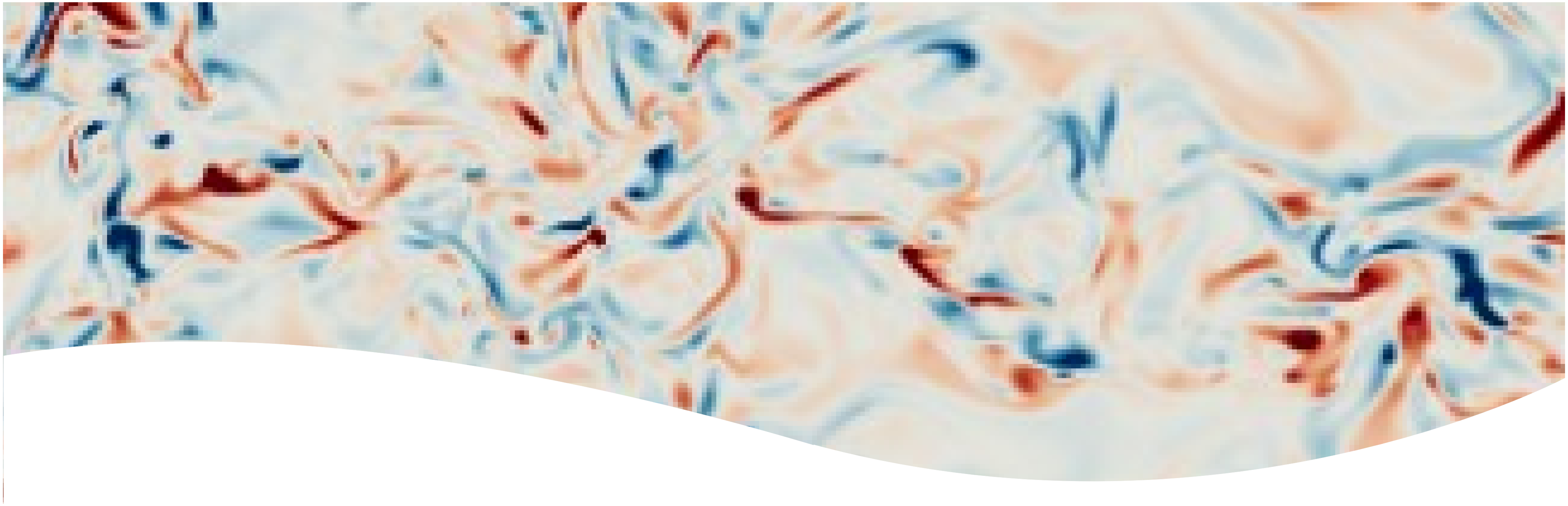

Stellar magneto-convection with RAMSES

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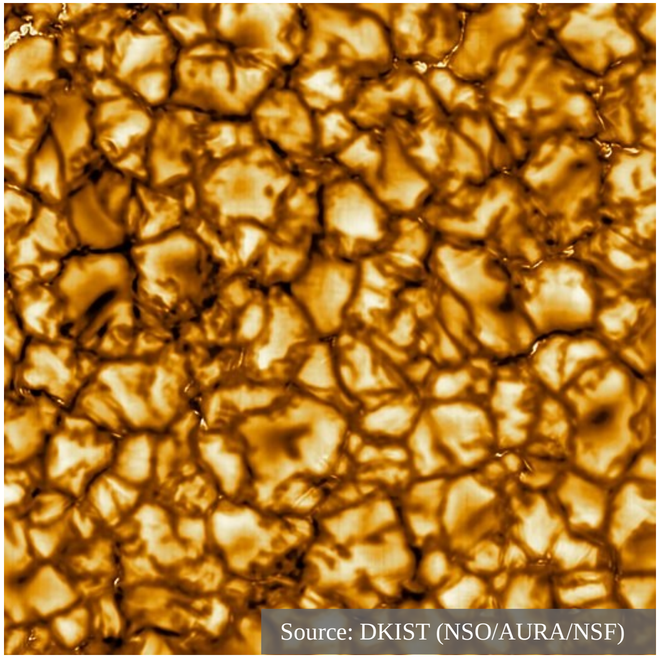
Introduction

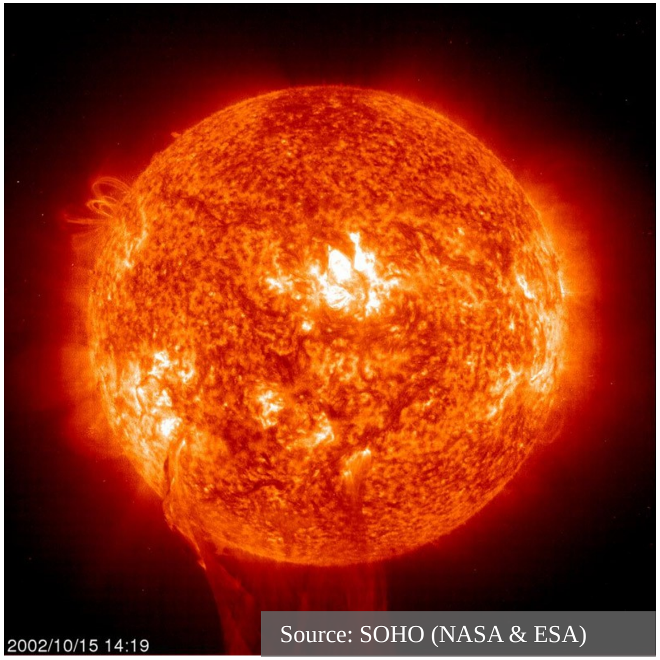
- Convection
  - Fundamental process in stellar interiors
  - Influences: evolution, oscillations, ...

- Magnetic fields
  - Sustained by large/small scale dynamo in turbulent convection zone
  - Key role in stellar activity

➢ Non-linear and complex dynamics

3D numerical simulations





Introduction

- Convection dynamics:

  Small amplitude perturbations around equilibrium solution

! *Problem*: numerical scheme introduces truncation errors

  - Erase dynamical fluctuations
  - Destroy equilibrium solution

- Possible solutions:

  ? Refine the mesh
  ✓ High-order methods
  ✓ Well-balanced schemes

Well-Balanced Scheme

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- Goal:

Satisfy exactly the discrete version of equilibrium solution

Separate equilibrium solution from perturbations
Impose the equilibrium solution in the Euler-Poisson eqs.

- Ex. 1D hydrostatic equilibrium

$$\rho = \rho_{\mathrm{eq}} + \rho', \; p = p_{\mathrm{eq}} + p', \; u = u', \qquad \partial_x p_{\mathrm{eq}} = -\rho_{\mathrm{eq}} g$$

$$\boxed{\partial_t \left(\rho u\right) + \partial_x \left(\rho u^2 + p'\right) = -\rho' g}$$

No perturbations → Equilibrium preserved

Well-Balanced Scheme

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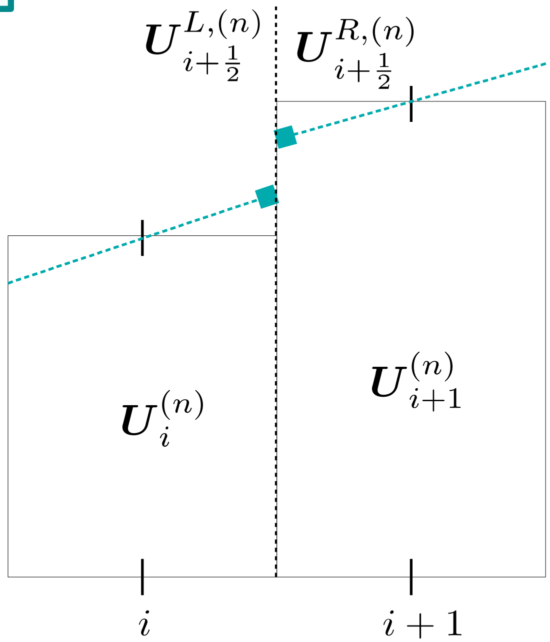
- In general, we want to solve Euler-Poisson system with a Godunov-like scheme

$$\boldsymbol{U}_i^{(n+1)} = \boldsymbol{U}_i^{(n)} + \frac{\Delta t}{\Delta x}\left(\boldsymbol{F}^\star_{i-\frac{1}{2}} - \boldsymbol{F}^\star_{i+\frac{1}{2}}\right) + \frac{\Delta t}{\Delta x}\boldsymbol{S}_i^{(n+\frac{1}{2})}$$

- For a well-balanced scheme, we have to:
  1. Correct the source term
  2. Correct the fluxes
  3. Correct the interface interpolation

  (4. Evolve entropy instead of internal energy)



✔ Implemented in hydro and mhd modules of RAMSES

Simulations - Setup

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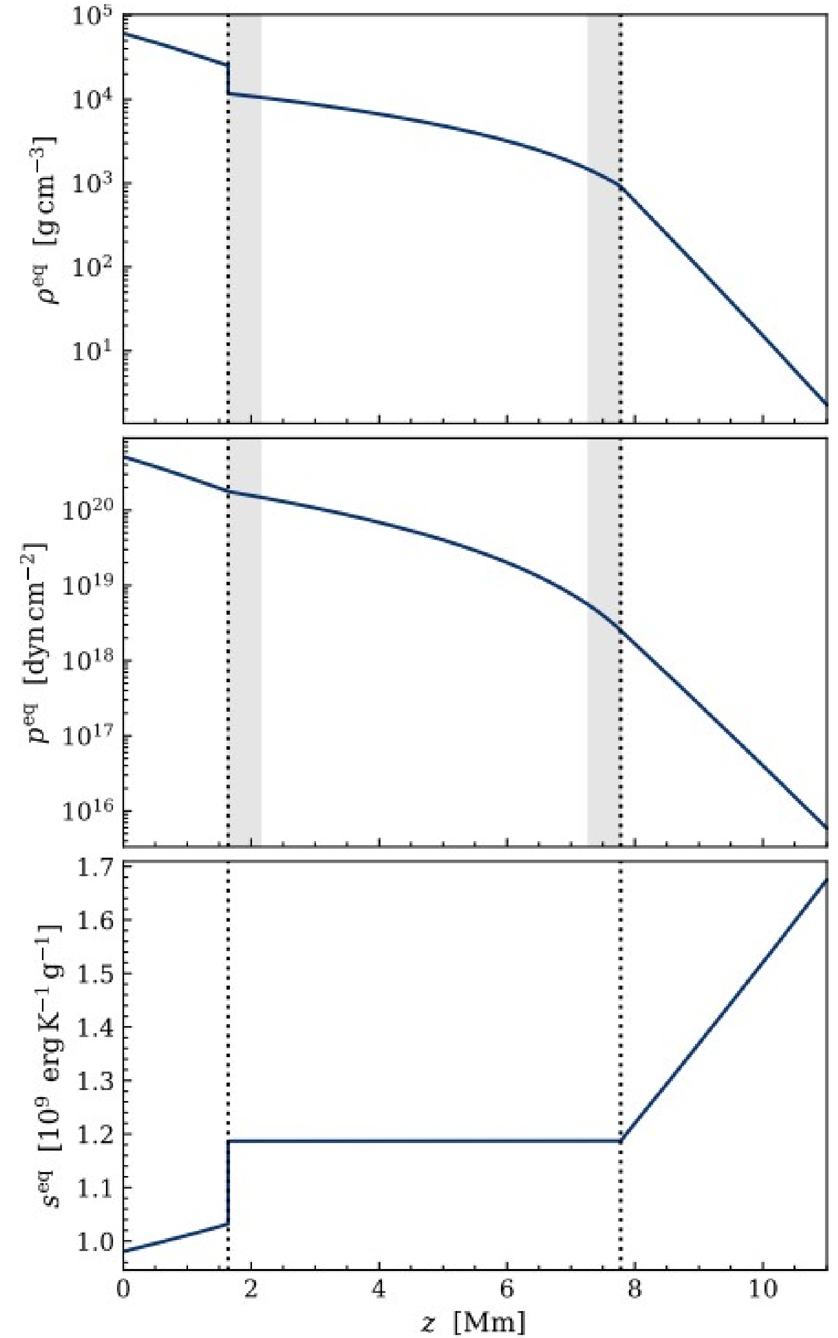
- Test code (proof-of-concept) on a plane-parallel, stellar convective region (*Herwig et al., 2006*)
  - 3 polytropic stratifications
  - Constant gravity downwards
  - Ideal gas (γ = 5/3)
  - Artificial heating and cooling
- HD and MHD simulations with $N = 64^3, 128^3, 256^3, 512^3$
- Add perturbations (% level) to trigger convection



Simulations - Convection

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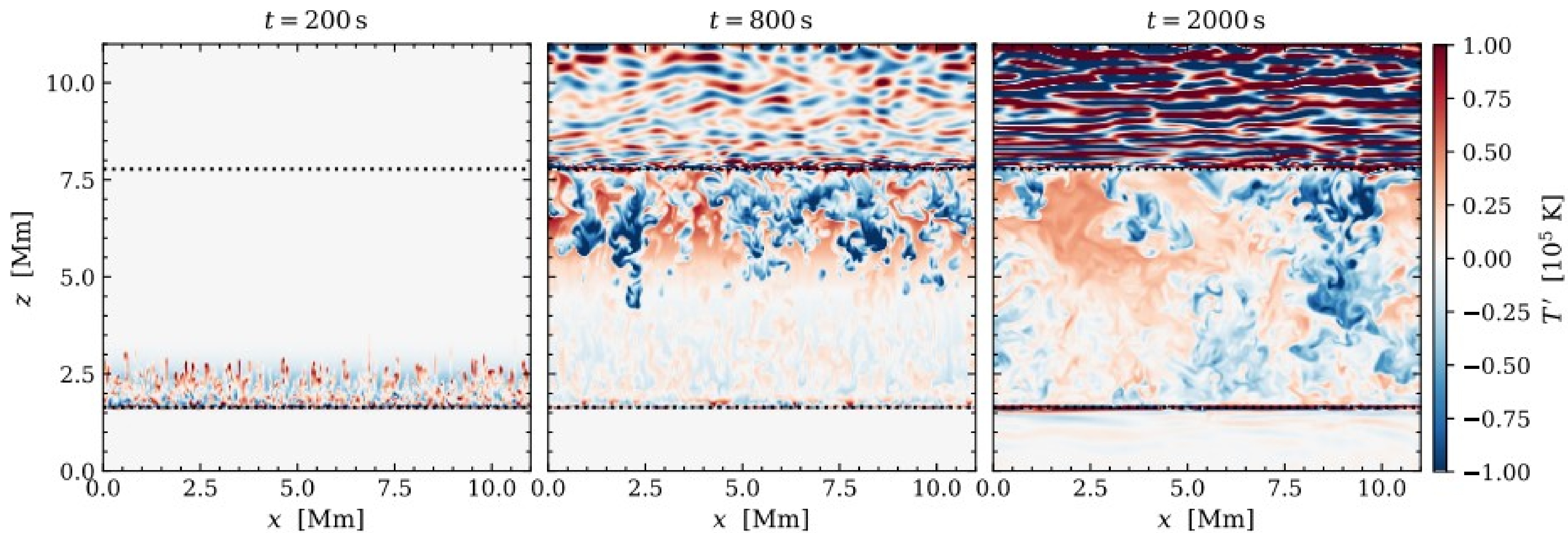

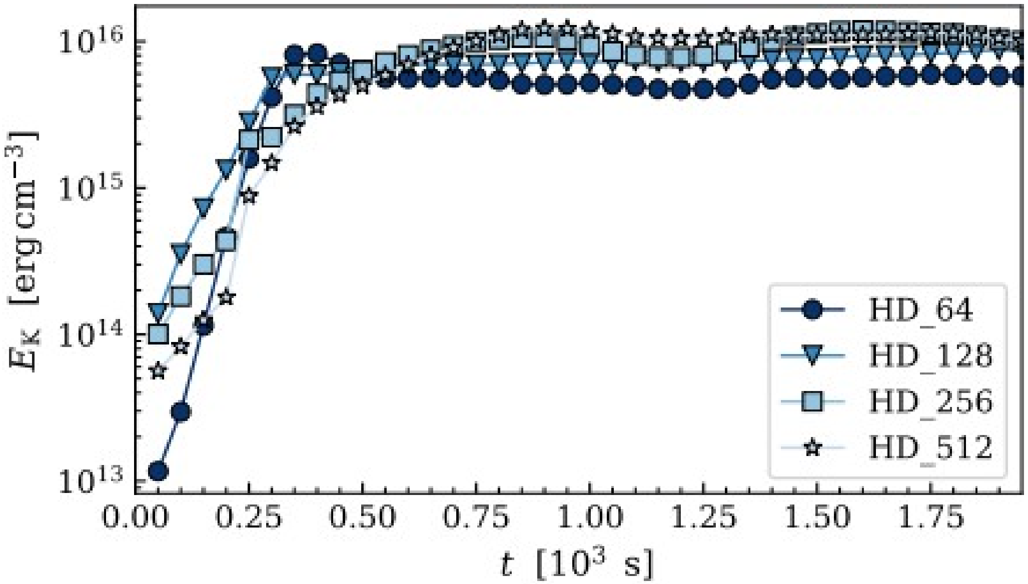

- Convective plumes develop from Rayleigh-Taylor instabilities
- Perturbations of the order of %
- Quasi-steady state reached (fully developed convection zone)

Simulations - Convection

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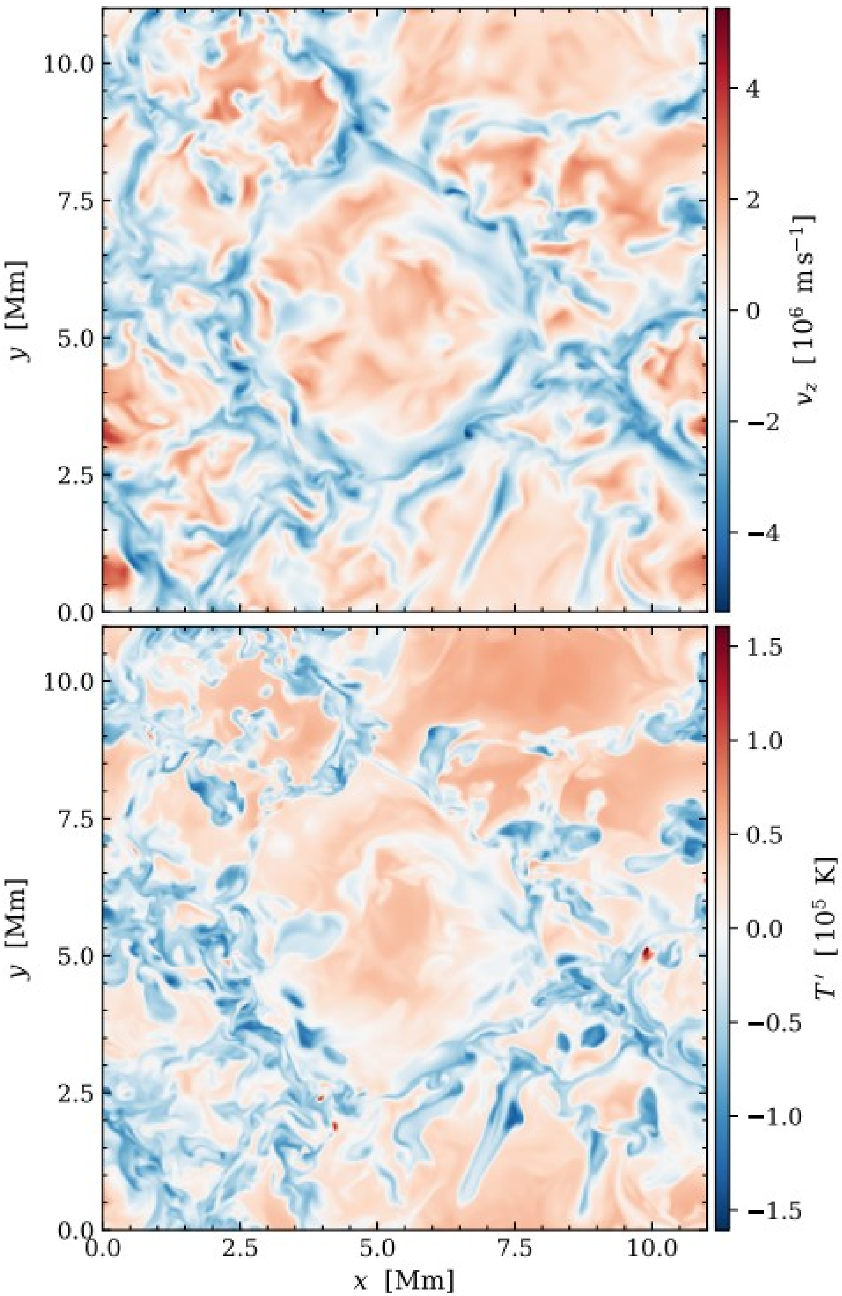

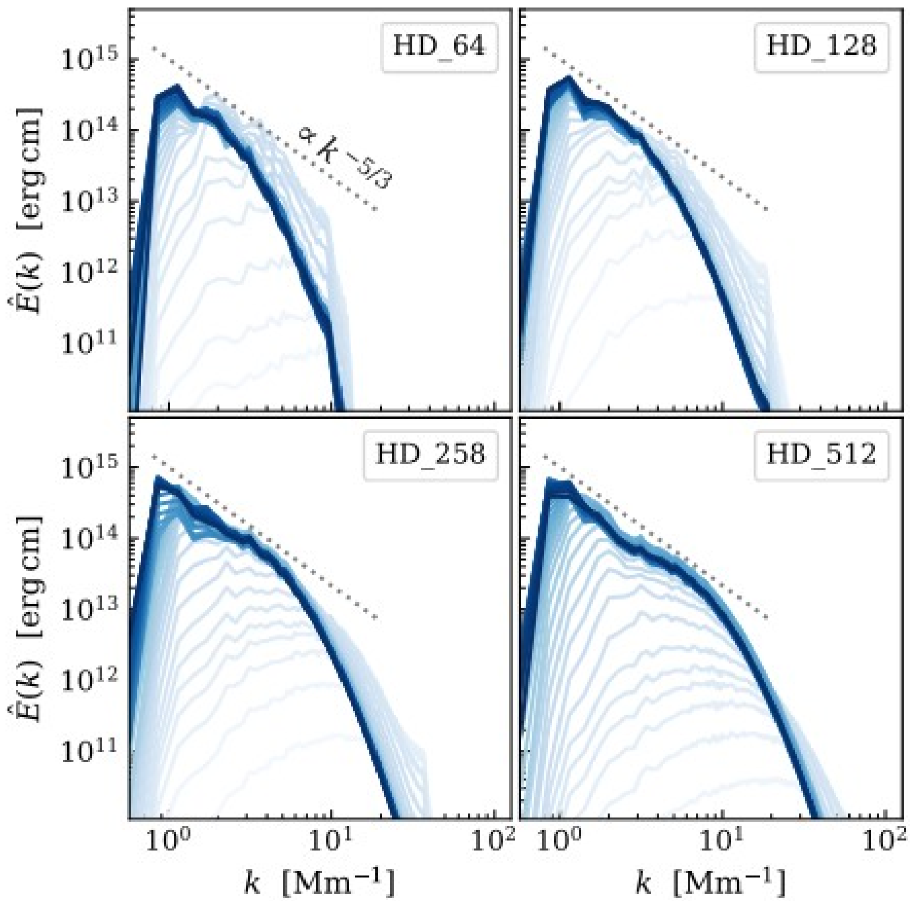

- Granulation pattern near the top of the convection zone
- Kolgomorov power law for K.E. power spectra

Simulations - Magneto-convection

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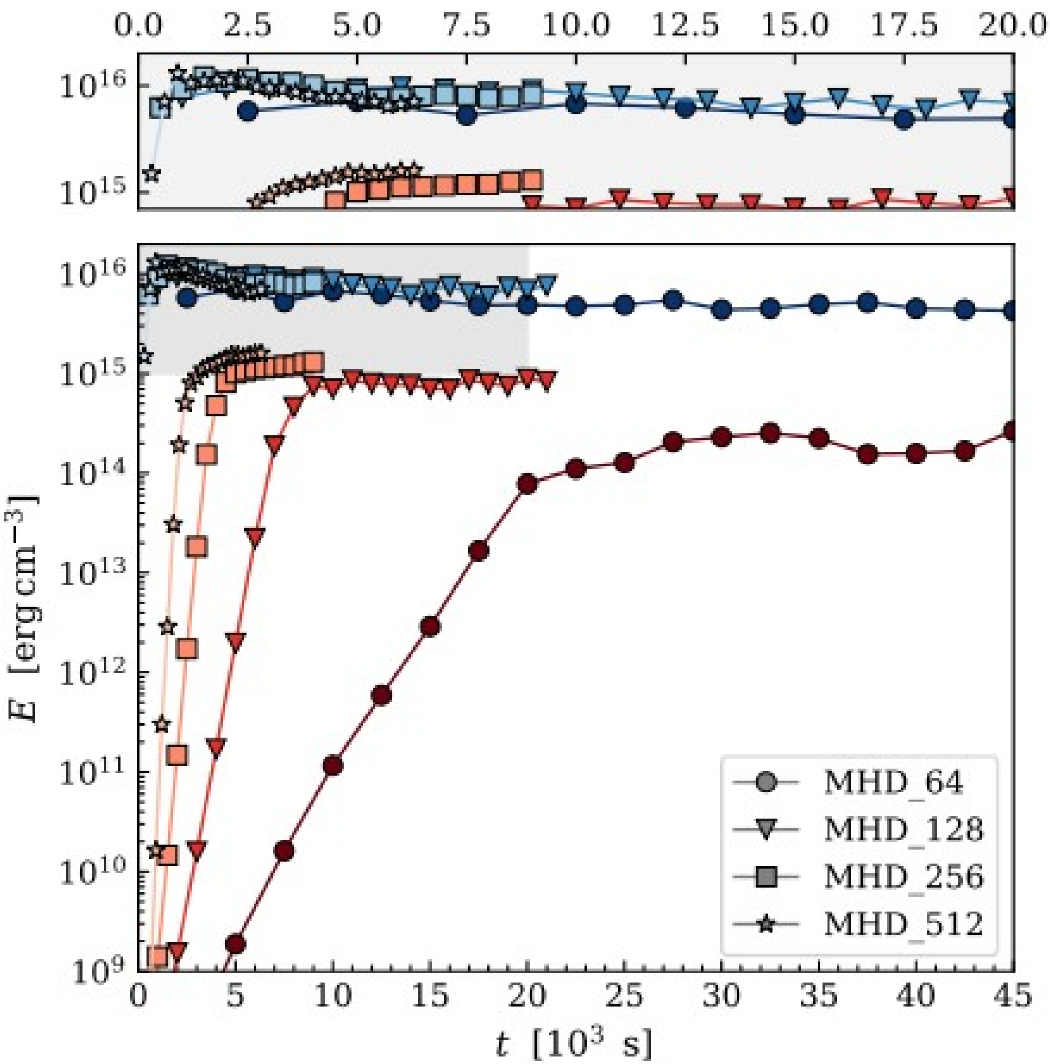

- Introduce seed (weak) magnetic field in convection zone
- Small-scale dynamo
- Growth rate is resolution dependent
- Quasi-steady state reached (saturated magnetic field)

$$B \sim 0.1 - 0.3\, B_{\text{eq}}$$

$$B_{\text{eq}} = \sqrt{4\pi\rho}\, v_{\text{rms}}$$

Simulations - Magneto-convection

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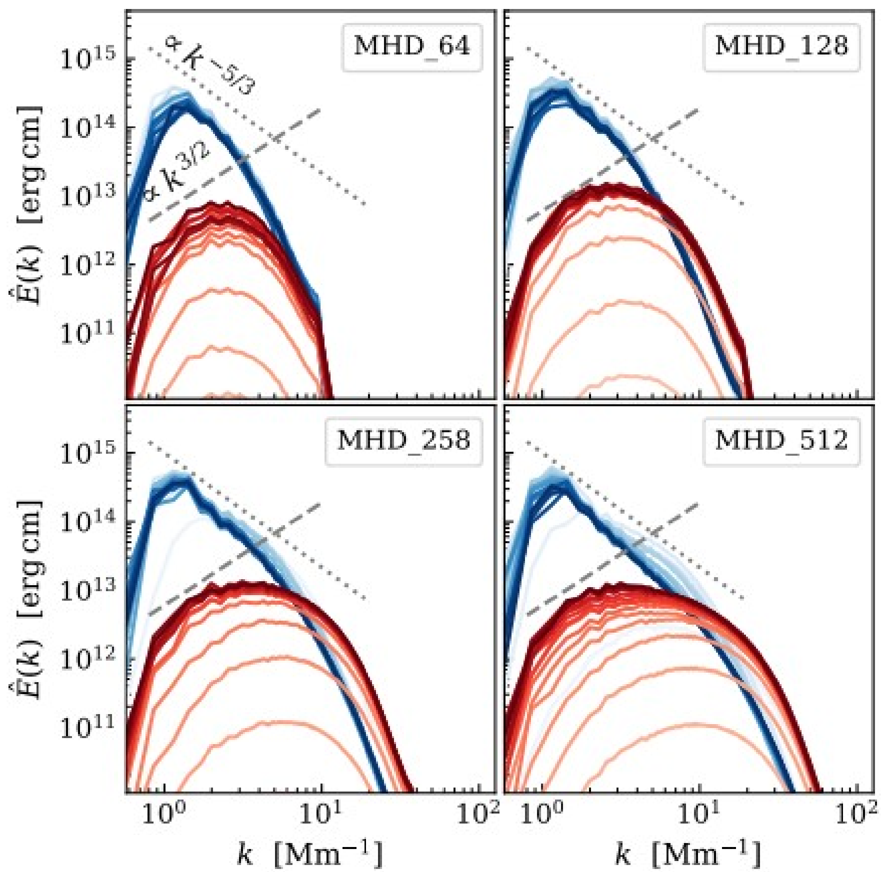

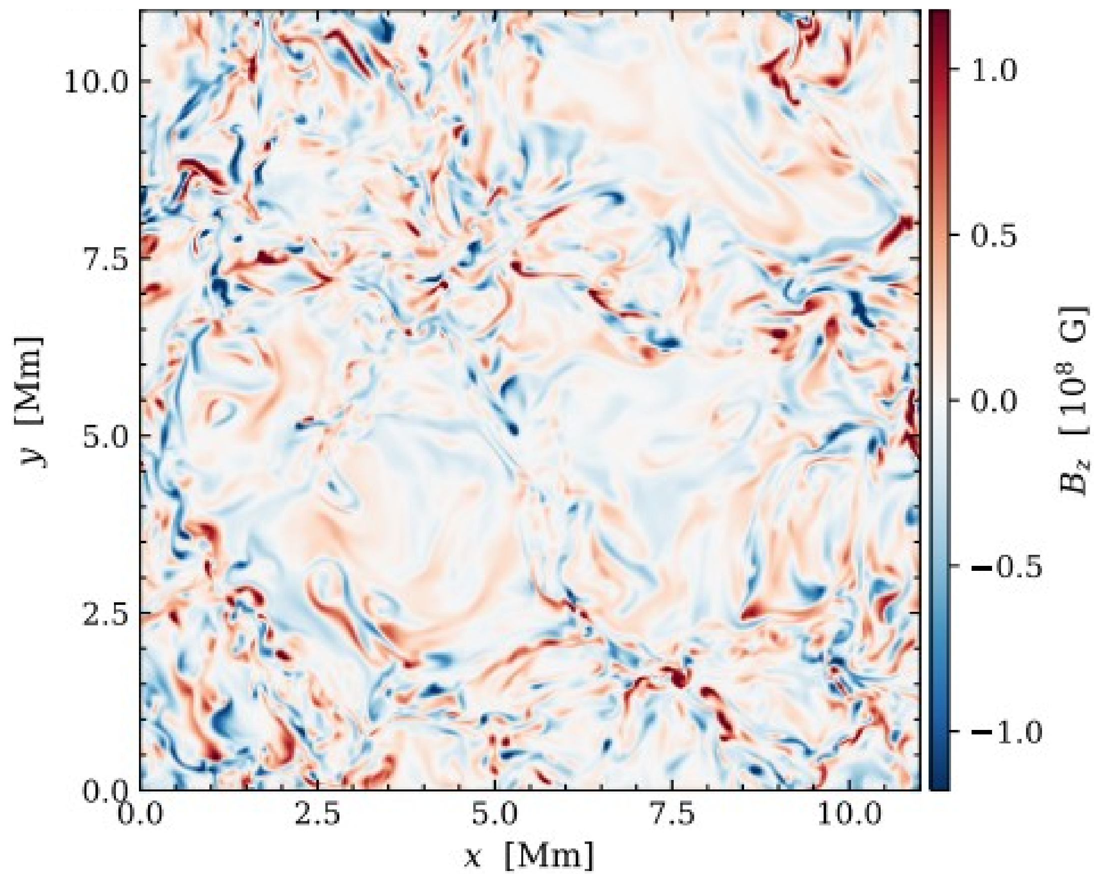

- Magnetic field dominates at small-scales
- Mixed polarity filaments concentrated in intergranular flows
- Similar results to *Rempel 2014* (top solar convection zone)

Simulations - PDF

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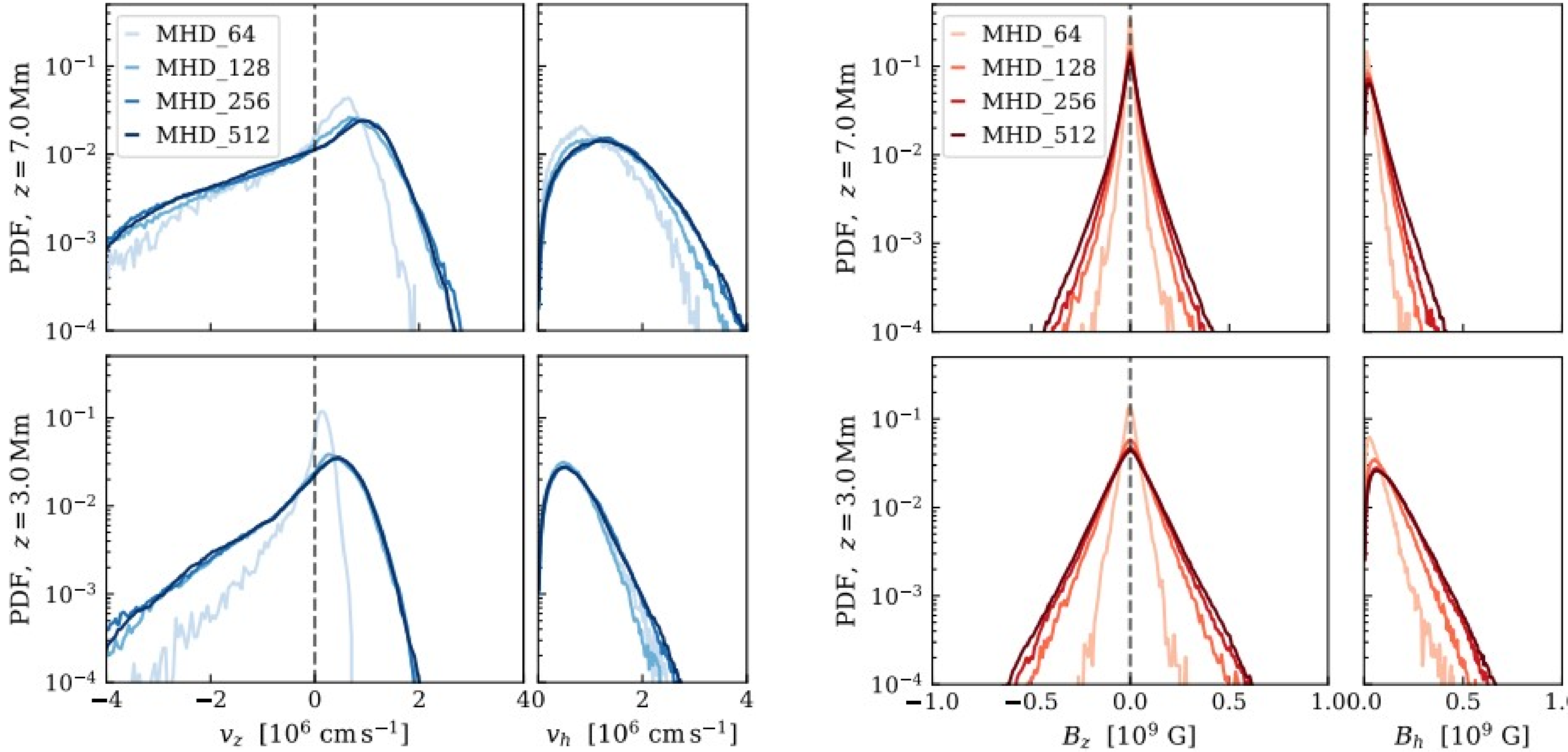

- Asymmetric velocity fields (granulation)
  Symmetric magnetic fields (turbulent small-scale dynamo)
- Similar to *Miesch et al., 2008*; *Hotta et al., 2014*; *Rempel 2014*
- Convergence by increasing resolution

Simulations - Waves

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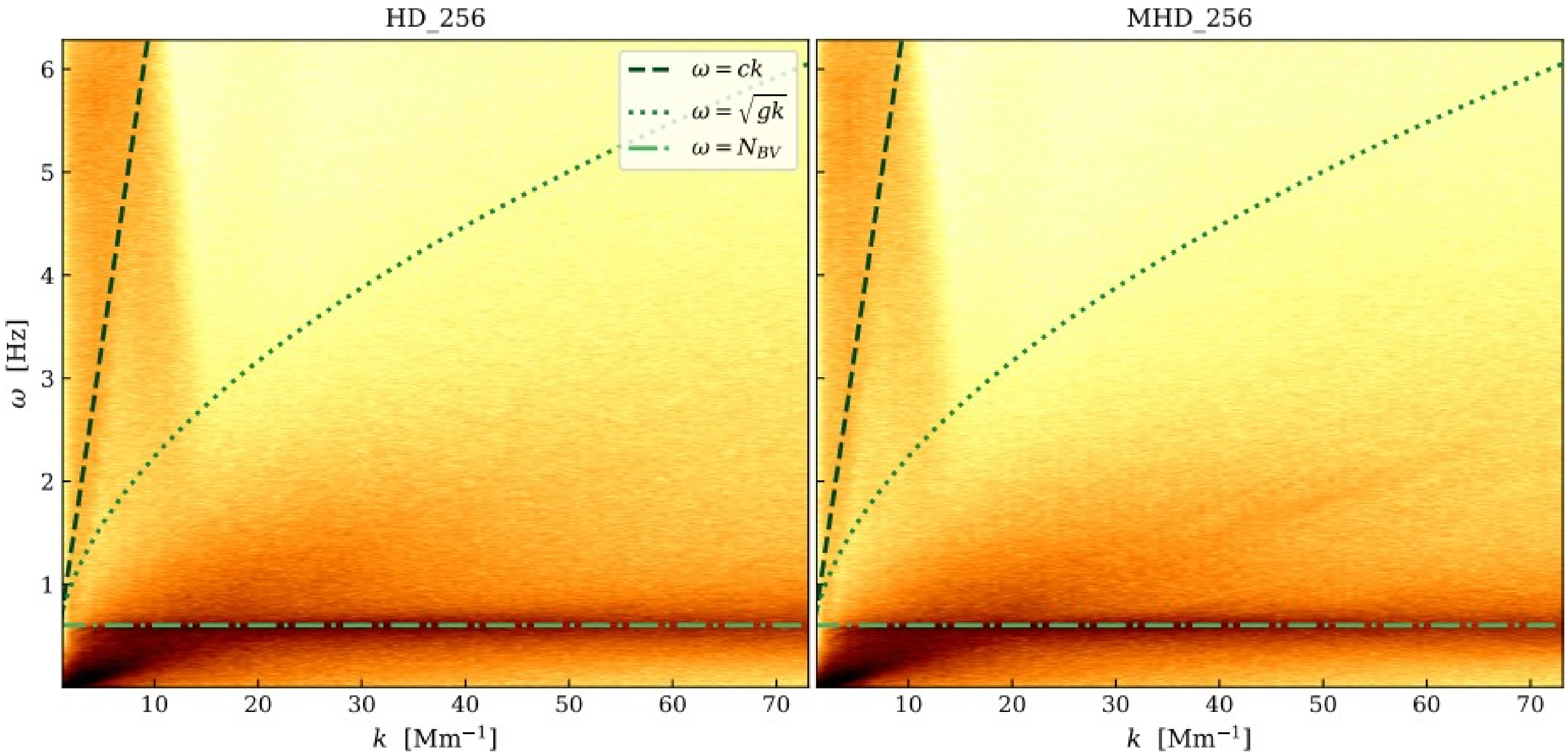

- k-ω for identification of waves in top stable region
- Presence of pressure, gravity and surface modes
- Similar to *Herwig al., 2006*

Conclusions & Outlook

- We implemented a well-balanced scheme in RAMSES to deal with stellar magneto-convection
- We tested the code on a slice of stellar convection zone

1. Full development of convective zone
2. Efficient small-scale dynamo action
3. Wave propagation in the stable regions

✔ Convergence with resolution
✔ Agreement with literature

- *Next?*
  - Full star simulations
  - Comparison with other codes
  - Interaction B fields/waves
  - ...

Conclusions & Outlook

Thank you!