Super flare WS @ Kyoto university, March, 3rd, 2016

Current understanding of solar global scale magnetic field and dynamo

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Dynamo ⇄ Flare

Flare is born from dynamo.

Who is studying flare?

Dynamo → Magnetic field → Reconnection → Flare

H. Hotta ← T. Yokoyama ← K. Shibata

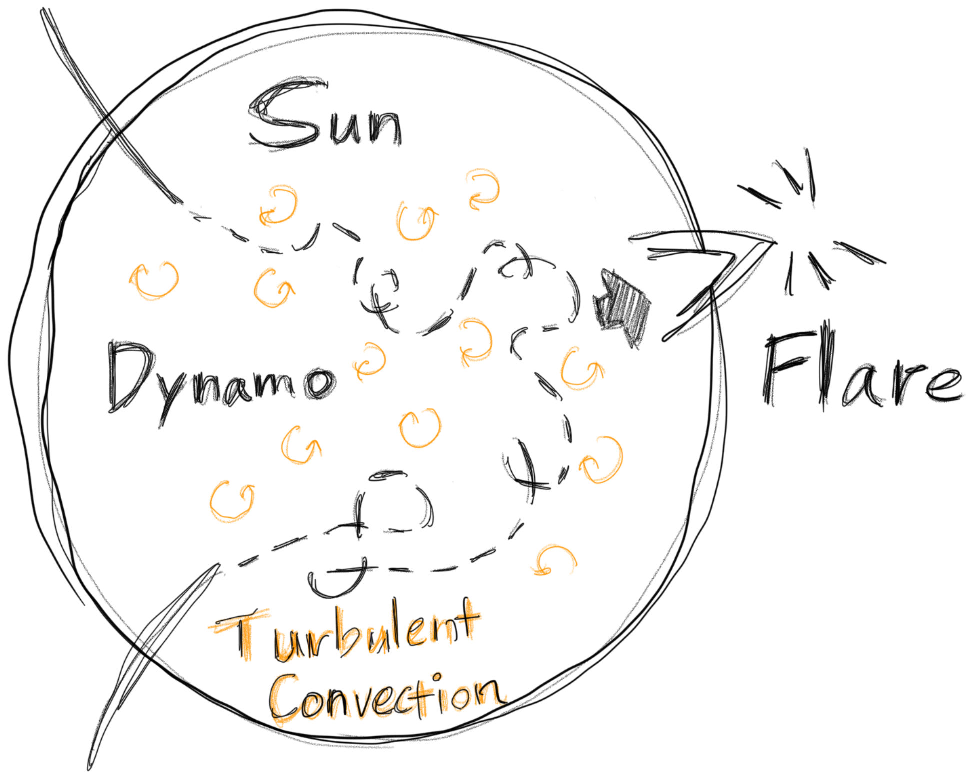
Who is educated by Shibata-san to study flare more?

Who is educated by Yokoyama-san to study the origin of flare?

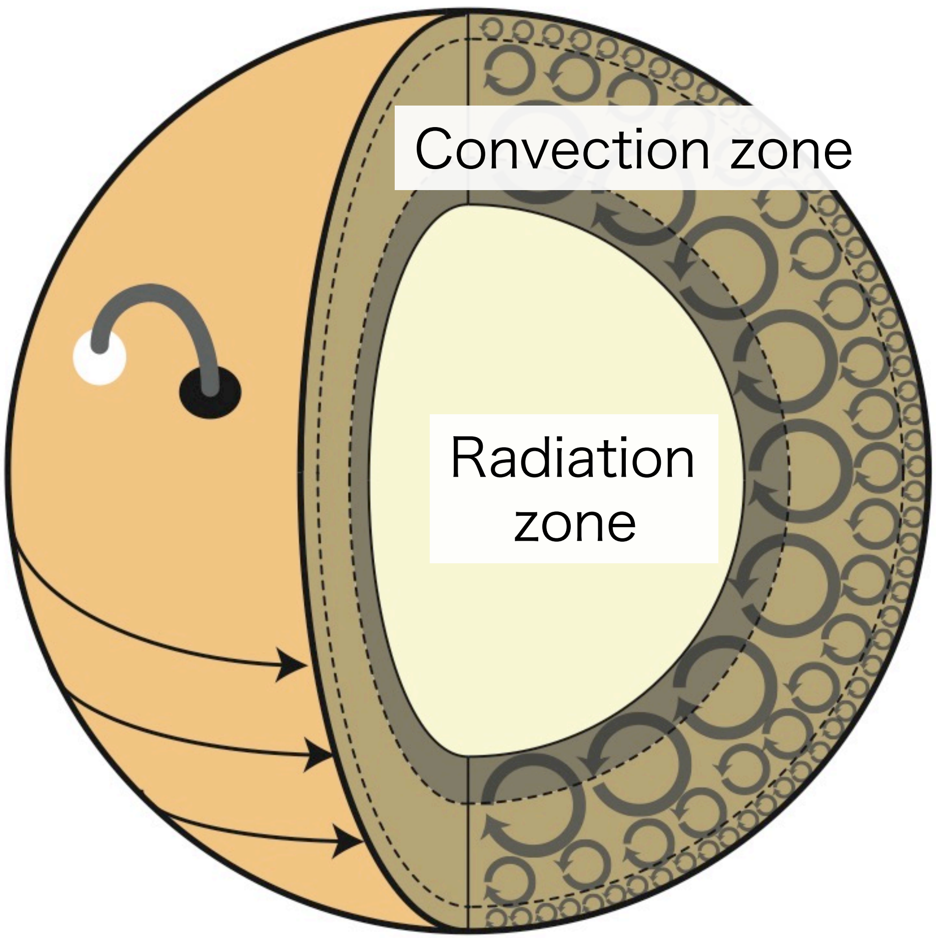
I am educated by flare to study dynamo.
I would be an appropriate person to have dynamo talk in a superflare workshop, even though I do not know anything about flare...

Rough sketch of my talk

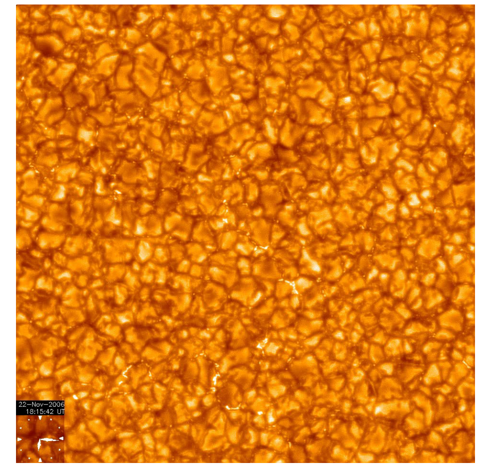
1. Large- and small-scale dynamo
2. Recent problem
3. Our result
4. Superflare



Solar interior, the origin of B

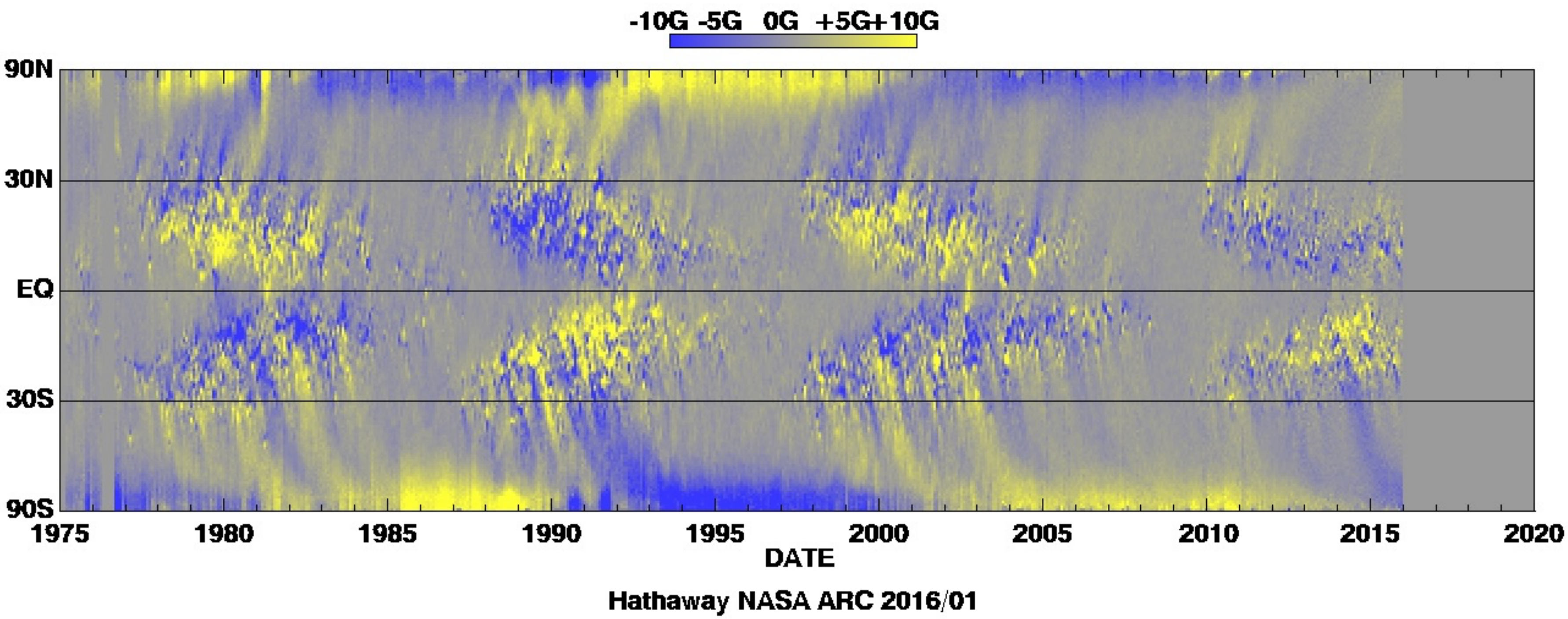


Hinode/SOT,visible right



Energy generated at the center of the sun is transported by the radiation in the first 70% and in the final 30%(convection zone) the energy is transported by the turbulent convection. Due to large Reynolds number velocity and magnetic field are highly turbulent.

Solar magnetic cycle



The most interesting point in the solar dynamo research is the process to construct the large-scale magnetic field from highly chaotic and turbulent magnetic field.

Small- and large-scale dynamos

Small-scale dynamo (SSD): Dynamo operating with non-helical turbulence in the scale smaller than energy carrying scale generating **no** net magnetic flux (Local dynamo, fluctuation dynamo). Origin of the **photospheric** magnetism (Catteneo 1999). Time scale is less than 1 minute (Rempel, 2014), determined by the smallest scale of the turbulence.

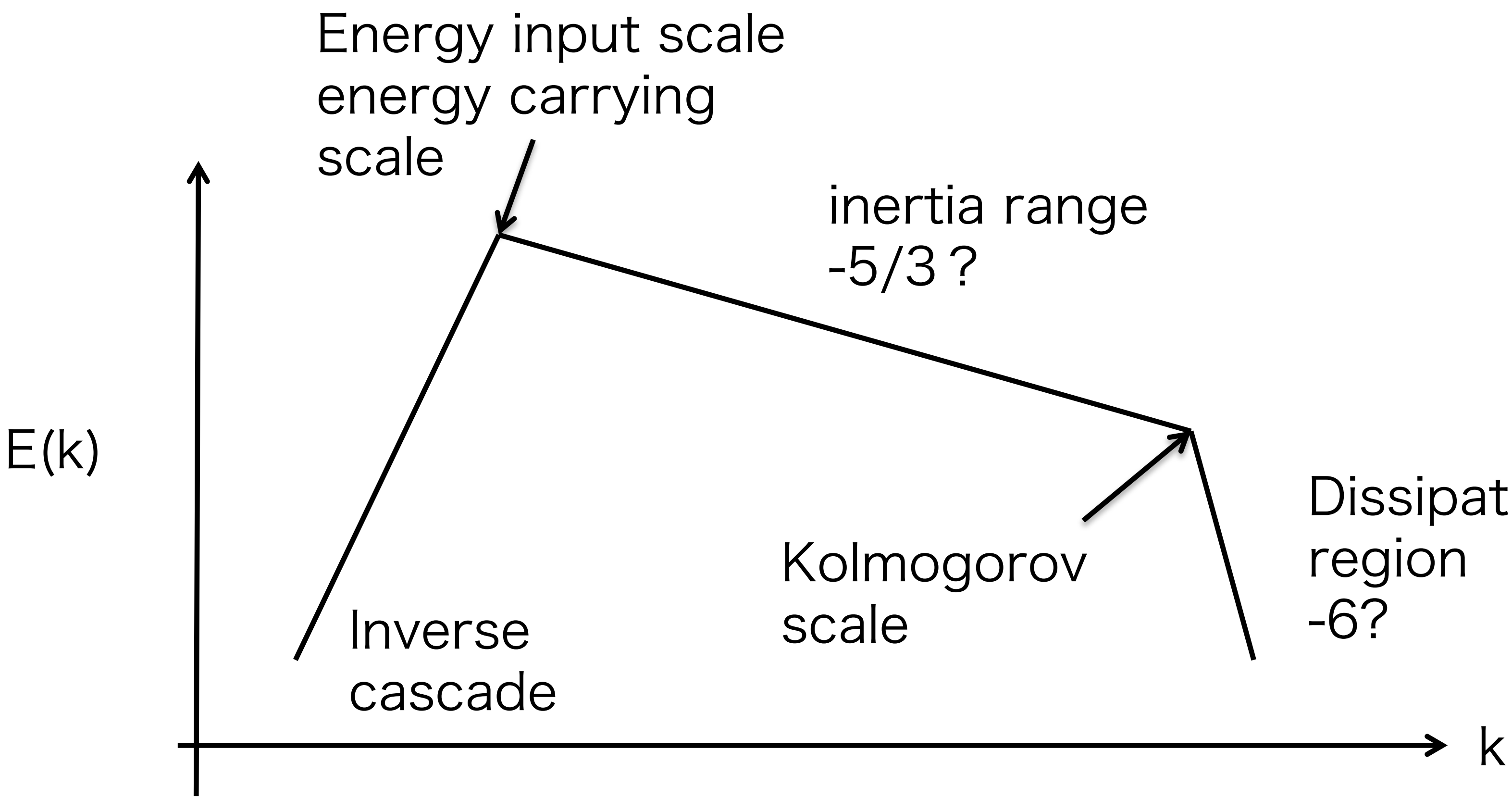
Large-scale dynamo (LSD): Dynamo with large-scale shear and/or mean turbulent electromotive force by helical turbulence generating net magnetic flux (Global dynamo).
Origin of the features related to solar cycle (e.g. **polar reversal**, **Hale's law**). Time scale is about 10 years in the solar case.

Sometimes there is no clear separation between them.
Combination of these constructs the solar magnetism.
(See also Brandenburg+2005, Physics Report, Section 5)

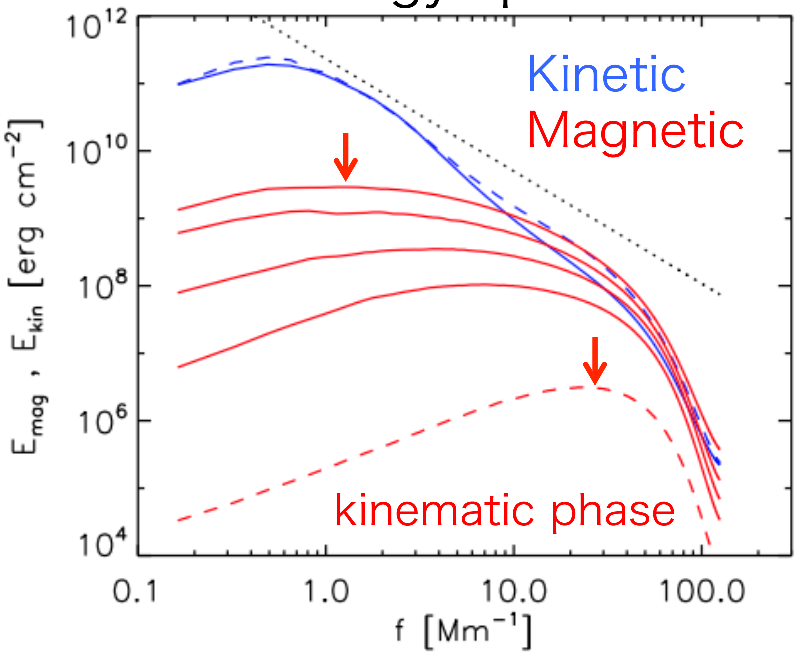
Turbulence and energy spectrum

Fourier transform or spherical harmonic expansion

$$v(x) \quad \longrightarrow \quad \tilde{v}(k) \qquad\qquad E(k) = \frac{1}{2}\rho[\tilde{v}(k)]^2$$



Kinematic and non-kinematic phase of small-scale dynamo



In the kinetic phase of the small-scale dynamo, where the Lorentz feedback can be ignored, the dynamo is most efficient in the smallest scale. Stretching there has shortest time-scale. Thus the magnetic energy peaks at the smallest scale.
e.g., high-resolution photospheric calculation by Rempel, 2014

When the dynamo can reach the non-kinematic phase, the magnetic energy reaches the small-scale kinetic energy and suppresses it. The peak of the magnetic energy shifts to large scale.
Enough resolution to resolve turbulent inertial scale is required to reach this stage. This is difficult in global dynamo calculation.

Large-scale dynamo

With some spatial average

$$\mathbf{B} = \langle \mathbf{B} \rangle + \mathbf{B}'$$
$$\mathbf{v} = \langle \mathbf{v} \rangle + \mathbf{v}'$$

$$\frac{\partial \langle \mathbf{B} \rangle}{\partial t} = \nabla \times (\langle \mathbf{v} \times \mathbf{B} \rangle)$$

and transformation

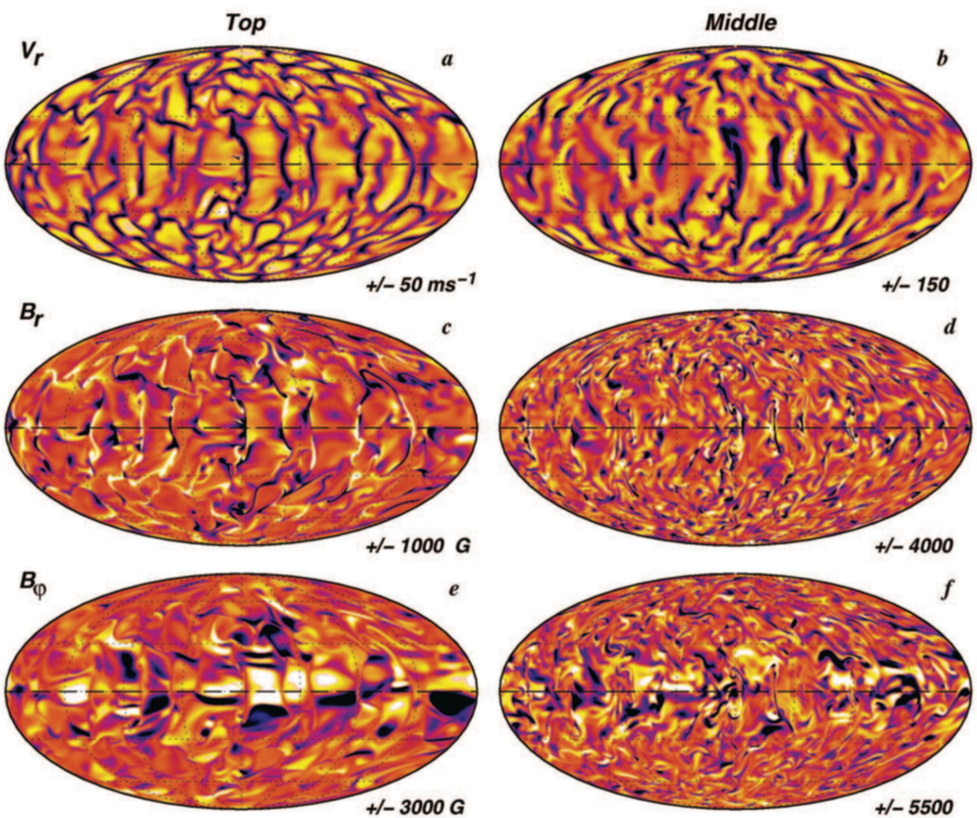
$$\frac{\partial \langle \mathbf{B} \rangle}{\partial t} = \nabla \times (\langle \mathbf{v} \rangle \times \langle \mathbf{B} \rangle) + \nabla \times (\langle \mathbf{v}' \times \mathbf{B}' \rangle)$$

$\nabla \times (\langle \mathbf{v} \rangle \times \langle \mathbf{B} \rangle)$: Influence from mean velocity to mean magnetic field.
Ω-effect, meridional flow.

$\nabla \times (\langle \mathbf{v}' \times \mathbf{B}' \rangle)$: Turbulent electro motive force
α-effect, β-effect, turbulent diffusivity
Rotation is important on this

Histroy of solar dynamo research(1/3)

Calculation with small viscosity and diffusivity by Brun+2004



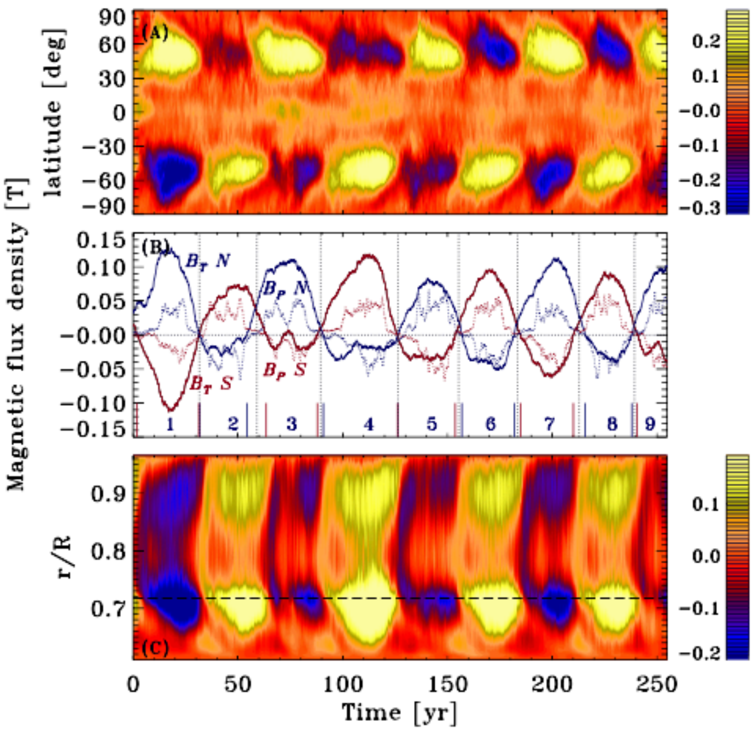
Very small
viscosity：ν=1.4×10^{12} cm^2/s
diffusivity：η=3.5×10^{11} cm^2/s
are used even at 2004.

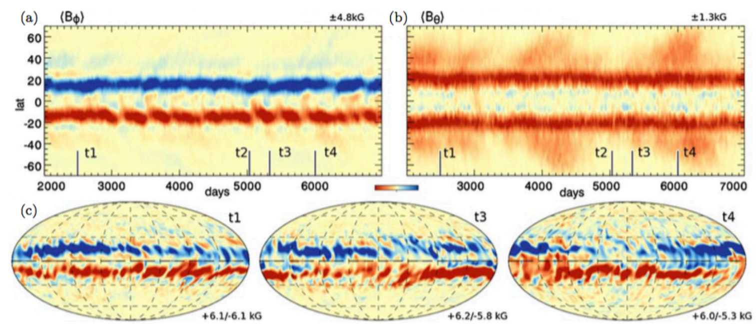
The calculation only shows very turbulent chaotic magnetic field and no coherent large-scale magnetic field, as expected.

Next 6 years are dark ages for solar dynamo.

History of solar dynamo research(2/3)

Discovery by Ghizaru and Brown for large-scale field and cycle





They found that large-scale magnetic field is constructed when the resolution is enough **low**.

47×64×128: Ghizaru+2010(ILES)

$\nu=1.32\times10^{12}$ cm^2/s

$\eta=2.64\times10^{12}$ cm^2/s: Brown+2010

Small-scale magnetic field is suppressed

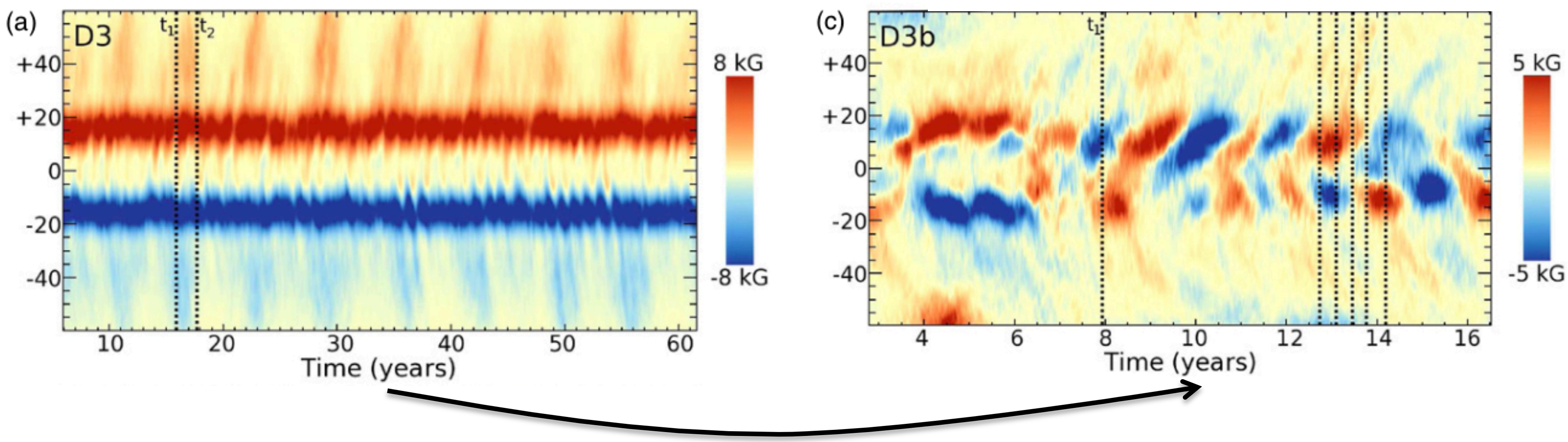
Then this method becomes very popular. Racine+2011, Käpylä +2012, Masada+2013, Warnecke+2015, Karak+2015 etc..

History of solar dynamo research(3/3)

Recently they had similar challenge, but the tendency is the same.

$\boxed{\Omega_0=3\Omega_{sun},\ Pm=0.25}$ (Nelson+2013)

$\eta=2.6\times10^{12}$ cm^2 s^{-1} $\eta=1.2\times10^{12}$ cm^2 s^{-1}



When the diffusivity is reduced by factor 2, the mean magnetic energy $\langle \mathbf{B} \rangle^2/8\pi$ becomes 1/3. Big mystery remains: how does the real sun maintains the large-scale magnetic field with very small diffusivity(～O(10^4) cm^2 s^{-1}).

Do we need suppression of small-scale dynamo in the solar convection zone?

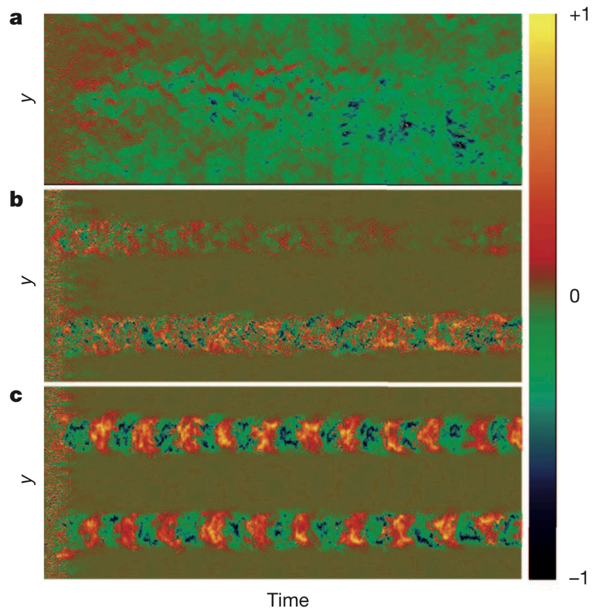
2D kinematic dynamo in high $R_m \sim 2500$
(Tobias+2013, Cattaneo+2014)

Mean B normalized for removing the exponential growth.

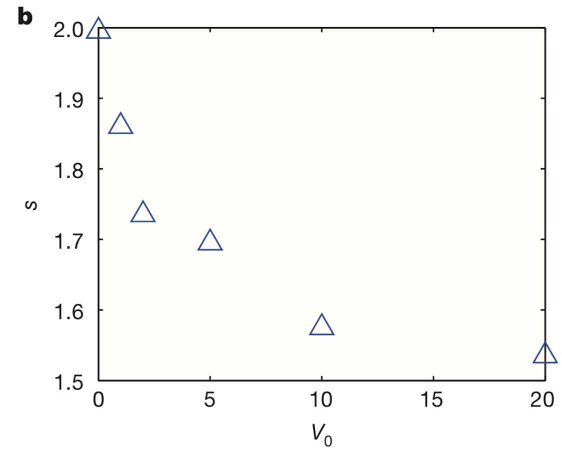
helical
no shear

non-helical
with shear

helical
with shear



Growth rate



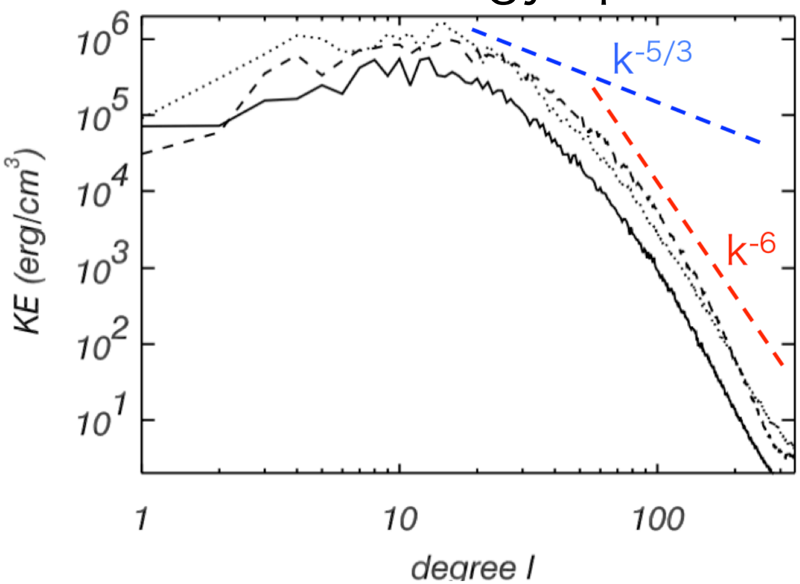
Amplitude of shear

The shear suppresses the growth rate of the SSD. Note that the non-linear effect is ignored.

Interesting argument is that suppressing the small-scale dynamo is required for achieving the large-scale dynamo.

Small-scale dynamo in global calculations

Kinetic energy spectra



Since the size of the sun (circumference : 4400 Mm) is much large than the turbulent energy input scale(density scale height : 60 Mm), inertia scale is not well resolved in the most global calculations. Thus the small-scale dynamo is not efficient.

Most people thought (or think) that turbulent magnetic energy in the convection zone is much weaker than the turbulent kinetic energy (flow is dominant).
For example, turbulent magnetic energy is **10%** of the turbulent kinetic energy (Fan+2014). Of course Lorentz feedback is very weak.

Small- and large-scale dynamos

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(See also Brandenburg+2005, Physics Report, Section 5)

Investigations for small- and large-scale dynamo

Recently we got nice method to increase resolution significantly. and large numerical resource at K-computer in Japan.

We carry out two series of calculations:

1. HD and MHD calculations in restricted Cartesian geometry exploring the possibility of small-scale dynamo in the convection zone without the rotation in high resolution which currently cannot be achieved in any global settings.
   (Hotta et al., 2015, ApJ, 803, 42)

2. MHD calculations in full spherical geometry exploring the interaction between small- and large-scale dynamos using rather low resolution.
   (Hotta et al., 2016 Science accepted. I have several preprint for this paper. Please ask me for it)

Equations

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \mathbf{v})$$

$$\rho \frac{\partial \mathbf{v}}{\partial t} = -\rho(\mathbf{v}\cdot\nabla)\mathbf{v} - \nabla p_1 - \rho_1 g \mathbf{e_r}$$

$$+2\rho\mathbf{v}\times\mathbf{\Omega_0} + \frac{1}{4\pi}(\nabla\times\mathbf{B})\times\mathbf{B}$$

$$\rho T \frac{\partial s_1}{\partial t} = -\rho T(\mathbf{v}\cdot\nabla)s_1 + \Gamma$$

$$p_1 = \left(\frac{\partial p}{\partial \rho}\right)_s \rho_1 + \left(\frac{\partial p}{\partial s}\right)_\rho s_1$$

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

$$\rho = \rho_0 + \xi^2 \rho_1$$

We solve the perturbation from spherically symmetric and steady background

$$\rho_0,\ p_0,\ T_0$$

In the calculations shown in this talk the perturbation is roughly,

$$\left(\frac{v_\mathrm{c}}{c_\mathrm{s}}\right)^2 \sim \frac{\rho_1}{\rho_0} \sim \frac{p_1}{p_0} \sim \frac{T_1}{T_0} \sim 10^{-6}$$

In some calculations magnetic field and/or rotation is not included. (depend on purpose.)

New method in dynamo work

Reduced Speed of Sound Technique

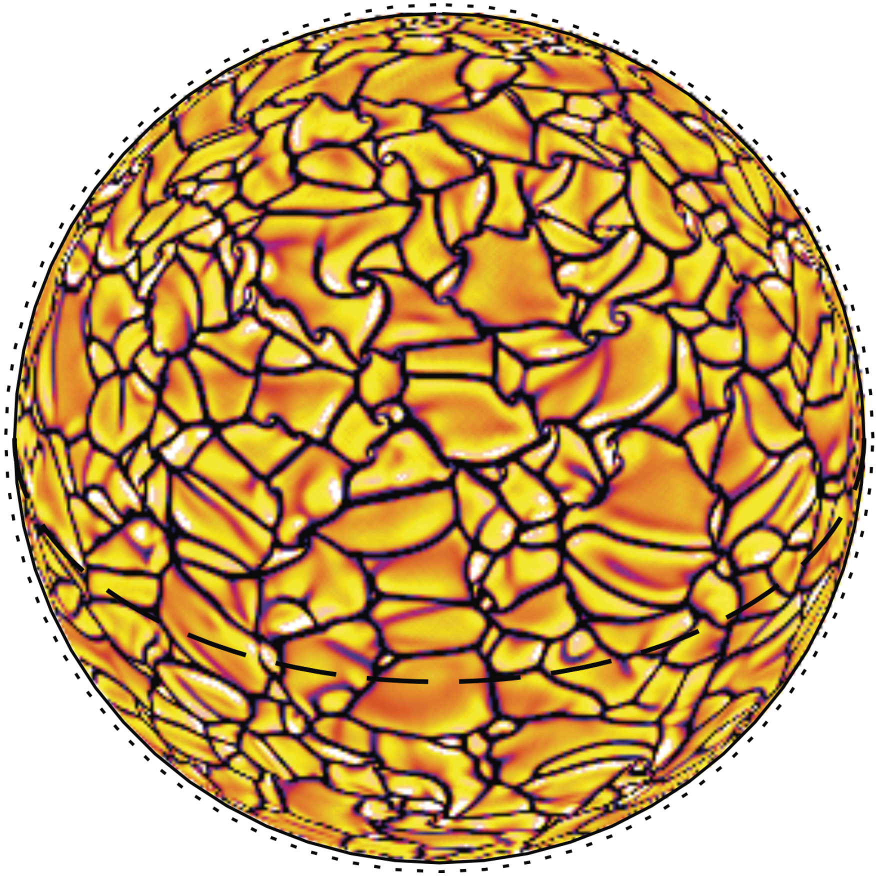
$$\rho = \rho_0 + \rho_1 \rightarrow \rho = \rho_0 + \xi^2 \rho_1$$

The effective speed of sound is reduced by a factor of ξ in order to calculate low Mach number condition easily.

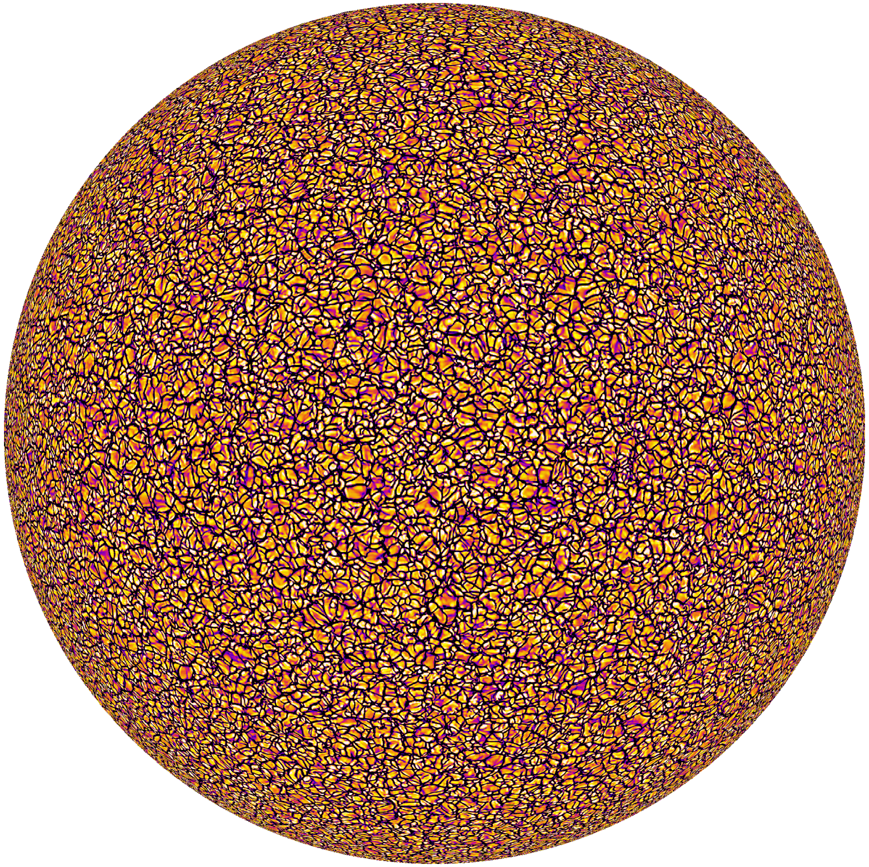
This method only requires local communication.
(Note, semi-implicit method like Boussinesq and Anelastic approximation requires global communication, since these assume infinite speed of sound).

In addition, we can reach photosphere with using inhomogeneous ξ. The validity of this is confirmed in our previous study (Hotta+2012)

Achievement with new code



Miesch+2008, 256x1024x2048
r_{top}=0.98R_{sun}

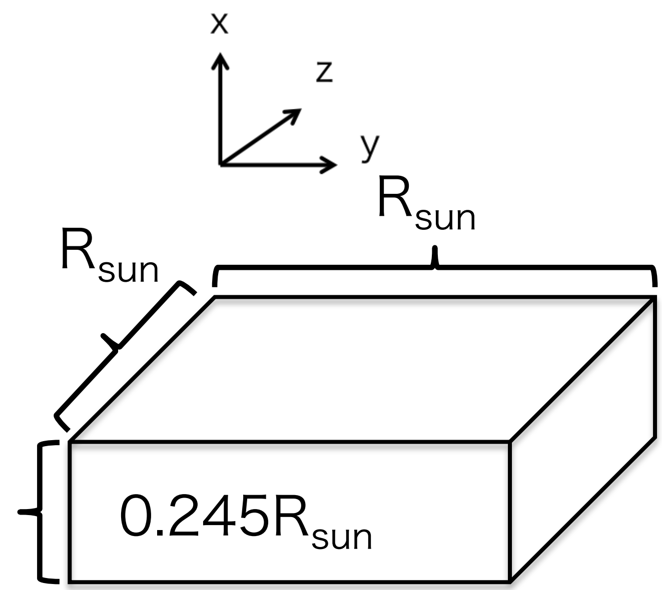


Hotta+2015, 512x2048x4096
r_{top}=0.99R_{sun}

Series 1: Numerical setting

・Calculation domain
$(0.715,0,0)<(x,y,z)/R_{sun}<(0.96,1,1,1)$

Cases	$N_x \times N_y \times N_z$
H256D,M256D	72x256x256
H2048, M2048	576×2048×2048

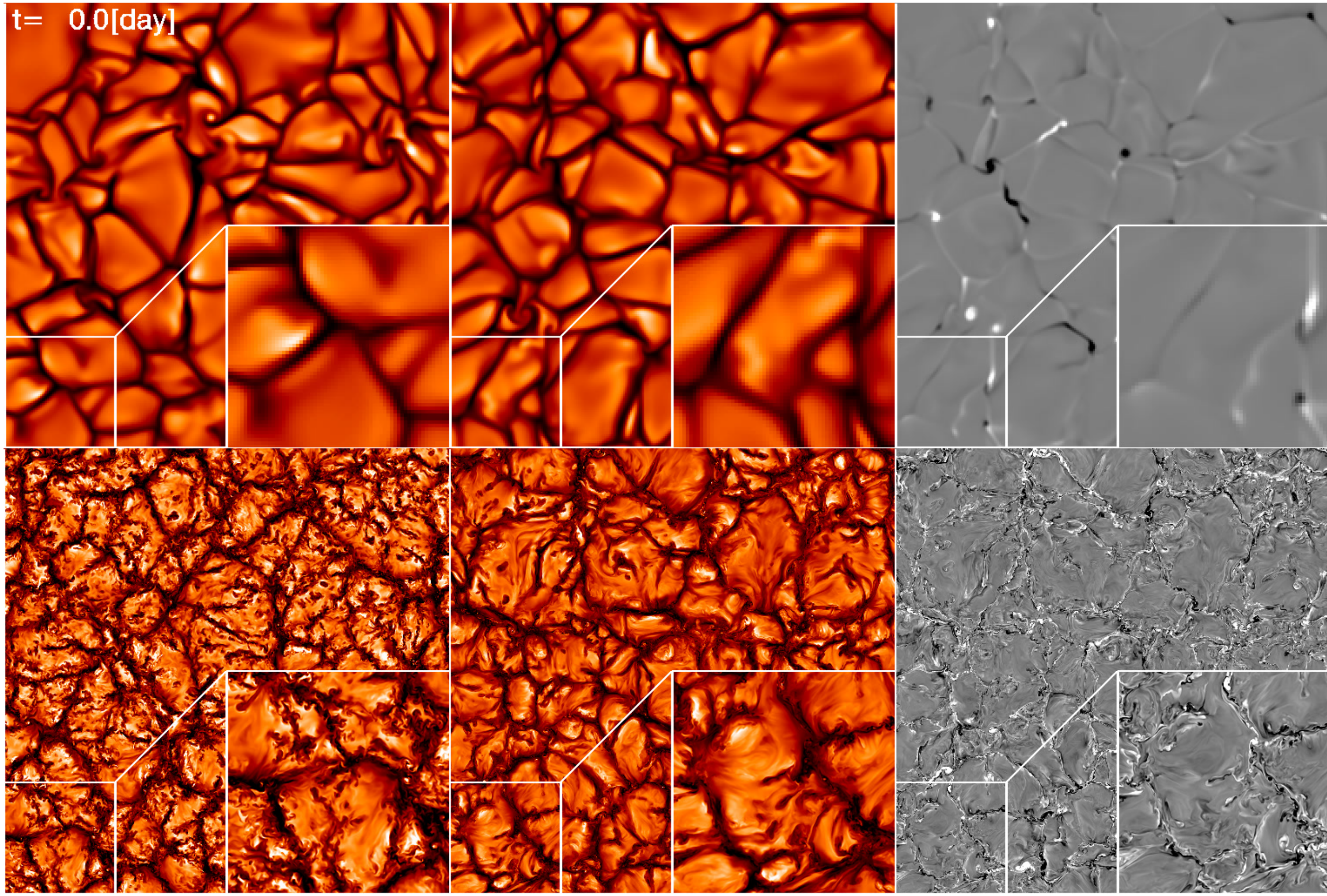


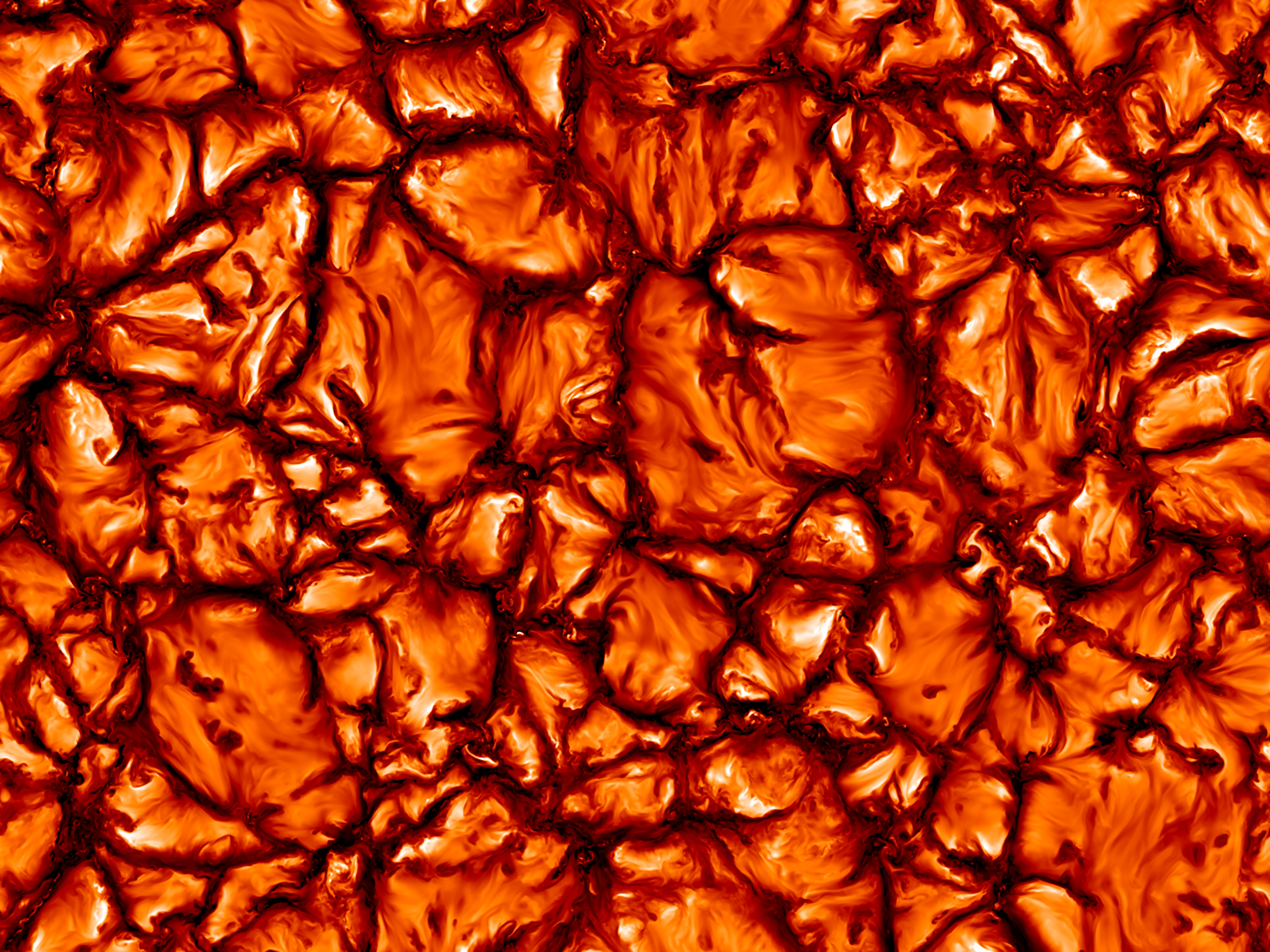
Solar luminosity at the base of the convection zone is adopted. Only H(M)256D have explicit diffusivities $\kappa=\nu=\eta=1\times10^{12}\ \mathrm{cm^2\,s^{-1}}$ in order to compare it with ordinary global calculations (Fan+2014). In the highest resolution, the grid spacing is smaller than 350 km. Hydrodynamic cases (H****) are calculated 100 days. Then weak random magnetic field is added with no net magnetic flux (M****).

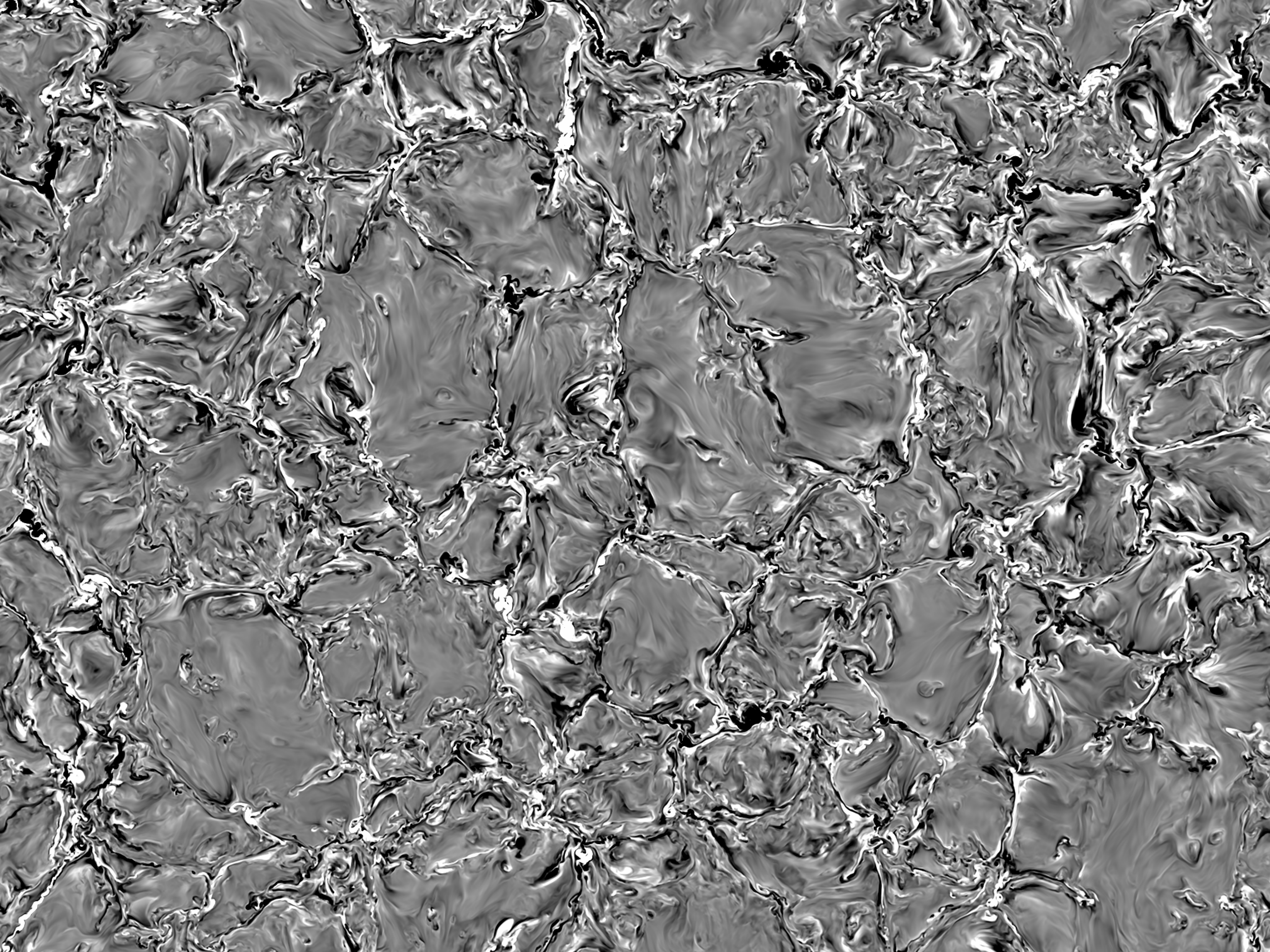
Comparison of two cases

Values at $r=0.95R_{sun}$

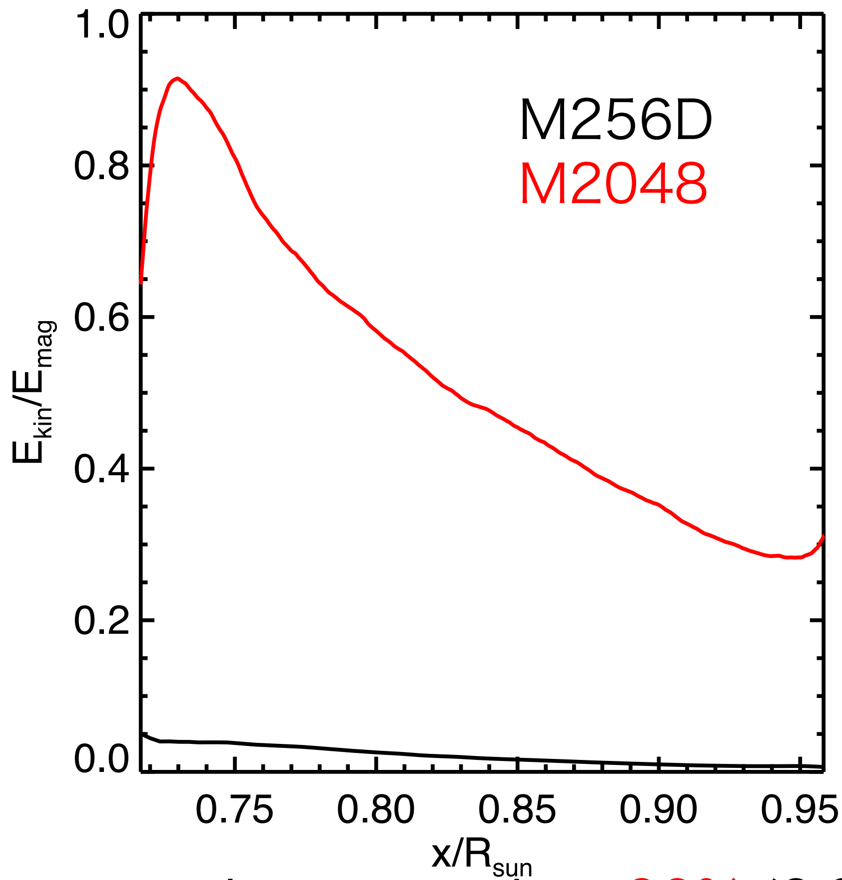
	v_x in HD	v_x in MHD	B_x in MHD
H256D M256D			
H2048 M2048			







Kinetic energy/Magnetic energy



The magnetic energy reaches more than 90% ($0.95B_{eq}$) of kinetic energy at the convection zone in M2048, while M256D can maintain 5% of kinetic energy.

What we learn from Cartesian calculations

We know that most of previous calculations significantly underestimate the efficiency of small-scale dynamo. High resolution calculation reveals the high efficiency of small-scale dynamo in the solar convection zone.

Next we carry out a series of high resolution calculations in the spherical geometry in order to investigate the interaction of small-scale dynamo with large-scale dynamo.

An important question is:
Does efficient small-scale dynamo destroy large-scale dynamo?

Next series in spherical geometry

In order to investigate the interaction between small- and large-scale dynamo, we carry out a series of high-resolution calculations in the spherical geometry.

Less diffusive

Cases	$N_r \times N_\theta \times N_\phi$	η, ν [cm^2 s^{-1}]	Note
Low_D	64x192x384	1×10^{12}	Fan+2014
Medium	64x192x384	N/A	
High	256x768x1536	N/A	

Initially, we put random and small fluctuation on the entropy and weak (100 G) antisymmetric toroidal field.
Then integrate the equation for 50 years. When without the character D, we only use slope limited diffusion. M256 costs 800,000 core hours.

Comparison of resolutions

Less diffusive

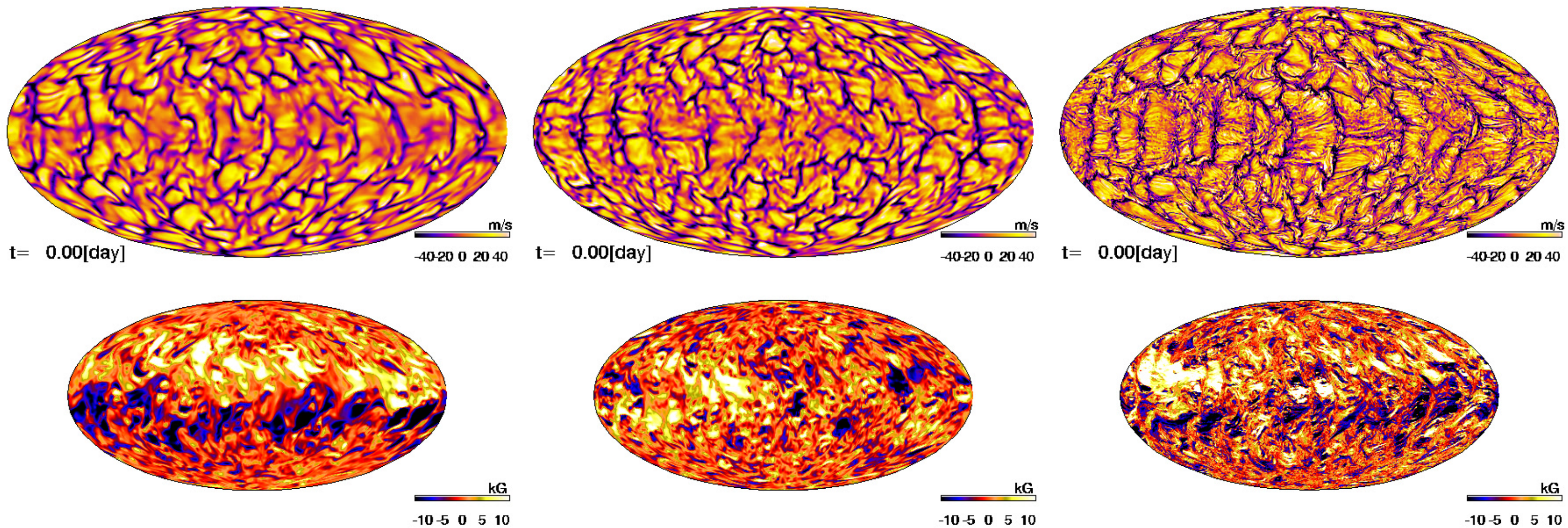
Low_D $\nu = \kappa = 1 \times 10^{12}$ cm^2 s^{-1}

Medium 64x192x384

High 256x768x1536

v_r at 0.95R

B_ϕ at 0.72R



In Low_D (Fan+2014), the coherent magnetic field is generated and concentrated around the base of the convection zone. Using higher resolution (M64) large scale magnetic field looks destructed. In the highest resolution calculation, we again see the indication of large-scale magnetic field at the bottom of the convection zone.

Mean magnetic field and cycle

$\langle E_{mag} \rangle$: mean magnetic energy

$\langle B_\phi \rangle$ at $r = 0.72R_{sun}$

Less diffusive

Low_D

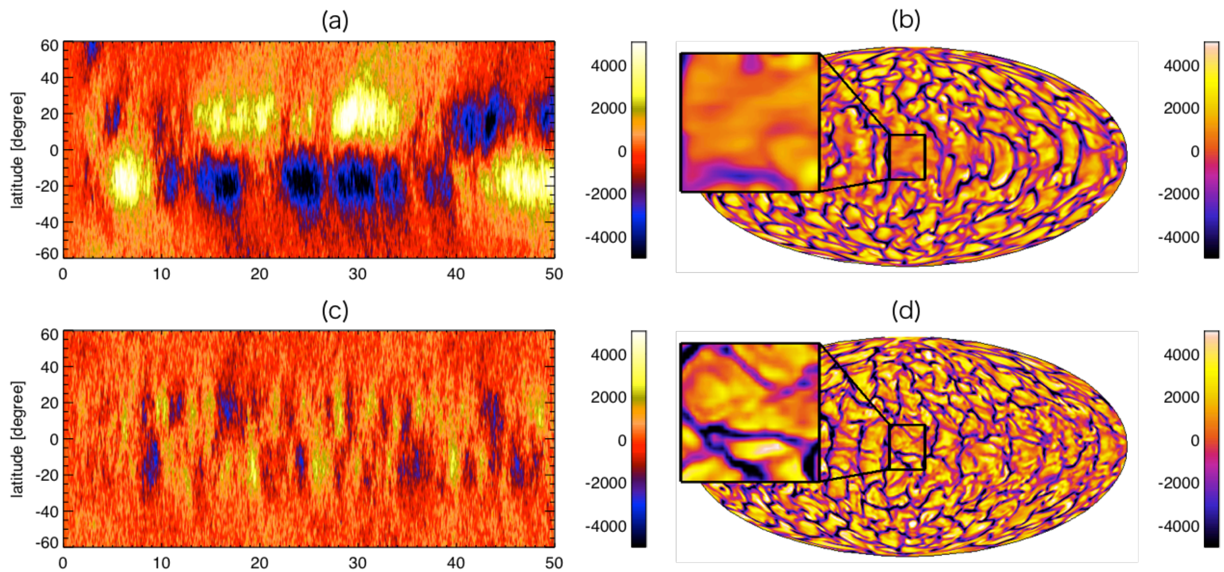
$\nu = \eta = 1 \times 10^{12}\ \mathrm{cm^2\ s^{-1}}$

$\langle E_{mag} \rangle = 2.9 \times 10^4\ \mathrm{erg\ cm^{-3}}$

Medium

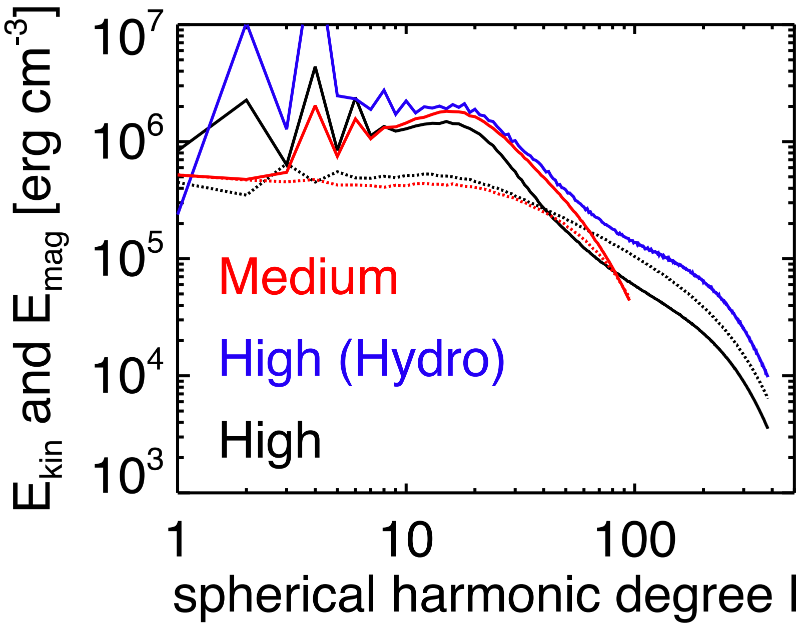
64x192x384

$\langle E_{mag} \rangle = 1.3 \times 10^4\ \mathrm{erg\ cm^{-3}}$



In the highest resolution calculation, the coherent cycle is recovered even at the large Rm regime.

Spectra



Solid : kinetic energy
Dotted : magnetic energy

When the resolution is enough high, small-scale dynamo can be in non-kinematic regime, i.e., the magnetic energy exceeds kinetic energy in small scale.

In this regime, small-scale magnetic field suppresses small-scale turbulence, which tends to destroys large-scale magnetic field.

As a result, turbulent diffusivity becomes small and large-scale magnetic field can be constructed.

Hotta, Rempel, Yokoyama, 2016, Science accepted

Approaching superflare issue

Are superflare sunspots able to be created?

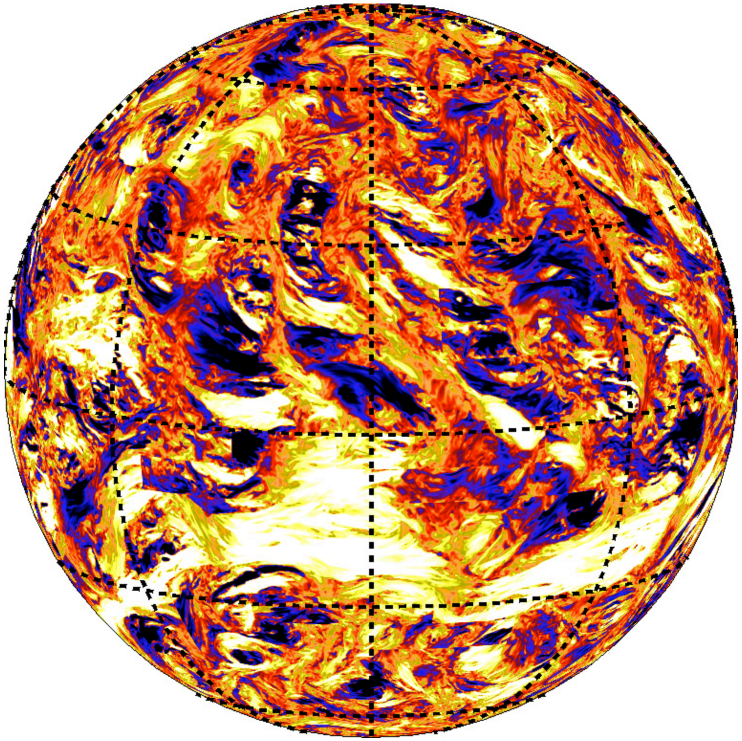
Sure, Why not?
Enough flux at the base of the convection zone.

We frequently see large-scale magnetic fluxes at the base of the CZ.
$L>200$ Mm and $B\sim20000$ G
Typical flux contents.
$\Phi\sim fL^2B\sim2\times10^{24}$ Mx.

This large-scale feature is not caused by low-resolution, but by high-resolution effect.

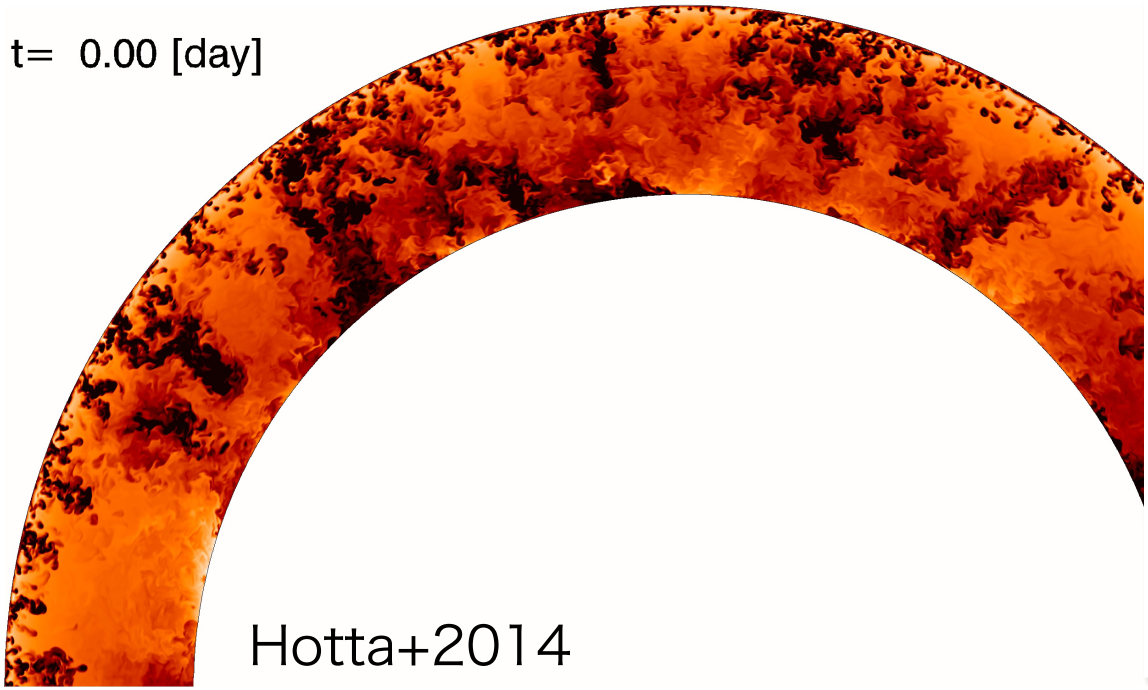
I can confidently say that large amount of the magnetic flux contents is hidden at the base of the CZ even now.

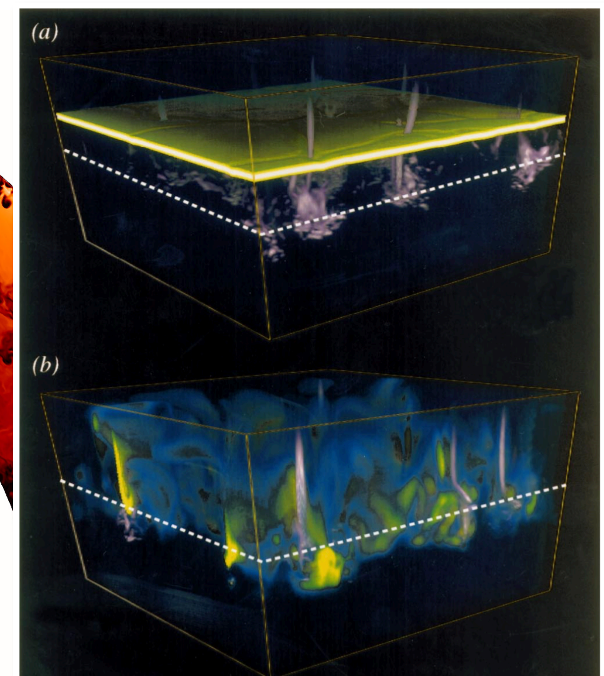
B_ϕ at the base of the CZ
$\pm$ 12000 G



Why is superflare rare in the real sun?

Due to difficulty in transporting large magnetic flux upward.





Large-scale magnetic flux tends to be transported downward by strong downflow (magnetic pumping, Tobias+1998, 2001)

My feeling on solar superflare

Issue of superflare in terms of dynamo is not a problem creating magnetic energy but a problem transporting a large magnetic flux.

Maybe by change, there is large strong upflow transports a large-scale magnetic flux(> 10^{24} Mx), then generates superflare sunspot.

Challenge for theorist: Investigate possibility that large-scale magnetic flux can be transported all the way from the base of CZ to photosphere.

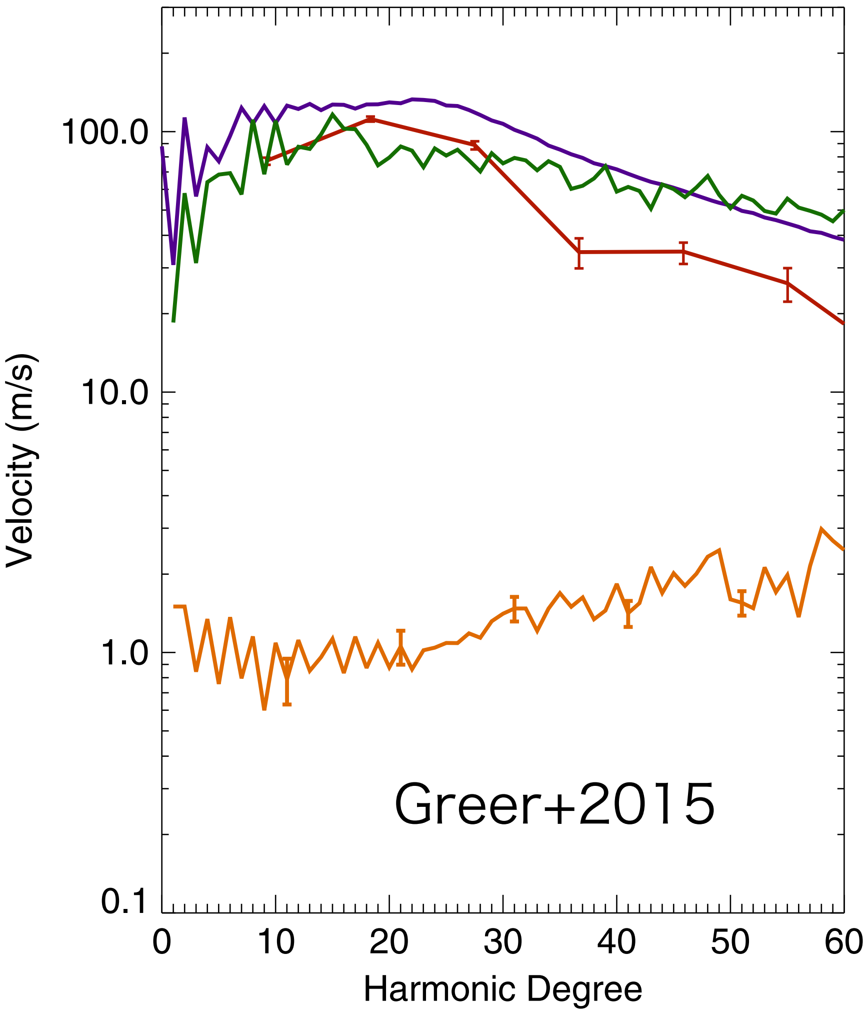
Challenge for observation: Confirm the existence of large-scale strong magnetic flux even in solar interior → How?

Observe convection velocity

Flow has information on strength of magnetic field.

If you want to know the possibility of the superflare sunspot in the sun, you MUST do helioseismology and find indication of large magnetic flux in the solar convection zone.

Suppression of the convection velocity which would be different from mixing length theory is a strong support on such large magnetic flux.



What's the role of rotation? (1/2)

Interesting thing around the superflares is dependence of magnetic field on the rotation.

Angular momentum transport is promoted by rotation with increasing the correlation between velocities

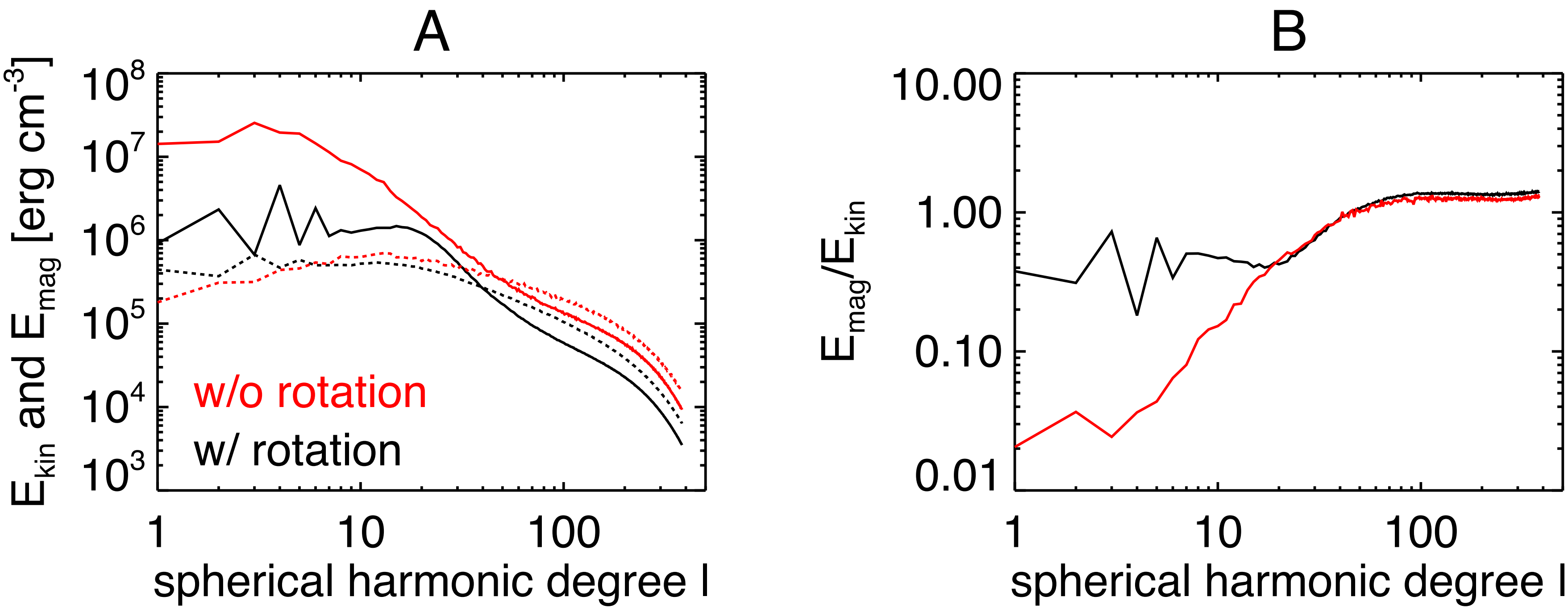
$\rightarrow$ Increase large-scale stretching (Ω-effect)

$$\rho_0 \frac{\partial \langle \mathcal{L} \rangle}{\partial t} = -(\rho_0 \langle \mathbf{v}_m \rangle \cdot \nabla)\langle \mathcal{L} \rangle - \rho_0 \nabla \cdot (\langle \mathbf{v}' \mathrm{L}' \rangle)$$

Turbulent electromotive force is increased by rotation which leads to larger-scale magnetic field.

$$\frac{\partial \langle \mathbf{B} \rangle}{\partial t} = \nabla \times (\langle \mathbf{v} \rangle \times \langle \mathbf{B} \rangle) + \nabla \times (\langle \mathbf{v}' \times \mathbf{B}' \rangle)$$

What's the role of rotation? (2/2)



Rotation likely suppresses convection velocity especially at large-scale.
On the other hand, large-scale magnetic field is promoted.
Small-scale dynamo does not change with rotation.

What should be observed?

Most important observation is for convection velocity in stellar interior, maybe using asteroseismology.

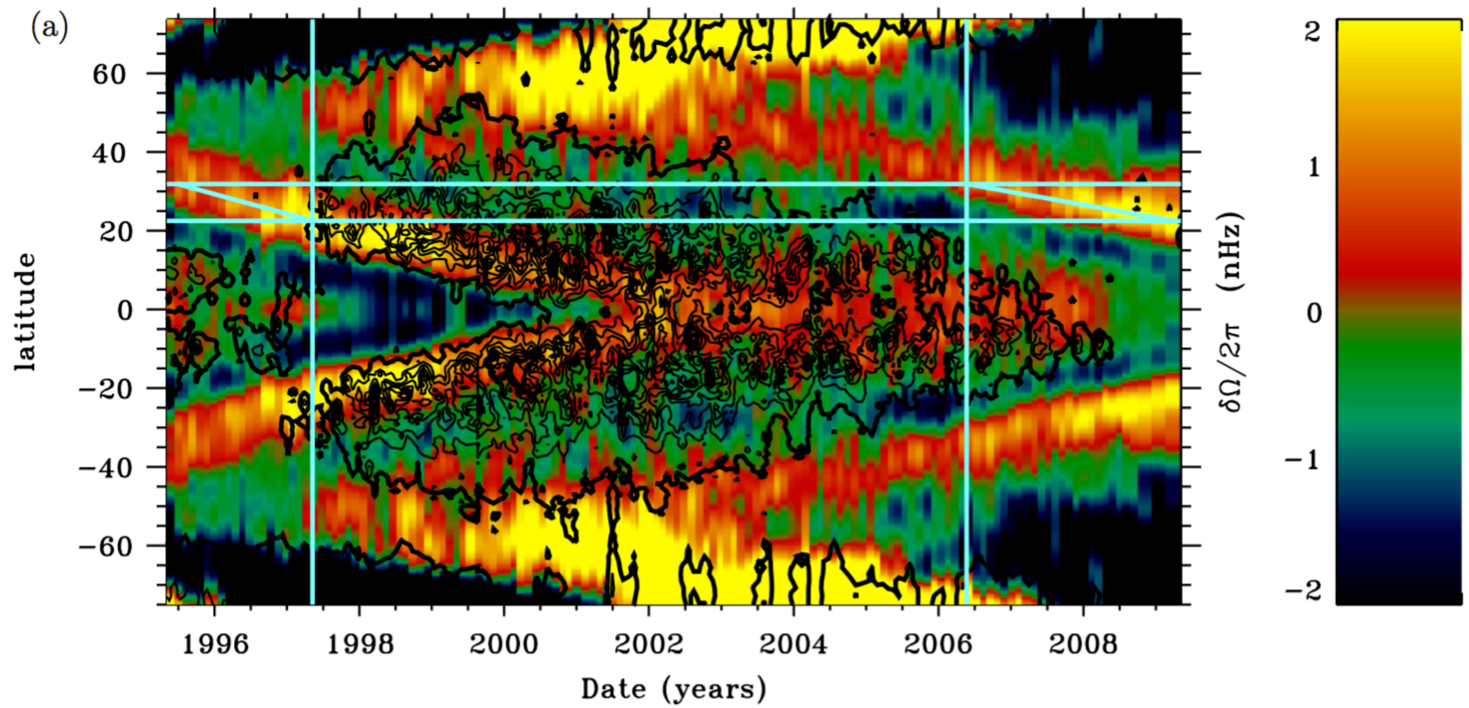
Next is strength of magnetic field.
Rempel, 2014 shows that if average line of sight magnetic field strength is 30 G, the convection zone is almost free from small-scale magnetic field, if it is 60 G convection zone is filled with equipartition small-scale magnetic field.
→ Hinode SP result shows 60 G.

The magnetic strength on the surface has important information on the interior.

Next next is topology of the magnetic field.
This has information on rotational influence on dynamo.
Ideally we need energy spectra of magnetic field.

Influence of starspot on differential rotation

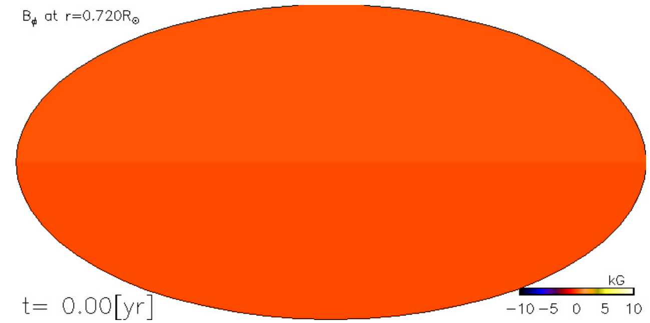
Variation of solar differential rotation.



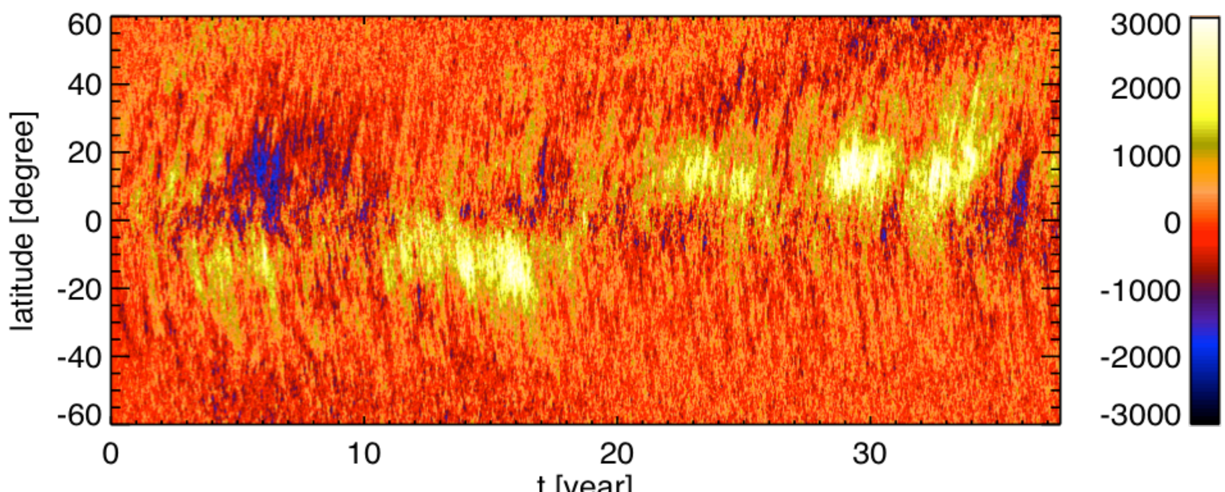
It is good to estimate the influence of starspot on differential rotation. Decrease of the differential rotation supports the existence large and strong magnetic field.

Challenge to create superflare sunspot

Grid : 256x1024x2048 → 512x2048x4096
Domain: $0.715<r/R_{sun}<0.99$
Rotation rate: $\Omega_0=3\Omega_{sun}$



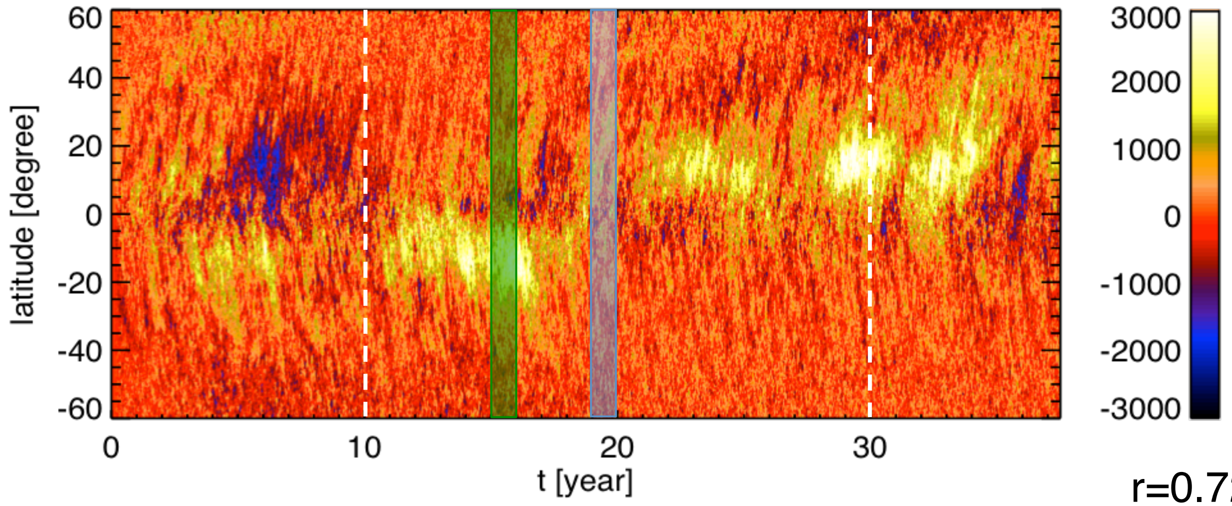
Zonally averaged toroidal magnetic field $\langle B_\phi \rangle$ at $0.72R_{sun}$



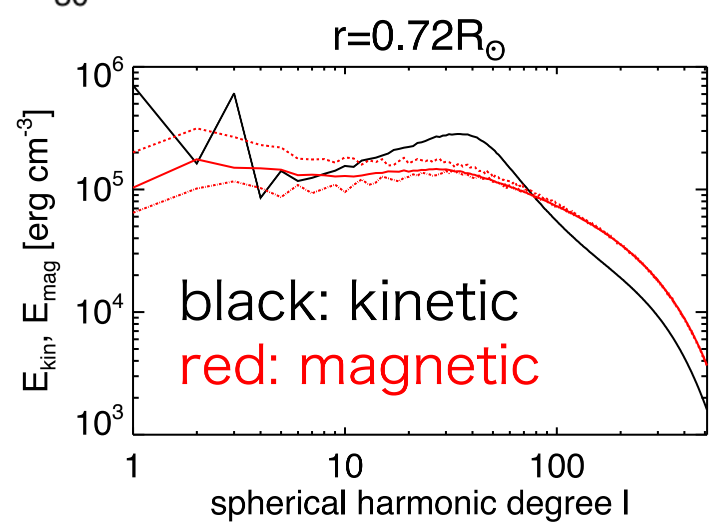
Asymmetric global-scale magnetic field is constructed.

Temporal evolution of global field

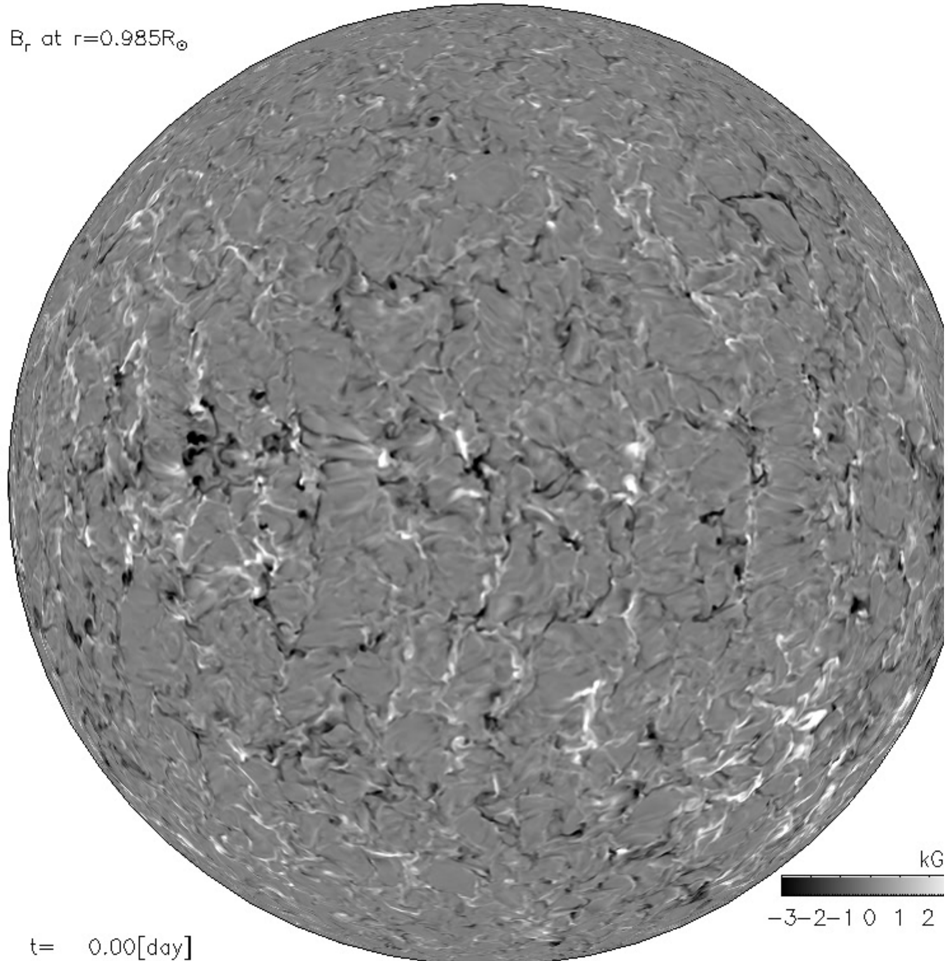
Zonally averaged toroidal magnetic field $\langle B_\phi \rangle$ at $0.72R_{sun}$

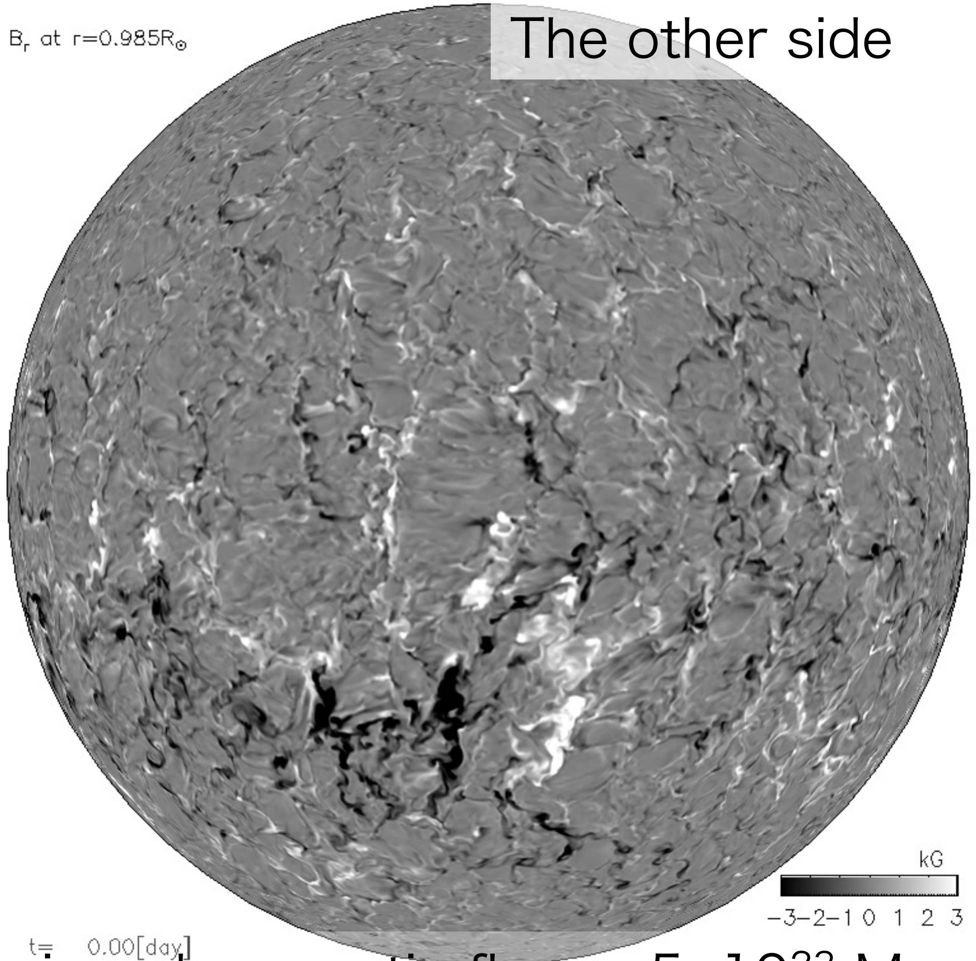


At the base of the convection zone, the small-scale is efficient enough to suppress the small-scale turbulent flow, which is necessary to have global magnetic field in high-resolution calculations (see my talk in dynamo workshop).



We can nicely have it 10 Mm below





unsigned magnetic flux $\sim 5\times10^{23}$ Mx

Summary

Recently we nicely understand generation mechanism of solar large-scale field.

If you believe in my calculations, there should be enough magnetic flux for superflare sunspot.

Convection velocity is the most important to be observed.
(and difficult...)

Any information on magnetic field is important (strength and topology.).