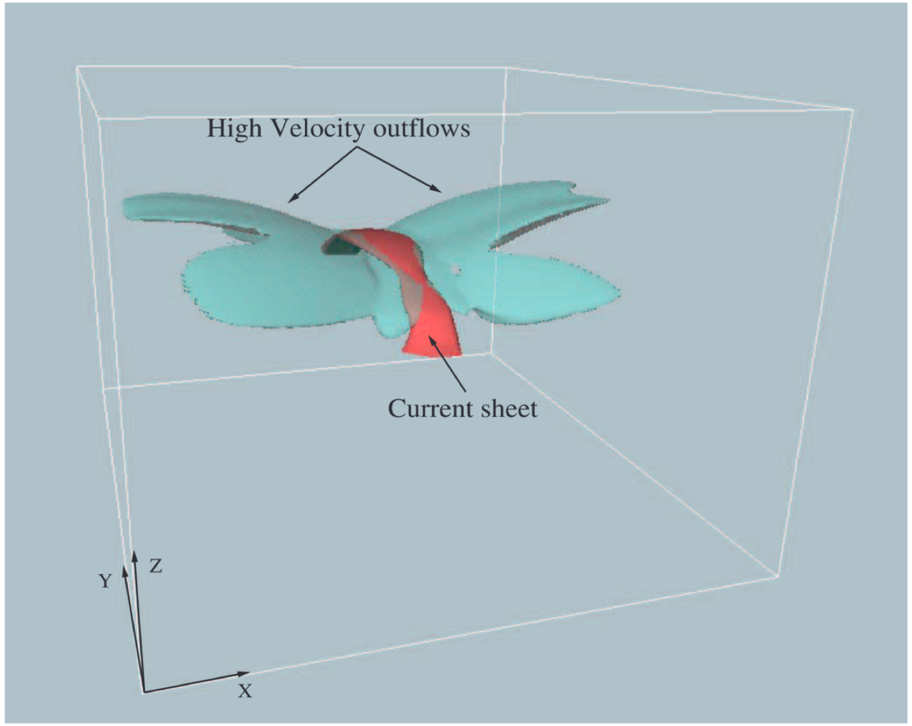
MHD modeling

Rosseland
Centre
for Solar
Physics

Interaction with the pre-existing field:

- The expansion of the dome pushes its magnetic field against the preexisting coronal magnetic field.
- This generates an orientation conflict, giving rise to a thin concentrated current sheet.
- This is the ideal scenario for magnetic reconnection.

$$L_B^{-1} = \frac{|\nabla \times \boldsymbol{B}|}{|\boldsymbol{B}|}.$$

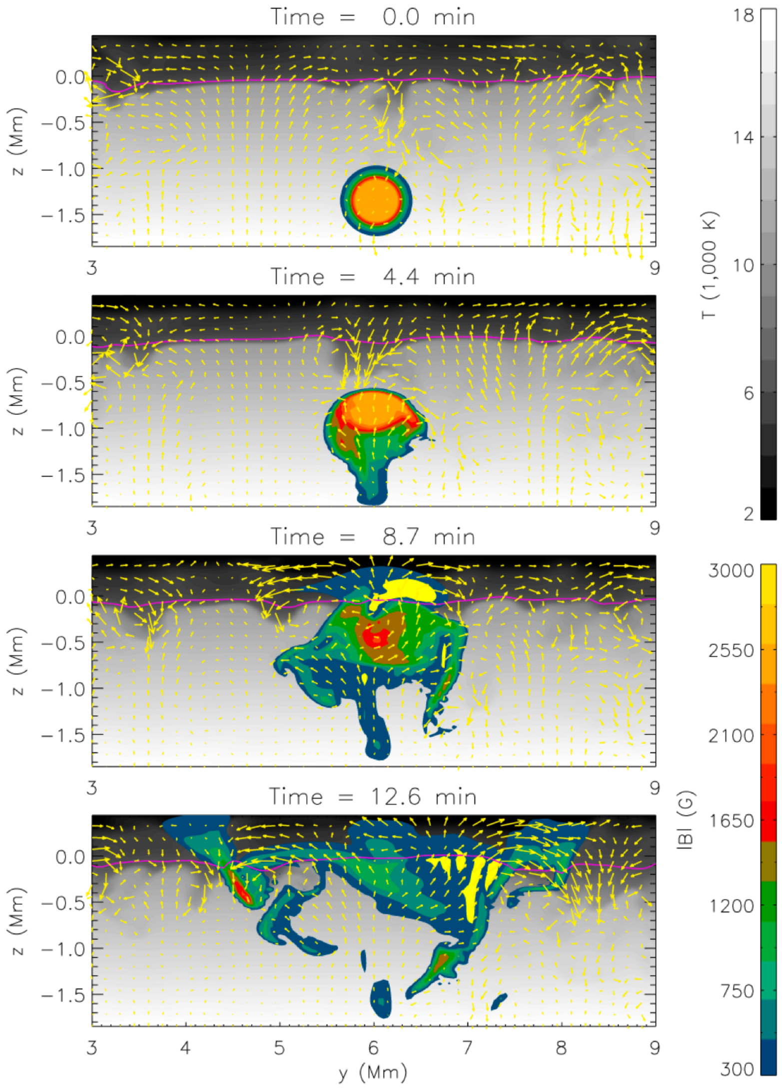


Archontis et al. 2005

Take away messages

Rise of the tube:

- Because of the stratification, the tube tends to split into counter-rotating vortex rolls and flattens into a pancake-like structure.
- Convection flows can deform and break the tube.
- Strong magnetic field values in the tube diminish the role of the convection flows.
- Higher values of the twist parameter *q* allow the tube to keep a more coherent structure.

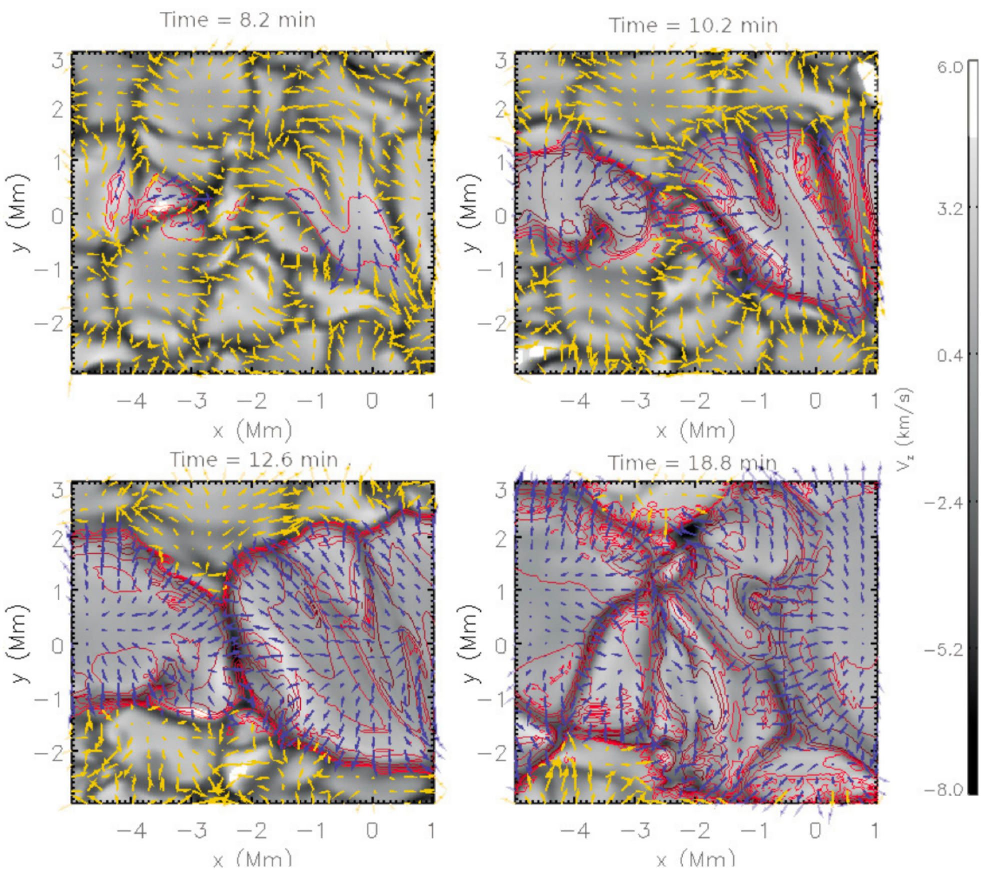


Cheung et al. 2007

Take away messages

Arrival at the surface:

- Strong subadiabaticity of the photosphere acts like a barrier for passage of flux from the solar interior to the chromosphere and beyond.
- The magnetized plasma piles up and deform the granulation pattern (anomalous granulations) due to the increasing magnetic pressure.
- When the vertical magnetic field gradient is large enough, buoyancy instability occurs, allowing the magnetized plasma to rise up into the atmosphere.



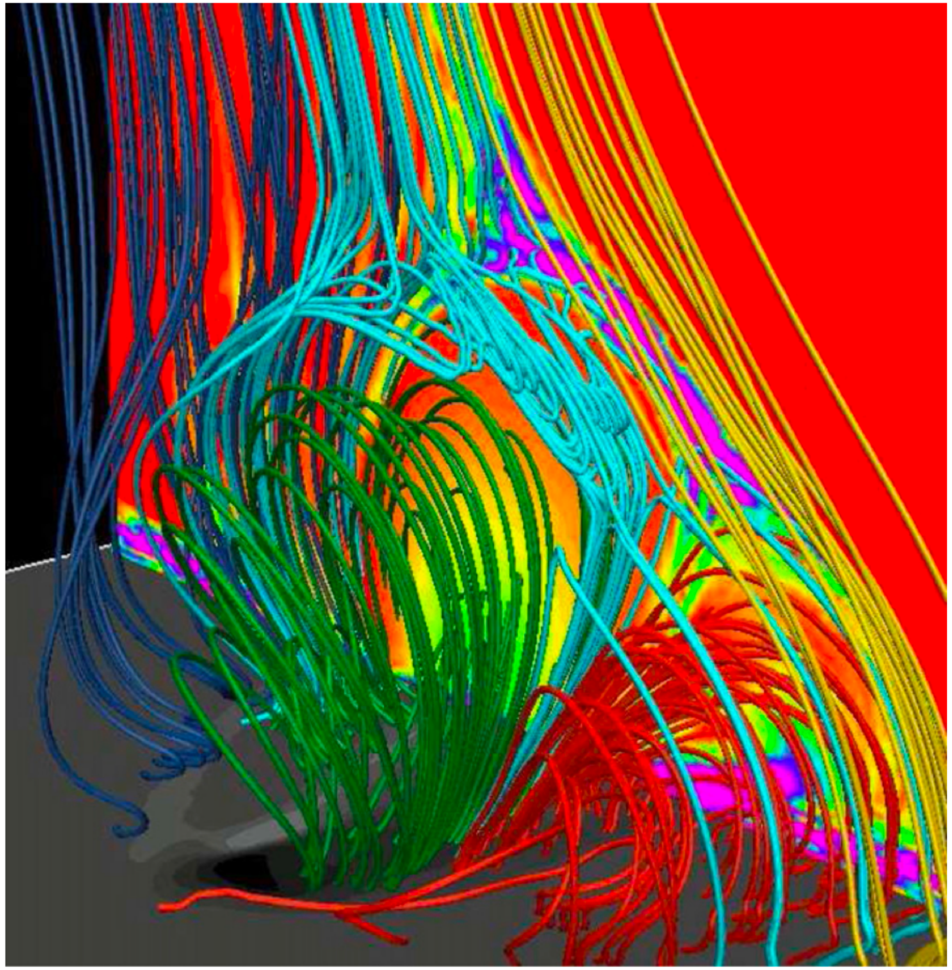
Tortosa-Andreu & Moreno-Insertis 2009

Take away messages

Rosseland
Centre
for Solar
Physics

Expansion into the atmosphere:

- Rapid expansion locally decreases temperature and density, and it leads to the formation of dome-like structures.
- The dome also suffers a rarefaction process due to gravitational downflows
- Because of the expansion,
  the emerging magnetic field is pushed against the pre-existing coronal ambient field and magnetic reconnection can be triggered.



Moreno-Insertis & Galsgaard 2013