光球-彩層間の波動現象とALMAによる多層間結合撮像

加藤 成晃（NAOJ）

研究協力者

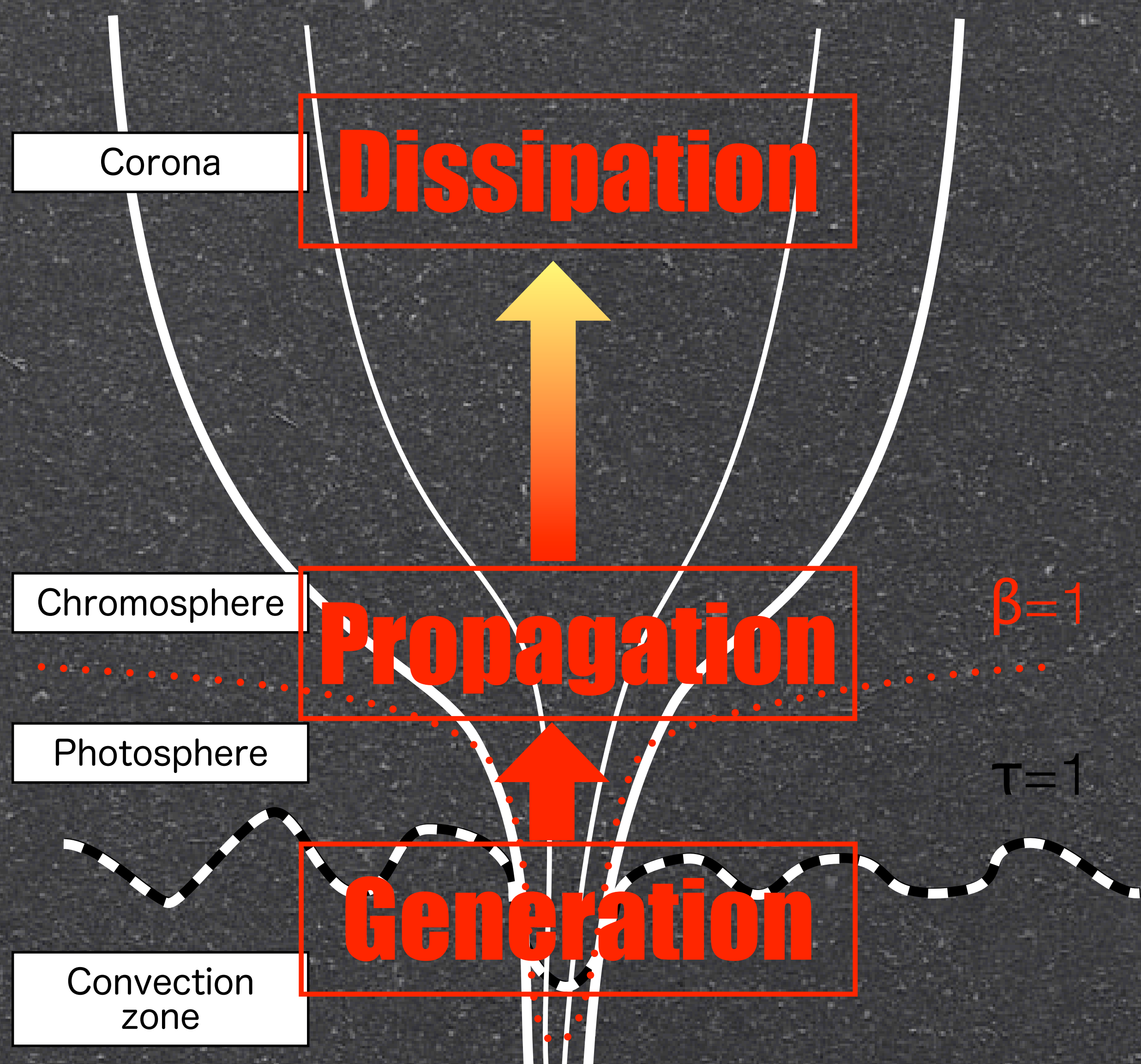
Mats Carlsson (ITA, Univ. of Oslo)

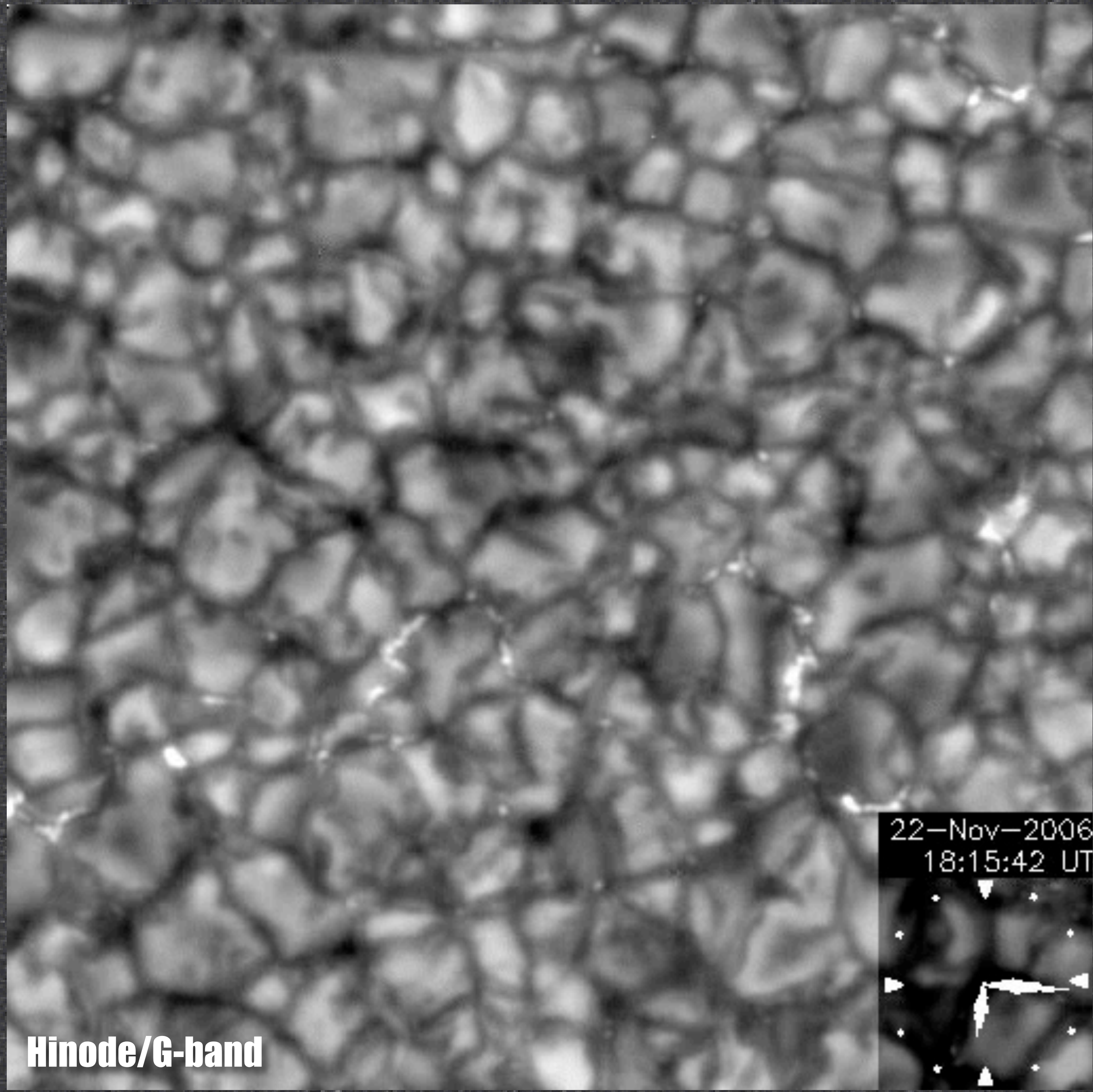
Jorrit Leenaarts (ITA, Univ. of Oslo)

概要

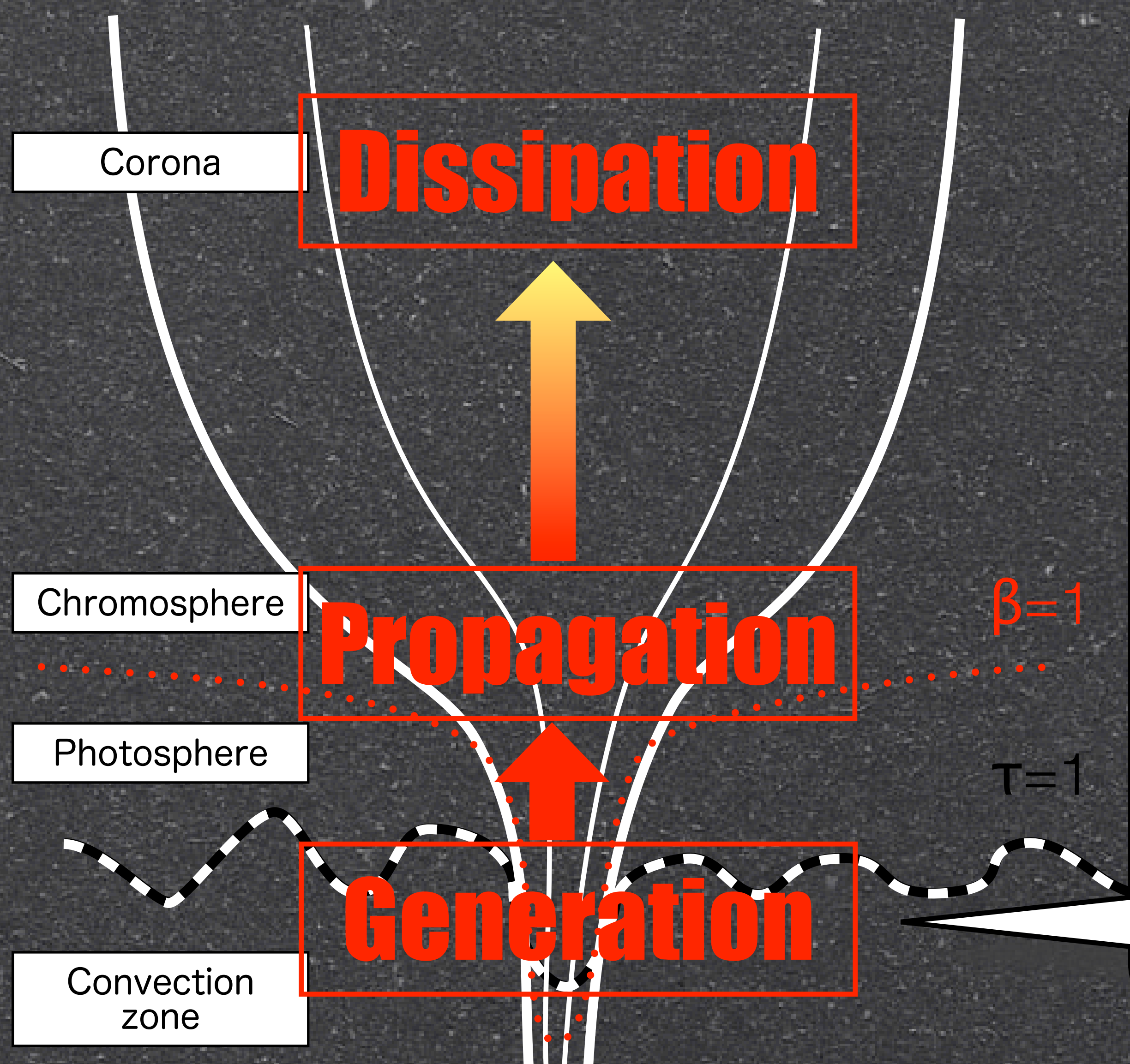
1. リアリスティック太陽大気モデリングとは
2. 光球-彩層をつなぐ磁束管での波動現象
3. ALMAによる多層間結合撮像への期待

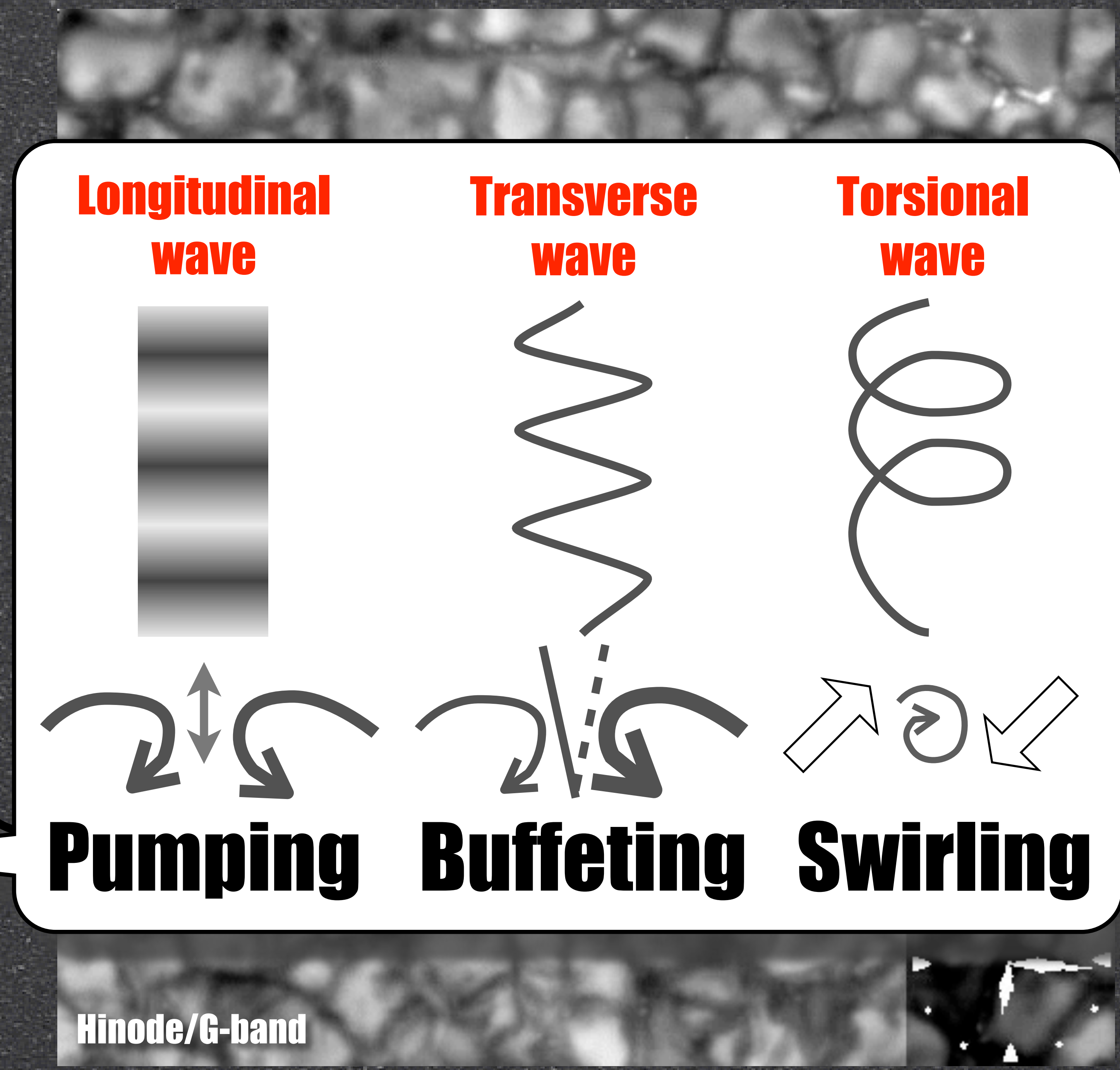
磁束管で自発的に生じる
磁気流体波とは？



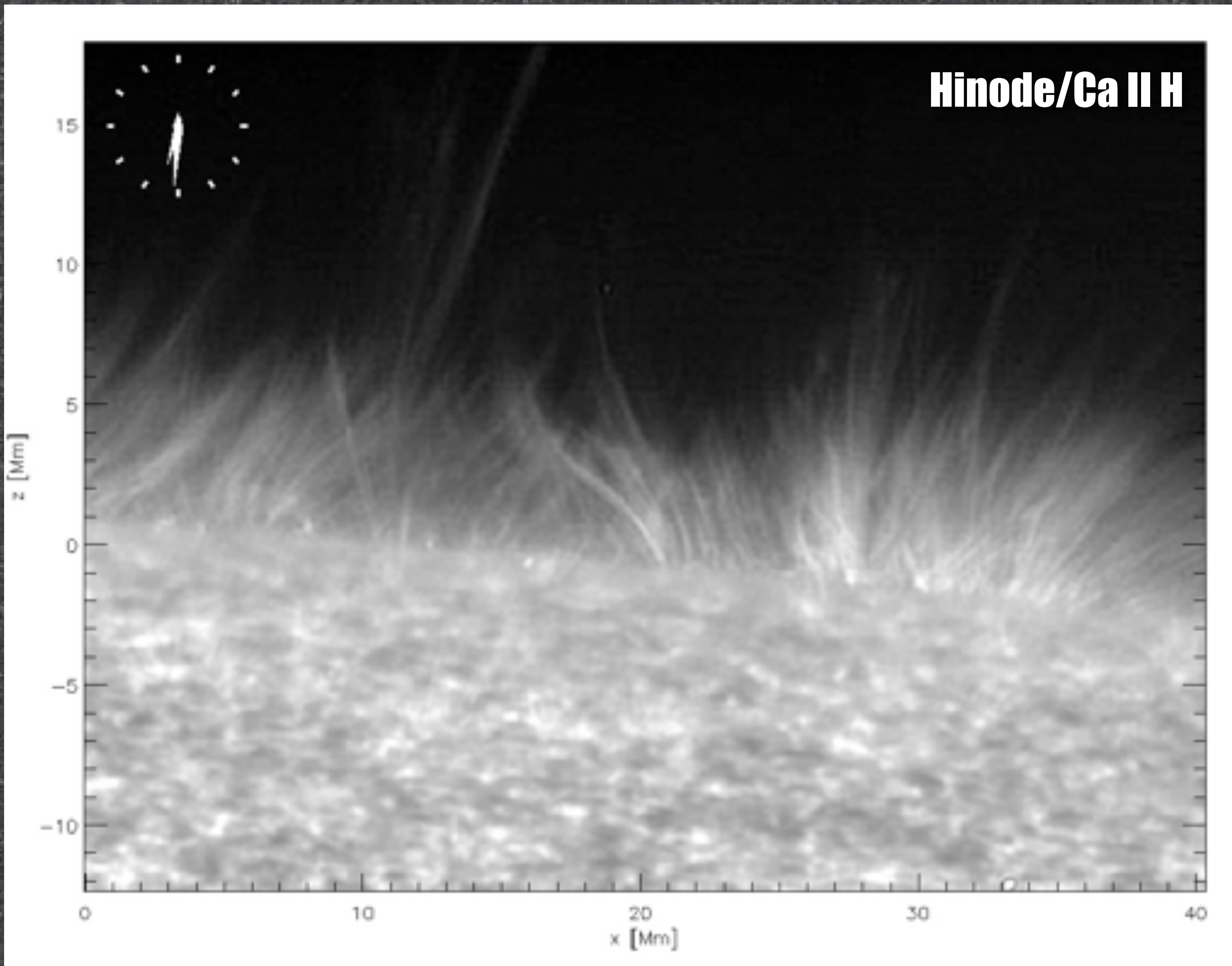


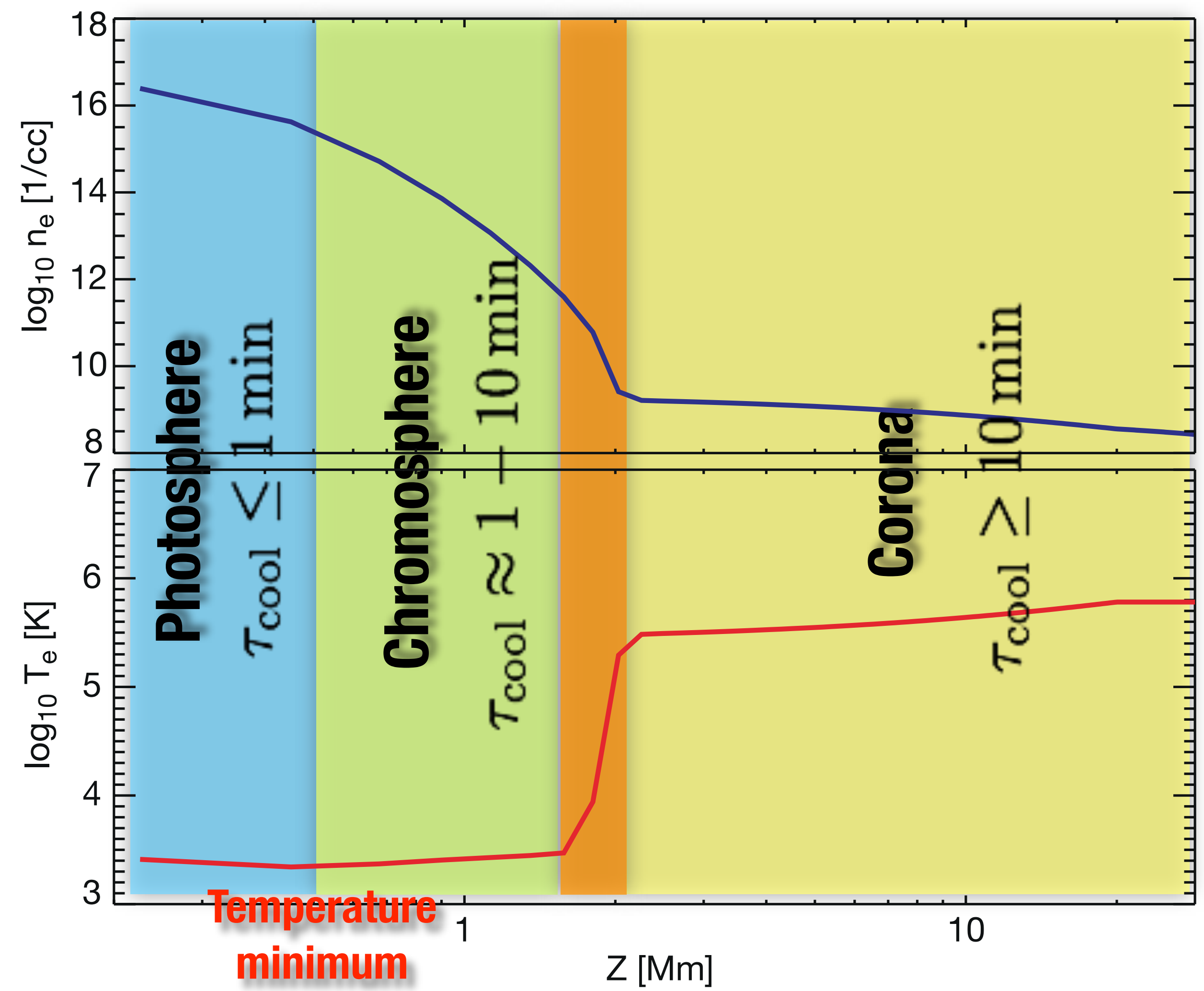
磁束管で自発的に生じる磁気流体波とは？





Why we need realistic modelings?





We wish to emphasize that the HSRA, like all models that have preceded it, should not be interpreted as an accurate description of the true solar atmosphere. The model describes an idealized plane-parallel homogeneous atmosphere in hydrostatic equilibrium; however, it is well known that in the Sun, and especially in the chromosphere, perturbations due to magnetic and hydrodynamic effects grossly distort the local structure from its mean configuration.

Toward Realistic

Modelings of Solar Atmosphere

- **Heat conduction** along field lines from corona
- **Radiative Transfer**
  - LTE + Non-LTE
  - Opacity
    - ✓ Continuum
    - ✓ Lines
  - Ionization
    - ✓ Collisional excitation
    - ✓ Photo-ionization
- Magneto-convection
  - **Radiative cooling**
  - **EOS**

Basic equations

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

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

$$\frac{\partial e}{\partial t} = -\nabla \cdot \left[\left(e + p + \frac{B^2}{2\mu} \right) \boldsymbol{v} - \frac{\boldsymbol{B}(\boldsymbol{B} \cdot \boldsymbol{v})}{\mu} \right] + \rho \boldsymbol{v} \cdot \boldsymbol{g} + Q$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = -\nabla \times \boldsymbol{E} \qquad \boldsymbol{E} = -\boldsymbol{v} \times \boldsymbol{B} + \eta \boldsymbol{J} \qquad \boldsymbol{J} = \frac{\nabla \times \boldsymbol{B}}{\mu}$$

$$e = \rho \varepsilon + \frac{1}{2} \rho v^2 + \frac{B^2}{2\mu}$$

$$p = p(\rho, \varepsilon) \qquad Q = Q_{\mathrm{rad}} + Q_{\mathrm{cond}}$$

Solar "ingredients": $\boldsymbol{g}$, $p(\rho, \varepsilon)$, Q

Waves inside Flux Tube

Overview

- **Analytical Solutions of Wave Equations**
  - Defouw 1976; Roberts & Webb 1978; Spruit & Zweibel 1979: Longitudinal waves
  - Roberts 1981; Rae & Roberts 1982; Spruit 1982,,,: Transverse waves
- **Wave Propagation Simulations**
  - Helbold et al. 1986; Musielak, Rosner, Ulmschneider 1989,,, too many!
  - Driving waves
    - ✓ Longitudinal piston-like motion
    - ✓ Transverse foot point motion
- **Wave Generation & Propagation Simulations**
  - Steiner 1998, 1999: Swaying; Bending; Squeezing
  - YK et al. 2011: Magnetic Pumping
  - Wedemeyer-Böhm et al. 2012: Swirling

Realistic Modelings

Issues of Analytical Solutions

Thin flux tube approximation

- Wave equations become much simpler forms that can be solved analytically,
- Most of papers consider pores and magnetic elements as a flux tube, but this approximation is valid only below the interface between convection zone and photosphere,
- Some papers apply their results to sunspots instead of pores and magnetic elements, but I think it's misleading.

Isothermal/Adiabatic atmosphere

- Radiation loss cannot be neglected in the Solar atmosphere, especially in the interface between convection zone and photosphere, and also in the lower chromosphere.

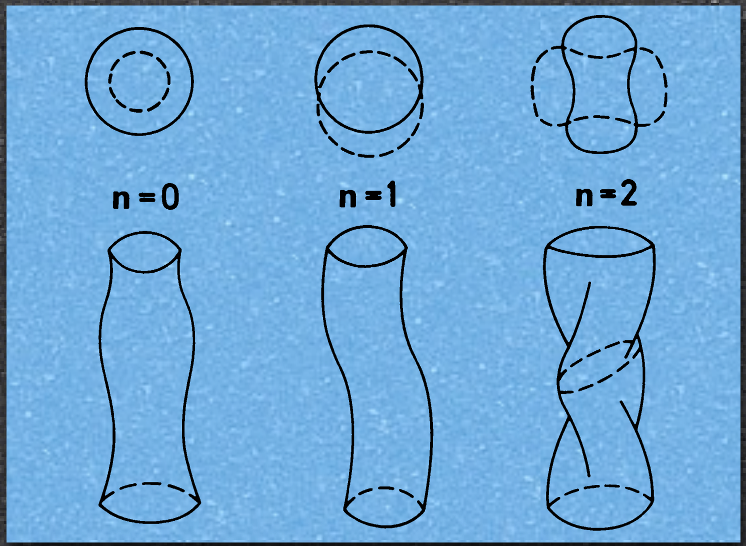
Issues of Wave Propagation Simulations

Source of Waves?

- Location of wave generation remains mystery.
- Steady or Impulsive?

Wave Modes?

- Generation of waves is poorly understood in both theory and observations.
- This is why there is a lot of choices and therefore any drivers can be applied.



What kind of MHD waves?
(Spruit 1982)

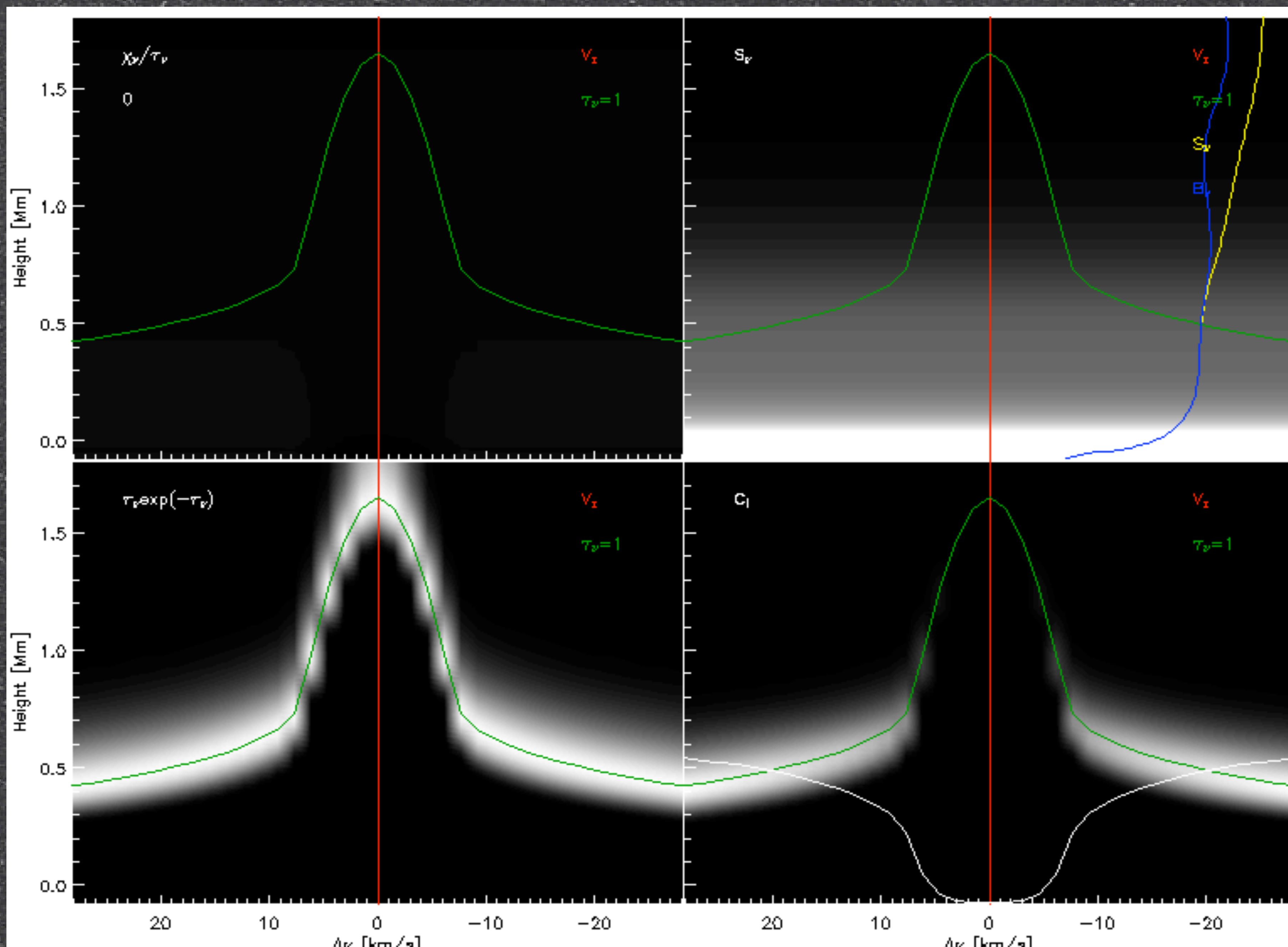
Energy Spectrum?

- Likewise, energy spectrum of generated wave is unknown.

Ca II H-line formation

in 1-D Non-LTE Model atmosphere

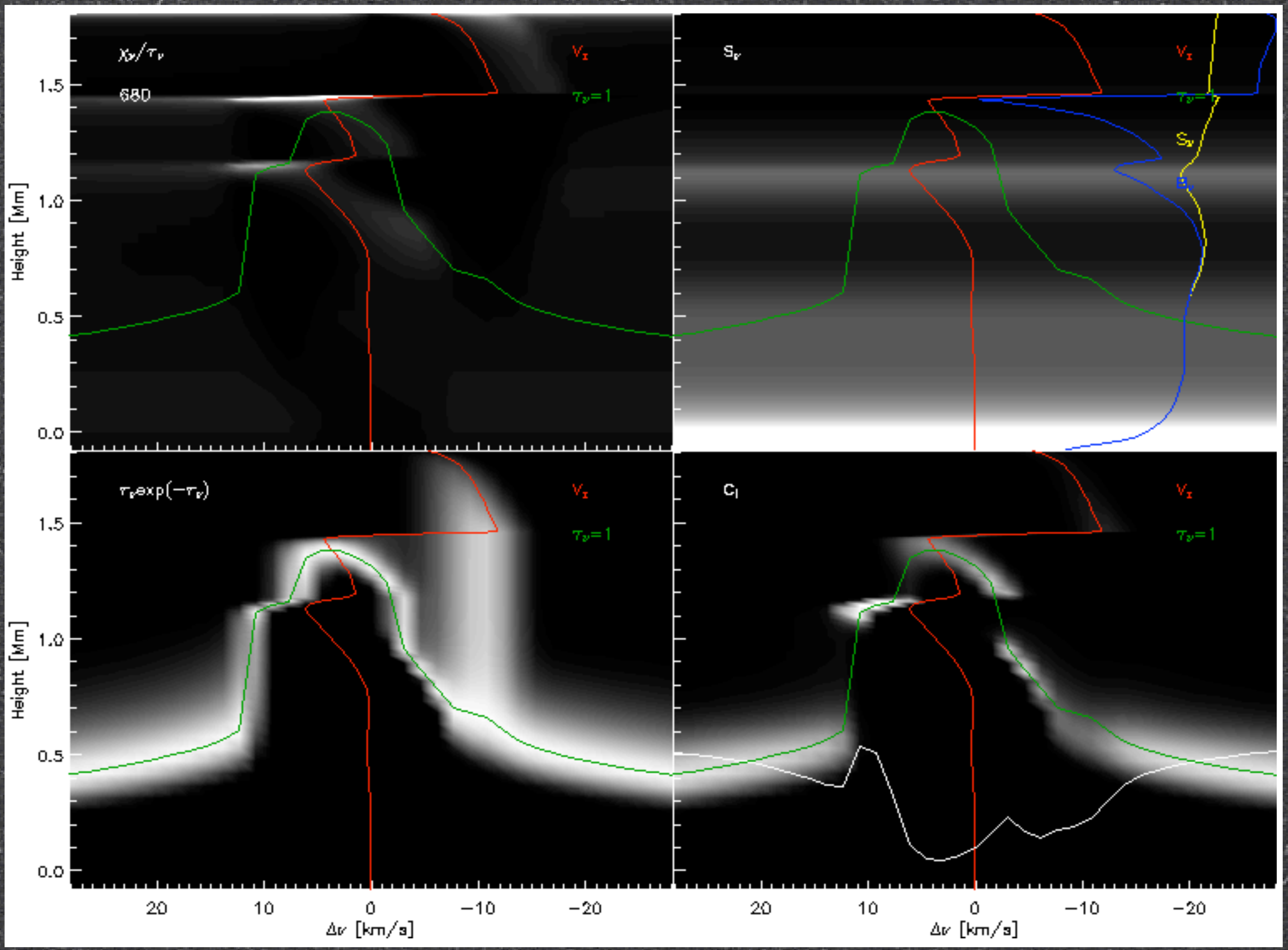
by Carlsson & Stein 1992, 1994, 1995, 1997; Fossum & Carlsson 2006; Carlsson 2007



Ca II H-line formation

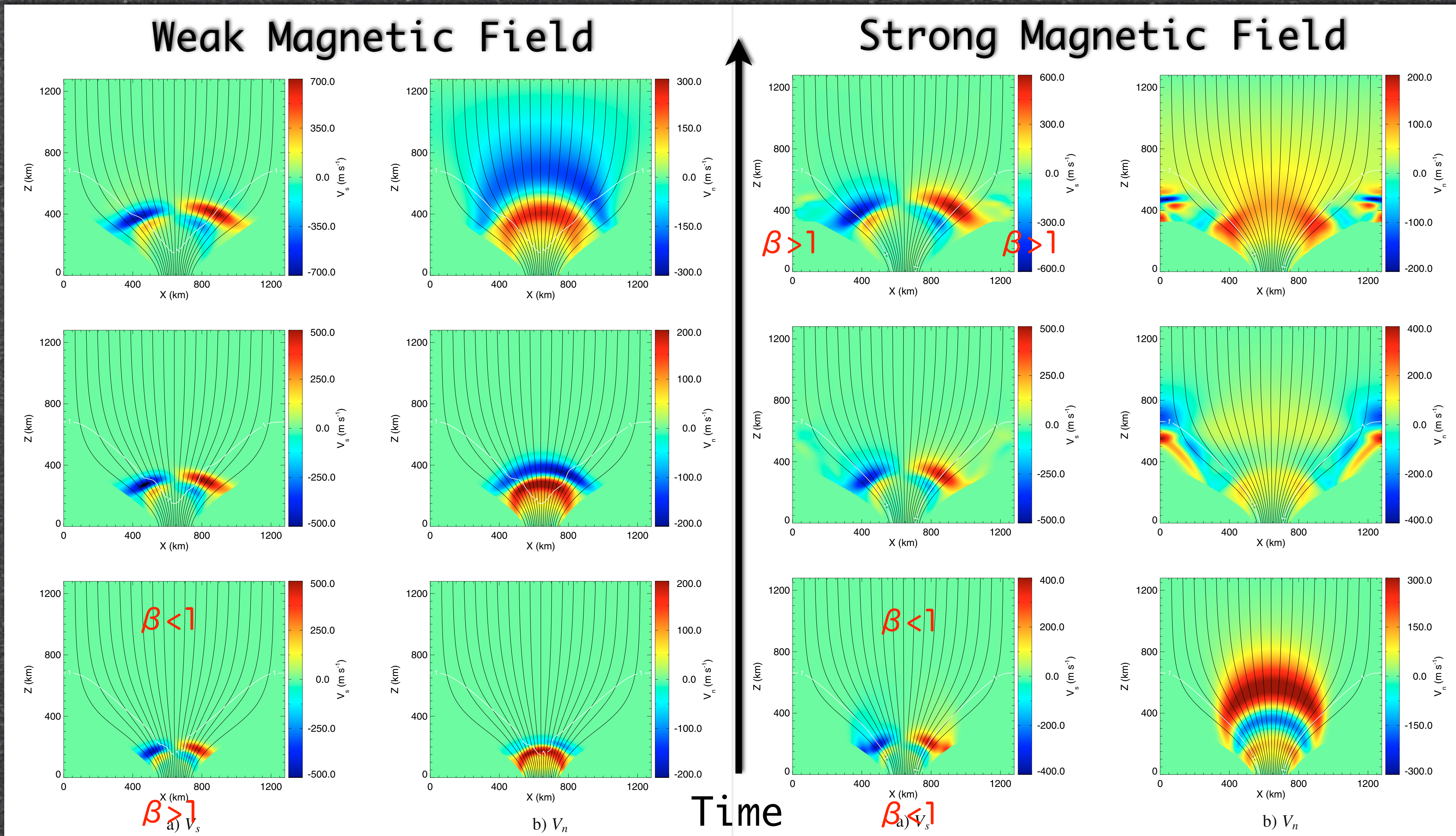
in 1-D Non-LTE Model atmosphere

by Carlsson & Stein 1992, 1994, 1995, 1997; Fossum & Carlsson 2006; Carlsson 2007



ALMA太陽観測WS 2012/09/04

Propagation of Transverse Waves
Vigeesh, Hasan, Steiner 2009

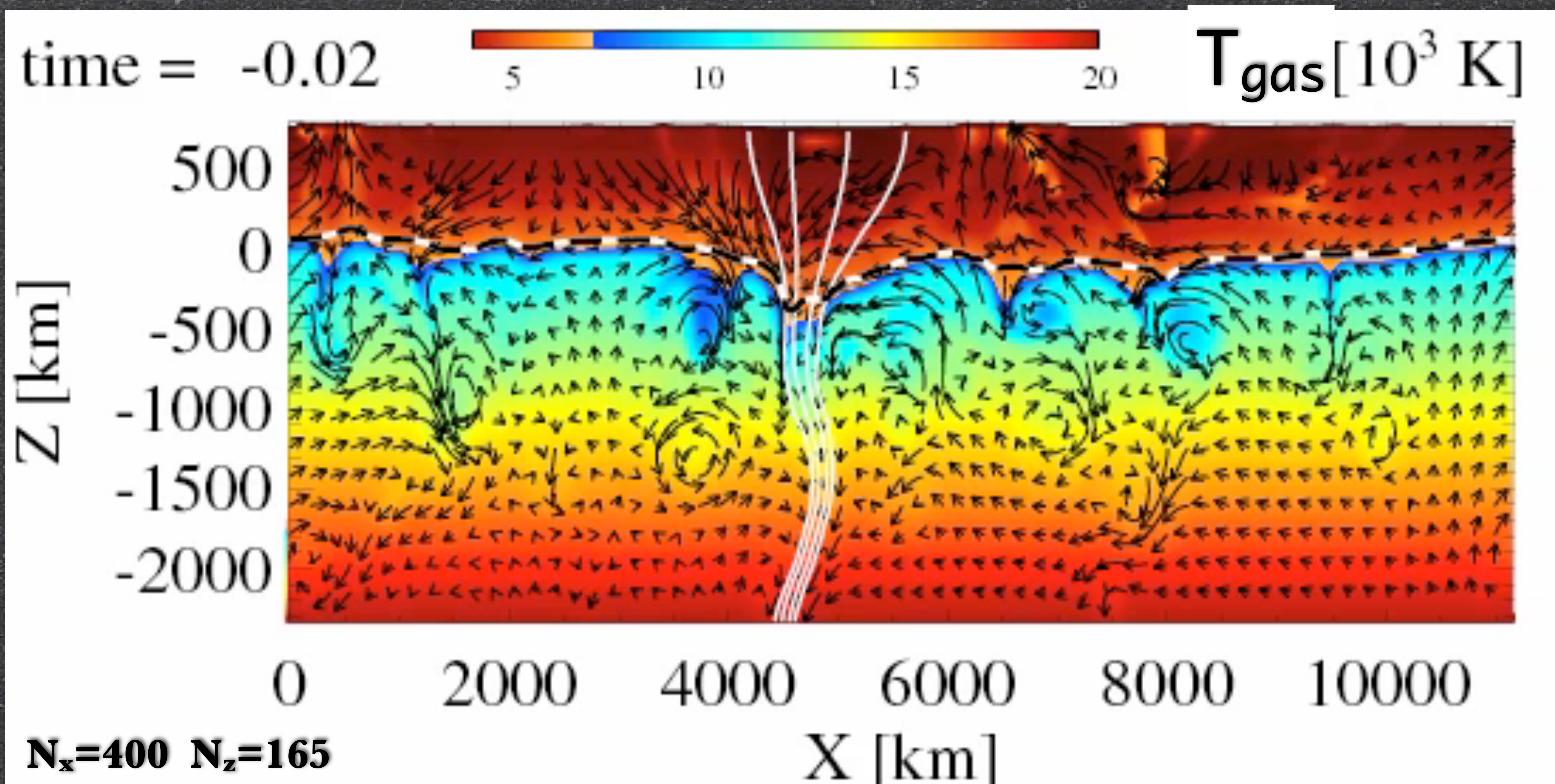


Time Evolution of Flux Tube in the Solar Atmosphere

YK, Steiner, Steffen, Suematsu (2011) by using CO5BOLD

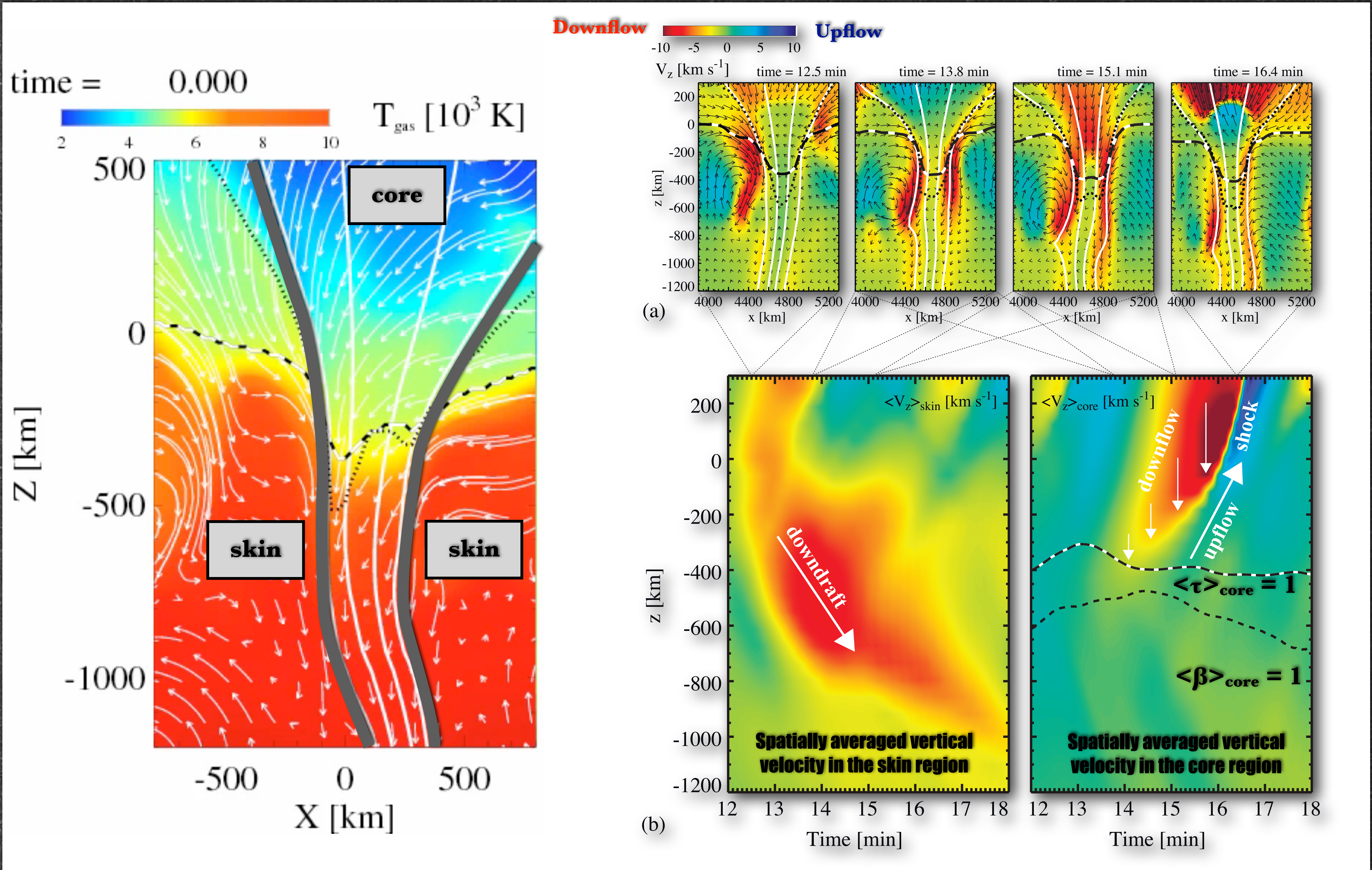
white contour: Magnetic field line, Arrows: velocity

White & Black curve: Optical surface



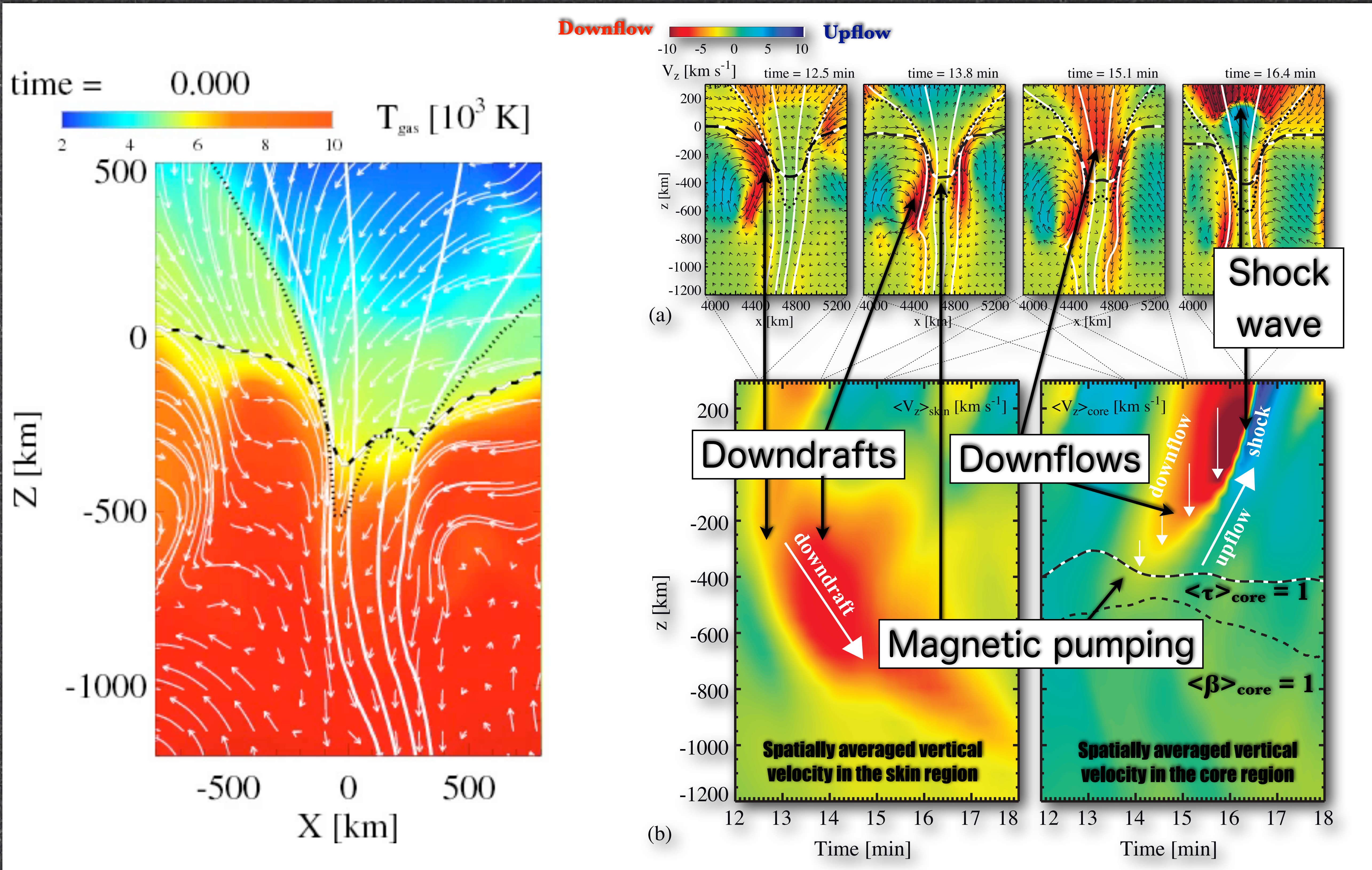
EXCITATION OF SLOW-MODE & SHOCK

YK, Steiner, Steffen, Suematsu (2011)



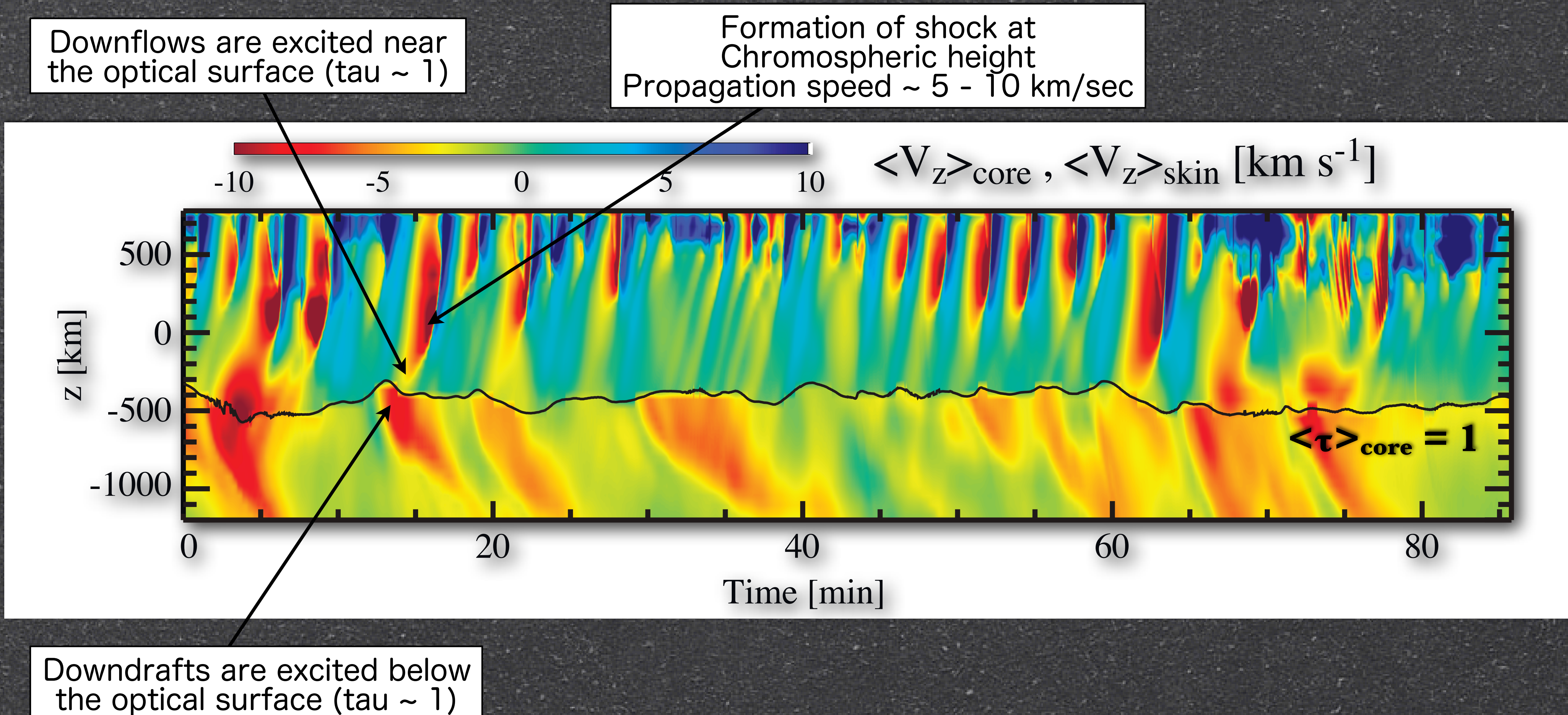
EXCITATION OF SLOW-MODE & SHOCK

YK, Steiner, Steffen, Suematsu (2011)

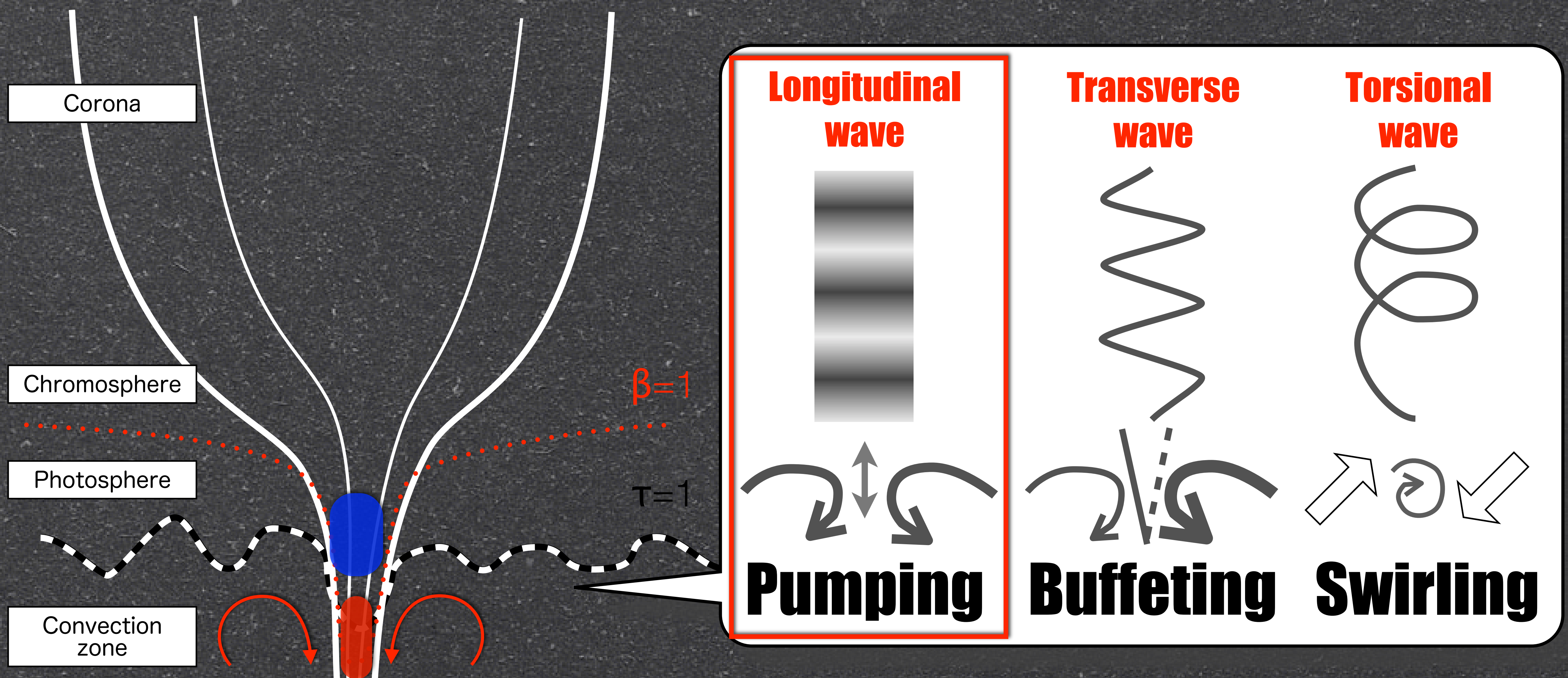


CORRELATION BEWTEEN
DOWNDRAFTS AND SLOW-MODES/SHOCKS

YK, Steiner, Steffen, Suematsu (2011)

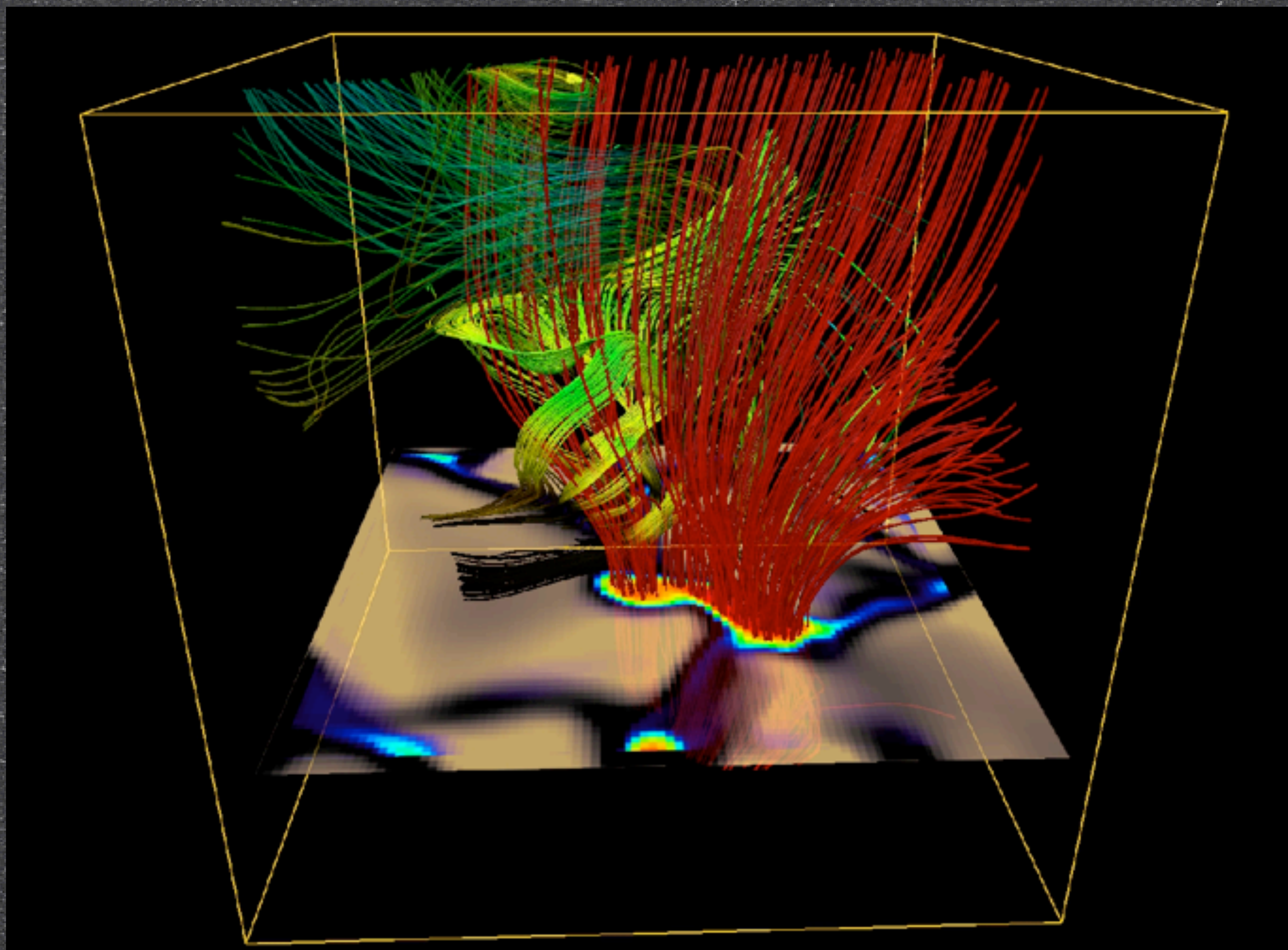


磁束管で自発的に生じる
磁気流体波とは？

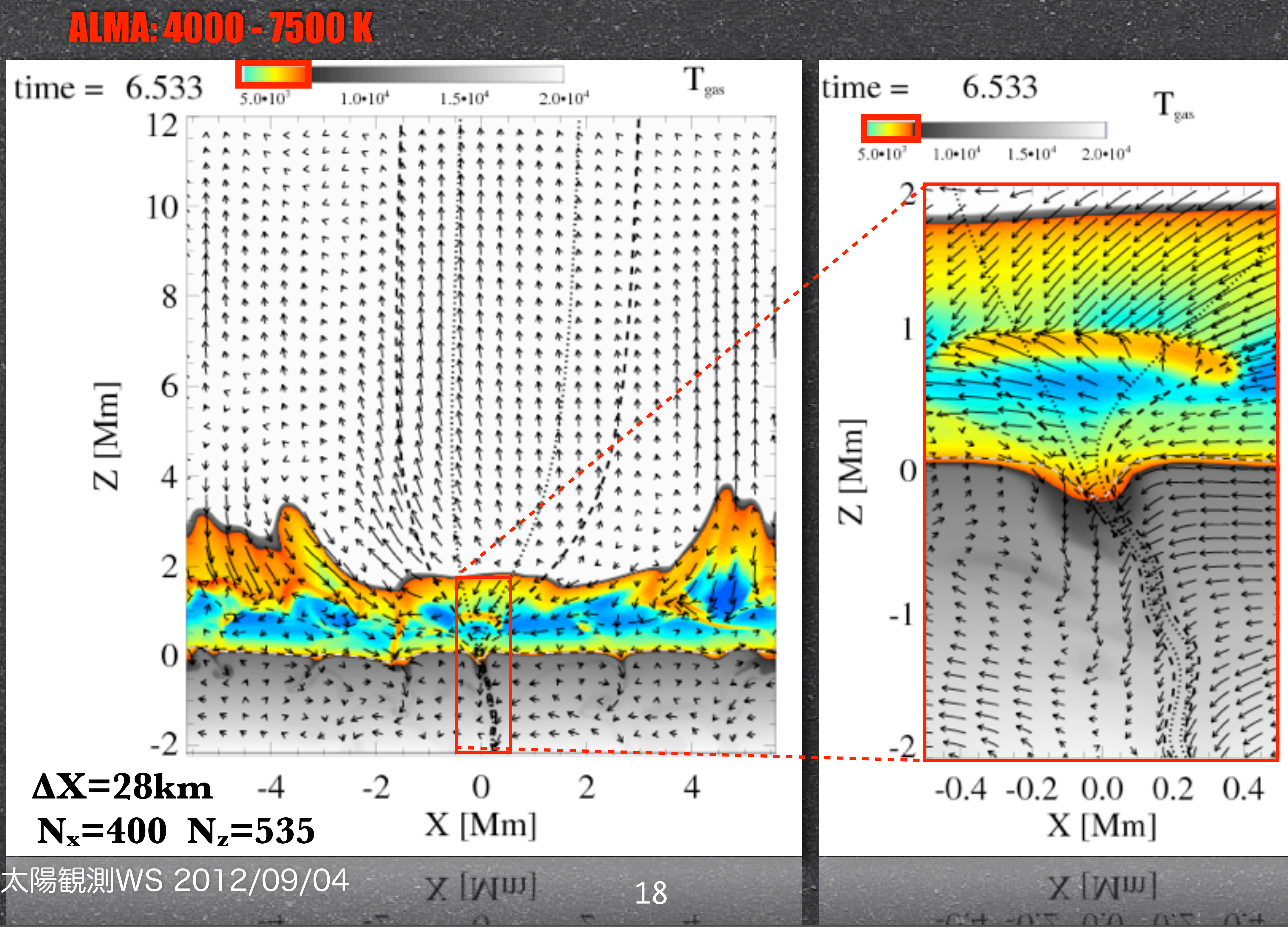


Magnetic Tornadoes in the Solar Atmosphere

Wedemeyer-Böhm et al. (2012) by using CO⁵BOLD



What we can observe by using ALMA?



ALMAによる多層間結合
高解像高速撮像

950GHz@0.04”

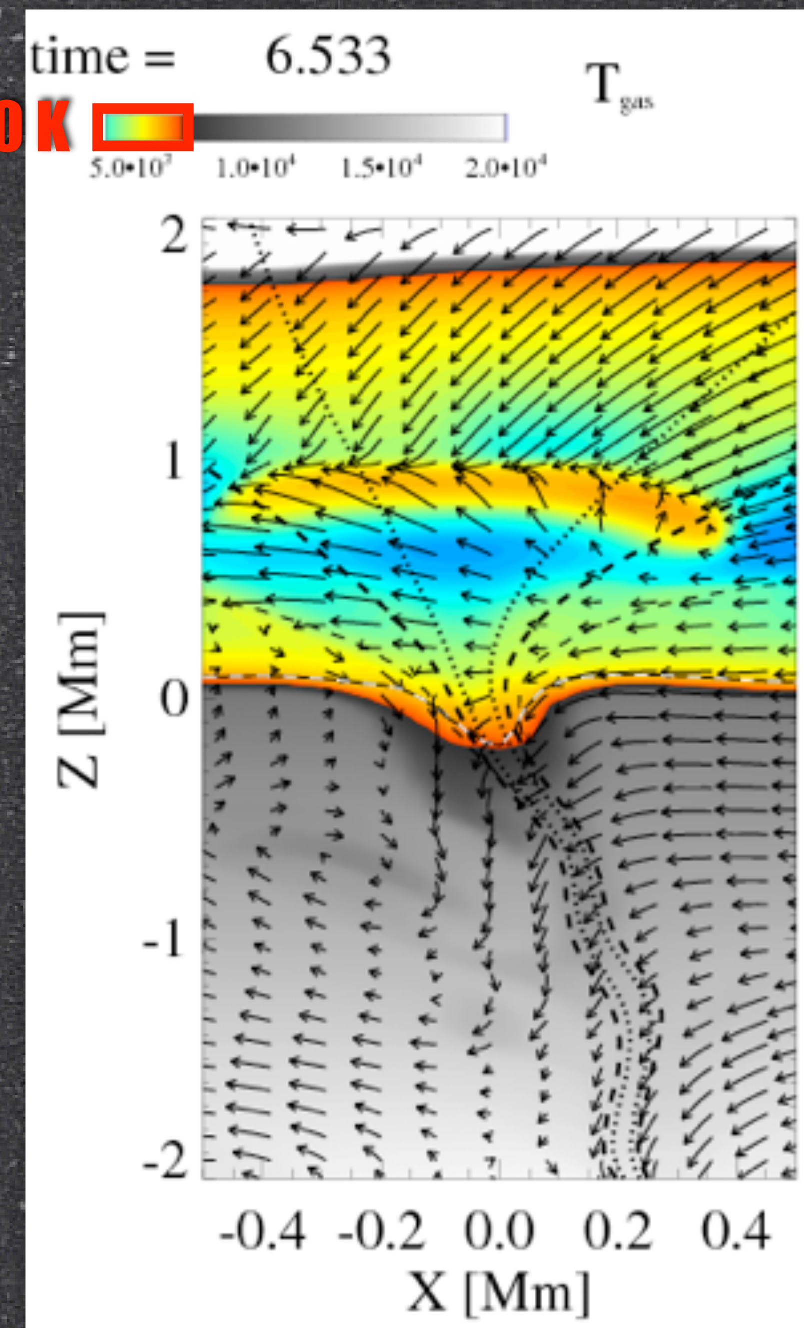
- Higher-spatial resolution ~ 10 km
- Internal structure of the base of flux tube (DC)
- Propagation of shocks along the flux tube (Limb)

300GHz@0.126”

- Comparable spatial resolution ~ 30 km to models
- Detect propagation of shocks inside the flux tube

100GHz@0.38”

- Lower-spatial resolution ~ 100 km
- Shock propagation time ~ 1000 km / 10 km/s = 100 s
- High-cadence observation is useful < 1 min



まとめ

- 動的な太陽大気モデリングにはRMHDが必要不可欠！
  - 磁気大気：Canopyなどの複雑な磁場構造によって大気構造が決まっている
- 磁束管で自発的に遅い磁気音波が発生
  - 上部対流層での速い下降流(downdraft)によって遅い磁気音波が励起
  - 光球から上空へ遅い磁気音波が伝播し、彩層で衝撃波となる
  - 3次元ならば渦を伴うトルネード状になるだろう
- 磁束管で光球・彩層の振動現象の存在を予言
  - 高解像度(< 0.1”)高頻度(< 60sec)の光球・彩層観測が必要
  - 磁束管の構造を知るには、光球・彩層磁場観測が必要不可欠

Solar-Cの分光偏光観測とALMAの高解像度撮像に期待