Mean Field Generation in Local Convective Dynamo Simulation

(Masada & Sano 2012 in prep.)

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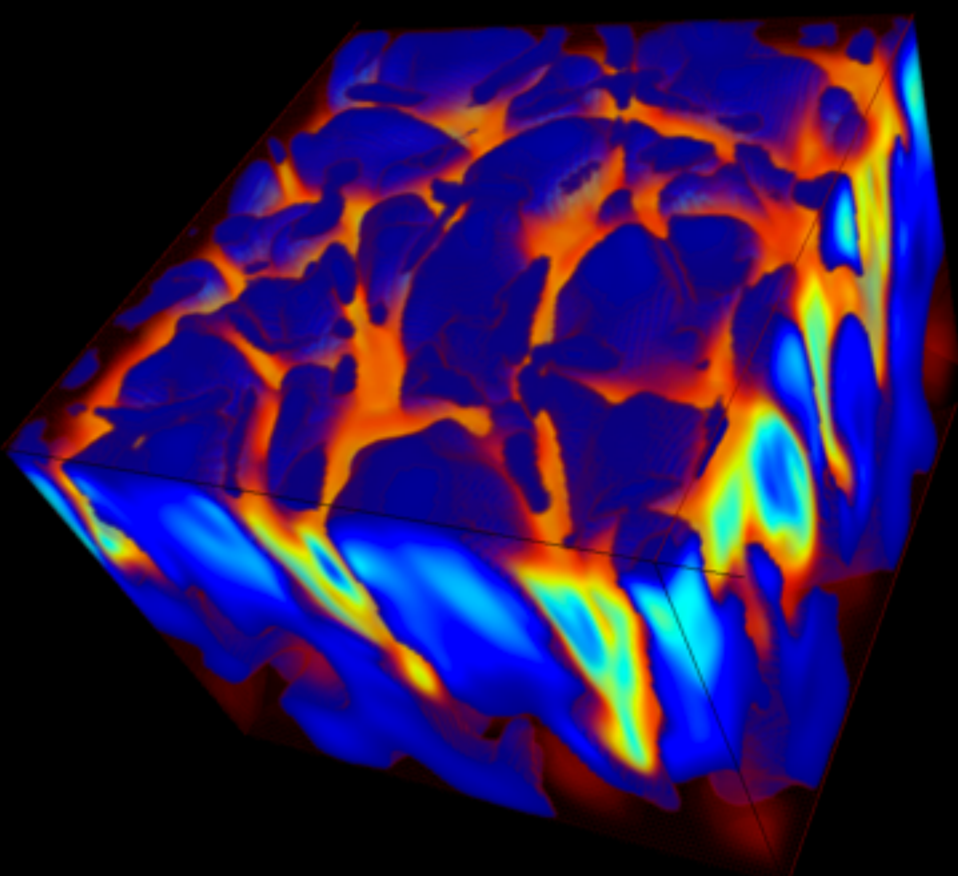
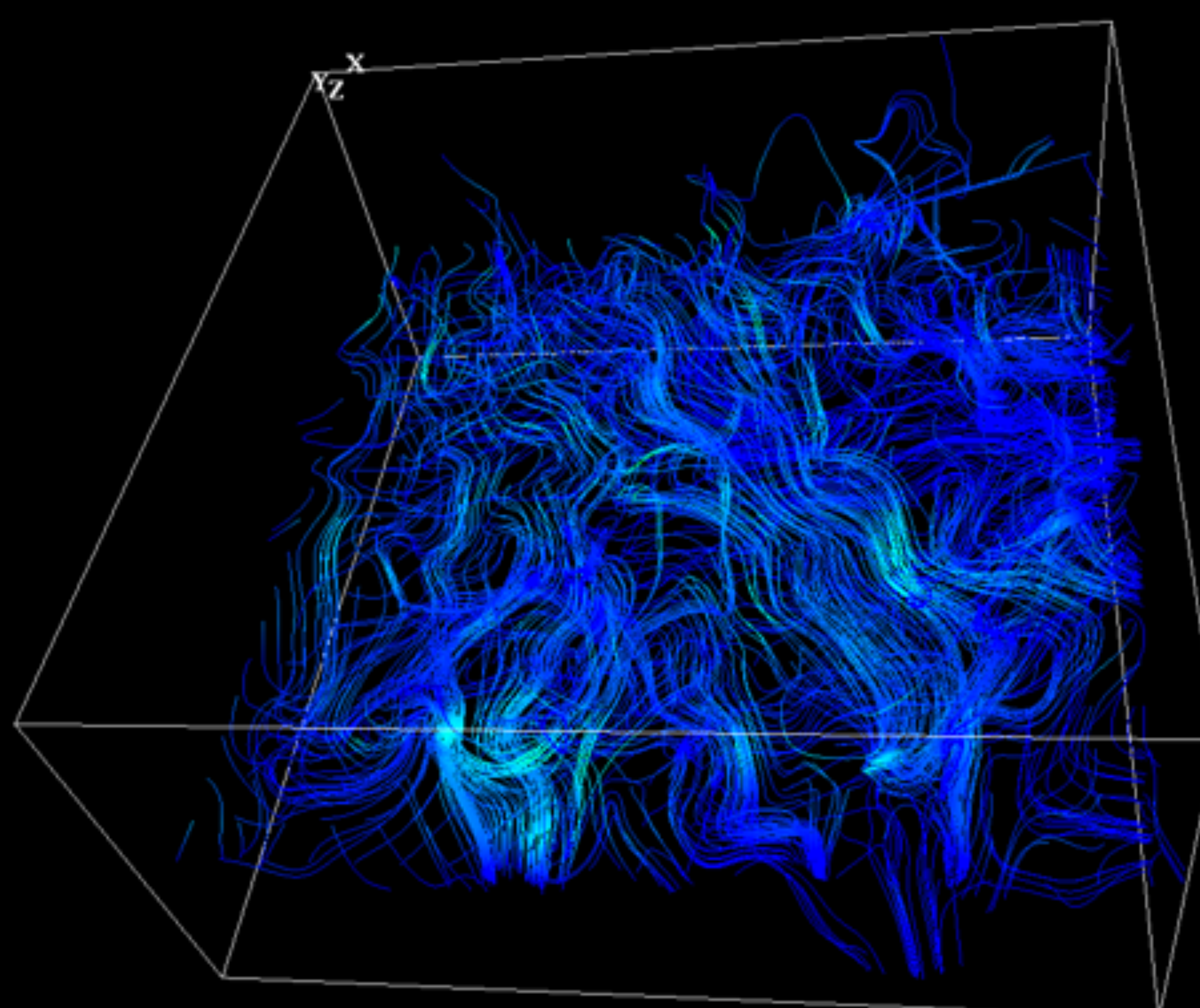
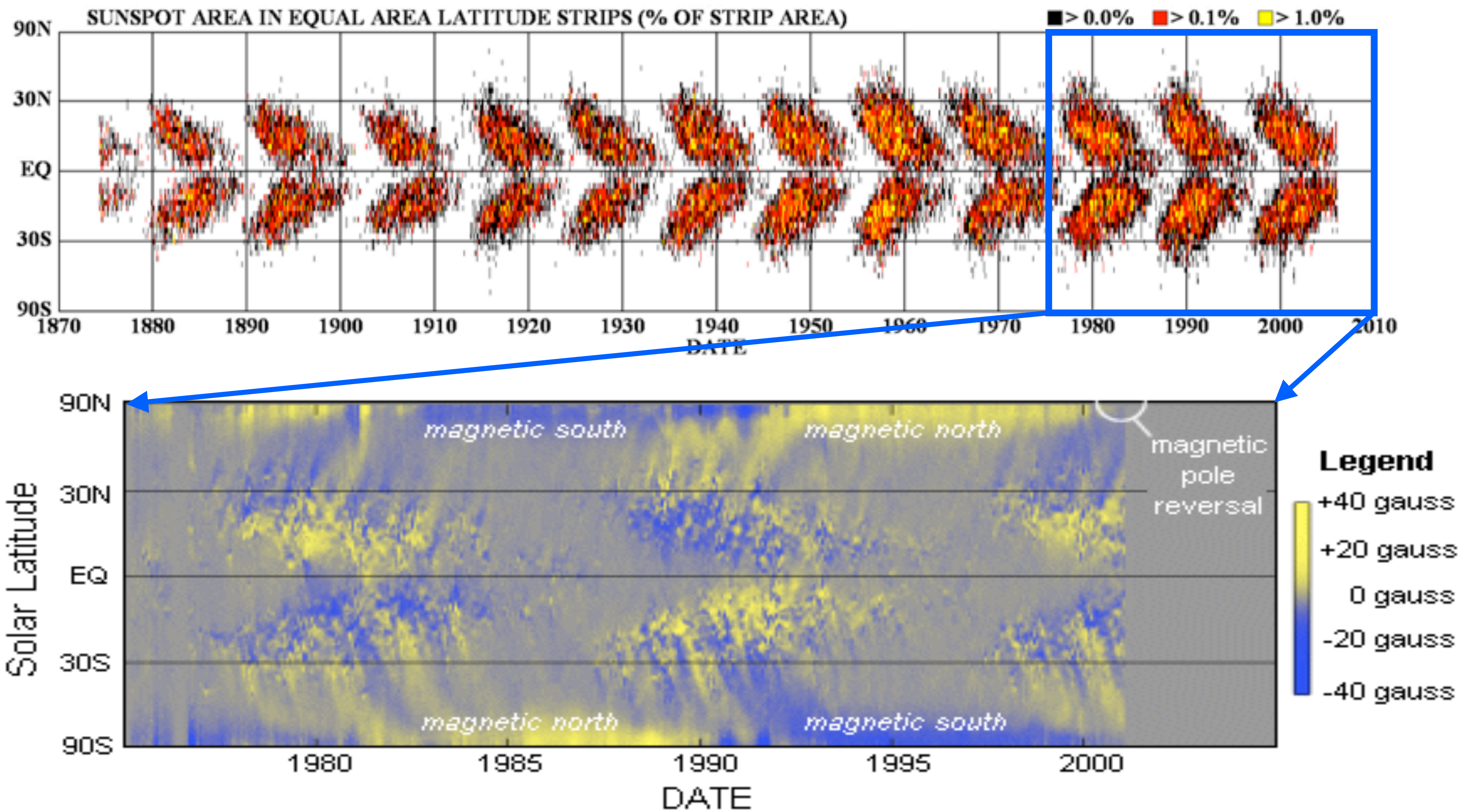
EANAM 2012 @ YITP, Kyoto University, 31 October 2012





Cyclic Properties of Dynamo Generated Field in the Sun

Butterfly diagram
: Time-evolution of latitudes of sunspots over several solar cycles.

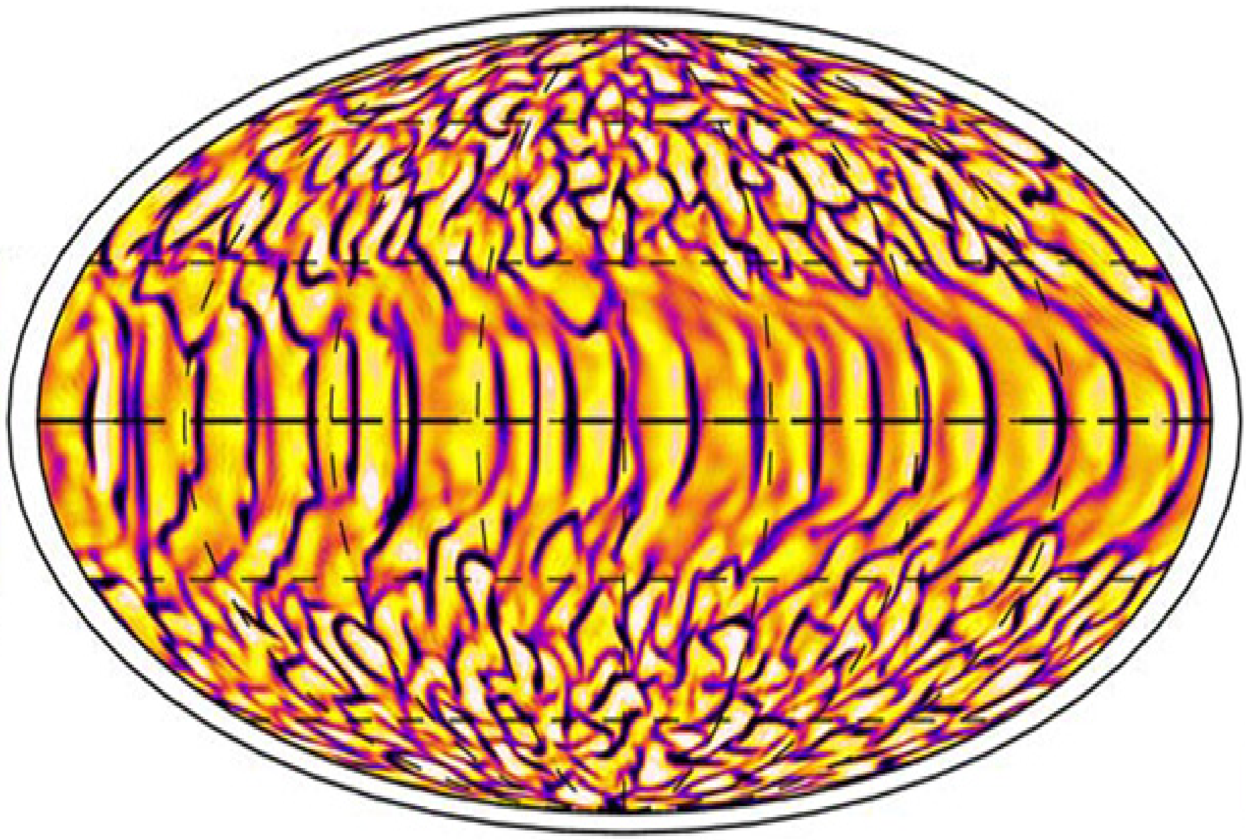


The butterfly diagram is a representative of cyclic properties in dynamo-generated magnetic fields in the Sun.

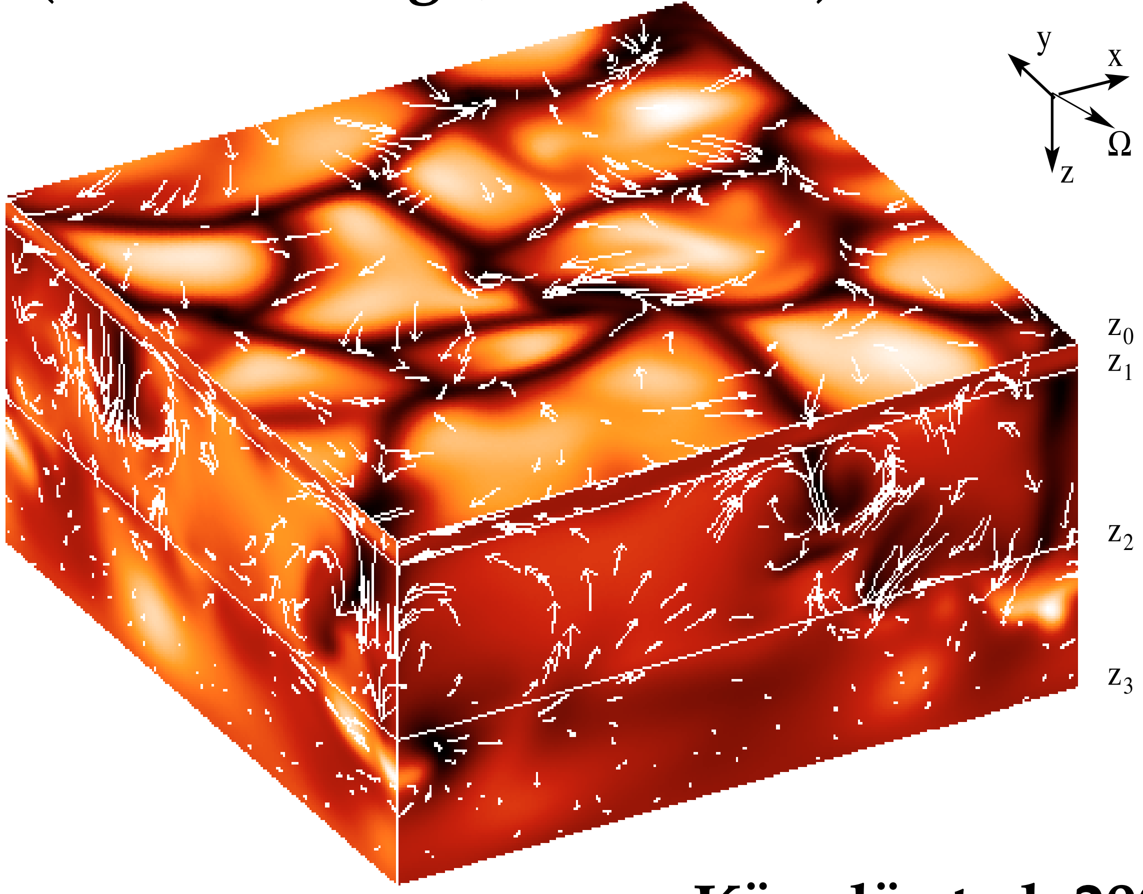
Motivation: Origin of Large-scale Magnetic Field

A lot of numerical studies on the solar dynamo.....

- Global Simulation:
  (Miesch+, Charbonneau+, Kapyla+...)
- Local Box Simulation:
  (Brandenburg+, Tobias+....)



Brown et al. 2010



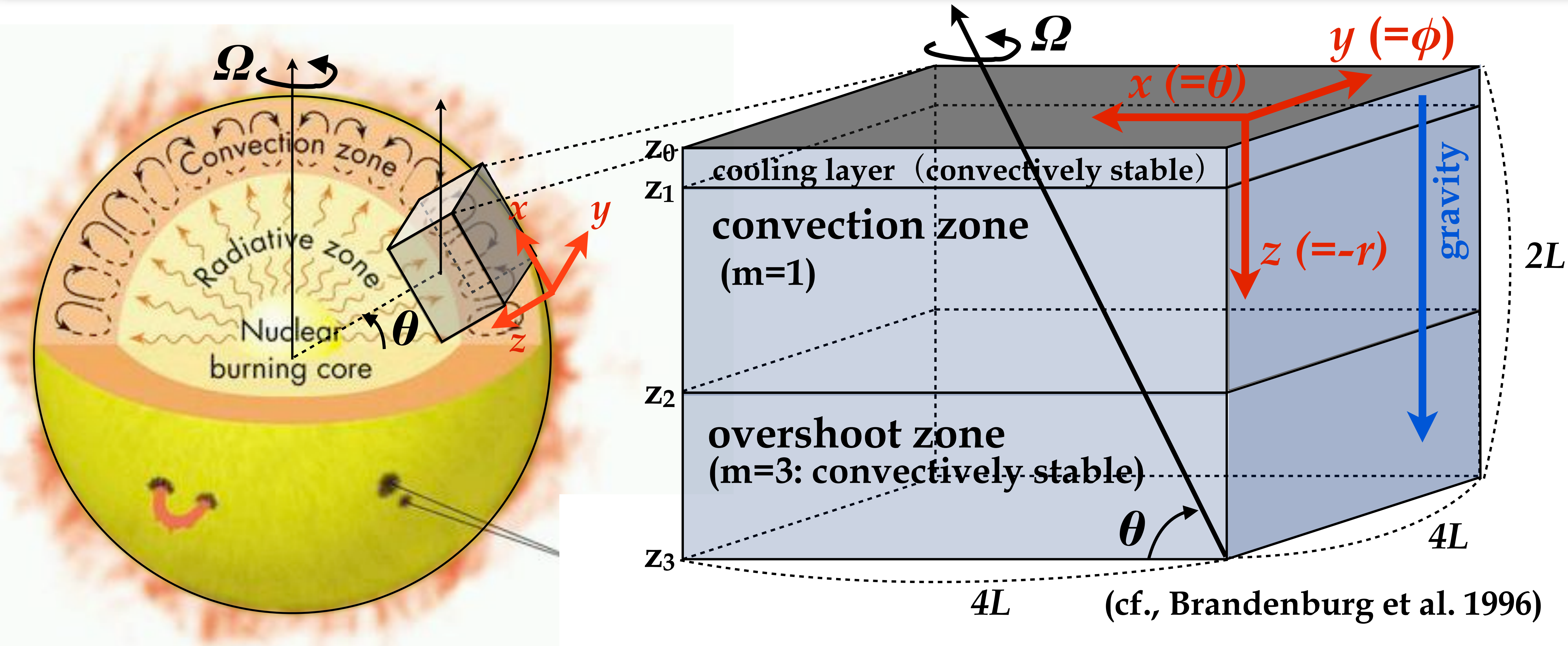
Käpylä et al. 2004

Turbulent field can be amplified and sustained in both dynamo simulations.

- Long-standing Issue in the solar dynamo simulation：
  How and Where is "Large-scale Magnetic Field (LMF)" generated ?

A purpose of our work is to find some hints for this issue by local box simulations.

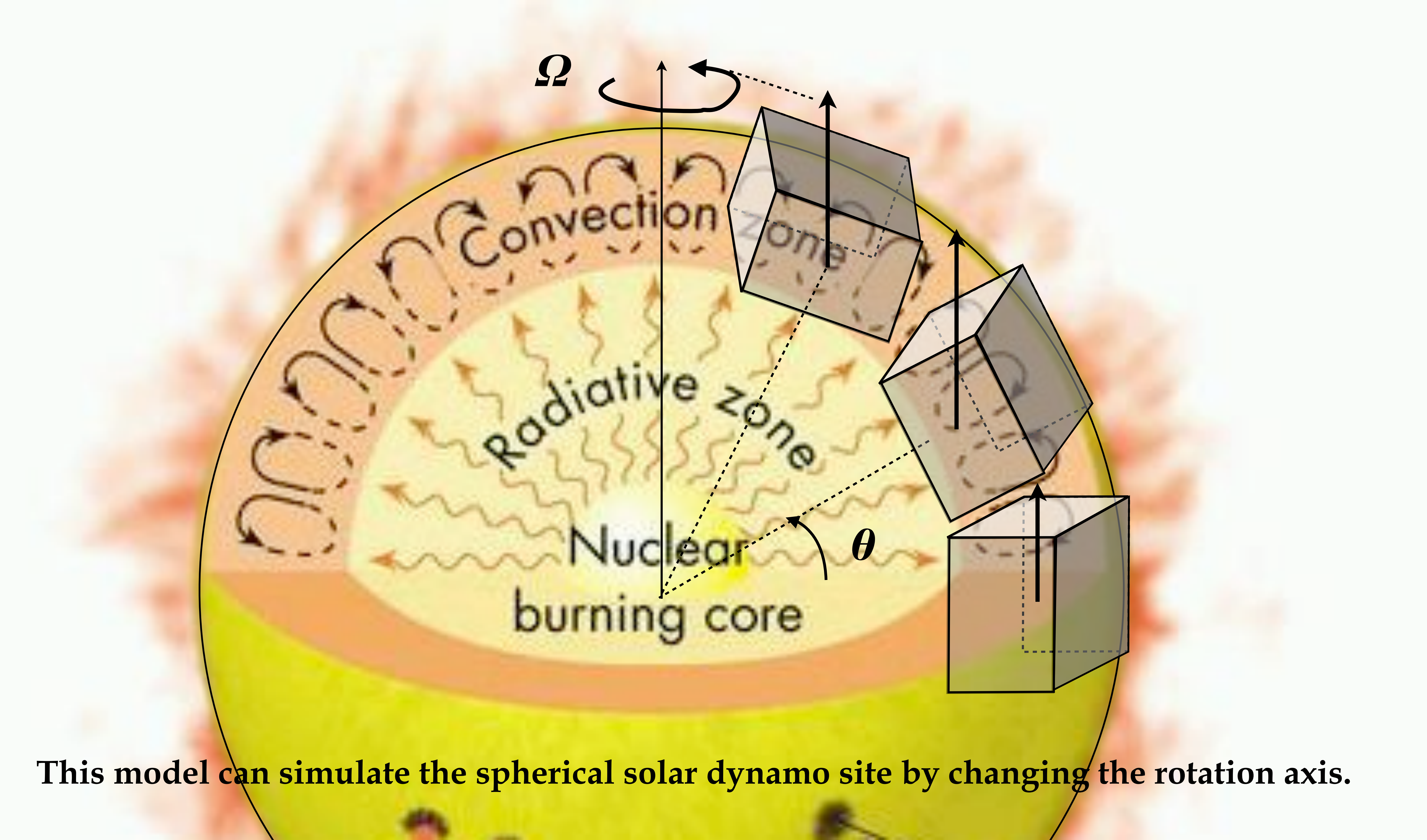
Numerical Setting：Local Cartesian Box



(cf., Brandenburg et al. 1996)

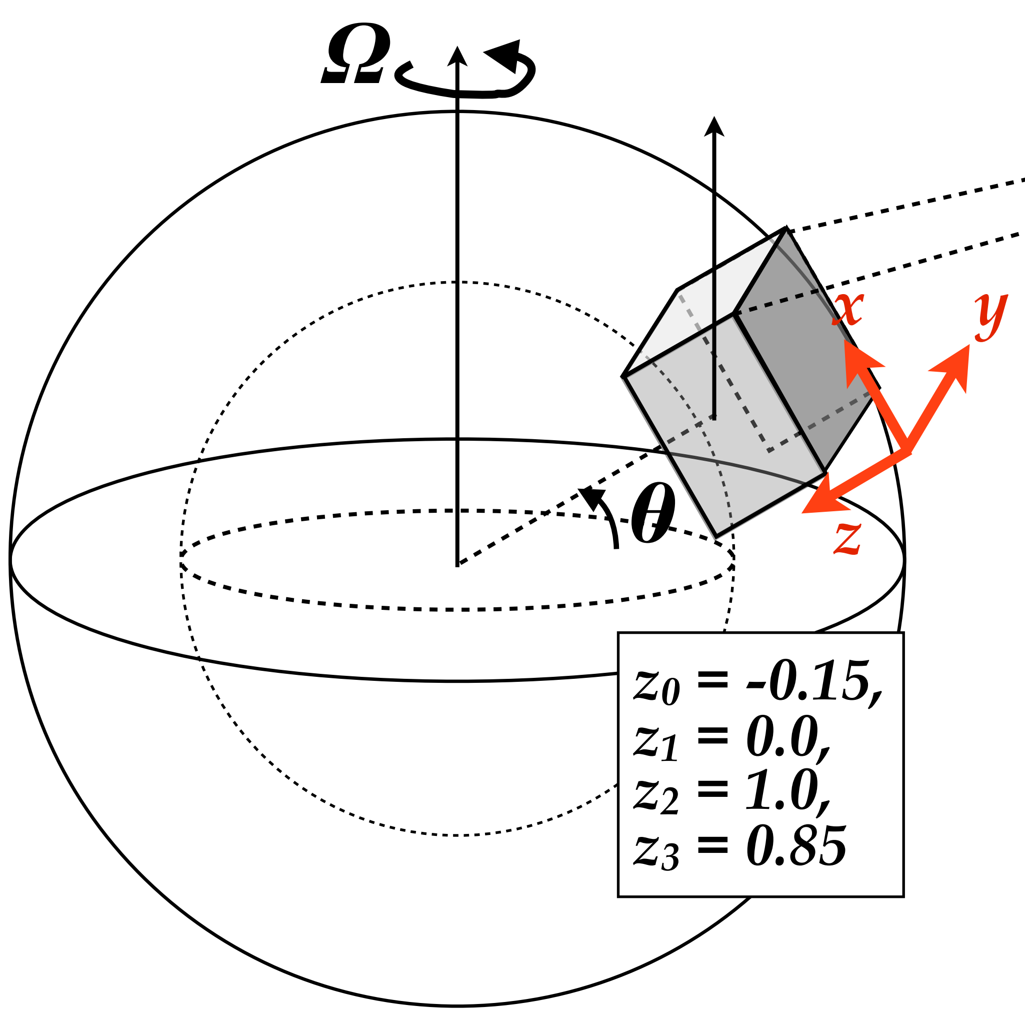
- Compressible MHD equations are solved in rotating frame.
- A local portion of the solar interior is modeled in a Cartesian domain.
- Initial Setting：Hydrostatic Polytropic 3 Layers Structure.
  （Top: cooling layer + Mid: convection + Bottom: overshoot）.
- Uniqueness: The direction of rotation axis (Coriolis force) is a control parameter.

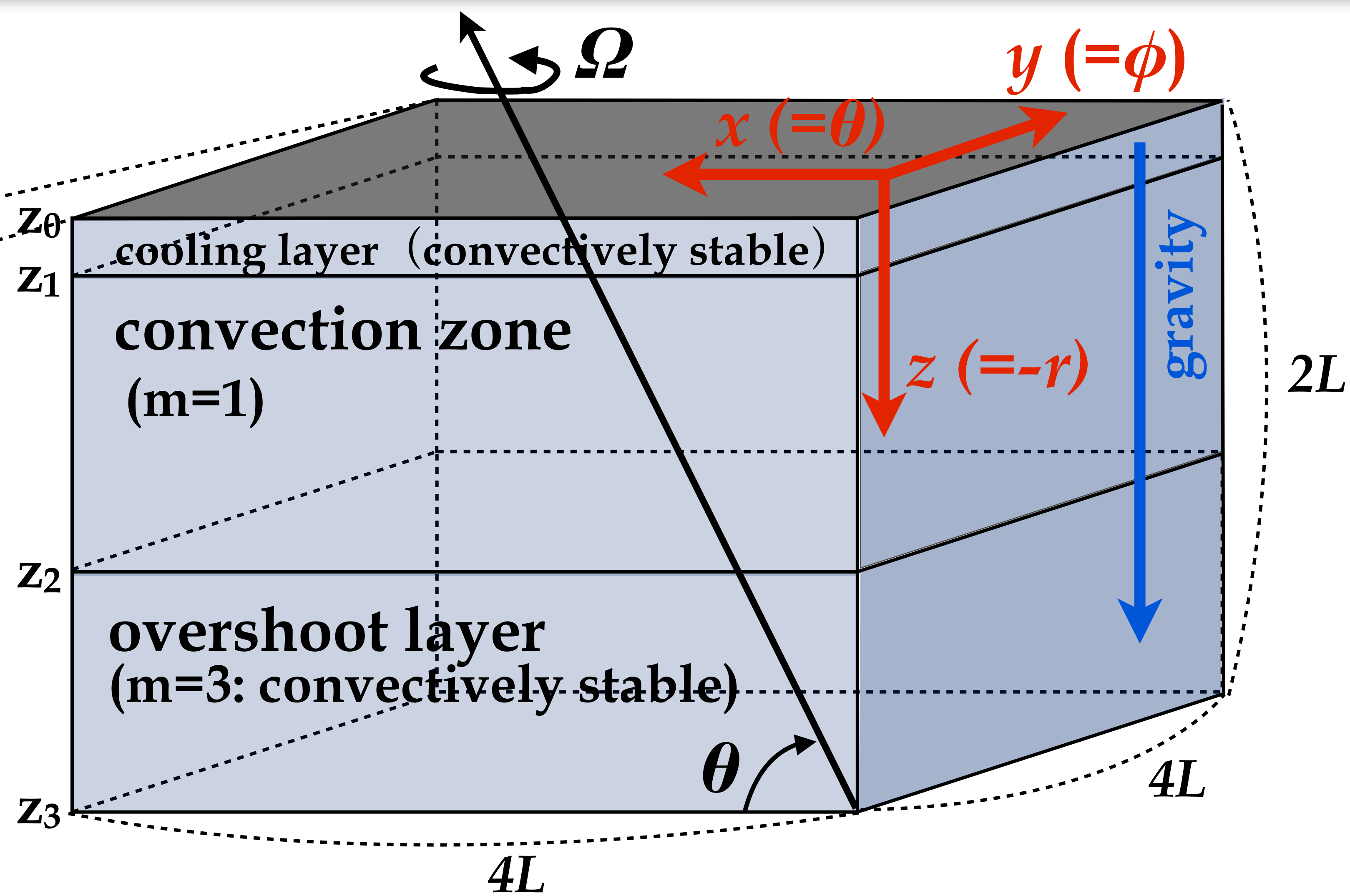
By changing the direction of the rotation axis, we can change and control the latitudinal location of the simulation box.



This model can simulate the spherical solar dynamo site by changing the rotation axis.

Numerical Setting：Local Box Simulation



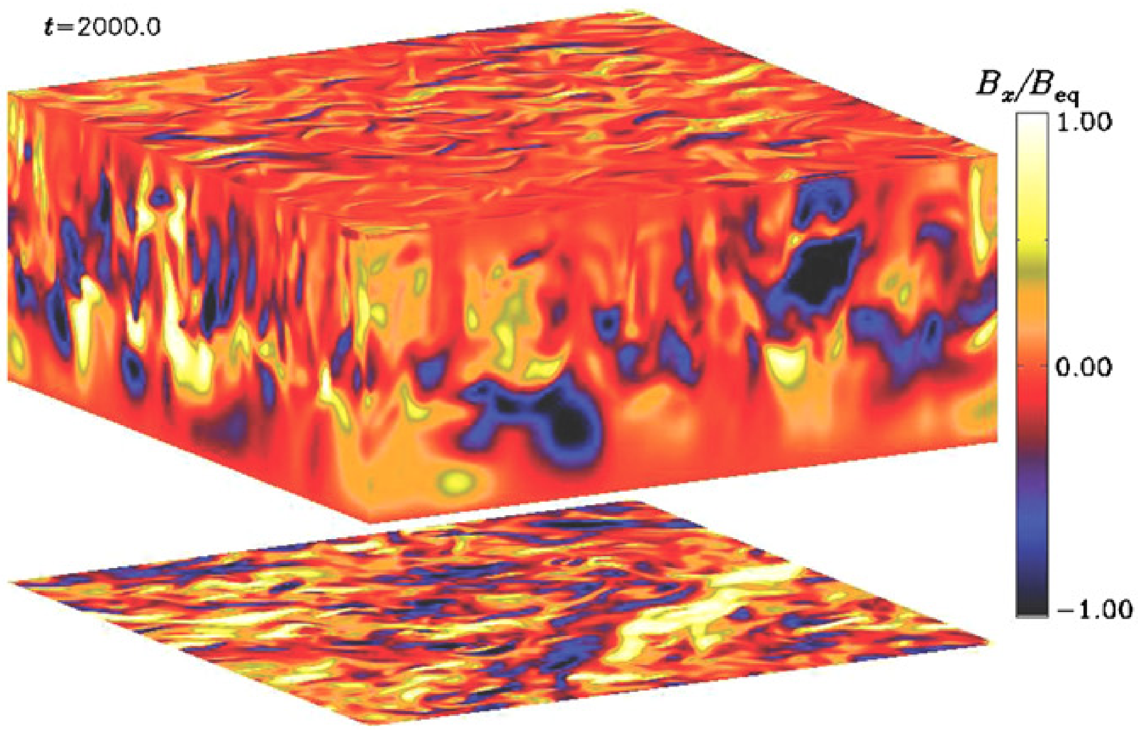


- Horizontal B.C.: Periodic B.C.
- Vertical B.C.:
  - stress free B.C. for V at z_0 and z_3
  - open field B.C. for B @ z_0
    perfect conductor B.C. for B @z_3
  - T = const. @z_0
    $\partial T/\partial z$ = const. @z_3

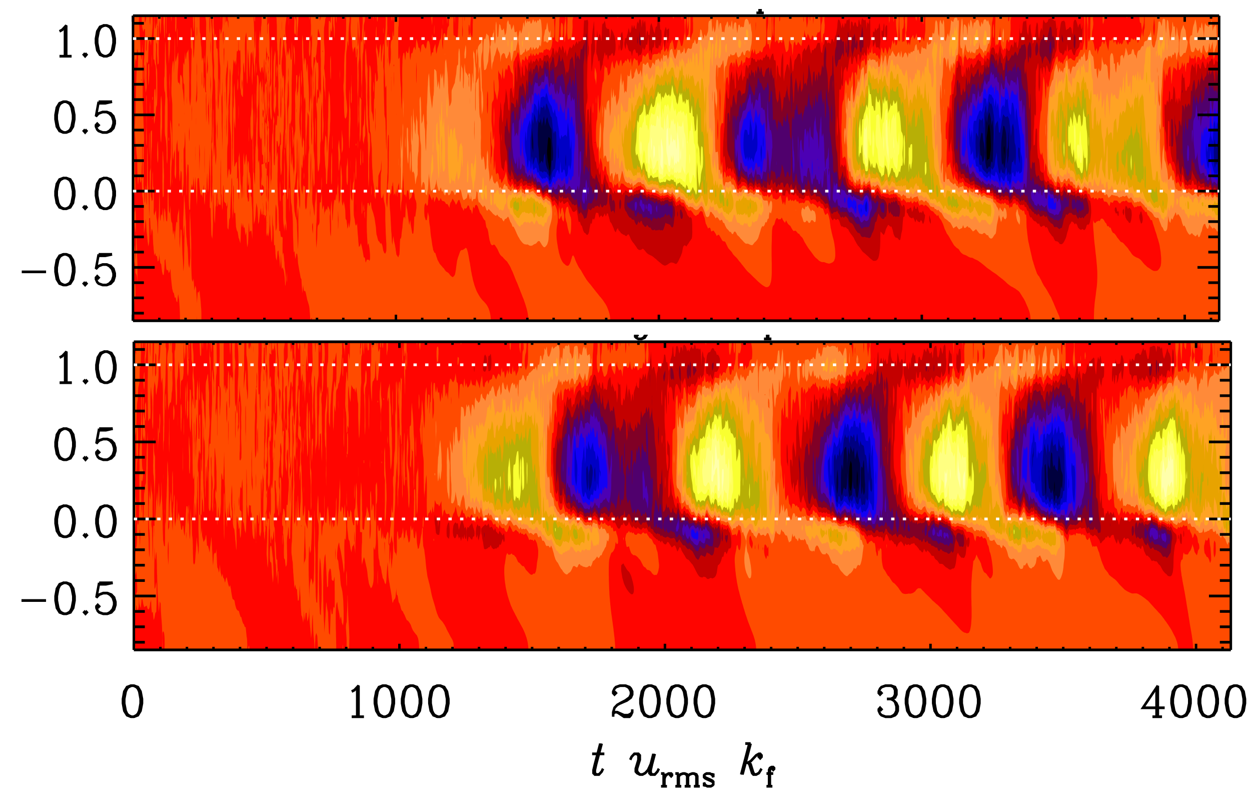
- Numerical Scheme：Godunov CMoC-CT (Sano et al. 1998)
- Resolution：$N_x \times N_y \times N_z = 256\times256\times128$
- Control Parameters：
  diffusivities：$\nu, \varkappa, \eta$ (fixed here)
  strength of the stratification：ξ (fixed)
  latitude：θ　angular velocity：Ω

Current Status of Local Convective Dynamo Simulation

- Käpylä, Korpi & Brandenburg 2009



- Käpylä, Mantere & Brandenburg 2011



- Generation of LMFs was found, <u>for the first time</u>, by Käpylä et al. 2009.
- The cyclic variation of the LMFs was reported in Käpylä et al. 2011.
- All the models in Kapyal et al. focus on the polar region with θ=90°.
- No sufficient explanations on the generation and cyclic variation mechanisms of LMFs appeared in local box simulations.

※ Tow questions naturally arise....

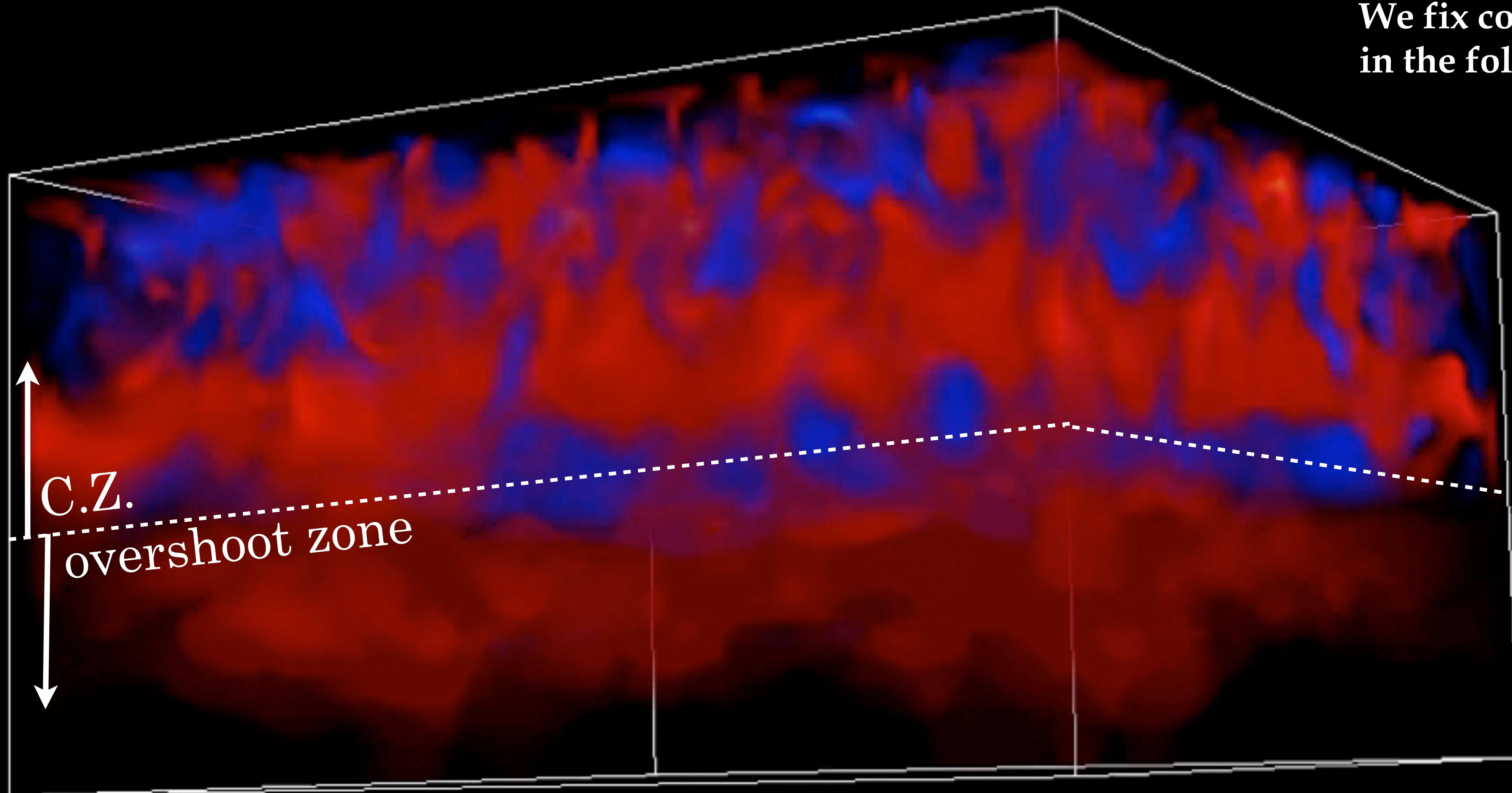
1) Can LMFs be generated in the local box located on the other latitudes ?

2) What is the mechanism for the generation and cyclic variation of LMFs ?

Convective Dynamo Simulation (Polar region model with $\theta = 90°$)

(B_y field at the saturated state is visualized by 3D volume rendering)

Generation of LMFs in the bottom of C.Z. and their reversals can be observed in this movie.



We fix control parameters in the following:

$Pr = 0.86$
$Pm = 4.0$
$Ra = 2.8 \times 10^6$
$\Omega = 0.4$

$Re \simeq 100$
$Rm \simeq 400$
$Ro \simeq 0.025$
(similar parameters with Kapyla's model)

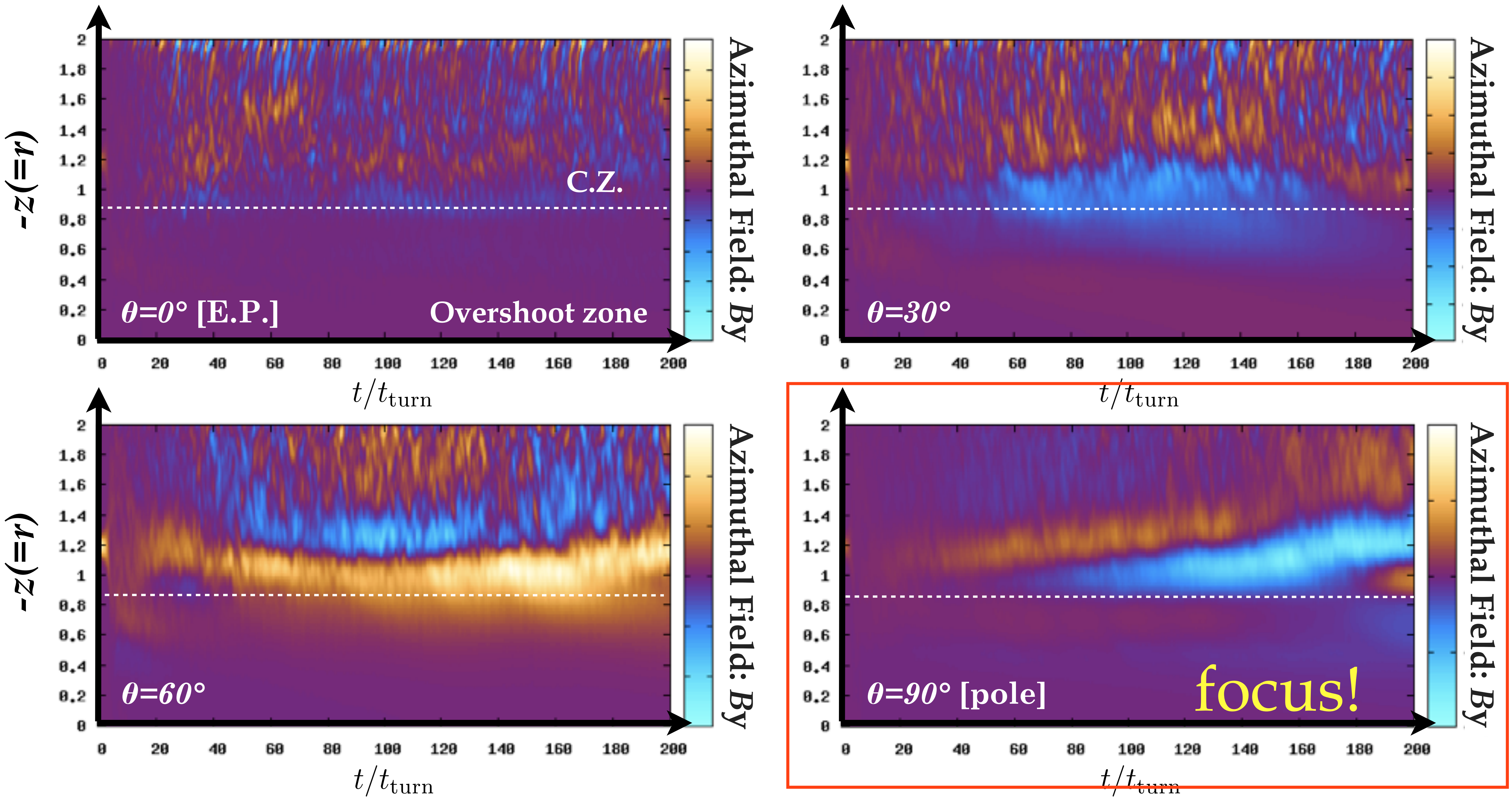
Blue: negative By components
Red: positive By components

$(N_x, N_y, N_z) = (256, 256, 128)$
$(L_x, L_y, L_{conv}) = (4, 4, 1)$

By changing the co-latitude θ, we study the generation and cyclic variation mechanisms of LMFs in the following.

The θ-dependence of magnetic field structures：Generation of Large-scale Magnetic Fields (LMFs)

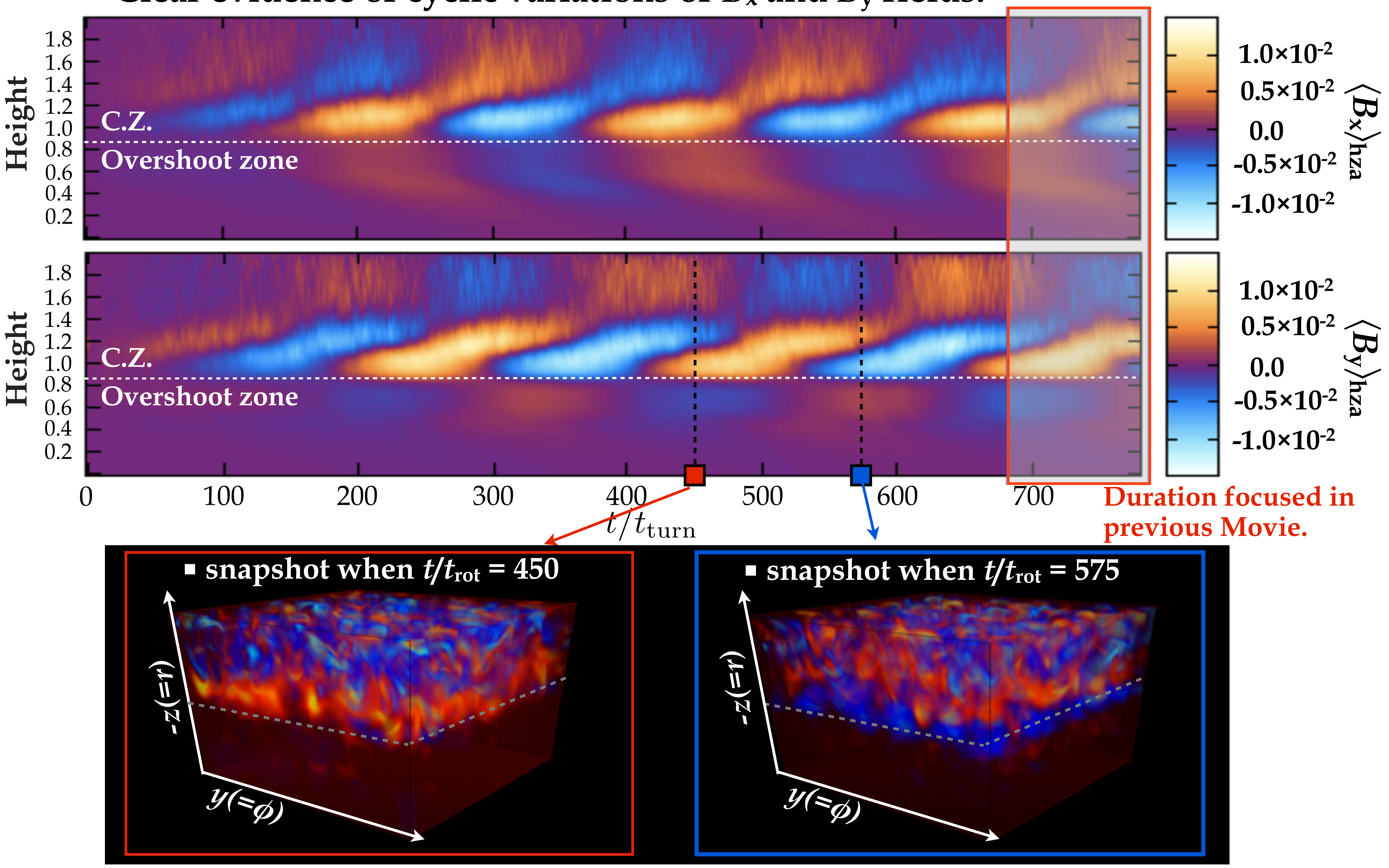
- Time-evolution of horizontally averaged B_y field as a function of z (height).



- LMFs are generated at almost all the latitude except the equatorial region.
- Common generation site of LMFs is the bottom of convective zone.

Long-term Evolution of Polar Region Model: Cycle Variation

- Clear evidence of cyclic variations of B_x and B_y fields.



※There is a phase difference of 90° between $\langle B_x \rangle$ and $\langle B_y \rangle$.

Summary:

This work adopts control parameters $Pr = 0.86$, $Pm = 4.0$, $Ra = 3\times10^6$, $\Omega = 0.4$

- Local Convective Dynamo Simulation with $Ro \fallingdotseq 0.025$.
- Coherent LMFs is generated except the model at $\theta=0°$ [equator].
- Common generation site of LMFs is the bottom of C.Z.
- Vortex sheets with alternating vortices would induce cyclic variations of LMFs.
- Overshoot zone seems to play an important role in sustaining
  - coherent vortex sheets with alternating vortices,
  - and thus LMFs in the bottom of C.Z..

A part of our Future works:

- We should reveal the formation mechanism of vortex sheets.
- Long-term evolution of the models located at the different latitudes.
- large Ro (Rossby number) model similar to that realized in solar C.Z..

  What is the most important factor for the "Solar Dynamo" ??
- Global simulation of solar-type convective dynamo with Yin-Yang Grid.