Buoyancy Instabilities from Anisotropic Conduction in Stellar and Planetary Atmospheres

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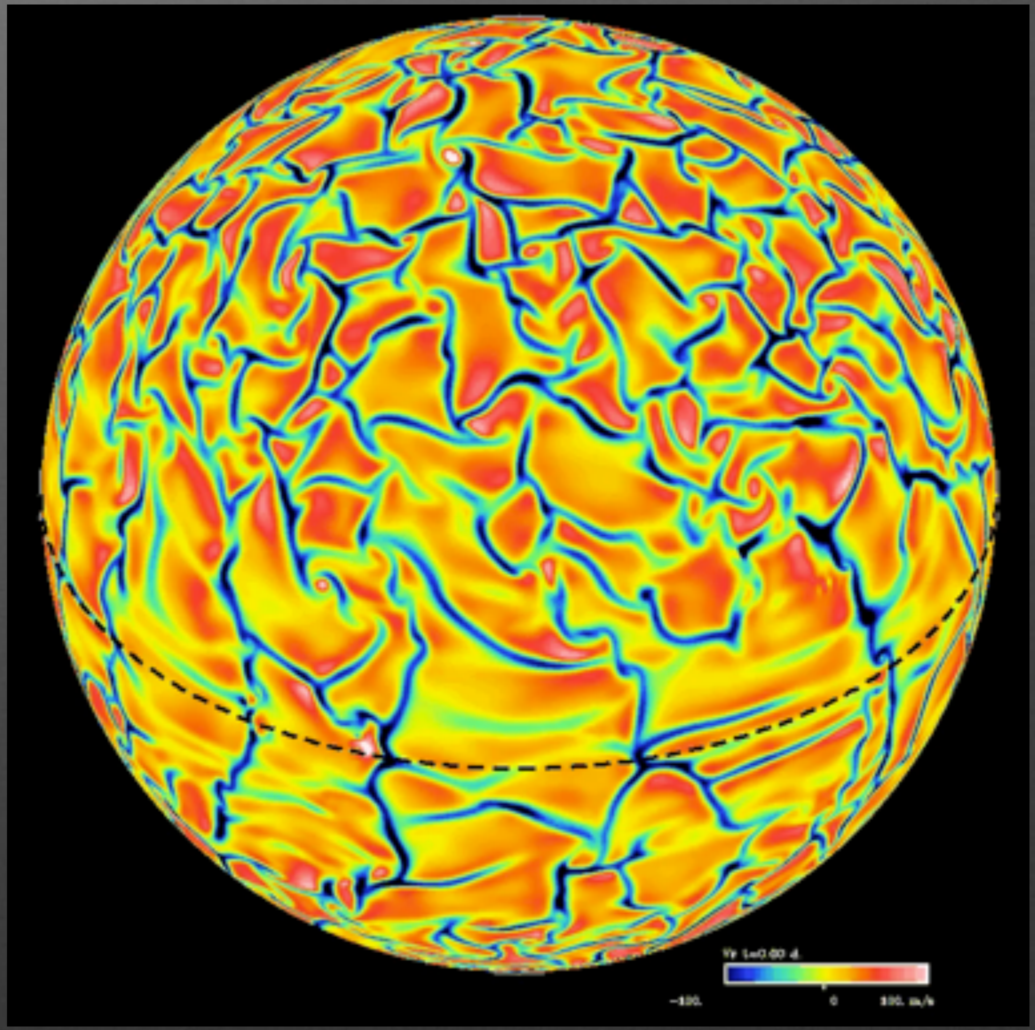
Convection

- Convective Instability requires an outwardly decreasing entropy gradient
    - Forms convective cells, with hot, less dense, material rising and cool, more dense, material sinking
    - Tightly linked to buoyancy forces
- The instability criterion can change in the presence of anisotropic conduction and a weak (High Beta) magnetic field



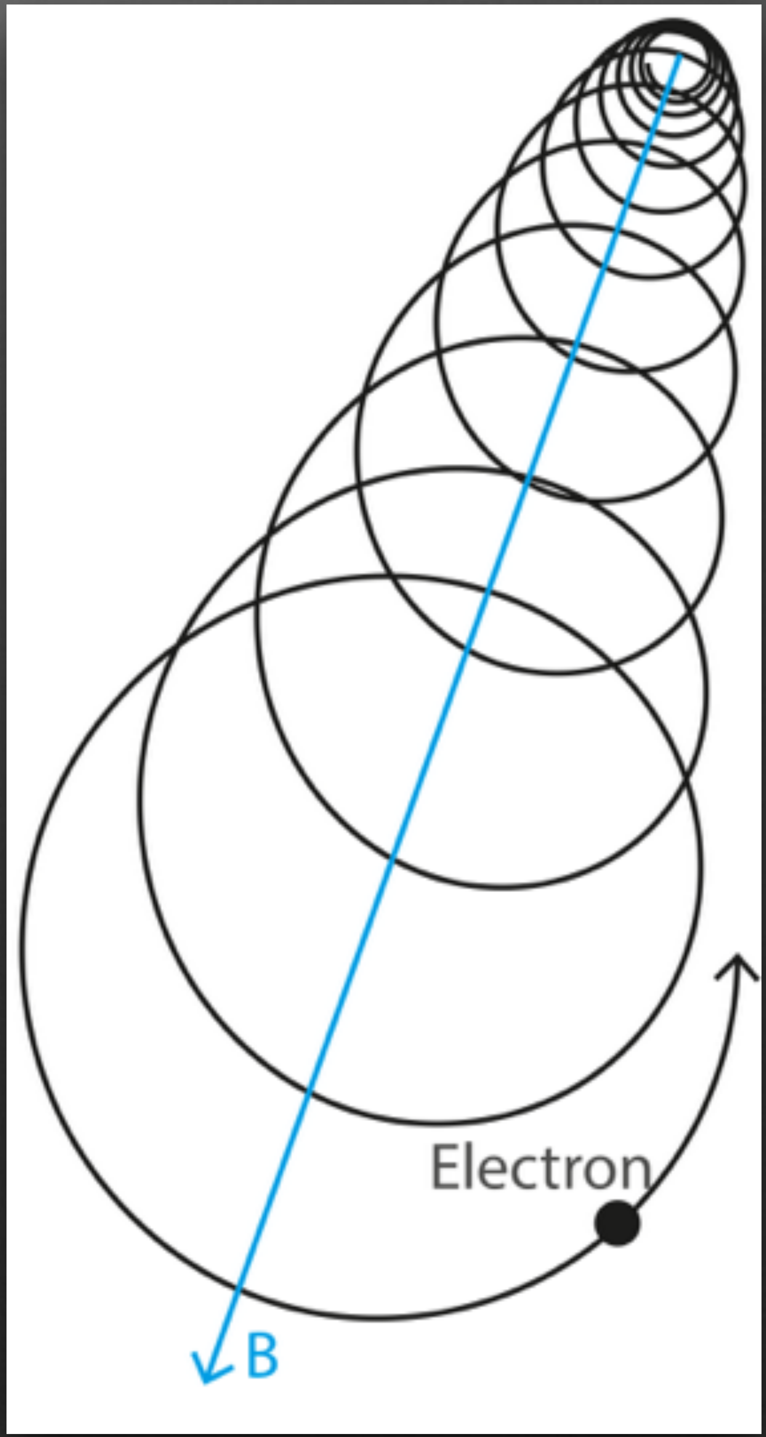
Anisotropic Thermal Conduction

- In the presence of a magnetic field, electrons will gyrate around the field axis, forming a helical path if any initial velocity components || to the field are present

- If — **mean-free-path > gyro-radius** — electrons can travel a significant distance in the field direction before experiencing a collision, i.e. anisotropic electron motion

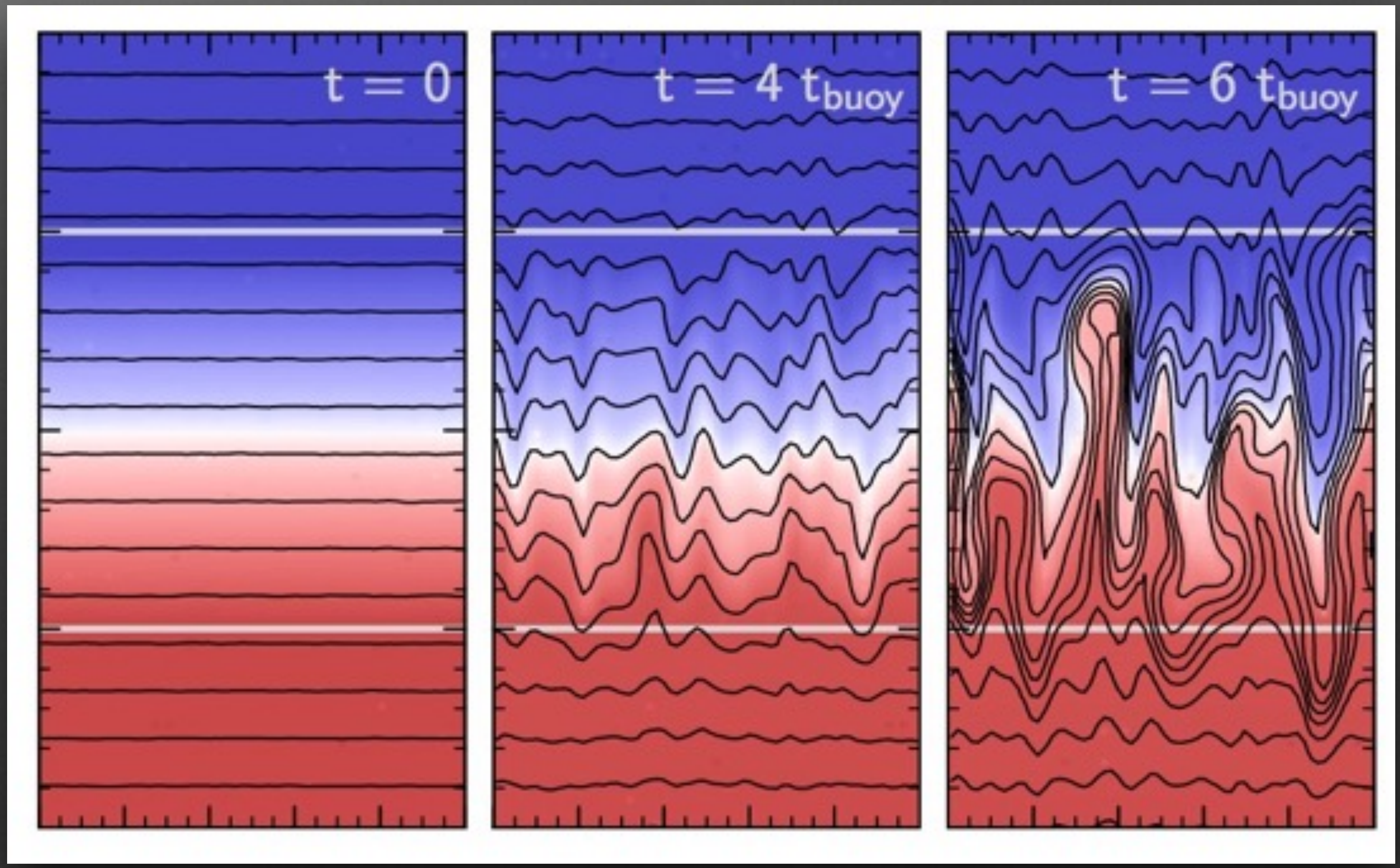
    - This leads to anisotropic thermal conduction since electrons are the main energy carriers

- The **instability criterion** then changes to be a **combination of the temperature gradient and magnetic field orientation**



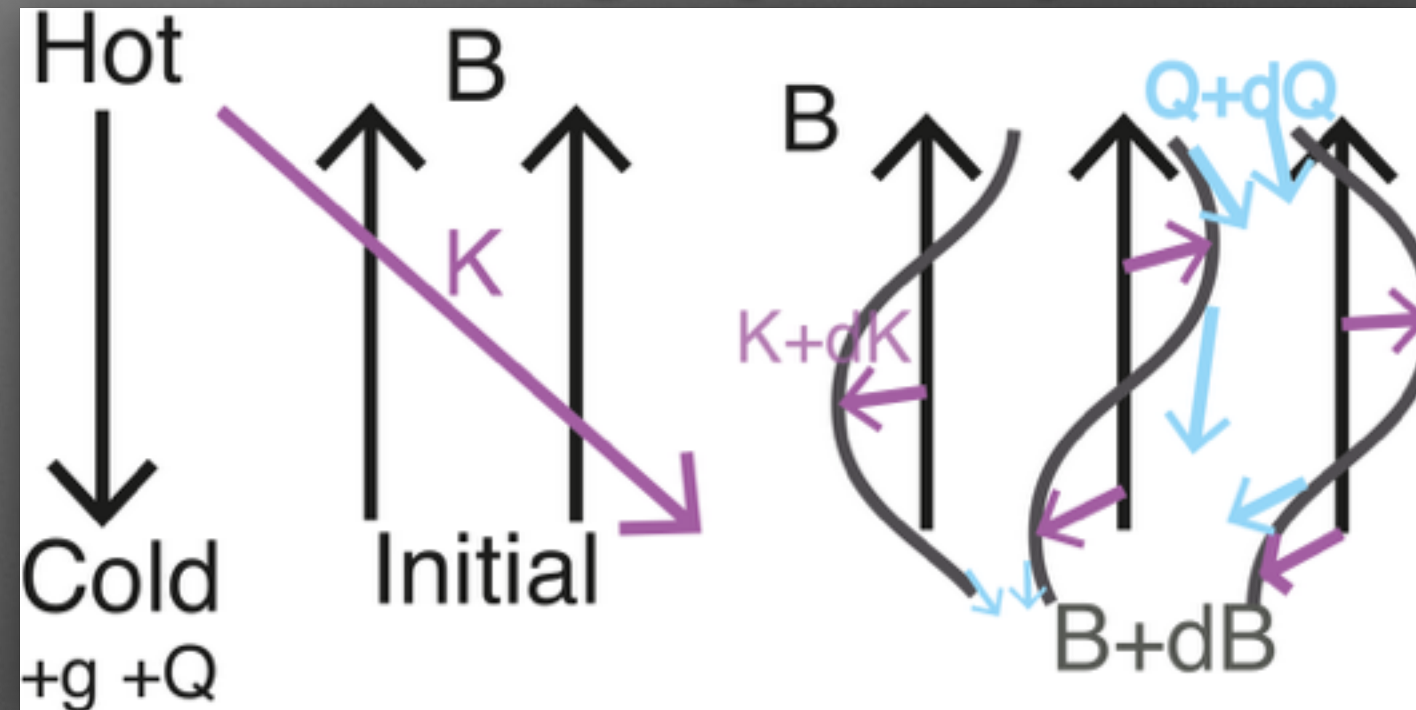
MagnetoThermal Instability (MTI): A Brief Overview

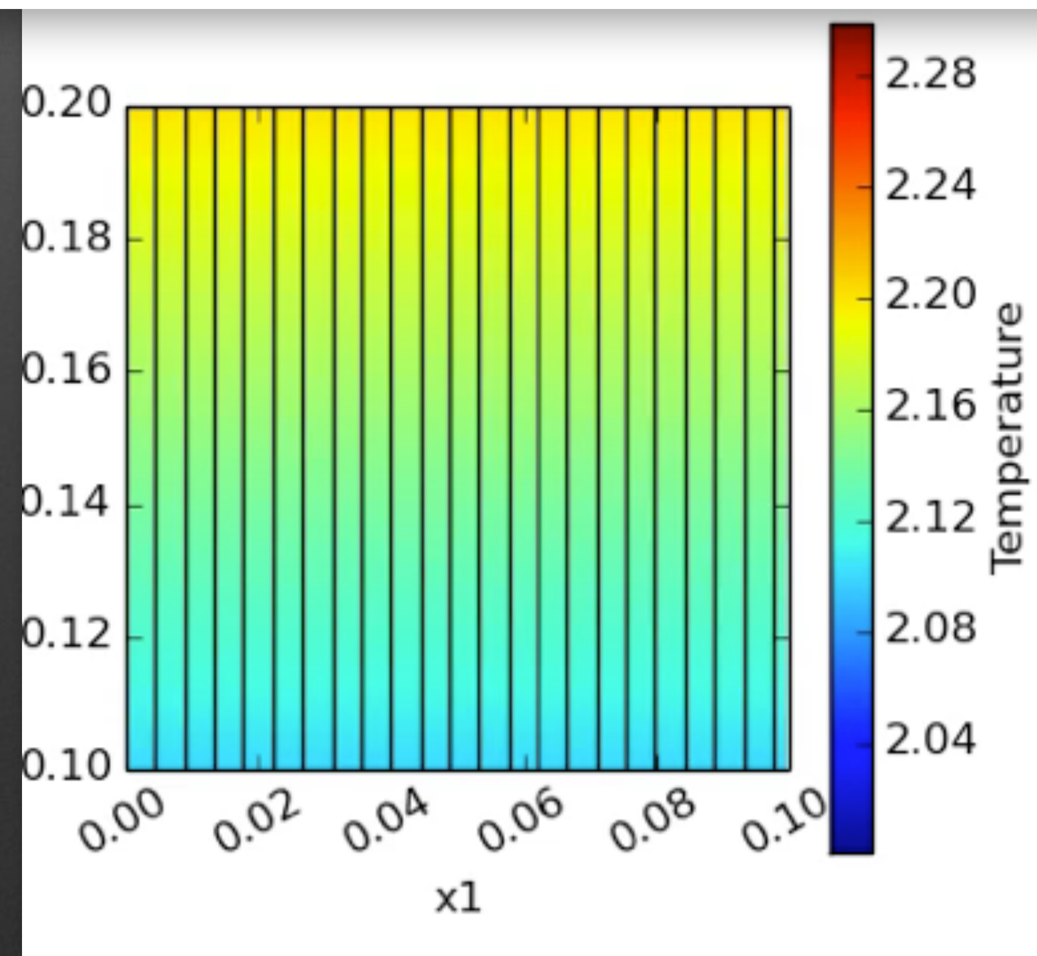
- The MTI can occur if:
  - The temperature **increases** in the direction of gravity
  - The magnetic field is primarily **horizontal**
  - **Perturbations** with non-vanishing perpendicular and parallel wave modes are present



The Heat-Flux-Driven Buoyancy Instability (HBI)

- The HBI can occur if:
  - The temperature decreases in the direction of gravity
  - The magnetic field is primarily vertical
  - **Perturbations** with non-vanishing perpendicular and parallel wave modes are present





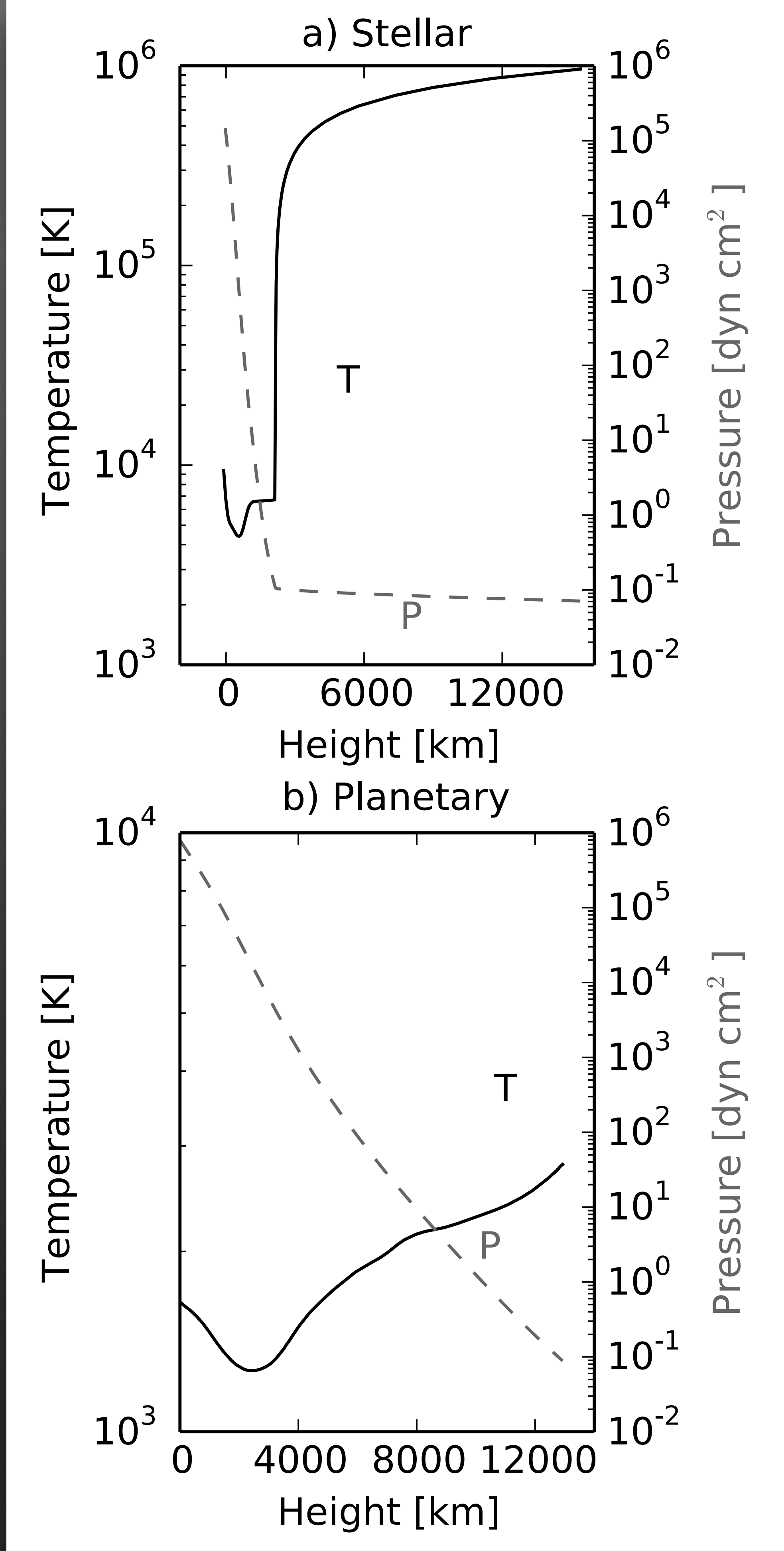
Galactic HBI: Cooling Cores

- Previous investigations into the HBI focused upon its applications within the intra-cluster medium (ICM) of galaxy clusters: The **cooling-flow problem** - why cool cores in galaxy clusters do not undergo catastrophic cooling
  - **Found:** HBI precipitates catastrophic cooling by reorienting magnetic field lines to the horizontal, thus inhibiting radial thermal conduction
  - **Observations:** In Hα, HBI consistent filaments near cooling cores, allowing for reduced levels of thermal conduction
  - **Solution:** Heating via AGN feedback leading to turbulent stirring

The Remarkable Phoenix Cluster - NASA 2012 - http://www.nasa.gov/mission_pages/chandra/multimedia/phoenix_cluster.html

The HBI in new environments

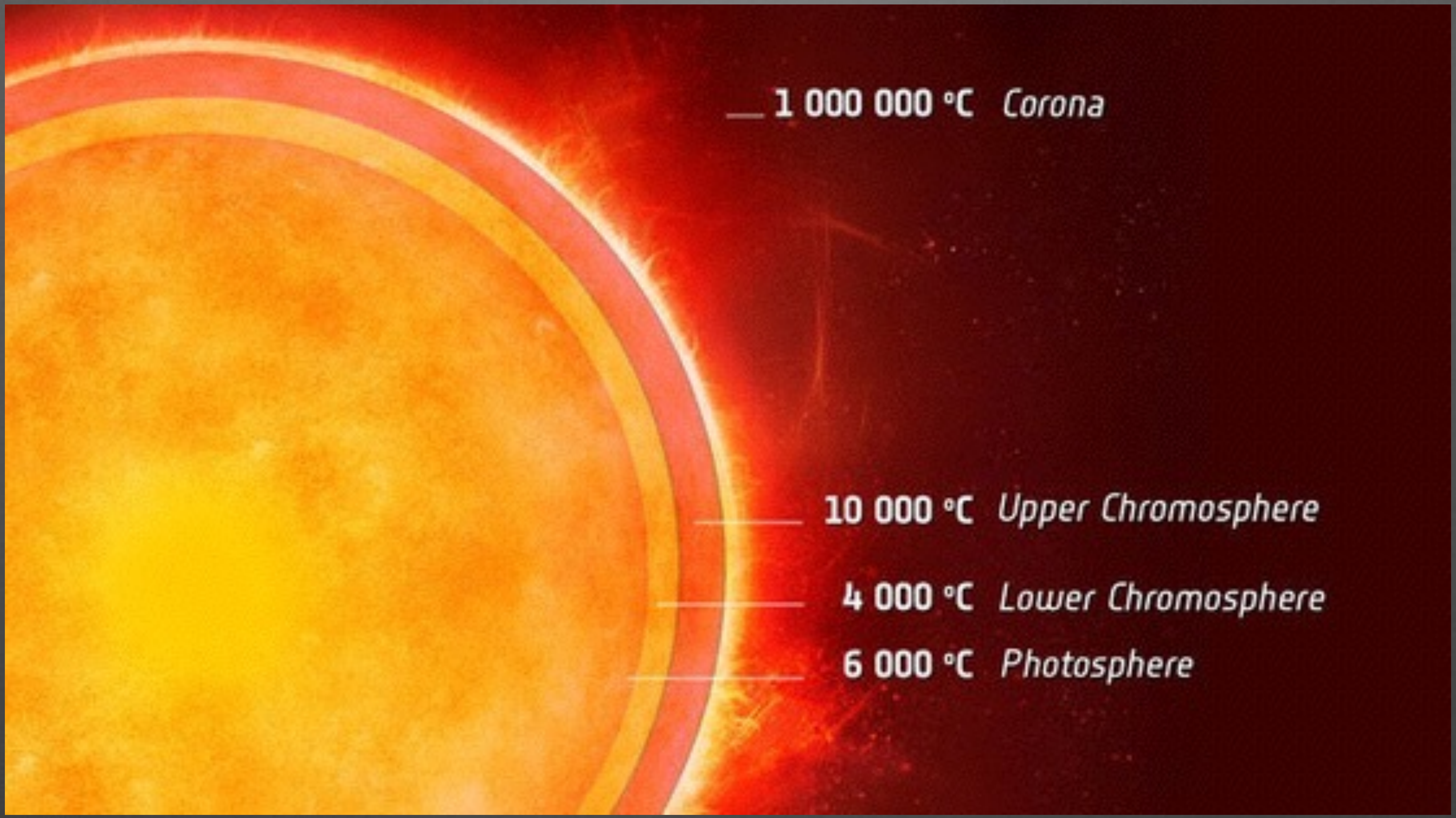
- Investigate the HBI on smaller scales:
  - a) **Stellar Atmospheres: e.g. The Solar Transition Region and Corona** using the Avrett and Loeser (2008) 'c7' average quiet Sun model
  - b) **The outer atmosphere of the Hot Jupiter, HD209458b,** using Moses et al. (2011) day-side average model



Avrett, E. H., and R. Loeser. 2008. The Astrophysical Journal Supplement Series 175:229–276.

Moses, J. I., et al. 2011. The Astrophysical Journal 737, 15

Possible Application: Coronal Heating Problem



- HBI exhibits **non-linear** behaviours:
  - Restriction of **Vertical Heat Flux**
  - Generation of **Horizontal Velocity Motions**

- As such: The HBI may provide a mechanism to **thermally isolate regions of an atmosphere**
  - The Coronal Heating problem - i.e. why the Solar corona is much hotter than the photosphere

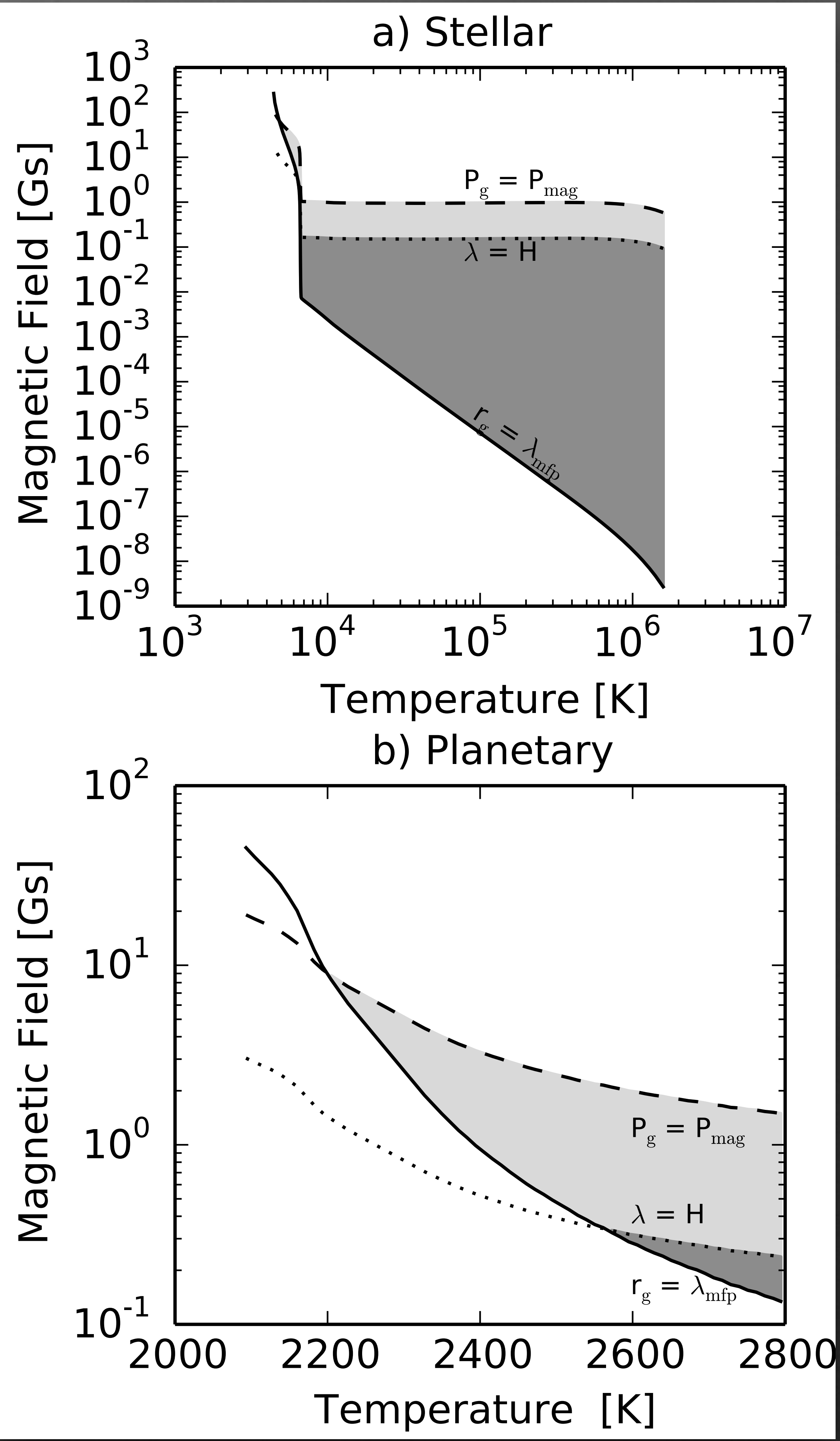
http://www.ascensionnow.co.uk/mystery-of-the-suns-corona.html

HBI Limits: An Overview

- Use T-P profiles to investigate *windows*, within the parameter space of atmospheric plasmas, for which the HBI may be able to operate
    - Lots of different limits can be applied to this parameter space, each with varying degrees of both strictness and importance
    - We focus upon limits on the:
        - **Magnetic Field Strength**
        - **Perturbation Wavelength** (via system timescales)

HBI Limits: Magnetic Field

- **Minimum** field limit:
  - Electron mean-free-path > Electron gyro-radius
- Two ways of formulating a **maximum** field limit:
  - 1) The magnetic pressure must be less than the gas pressure, i.e. $\beta>1$
  - 2) The effect of magnetic tension, at typical length scales, is negligible, i.e. $\beta>4\pi^2$



HBI Limits: Timescales

- **Maximum** mode wavelength limits:
  - Rapid Conduction
  - Thermal Conduction dominates over Radiative Loss
- **Minimum** mode wavelength limit:
  - Magnetic tension stabilises short wavelength perturbations

$$t_c \sim \frac{L^2}{\frac{\chi T}{P}} \approx \frac{L^2 n k_B}{(6 \times 10^{-7}) T^{5/2}}$$

$$t_{\rm dyn} = \frac{2\pi}{\omega_{\rm dyn}} = 2\pi \sqrt{\frac{H}{g}}$$

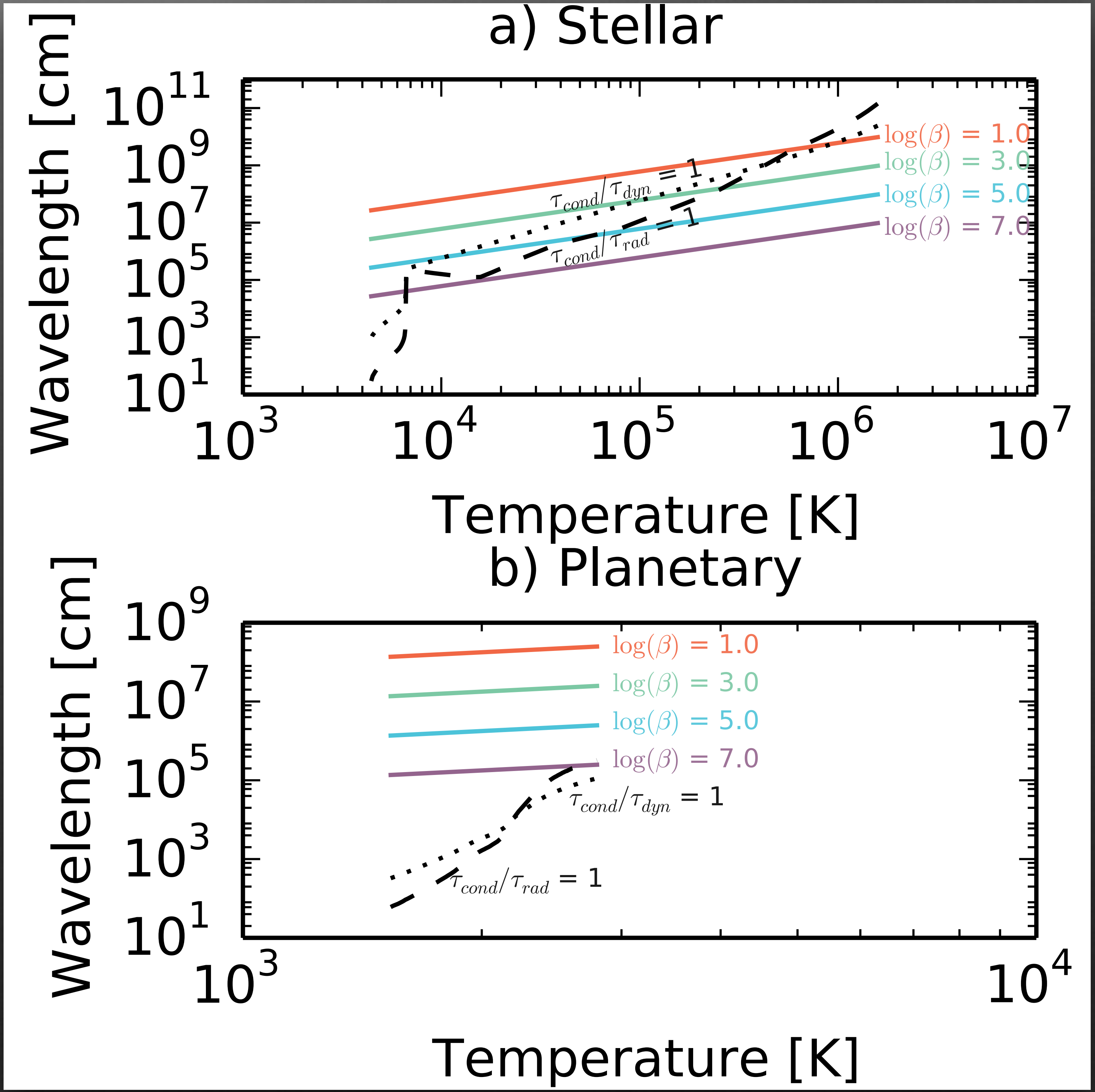
$$t_{\rm rad} = \frac{E_{\rm thermal}}{\frac{dE}{dt}} \approx \frac{3 k_B T}{n_e \Lambda (T)}$$

$$t_c \ll t_{\rm dyn} \qquad t_c \ll t_{\rm rad}$$

$$kH < \sqrt{\beta}$$

HBI Limits: Timescales

- **Stellar Case:**
  - For *low* plasma betas, the only available HBI modes have long wavelengths, on the order of the scale height of the atmosphere
- **Planetary Case:**
  - No obviously available modes at typical field strengths



Simulating the HBI

- We use ATHENA*, a grid based, astrophysical, MHD code
- 2D Simulations on both Local and Global scales with a:
    - Linear, outwardly increasing temperature profile:
    - Purely vertical magnetic field: $\boldsymbol{B} = B_0 \hat{z}$
    - Constant, downwards, gravitational acceleration: $\boldsymbol{g}(z) = -g_0 \hat{z}$
- Apply a, single mode, velocity perturbation to the initial equilibrium configuration.

$$T\left(z\right) = T_0 \left(1 + \frac{z}{H_T}\right)$$

$$\rho\left(z\right) = \rho_0 \left(1 + \frac{z}{H_T}\right)^{-2}$$

$$P\left(z\right) = P_0 \left(1 + \frac{z}{H_T}\right)^{-1}$$

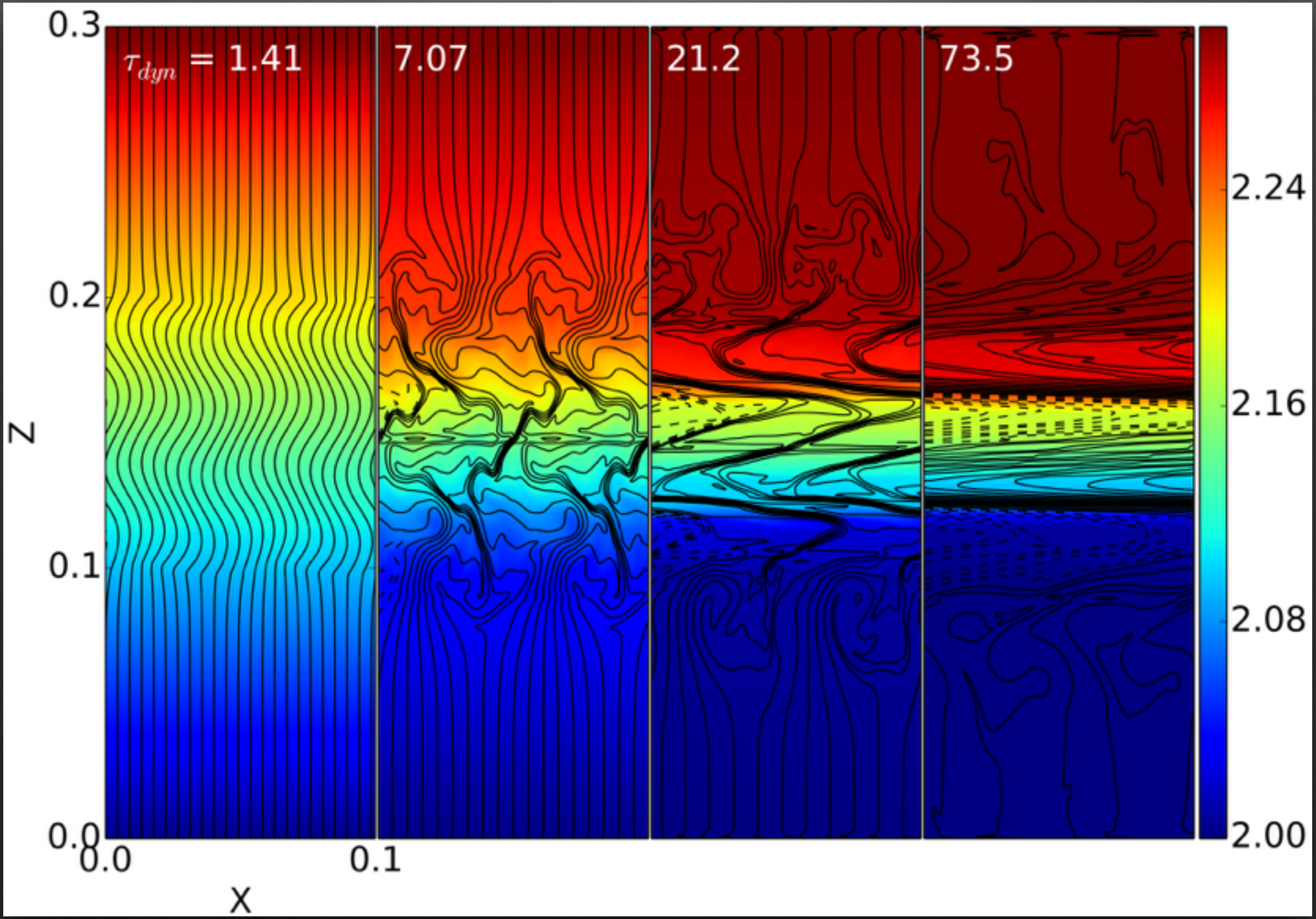
$$T_0 = 2\rho_0 =$$
$$P_0 = 2\mu = 2g_0 = 2$$
$$H_T = 2$$
$$\beta = 2 \times 10^{(9,\ 7,\ 5,\ 3)}$$

*Stone et al., ApJS, 178, 137 (2008)

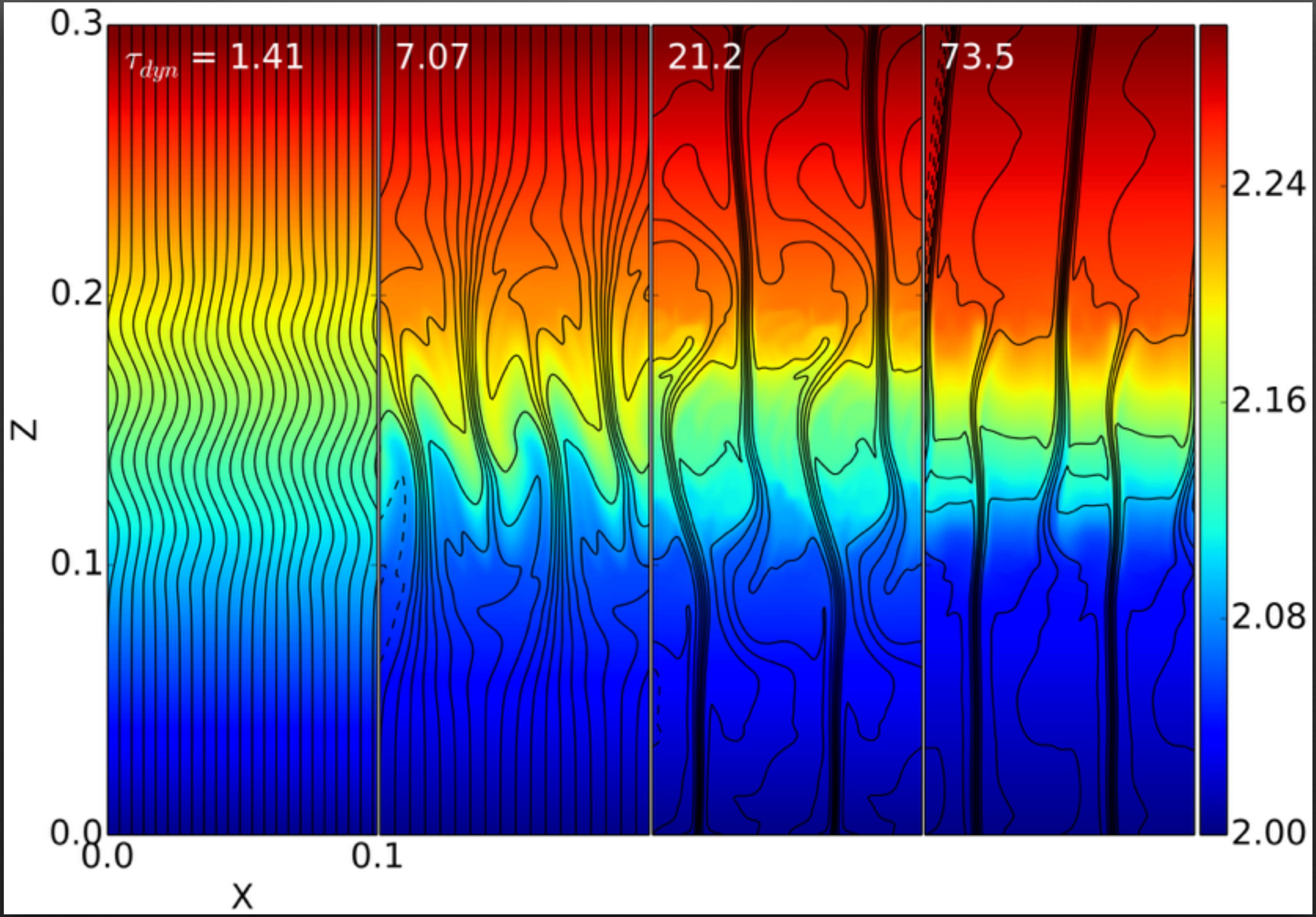
Simulating the HBI (2)

- We make two changes to the way ATHENA works:
  - We set the top and bottom boundaries conditions to be:
    - Momentum Reflective
    - **Constant Temperature**
    - Magnetic field vectors set to last active cell in each column
  - Horizontally, we use ATHENAs periodic BC’s
  - Change the conduction module to split the simulation into three regions:
    - **Top and Bottom buffer regions** with **isotropic** conduction.
    - **Central, HBI, region** with **anisotropic** conduction.

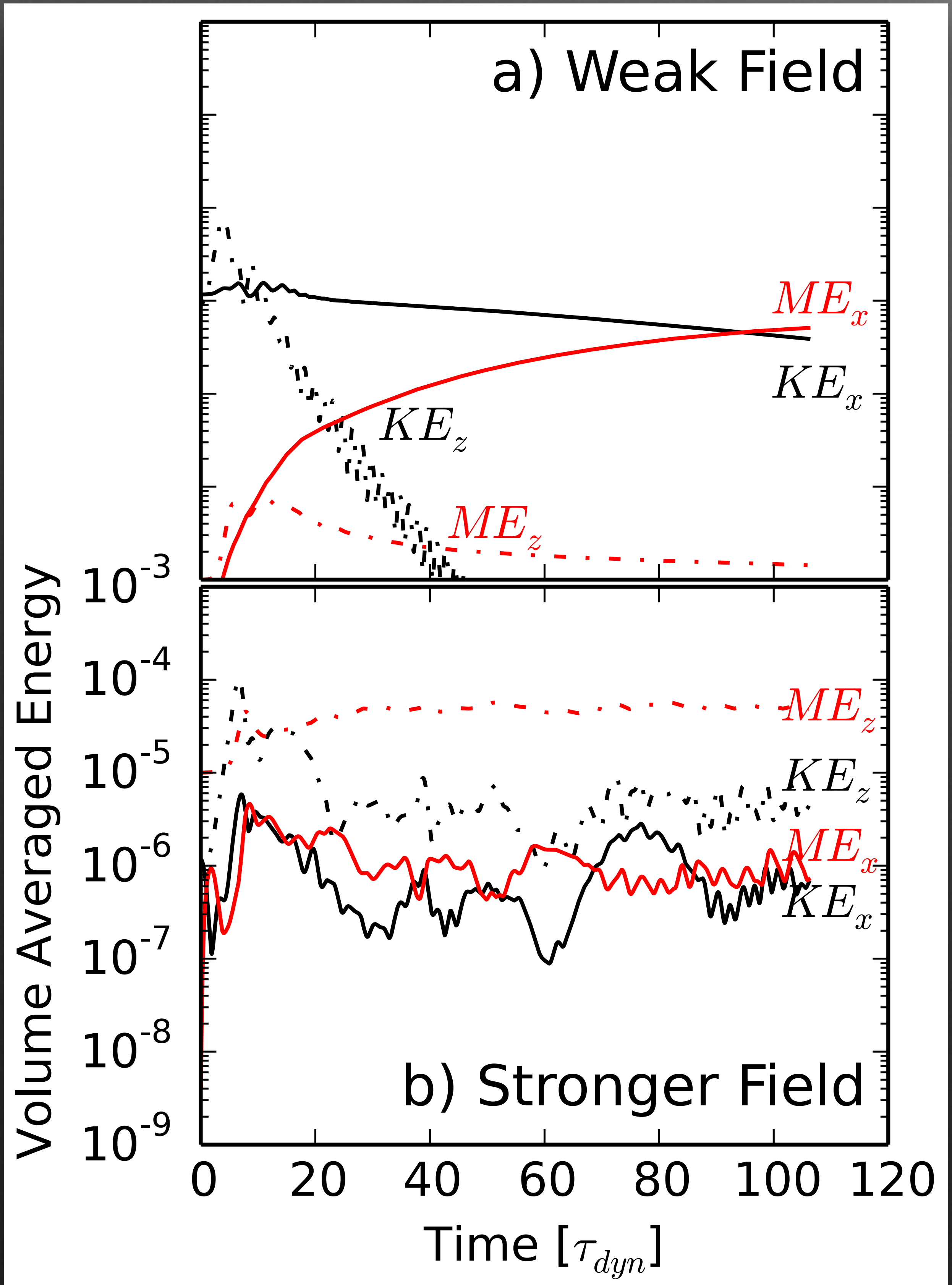
Local-Scales: Weak Fields

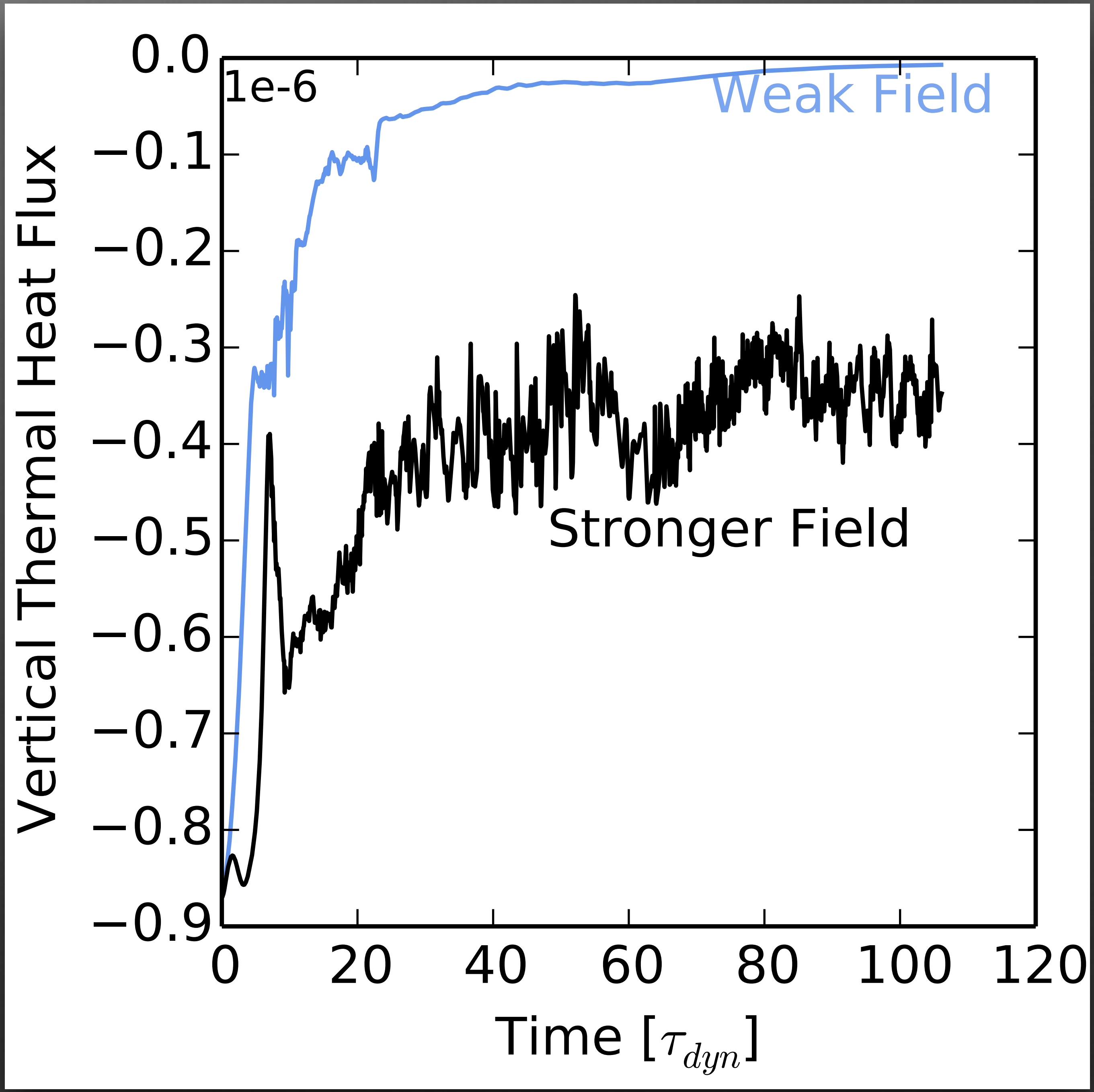


Local-Scales: Stronger Fields



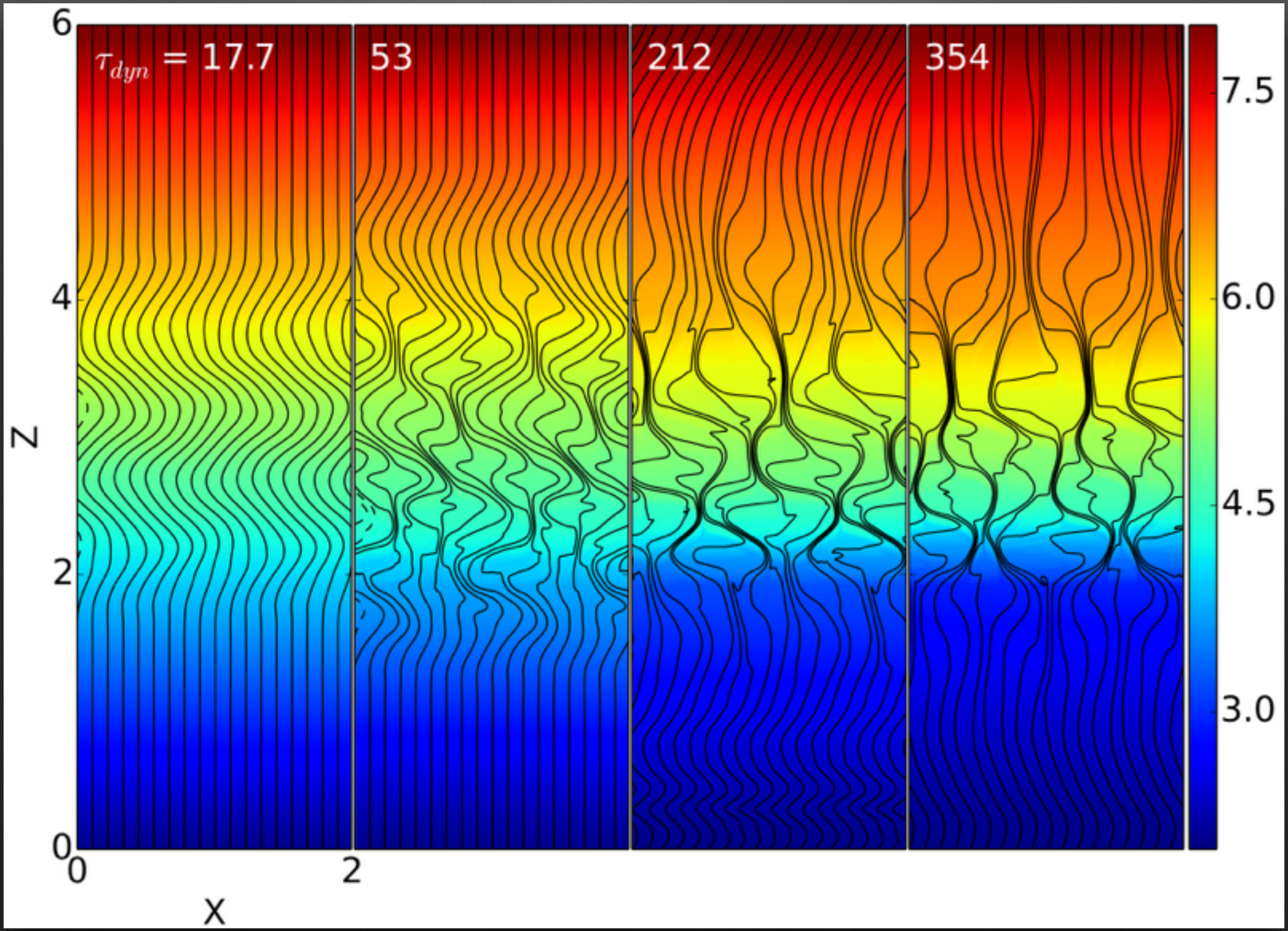
Local-Scales: Energies and VHF





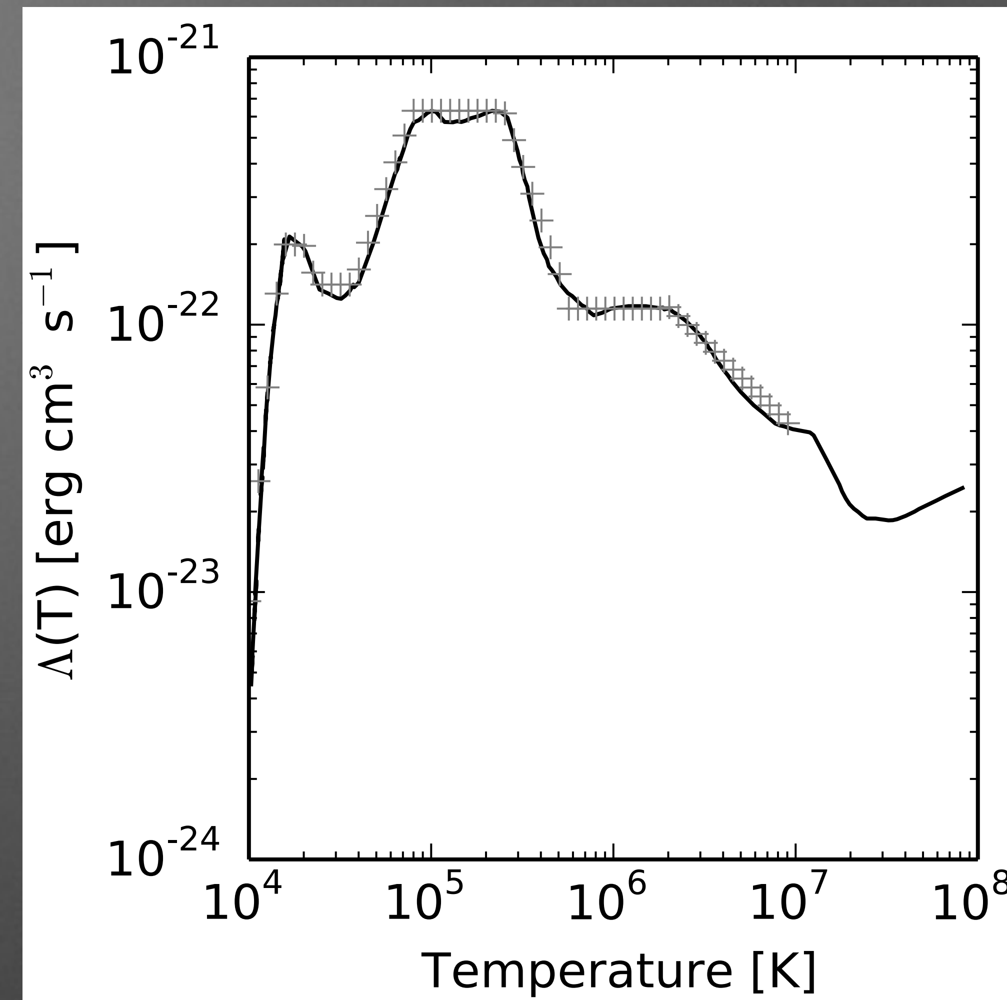
$$\mathrm{VHF} = -\int_S \chi \hat{b} \left(\hat{b} \cdot \nabla \right) T \cdot dS$$

Global-Scales: Stronger Fields



Radiative Loss

- Important for simulations of the Stellar HBI
- Two main methods by which radiative loss can be included:
    - Through a radiative loss function
    - **By varying the ratio of the conductive and radiative timescales**
- Found that the HBI:
    - **Remains unchanged for low levels of radiative loss**
    - As radiative loss starts to dominate over conduction, the evolution of the HBI is suppressed

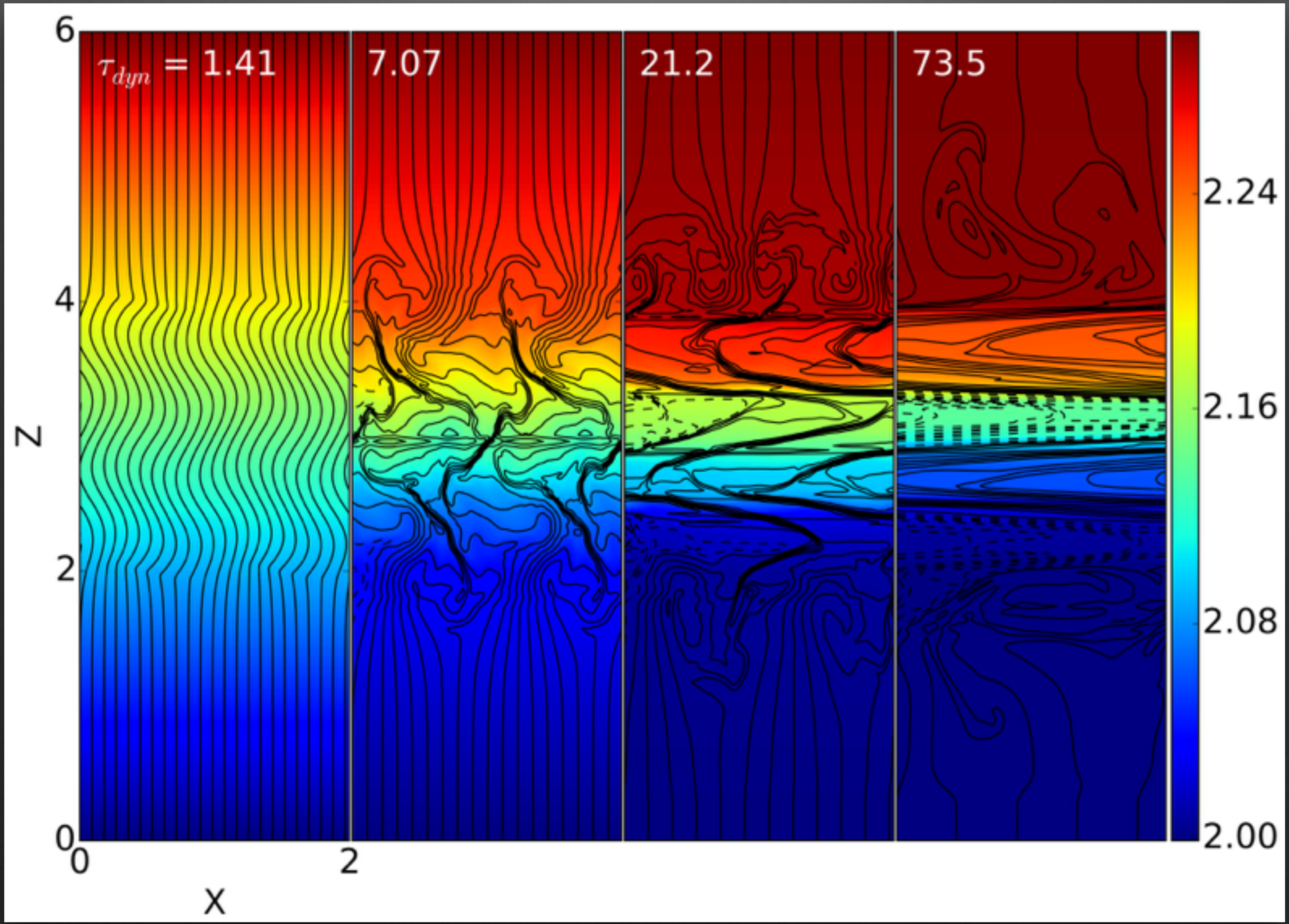


Rosner, R., W. H. Tucker, and G. S. Vaiana. 1978. "Dynamics of the quiescent solar corona." ApJ 220: 643–645.

$$\Lambda(T^\star) = \frac{t_c}{t_{rad}} \frac{3P\kappa_c}{n^2\lambda^2}$$

$$P = nT^\star$$

Local-Scales: Radiative Loss



Summary

- The HBI definitely could have applicability beyond the ICM, e.g. in Stellar and Planetary atmospheres.
- To understand this, we are investigating:
  - Temperature-Pressure profiles of other stellar and exoplanetary atmospheres, and of the Earths thermosphere
  - The effect of extended transition-regions and chromospheres on the HBI parameter space
  - Slowed thermal conduction - critical for our understanding of the HBI in exoplanet atmospheres
  - The magnetic field strength structure of stellar coronas, transition regions, and chromospheres