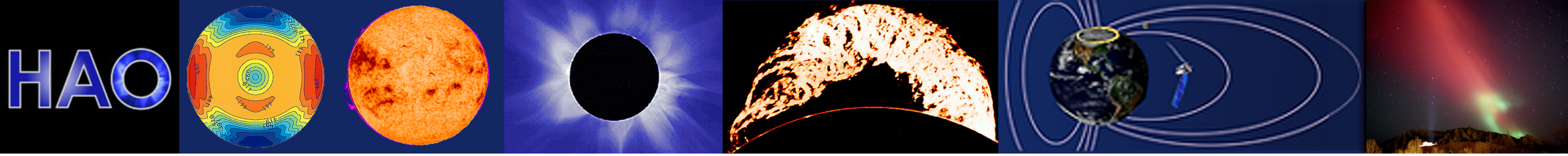

Modeling the Solar Dynamo and Emerging Flux and Integration into the SWMF

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NCAR

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- Finite-difference Spherical Anelastic MHD (FSAM) code solves the following anelastic MHD equations in a partial spherical shell domain:

$$\nabla \cdot (\rho_0 \mathbf{v}) = 0,$$

$$\rho_0 \left[\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} \right] = 2\rho_0 \mathbf{v} \times \mathbf{\Omega} - \nabla p_1 + \rho_1 \mathbf{g} + \frac{1}{4\pi}(\nabla \times \mathbf{B}) \times \mathbf{B} + \nabla \cdot \mathcal{D}$$

$$\rho_0 T_0 \left[\frac{\partial s_1}{\partial t} + (\mathbf{v} \cdot \nabla)(s_0 + s_1) \right] = \nabla \cdot (K \rho_0 T_0 \nabla s_1) - (\mathcal{D} \cdot \nabla) \cdot \mathbf{v} + \frac{1}{4\pi} \eta (\nabla \times \mathbf{B})^2 - \nabla \cdot \mathbf{F}_{\mathrm{rad}}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) - \nabla \times (\eta \nabla \times \mathbf{B}),$$

$$\frac{\rho_1}{\rho_0} = \frac{p_1}{p_0} - \frac{T_1}{T_0},$$

$$\frac{s_1}{c_p} = \frac{T_1}{T_0} - \frac{\gamma - 1}{\gamma} \frac{p_1}{p_0},$$

where D is the viscous stress tensor, and $\mathbf{F}_{\mathrm{rad}}$ is the radiative diffusive heat flux :

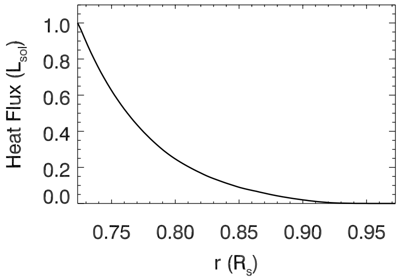
$$\mathbf{F}_{\mathrm{rad}} = \frac{16 \sigma_s {T_0}^3}{3 \kappa \rho_0} \nabla T_0,$$

A convective dynamo simulation

(Fan and Fang 2014, ApJ, in press)

- Simulation domain $r \in (0.722R_s, 0.971R_s)$, $\theta \in (\pi/2 - \pi/3, \pi/2 + \pi/3)$, $\phi \in (0, 2\pi)$
- Grid: $96 \times 512 \times 768$, horizontal res. at top boundary 2.8 Mm to 5.5 Mm, vertical res. 1.8 Mm
- $K = 3 \times 10^{13}\ cm^2 s^{-1}$, $\nu = 10^{12}\ cm^2 s^{-1}$, $\eta = 10^{12}\ cm^2 s^{-1}$, at top and all decrease with depth as $1/\sqrt{\rho}$
- Convection is driven by the radiative diffusive heat flux as a source term in the entropy equation:

$$\nabla \bullet (\mathbf{F}_{\mathbf{rad}}) = \nabla \bullet \left(\frac{16\sigma_s T_0^3}{3\kappa\rho_0} \nabla T_0 \right)$$



- The boundary condition for s_1:

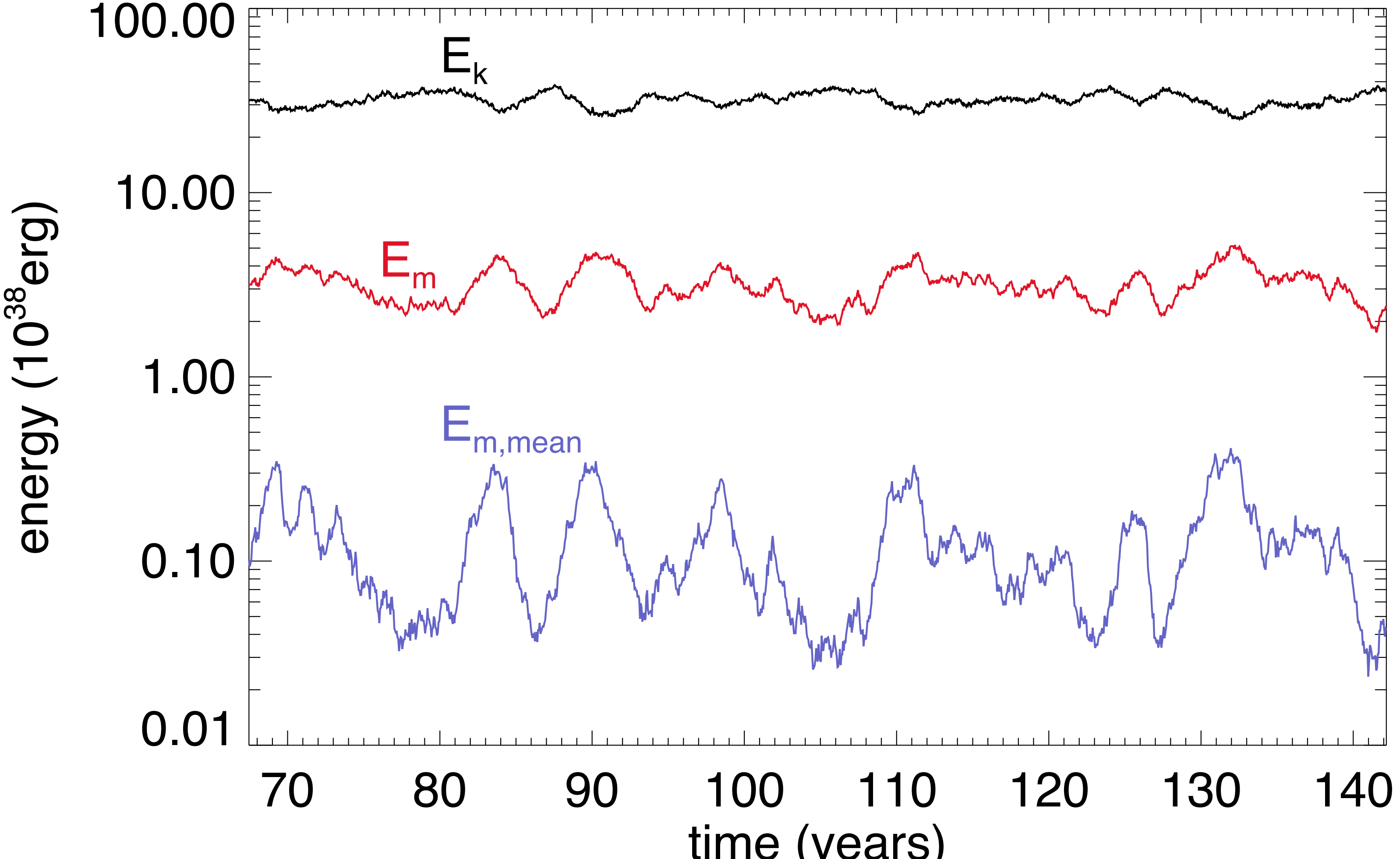
at the bottom $\frac{\partial s_1}{\partial r} = 0$, and a latitudinal gradient is imposed: $\left(\frac{\partial s_1}{\partial \theta}\right) = \frac{ds_i(\theta)}{d\theta}$ where $s_i(\theta) = -\Delta s_i \cos\left(\frac{\theta - \pi/2}{\Delta\theta}\pi\right)$

at the top s_1 is held fixed, and s_1 is symmetric at the θ - boundaries

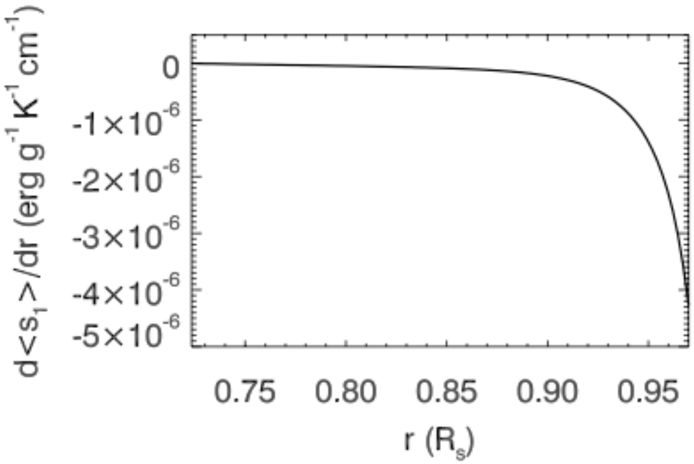
- The velocity boundary condition is non-penetrating and stress free at the and the top, bottom and θ−bondaries

- For the magnetic field: perfect conducting walls for the bottom and the θ−boundaries; radial field at the top boundary

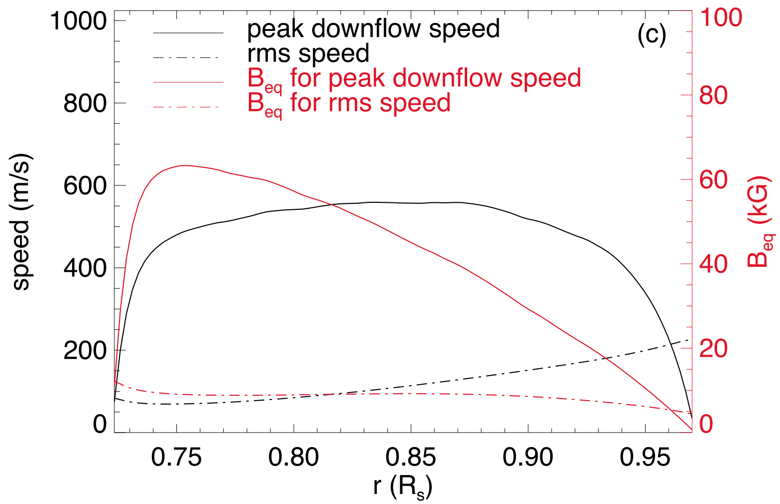
- Angular rotation rate for the reference frame $\Omega = 2.7 \times 10^{-6}$ rad/s, net angular momentum relative to the reference frame is zero.



100.00
10.00
1.00
0.10
0.01
energy (10^{38}erg)
E_k
E_m
$E_{m,mean}$
70
80
90
100
110
120
130
140
time (years)



Consistent with Model S of JCD: the entropy gradient at $0.97R_s$ is ~10^{-5} erg g^{-1} K^{-1} cm^{-1}



$\mathrm{Re} = u_{rms}/\nu k_f \approx$ 130 to 50 from bottom to top

$Co = 2\Omega/u_{rms,all}k_f \approx 1.3$, where $k_f = 2\pi/(r_o - r_i)$

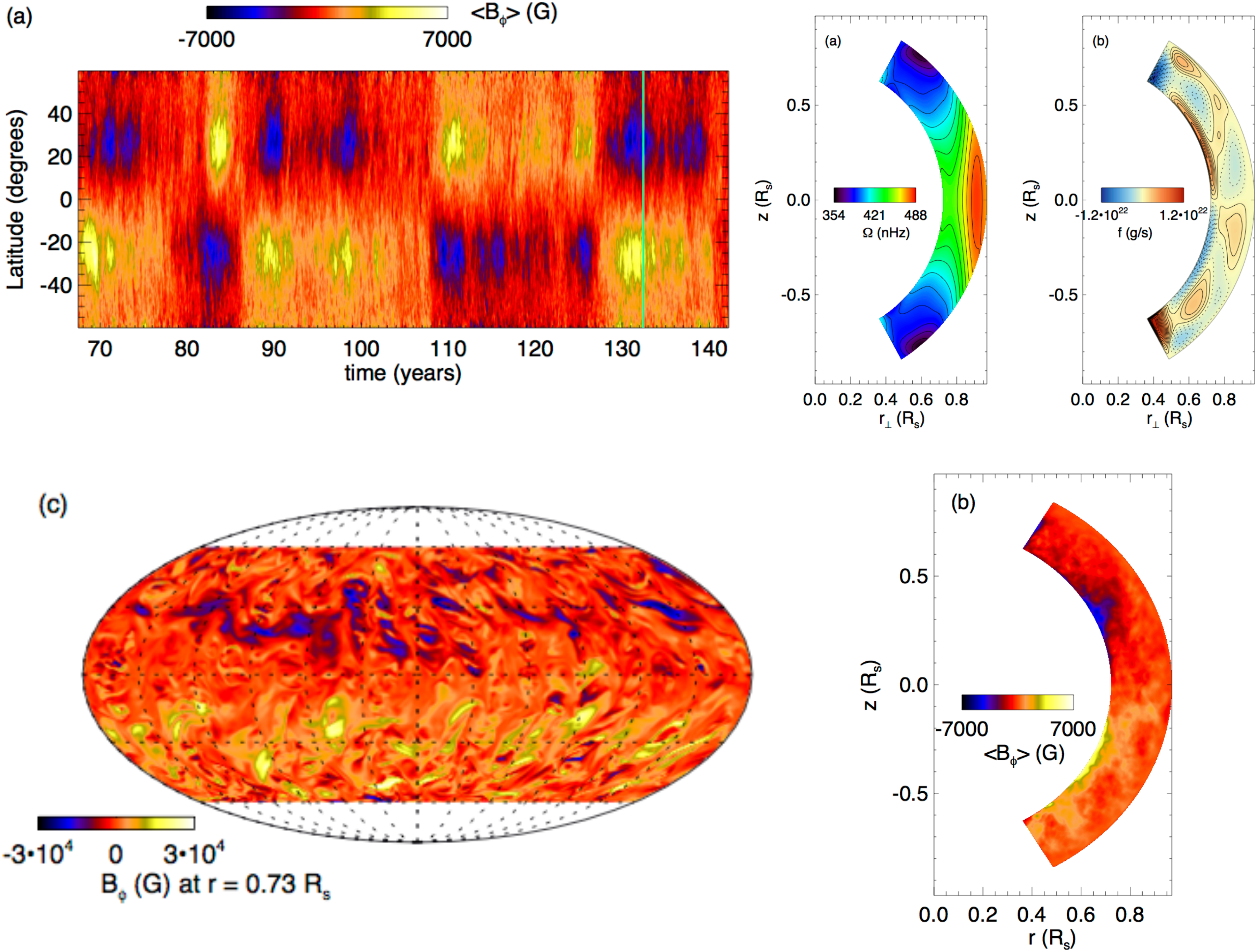
$Ro = u_{rms,all}/\Omega l \approx 0.74$, where $l = H_p$ at bottom

Compared to Kapyla et al. (2012):

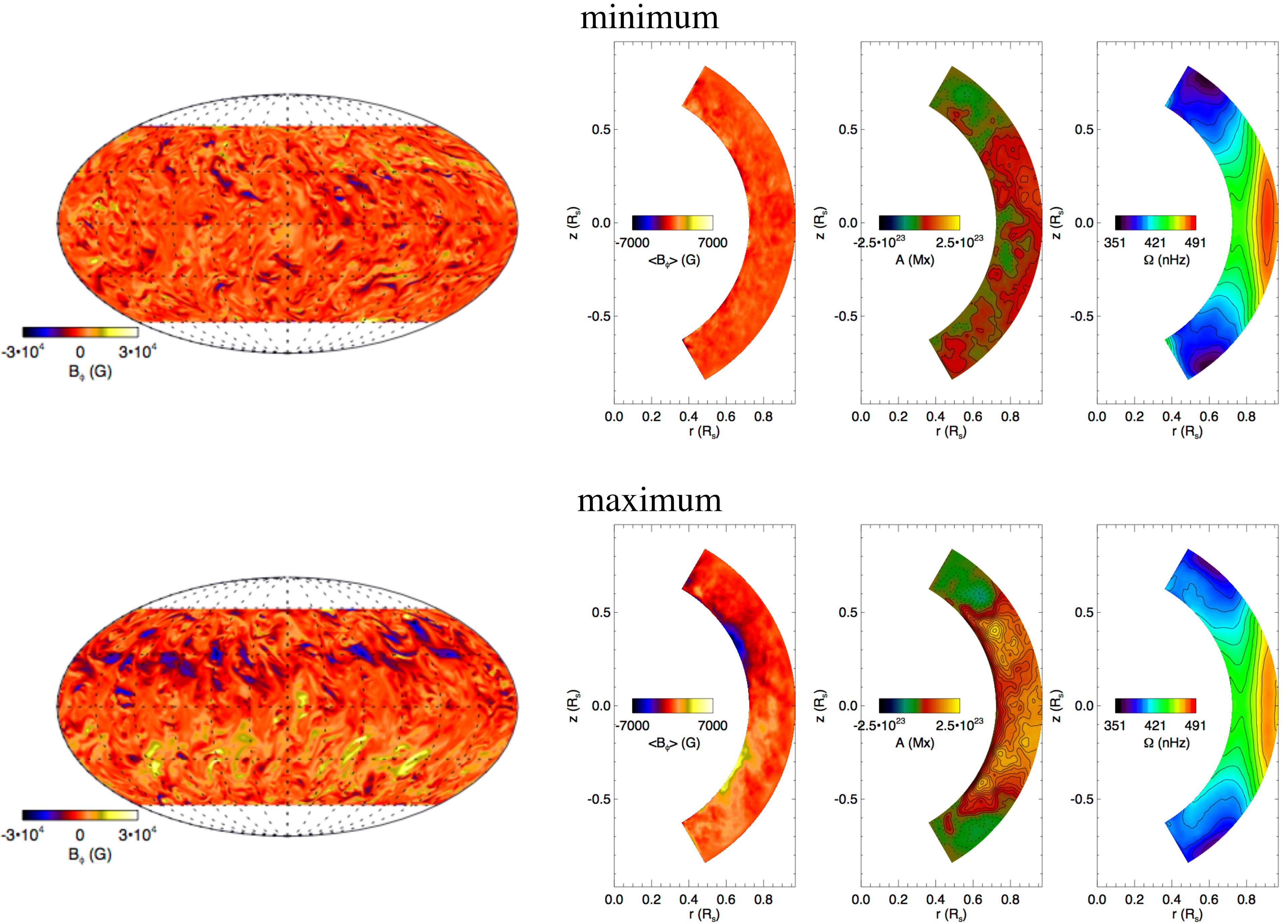
$\mathrm{Re} = 36$

$Co = 7.6$

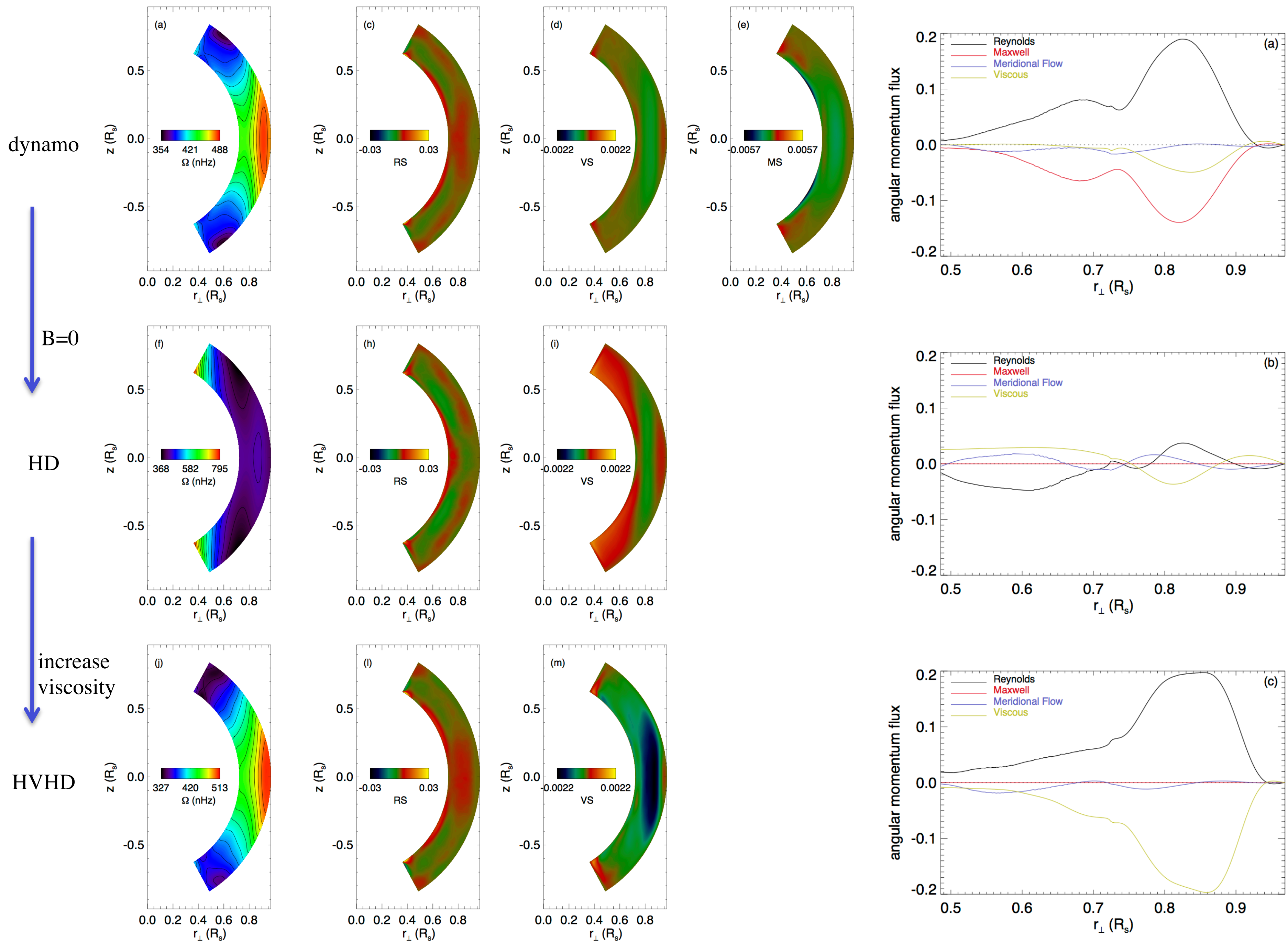
Our dynamo is in a much less rotationally constrained regime compared to Kapyla et al. (2012), Nelson et al. (2013), Augustson et al. (2013).



(a)
<B$_\phi$> (G)
-7000
7000
Latitude (degrees)
40
20
0
-20
-40
70
80
90
100
110
120
130
140
time (years)
(a)
z (R$_s$)
0.5
0.0
-0.5
354
421
488
Ω (nHz)
0.0
0.2
0.4
0.6
0.8
r$_\perp$ (R$_s$)
(b)
z (R$_s$)
0.5
0.0
-0.5
-1.2•10^{22}
1.2•10^{22}
f (g/s)
0.0
0.2
0.4
0.6
0.8
r$_\perp$ (R$_s$)
(c)
-3•10^4
0
3•10^4
B$_\phi$ (G) at r = 0.73 R$_s$
(b)
z (R$_s$)
0.5
0.0
-0.5
-7000
7000
<B$_\phi$> (G)
0.0
0.2
0.4
0.6
0.8
r (R$_s$)

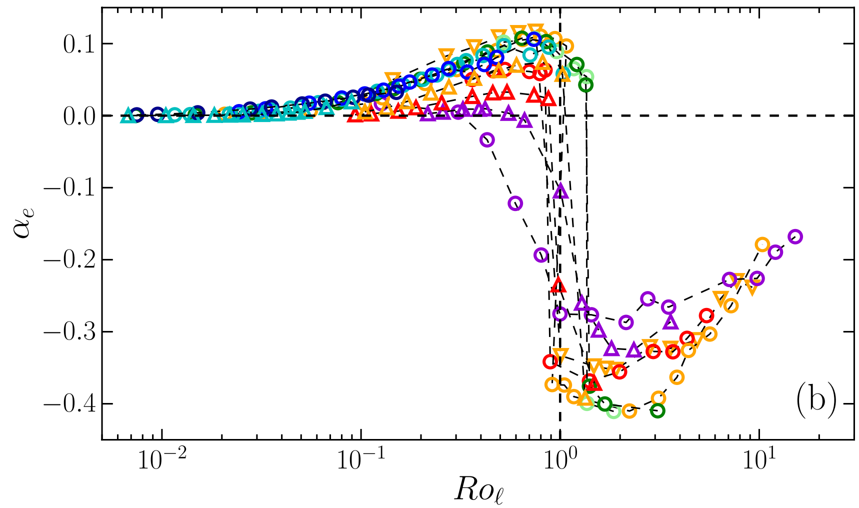


minimum
maximum
-3•10^4 0 3•10^4
B_φ (G)
-7000 7000
<B_φ> (G)
-2.5•10^23 2.5•10^23
A (Mx)
351 421 491
Ω (nHz)
z (R_s)
r (R_s)
0.0 0.2 0.4 0.6 0.8
0.5 0.0 -0.5


dynamo
B=0
HD
increase viscosity
HVHD
(a)
Ω (nHz)
354 421 488
(c)
RS
-0.03 0.03
(d)
VS
-0.0022 0.0022
(e)
MS
-0.0057 0.0057
(f)
368 582 795
(h)
(i)
(j)
327 420 513
(l)
(m)
z (R$_s$)
r$_\perp$ (R$_s$)
angular momentum flux
Reynolds
Maxwell
Meridional Flow
Viscous
(a)
(b)
(c)

• **Transition between solar-like and anti-solar differential rotation takes place at *Ro* ~ 1:**

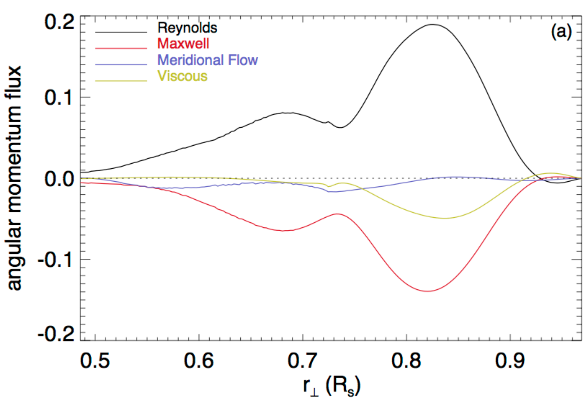
Gastine et al. (2014)



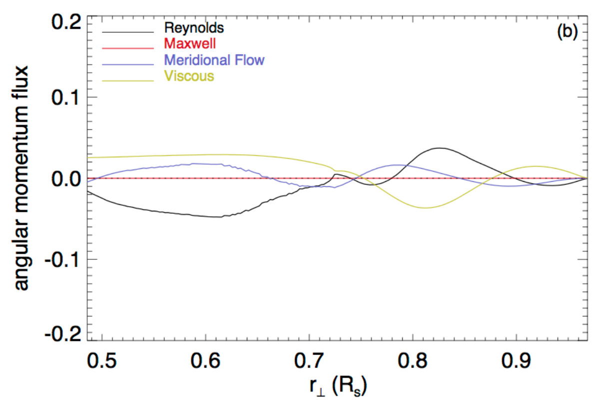
• **Presence of the magnetic field suppresses convection, making the flow more rotationally constrained, and changes the Reynolds stress transport of angular momentum:**

$$Ro = u_{rms,all} / \Omega H_p$$

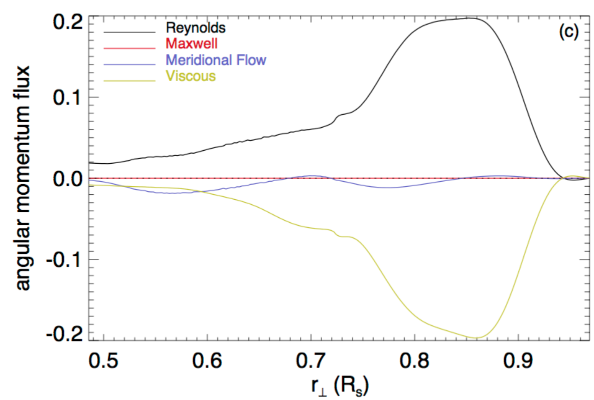
dynamo: $Ro = 0.74$

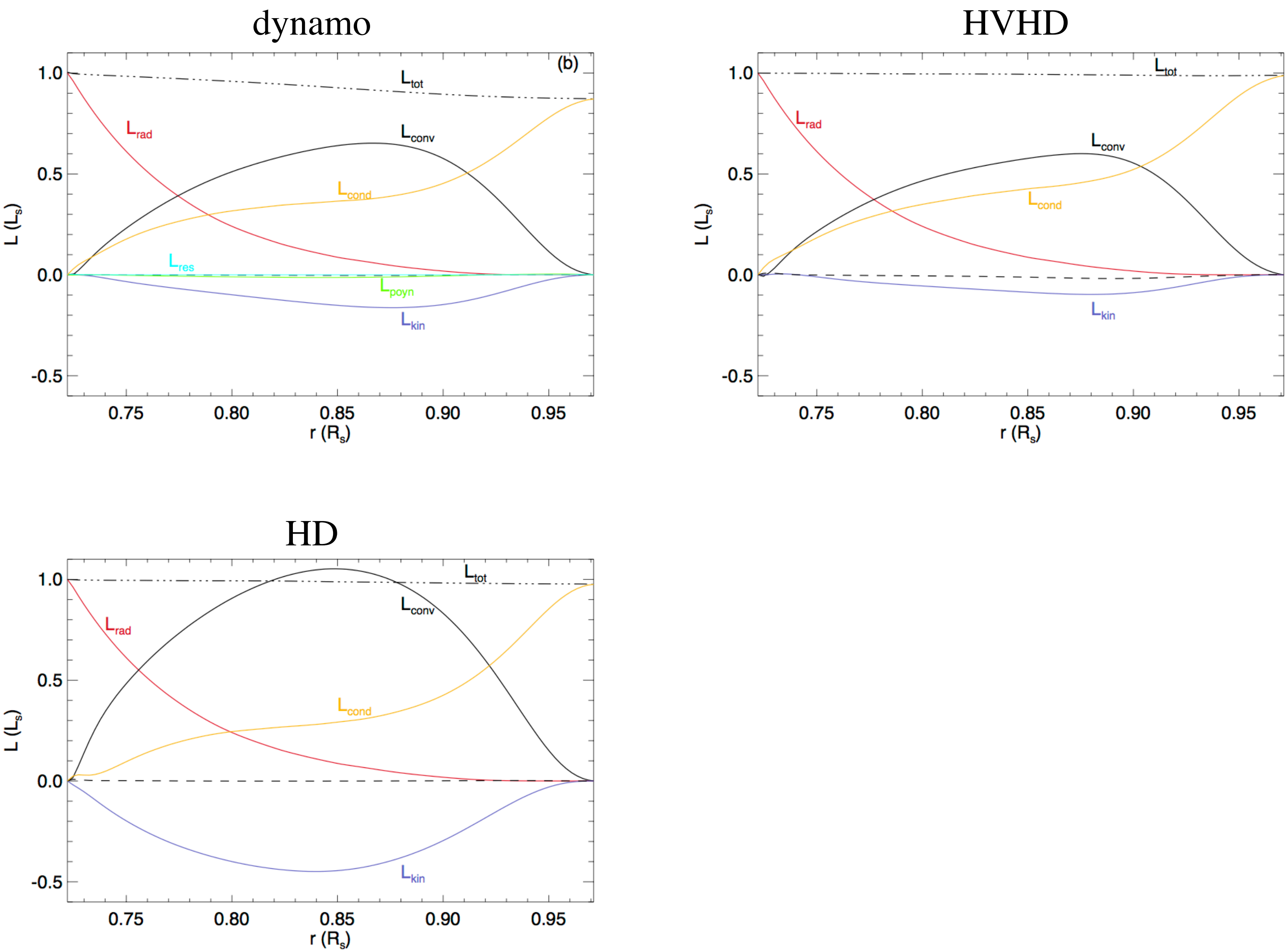


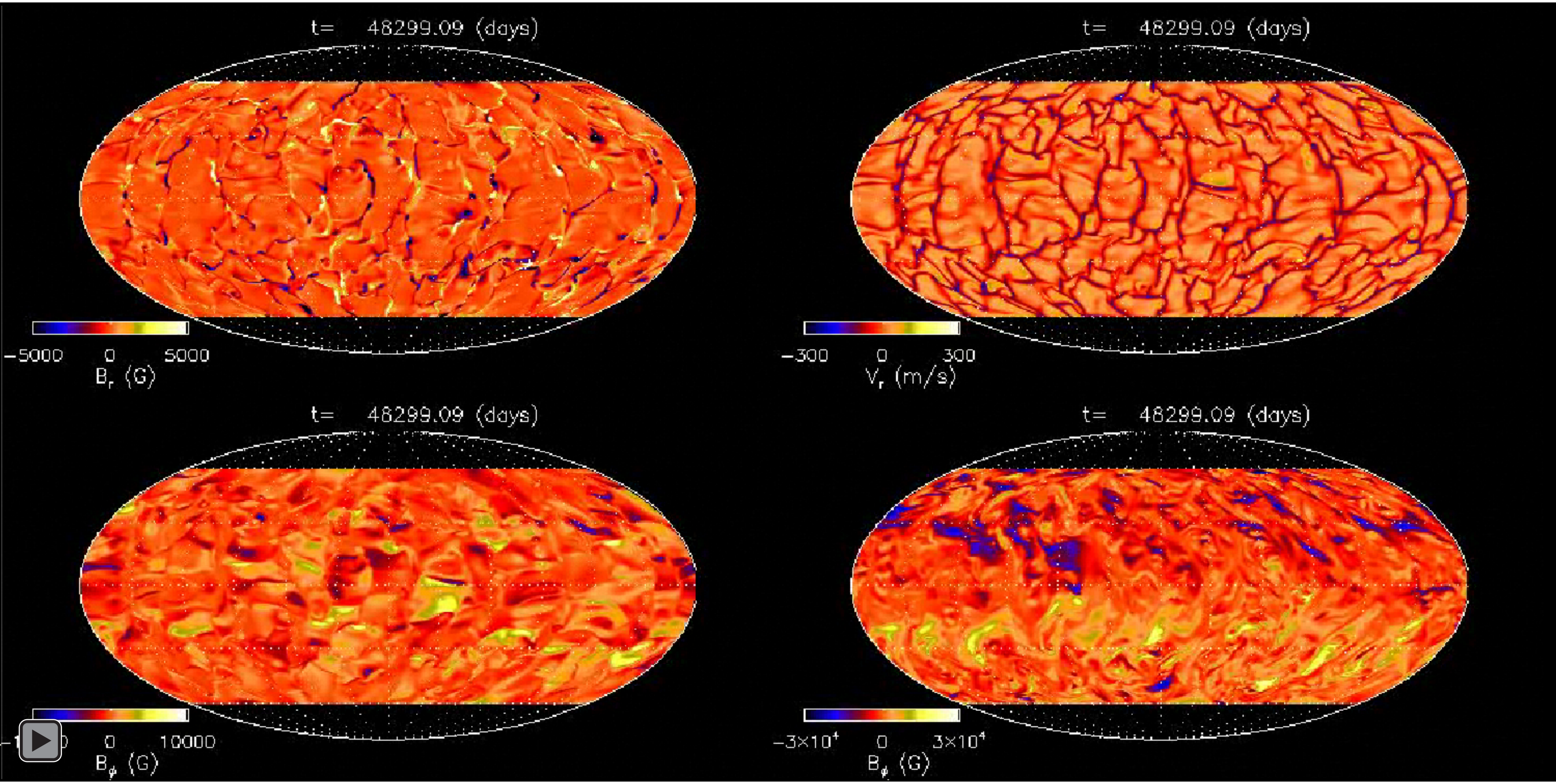
HD: $Ro = 0.96$



HVHD: $Ro = 0.71$

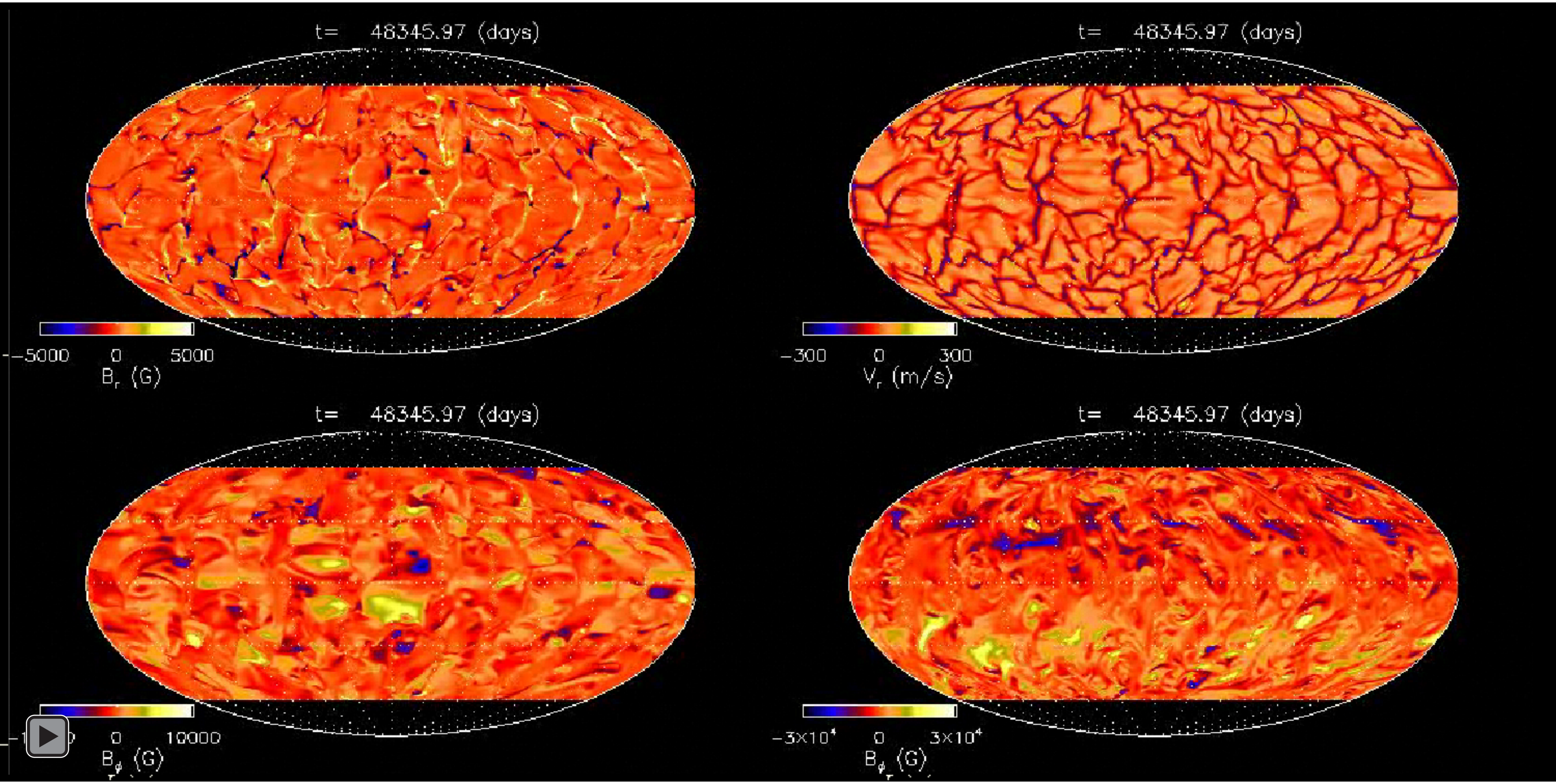


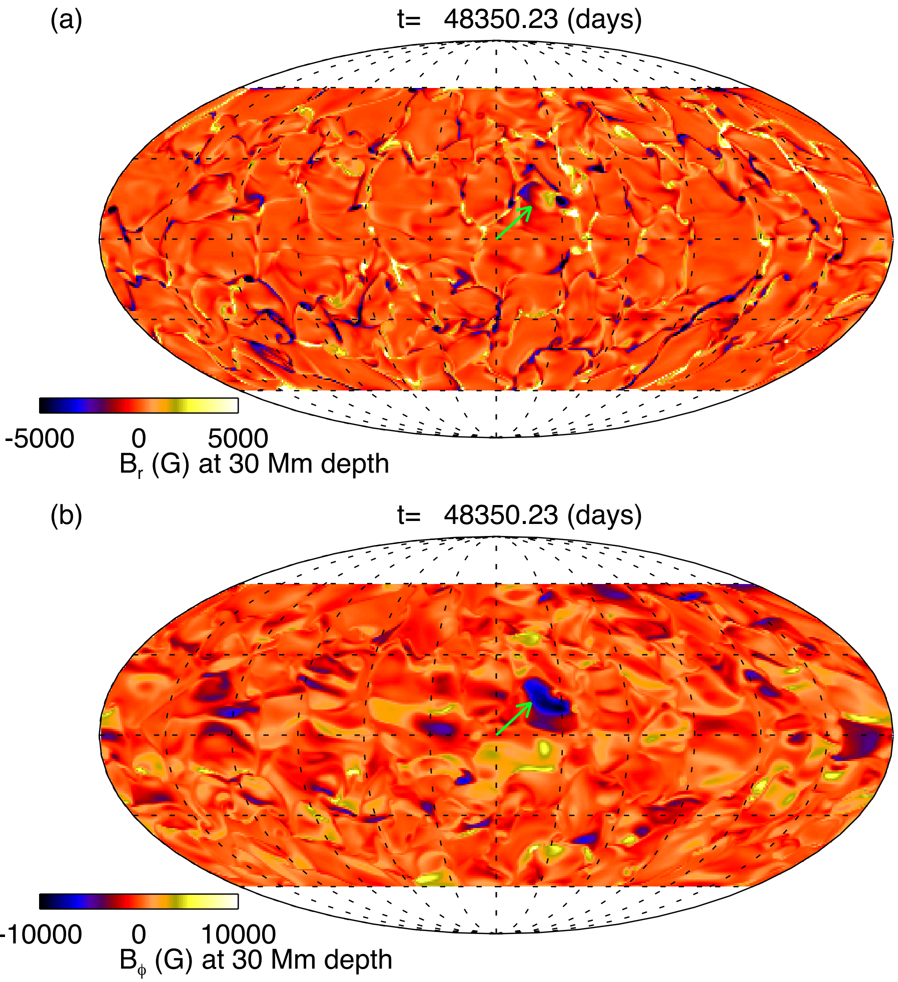

dynamo
(b)
1.0
0.5
0.0
-0.5
L (L_s)
L_tot
L_rad
L_conv
L_cond
L_res
L_poyn
L_kin
0.75
0.80
0.85
0.90
0.95
r (R_s)
HVHD
1.0
0.5
0.0
-0.5
L (L_s)
L_tot
L_rad
L_conv
L_cond
L_kin
0.75
0.80
0.85
0.90
0.95
r (R_s)
HD
1.0
0.5
0.0
-0.5
L (L_s)
L_tot
L_rad
L_conv
L_cond
L_kin
0.75
0.80
0.85
0.90
0.95
r (R_s)

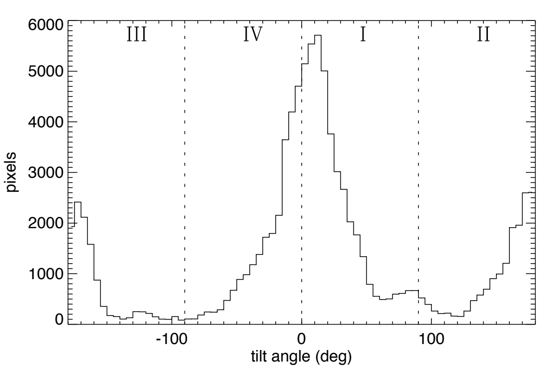


t= 48299.09 (days)
−5000 0 5000
B_r (G)
t= 48299.09 (days)
−300 0 300
V_r (m/s)
t= 48299.09 (days)
0 10000
B_ϕ (G)
t= 48299.09 (days)
-3×10^4 0 3×10^4
B_ϕ (G)

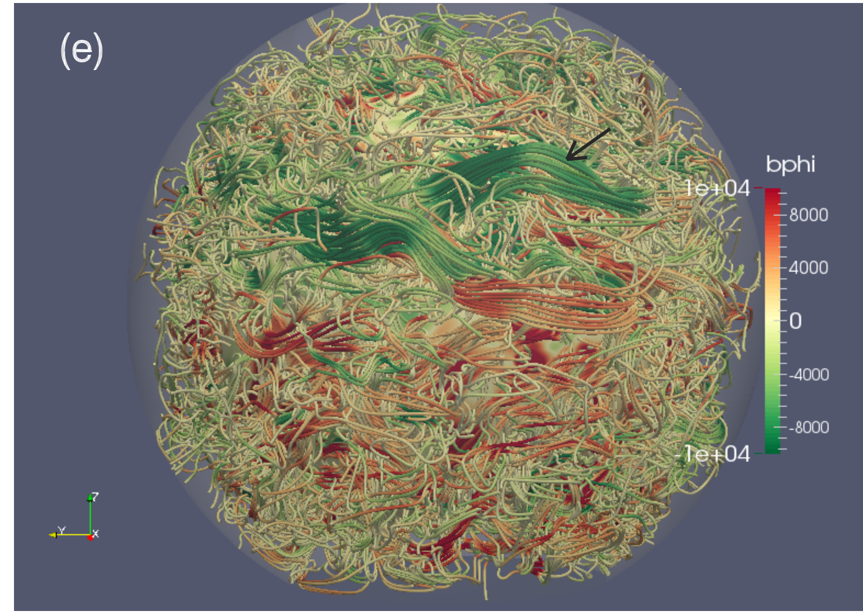
Examples of strong flux emergence events

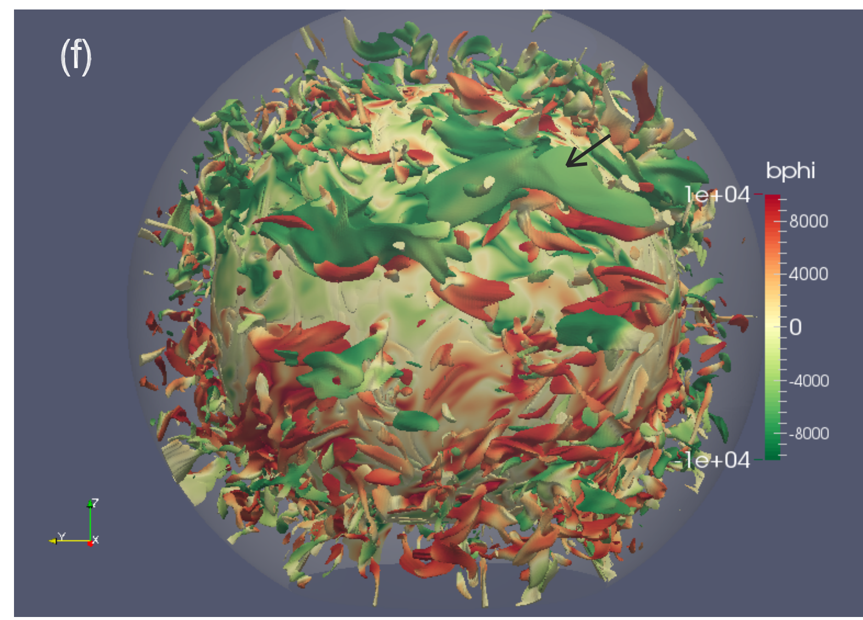


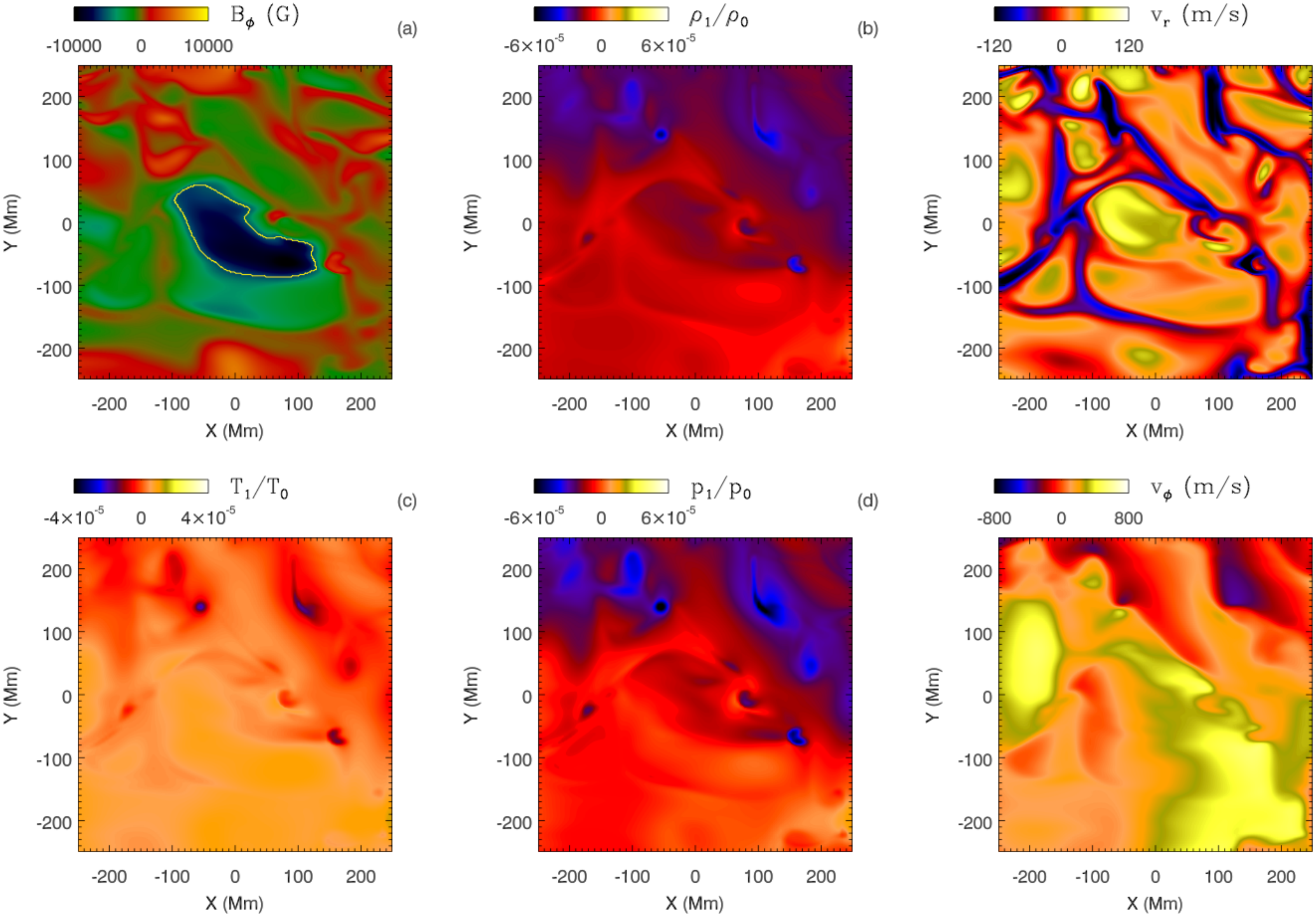




- Conform to Hale's rule by 2.4 to 1 in area
- Tilt angle 7.5° ± 1.6°

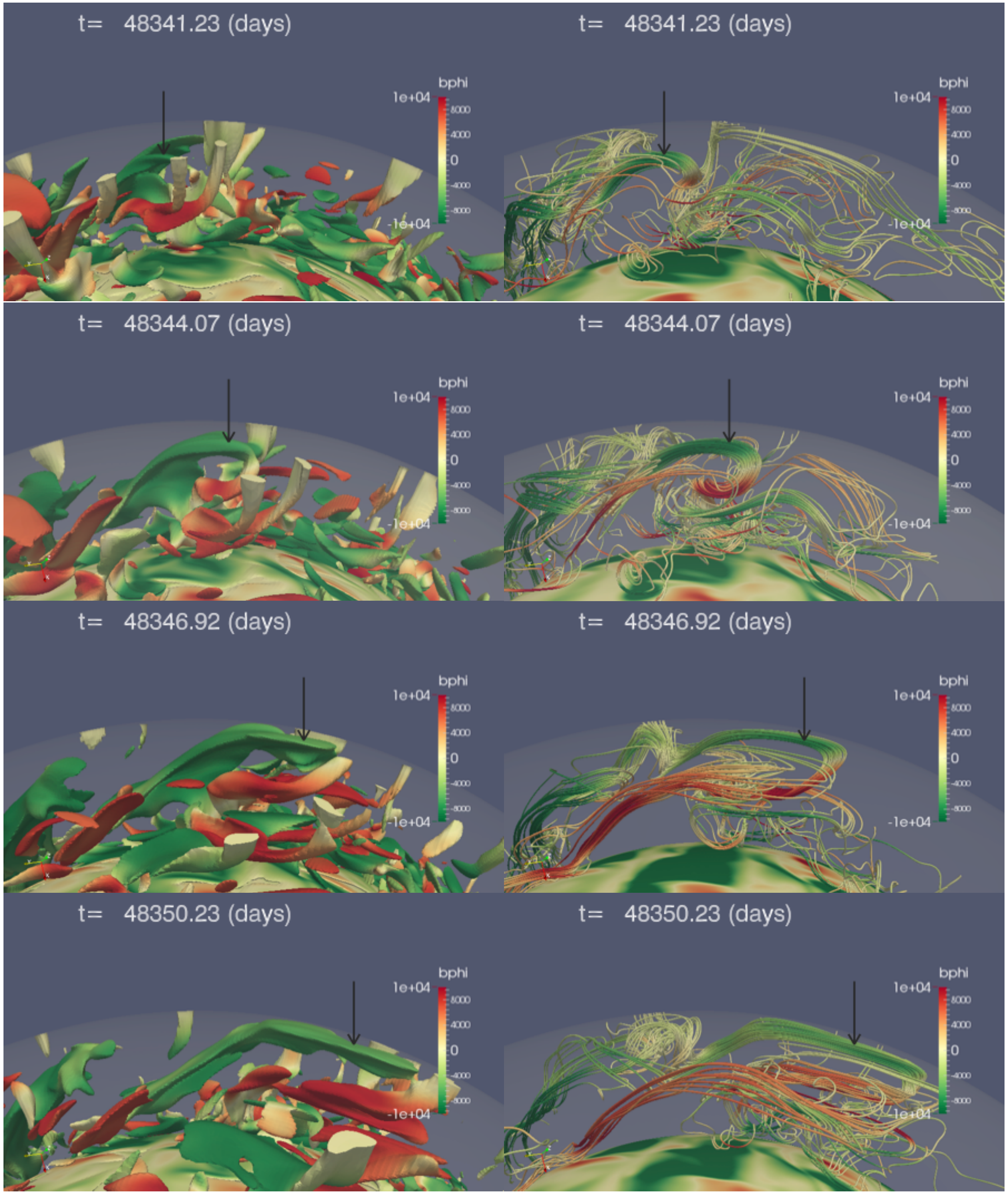






$$\langle \rho_1/\rho_0 \rangle \approx -1.6\times10^{-5},\ \ \langle p_1/p_0 \rangle \approx -1.1\times10^{-5},\ \ \langle T_1/T_0 \rangle \approx 0.5\times10^{-5}$$

$$\langle V_\phi \rangle \approx 129 \text{ m/s relative to mean zonal velocity of the latitude } (15^\circ)$$


t= 48341.23 (days)
t= 48341.23 (days)
t= 48344.07 (days)
t= 48344.07 (days)
t= 48346.92 (days)
t= 48346.92 (days)
t= 48350.23 (days)
t= 48350.23 (days)
bphi
1e+04
8000
4000
0
-4000
-8000
-1e+04

Summary

- A 3D convective dynamo in the rotating solar convective envelope driven by the radiative heat flux produces a large-scale mean magnetic field that exhibits irregular cyclic behavior with oscillation time scales ranging from about 5 to 15 years and undergoes irregular polarity reversals

- The mean axisymmetric toroidal magnetic field peaks at the bottom of the convection zone, reaching a value of about 7000 G. Including the fluctuating component, individual channels of strong field reaching 30kG are present.

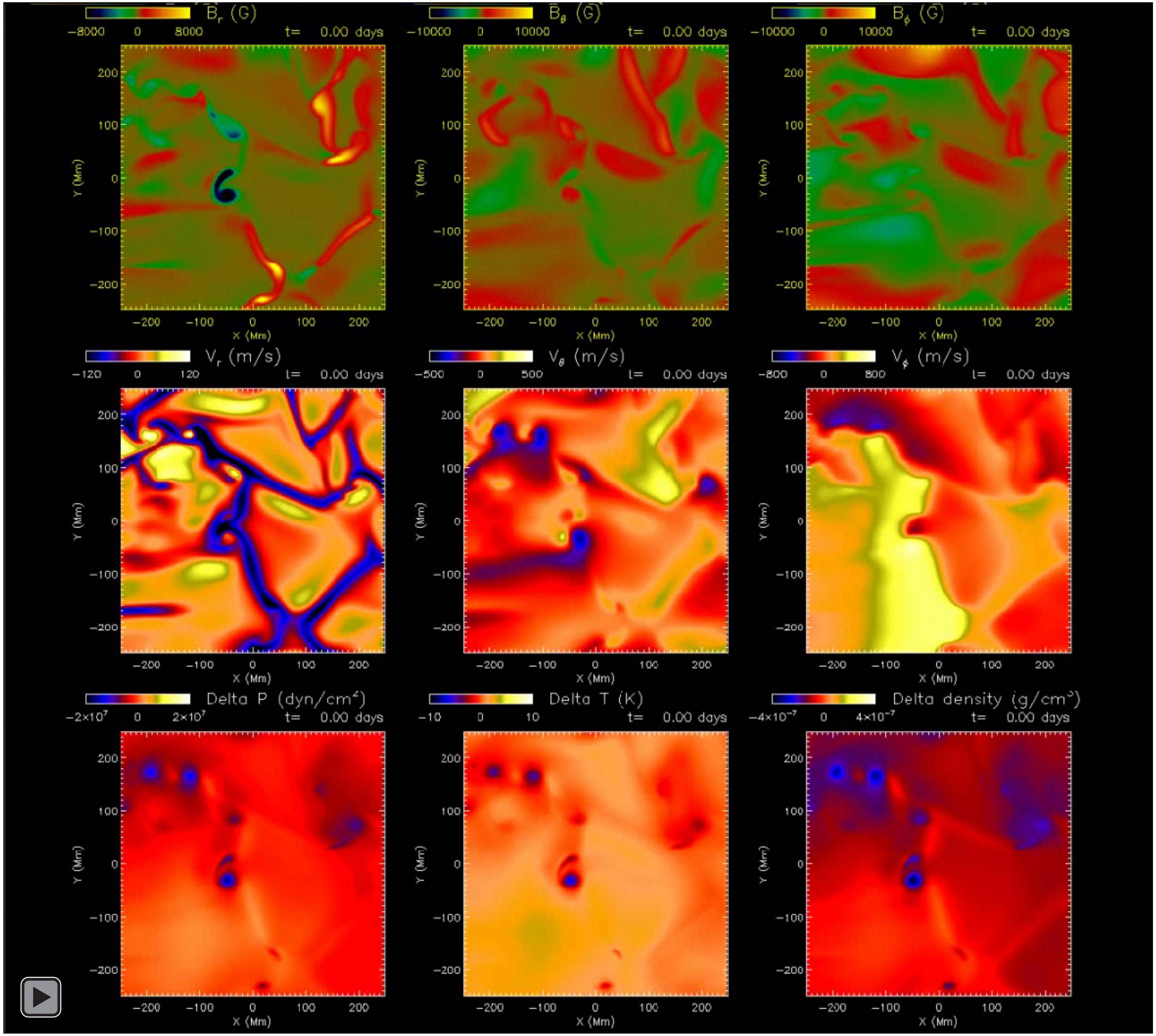
- The presence of the magnetic fields plays an important role in the self-consistent maintenance of the solar-like differential rotation. In several ways acts like an enhanced viscosity:
  - Suppress large scale convection, make it more rotationally constrained → outward transport of angular momentum by the Reynolds stress.
  - Take up the main role of balancing the Reynolds stress transport with the Maxwell stress transport.
  - Reduce the downward kinetic energy energy flux

- In the midst of magneto-convection, we found occasional emergence of strong super-equipartition toroidal flux bundles near the surface, exhibiting properties that are similar to emerging solar active regions. They are not rising in isolation from the bottom of the CZ, but are product of continued reconnection and shear amplification by local flows in the bulk of CZ.

Integration of FSAM into SWMF (work in progress)

- Fang Fang has rewritten FSAM completely following standards and conventions of other existing components in SWMF such as EE
- FSAM has been put into SWMF as the CZ component, but is not yet part of default download.
  - Can be checked out from CVS specifically under CZ directory:

    "cvs co FSAM"
  - The checked out version of FSAM is set up to work on Yellowstone/NWSC so far. Need to work out a general way to compile the FISHPAK library for different compiler.



B_r (G)
−8000 0 8000 t= 0.00 days
B_θ (G)
−10000 0 10000 t= 0.00 days
B_φ (G)
−10000 0 10000 t= 0.00 days
V_r (m/s)
−120 0 120 t= 0.00 days
V_θ (m/s)
−500 0 500 t= 0.00 days
V_φ (m/s)
−800 0 800 t= 0.00 days
Delta P (dyn/cm²)
−2×10⁷ 0 2×10⁷ t= 0.00 days
Delta T (K)
−10 0 10 t= 0.00 days
Delta density (g/cm³)
−4×10⁻⁷ 0 4×10⁻⁷ t= 0.00 days
Y (Mm)
X (Mm)