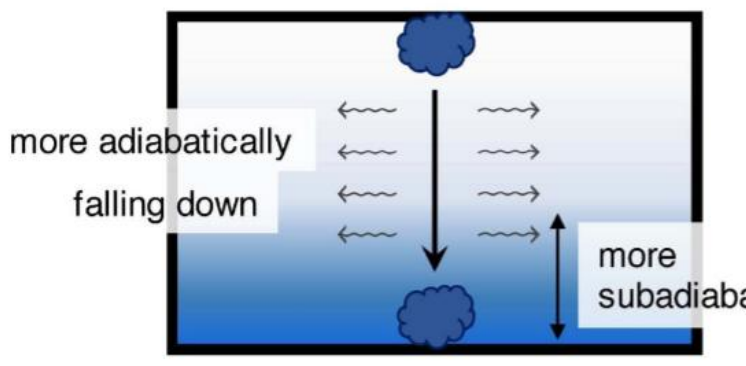
Numerical Study of Magnetic Influences on Plume-Driven Convection in the Sun

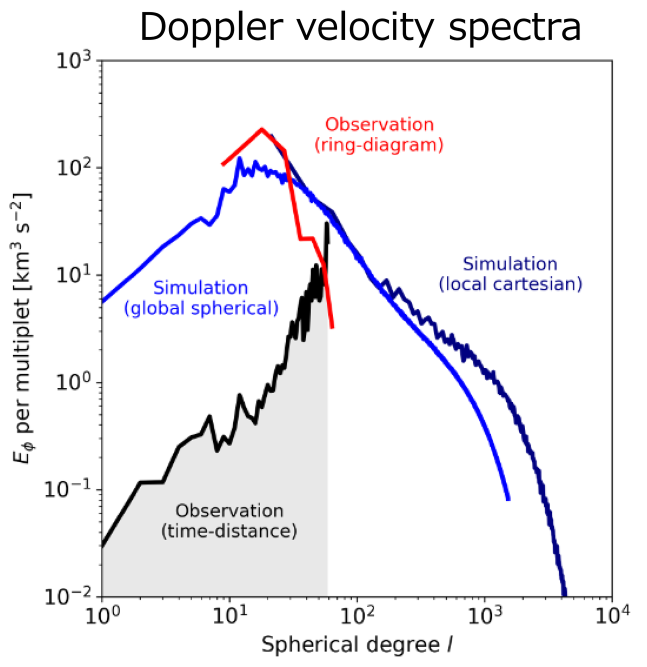
Kazuma Saito[1], Hideyuki Hotta[1], Allan Sacha Brun[2,1]
1) ISEE/Nagoya-U, 2) CEA Paris-Saclay



Introduction

Convection conundrum

- Conventional solar convection models predict the existence of large-scale convection.
- Global simulations also reproduce the large-scale convection.
- In contrast, large-scale convection has not been observed.



(Hotta+2023)

Why Large-Scale Convection Occurs?

- superadiabaticity: a measure of convective efficiency

$$\delta = -\frac{H_\mathrm{p}}{c_\mathrm{p}}\frac{ds}{dz}$$

1. Surface cooling generates low-entropy perturbation.
2. Overdense low-entropy perturbations move downward.
3. During transport, the low-entropy perturbation is mixed.

➢ Negative entropy gradient develops.

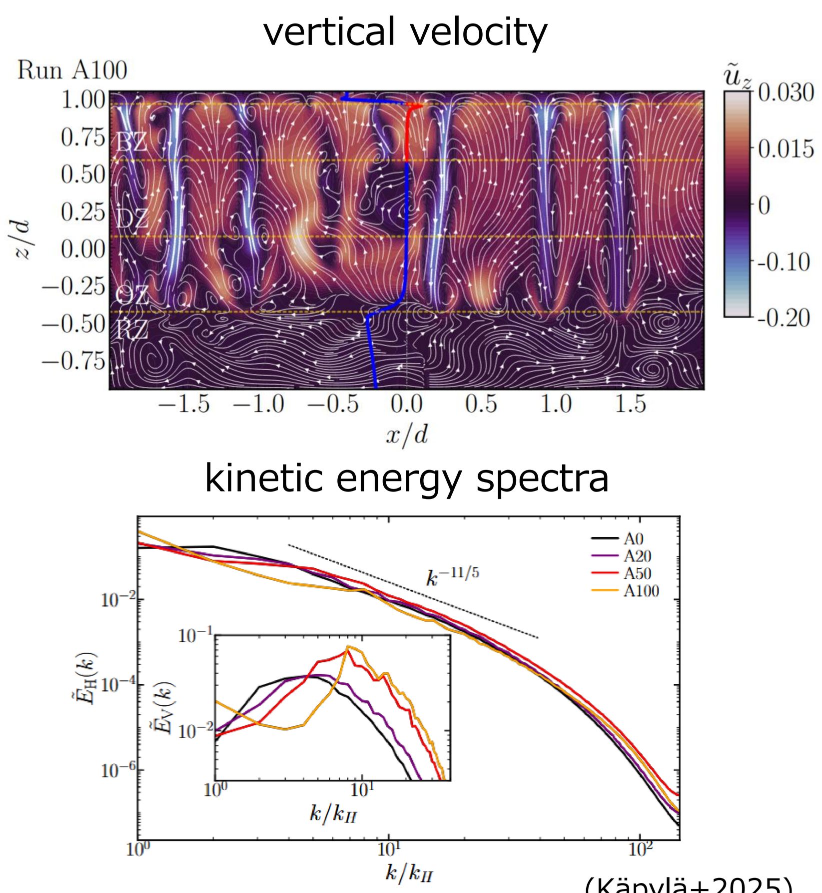
- The dominant convection scale is thought to be proportional to the density scale height.
- The density scale height increases with depth.
- Conventional solar convection models consider the deep convection zone to be convectively unstable.

➢ Large-scale convection occurs.

Previous studies

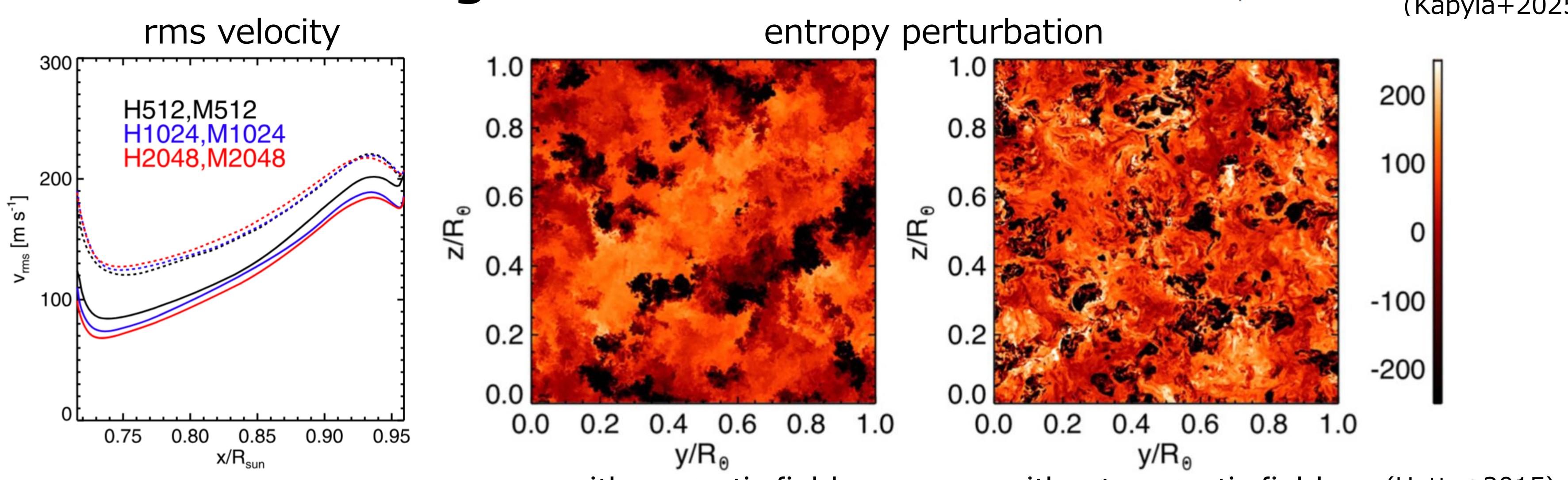
Plume-driven convection

- Thermal convection driven by strong downflows (plumes) generated by radiative cooling at the photosphere.
- Previous studies have shown that this mechanism limits the power of large-scale convection.
- Previous studies do not include magnetic fields.



(Käpylä+2025)

Influences of magnetic field



(Hotta+2015)

- Lorentz force feedback: the conversion of kinetic energy into magnetic energy leads to a reduction in velocity.
- Suppress entropy mixing: magnetic fields suppress the mixing of low-entropy perturbations with their surroundings and enhance entropy transport.

➢ These effects enhance convective stability and help resolve the convection conundrum.

➢ How does plume-driven convection change when magnetic fields are included?

Purpose

We investigate how magnetic fields affect plume-driven convection, focusing on plume dynamics, entropy mixing, and low-entropy transport. We examine whether these magnetic effects can stabilize convection and further reduce large-scale convective motions in the solar convection zone.

Model

- Magnetohydrodynamic simulations in a Cartesian box.
- A weak random field grows to saturation via convection.
- Plumes are generated by cooling patches at the top boundary.

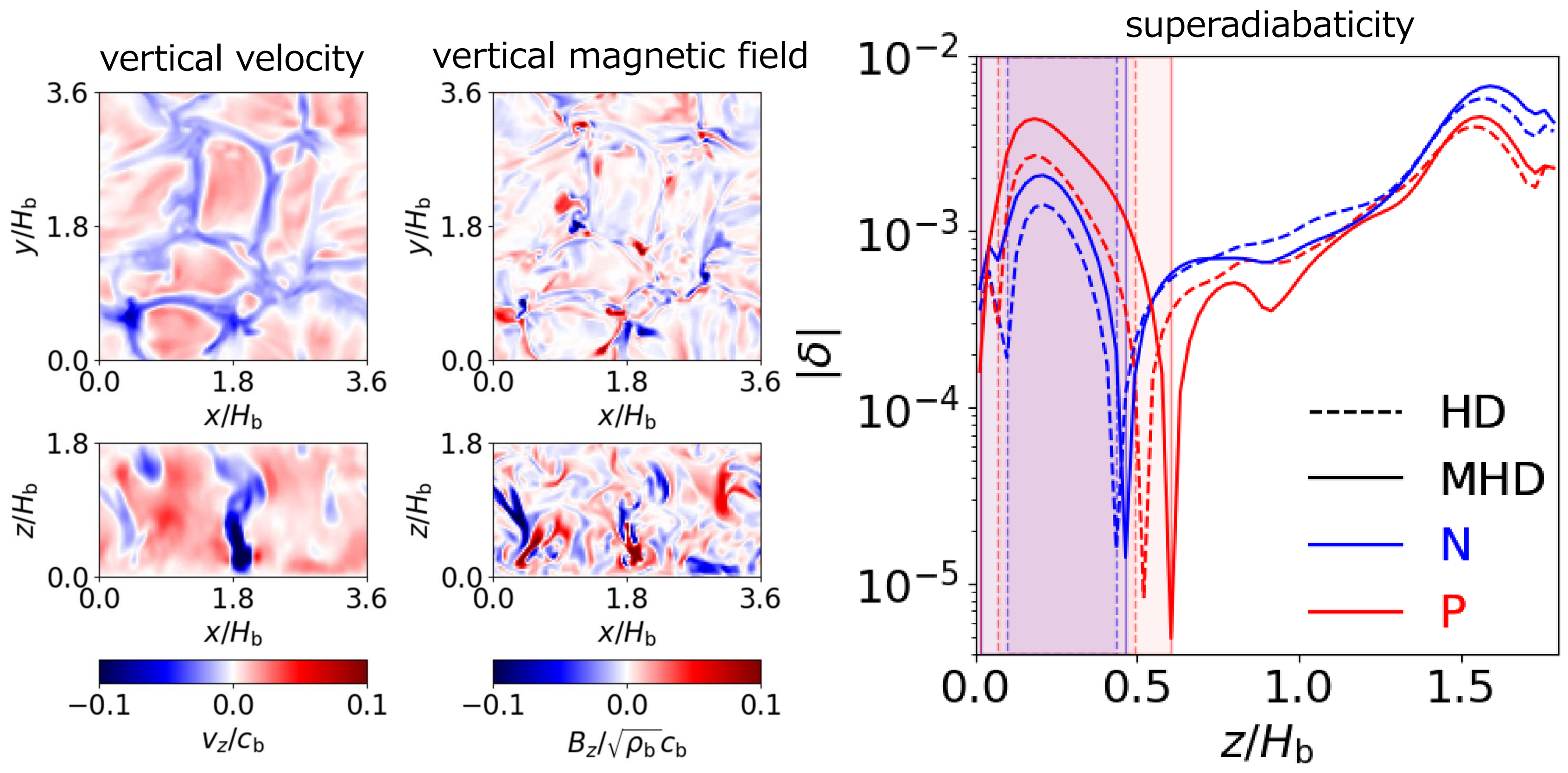
Numerical Setting

(Bekki+2017)

No. of gird points	Domain size	No. of timestep
128 × 128 × 64	400.3 Mm × 400.3 Mm × 200.1 Mm	90,000 (HD) 273,000 (MHD)

Results

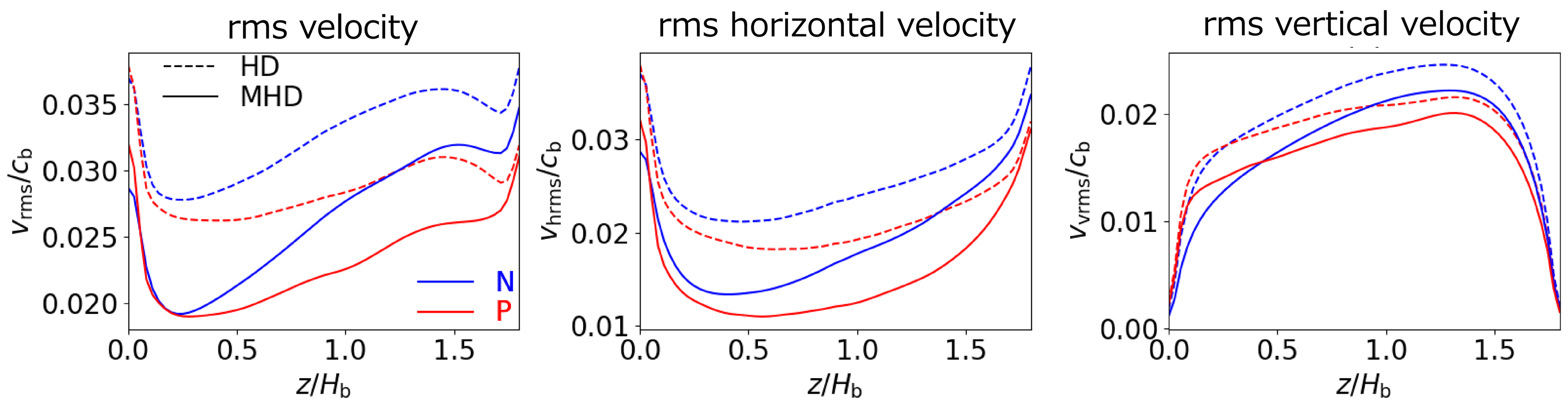
N: gradient-driven convection, P: plume-driven convection



- A plume downflow is clearly seen at the horizontal center of the lower-left panel.
- Decrease in superadiabaticity
- Expansion of the subadiabatic region

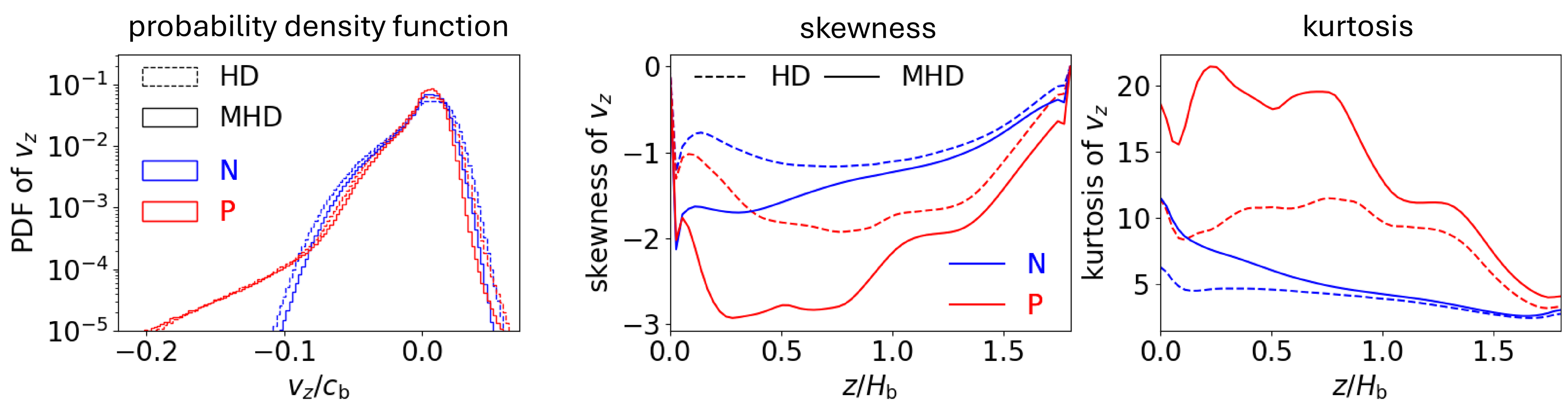
➢ Convective stabilization

➢ Enhanced transport efficiency of low-entropy material.



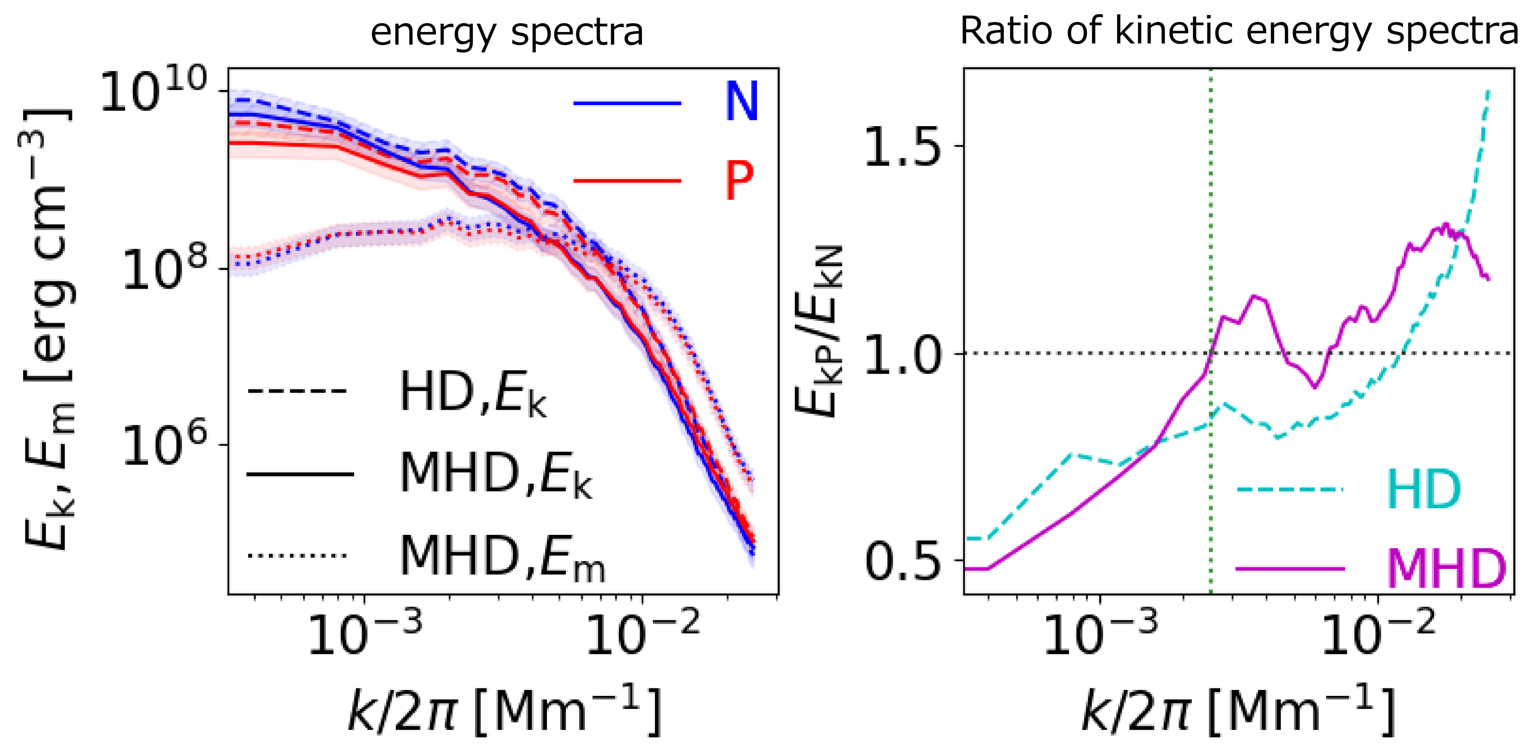
- Reduction by magnetic fields: increase with depths
- Reduction by plumes: larger in the upper half of the domain

➢ This is because cooling is weaker outside the plume tops than in the uniform-cooling case.



- Skewness and kurtosis increase.

➢ This is because plumes penetrate into the subadiabatic region.



- Without magnetic fields: plumes increase small-scale kinetic energy and decrease large-scale kinetic energy.
- With magnetic fields: small-scale kinetic energy is converted into magnetic energy, and large-scale kinetic energy is reduced more significantly.

Summary

Magnetic fields suppress entropy mixing and enhance the downward transport of low-entropy perturbations. Thus, convection becomes more stable, and large-scale kinetic energy is reduced more significantly.