CHIBA UNIVERSITY

第6回 DTAシンポジウム
「星形成を軸に俯瞰する磁場の役割とその観測的検証」

太陽の大スケールダイナモにおける小スケールダイナモの役割

Hotta et al., 2016, Science, 351, 1427

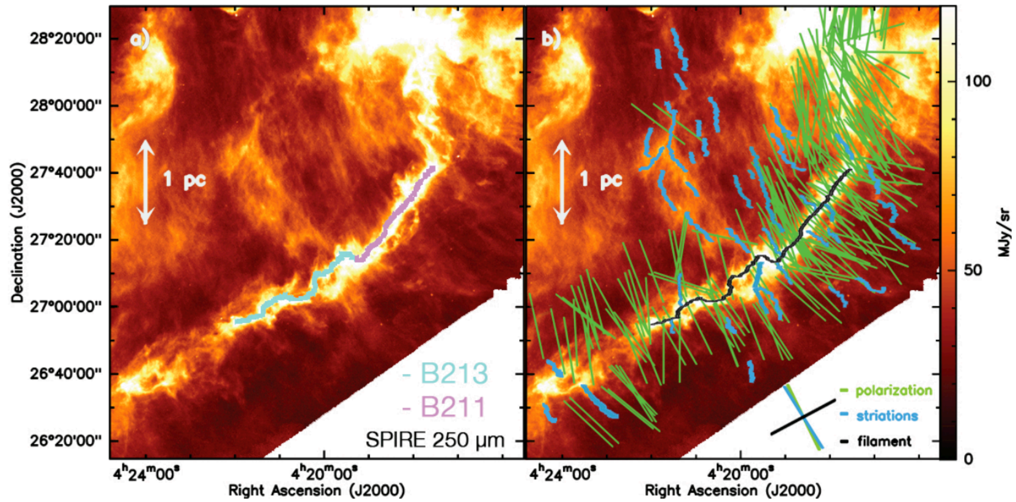
千葉大学

堀田英之

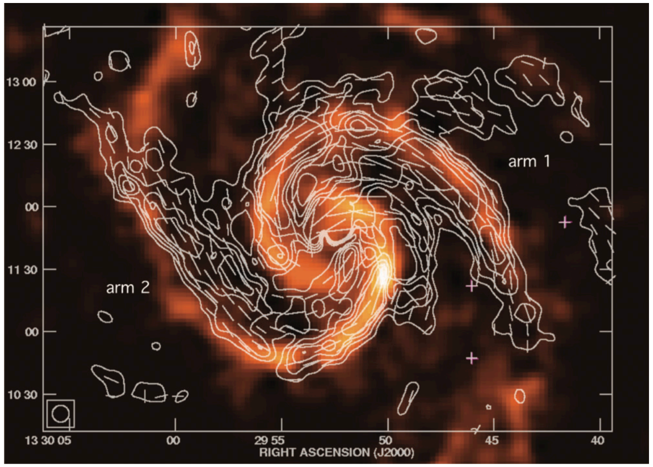
Magnetic field is frequently coherent and large-scale

Plasma in the universe frequently constructs high-level turbulence with large Reynolds numbers.

Magnetic field in smallest scale has the largest growth rate for the small-scale dynamo.
In addition, large-scale feather is expected to be destructed with the turbulent motion



Palmeirim+2013, molecular cloud

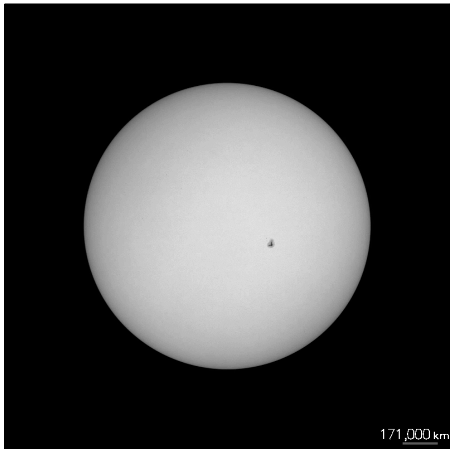


Fletcher+2011
Galaxy

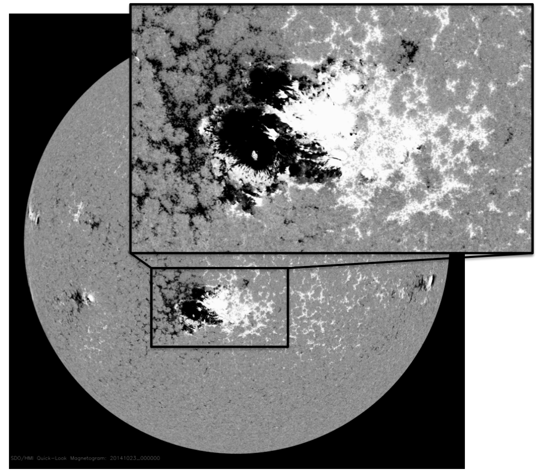
How can they construct such large-scale magnetic fields.

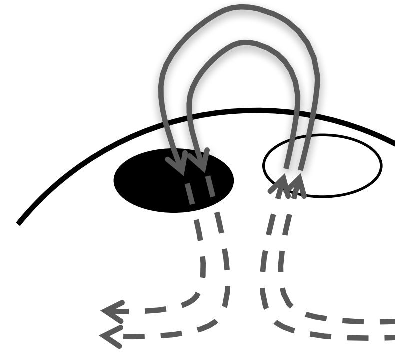
Sunspot and solar cycle

(Courtesy of Okamoto)

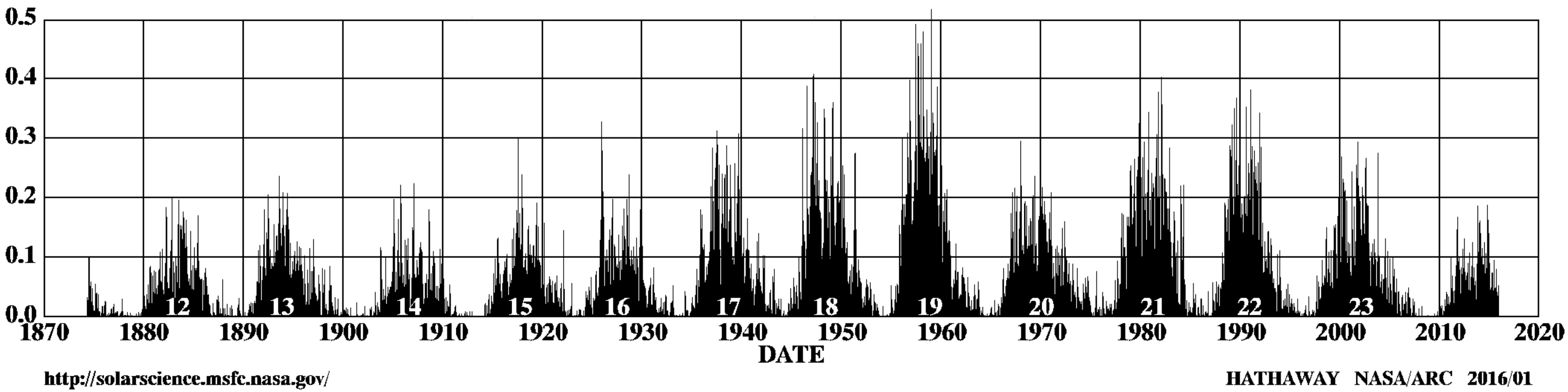


(SDO/HMI)



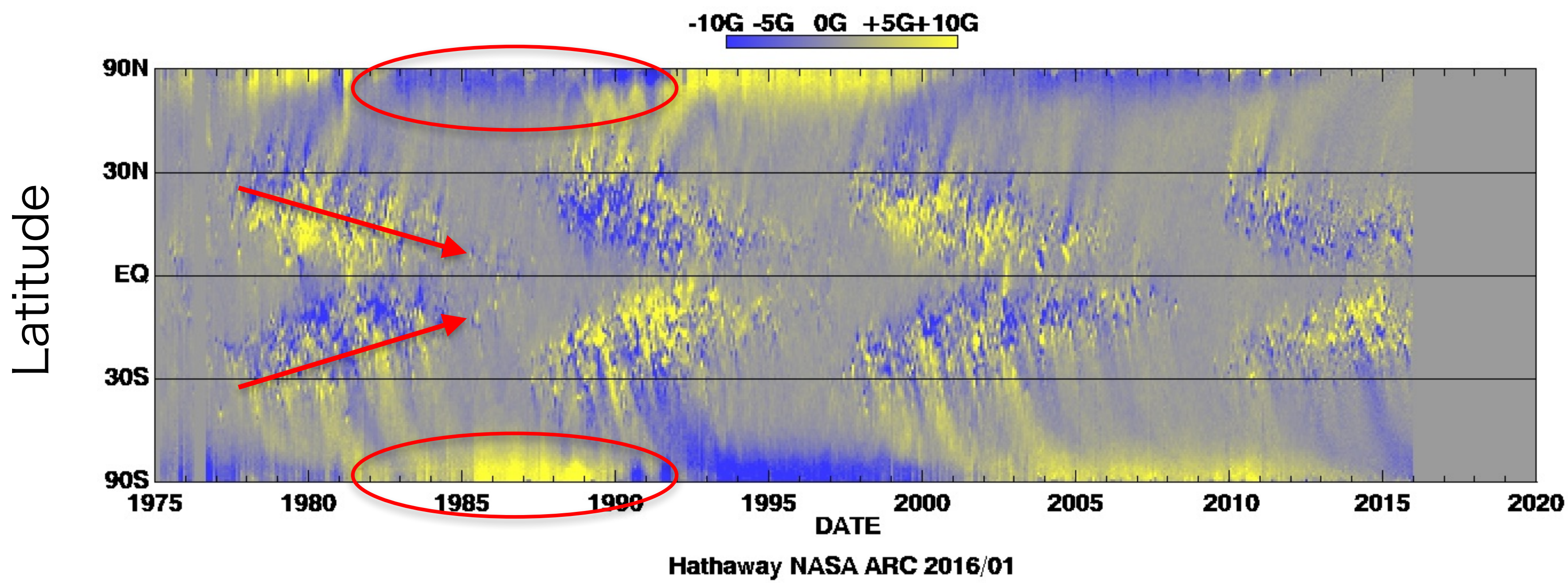


Average daily sunspot area (% of visible hemisphere)



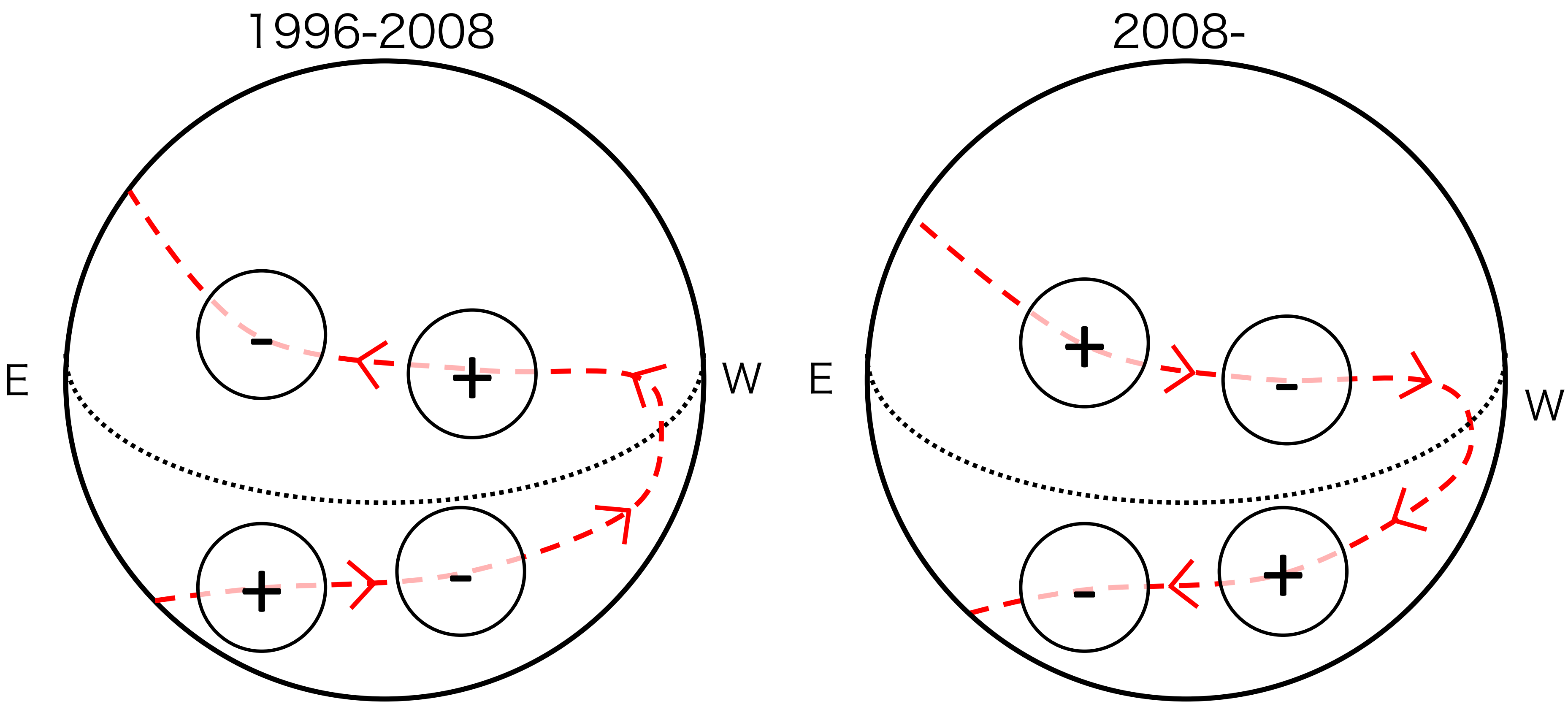
Butterfly diagram

11 year solar cycle is filled with ordered rules



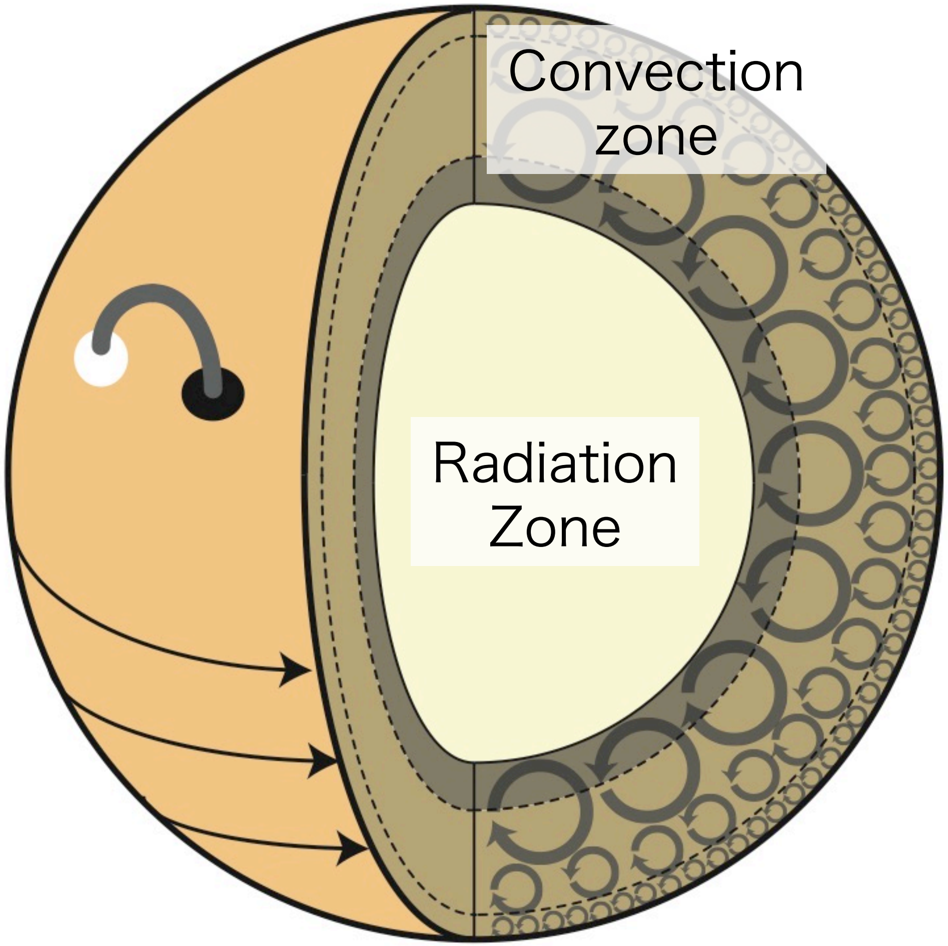
- ✓ Sunspot latitude migrates equatorward during a cycle.
- ✓ Large-scale dipole field reverses every 11 years.

Hale-Nicholson's law



More than 90% of sunspot pairs obey a coherent polarity rule.
This indicates large-scale magnetic field in the solar interior.

Convection generates magnetic field

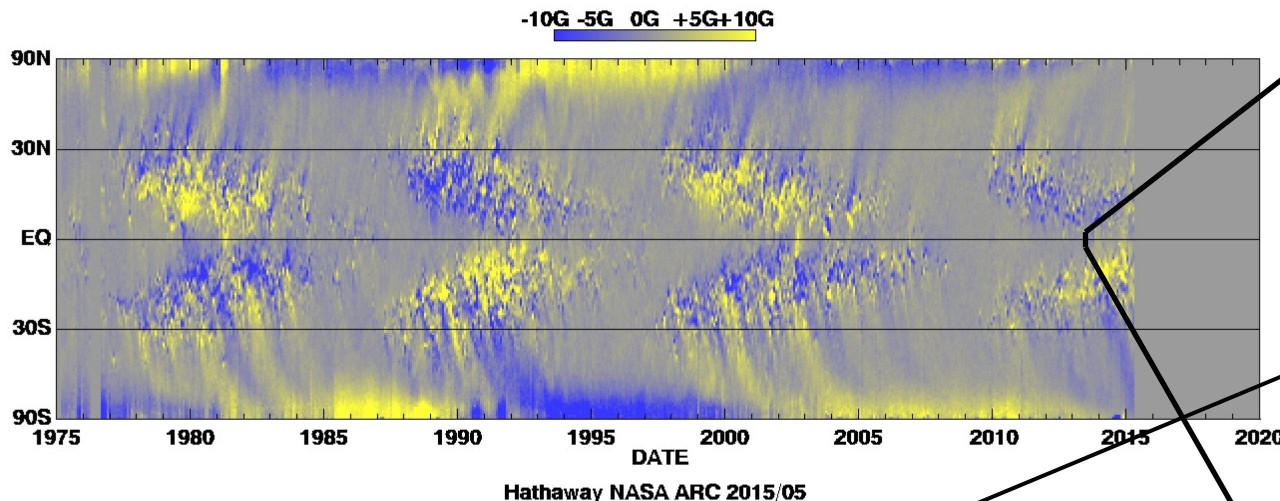


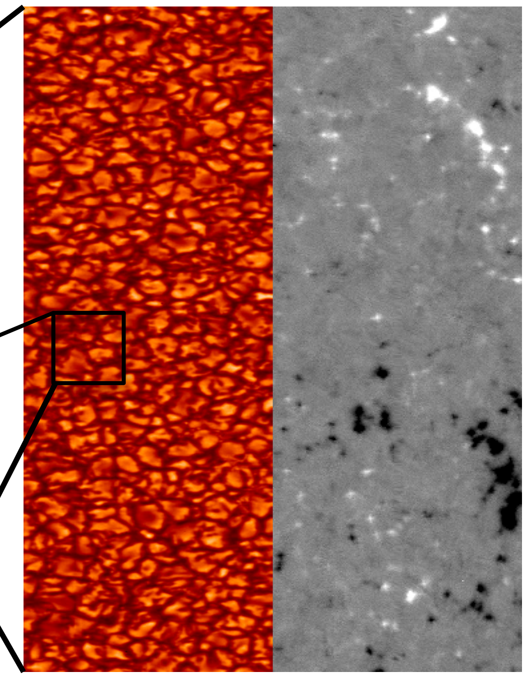
The solar convection zone, the outer 30% of the solar interior, is filled with the turbulent convection due to the energy input from the radiation zone.

The turbulent motion of the ionized plasma amplifies the magnetic field → dynamo

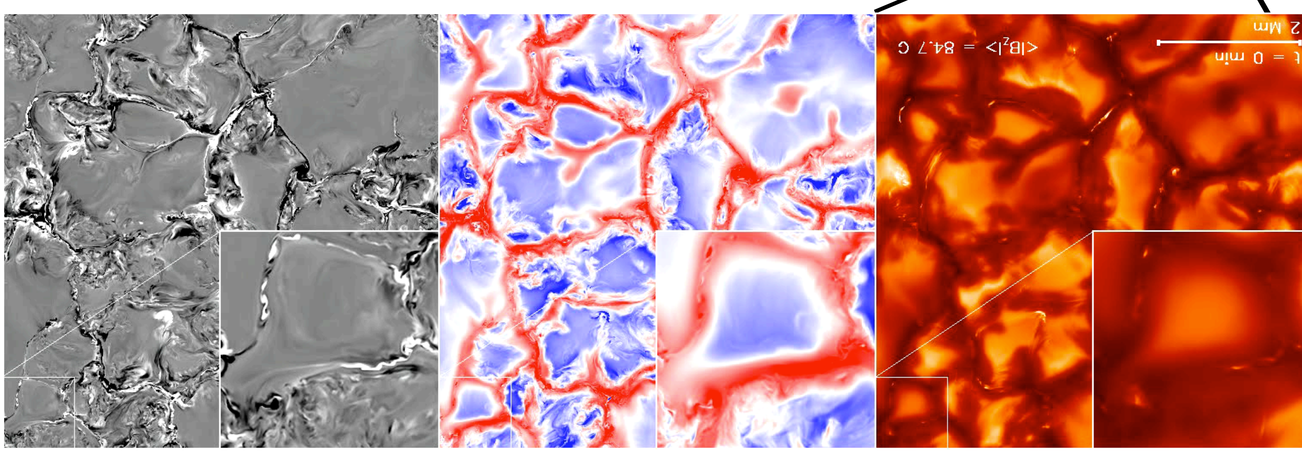
We need to understand the details of the turbulence and magnetic field to understand the 11 year cycle problem.

Order from Chaos





(Hinode/SOT)

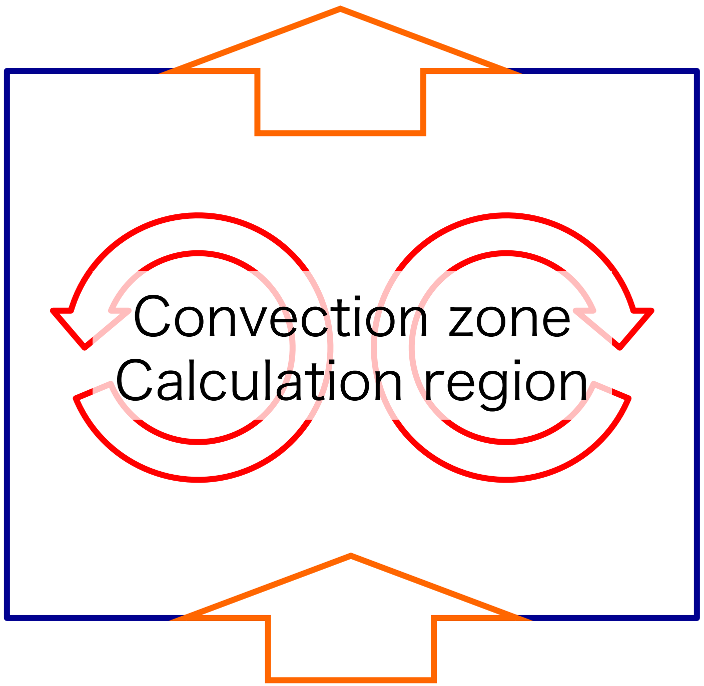


(Rempel, 2014, Numerical Calculation)

How can we make large-scale feature from such small-scales.

Solar physics is lucky

$$L_\odot = 3.84 \times 10^{33}\ \mathrm{erg\ s^{-1}}$$



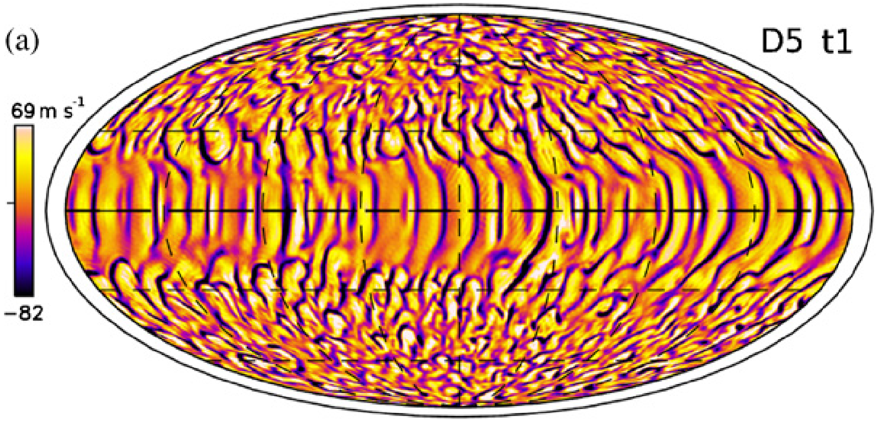
Energy flux
(The value is well known)

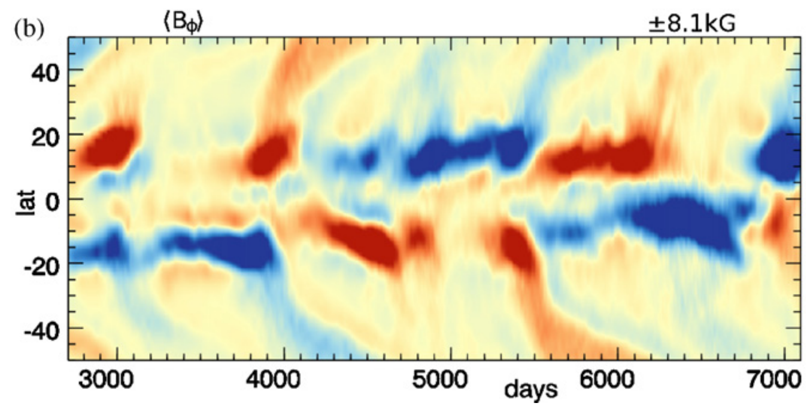
Thanks to detailed solar observation (mainly helioseismology) and the solar standard model, we know the details of the energy flux, and the stratification (density, pressure, and temperatures) in the solar convection zone.

That means that input parameters for calculations are well determined and ideally we can calculate the turbulence and magnetic field properly with nice supercomputers.

Convection can produce global field

5 times larger than solar rotation





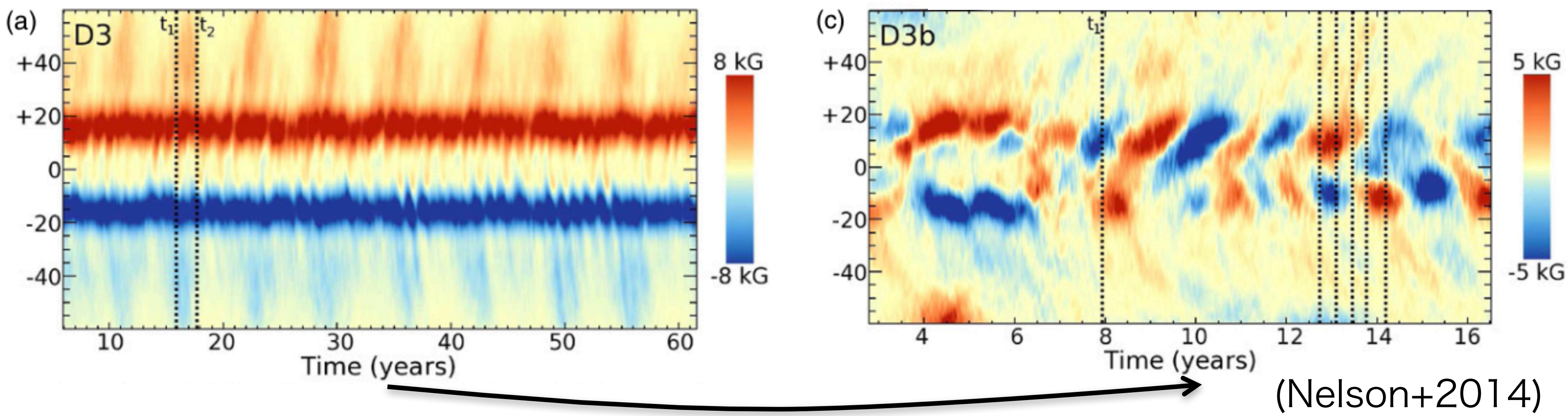
(Brown+2010)

Recent 3D calculations are able to produce global scale magnetic field and cycle (Ghizaru+2010, Brown+2010, Racine+2011, Käpylä+2012, Masada+2013, Fan+2014, Warnecke+2015, Karak+2015).

High resolution destroys the order

Most solar global dynamo models are carried out in low resolutions, i.e., small-scale dynamo is inefficient.
Higher resolution kills the large-scale features.

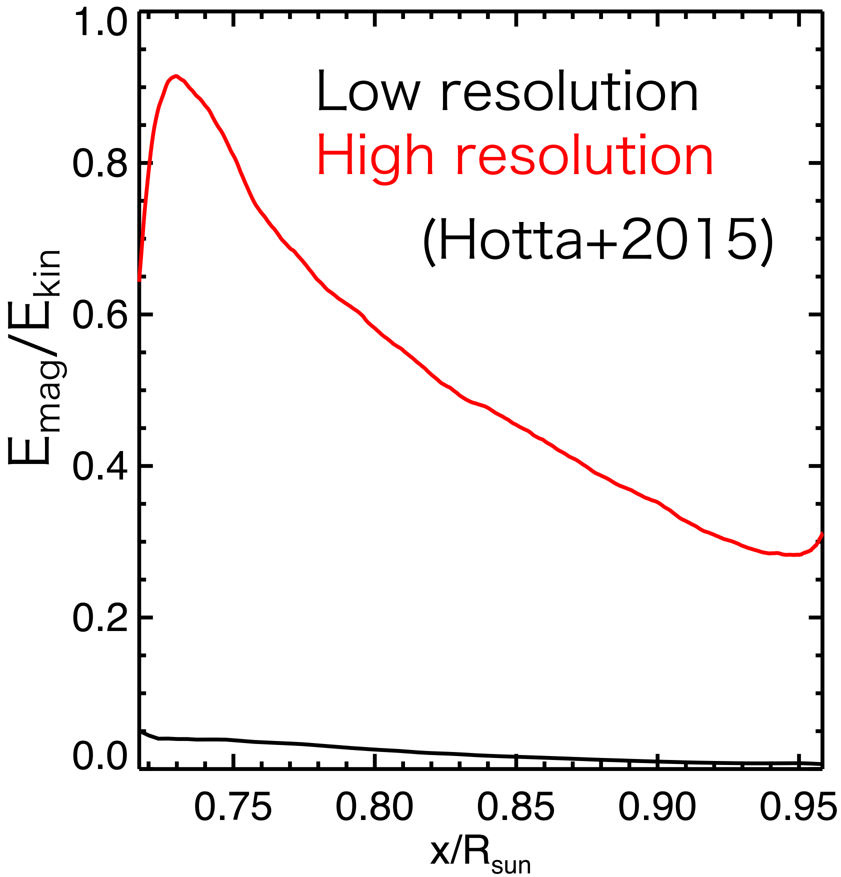
Diffusivity : $\eta = 2.6\times10^{12}\ \mathrm{cm^2\ s^{-1}}$ Diffusivity : $\eta = 1.2\times10^{12}\ \mathrm{cm^2\ s^{-1}}$

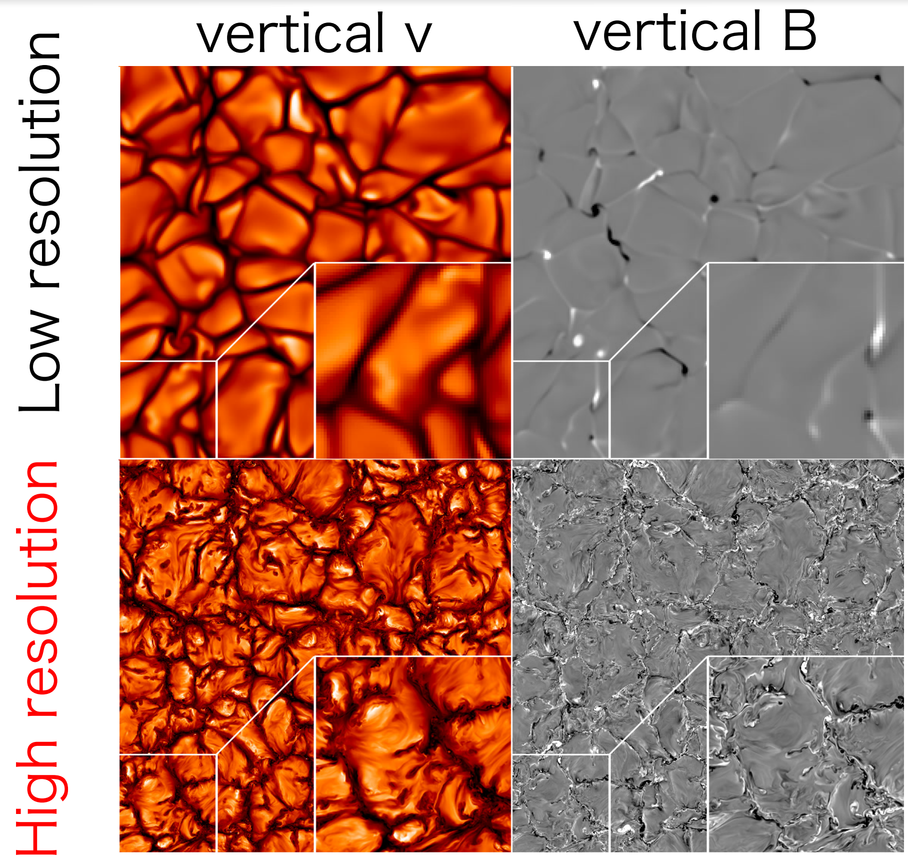


(Nelson+2014)

In small-scale dynamos, stretching is the essential process and the smallest scale has largest linear growth rate.
How can the sun maintain the large-scale field with very small viscosity($O(1\ \mathrm{cm^2\ s^{-1}})$) and magnetic diffusivity($\sim O(10^4\ \mathrm{cm^2\ s^{-1}})$)?

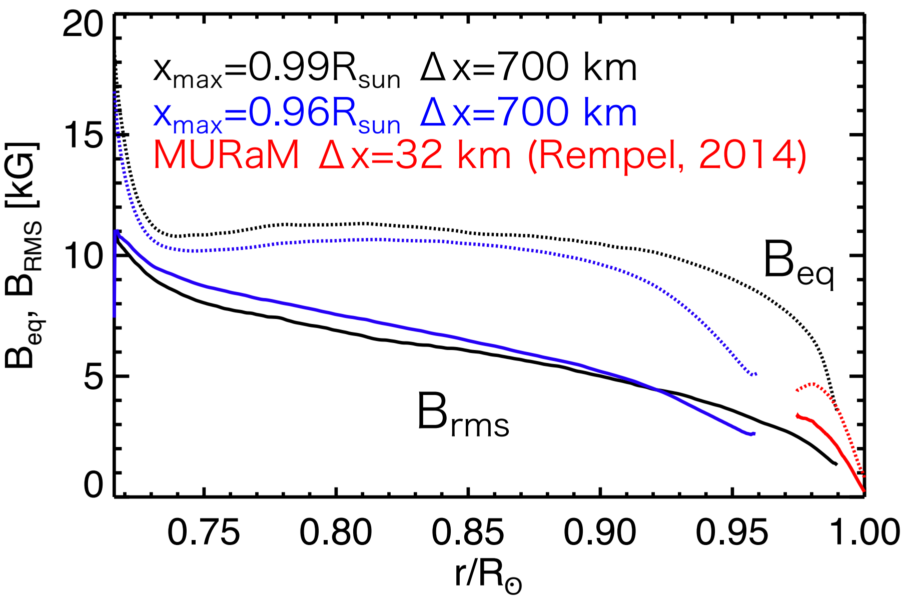
Magnetic energy/Kinetic energy

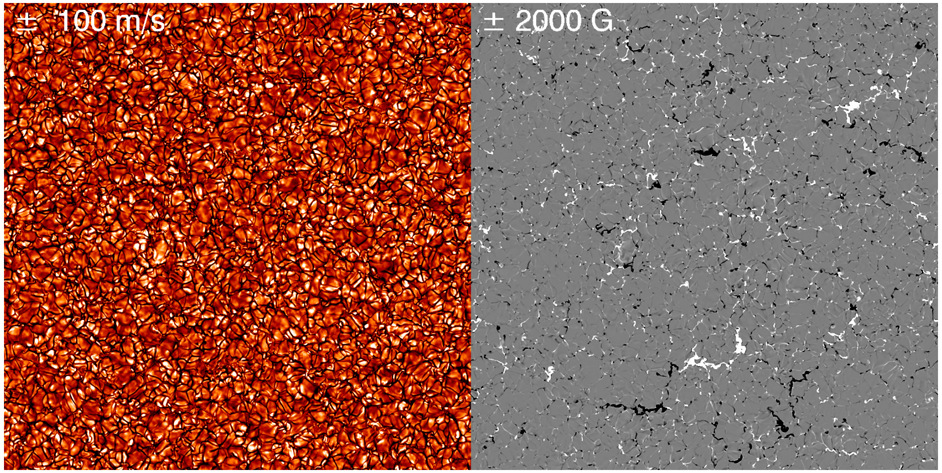




The magnetic energy reaches more than 90% ($0.95B_{eq}$) of kinetic energy at the convection zone in High resolution, while low resolution achieved in other studies can maintain 5% of kinetic energy.

Comparison with MURaM





V_x and B_x from x_{max}=0.99R_{sun}

MURaM calculation is nicely consistent with the solar observation (e.g., *Hinode*). At the bottom of MuRAM calculation (x=0.97R_{sun}), B_{rms}=3300 G(MuRAM) and 2500 G(Ours). Although our calculation can be influenced by lower top boundary and resolution. The agreement is good, i.e., we can assume solar convection zone filled with SSD!

Summary of introduction

In global calculations, higher resolution tends to show lower energy of mean (global scale) magnetic field. Small-scale dynamo should be suppressed.

Photospheric magnetic field requires efficient (almost equipartition) small-scale dynamo deep in the convection zone in order to be consistent with the solar obsevation.

Large-scale dynamo

Theoretically (in numerical calculation), they cannot coexist.
Both are necessary to explain observations.

Small-scale dynamo

New method for increasing resolution

$$\nabla \cdot (\rho_0 \mathbf{v}) = 0 \longleftrightarrow \rho = \rho_0 + \rho$$

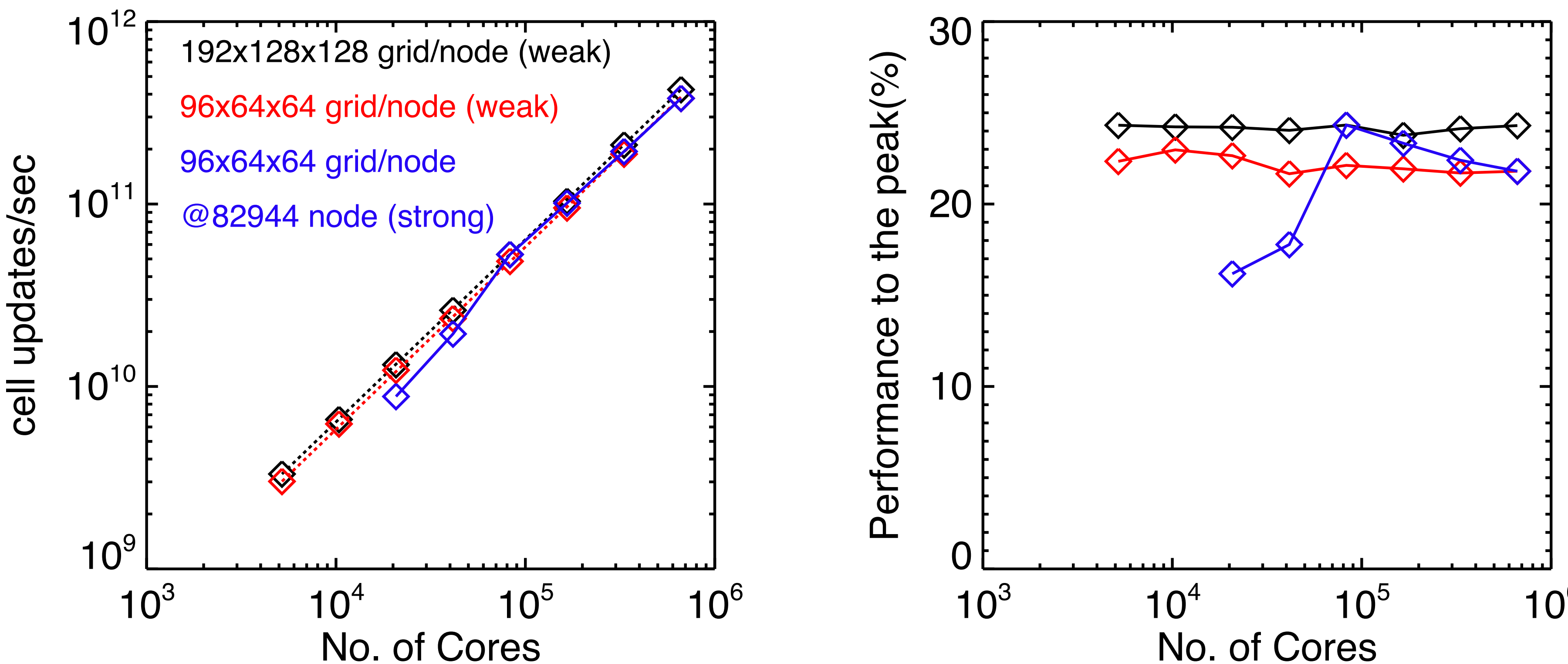
$$\longrightarrow \quad \frac{\partial \rho_1}{\partial t} = -\frac{1}{\xi^2} \nabla \cdot (\rho \mathbf{v})$$

In order to avoid severe constraint by fast sound wave in the solar convection zone, the anelastic approximation (infinite speed of sound), is broadly used. But, frequent global communications in parallel computer is needed and scaling is limited.

We develop reduced speed of sound technique (RSST), in which the speed of sound is reduced (moderate speed of sound and easily scales in massive super computer.)

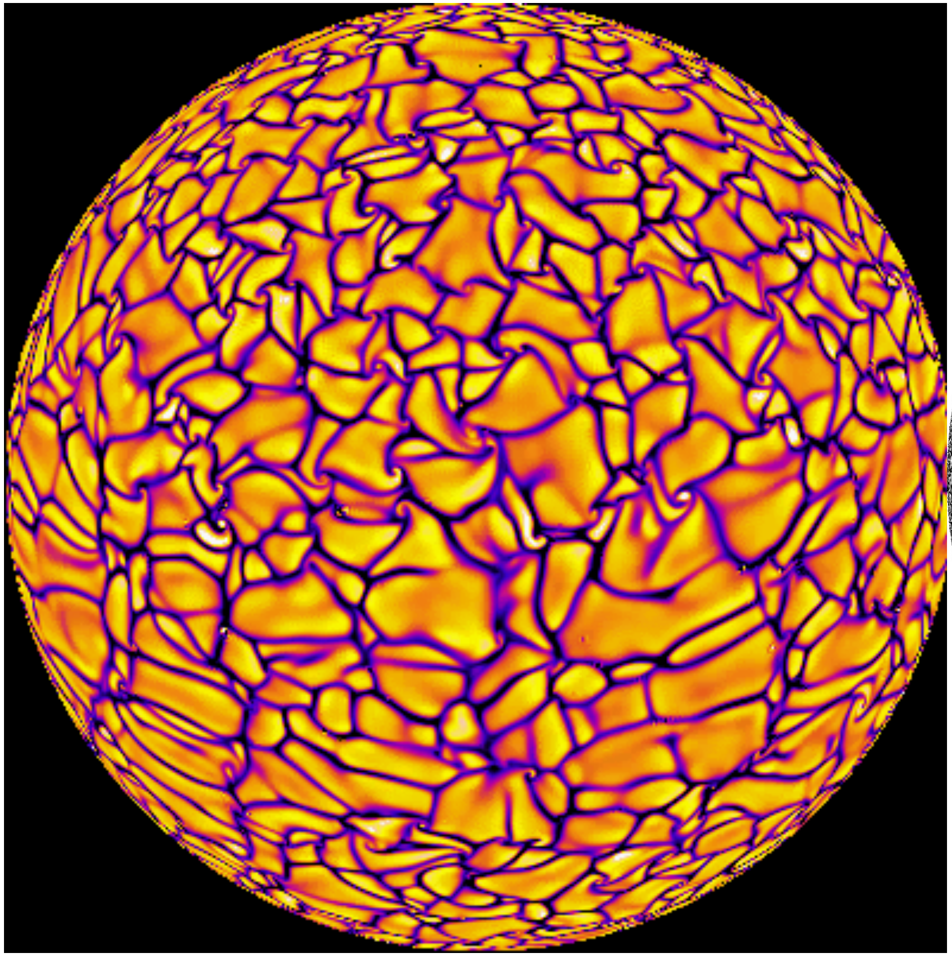
The validity is confirmed in Hotta+2012 (see also Hotta+2015)

Achievement

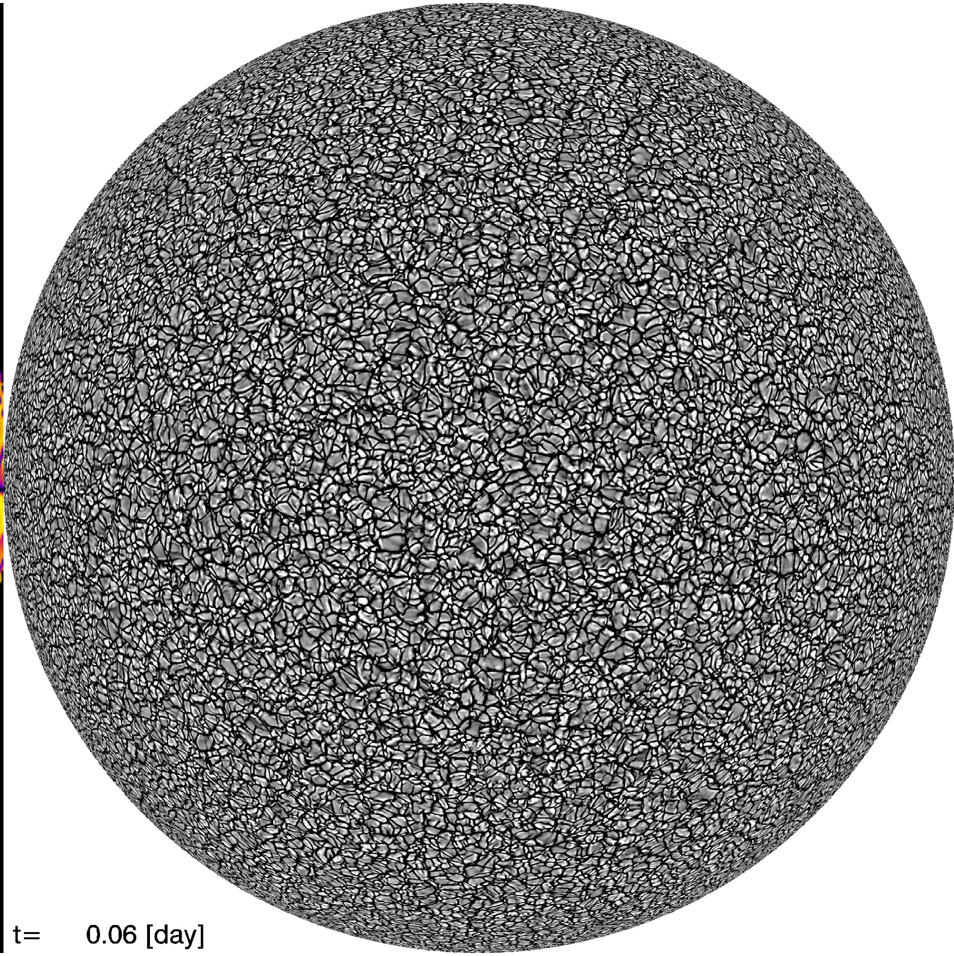


Our code is super efficient. Scales up to 663,552 core (full K-computer) and shows about 24% efficiency to the theoretical peak!

Achievement



Miesch+2008



Hotta+2014

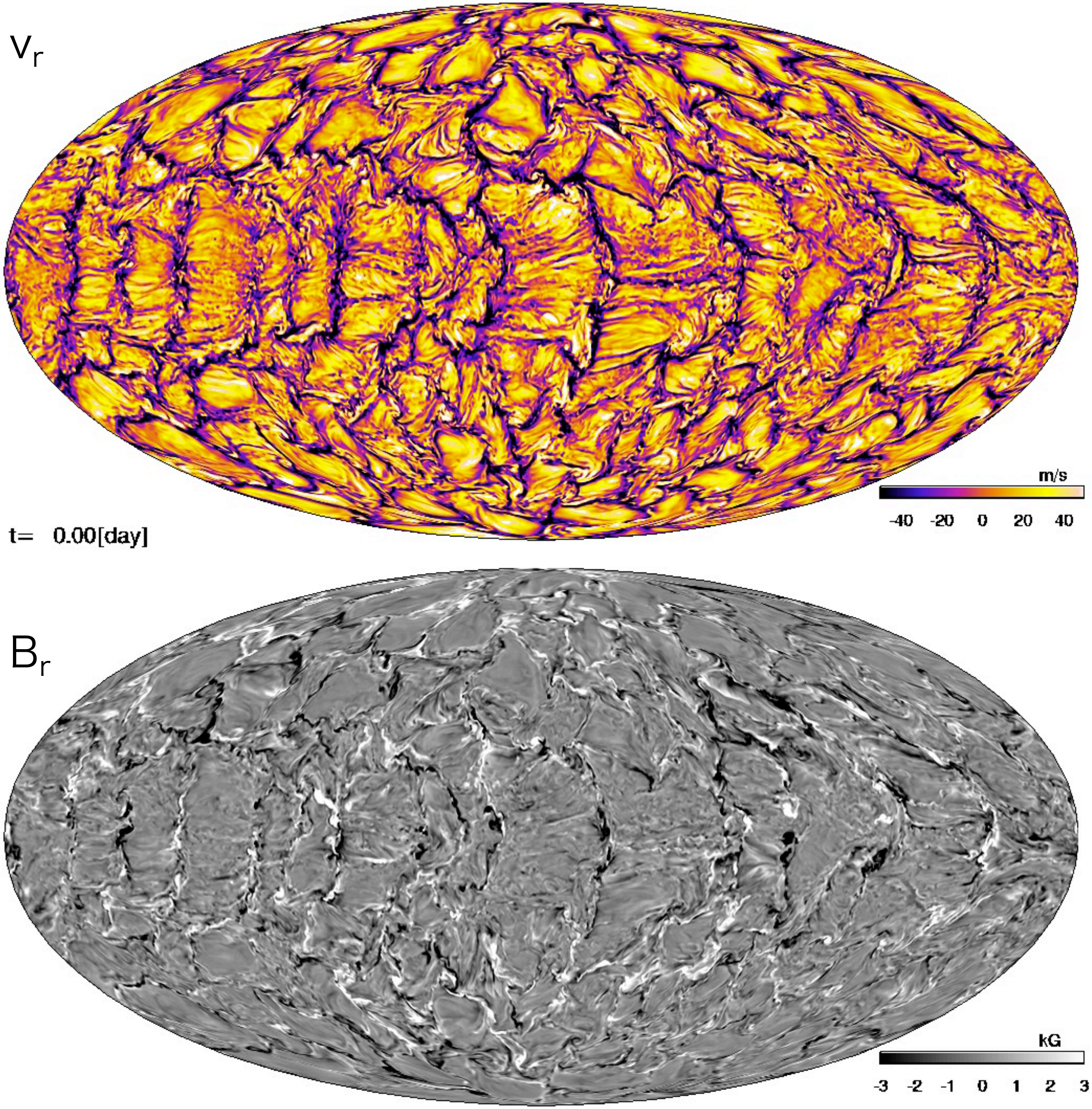
Further high resolution

We check if the tendency that the high-resolution kills large-scale magnetic field continues even in extremely high resolutions? Do we miss some important physics?

Low diffusivity ↓

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 100 G antisymmetric toroidal magnetic field and very small perturbation on entropy. Then calculate 50 years.
The case name "D" has explicit viscosity and magnetic diffusivity, without "D", only numerical diffusivity exists.



京
K computer

Resolution comparison

Low diffusivity

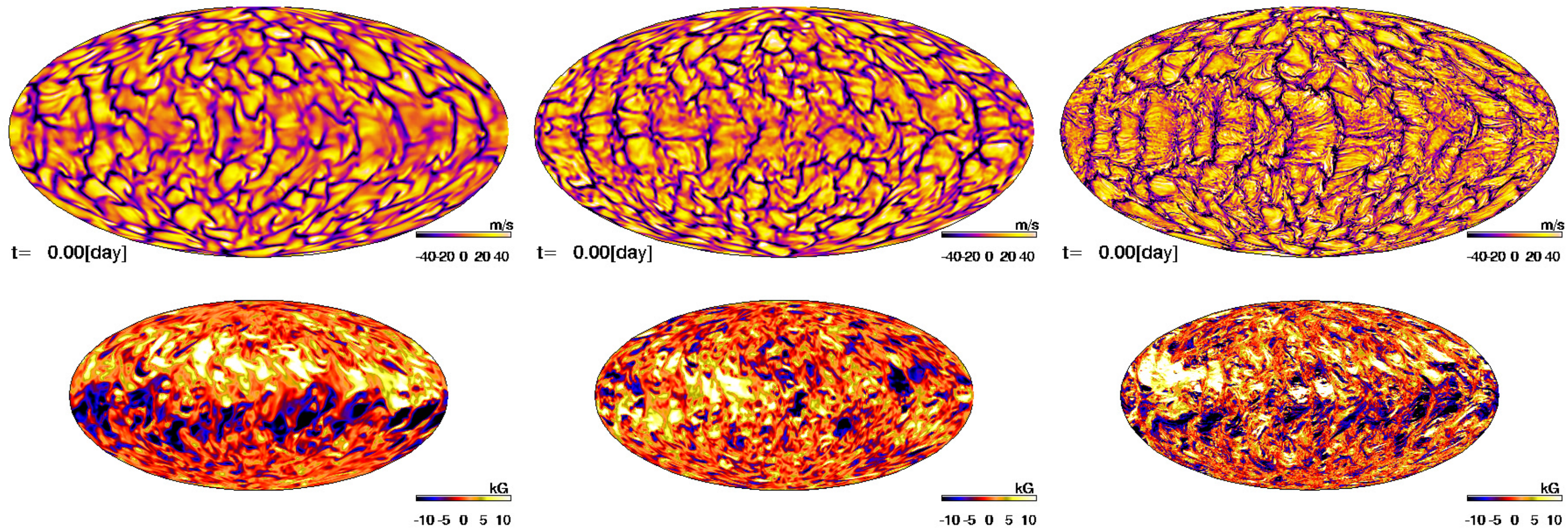
Low_D $\nu = \kappa = 1\times10^{12}$ cm^2 s^{-1}

Medium 64x192x384

High 256x768x1536

v_r at 0.95R

B_ϕ at 0.72R



Coherent magnetic field is generated in Low_D (Fan+2014). When effective resolution is increased (Medium), large-scale magnetic field seems disappeared. In further high resolution (High), the large-scale magnetic field seems generated again. We need to see butterfly diagram to check the tendency properly.

Large-scale magnetic field and cycle

<E_{mag}>: mean magnetic energy

<B_ϕ> at $r=0.72R_{sun}$

Less diffusive

Low_D

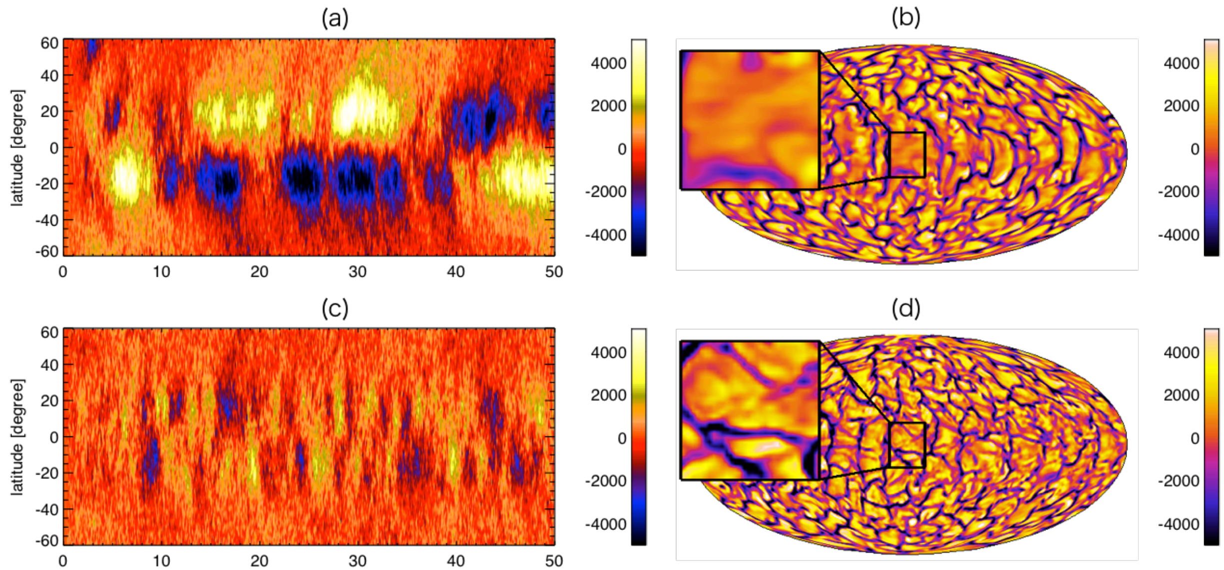
$\nu=\eta=1\times10^{12}$ cm^2 s^{-1}

<E_{mag}>=2.9×10^4 erg cm^{-3}

Medium

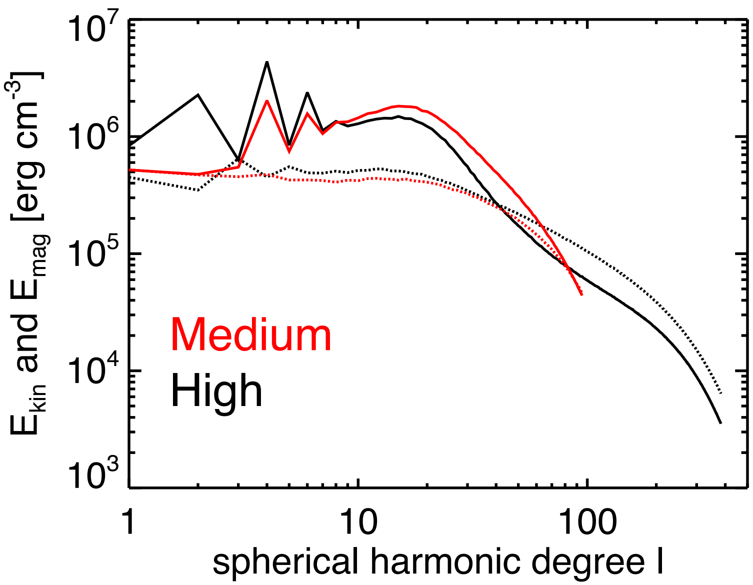
64x192x384

<E_{mag}>=1.3×10^4 erg cm^{-3}



In the highest resolution, coherent large-scale magnetic field is generated even in high Reynolds numbers.

Why high resolution creates large-scale?



Solid : Kinetic energy
Dotted : Magnetic energy

In the highest resolution, the small-scale dynamo is very efficient and small-scale magnetic energy exceeds small-scale kinetic energy.

As a result, the Lorentz force suppresses the small-scale turbulent motion which originally destroyed large-scale feature.

Therefore, the large-scale magnetic field can be maintained even in high resolutions.

Summary

Previous calculations indicate that high resolution, i.e., low diffusivities, reduces the large-scale magnetic energy. (Nelson+2013)

In these calculations small-scale Lorentz feedback is not effective, due to low resolution.

3D high-resolution MHD calculation shows **a recovery of large-scale magnetic field, with suppressing the small-scale turbulence by small-scale Lorentz feedback.**