Large-scale Magnetic Field and α^2 Dynamo Wave in Turbulent Convective Dynamo Sim.

(Masada & Sano 2013 in prep)

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Introduction

~ Where does the solar butterfly comes from ? ~

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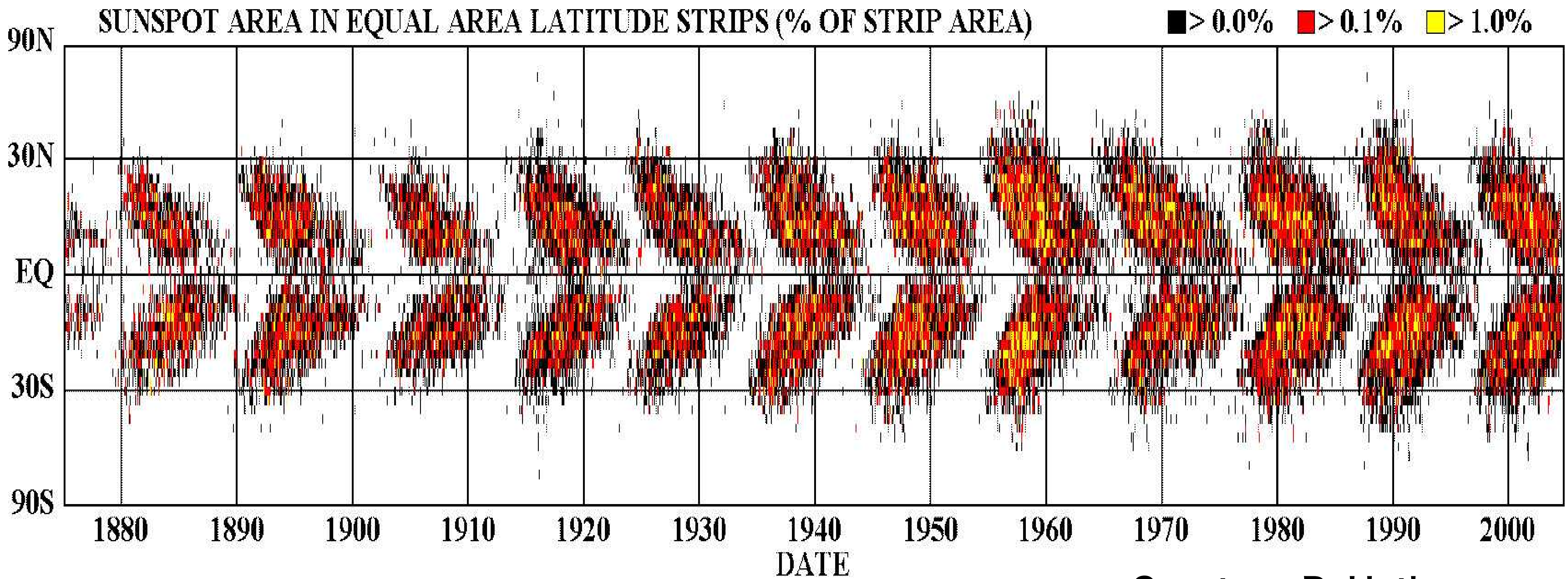
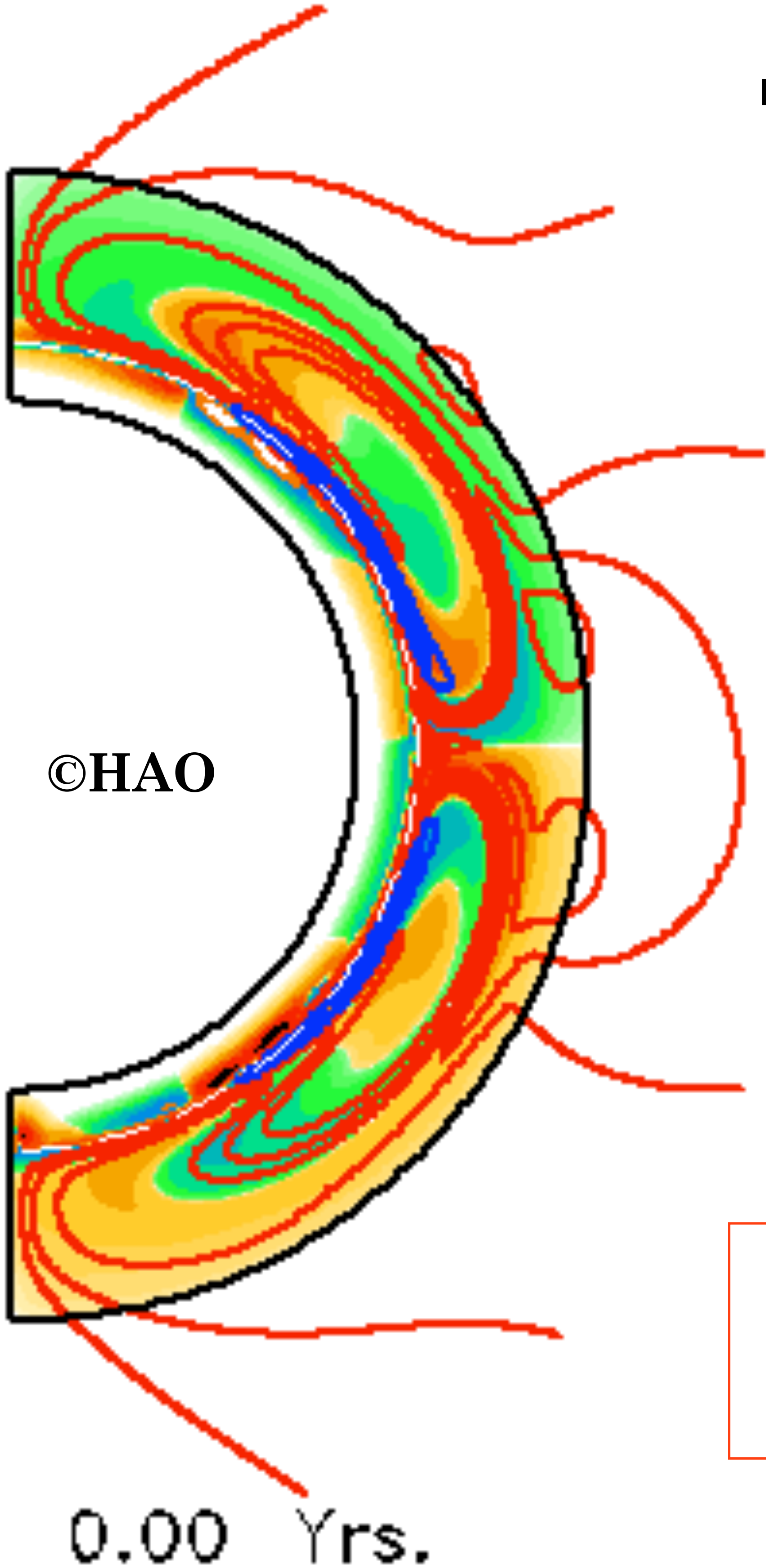
- **The solar magnetic field shows a remarkable spatiotemporal coherence though it is generated by convective dynamo within its interior.**



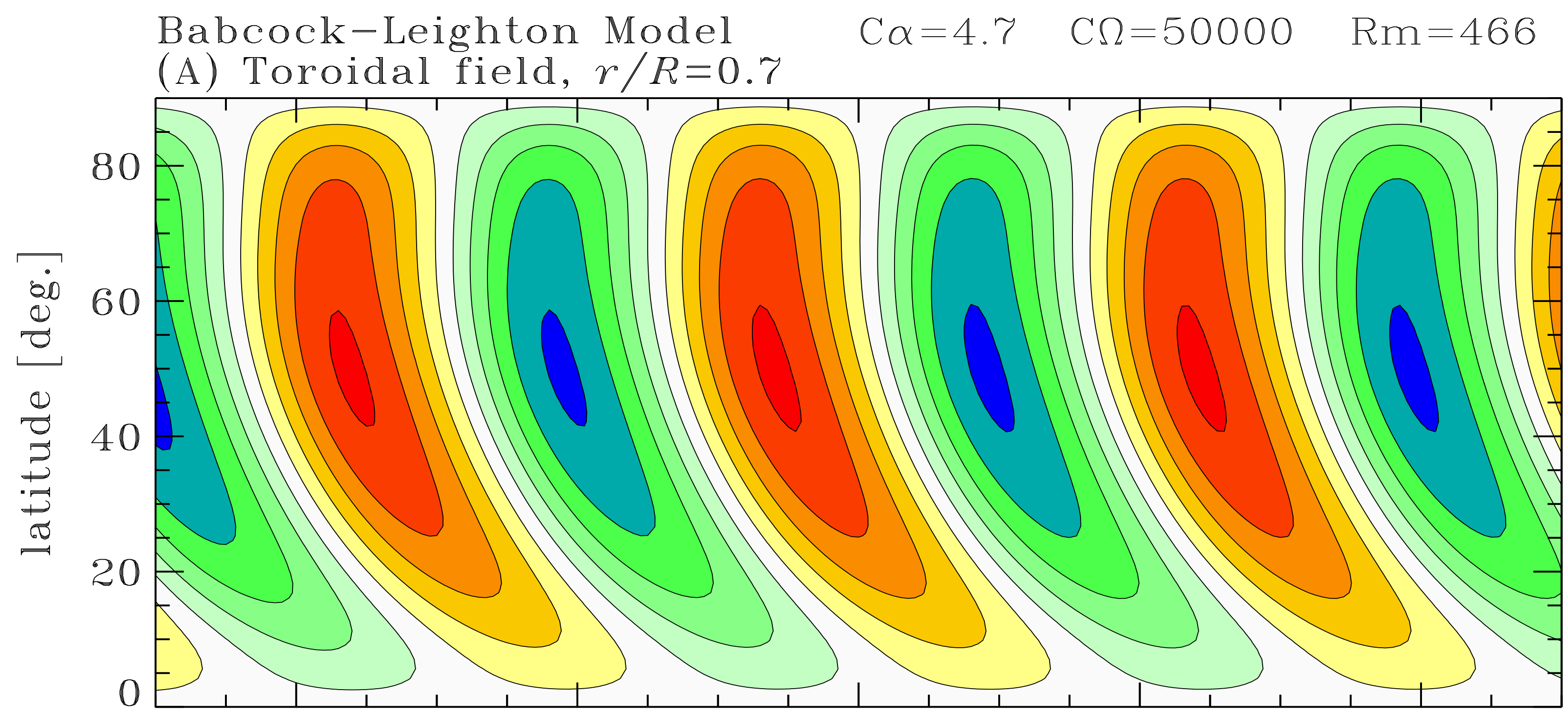
Courtesy D. Hathaway

- **Still unclear what dynamo mode is excited in the solar interior and how it regulates magnetic cycle.**
- **Seeking "PIECEs" to solve the solar dynamo puzzle by the help of global and local convective dynamo simulations.**

Where does the solar butterfly come from ?



- **Solar butterfly mainly comes from**
  - **- differential rotation : Ω-process**
  - **- convection (+ mag. buoyancy) : α-process**



(Charbonneau 2005)

Is the Ω-process essential piece for cyclic magnetic dynamo ?

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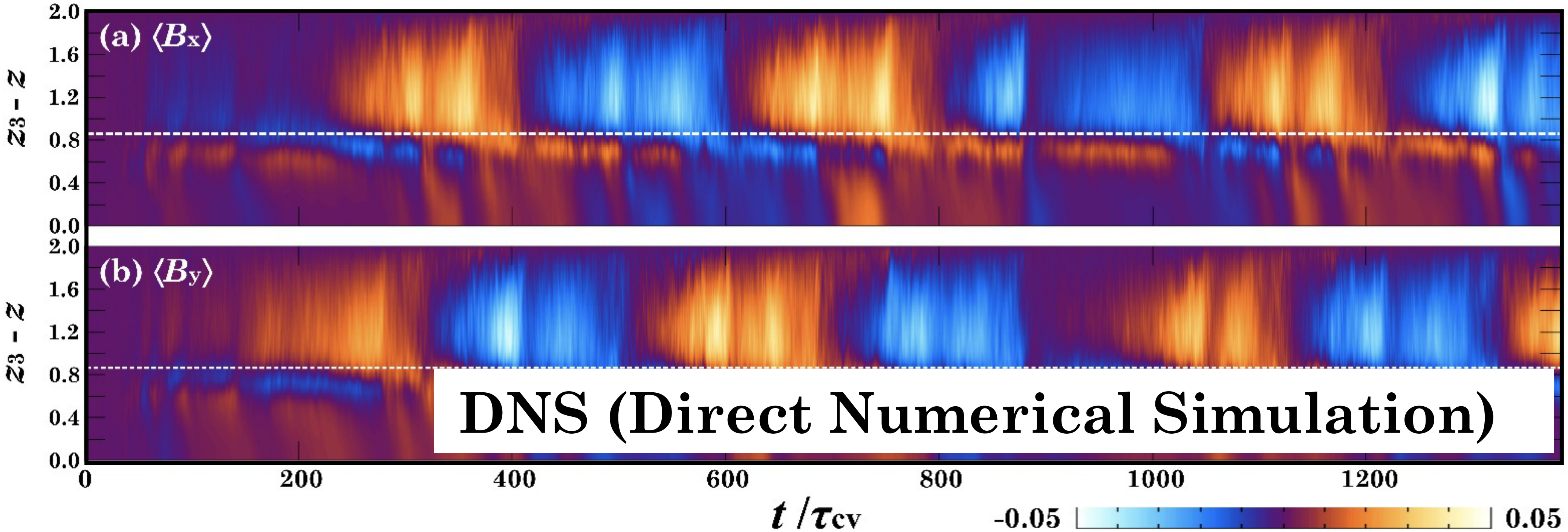
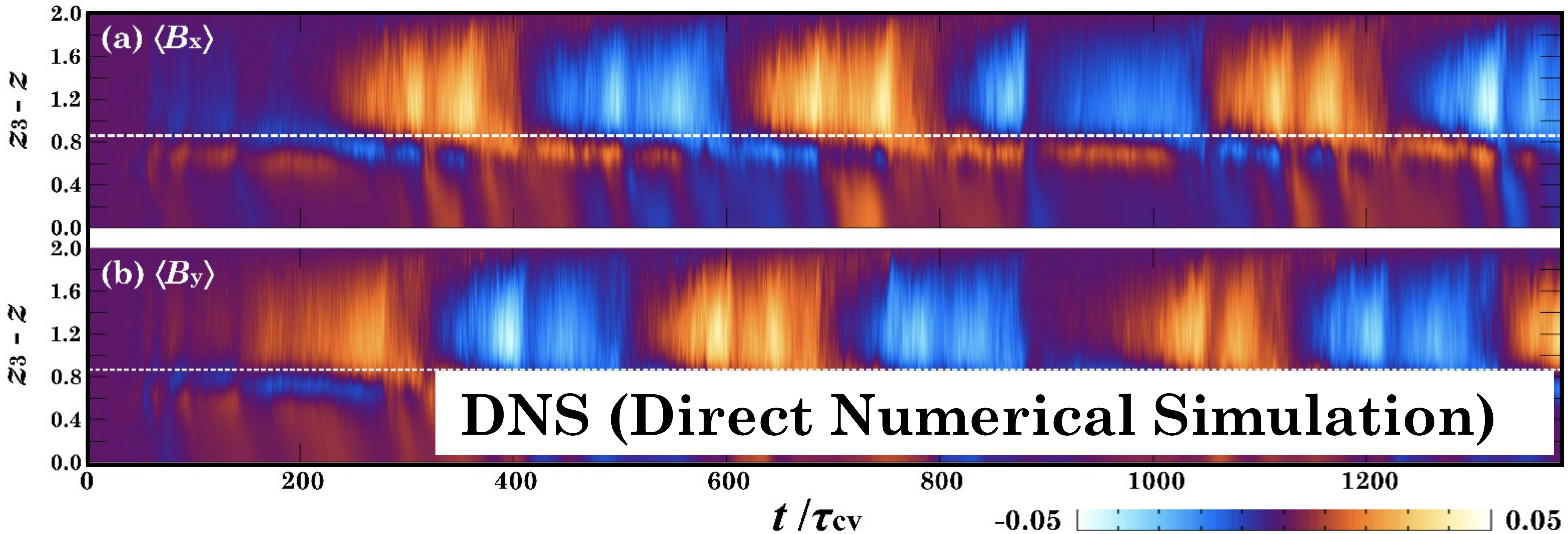
- Answer : *Ω*-process is NOT NECESSARILY.



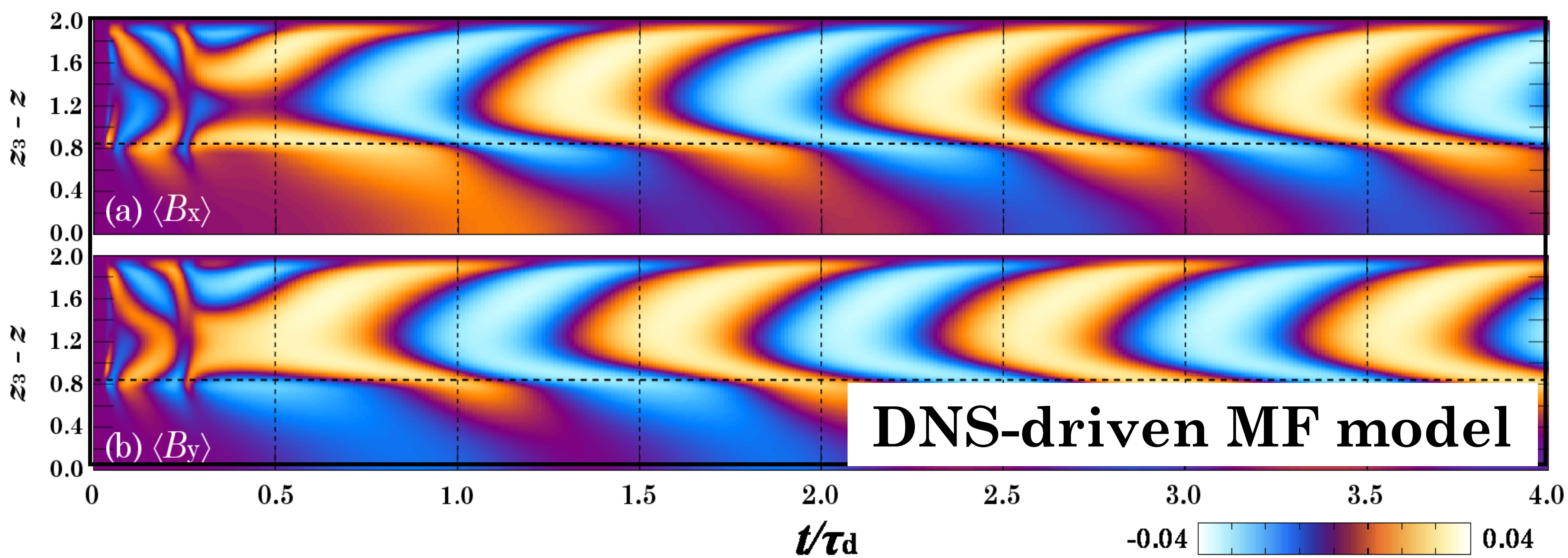
Cyclic large-scale magnetic field can emerge spontaneously from convective turbulence WITHOUT *Ω*-process.

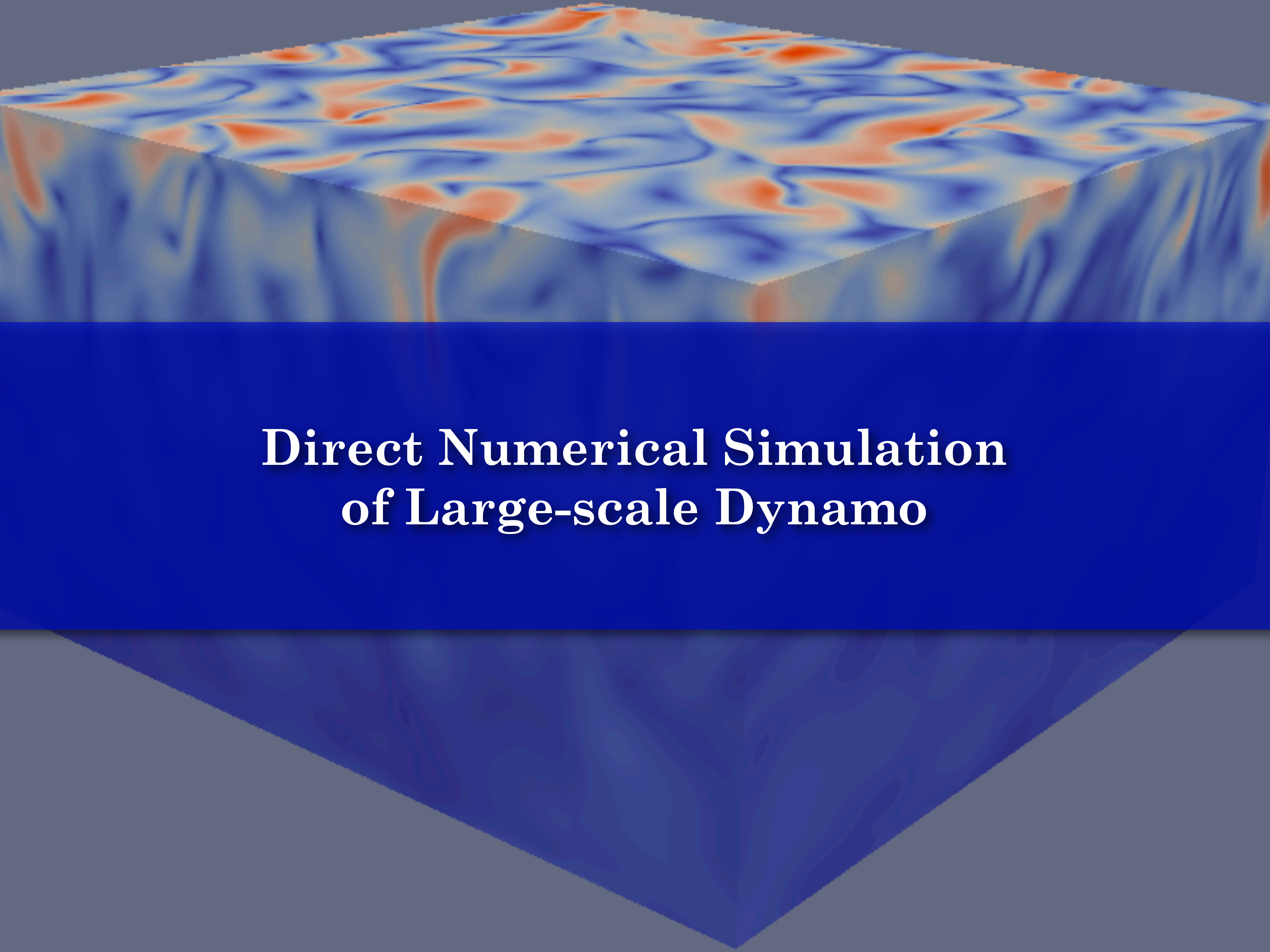
What is dynamo mode excited in our DNS ?

- **Answer : Ω-process is NOT NECESSARILY.**



- **Answer : That would be the "α^2-dynamo mode".**



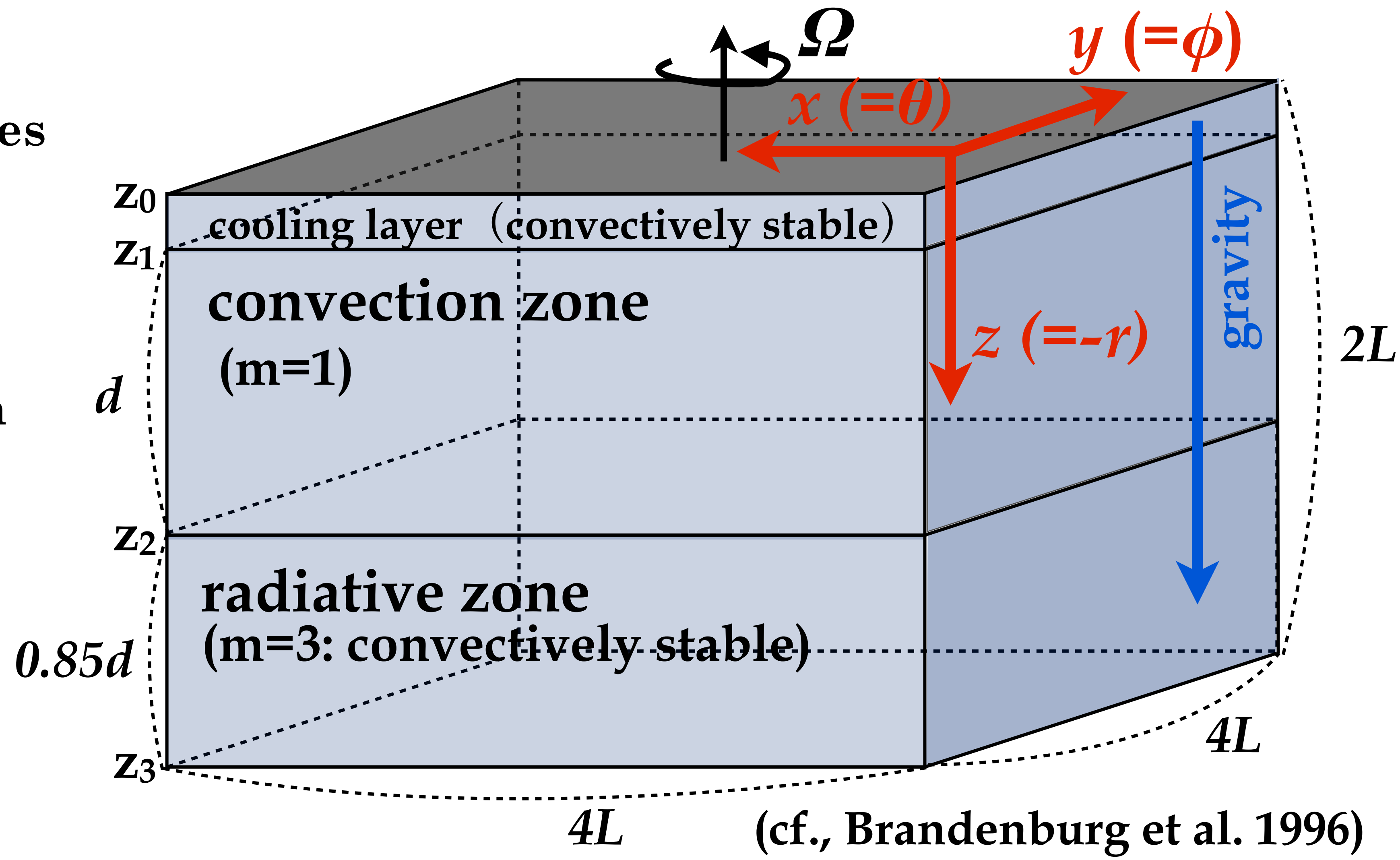


Direct Numerical Simulation of Large-scale Dynamo

Simulation Setup

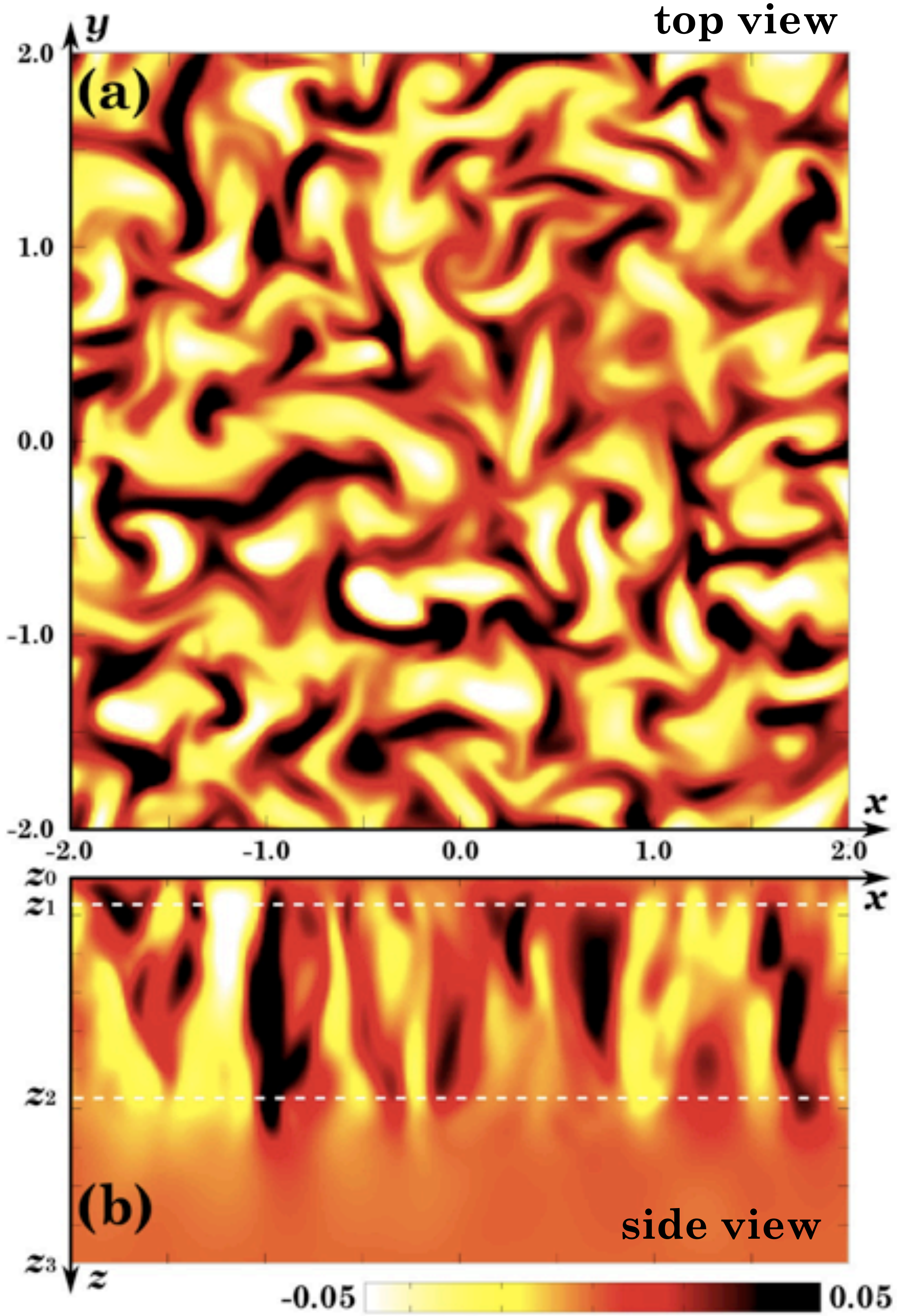
- Basic equations. : fully Compressible MHD equations
- Model : top cooling layer, middle convection & bottom radiative zones
  Ω is anti-parallel to g, aspect ratio: $L_x/L_{cz} = L_y/L_{cz} = 4$
- Parameters : Pr = 1.2, Pm = 4, Ra = 4×10^6, Ro = $v_{rms}/2\Omega_0 d \sim 0.03$ @mid-CZ
  $\rho_{bottom}/\rho_{top} \sim 10$

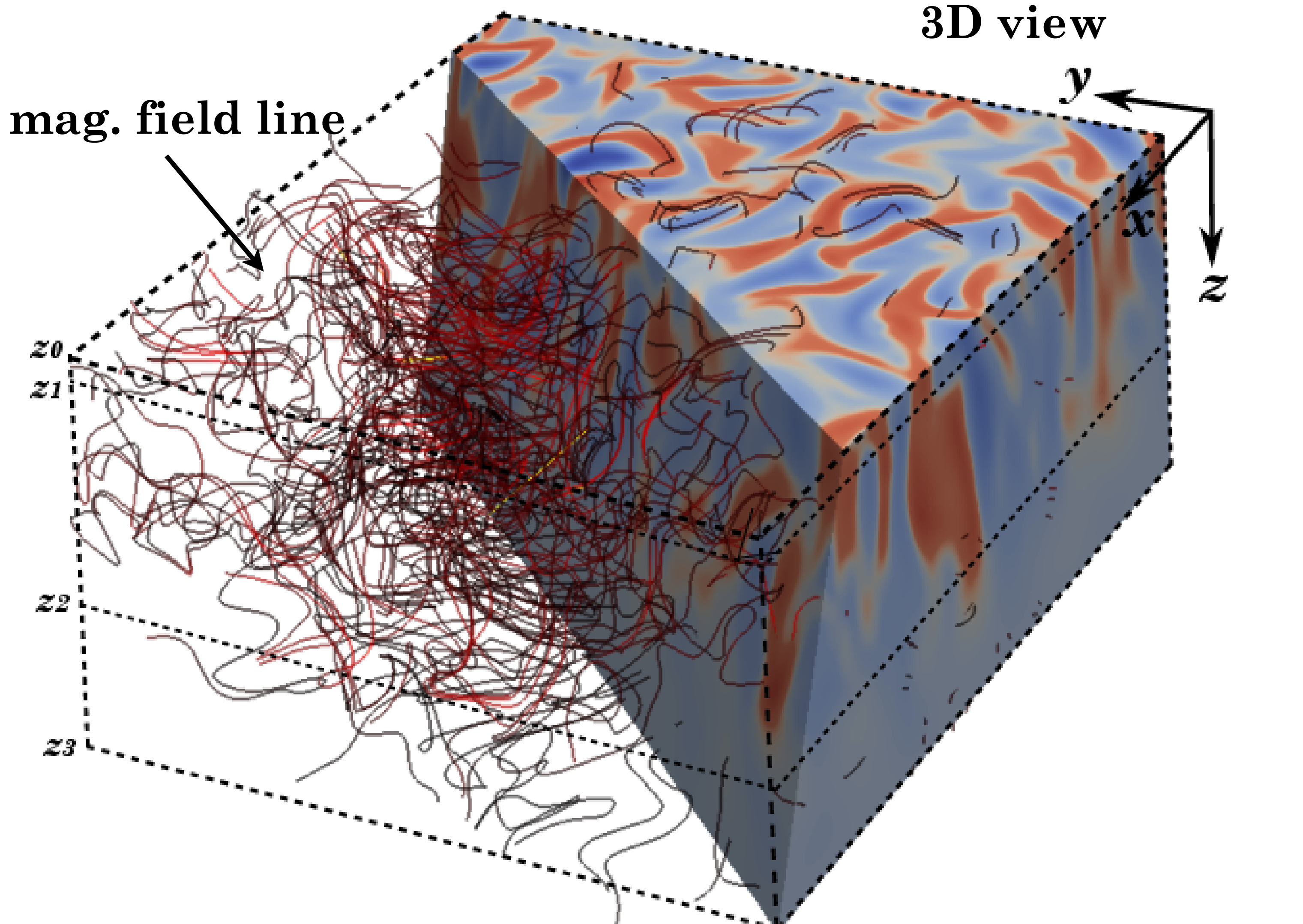
- ***Horizontal Boundary:***
  - periodic for all the variables
- ***Vertical Boundary:***
  - stress-free for the velocity
  - $B_x = B_y = \partial_z B_z = 0$ @top
    $\partial_z B_x = \partial_z B_y = B_z = 0$ @bottom
  - $\partial_z T$ = const @bottom
    T = const @top
- ***Numerical Scheme***
  - Second-order Godunov-type finite-difference scheme
  [256 (x) × 256 (y) × 128 (z)]



(cf., Brandenburg et al. 1996)

Properties of Rotating Stratified Convection

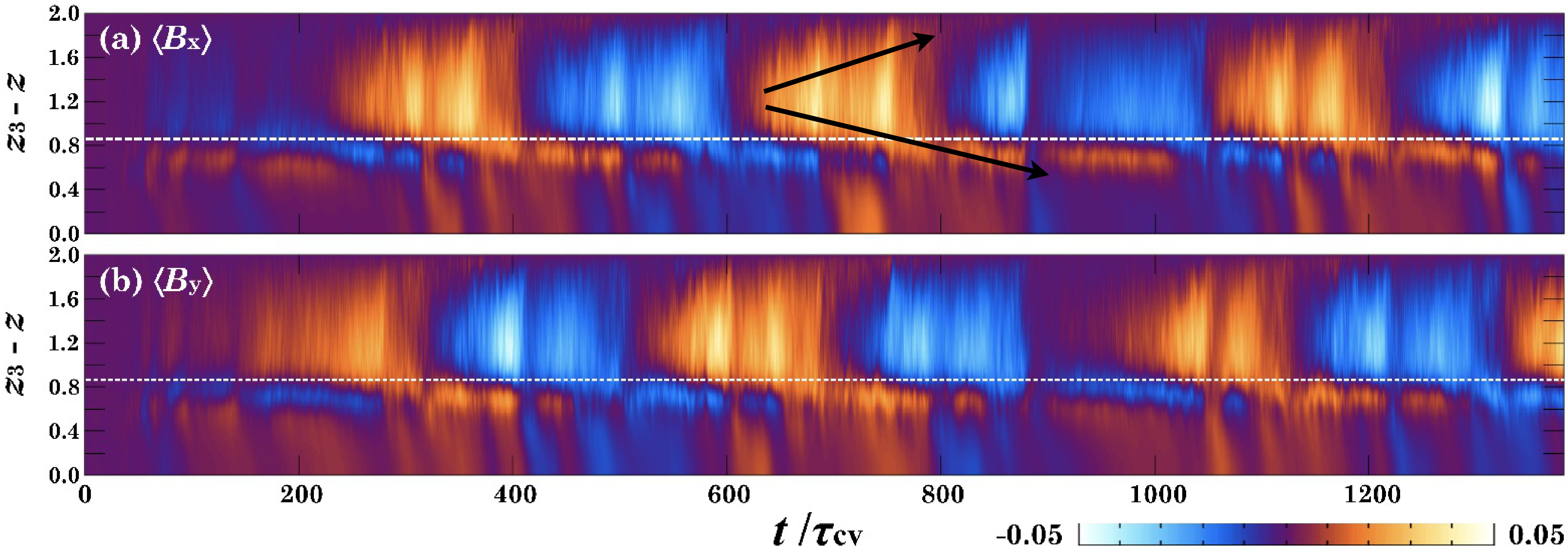




- Broader and slower upflow surrounded by narrower and faster downflow lanes (→ up-down asymmetry).

- No mean horizontal flow (and shear) because of no symmetry breaker in *x*-*y* (horizontal) directions.

Oscillatory Large-scale Magnetic Field

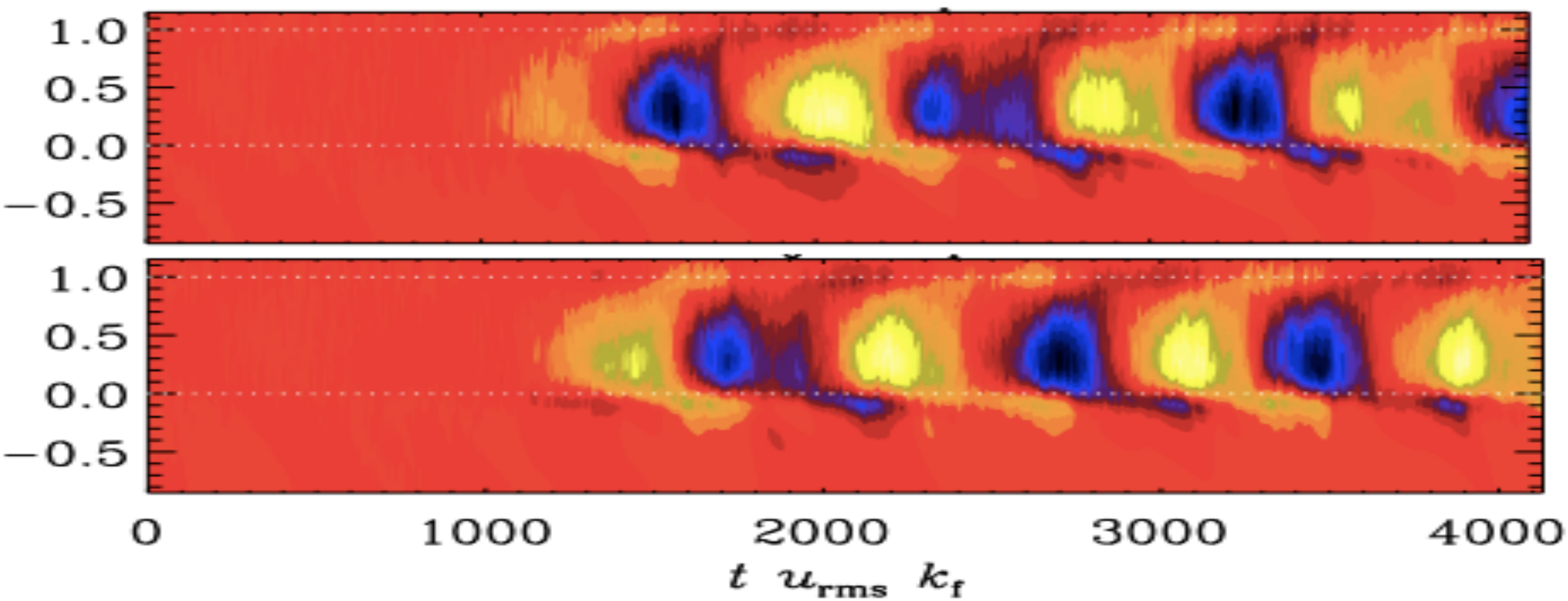


- Mean-horizontal field with a remarkable spatiotemporal coherency is spontaneously organized in the bulk of the convection zone.
- $\langle B_x \rangle$ and $\langle B_y \rangle$ reach maximally the equipartition field strength ($B_{eq} \sim 0.035$).
- The mean-field is the strongest at around the mid-CZ and propagates from there to top and base of the convection zone.
- A phase difference of about $\pi/2$ between $\langle B_x \rangle$ and $\langle B_y \rangle$.
- $\langle B_z \rangle$ does not show any coherent signature, is dominated by turbulent field.

Kapyla, Mantere & Brandenburg (2013)

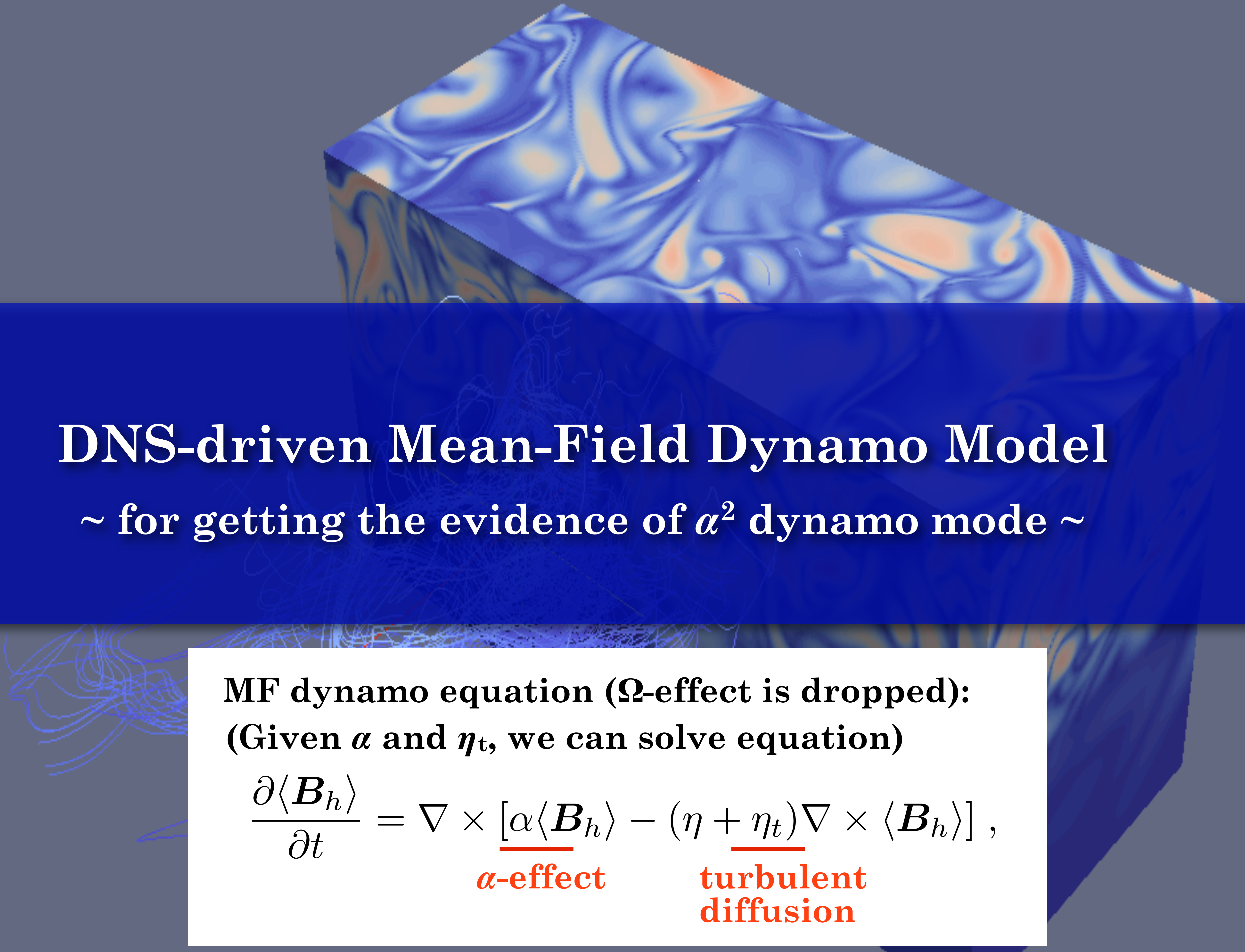
Similar DNS results have been already reported.

- **Kapyla, Mantere & Brandenburg 2013**



- **They conjectured that this is a manifestation of α^2 dynamo mode. However, the "evidence" has not yet been exhibited.**

Try to show the evidence !



DNS-driven Mean-Field Dynamo Model

~ for getting the evidence of α^2 dynamo mode ~

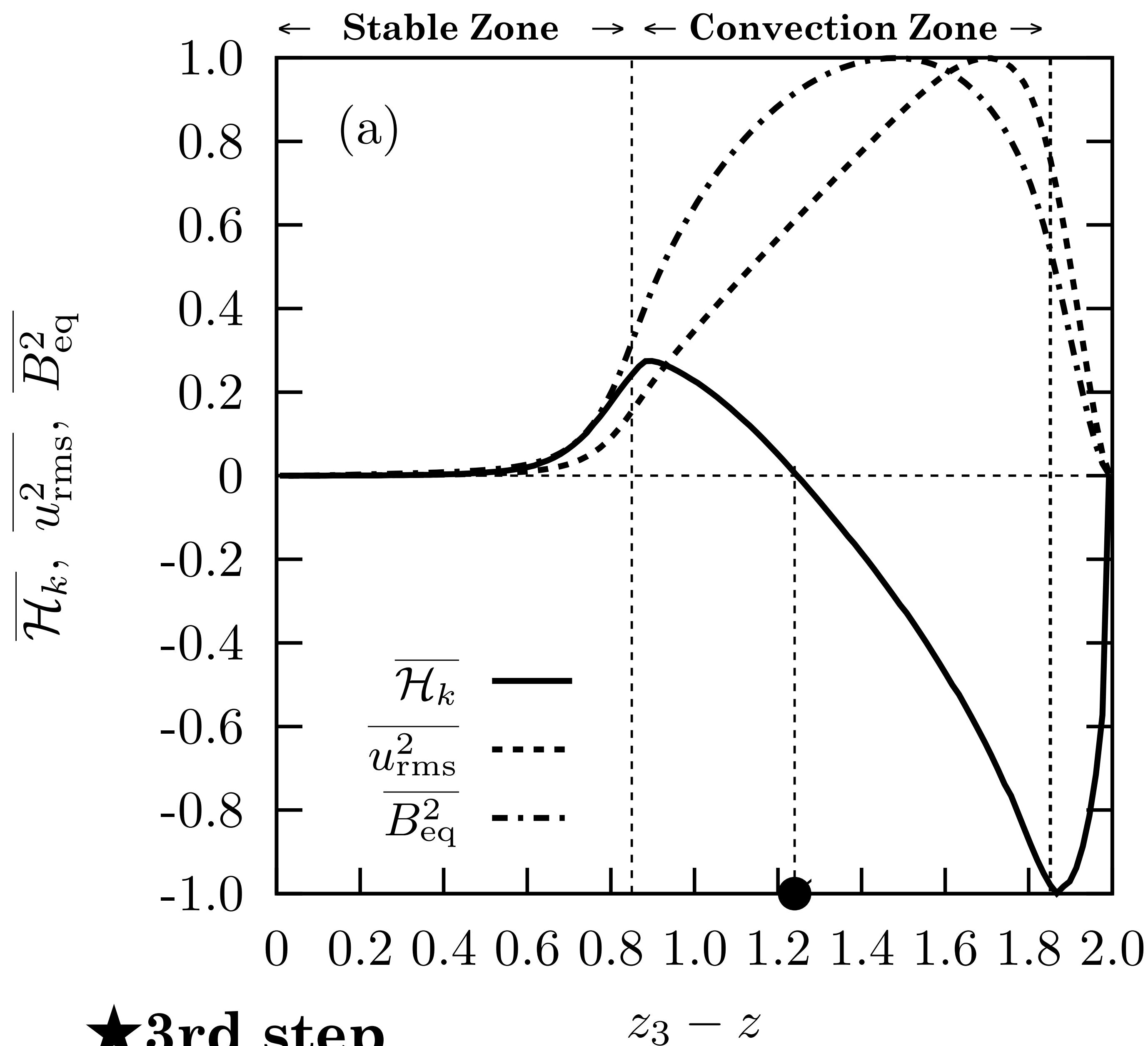
MF dynamo equation (Ω-effect is dropped):
(Given α and η_t, we can solve equation)

$$\frac{\partial \langle \boldsymbol{B}_h \rangle}{\partial t} = \nabla \times \left[\underline{\alpha} \langle \boldsymbol{B}_h \rangle - (\eta + \underline{\eta_t}) \nabla \times \langle \boldsymbol{B}_h \rangle \right] ,$$

α-effect

turbulent diffusion

DNS-driven MF model ~ Modeling Procedures ~



★1st step

Take time & horizontal averages and derive mean vertical profiles of helicity and RMS velocity

★2nd step

Determine the profiles of dynamo coefficient α and η_t:

$$\alpha_k(z) = -\frac{1}{3}\tau_c\langle\langle \boldsymbol{u}' \cdot \nabla \times \boldsymbol{u}' \rangle\rangle = -\frac{1}{3}\tau_c \mathcal{H}_k ,$$

$$\eta_t^k(z) = \frac{1}{3}\tau_c\langle\langle \boldsymbol{u}'^2 \rangle\rangle = \frac{1}{3}\tau_c u^2_{\rm rms} ,$$

$\tau_c = 1/(u_{\rm rms} k_c)$

$k_c = H_{\rm p}(z)/2\pi$

no arbitrary parameters !

★3rd step

Solve 1D MF dynamo equation (all the variables depend on t and z):

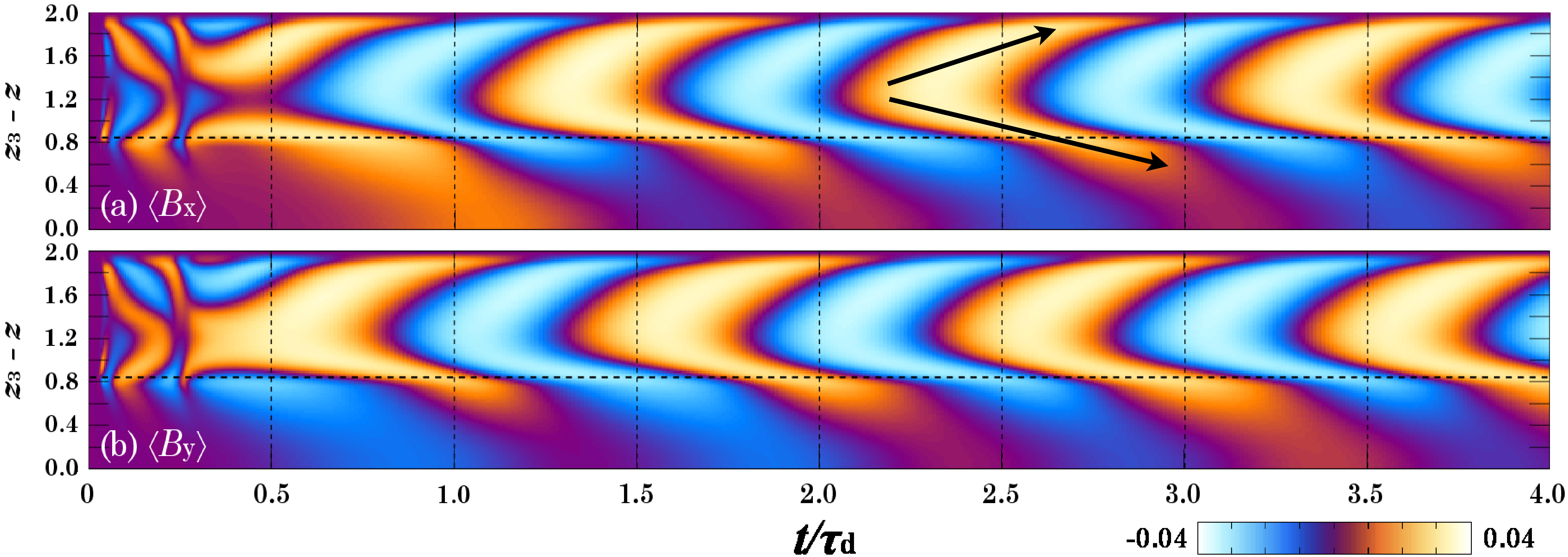
$$\frac{\partial \langle \boldsymbol{B}_h \rangle}{\partial t} = \nabla \times [\alpha \langle \boldsymbol{B}_h \rangle - (\eta + \eta_t)\nabla \times \langle \boldsymbol{B}_h \rangle] ,$$

with non-linear back-reaction from MF.

$B_{\rm h}$: horizontal magnetic components

(c.f., Blackman & Brandenburg 02)

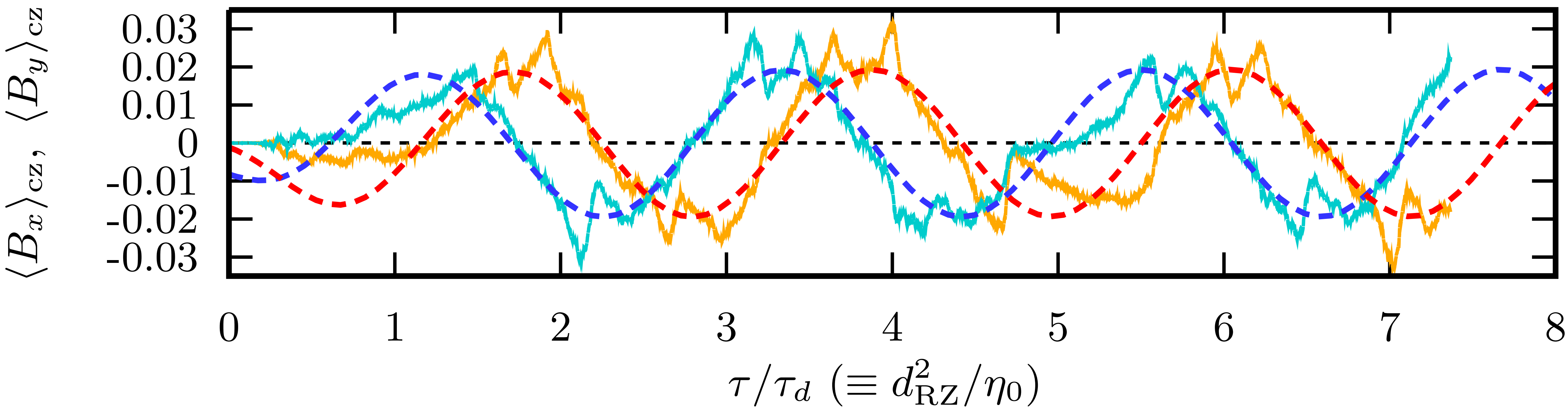
Nonlinear Solution: Propagating α^2-Dynamo Wave



- **A spatiotemporal evolution of the mean-field in the DNS is reproduced by the MF (α^2-dynamo) model.**
- **Like as the DNS, the mean-field is the strongest at around mid-CZ and propagates from there to top and base of the convection zone.**
- **A phase difference of about π /2 between $\langle B_x \rangle$ and $\langle B_y \rangle$.**

Quantitative Agreements between DNS and MFM

Not only qualitatively, there are quantitative agreements.



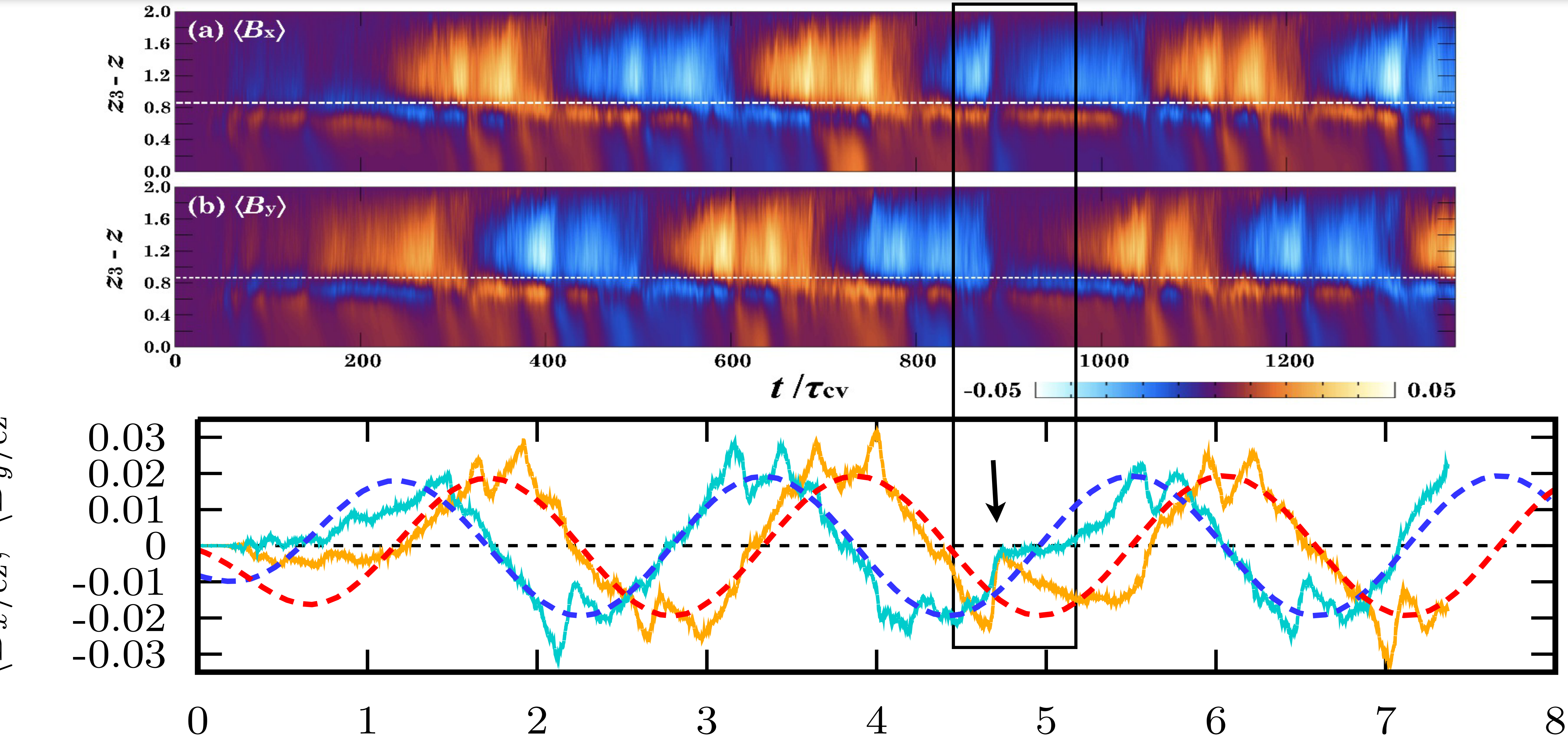
Orange: B_x in DNS, **Cyan: B_y in DNS**
Red : B_x in DNS-driven MF, **Blue : B_y in DNS-driven MF**

- **The times of DNS and MF model are normalized by the same microscopic (Spitzer's) diffusion time throughout the radiative zone.**
- **All the large-scale features, cycle period, amplitude, and phase difference in the DNS are identical to those in the MF model.**

Evidences of α^2 dynamo mode

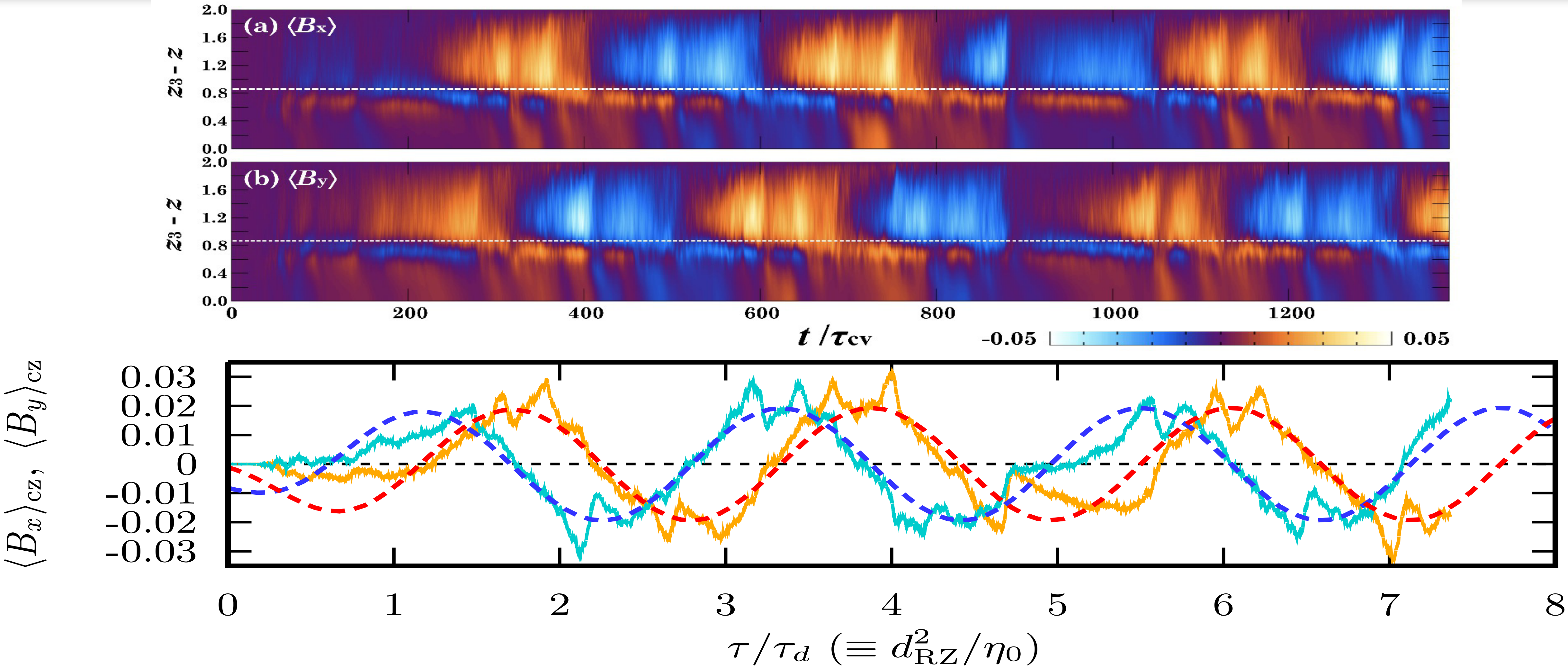
Discussion

Discussion : Self-excited nature of α^2-mode



- The prolonged minimum is reminiscent of ``Grand Minima" in the solar cycle.
- The minimum phase and the spontaneous revival from it would be a manifestation of the self-excited nature of the α^2-dynamo mode.
- During the prolonged minimum, the magnetic cycle seems to continue....

Summary ~ Possibility of α^2 dynamo mode ~



- **DNS of turbulent convective dynamo**
  → Oscillatory large-scale magnetic field
- **DNS-driven MF α^2-dynamo model**
  → large-scale features are quantitatively reproduced.
- **Message**
  : For the cyclic dynamo, Ω-process is not necessary ingredient.
  Please keep in mind the possibility of the α^2 mode in the Sun.

Our Global "Solar-type" Dynamo Simulation

EFFECTS OF PENETRATIVE CONVECTION ON SOLAR DYNAMO

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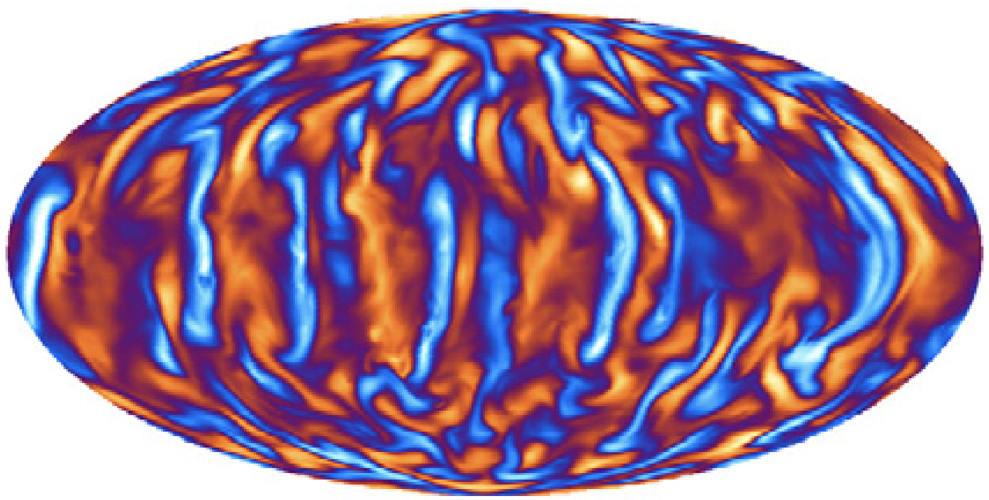
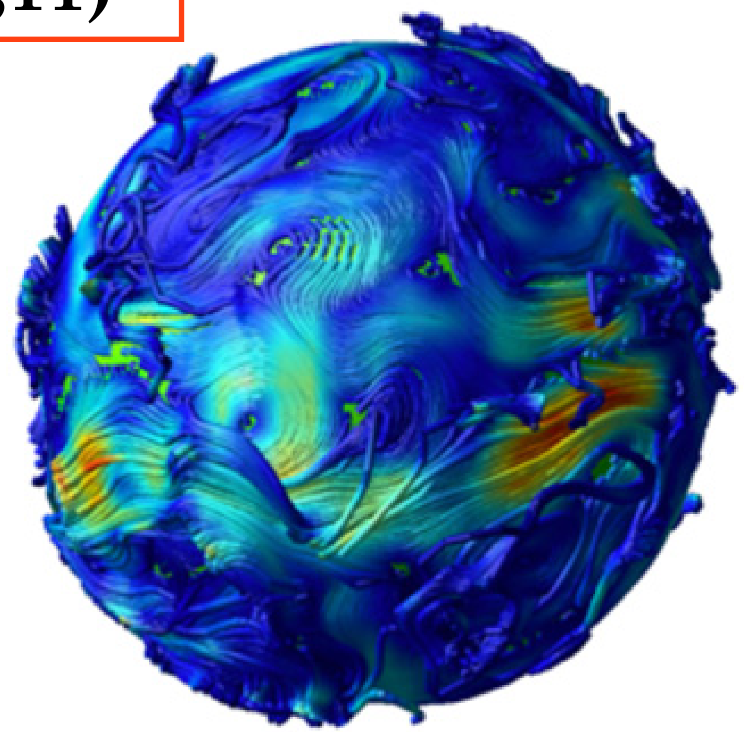
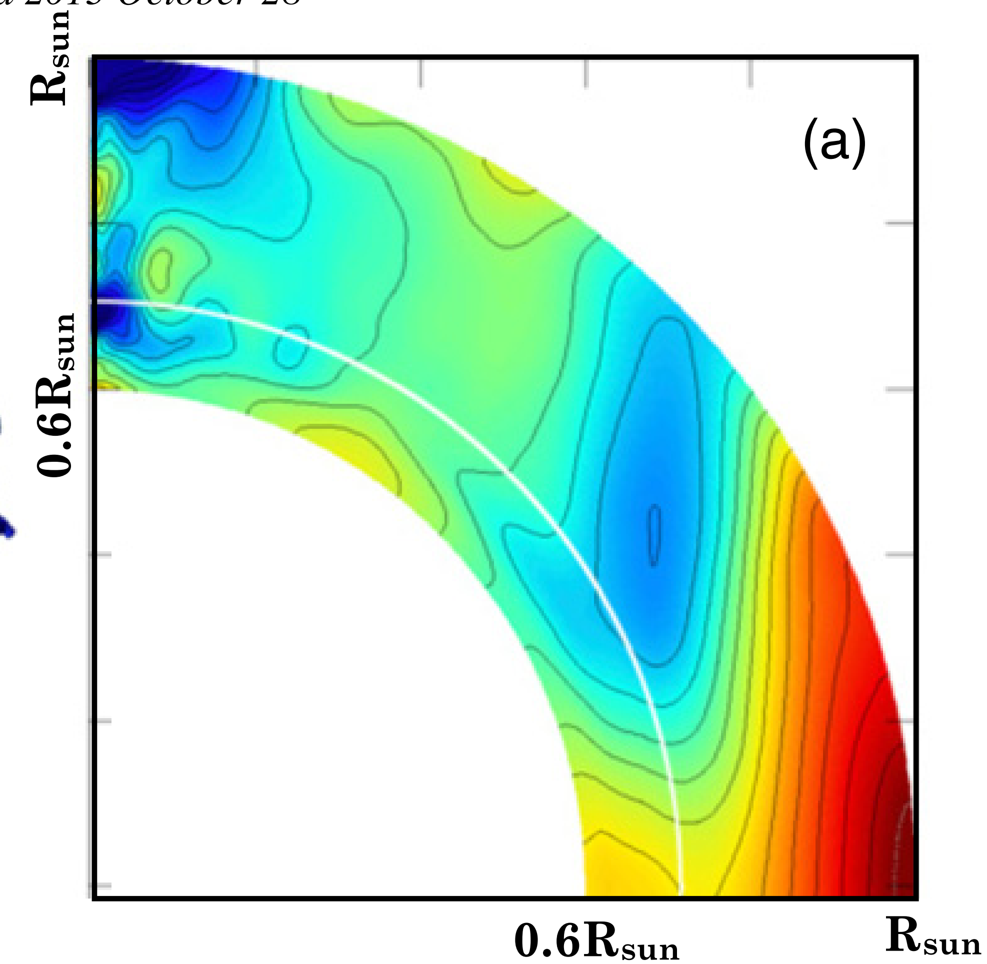
Masada+2013 (ApJ, 778,11)







Cyclic B_ϕ-Field in Tachocline