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Dynamics of non-twisted flux tube emergence

P. Syntelis[1,2], V. Archontis[3], C. Gontikakis[2], K. Tsinganos[1]

[1]University of Athens, [2]Academy of Athens, [3]St. Andrews University

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Overview

Introduction

- What is flux emergence
- Twist in simulations
- The effect of twist: Highly twisted vs Weakly Twisted

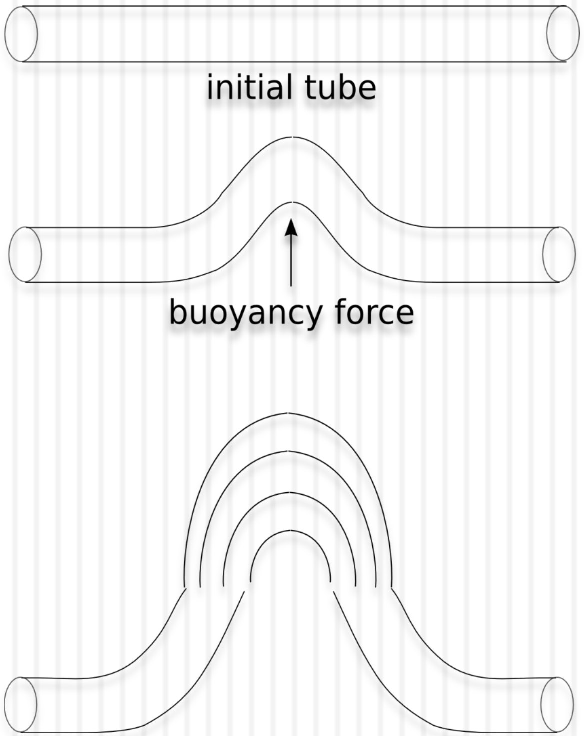
Results on non-twisted flux tube

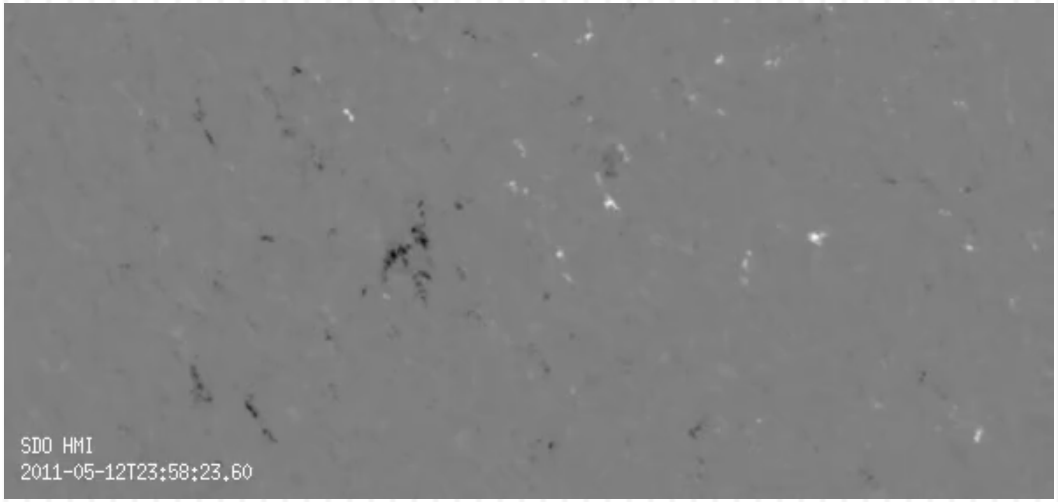
- Initial Conditions
- Below the photosphere
- Emergence into the atmosphere
- Resulting dynamics

Flux Emergence – Observations and Physics

Flux emergence is the process where magnetic fields emerge from the solar interior into the solar atmosphere and create dynamical phenomena.

1. Total pressure continuous $P_i + \frac{B_i^2}{8\pi} = P_e$
2. Thermal equilibrium $T_i = T_e$
3. To rise, $P_i < P_g \rightarrow \rho_i < \rho_e$
4. Buoyancy Instability(Parker 1955)





Introduction - Twist

Assuming a flux tube oriented along the y-axis:

$$B_y = B_0 e^{-\frac{r^2}{R^2}}$$

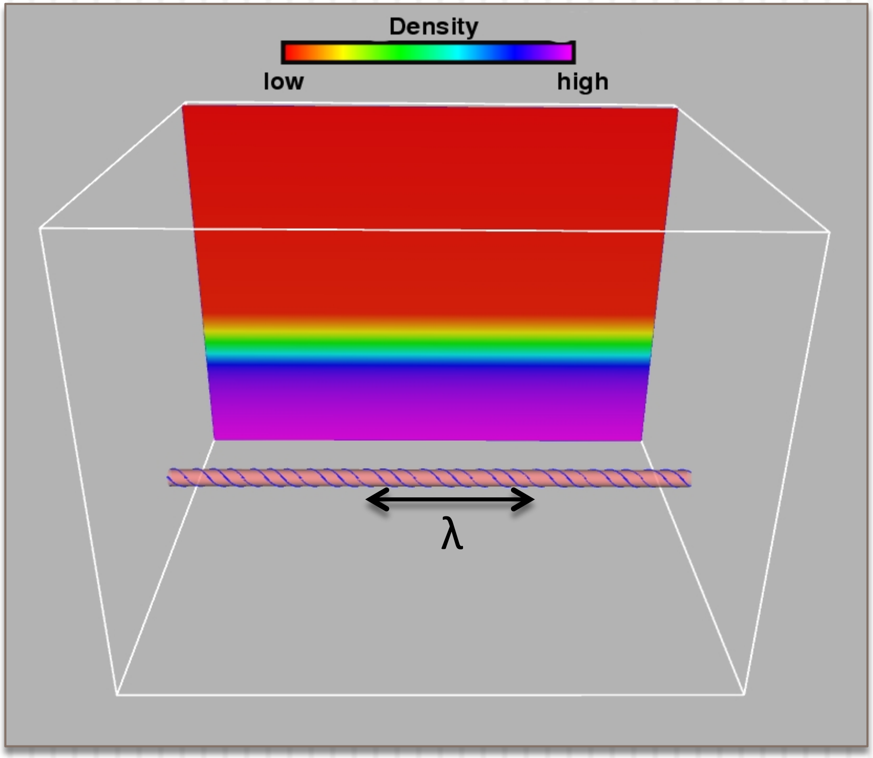
$$B_\phi = \alpha r B_y$$

$$\Delta\rho = \frac{p_t(r)}{p_{st}(z)} \rho_{st} e^{-\frac{y^2}{\lambda^2}}$$

Parameter α: twist per unit of length.

High twist: *45° B_φ, B_y (a=0.4)*
Weak twist: *15° B_φ, B_y (a=0.1)*
No twist: *a=0*

Parameter λ: buoyant part of FT



Highly Twisted Flux Tube

Highly Twisted Flux Tube – Basic Aspects

The key characteristics of the emergence of a highly twisted flux tube are:

- Formation of a bipolar region.
- Shearing motions along the Polarity Inversion Line (PIL)

Interactions and eruptive phenomena:

1. Reconnection along the PIL due to sharing *(e.g. van Ballegooijen and Martens 1989)*

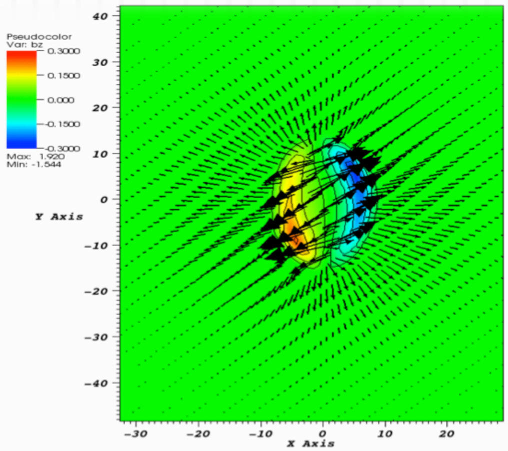


Fig: V. Archontis

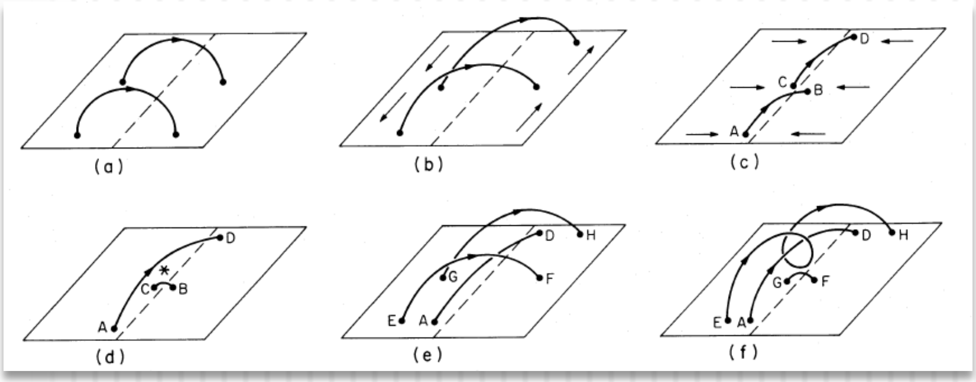


Fig: Van Ballegooijen and Martens 1989

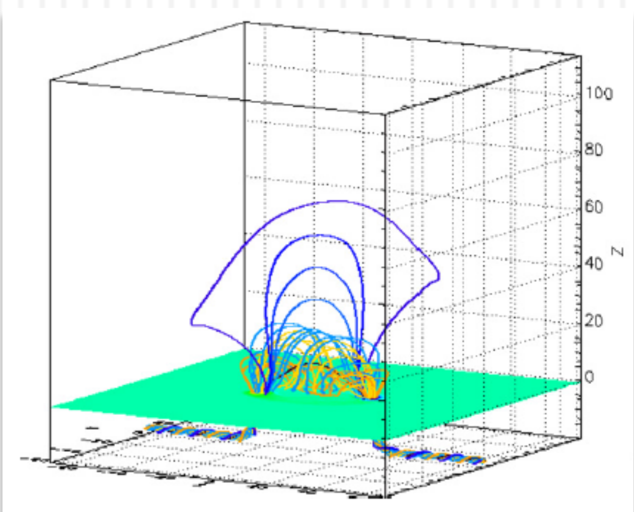
Highly Twisted Flux Tube – Basic Aspects

The key characteristics of the emergence of a highly twisted flux tube are:

- Formation of a bipolar region.
- Shearing motions along the Polarity Inversion Line (PIL)

Interactions and eruptive phenomena:

2. Formation of post-emergence flux rope (PEFR) (e.g. *Manchester et al. 2004, Archontis et al 2009)*



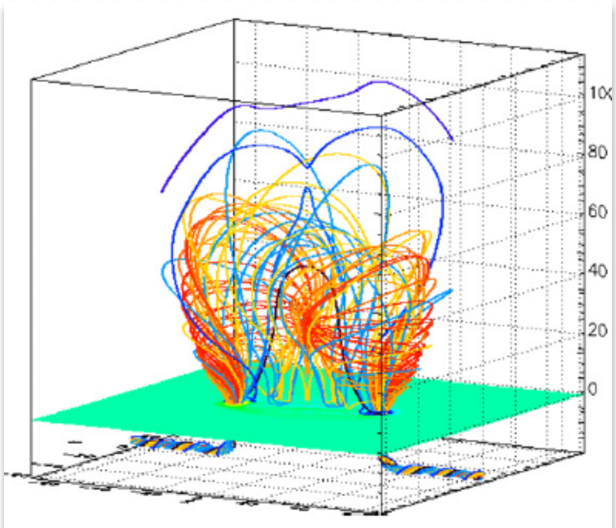


Fig: Fan 2009

Highly Twisted Flux Tube – Basic Aspects

The key characteristics of the emergence of a highly twisted flux tube are:

- Formation of a bipolar region.
- Shearing motions along the Polarity Inversion Line (PIL)

Interactions and eruptive phenomena:

3. Eruption of the PEFR depending on initial field magnitude, external field etc. *(e.g. Torok & Kliem 2005, Archontis and Hood 2012)*

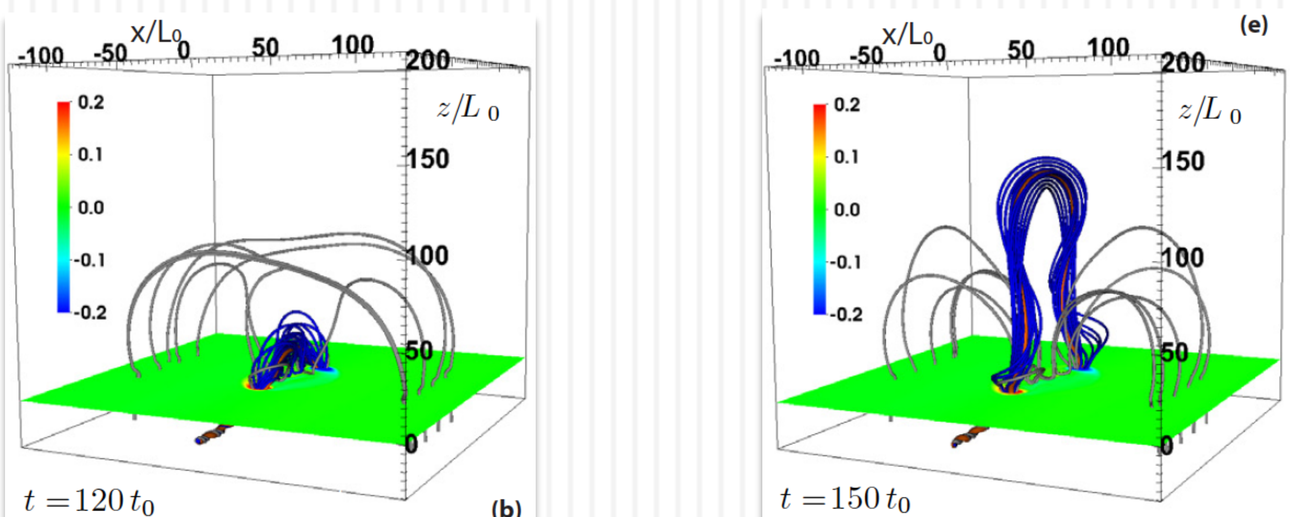


Fig: Leake et al 2014

Highly Twisted Flux Tube – Basic Aspects

The key characteristics of the emergence of a highly twisted flux tube are:

- Formation of a bipolar region.
- Shearing motions along the Polarity Inversion Line (PIL)

Interactions and eruptive phenomena:

3. Formation of CME-like eruption *(Archontis et al 2014, Syntelis et al in preparation, Poster 6.36)*

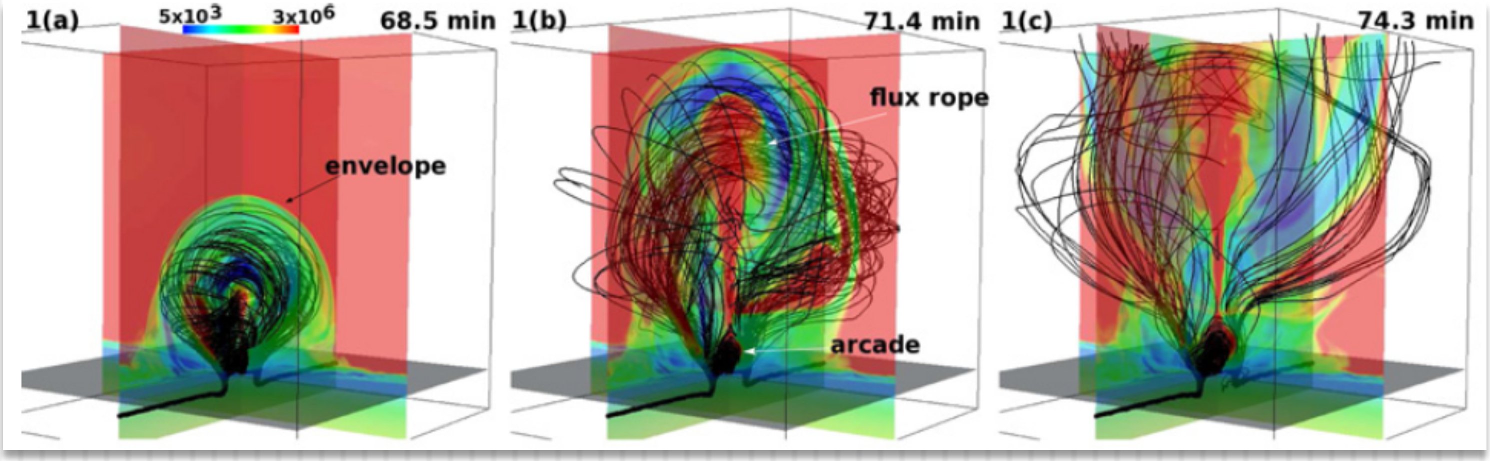


Fig: Archontis et al 2014

Highly Twisted Flux Tube – Basic Aspects

The key characteristics of the emergence of a highly twisted flux tube are:

- Formation of a bipolar region.
- Shearing motions along the Polarity Inversion Line (PIL)

Interactions and eruptive phenomena:

4. Formation of jets and other eruptive phenomena *(e.g. Yokohama and Shibata 1996, Archontis et al 2010, Gontikakis et al 2009)*

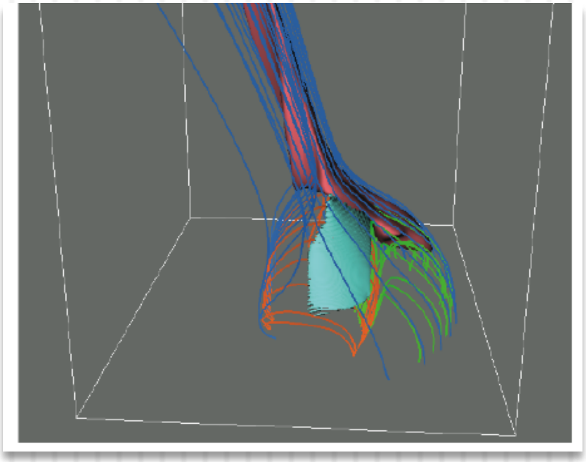


Fig: Moreno-Insertis et al 2008

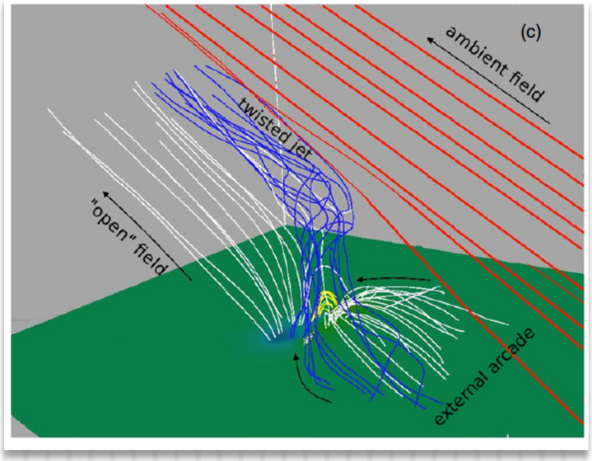


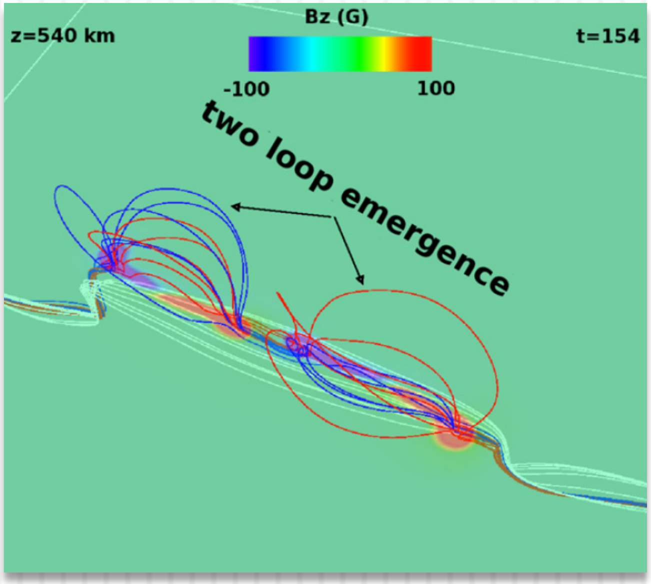
Fig: Archontis et al 2014

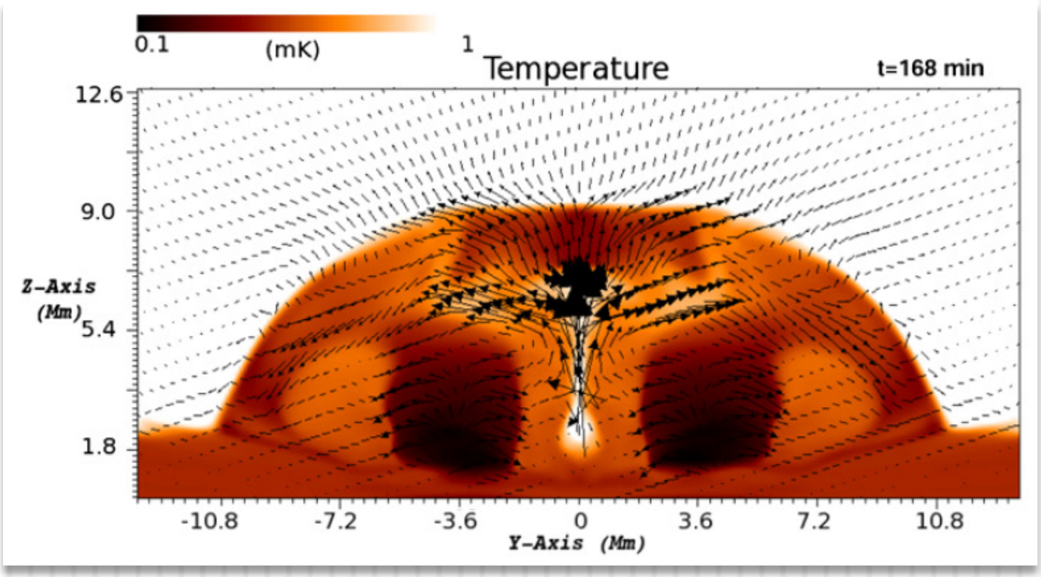
Weakly Twisted Flux Tube

Weakly Twisted Flux Tube – Basic Aspects

Weakly twisted flux tubes are less studied. Main Characteristics:

1. Formation of two bipolar regions *(e.g. Murray et al 2006, Archontis et al 2013)*
2. Interacting magnetic lobes form jets and FRs. Building up high twist (*e.g. Archontis et al 2013*)





Figures from Archontis, Hood, Tsinganos 2013

Low/Non Twisted Flux Tube

Low/Non Twisted Flux Tubes

We know that:

- Lower twisted (α=0.1 and below $<14_o$ B_φ, B_y) with λ=20 flux tubes fail to emerge. They just expand below the photosphere (e.g. Murray et al 2006, Toriumi et al 2011).
- But weakly twisted flux (0.1) tubes with λ=10 can emerge (Archontis et al 2013).

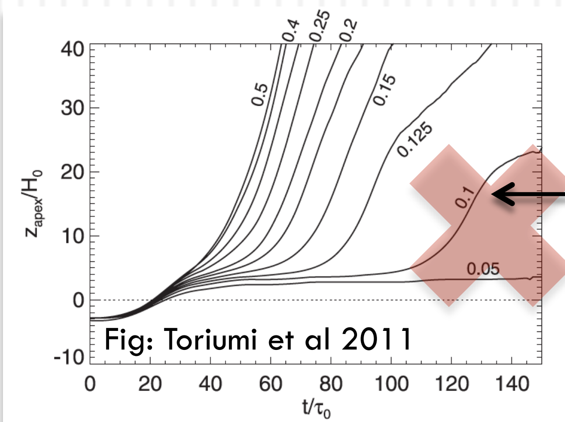


Fig: Toriumi et al 2011

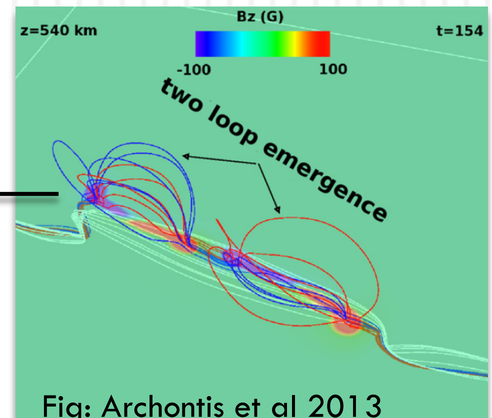


Fig: Archontis et al 2013

Questions:

- Is λ critical for the emergence of low twist flux tubes?
- Can low twist FTs emerge in some cases from the sub-photospheric layer?
- Are there any resulting dynamics?

We study the highly idealized limit case of a non-twisted flux tube

Non Twisted Flux Tube

Initial Conditions

Initial Conditions – Initial Conditions

- Flux tube oriented along the y-axis

$$B_y = B_0 e^{-\frac{r^2}{R^2}},\ R = 450km$$

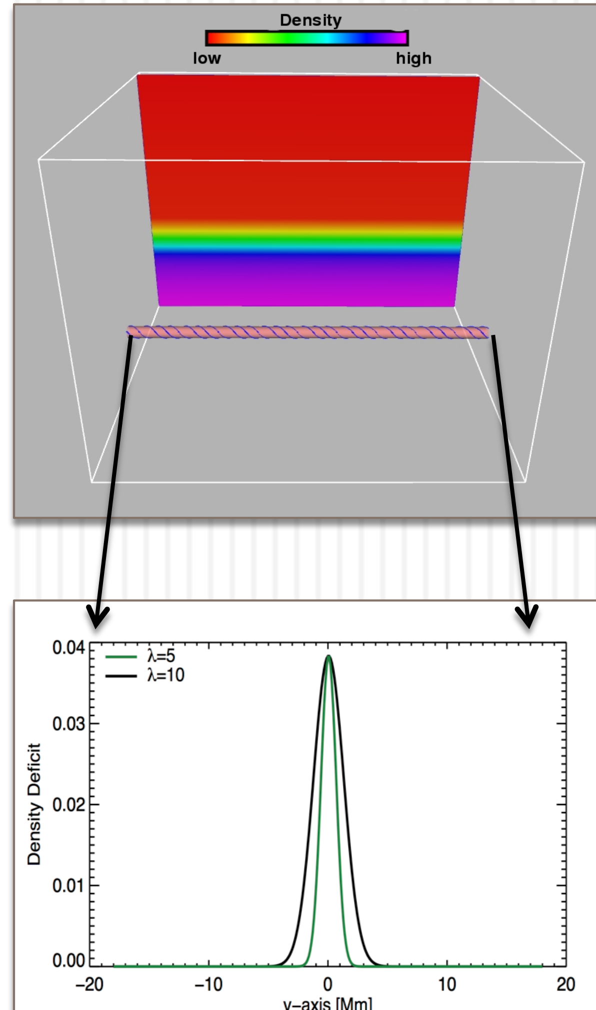
$$B_\phi = \alpha r B_y$$

$$\Delta\rho = \frac{p_t(r)}{p_{st}(z)} \rho_{st}(z) e^{-\frac{y^2}{\lambda^2}},\ \lambda = 5, 10$$

$$B_0 = 2.8kG,\ \beta = 25$$

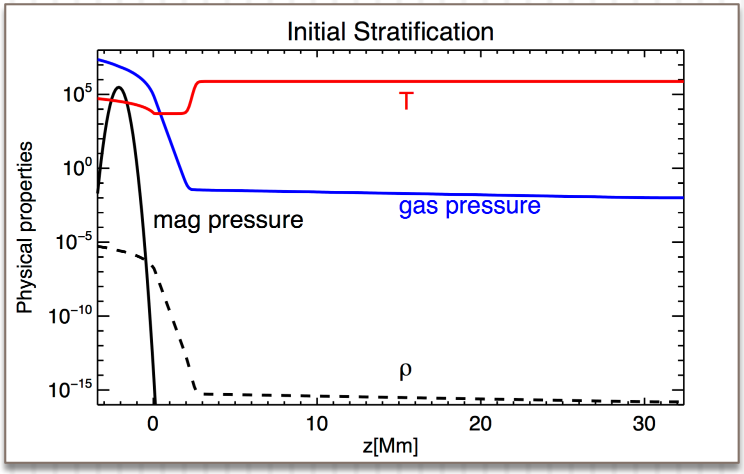
- Parameter α: twist per unit of length.
  High twist: *45º B_φ, B_y (α=0.4)*
  Weak twist: *15º B_φ, B_y (α=0.1)*
  No twist: *α=0*

- Locate at 2.1Mm below the photosphere



Initial Conditions – Initial Conditions

- Non magnetised atmosphere
- constant resistivity, no thermal conduction, no radiative transfer
- Stratified Atmosphere (like Archontis et al 2013)



LARE3D

- time dependent
- Resistive
- compressible MHD
- constant resistivity,
- joule and viscous heating

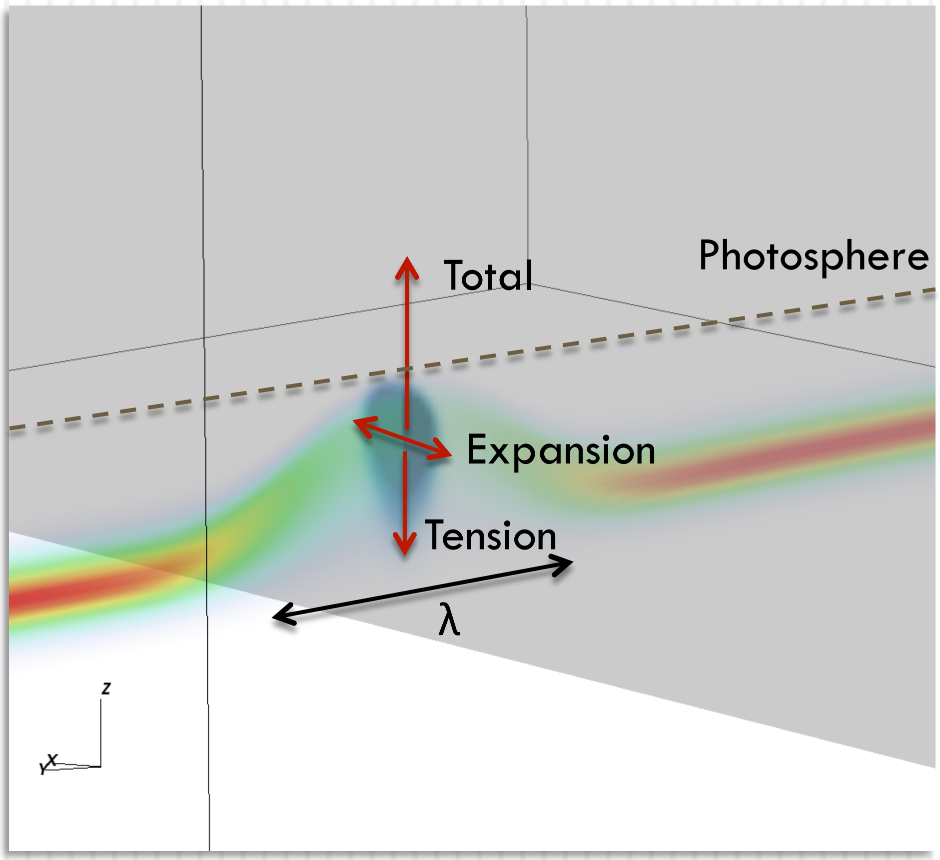
$$\begin{cases} \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0, \\ \frac{\partial (\rho \mathbf{v})}{\partial t} = -\nabla \cdot (\rho \mathbf{v}\mathbf{v}) + (\nabla \times \mathbf{B}) \times \mathbf{B} - \nabla P + \rho \mathbf{g} + \nabla \cdot \mathbf{S}, \\ \frac{\partial (\rho \epsilon)}{\partial t} = -\nabla \cdot (\rho \epsilon \mathbf{v}) - P \nabla \cdot \mathbf{v} + Q_{joule} + Q_{visc}, \\ \frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}, \\ \epsilon = \frac{P}{(\gamma - 1)\rho} \end{cases}$$

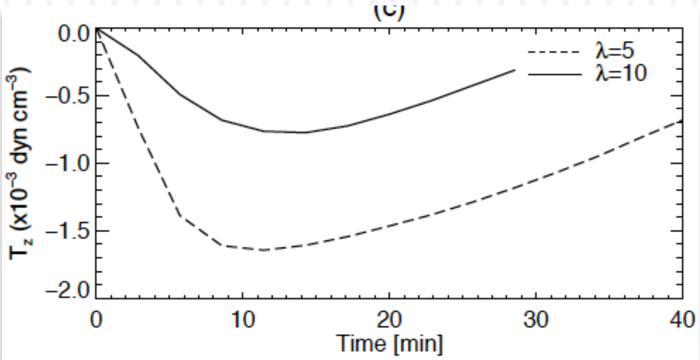
Non Twisted Flux Tube

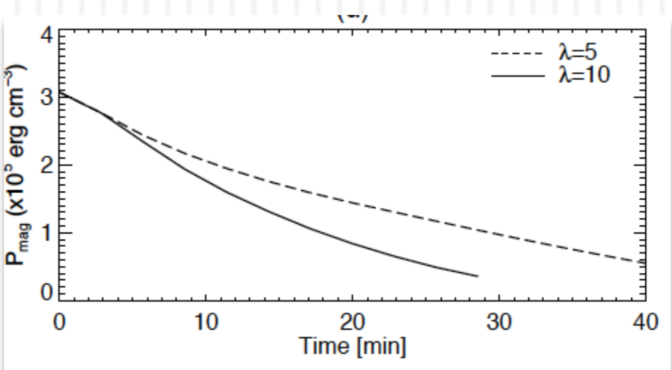
Results

Non Twisted FT – Below photosphere

1. We examine the xz-midplane where Δρ is equal for both λ.
2. Higher λ ➔ lower downwards tension ➔ higher upwards total force.
3. λ=10 reaches the photosphere faster and expands more.
4. λ=10 has less P_{mag} when it reaches the photoshpere.







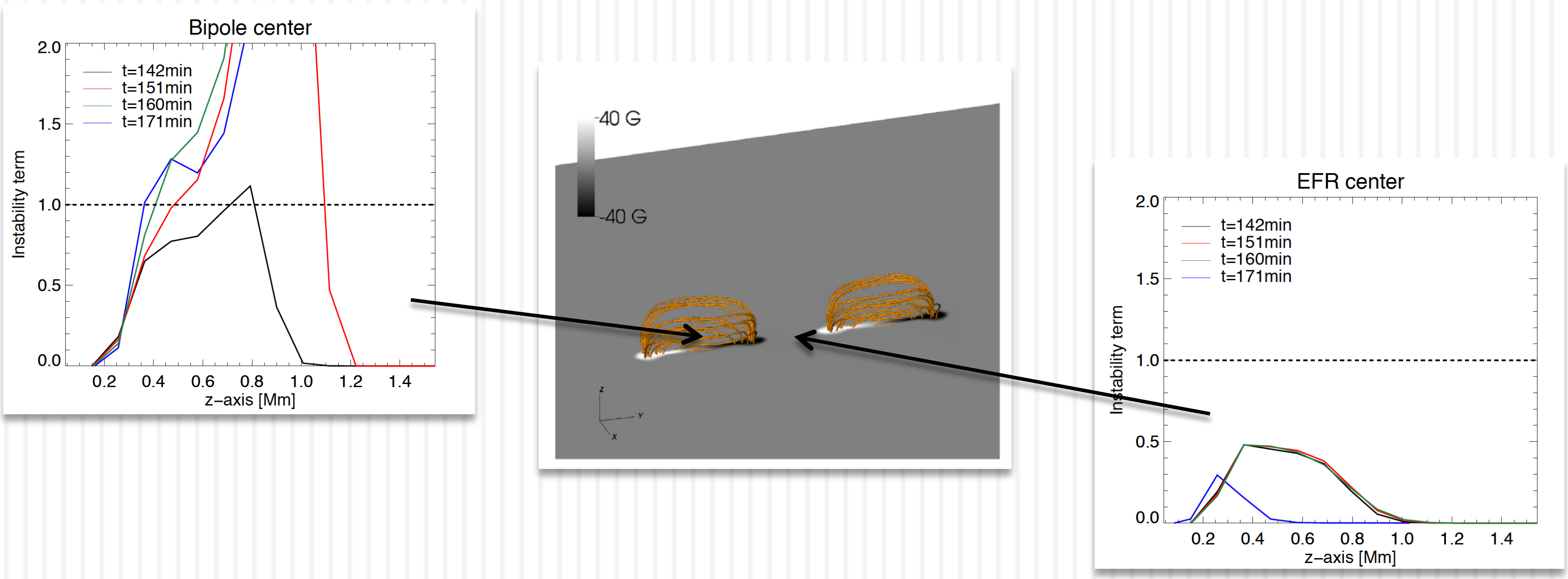
Non Twisted FT – Buoyancy Instability

Buoyancy Instability Critical Condition (Acheson, 1979):

$$-H_{\mathrm{p}}\frac{\partial}{\partial z}(\log B)/\left[-\frac{\gamma}{2}\beta\delta+k_{\parallel}^{2}\left(1+\frac{k_z^2}{k_{\perp}^2}\right)\right]>1$$

1. Smaller λ ➔ higher B and lower β
2. Satisfies the buoyancy Instability faster
3. λ=5 emerges into the atmosphere before λ=10

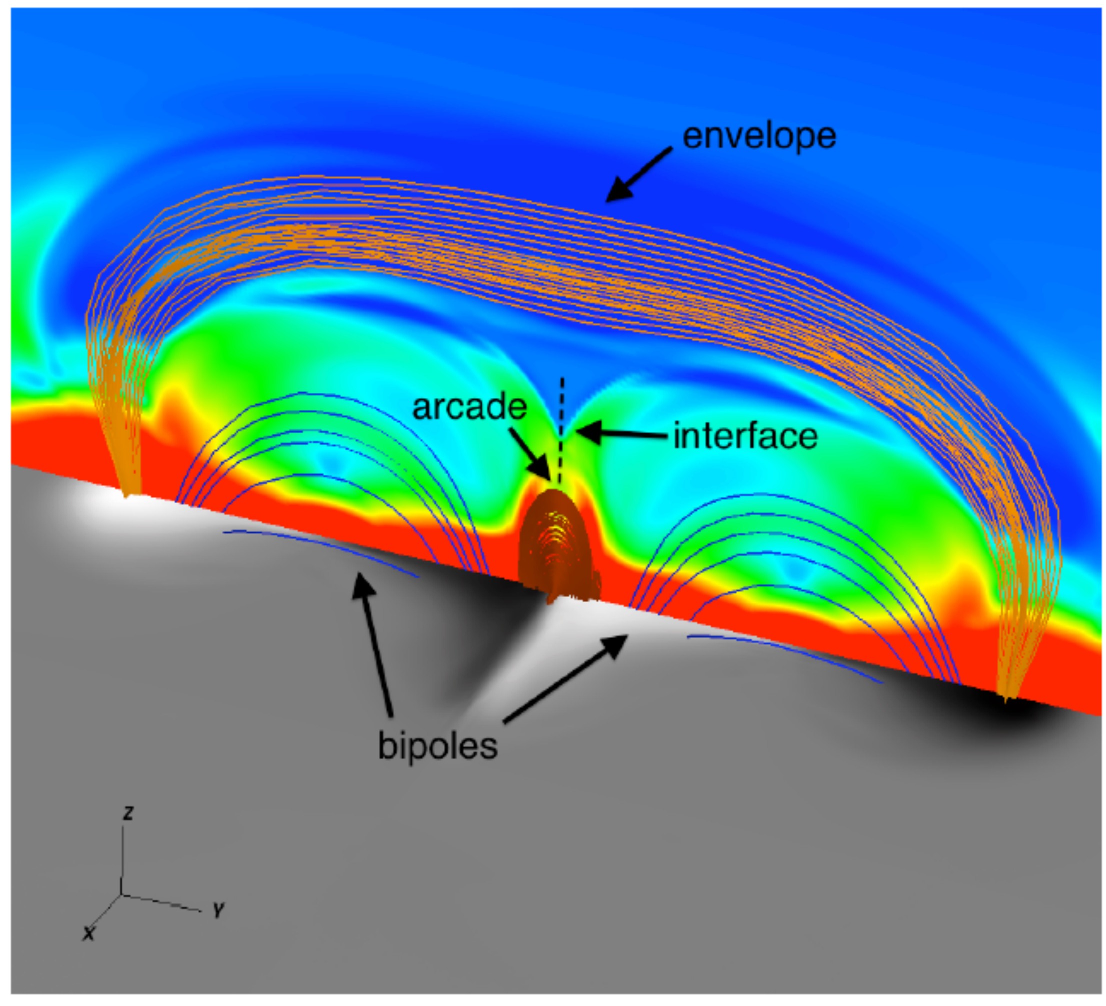
Emergence in a two-loop configuration



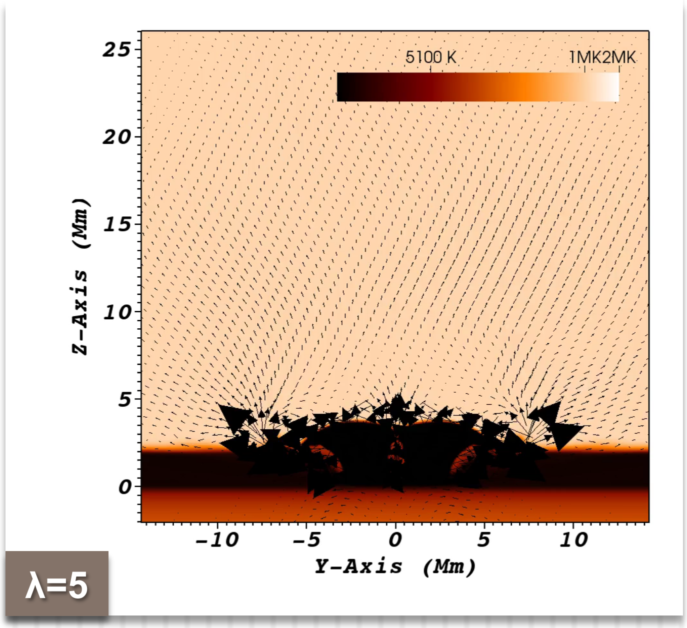
Non Twisted FT – Field Topology

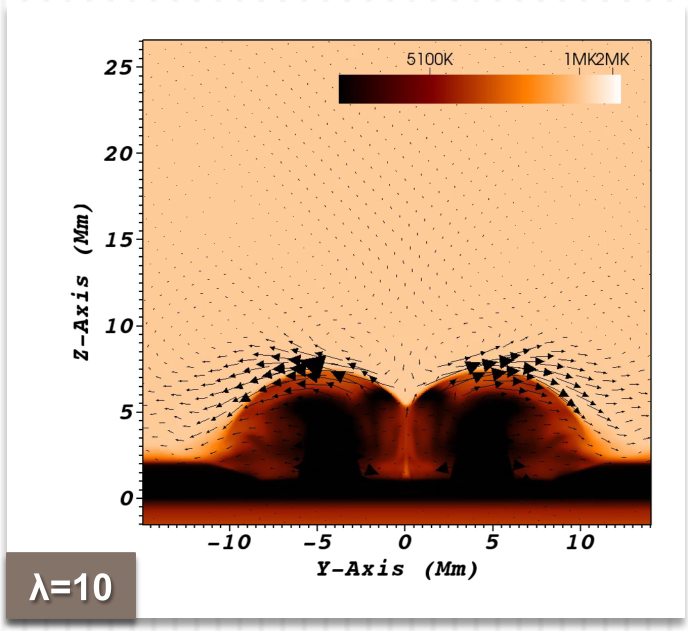
Topology of field:

- Two linearly aligned bipoles
- Two expanding magnetic lobes
- Reconnection occurs at the interface of the lobes
- Forms an envelope field
- Forms an arcade



Non Twisted FT – Lobe Interaction I





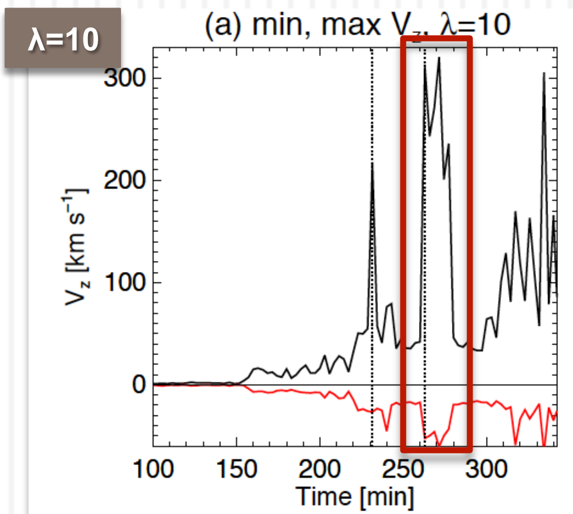
Main points:

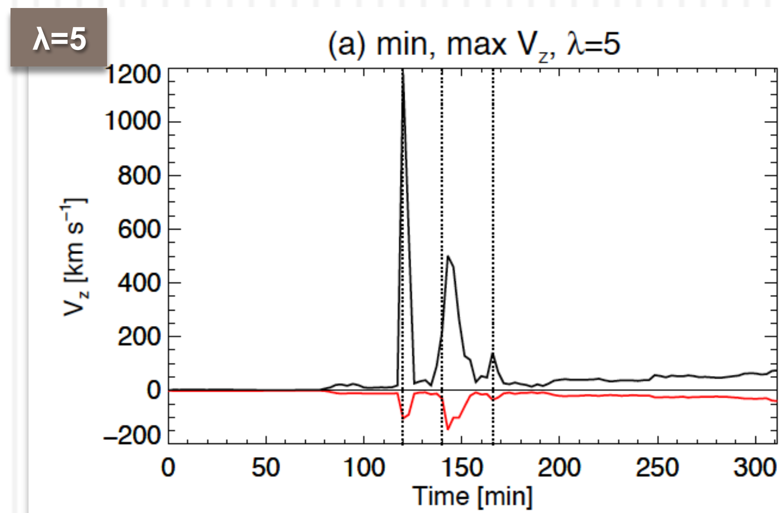
- Faster dynamics for λ=5
- Series of hot and cold jets are ejected
- Current sheet becomes subject to tearing instability forming plasmoids
- Followed by recurrent jets

Non Twisted FT – Lobe Interaction II

Jet Dynamics:

- Series of jet ejections in a recurrent manner
- Higher velocity/higher temperature jets in λ=5





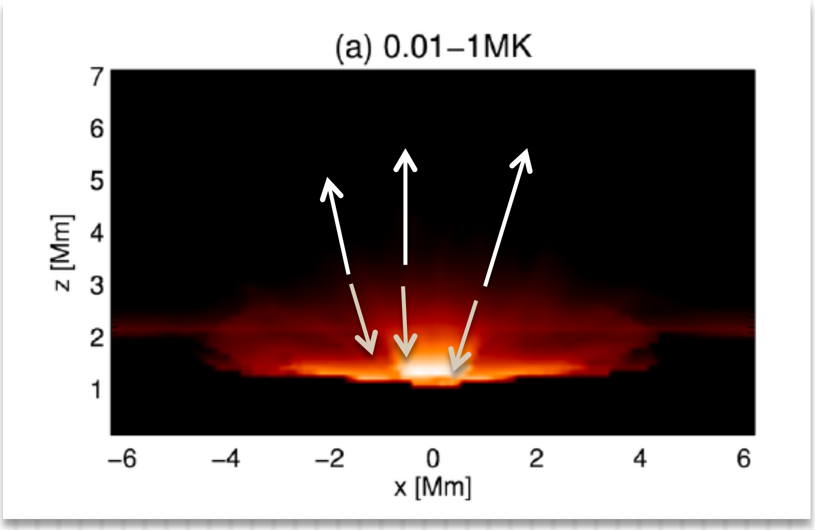
Energy and flux:

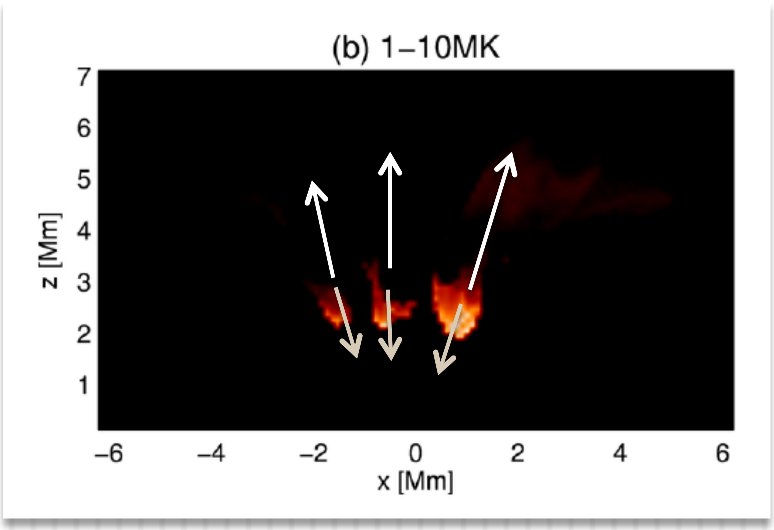
- 5 times more Poynting flux on photosphere for λ=5
- 32% of the initial axial flux is transferred to the corona for λ=5
- 18% of the initial axial flux is transferred to the corona for λ=10

Non Twisted FT – Lobe Interaction III

We calculate the emission term: $I_i = \begin{cases} \rho^2, & \text{if } T_{\min} < T < T_{\max} \\ 0, & \text{if } T < T_{\min},\ T > T_{\max} \end{cases}$

And calculate for λ=10 $I = \int I_i dy$ for 0.01-1MK and 1-10MK





- The arcade is found in the low temperatures.
- In high temperatures we find that the jets along the interface could increase T in of the low arcade in an intermittent manner.

Non Twisted FT – Summary

In the study of the non-twisted flux tubes we find:

1. Smaller buoyant part of the flux tube (λ) results to higher tension that affects whether the non-twisted flux tube can emerge above the photosphere.
2. The higher tension FT (λ=5) brings stronger B below the photosphere and leads to faster emergence above the photosphere.
3. The emergence produces a quadrapolar region (similar to the weakly twisted cases).
4. The interaction of the magnetic lobes results into dynamic phenomena (jet ejections) and forms post-emergence twisted structures (plasmoids)
5. More flux/energy is injected into the atmosphere in the lower λ
6. The dynamics of nearby jets along the current sheet deposits heat on the arcade in an intermittent manner.

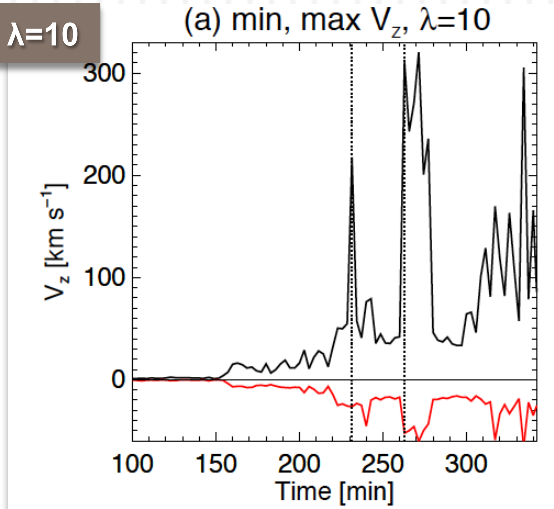
Submitted in A&A

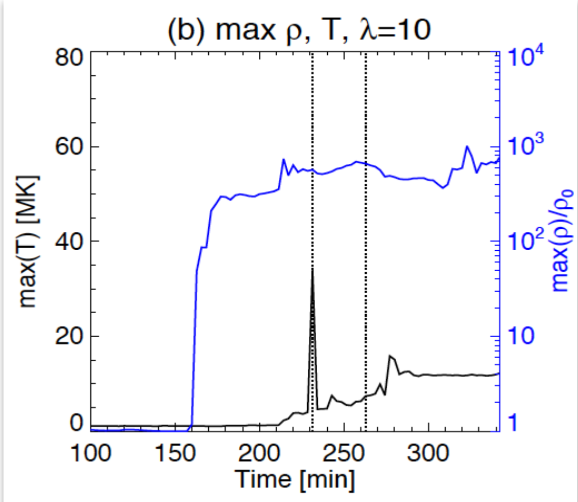
Syntelis, P; Archontis, V.; Gontikakis, C.; Tsinganos, K. 2014

Thank you!

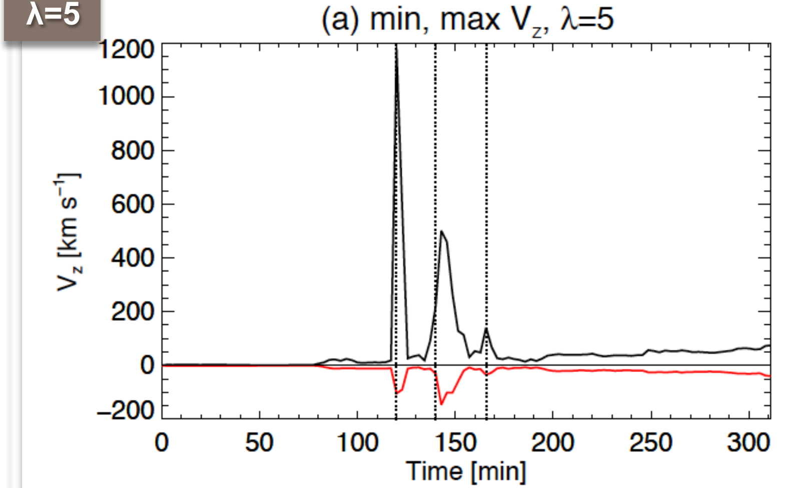
Non Twisted FT – Lobe Interaction II

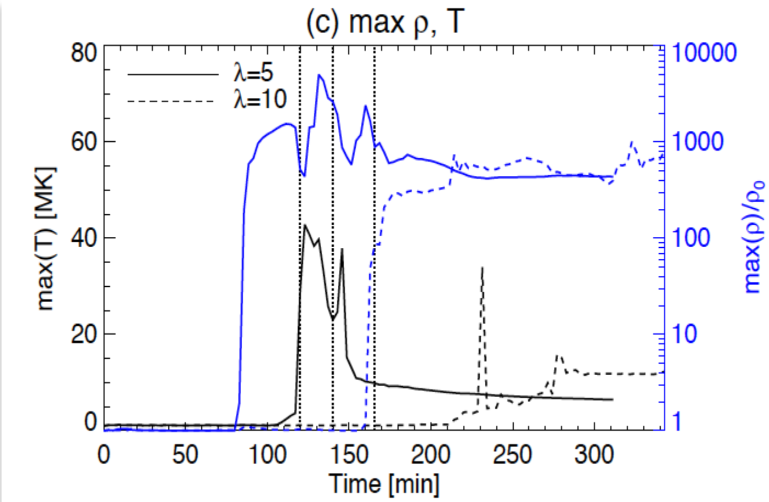
λ=10





λ=5



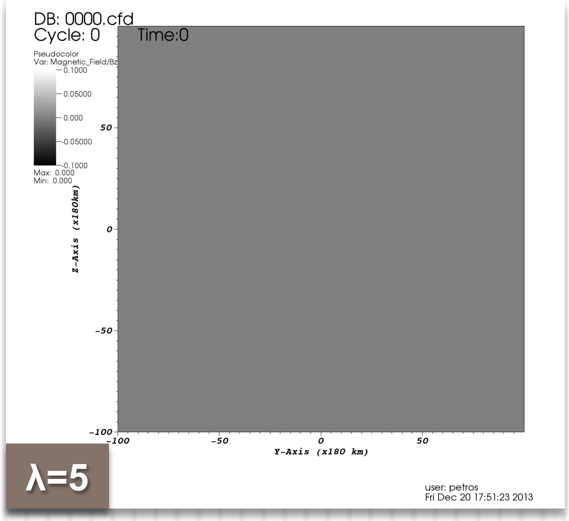


Non Twisted FT – Emergence

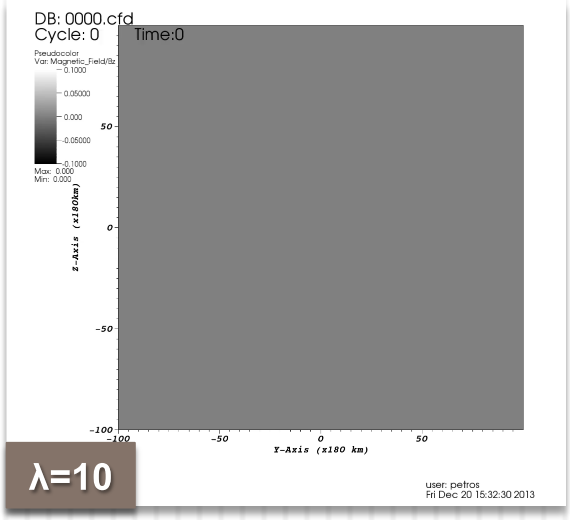
In both cases:
- Lobe formation
- Collision of bipoles
- Absence of complex magnetic tails
- No rotation

In λ=5 case emergence shows:
- More rapid evolution
- Smaller Region
- Higher photospheric vecolity field
- Diffusion of finger

	λ=5	λ=10
First emergence (min)	80	166
Horizontal distance (Mm)	3	8.6

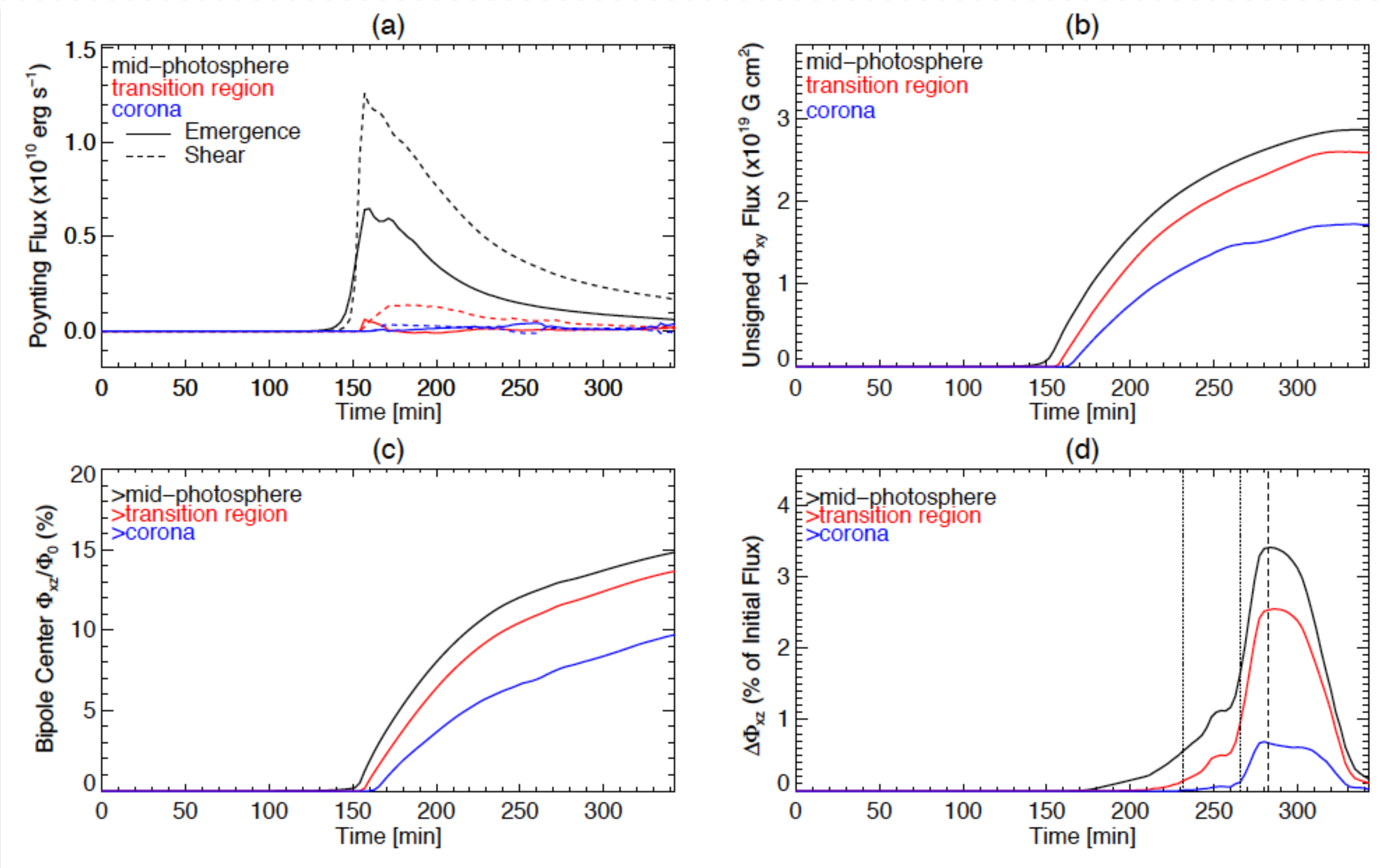


λ=5



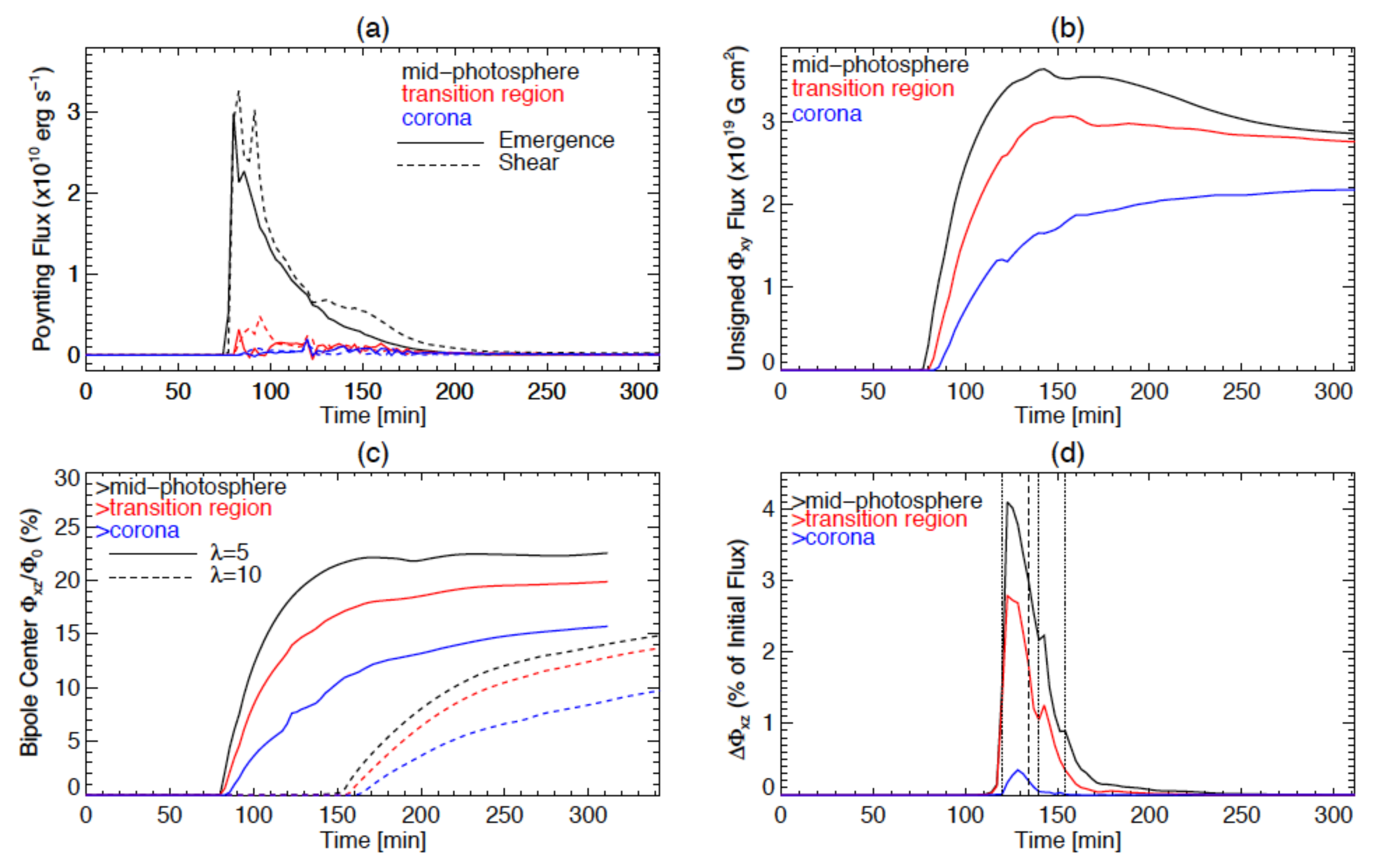
λ=10

Non Twisted FT – Energy λ=10



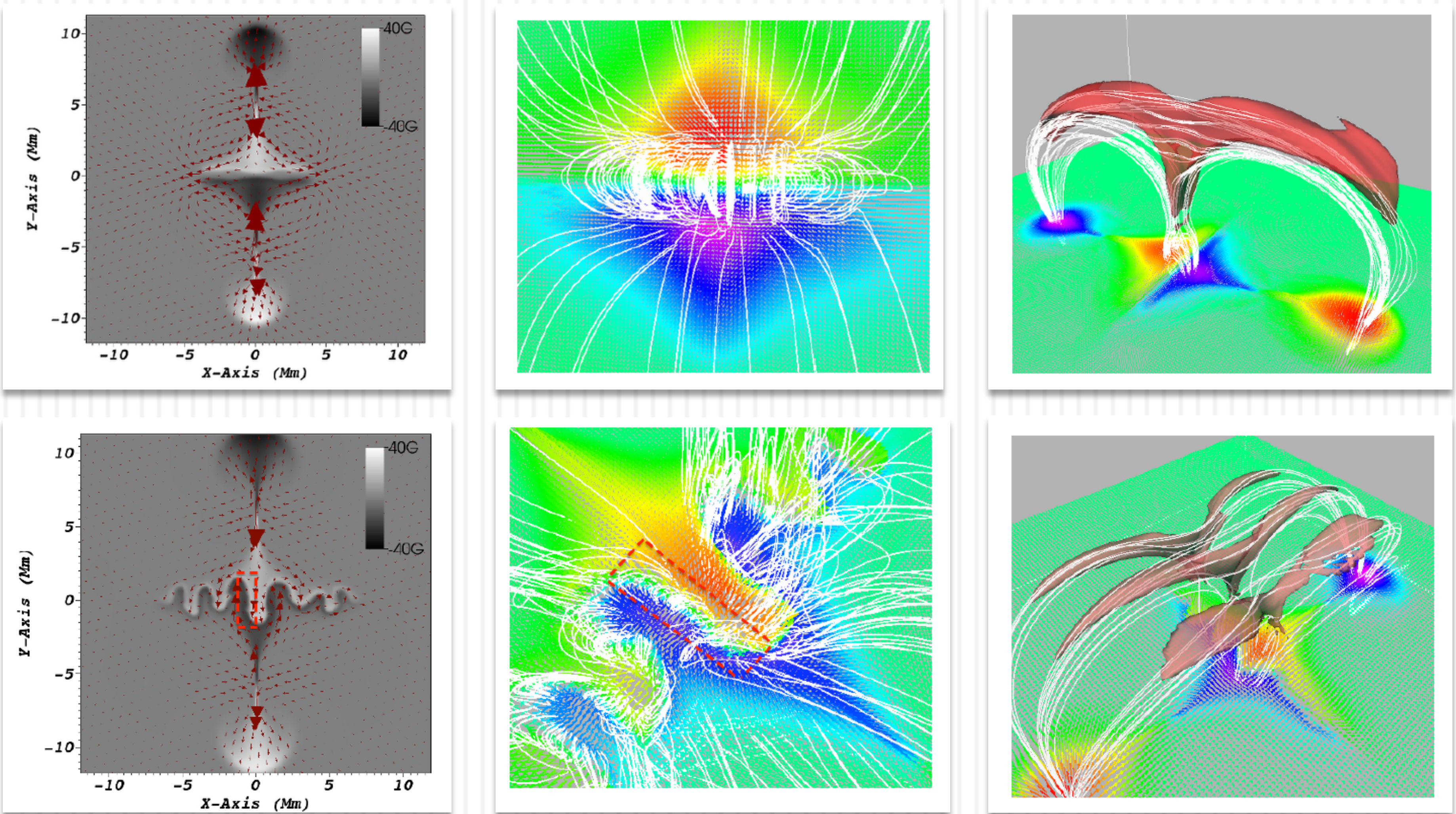
Non Twisted FT – Energy λ=5

In the larger tension case more flux/energy is injected into the corona

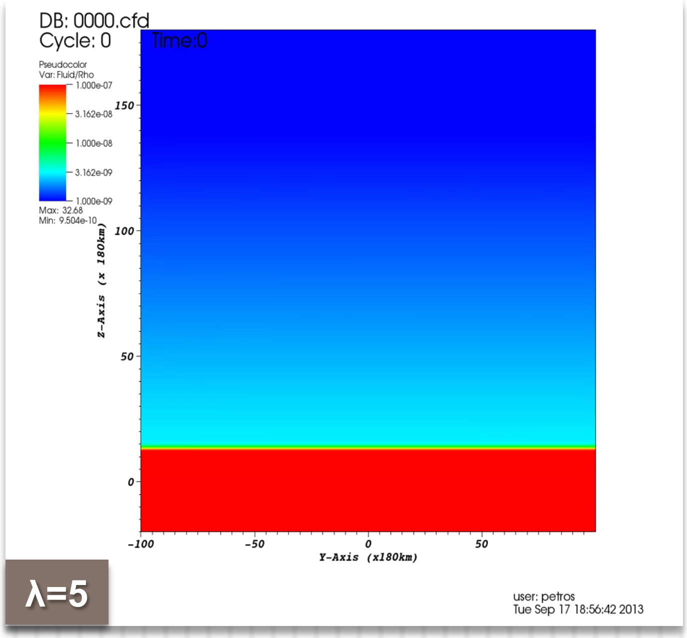


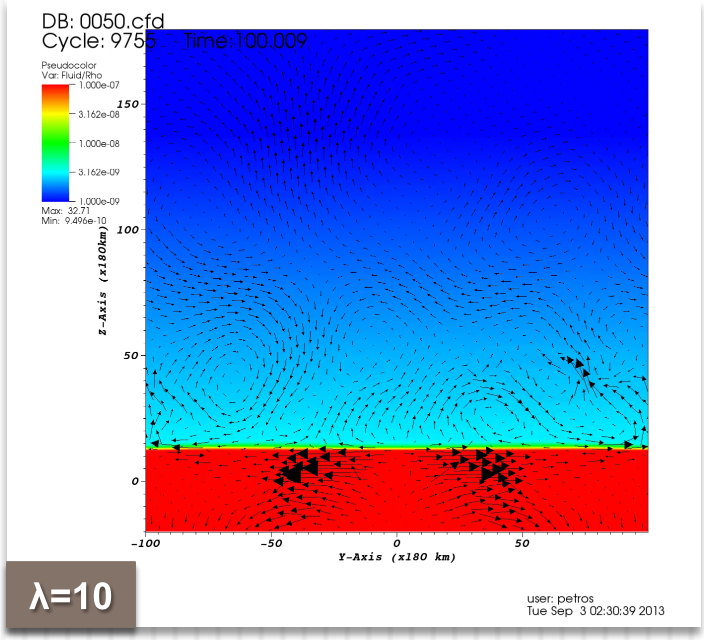
Non Twisted FT – Undulation

In both cases we find undulation of the PIL due to pressure differences after the plasmoid ejections.



Non Twisted FT – Lobe Interaction





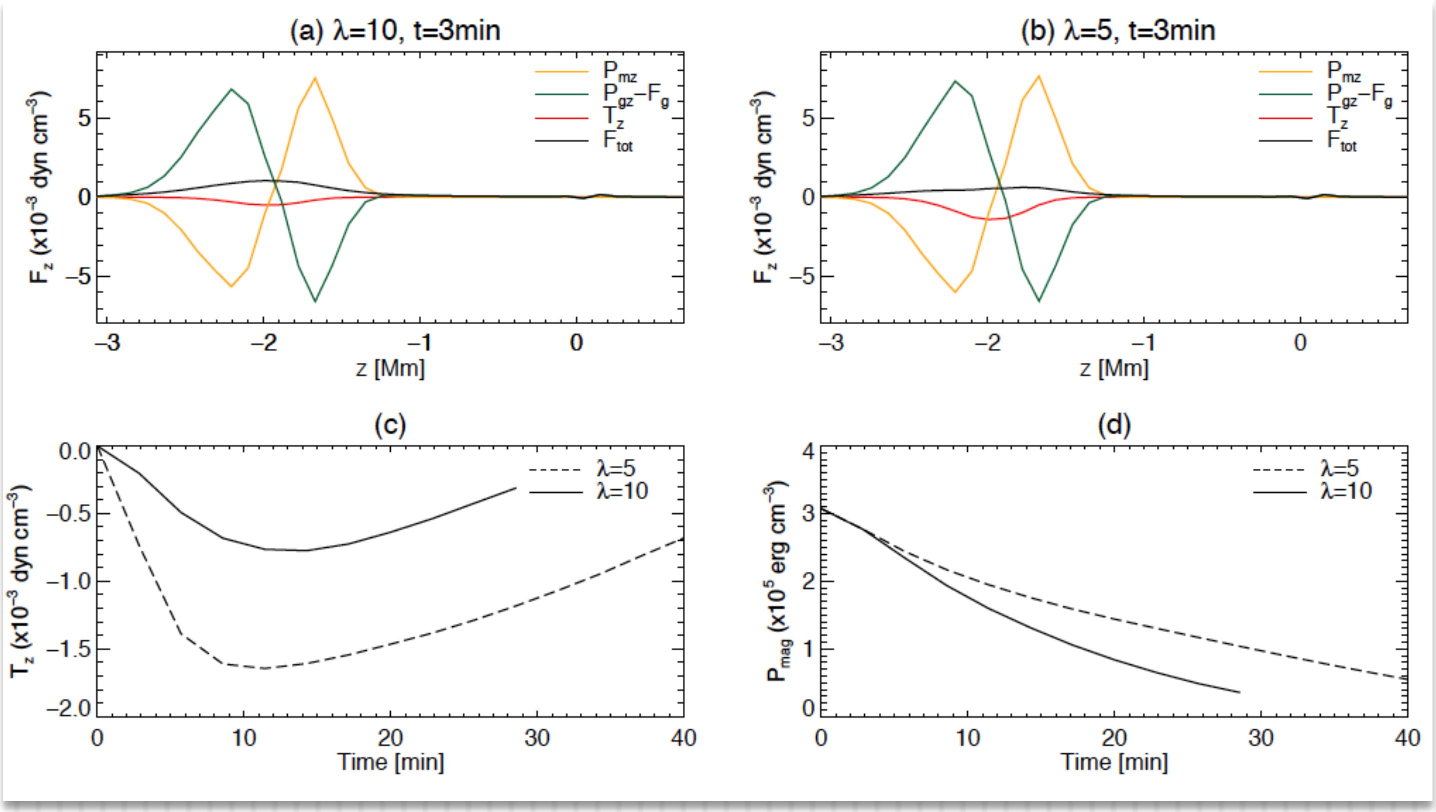
In the λ=5 case:

- ~5 higher reconnection rate $|\eta J|$
- Higher jets **v**, T
- 2-3 more cool plasma transferred
- Plasmoid formation

	λ=5	λ=10
T (MK)	7MK	5.2MK
V (kms^{-1})	1179	220

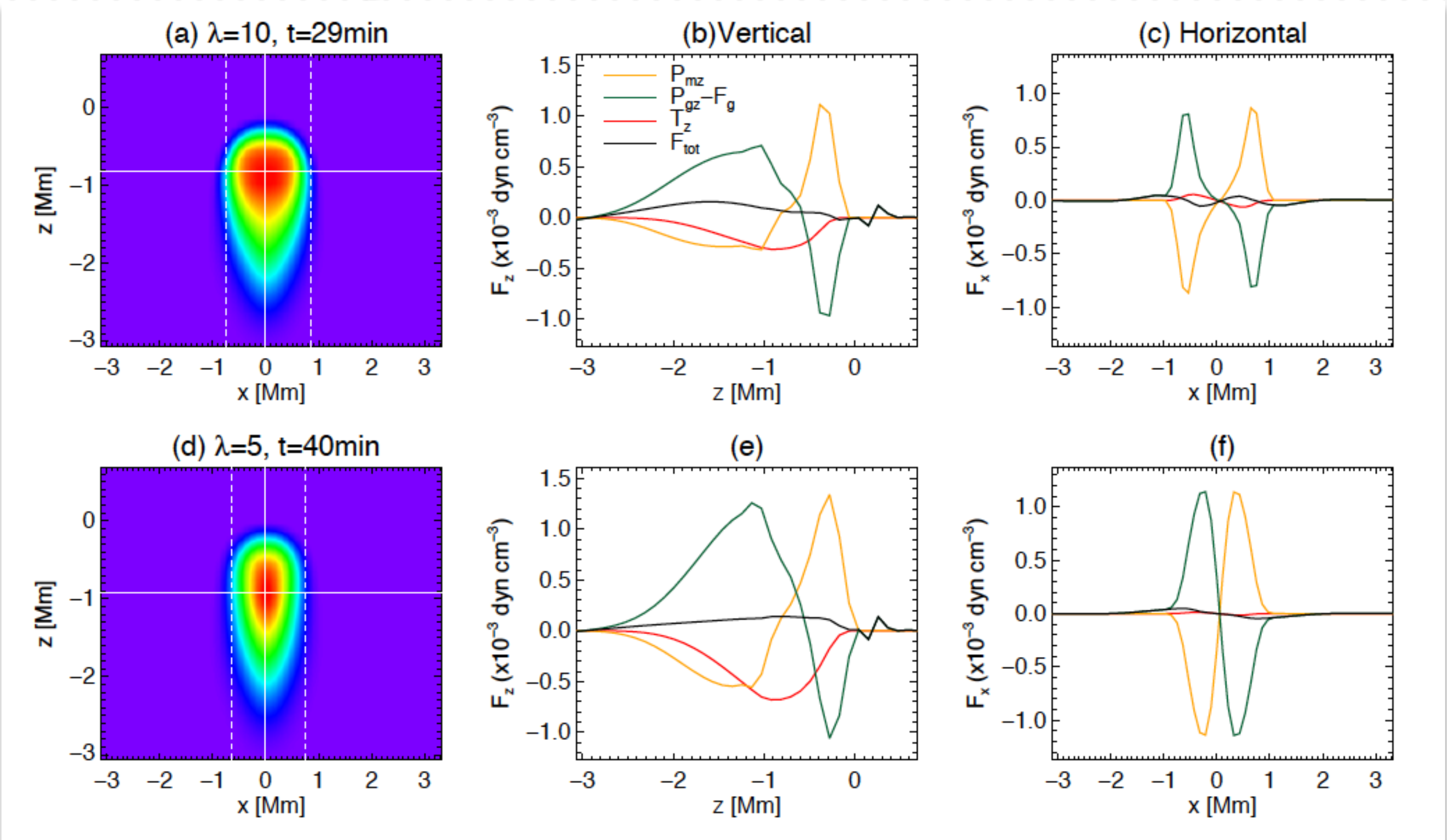
Non Twisted FT – Below photosphere

1. We examine the xz-midplane where Δρ is equal for both λ.
2. Higher λ ➔ lower downwards tension ➔ higher upwards total force.
3. λ=10 reaches the photosphere faster and expands more.
4. λ=10 has less P_{mag} when it reaches the photoshpere.

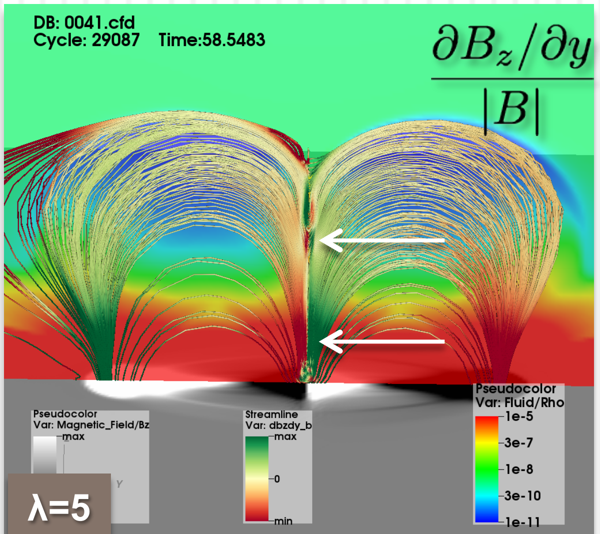


Non Twisted FT – Below photosphere

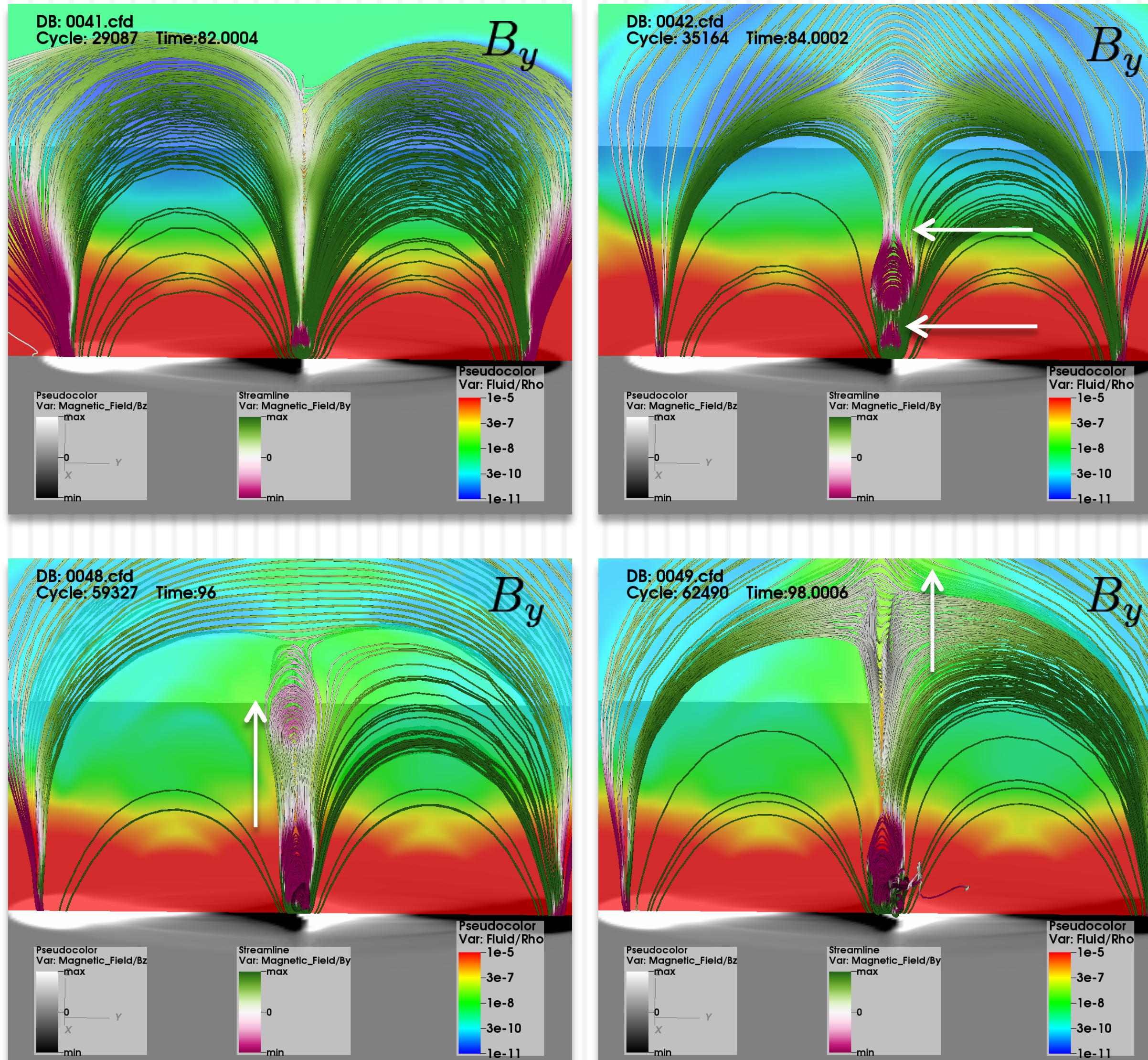
1. We examine the xz-midplane where $\Delta\rho$ is equal for both λ.
2. Higher λ ➔ lower downwards tension ➔ higher upwards total force.
3. $\lambda=10$ reaches the photosphere faster and expands more.
4. $\lambda=10$ has less P_{mag} when it reaches the photoshpere.



Non Twisted FT – Plasmoid formation



- Increased $\frac{\partial B_z/\partial y}{|B|}$
- Fragmentation, 1st eruption, plasmoid formation
- Ascent of plasmoid
- 2nd eruption, plasmoid ejection - diffusion



Low/Non Twisted Flux Tubes

We know that:

- Non twisted flux tubes emerging from bottom of the convection zone become fragmented into two counter-rotating vortices (e.g. Shussler 1979 ; Longcope et al 1996).

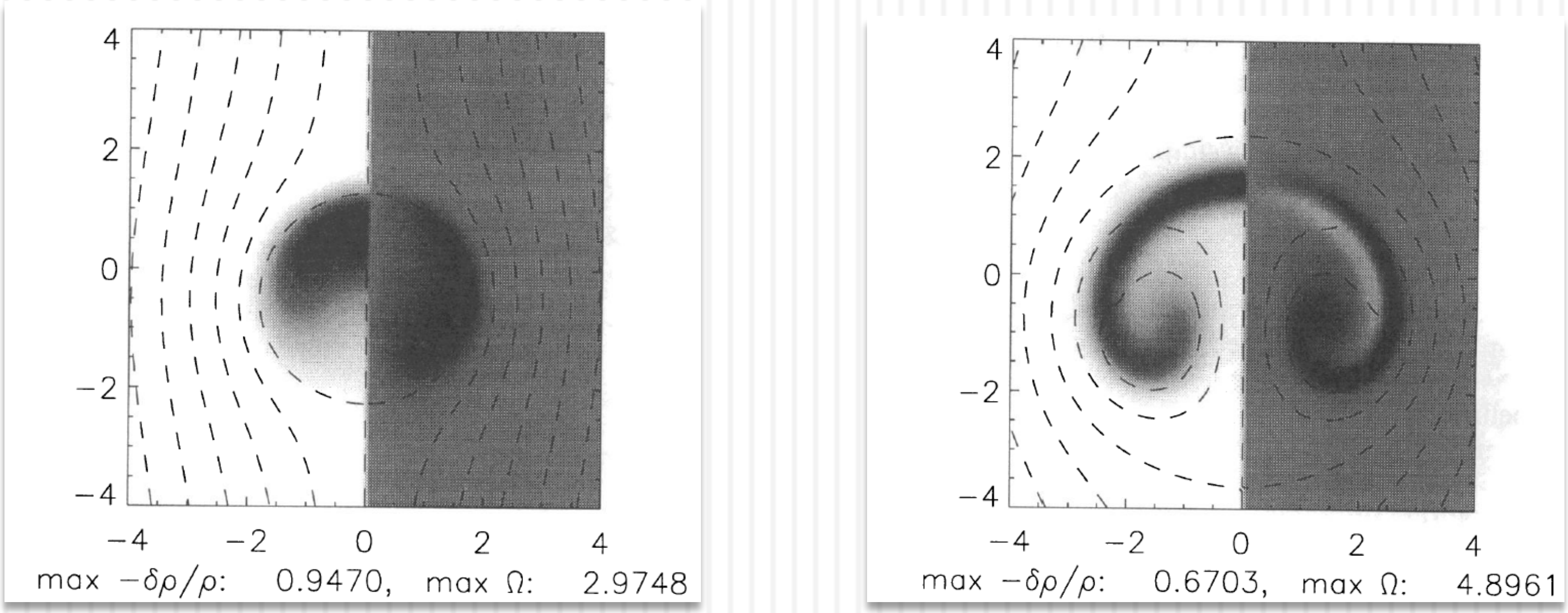


Fig: Longcope et al 1996

Highly Twisted Flux Tube – Basic Aspects I

The key characteristics of the emergence of a highly twisted flux tube are:

- Formation of a bipolar region.
- Shearing motions along the Polarity Inversion Line (PIL)

Interactions and eruptive phenomena:

1. Reconnection along the PIL due to sharing *(e.g. van Balleggooijen and Martens 1989)*
2. Formation of post-emergence flux rope (PEFR) (e.g. *Manchester et al. 2004, Archontis et al 2009)*
3. Eruption of the PEFR depending on initial field magnitude, external field etc. *(e.g. Torok & Kliem 2005, Archontis and Hood 2012)*
4. Formation of jets and eruptive phenomena *(e.g. Gontikakis et al 2009, Moreno-Insertis et al 2008)*
5. Formation of CME-like eruption *(Archontis et al 2014, Syntelis et al in preparation, Poster <POSTER NUMBER>*)