# Current status of understanding about solar global convection

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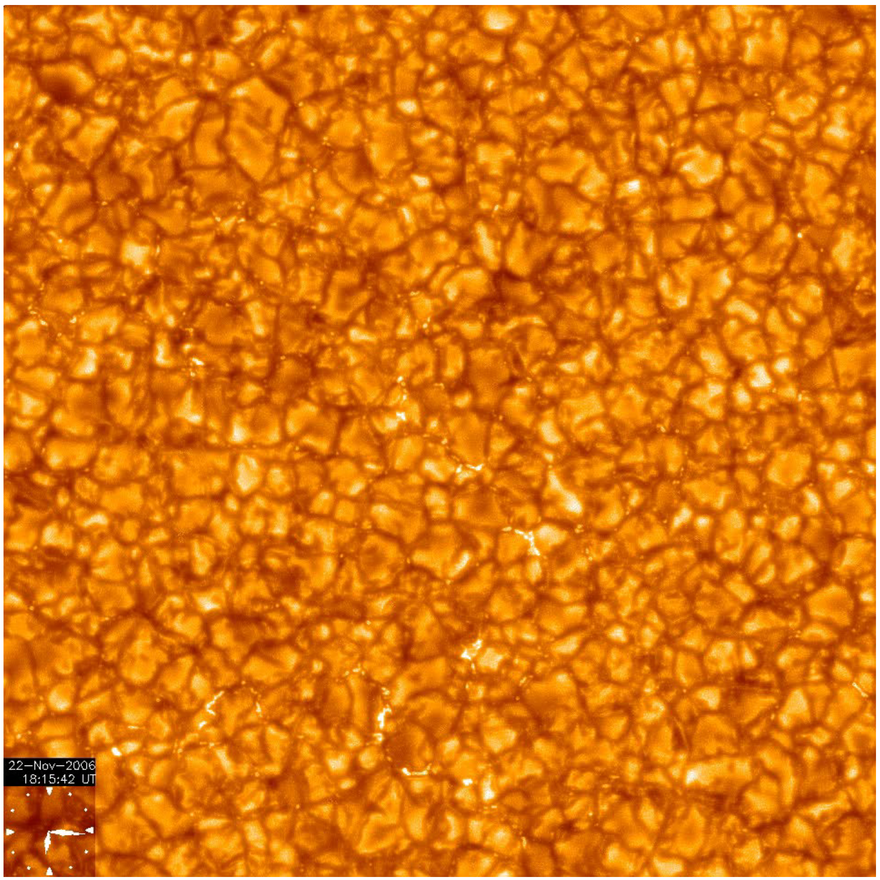
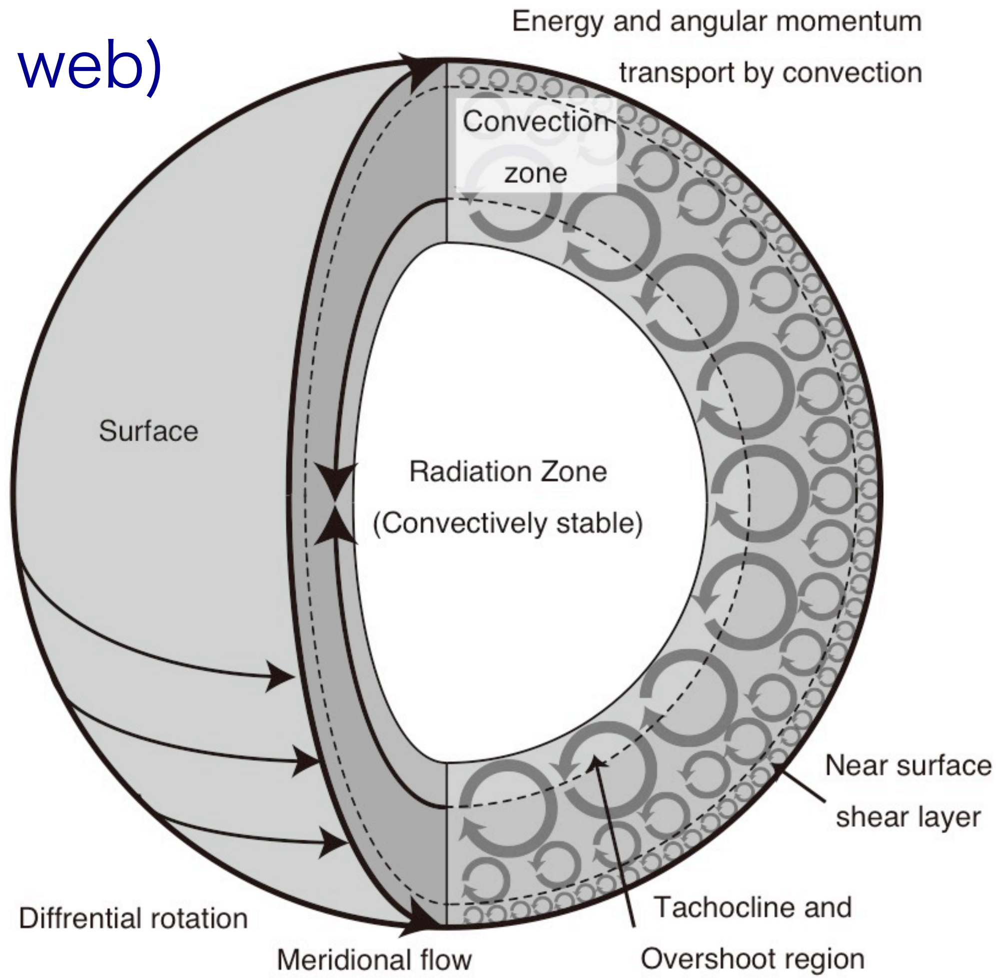
# Solar convection

## Hinode/SOT(Okamoto-san's web)



# Why is the convection important?

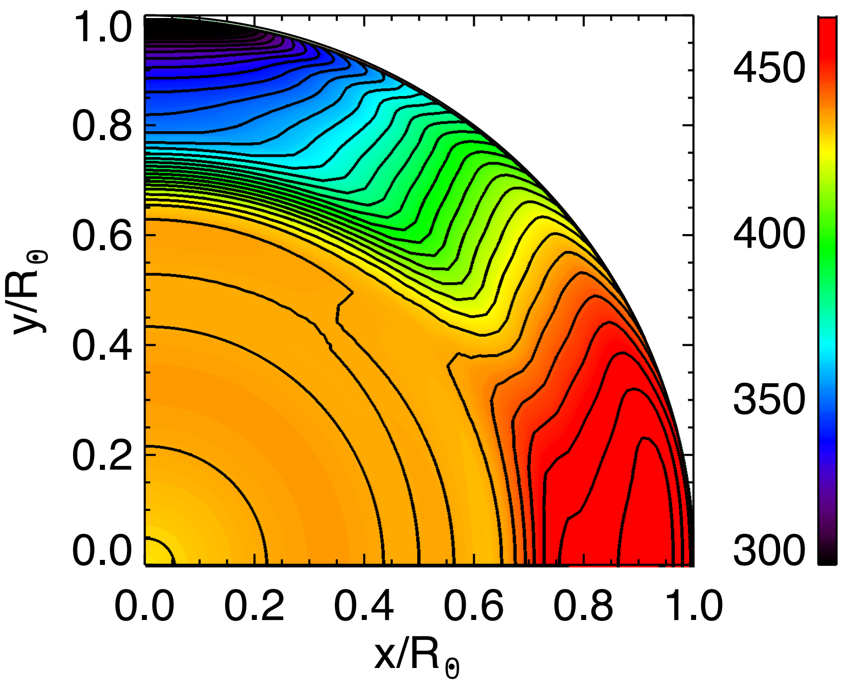
The convection transports:
energy → the stratification
angular momentum → the mean field
(differential rotation and meridional flow)

The mean flows are important for the magnetic field:
differential rotation → generation (Ω-effect)
meridional flow → transport (flux transport dynamo)

The detailed characters of the thermal convection in the sun should be understood.

# Observation

Helioseismology
SDO/HMI inversion




Courtesy of R. Howe

Interesting features:

1. Equator is accelerated
2. Conical profile
3. Tachocline
4. Near surface shear layer

The angular momentum transport and the dynamical balance must be understood

The previous studies revealed mechanisms for 1, 2, and 3.

# Accelerated equator (1/2)

Angular momentum transport $\mathcal{L} = r \sin\theta v_\phi + r^2 \sin^2\theta \Omega_0$

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

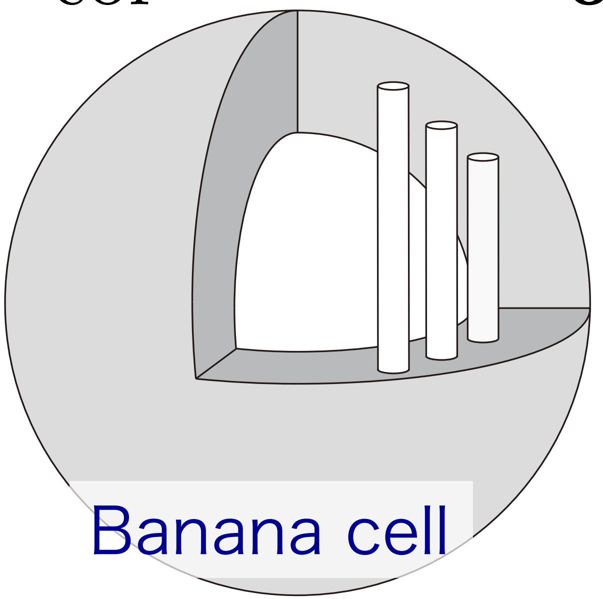
mean angular momentum transport by mean field

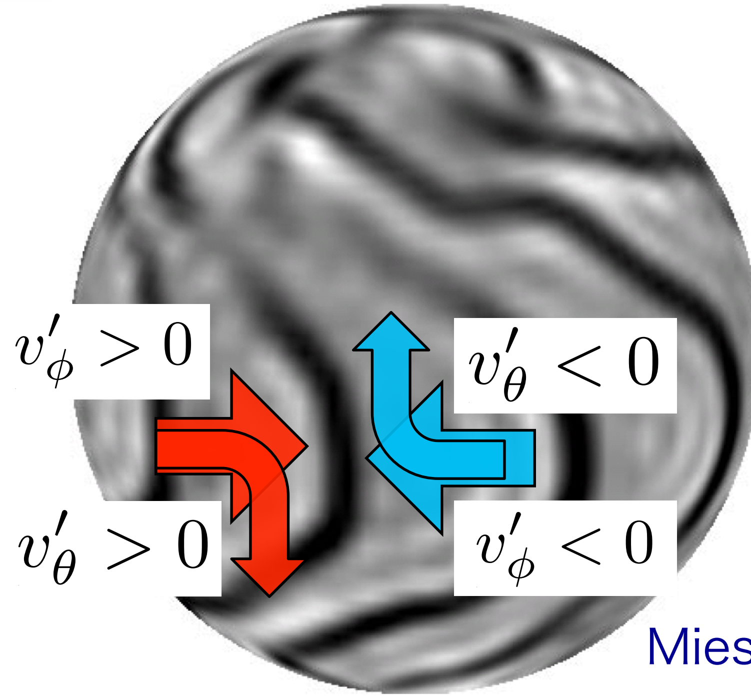
Reynolds stress from turbulent field

When we compute the turbulent thermal convection, the distribution of the Reynolds stress is revealed.

# Accelerated equator (2/2)

$$\mathbf{F}_{\mathrm{cor}} \propto \mathbf{v} \times \mathbf{\Omega_0}$$




Miesch+2000

$$\langle v'_\lambda v'_\phi \rangle > 0$$

$$\Rightarrow \langle v'_r v'_\phi \rangle > 0$$

$$\langle v'_\theta v'_\phi \rangle > 0$$

Angular momentum is transported equatorward by the Reynolds stress

(Gilman+1976,1977,1988, Miesch+2000, 2005, Brun+2002, Käpylä+2011, Gastine+2012)

# Conical profile and tachocline (1/3)

## Dynamical balance on the meridional plane

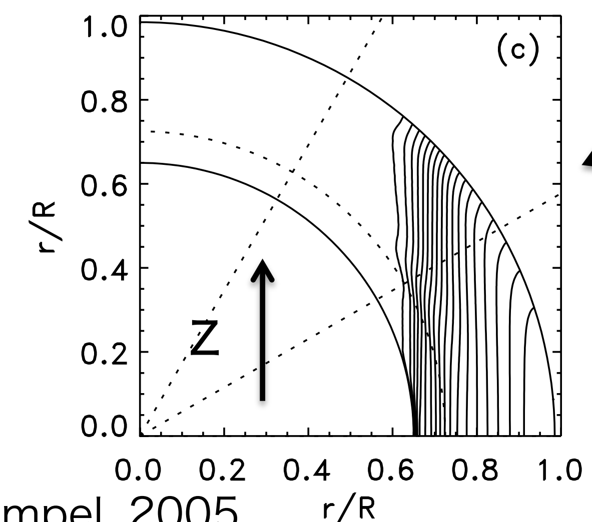
$$\frac{\partial\langle\omega_\phi\rangle}{\partial t} = [\langle\nabla\times(\mathbf{v}\times\omega)\rangle]_\phi + 2r\sin\theta\Omega_0\frac{\partial\langle\Omega_1\rangle}{\partial z} + \frac{g}{\rho_0 r}\left(\frac{\partial\rho}{\partial s}\right)_p\frac{\partial\langle s_1\rangle}{\partial\theta}$$

Steady state

Advection term can be ignored

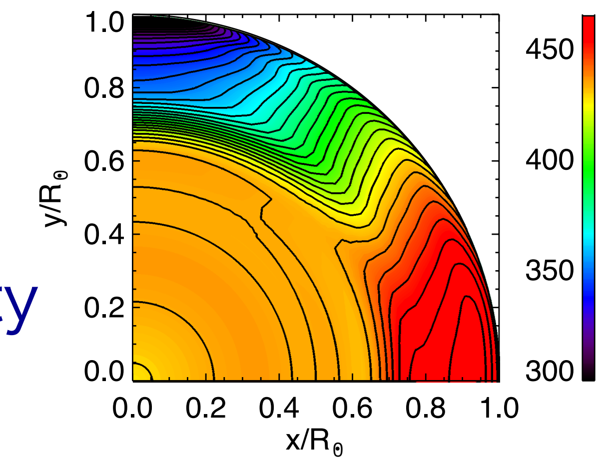
Adiabatic atmosphere

$$\frac{\partial\langle\Omega_1\rangle}{\partial z} = 0$$




Rempel, 2005

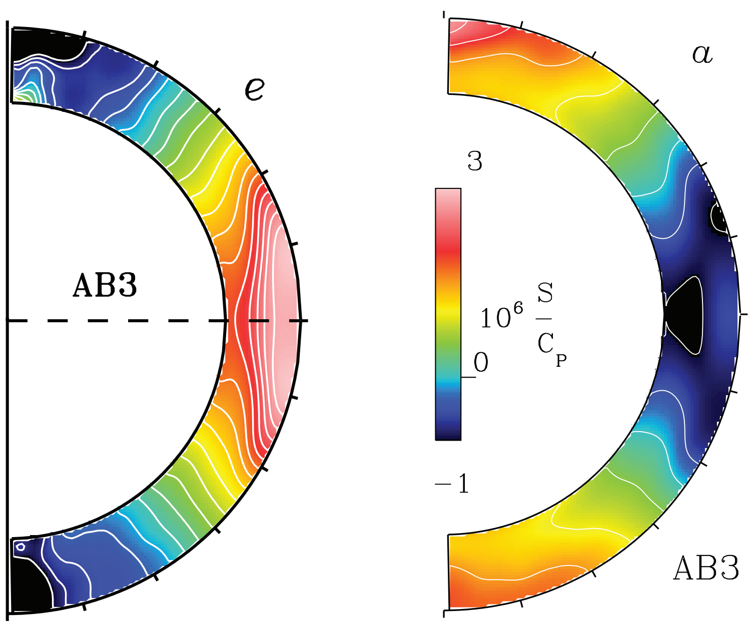
In this situation the angular velocity does not change along the z-axis



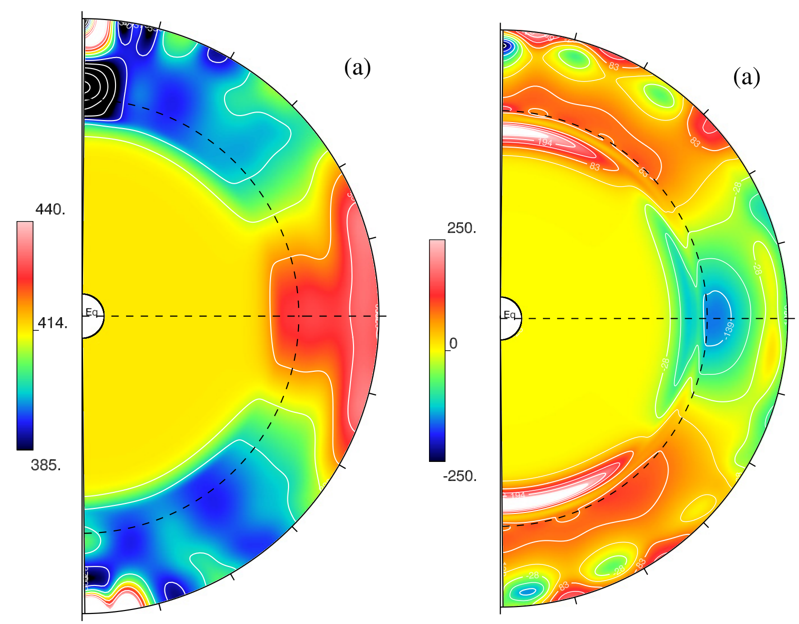
# Conical profile and tachocline (2/3)

The entropy gradient has significant role on this issue

$$-2r\sin\theta\frac{\partial\langle\Omega_1\rangle}{\partial z}\sim\frac{g}{\rho_0 r}\left(\frac{\partial\rho}{\partial s}\right)_p\frac{\partial\langle s_1\rangle}{\partial\theta}$$



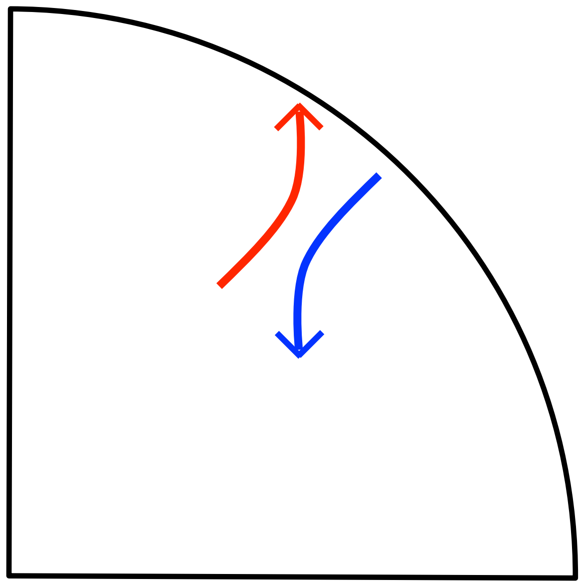

Miesch+2006




Brun+2011

# Conical profile and tachocline (3/3)

(1)



Thermal convection

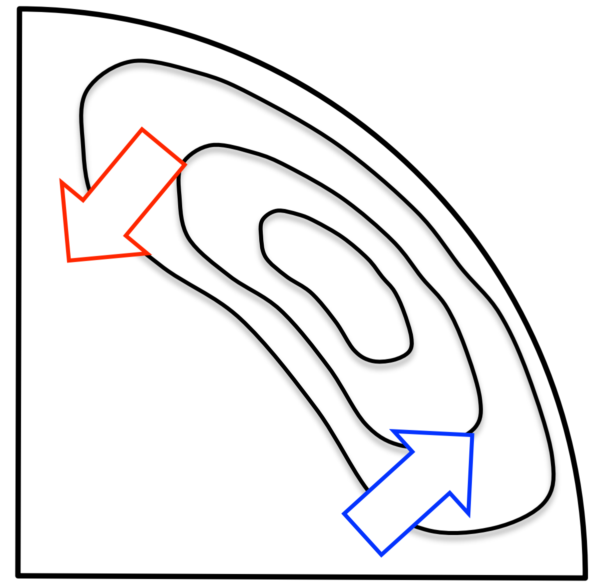
$$\langle v'_r s'_1 \rangle > 0$$

Coriolis force

$$\langle v'_r v'_\theta \rangle < 0$$

$$\rightarrow \boxed{\langle v'_\theta s'_1 \rangle < 0}$$

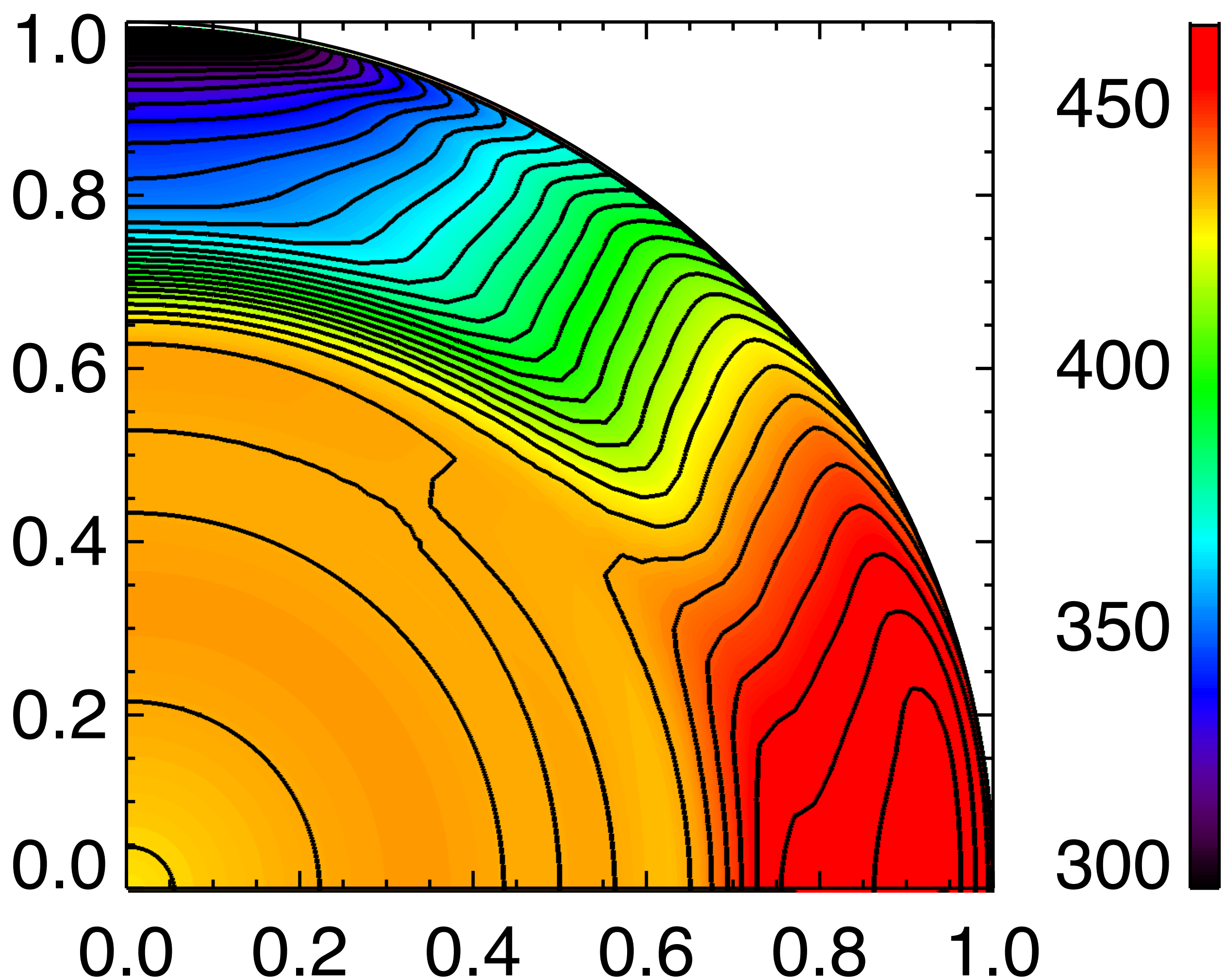
(2)



Effect of meridional flow and the subadiabatic radiative zone. (Rempel+2005)

# Our new challenge for near surface shear layer

What is required for understanding of near surface shear layer?



# Near surface shear layer (NSSL)

In the near surface shear layer, the Rossby number is high (>10), i.e., the rotation effect is very ineffective.

This means the generation mechanism for the entropy gradient is probably ineffective.

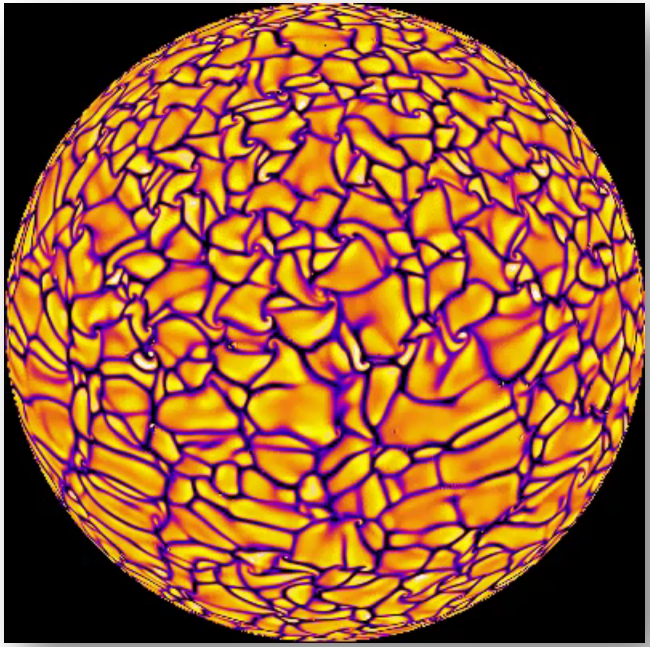
The possible key point is the small spatial and short time scale convection in the near surface shear layer.

High resolution calculation including near surface layer ($>0.98R_{sun}$) is probably required (covering both small and large scale convection).

# Anelastic approximation

In order to avoid short time step ($\Delta t$) owing to the high speed of sound the anelastic approximation is frequently adopted,

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



Miesch 2005

but the approximation has problems:

1. Elliptic equation exists. ASH solves it using spherical harmonics which costs much in the higher resolution.
2. The anelastic approximation is not valid in the near surface shear layer.

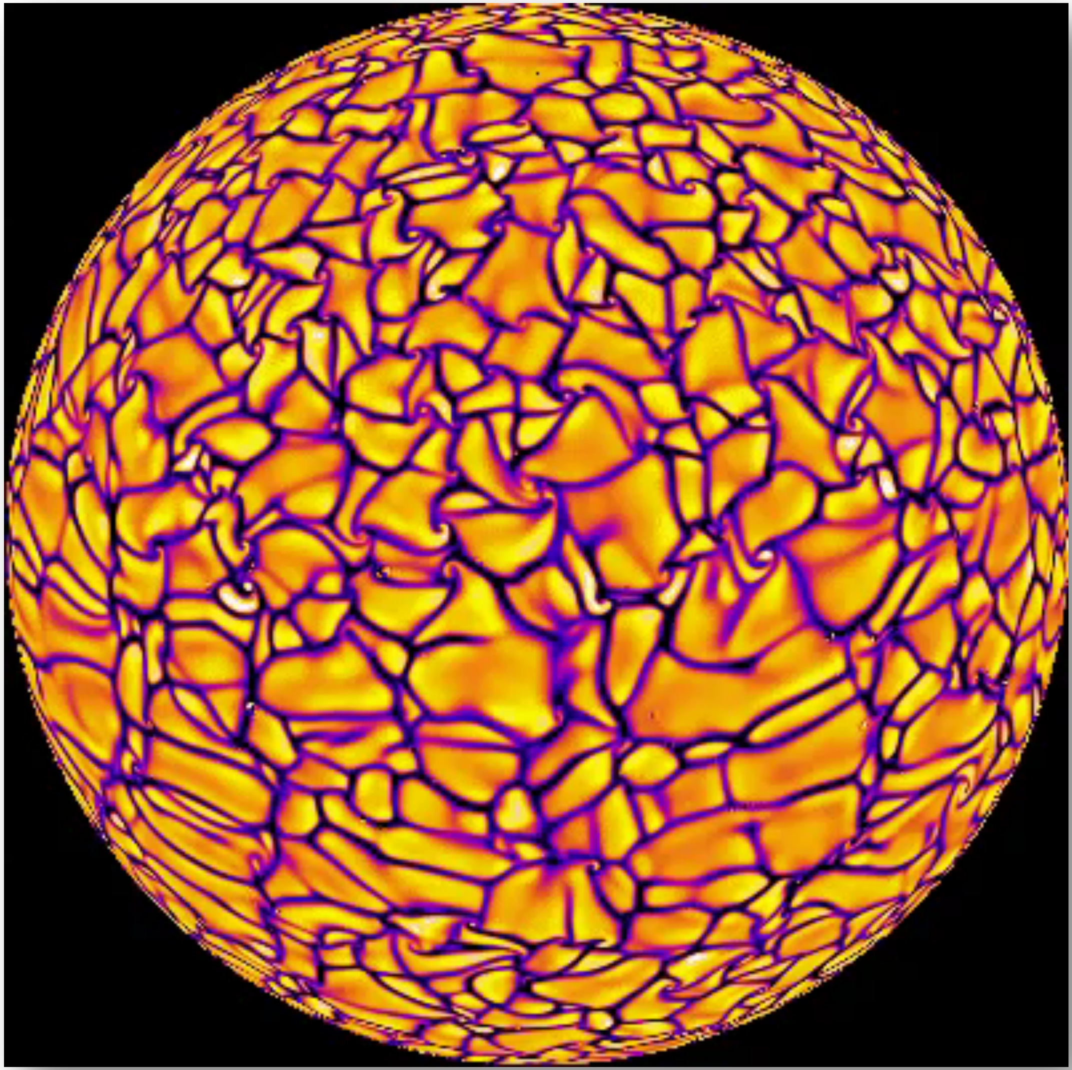
Other method is required for NSSL

# Reduced Speed of Sound Technique

$$\frac{\partial \rho}{\partial t} = -\frac{1}{\xi^2}\nabla \cdot (\rho_0 \mathbf{v})$$

Applying this transformation to equation of continuity, effective speed of sound is reduced by $\xi$ times.
No need to solve elliptic equation.
An simple algorithm and good scaling in parallel computing is expected.
We have checked the validity of this method.
(Hotta et al., 2012, A&A, 539, A30 for details)
We can reach near surface layer with inhomogeneous $\xi$

# Result of RSST



# Result of RSST

Performance

Scale to $10^5$ cores

14% to peak in K

Resolution

384x1296x2592

Domain

$0.715 < r/R_{sun} < 0.99$

in all the sphere

Parameters

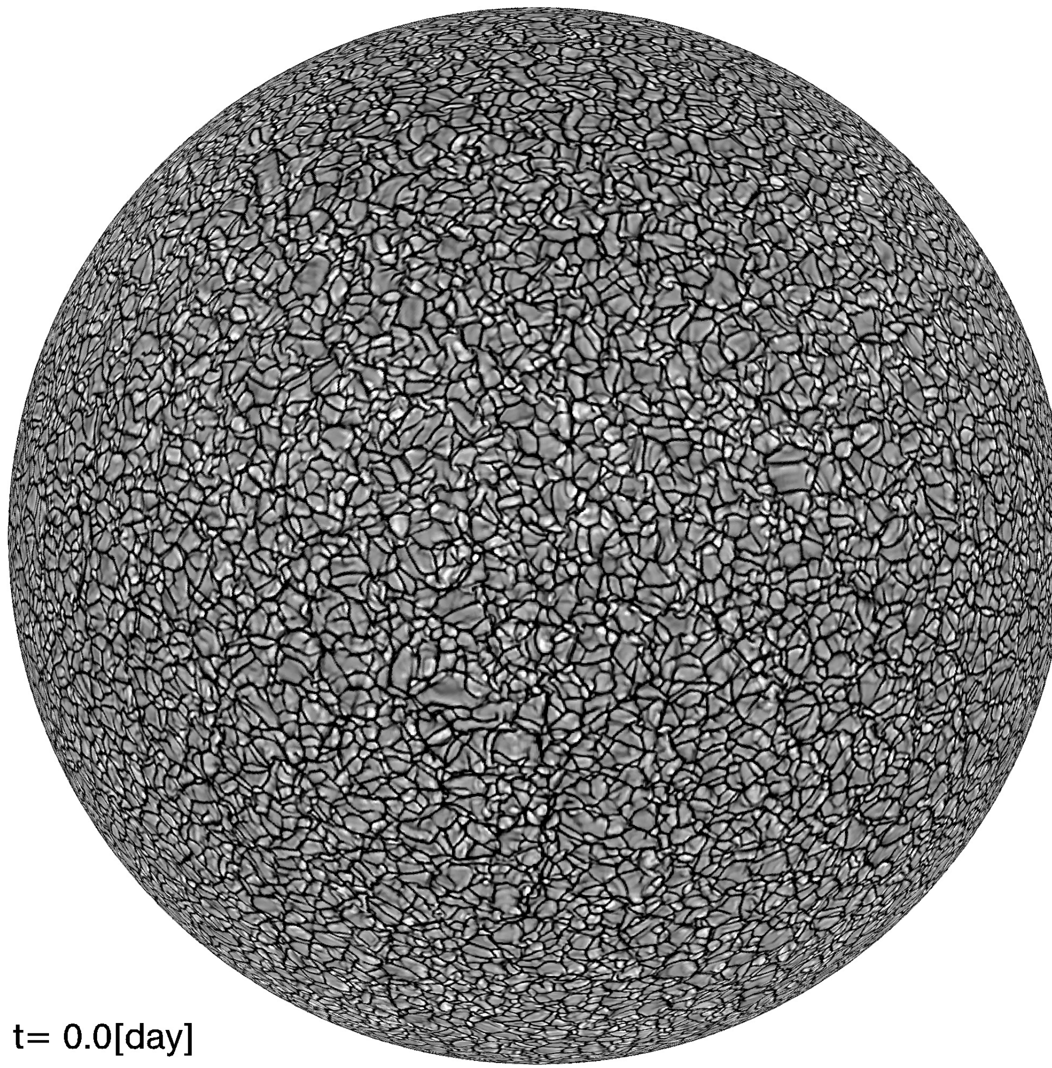
$\Omega_0/2\pi = 413$ nHz

(solar rotation)

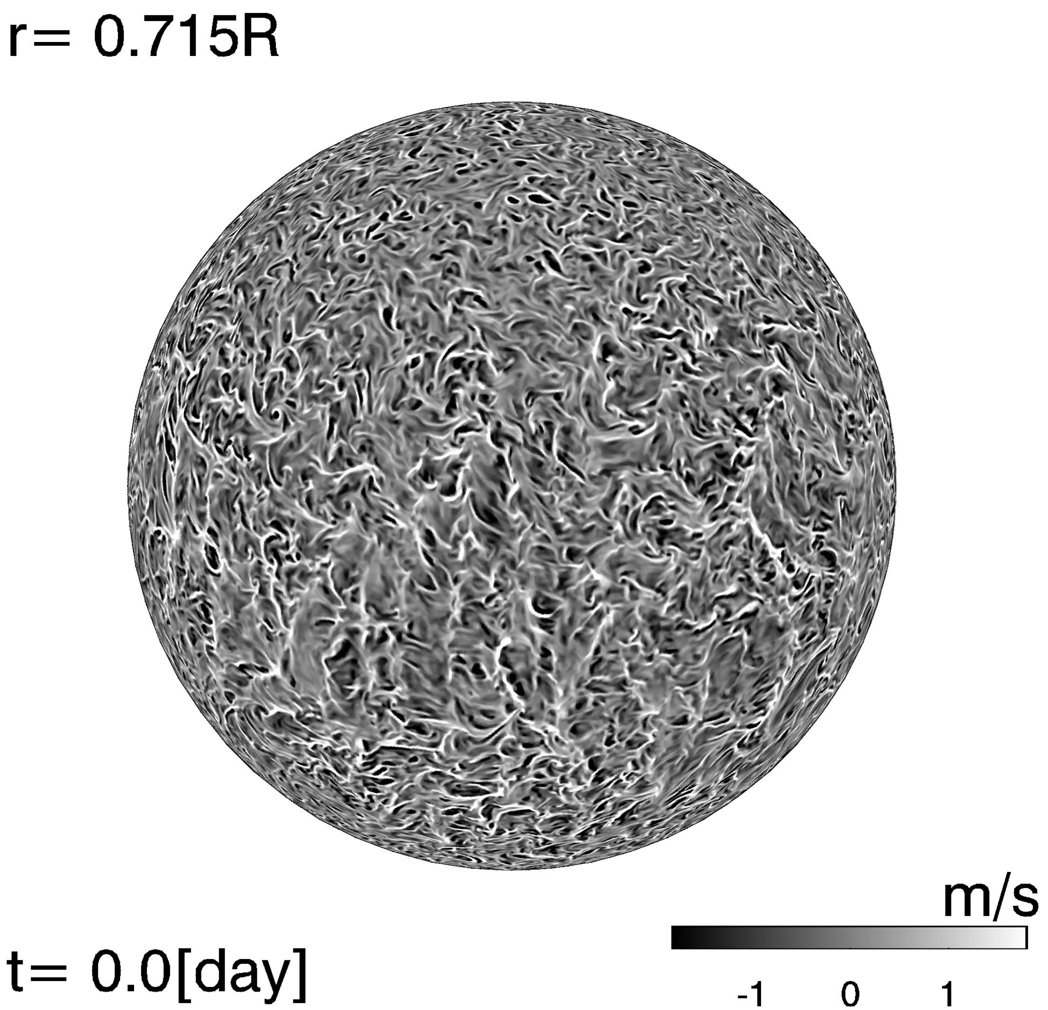
Features

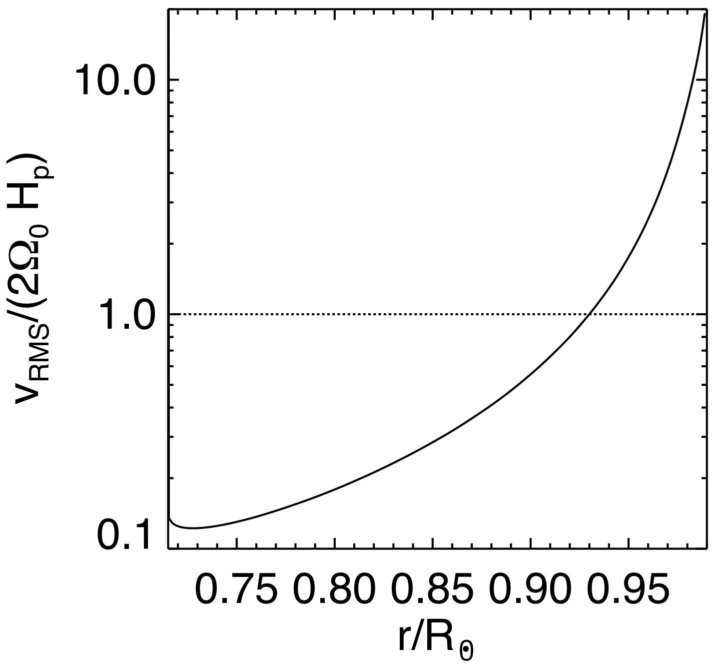
Yin-Yang grid

Realistic EOS



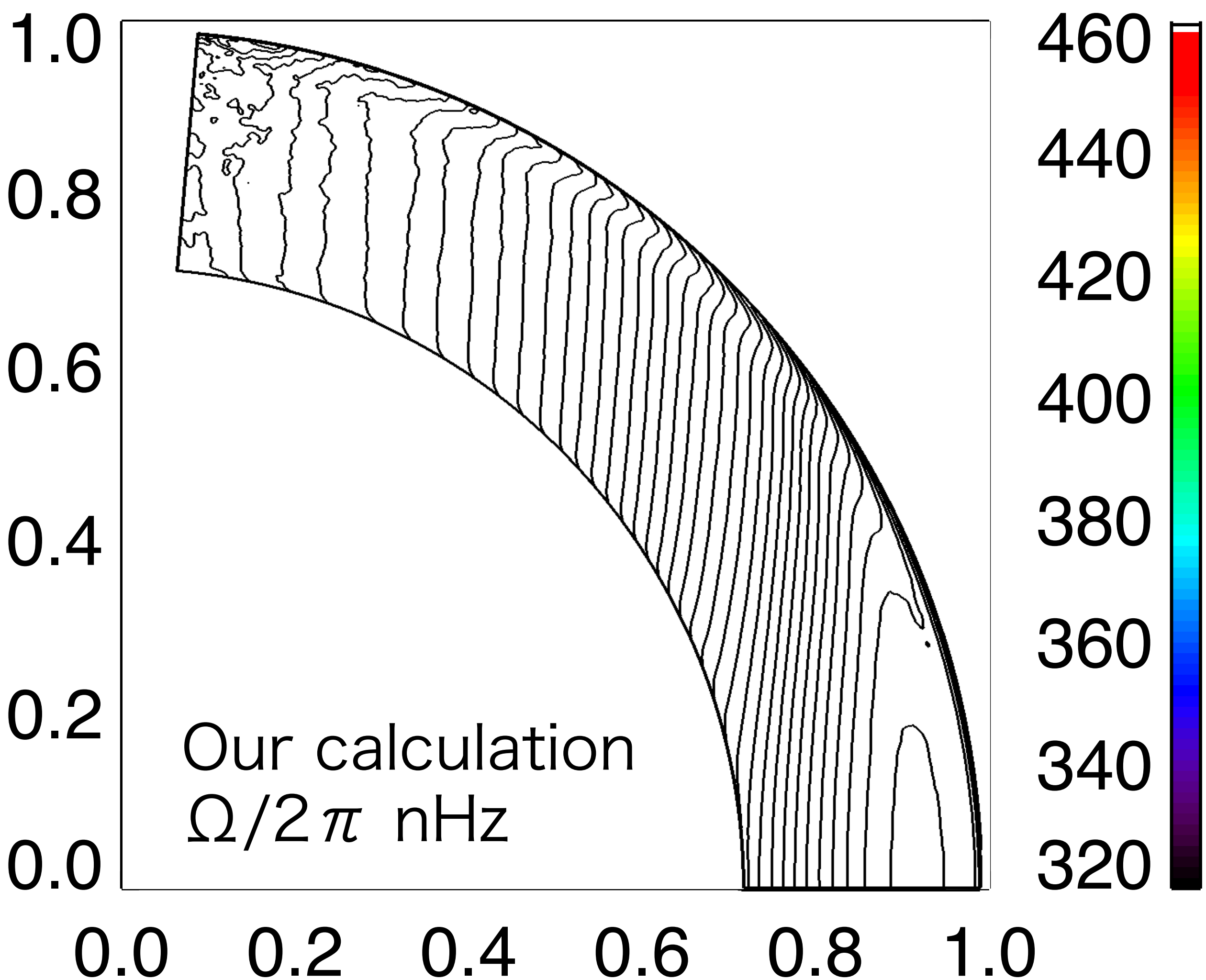
# Dependence of Rossby number on depth

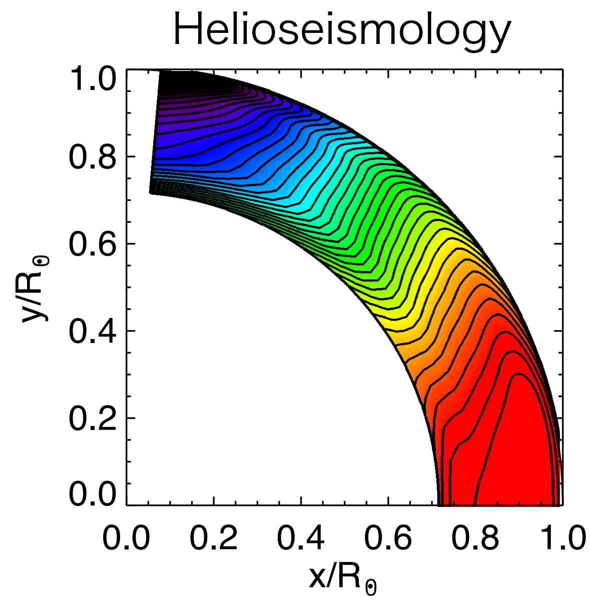



The requirement for NSSL is satisfied.

# Differential rotation




NSSL is established by the small scale convection in the near surface layer.

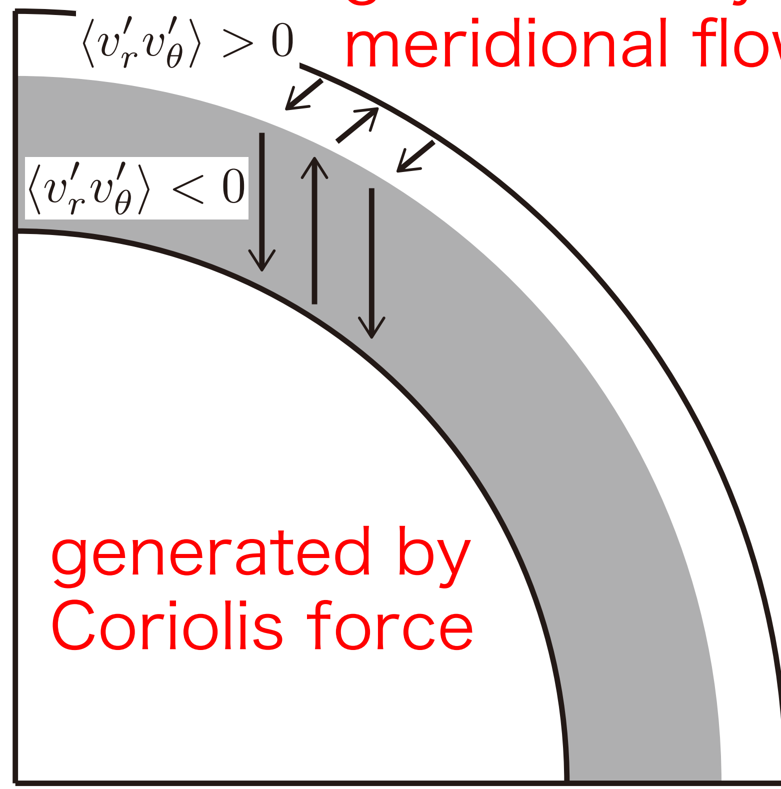
Entropy gradient is not well established

# Mechanism for NSSL

$$-2r\sin\theta\frac{\partial\langle\Omega_1\rangle}{\partial z}\sim[\nabla\times(\mathbf{v}'\times\omega')]_\phi$$

Near surface shear layer is maintained by the Reynolds stress.

In the NSSL the Coriolis force is ineffective, and the meridional flow has significant role.




generated by meridional flow

generated by Coriolis force

$$\frac{\partial v_\theta'}{\partial t}=[\dots]-v_r'\frac{\partial\langle v_\theta\rangle}{\partial r}-2v_r'\tau\Omega_0^2\sin(2\theta)$$

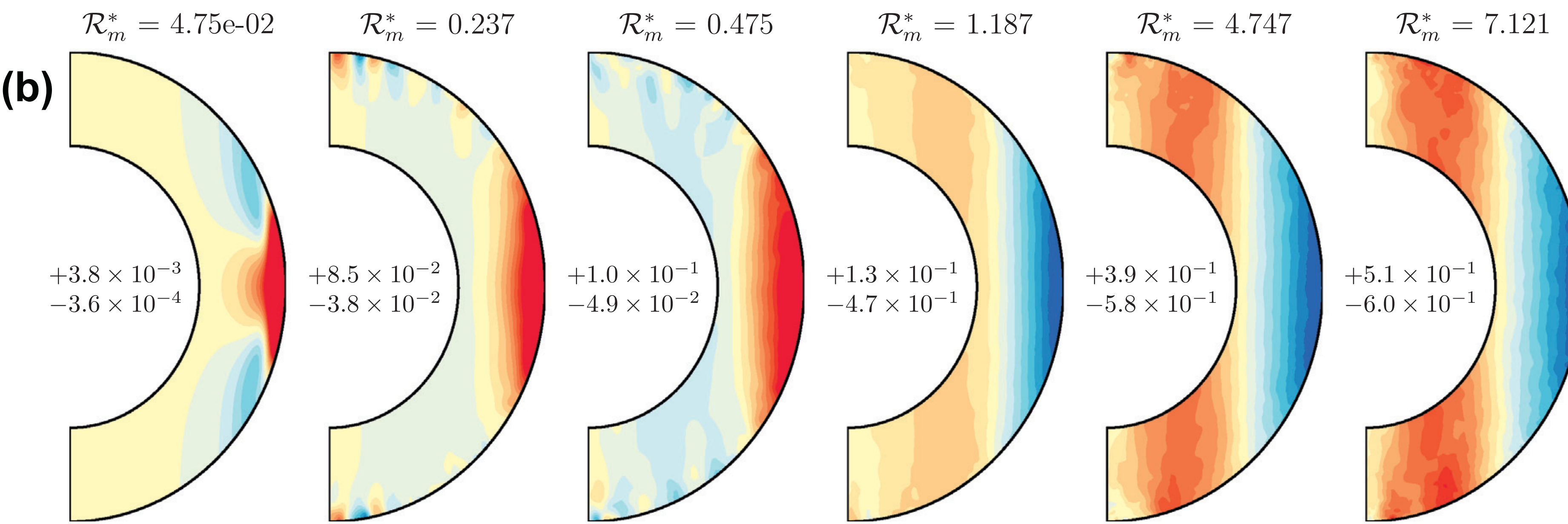
# Remaining problem

# Is solar global convection well understood?

| | |
|---|---|
| Equator acceleration | ○(Gilman+1976, Miesch+2000) |
| Conical profile | ○(Rempel+2005, Miesch+2006) |
| Tachocline | ○(Brun+2011) |
| Near surface shear layer | ○ Today's talk |

However,
There remains a fundamental problem of
accelerated pole (Featherstone+2013, in prep)

# Accelerated pole (1/2)




Fast rotation
Slow convection

Slow rotation
Fast convection

Current sun

Gastine+2013

# Accelerated pole (2/2)

The problem is that, when we adopt solar parameter:

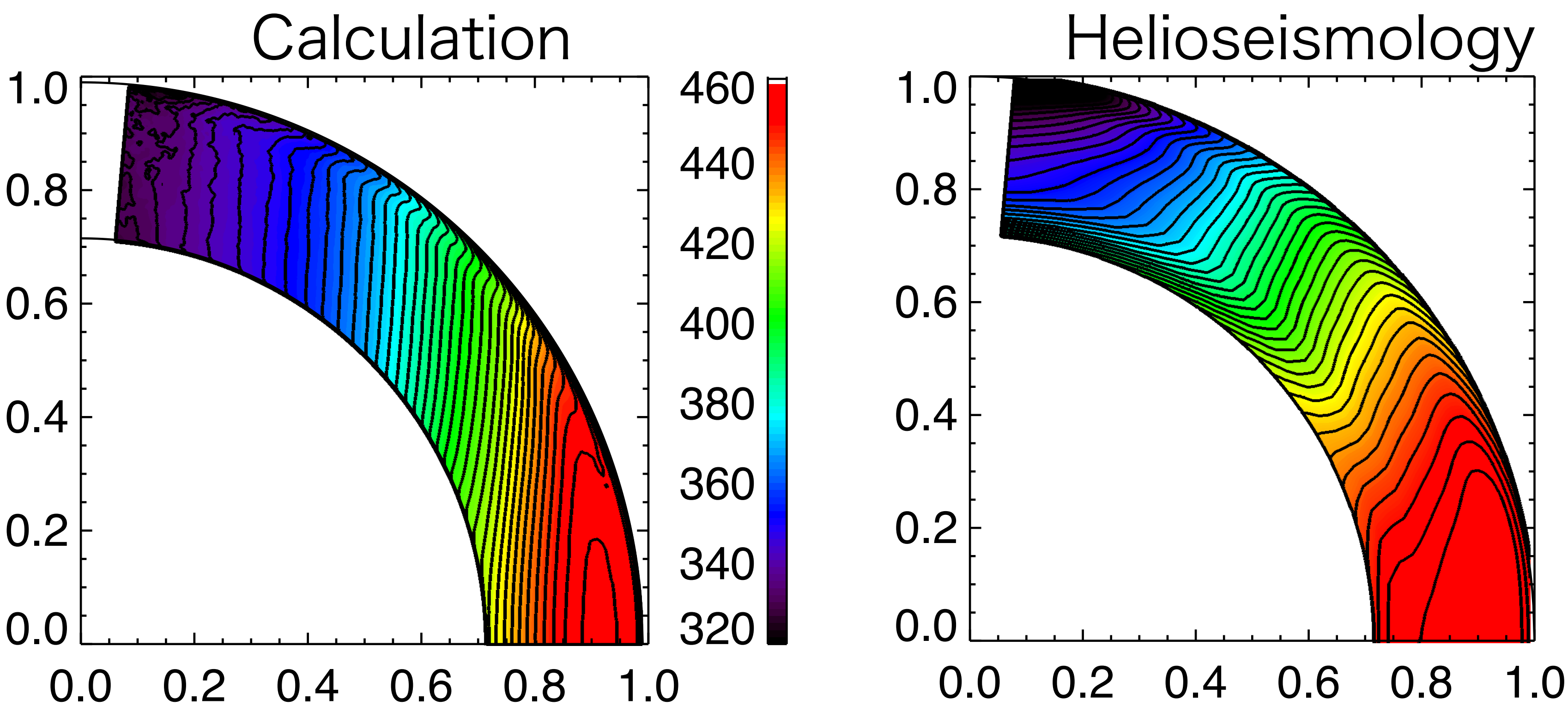
1. Solar rotation (413 nHz)
2. Solar luminosity ($3.84\times10^{33}$ erg $s^{-1}$)
3. Solar stratification (density, pressure, temperature...)

in high resolution, i.e., small viscosity and diffusivity,
**the polar region is accelerated.**
(Featherstone and Miesch, 2013, Fan+2013)

This means that when we adopt solar parameter,
the reproduced convection velocity is too high, i.e.,
too small Rossby number.
→What did we do to reproduce solar differential rotation?

# Energy flux is reduced

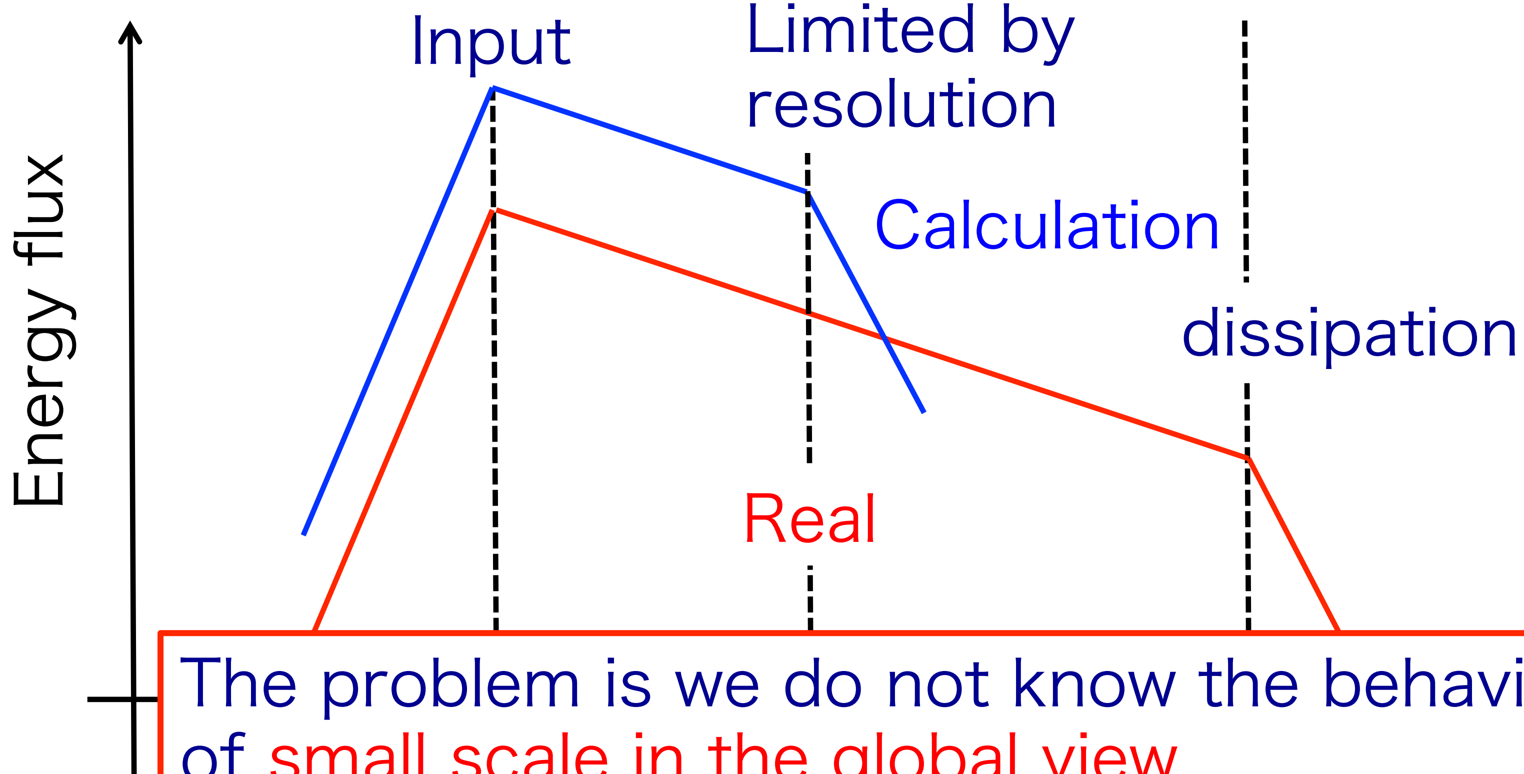
Our solar luminosity is 1/18 of solar one.
The convection velocity is reduced accordingly.




Interestingly the solar differential rotation is reproduced

# Small scale convection (1/2)

We hope this indicates the small scale unresolved convection transports substantial energy and this decreases the energy flux by the large scale.




The problem is we do not know the behaviour of small scale in the global view

# Small scale convection (2/2)

Whose responsibility is the small scale?
→Hinode and Solar-C

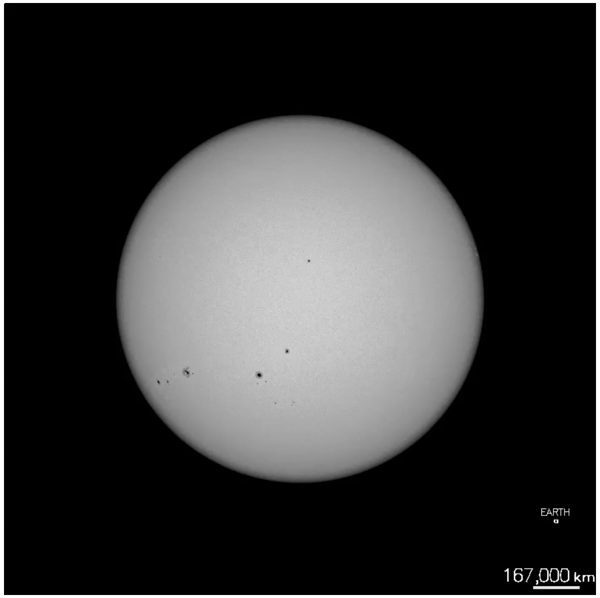
It is time to compare everything.

High resolution observation (Hinode, Solar-C)

Local box (MURaM, Stagger)

Global scale (ASH, Our calculation)

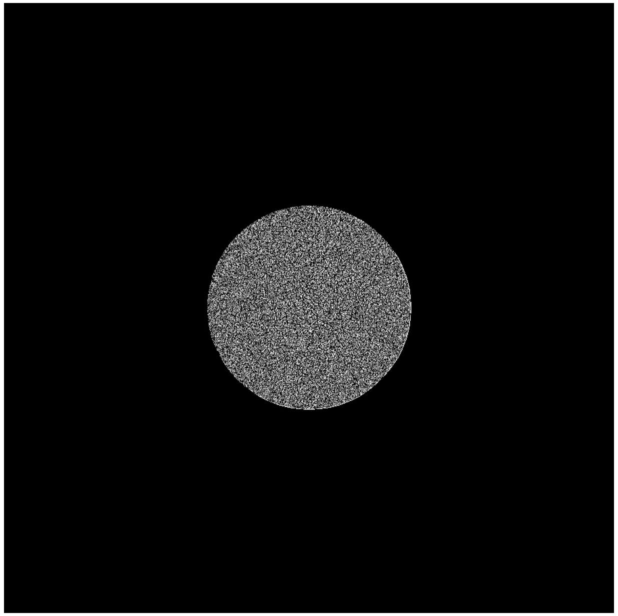
Courtesy of Okamoto-san



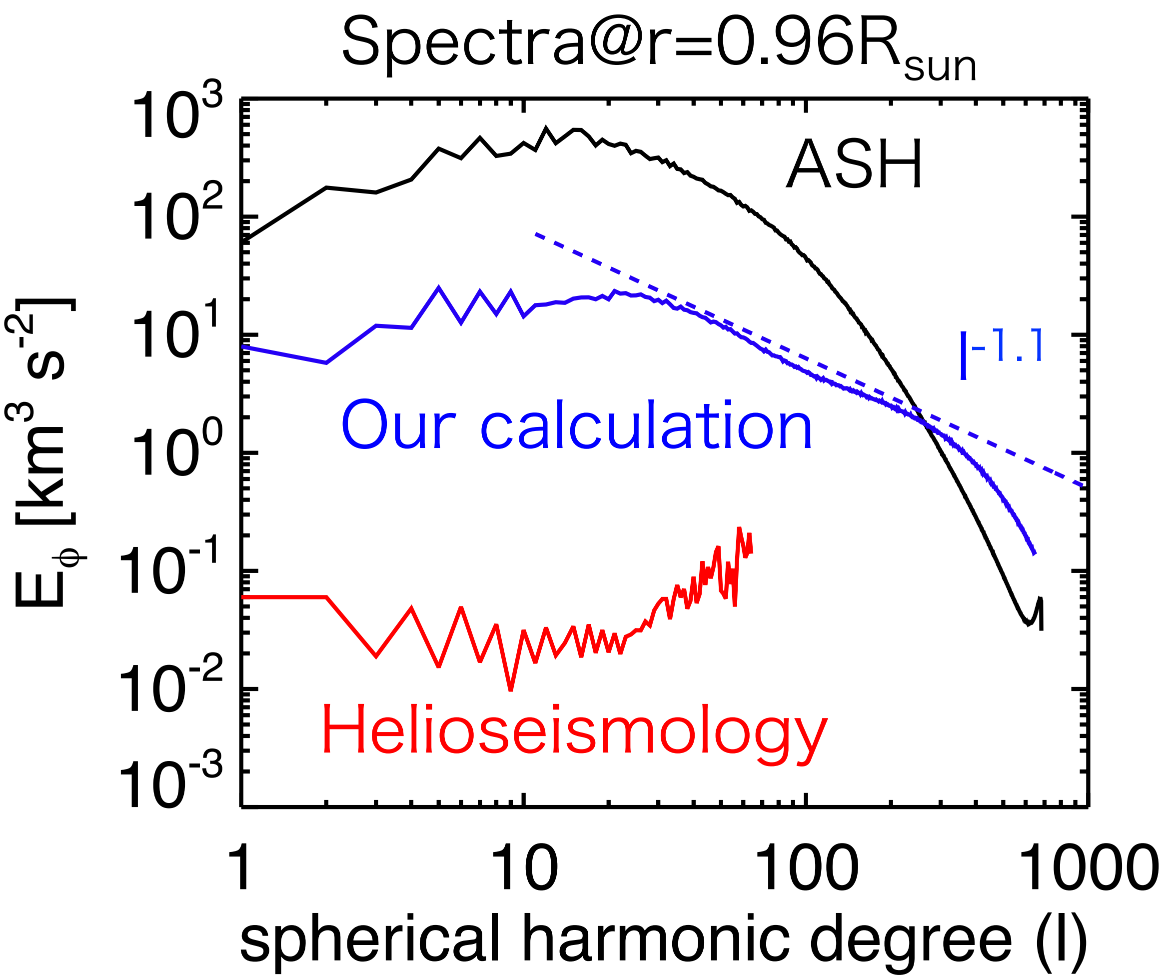

The question is "how does the small scale behave"

# Summary

1. We have understood the accelerated equator, conical profile, and tachocline.
2. Our new challenge including near surface shear layer reveals the maintenance mechanism for NSSL.
3. There remains a fundamental problem related to high speed of computed velocity.
4. The small scale convection which cannot be treated in the global calculation might have a key role.
5. High resolution observation can give significant contribution to this issue.

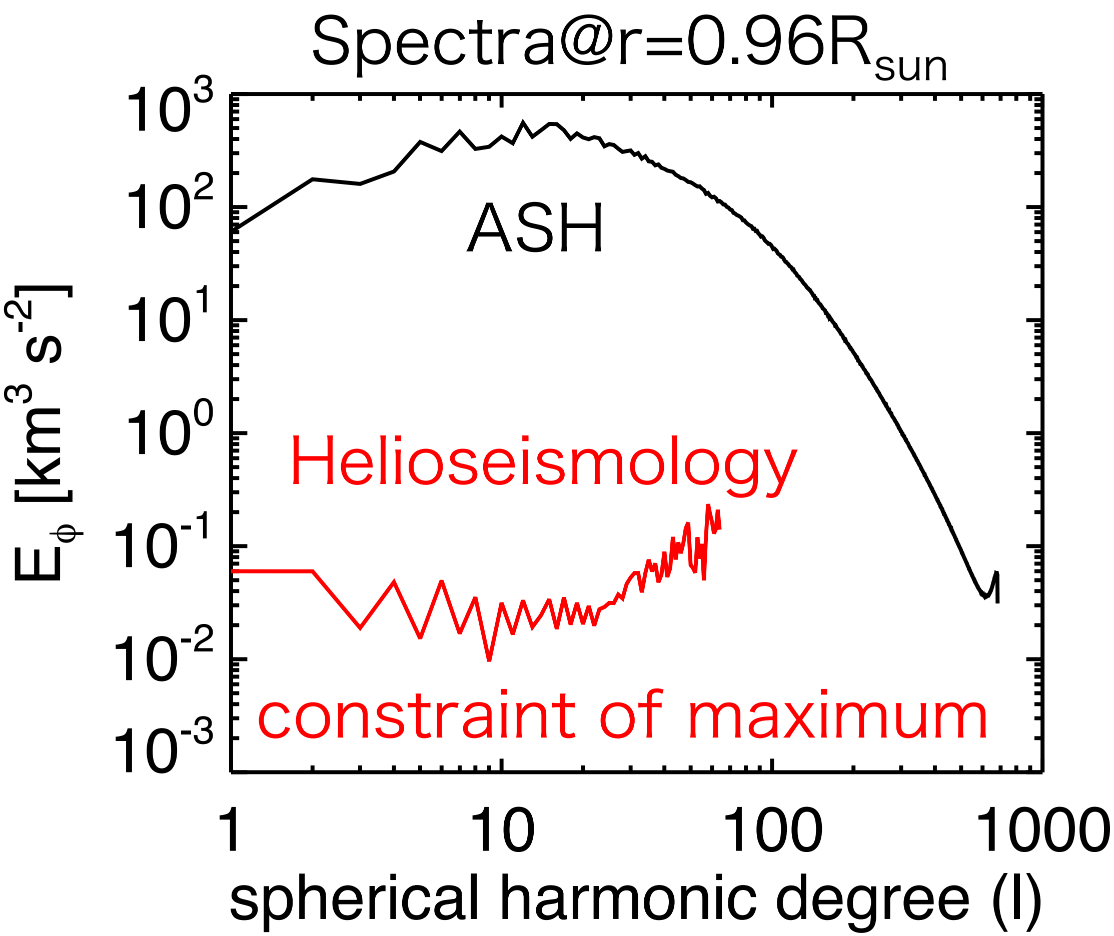


# Spectra



Spectra@r=0.96R_sun
ASH
Our calculation
Helioseismology
l^-1.1
E_φ [km^3 s^-2]
spherical harmonic degree (l)
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
1
10
100
1000

# Difference between calculation and helioseismology



# Small scale convection (1/2)

Summary of the problem:
1. The computed solar convection speed is too high.
2. When we reduce the luminosity, we can reproduce the differential rotation.

We hope this indicates the small scale unresolved convection transports substantial energy and this decreases the energy flux by the large scale.

Again, the problem is:
We do not know the behavior of small scale convection in the view from global scale.