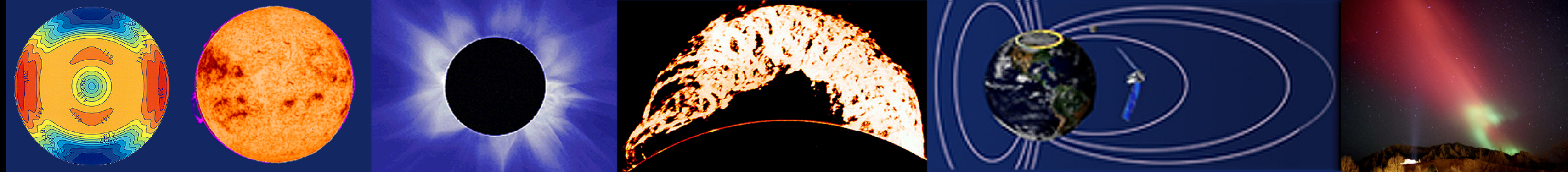

Simulations of Solar Convective Dynamo and Active Region formation

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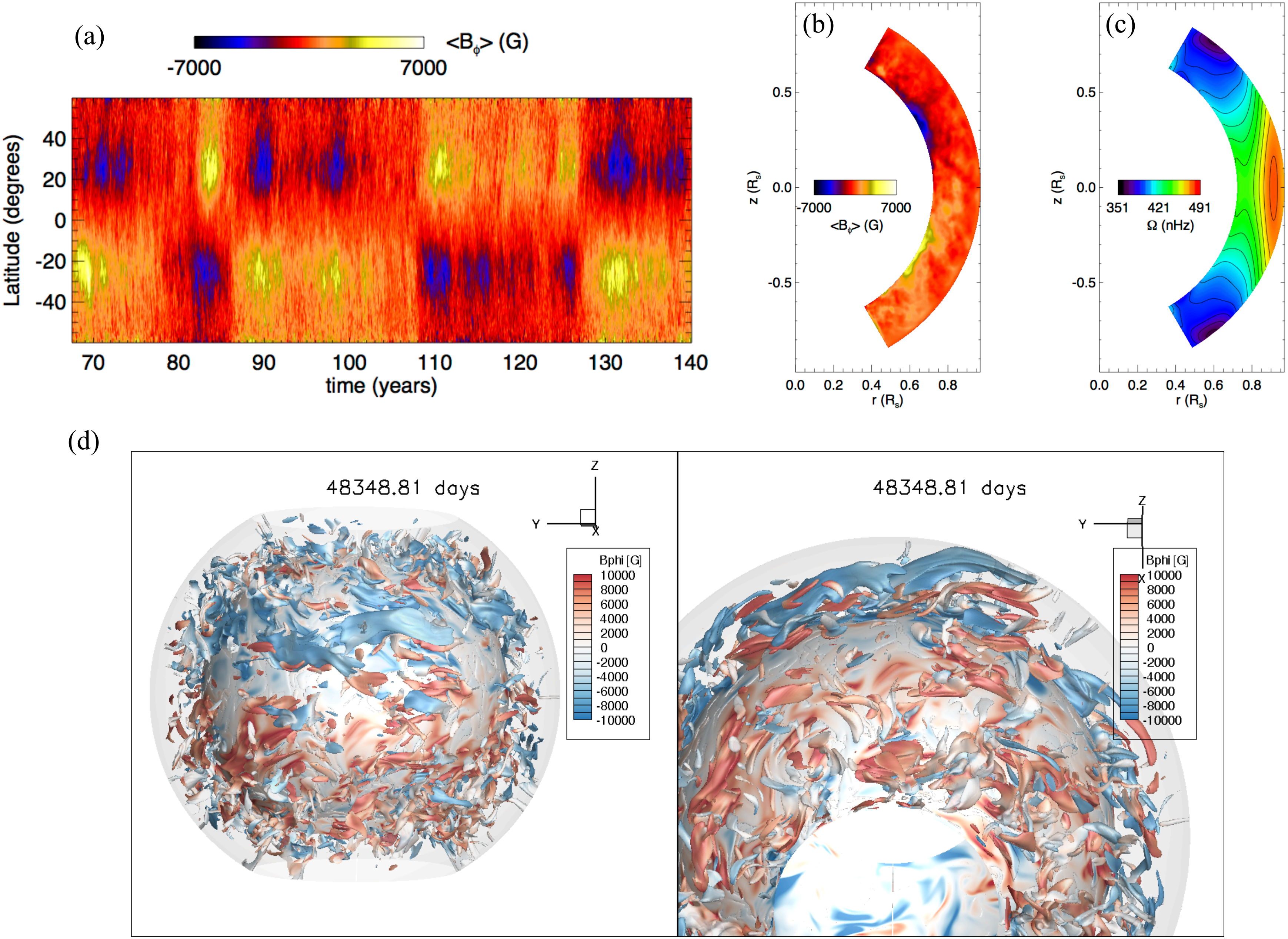
Simulations of solar convective dynamo and emerging flux with FSAM

(*Fan and Fang 2014, 2016*)



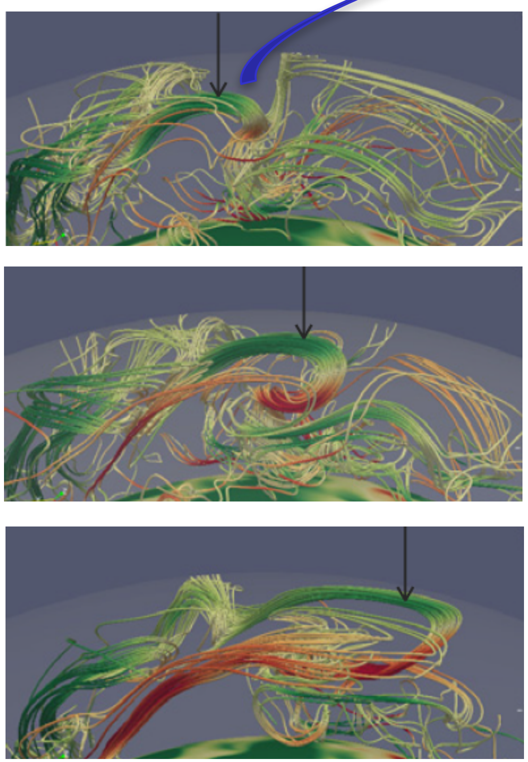
Coupling to near surface layer radiation MHD simulations of active region formation with MURaM (*Chen, Rempel, and Fan 2017, ApJ, submitted*)

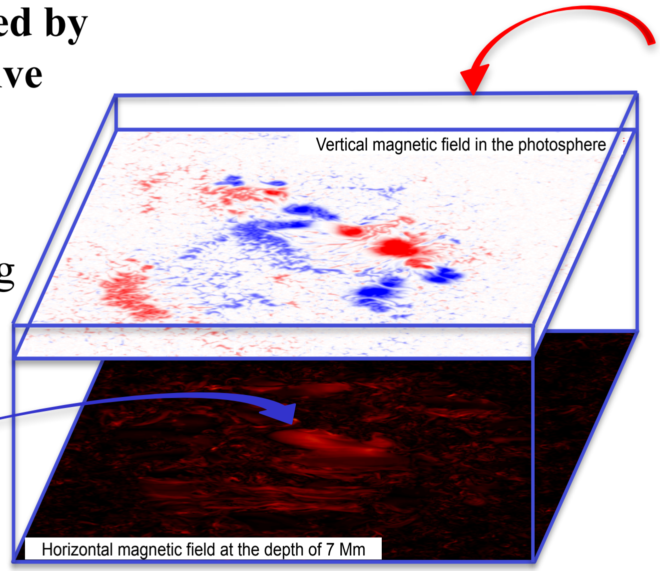
Emerging flux bundles generated by FSAM simulation of convective dynamo *Fan & Fang, 2014*

– solar-like differential rotation

– large scale mean field exhibiting cyclic behavior

– emerging super-equipartition flux bundle:





Time-dependent lower boundary from FSAM:

– follow a region centered on the emerging flux bundle

– extract horizontal slices of **B**, **v** fields at 30 Mm depth

– vertical velocity is increased to be > rms of the convection

– Rescale the horizontal slices to fit the MURaM simulations

Further emergence of the flux bundles to the photosphere

MURaM: Vögler et al. 2005 & Rempel, 2009

– realistic simulation:

– solve fully compressible MHD
realistic equation of state (tabular)
radiative transfer

➢ **formation of an active region in the photosphere**

The MURaM simulations

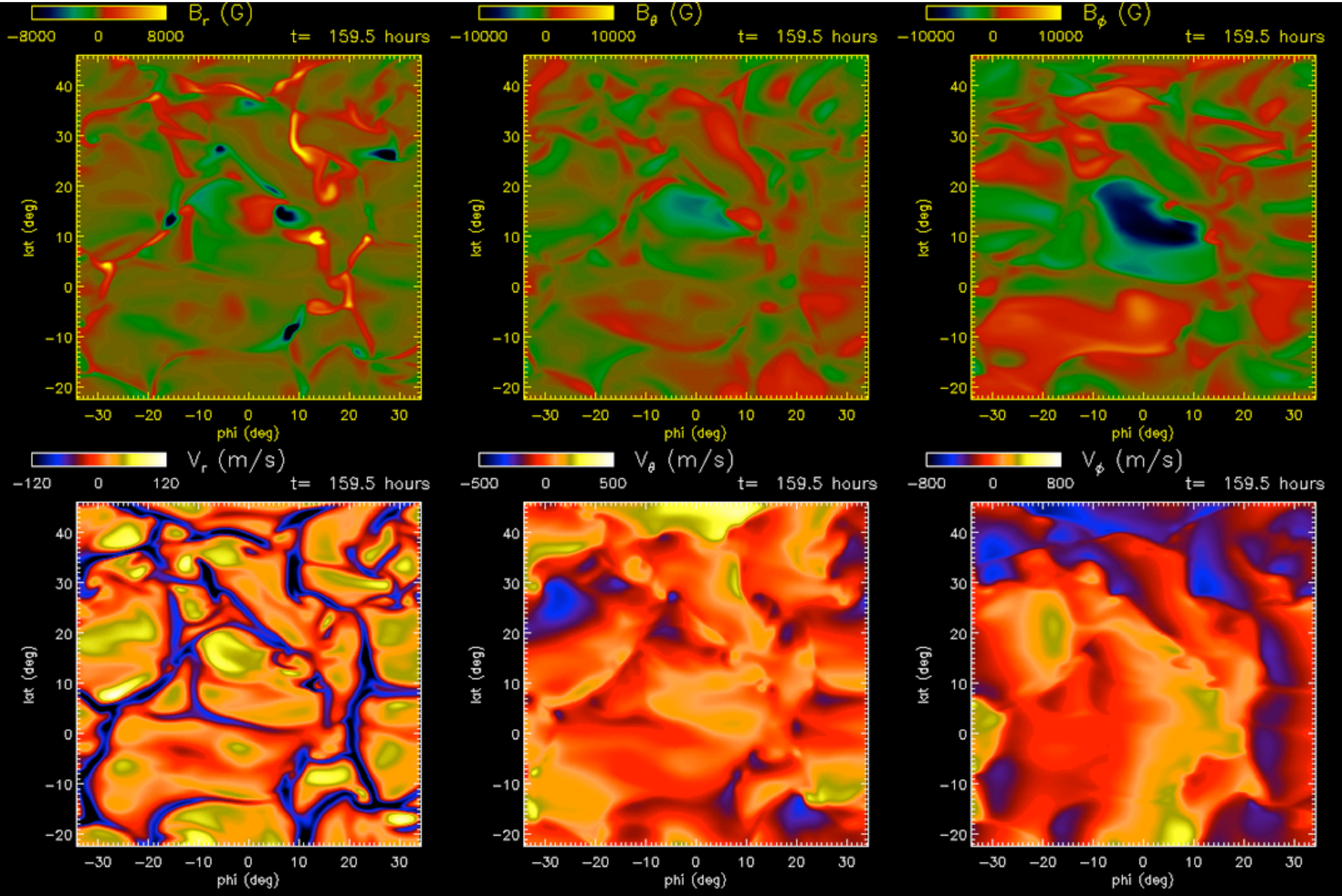
– domain sizes: depths 8, 18, 32 Mm
horizontal sizes: 98, 196 Mm
upper boundary: 640 km above $\tau=1$

– horizontal resolution of 192 km:
good enough to resolve the granulation

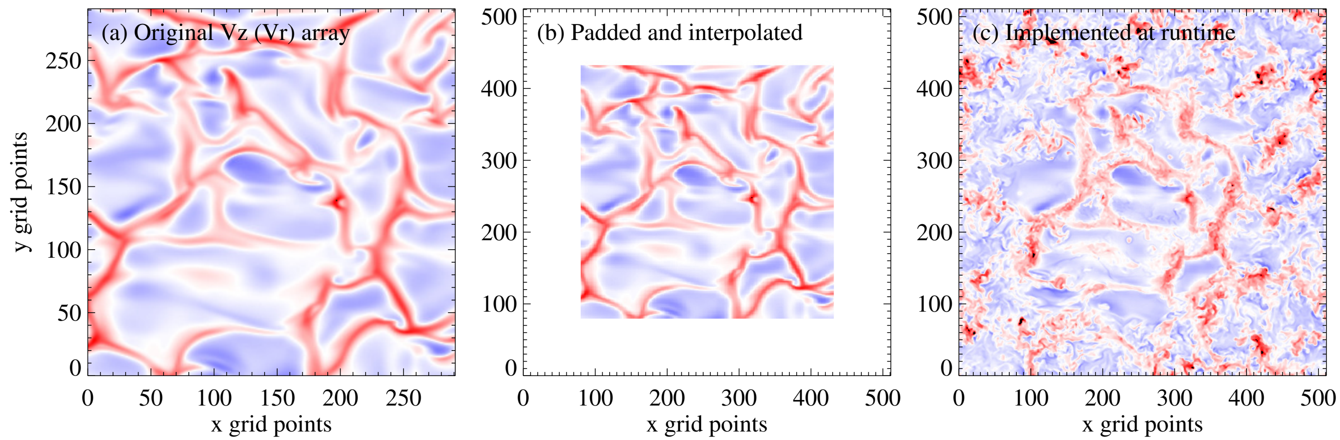
– vertical resolution of 64 km

– initial condition:
relaxed magneto-convection
small-scale *B* by a local dynamo

B and V fields extracted from a horizontal surface near the top boundary of the FSAM simulation (at 30 Mm depth) tracking an emerging flux region



Adapt the extracted B and V fields to the lower boundary of the MURaM simulation



- The edges are padded with zeros to make the fields compatible with periodic horizontal boundary. The horizontal dimension size is scaled down by a factor of 12.4 and 6.2 for the 98 Mm and 196 Mm domain size respectively
- ϕ, $-\theta$, and r components of the fields → x, y and z components.
- Only Vx, Vy, Vz, Bx, By are imposed at the lower boundary, and Bz is determined based on the divB = 0 condition.
- Vz is scaled up by 5 times so the upflow speed matches the typical convective upflow speed at depth of 8Mm in MURaM simulations.The values of Vx, Vy, Bx, By remain unchanged.
- Time is rescaled by a factor of 1/5 for the 8Mm depth simulations, 2/5 for the 18 Mm and 32 Mm depth simulations.
- Lower boundary is a combination of the dynamo extracted field and the MURaM convection lower boundary field:

$$\mathbf{U}_{\mathrm{gc}} = \mathbf{U}_{\mathrm{dynamo}} M + \mathbf{U}_{\mathrm{MURaM}} (1 - M)$$

where

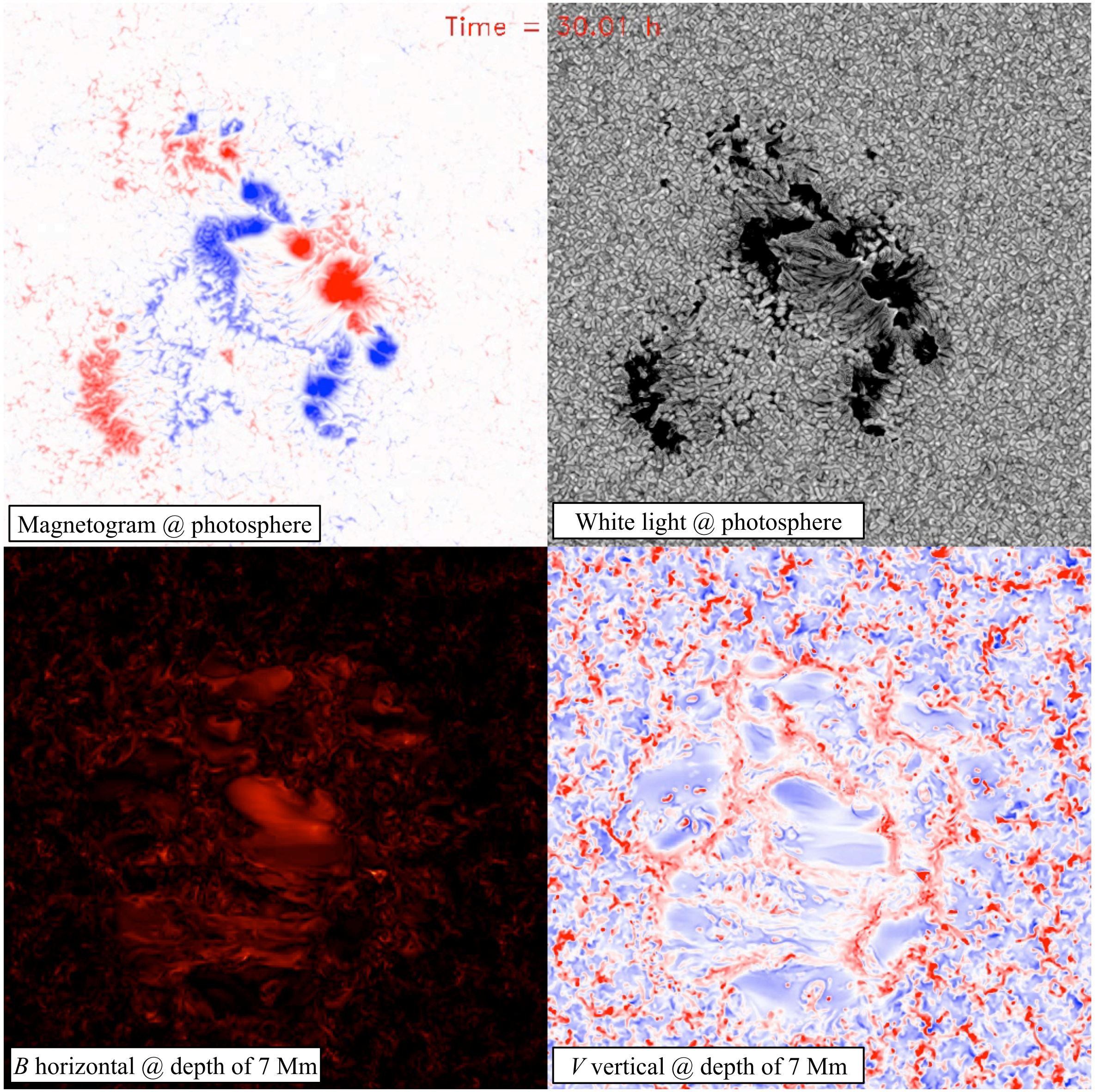
M : 1 for central region → 0 at outer rim.

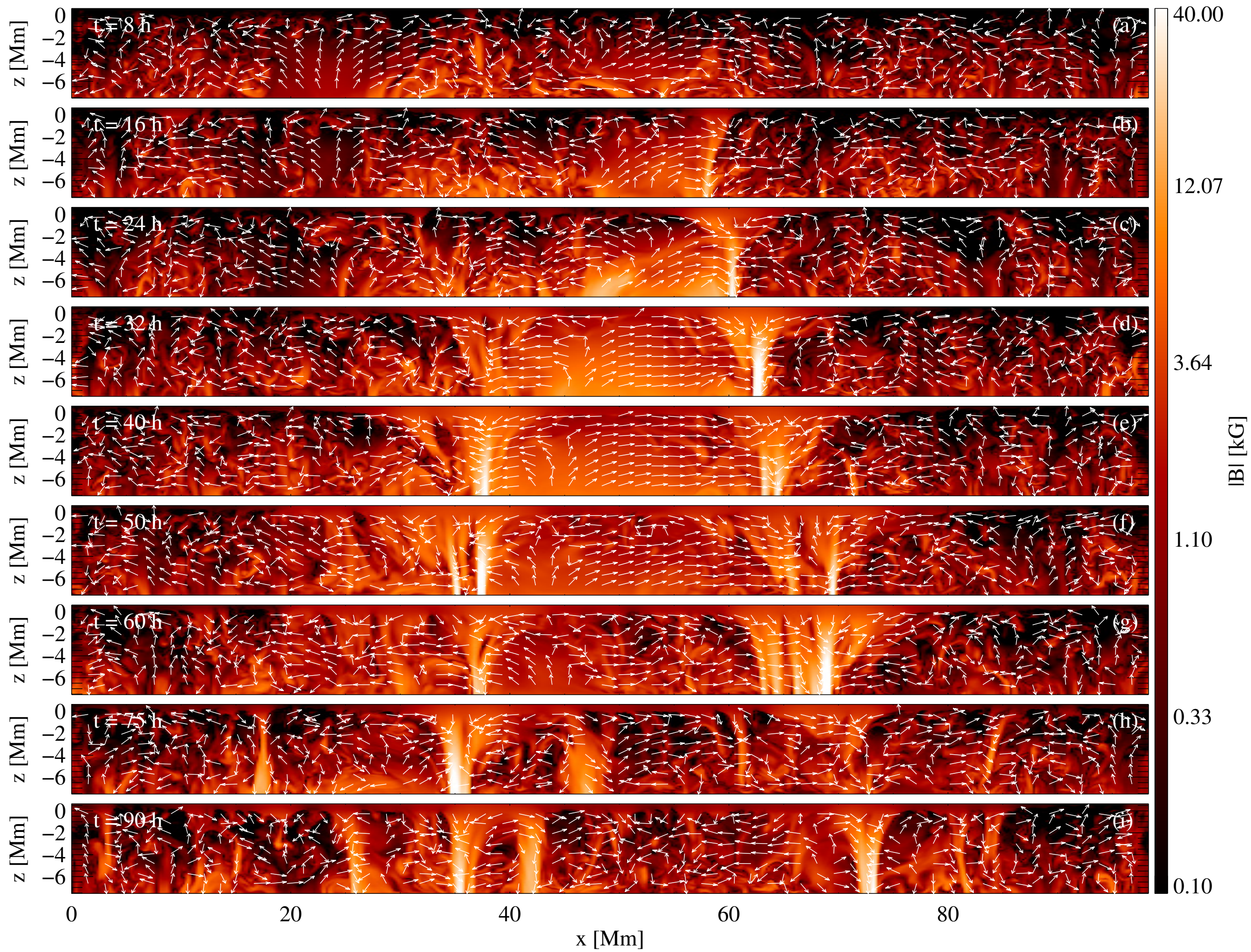
$\mathbf{U}_{\mathrm{dynamo}}$: $(V_x, V_y, V_z, B_x, B_y)$ after above rescaling

$\mathbf{U}_{\mathrm{MURaM}}$: boundary condition for convection simulations

Formation of active regions: earlier formation and more coherent leading polarity sunspots

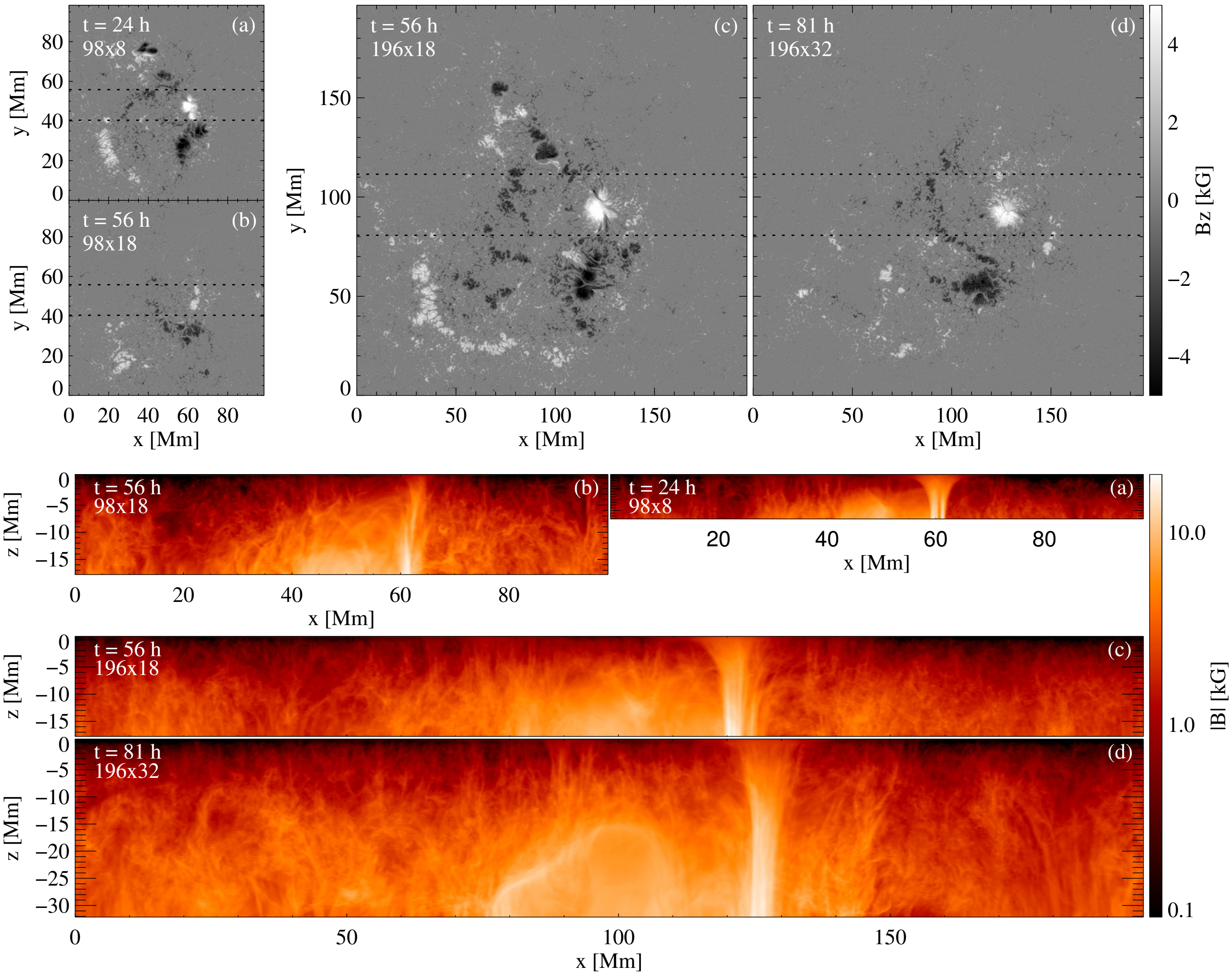
- The rescaled **B** and **V** slices extracted from FSAM covers parts of both the northern and southern hemispheres, and contains two major, oppositely directed emerging flux bundles.
- An earlier emerging bundle in the south → formation of the lower sunspot pair with negative leading polarity
- Then the emergence of the northern flux bundle in the center → formation of the central sunspot pair with positive leading polarity
- Both sunspot pairs form asymmetrically with the leading polarity spot forms first and appears more coherent
- Sunspots tend to form above the downdraft lanes of the giant convection cells (imposed at the lower boundary). The leading side of the emerging flux bundle is pushed up against a strong down flow lane.



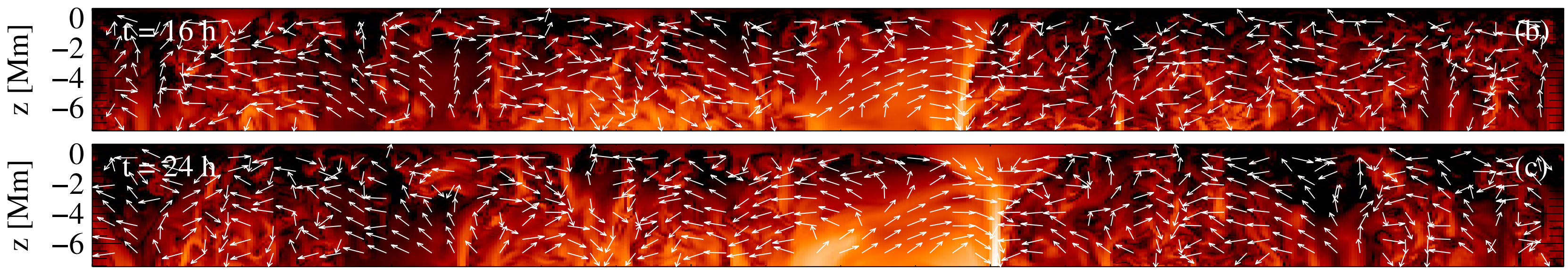

t = 8 h
t = 16 h
t = 24 h
t = 32 h
t = 40 h
t = 50 h
t = 60 h
t = 75 h
t = 90 h
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
z [Mm]
0
−2
−4
−6
x [Mm]
0
20
40
60
80
|B| [kG]
40.00
12.07
3.64
1.10
0.33
0.10

Simulations of different domain sizes (up to 196 Mm horizontal width and 32 Mm depth): robust result on the asymmetric formation of sunspot pairs.

- Top: vertical magnetic field at $\tau = 1$ at a similar stage of evolution for the different domain-size simulations
- Bottom: corresponding magnetic field strength in the vertical x-z slice, averaged over the y range between the dotted lines shown in the top panels. It shows the stronger monolithic leading sunspot field concentration vs. the more spread out following spot field for the central sunspot pair.



Cause of the asymmetric sunspot pair



divergence free of mass flux:

$$\frac{V_z}{H_\rho} = \nabla \bullet \mathbf{V} = \frac{\partial V_x}{\partial x} + \ldots$$

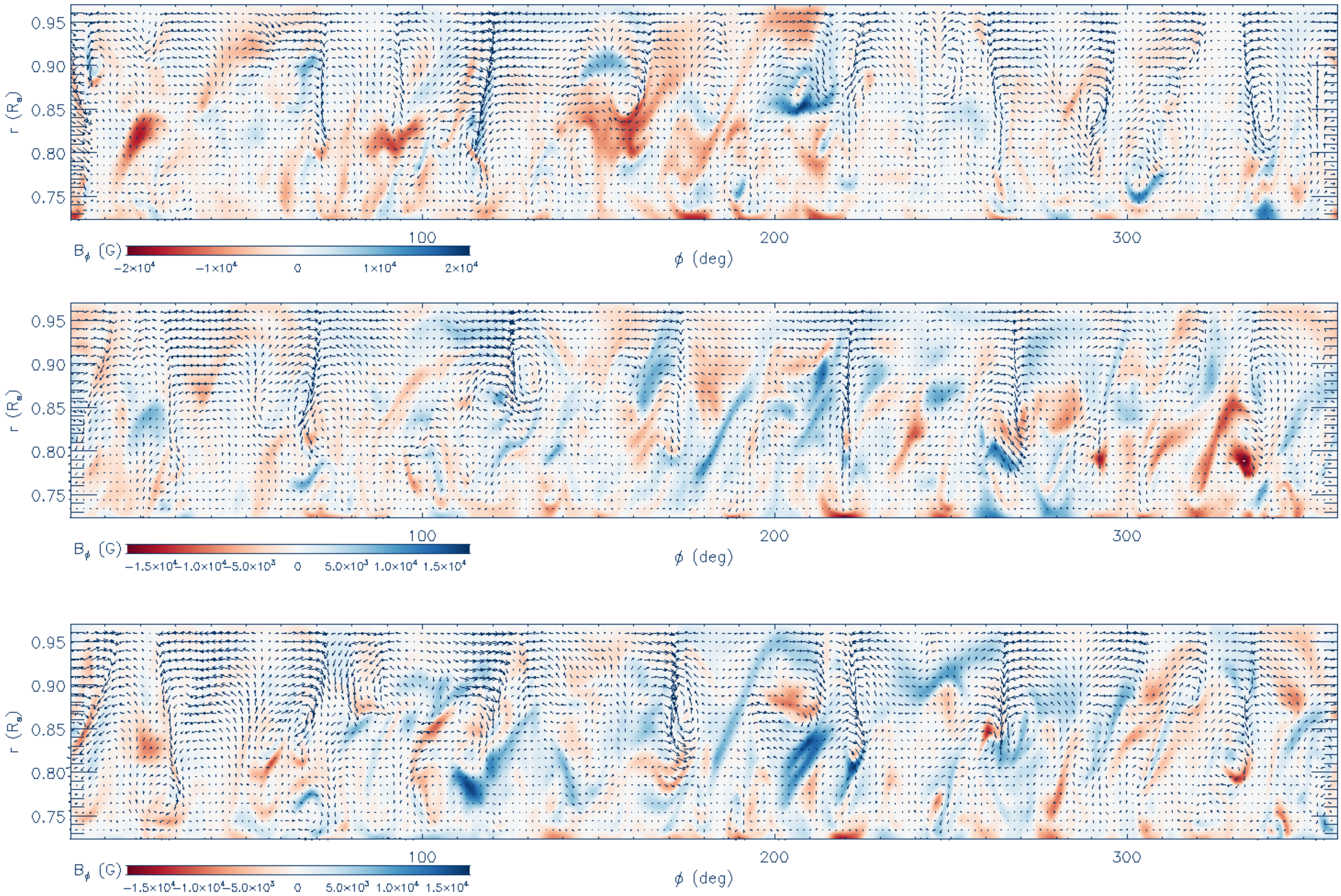
z-component of the induction equation:

$$\frac{dB_z}{dt} = -(\nabla \bullet \mathbf{V})B_z + (\mathbf{B} \bullet \nabla)V_z$$

$$\frac{dB_z}{dt} \approx -\frac{V_z}{H_\rho} B_z + B_x \frac{\partial V_z}{\partial x}$$

- Prograde flow causes emerging loops to lean forward → push leading side closer to the strong downdraft → greater amplification of Bz on the leading side

Forward leaning loops in the giant cell convection



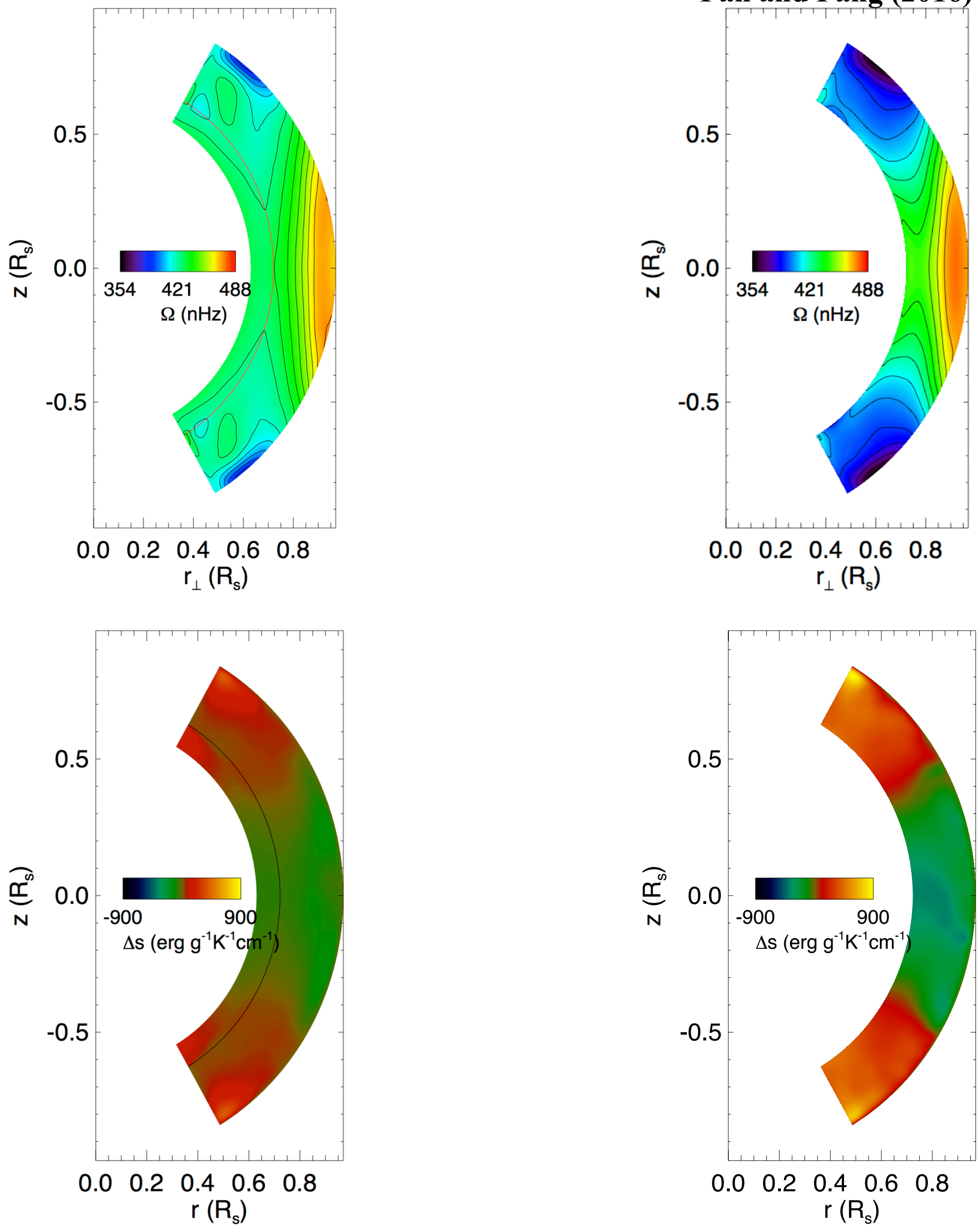
Simulation of convective dynamo with an overshoot shear layer at bottom of CZ

- Enforcing a sub-adiabatic mean (horizontally- averaged) entropy gradient in the overshoot layer
- Uniform rotation enforced at the bottom boundary of the overshoot layer.
- The radial shear in the overshoot layer naturally produces a latitudinal entropy gradient for the bottom of CZ, which transported into the bulk of the CZ to tilt the convection zone iso-rotation contours towards conical.

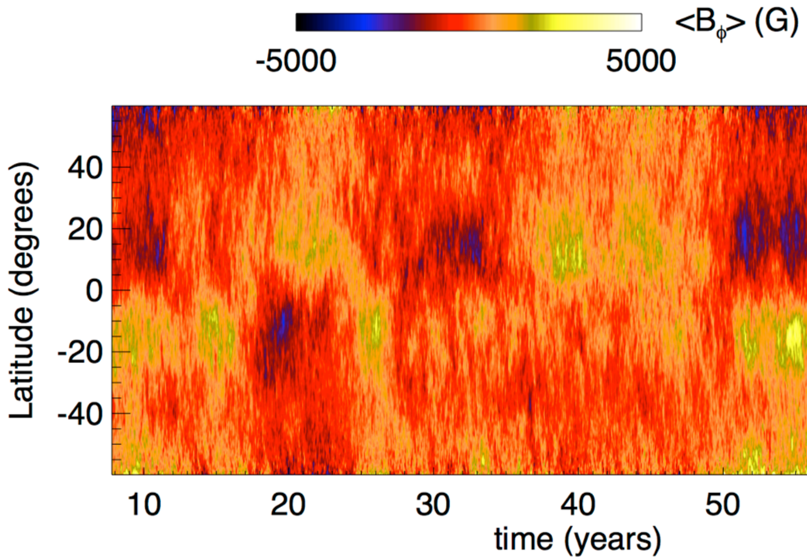
ϕ component of the vorticity equation: (Rempel 2005):

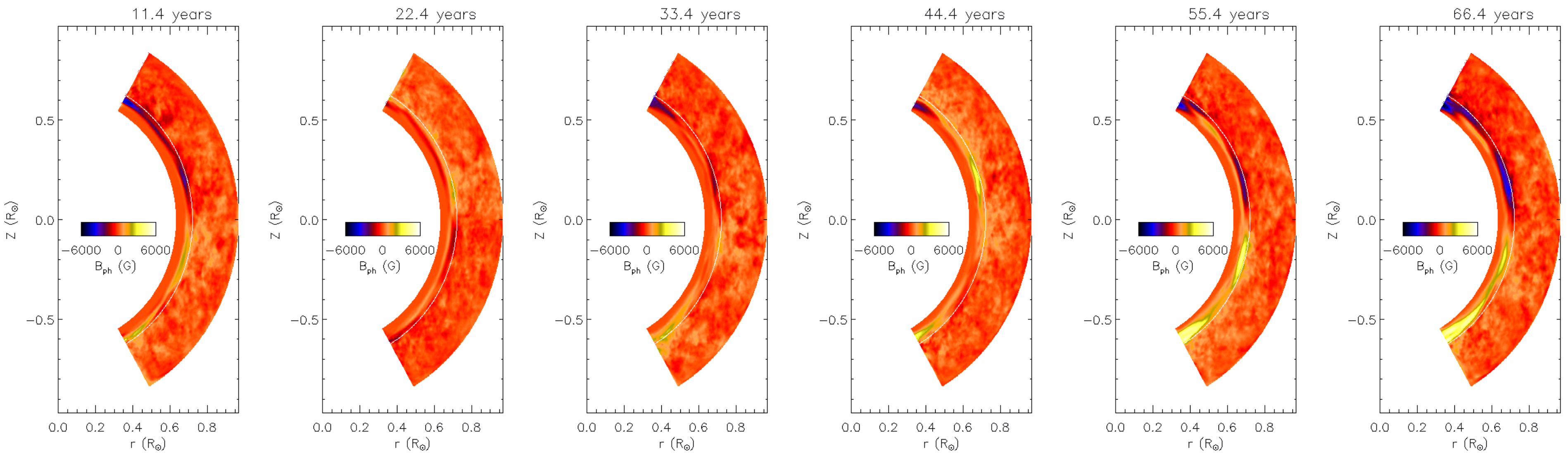
$$\frac{\partial \omega_\phi}{\partial t} = [\ldots] + r\sin\theta \frac{\partial \Omega^2}{\partial z} - \frac{g}{r c_p}\frac{\partial s}{\partial \theta}$$

Fan and Fang (2016)



Simulation of convective dynamo with an overshoot shear layer at bottom of CZ





Summary

- Simulations of convective dynamo at the solar rotation rate and driven by the solar radiative heat flux:
  - produce a large-scale mean magnetic field that exhibits irregular cyclic behavior with polarity reversals and self-consistently maintain a solar-like differential rotation.
  - produce emergence of coherent super-equipartition toroidal flux bundles with a statistically significant mean tilt angle that is consistent with the mean tilt of solar active regions.
  - Simulations incorporating a shear overshoot layer at the bottom of CZ naturally produce a latitudinal entropy gradient at the bottom of CZ, but not sufficiently strong in the present case to tilt the iso-rotation contours to the conical shape as observed. The large scale mean field initially show polarity reversals, but then the storage of toroidal mean field in the overshoot layer leads to steady mean field.

- Near surface layer flux emergence simulations driven at the lower boundary by the emerging B and V fields from the convective dynamo:
  - The asymmetric emerging flux bundle with a prograde motion and a strong down flow at its leading end can cause formation of active regions with earlier formation and more coherent, stronger leading sunspots.