ENERGY TRANSPORT FROM THE SOLAR INTERIOR TO THE CORONA

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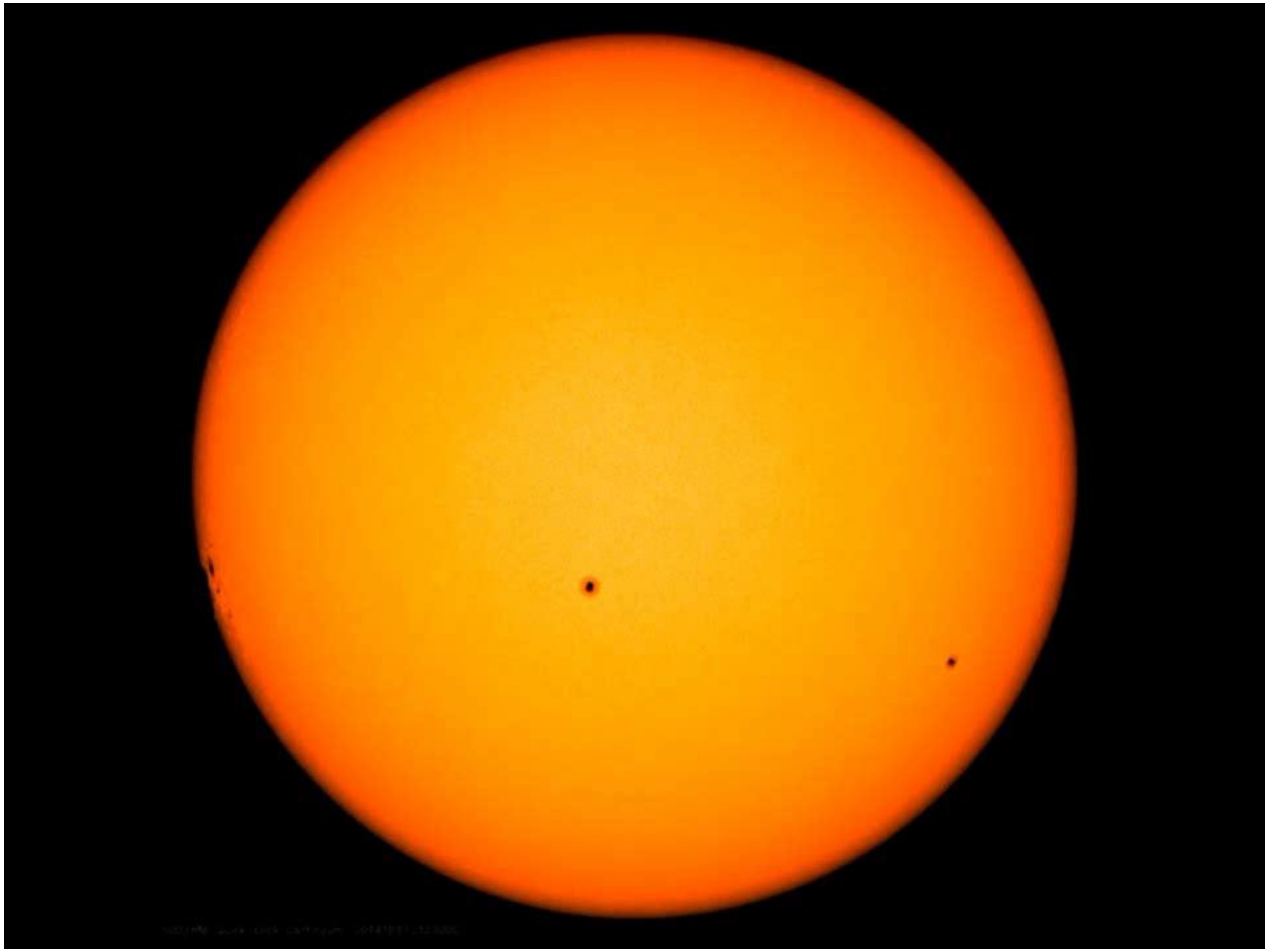
INTRODUCTION



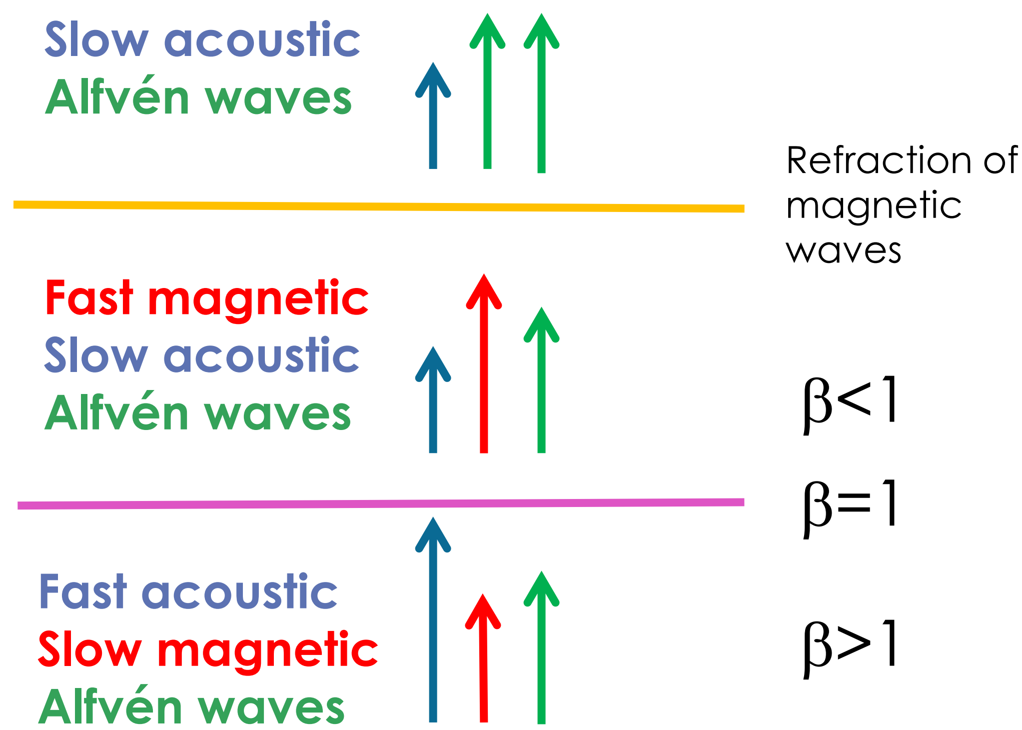
INTRODUCTION

- **Chromospheric and coronal heating**
  - DC models: reconnection
  - AC models: wave heating

Heating by waves:

- Waves transport energy into the chromosphere and corona
  - Acoustic waves partially refracted at TR
  - Most of the fast waves are refracted at TR
  - Alfven waves needed in the corona: mode conversion

MHD waves: schematic picture



Plane-parallel stratified atmosphere

INTRODUCTION

MANCHA code (http://www.iac.es/proyecto/spia/)

SPIA
Solar Partially Ionized Atmosphere

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0$$

Continuity

$$\frac{\partial (\rho \boldsymbol{v})}{\partial t} + \nabla \cdot \left[\rho \boldsymbol{v}\boldsymbol{v} + \left(p + \frac{\boldsymbol{B}^2}{2\mu_0} \right) \boldsymbol{I} - \frac{\boldsymbol{B}\boldsymbol{B}}{\mu_0} \right] = \rho \boldsymbol{g} + \boxed{\nabla \cdot \bar{\bar{\tau}}}$$

Motion

$$\frac{1}{\gamma - 1} \left(\frac{\partial p}{\partial t} + (\boldsymbol{v} \cdot \nabla) p + \gamma p (\nabla \cdot \boldsymbol{v}) \right) = \cancel{Q_{rad}} + \nabla \cdot \cancel{(\kappa \nabla T)} + \boxed{\mu_0 \eta \, j^2}$$

Internal energy

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) - \boxed{\nabla \times (\eta \, \nabla \times \boldsymbol{B})}$$

Induction

INTRODUCTION

MANCHA code (http://www.iac.es/proyecto/spia/)

SPIA
Solar Partially Ionized Atmosphere

Continuity

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = \left(\frac{\partial \rho}{\partial t}\right)_{diff}$$

Motion

$$\frac{\partial (\rho \boldsymbol{v})}{\partial t} + \nabla \cdot \left[\rho \boldsymbol{v}\boldsymbol{v} + \left(p + \frac{\boldsymbol{B}^2}{2\mu_0}\right)\boldsymbol{I} - \frac{\boldsymbol{B}\boldsymbol{B}}{\mu_0}\right] = \rho \boldsymbol{g} + \left(\frac{\partial (\rho \boldsymbol{v})}{\partial t}\right)_{diff}$$

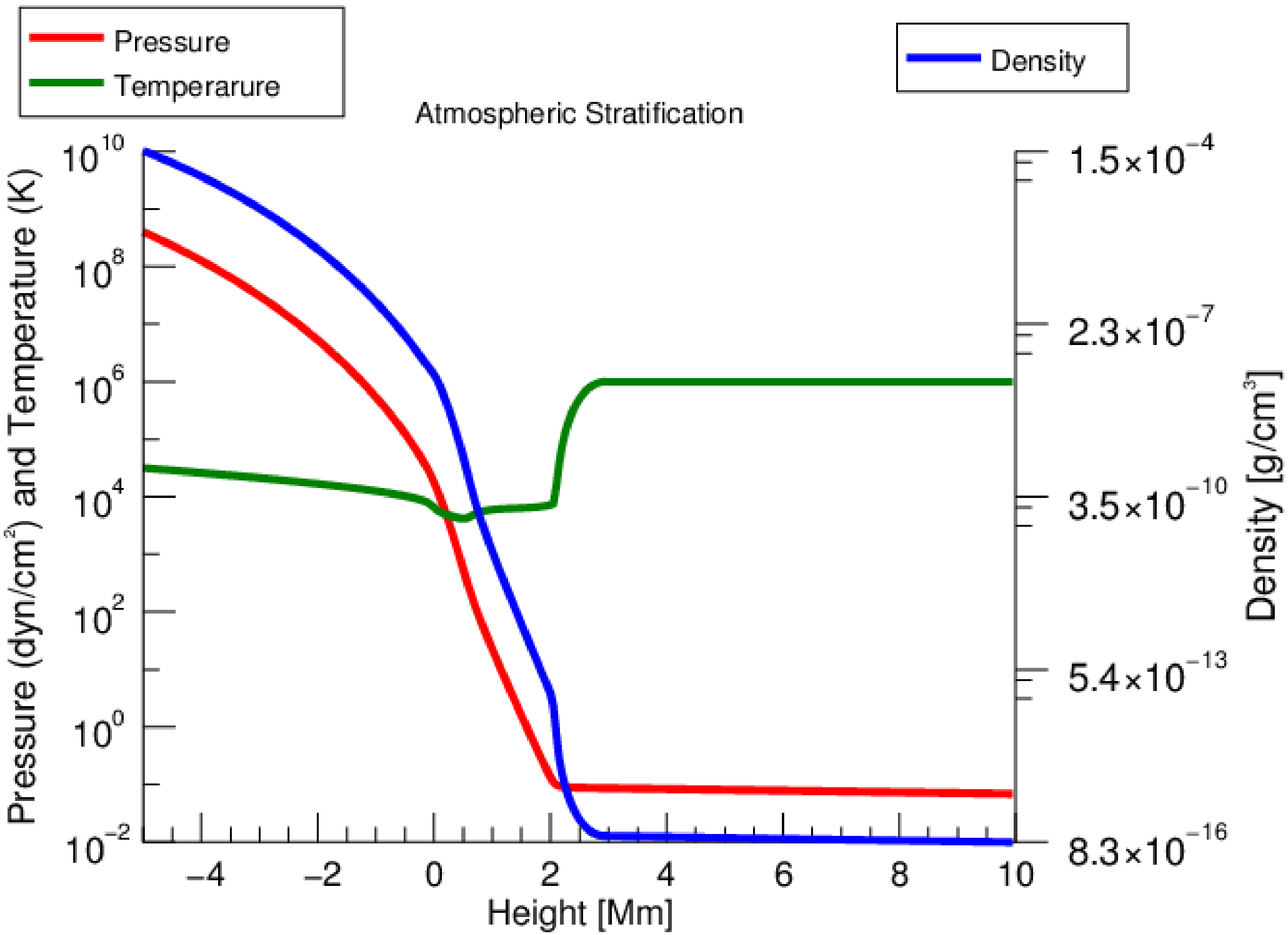
Internal energy

$$\frac{1}{\gamma - 1}\left(\frac{\partial p}{\partial t} + (\boldsymbol{v} \cdot \nabla) p + \gamma p (\nabla \cdot \boldsymbol{v})\right) = Q_{rad} + \nabla \cdot (\kappa \nabla T) + \left(\frac{\partial p}{\partial t}\right)_{diff}$$

Induction

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) + \left(\frac{\partial \boldsymbol{B}}{\partial t}\right)_{diff}$$

HYDROSTATIC MODEL



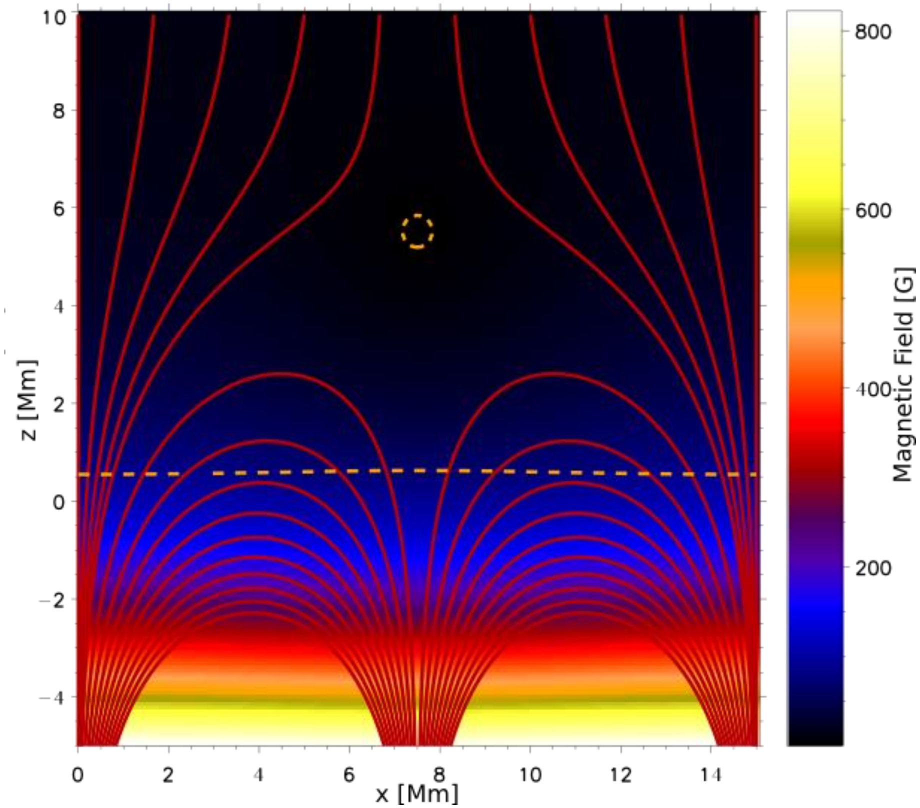
2D MAGNETOSTATIC MODEL

$$\boldsymbol{B}_o = B_{0x}\boldsymbol{e}_x + B_{0z}\boldsymbol{e}_z$$

$$B_{0x} = B_{00}\, e^{-kz} \sin(kx)$$

$$B_{0z} = B_u + B_{00}\, e^{-kz} \cos(kx)$$

$$B_{00} = 100\ G$$
$$B_u = 10\ G$$



3D MAGNETOSTATIC MODEL

Non-potential $(\vec{J} \neq \mathbf{0})$ and force-free $(\vec{J} || \vec{B})$ magnetic field

$$\nabla \times \vec{B} = \alpha \vec{B}$$

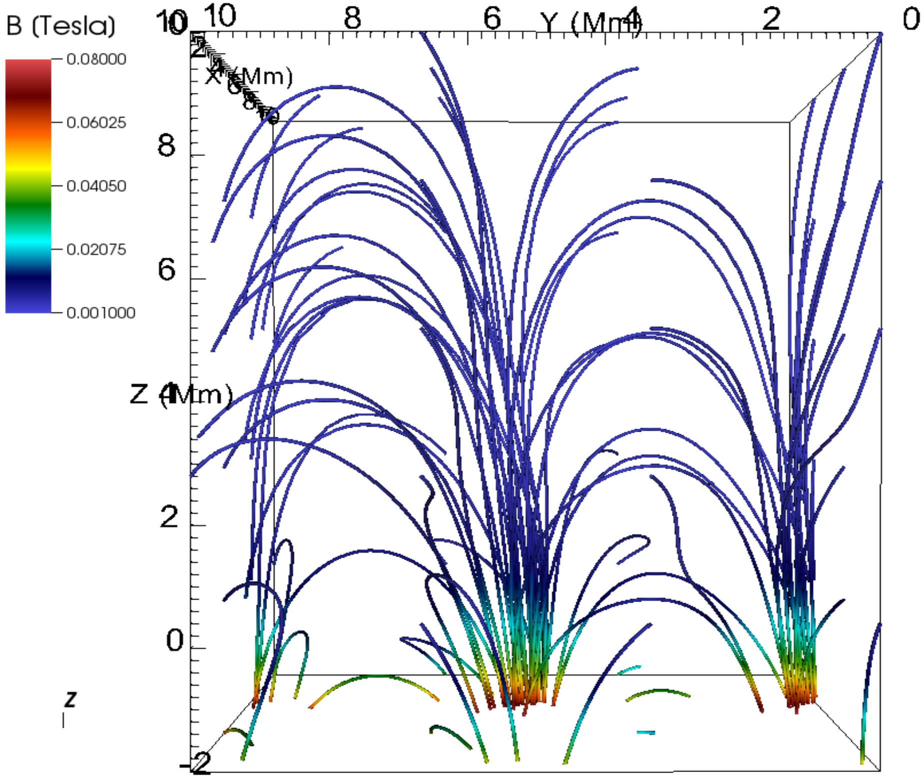
If $\alpha = 0$ → Potential Magnetic Field

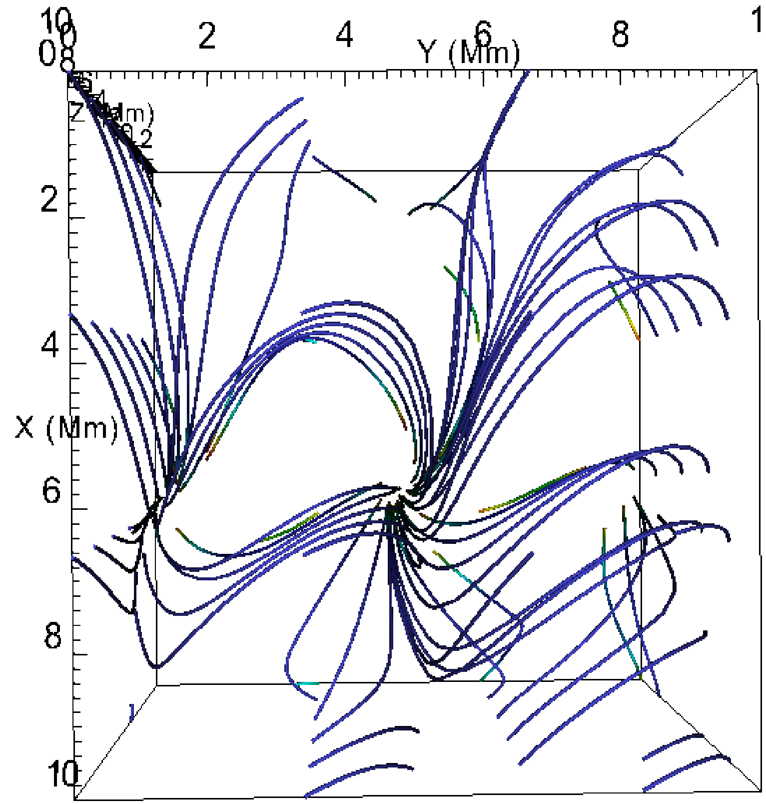
If $\alpha = cnst$ → Linear Force-Free Field

If $\alpha \neq cnst$ → Non-Linear Force-Free field

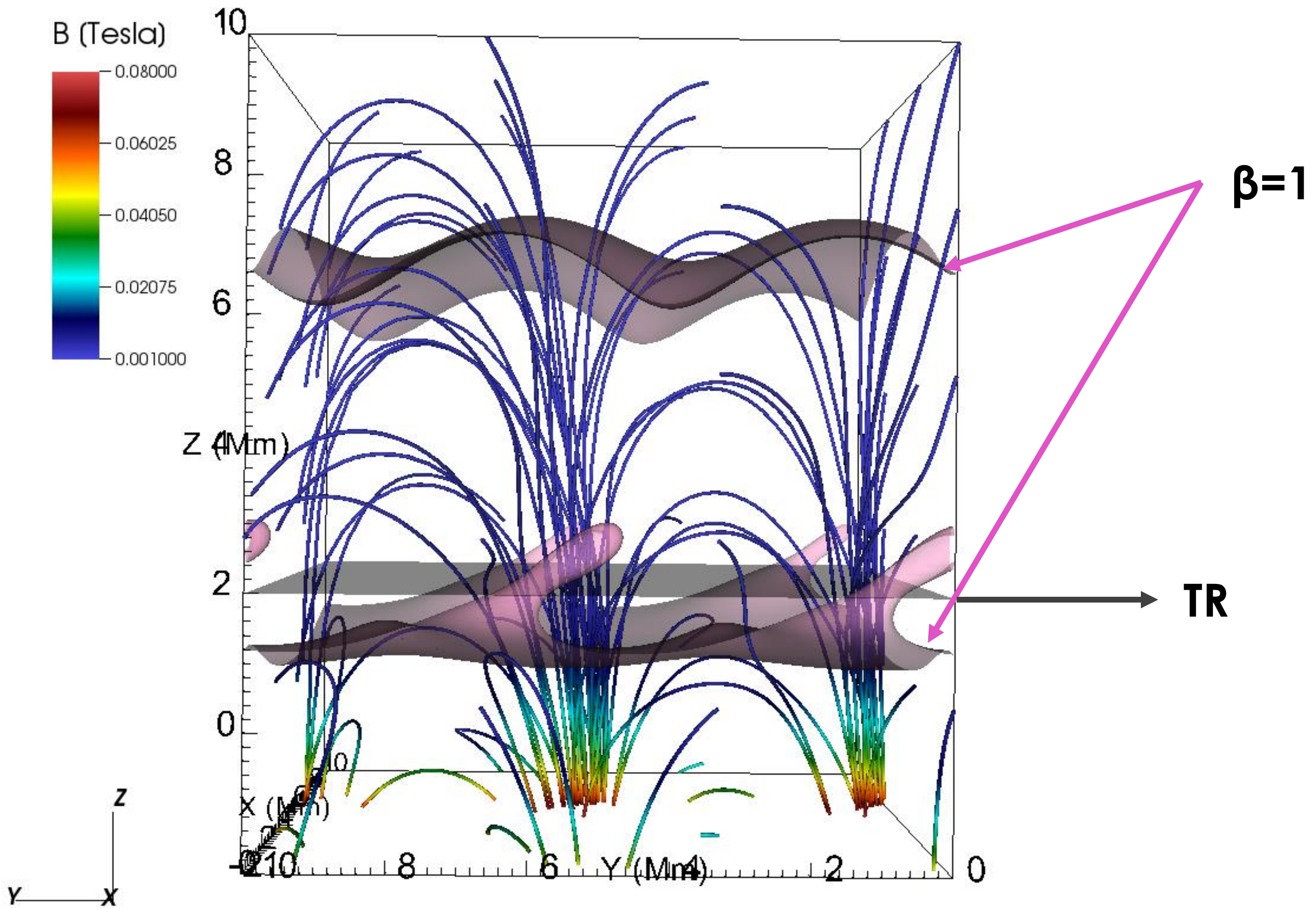
Nakagawa & Raadu (1972)

MAGNETOSTATIC MODEL

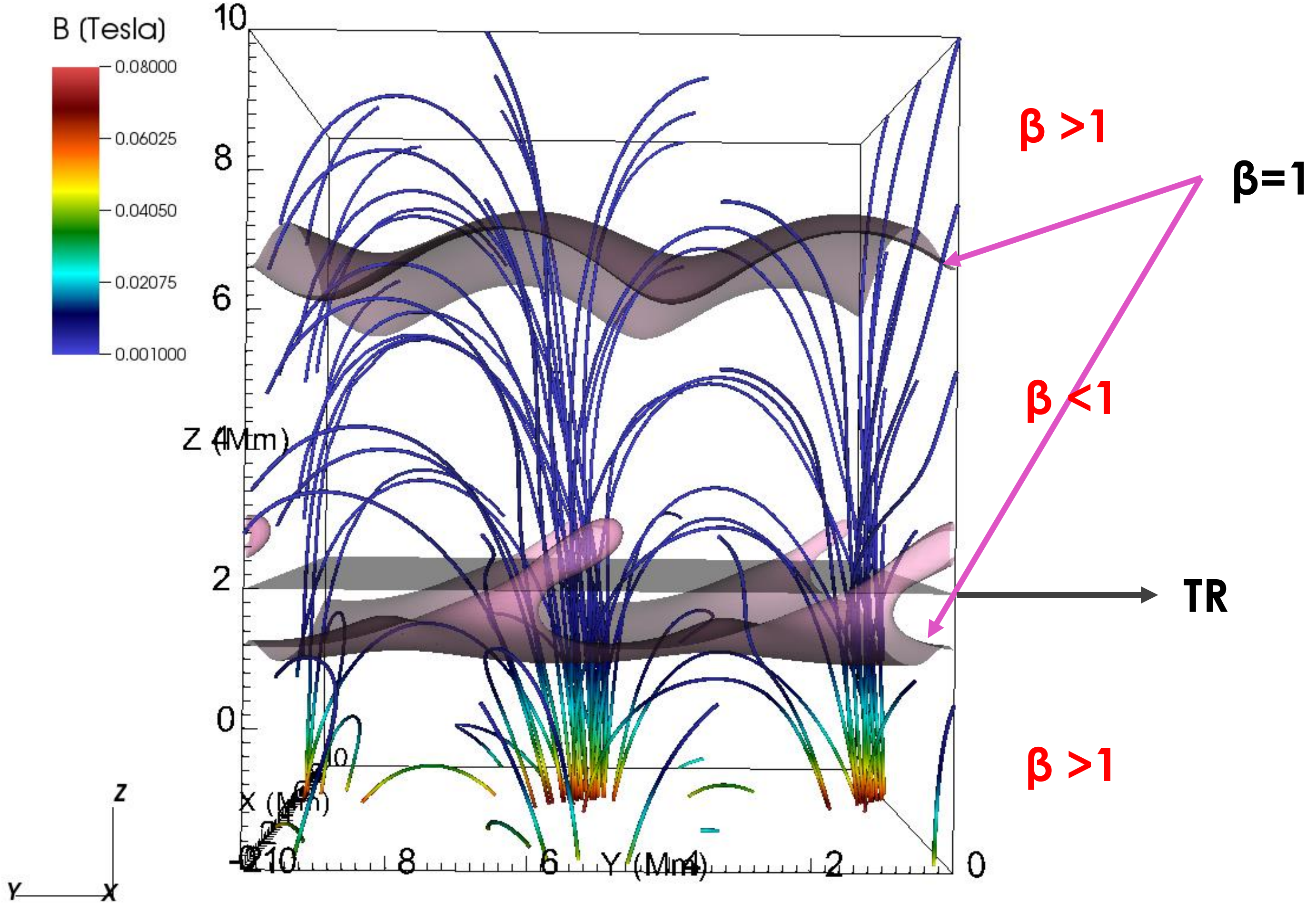




EQUILIBRIUM MODEL



EQUILIBRIUM MODEL



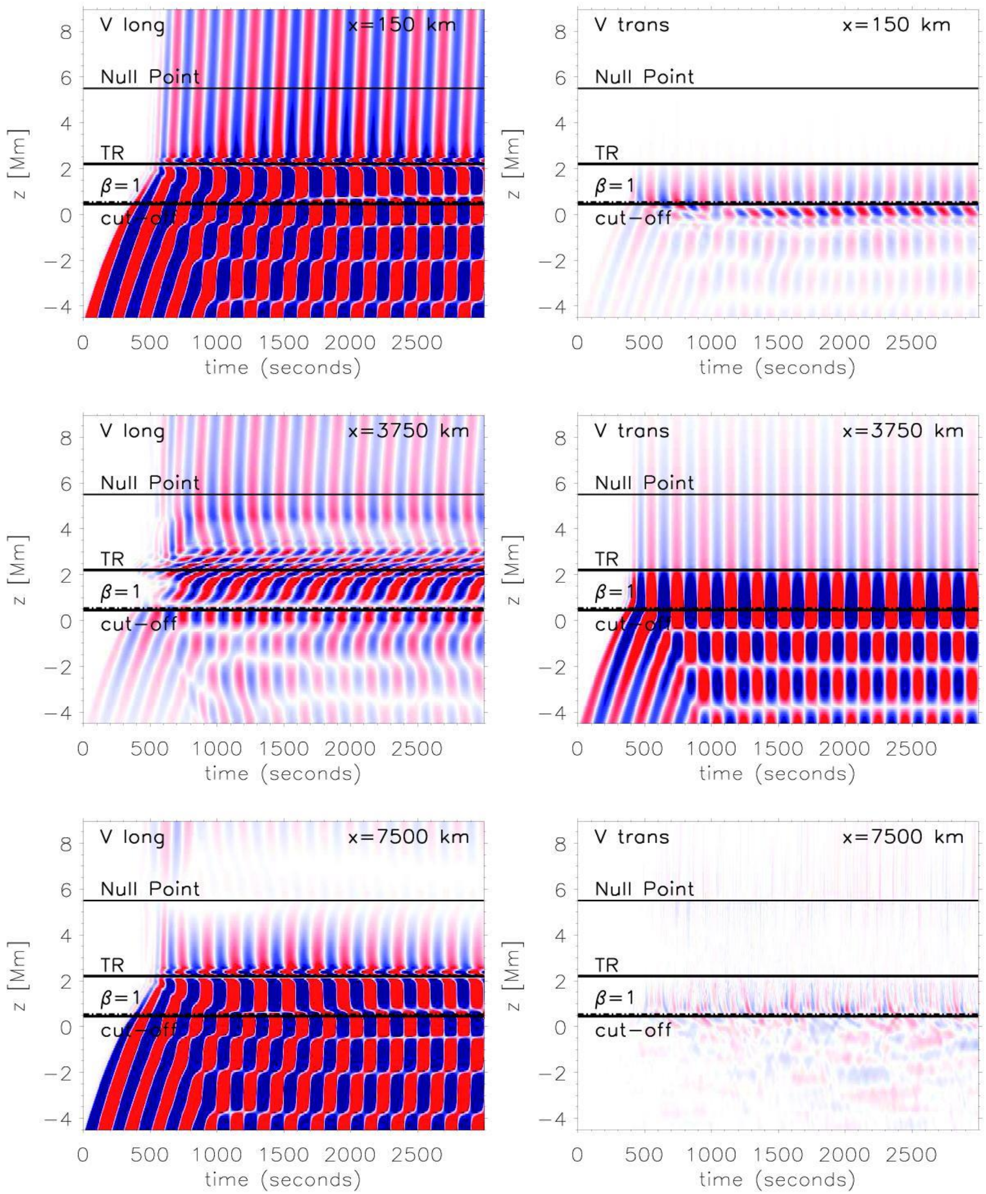
WAVE PROPAGATION

Aims of the set of simulations

- Energy transport to the corona
- Frequency distributions in different magnetic field topologies

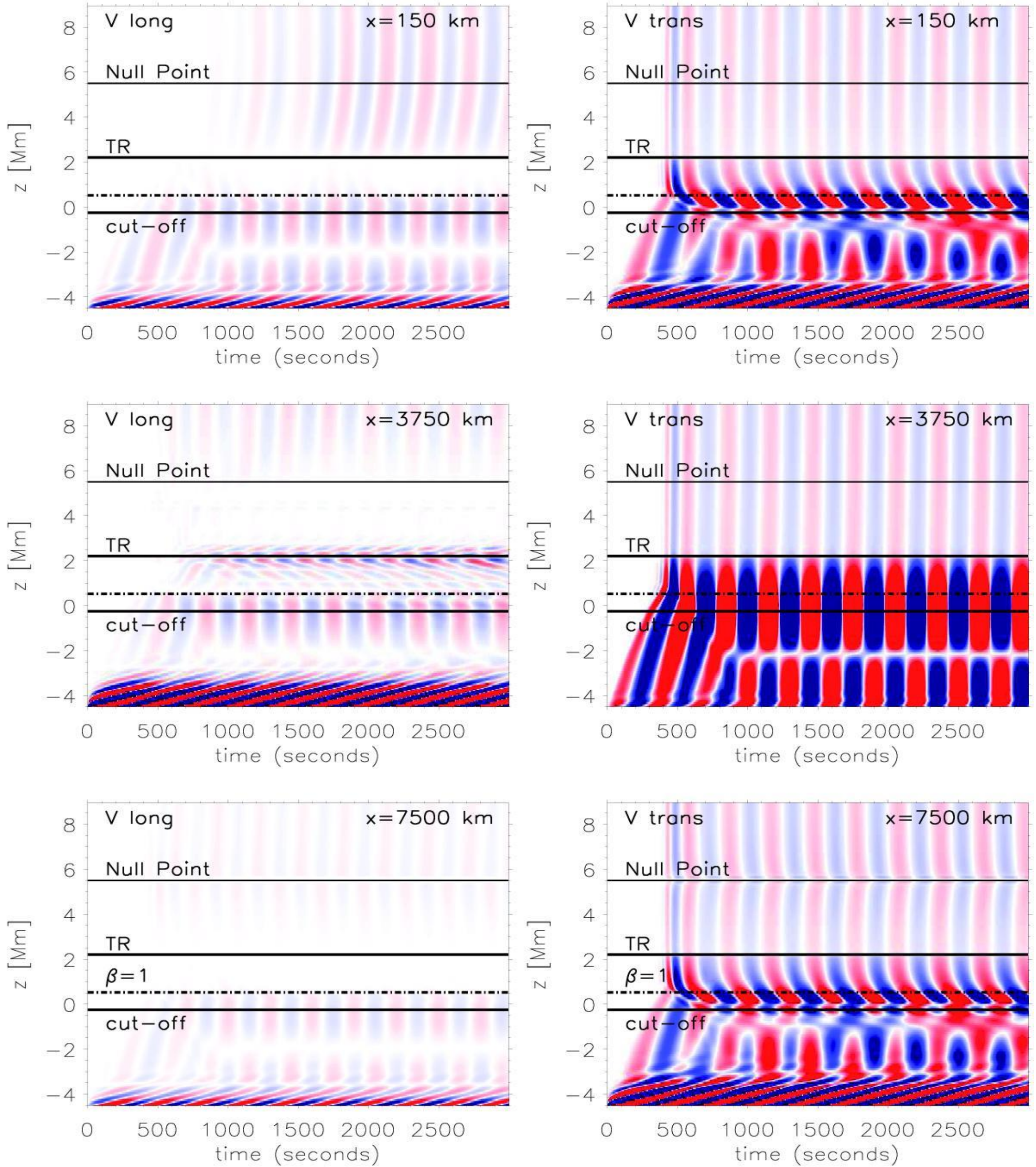
Dim.	Regime	Driver	Period
2D	Linear regime	Vertical periodic driver	200 s
2D	Linear regime	Horizontal periodic driver	300 s
2D	Linear regime	Instantaneous pulse	*
2D	Non-linear regime	Instantaneous pulse	*
3D	Linear regime	Instantaneous pulse	*

ENERGY TRANSPORT



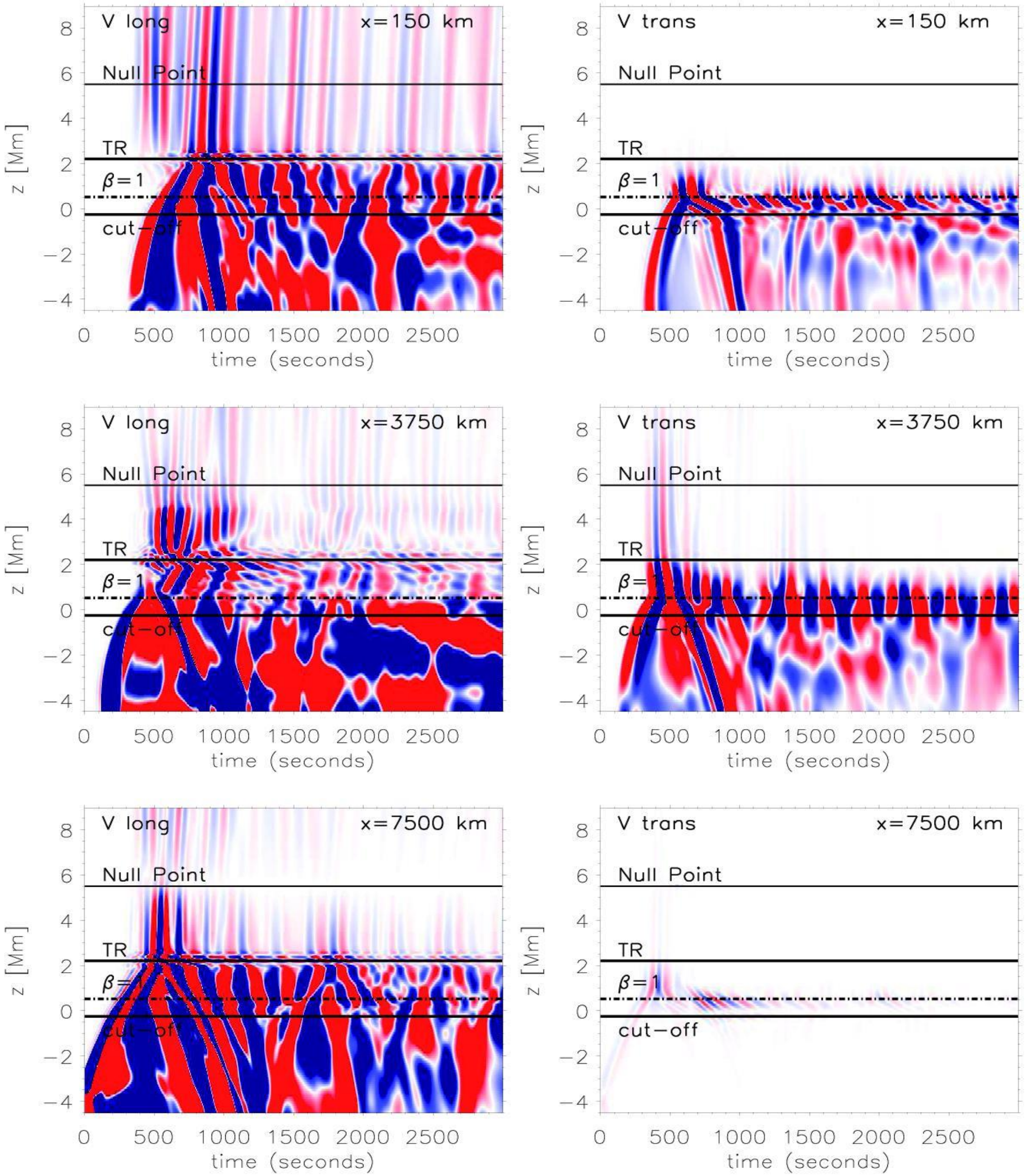
Vertical periodic driver

ENERGY TRANSPORT



Horizontal periodic driver

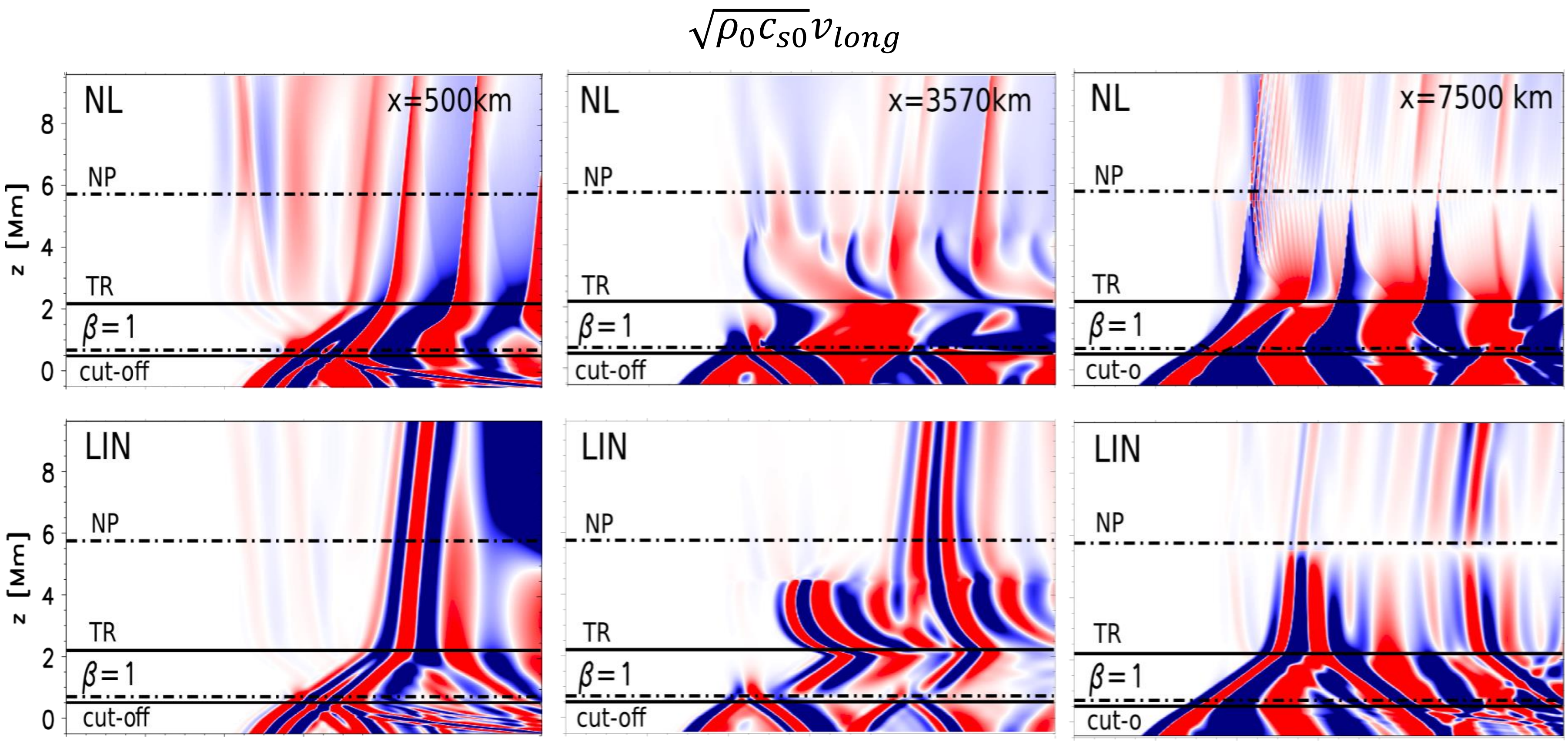
ENERGY TRANSPORT



Instantaneous
Pressure pulse

ENERGY TRANSPORT

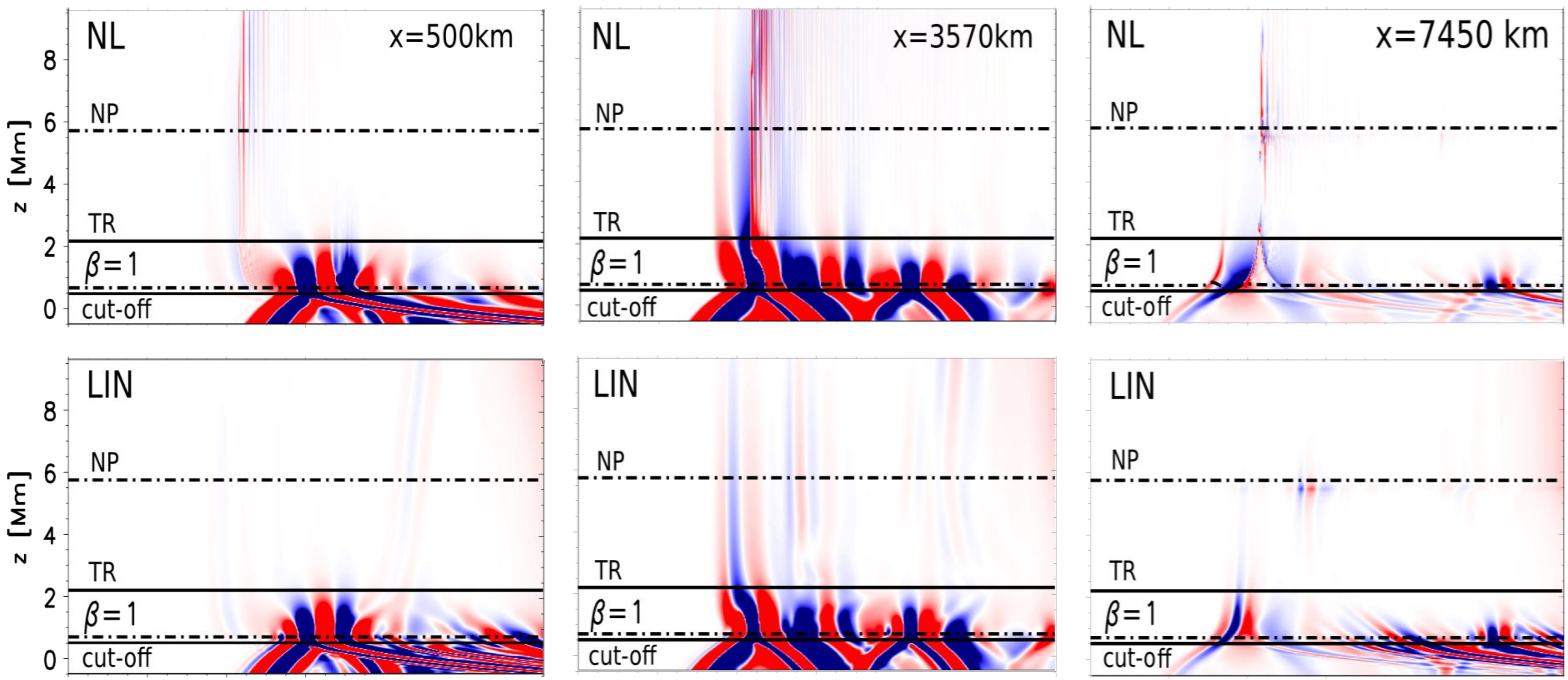
Linear vs Non-linear wave propagation



ENERGY TRANSPORT

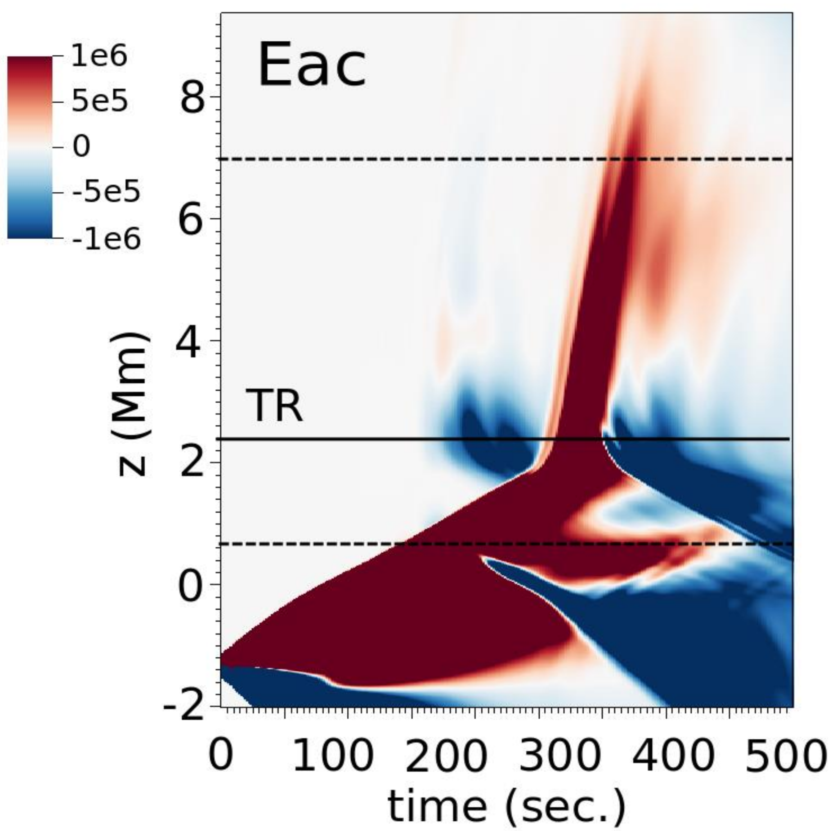
Linear vs Non-linear wave propagation

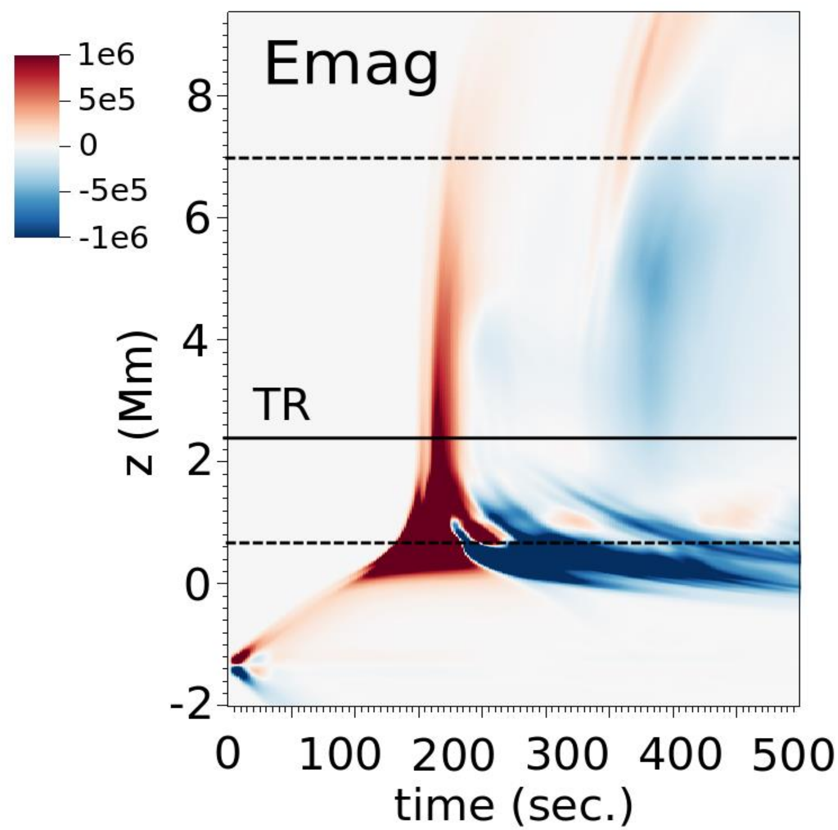
$$\sqrt{\rho_0 v_{a0}} v_{trans}$$



ENERGY TRANSPORT

$$E_{ac}(z,t) = \iint_{x\,y} F_{ac,z}(x,y,z,t)\,dxdy \qquad E_{mag}(z,t) = \iint_{x\,y} F_{mag,z}(x,y,z,t)\,dxdy$$





CONCLUSIONS

- In the 2D simulations the amount of energy reaching the corona is mostly acoustic.
- In the horizontal driving case there is more magnetic energy reaching the corona but still not enough.

- In the 3D case, still the amount of acoustic energy reaching the corona is larger than the amount of magnetic energy. This is BAD since the heating by acoustic waves is not enough to heat the corona. A larger amount of magnetic energy needed!
- How do we feed the corona with magnetic energy?