CHIBA UNIVERSITY

NAOJ Future Planning Symposium 2021
Nov. 9-10, 2021

Solar/Stellar magnetic field and dynamo

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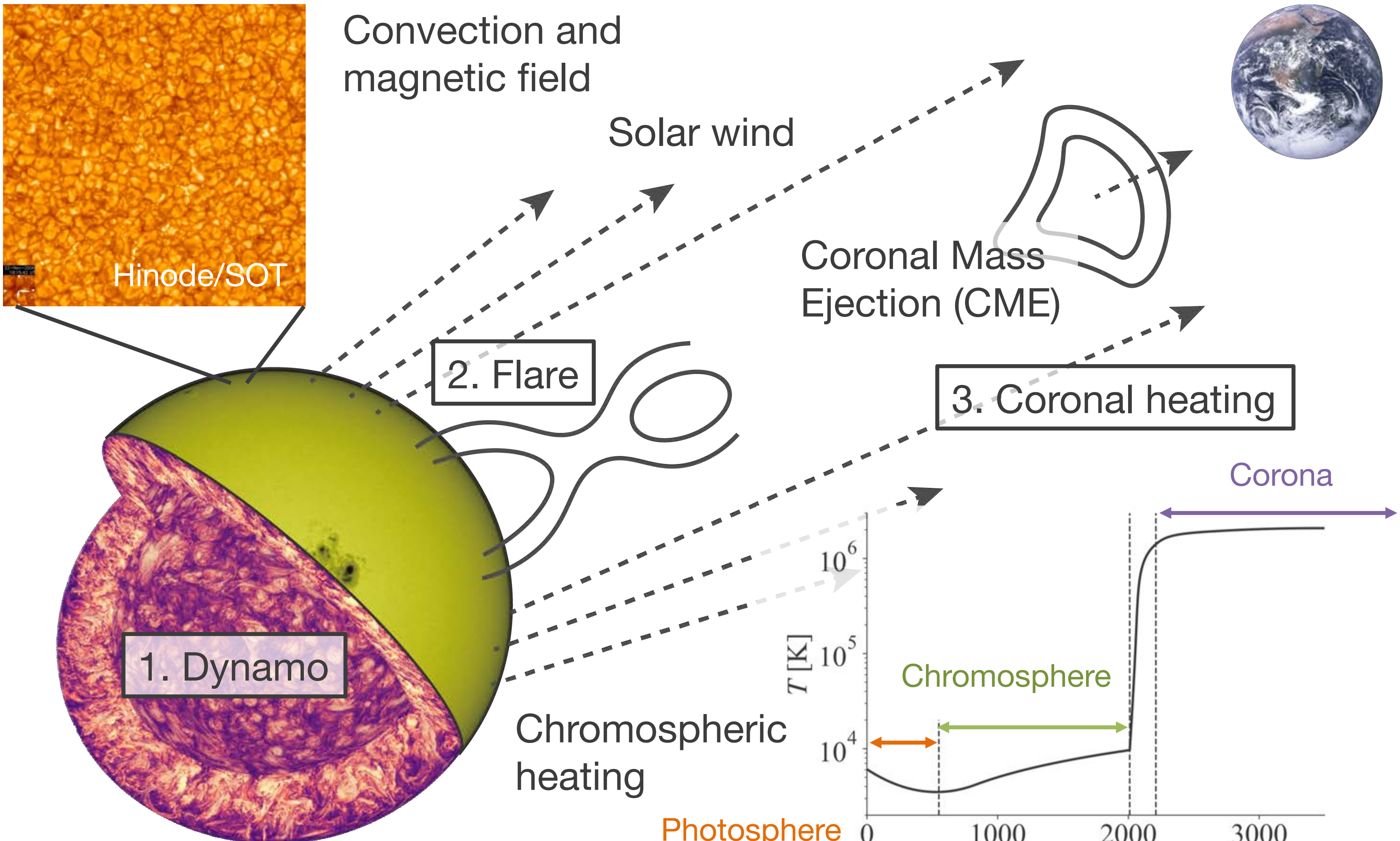
Contents

1. Current solar missions/projects in Japan
2. Solar magnetic field and dynamo
   a. Theoretical view
   b. Current observational achievement
   c. Future perspective
3. Connection to stellar magnetism (if time allows)
4. Summary

Major problems in solar physics



Scale is not precise

Japanese projects in solar physics

Provided by JSPC(太陽研究者連絡会)

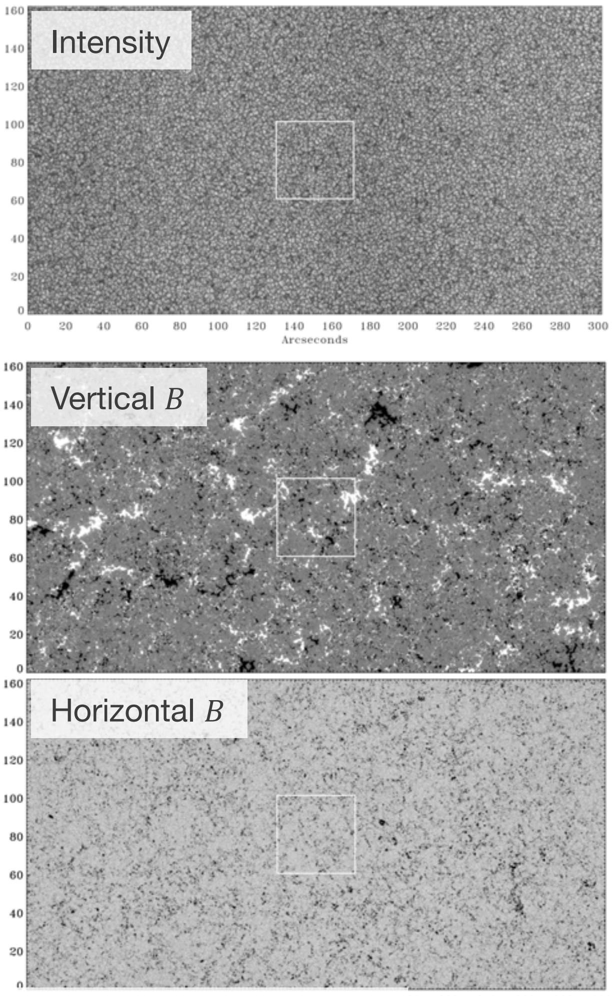
		Chromosphere/coronal heating and solar wind	Solar flare and CME	Solar cycle and dynamo
Solar-C_EUVST	space	○	○	
PhoENiX	space		○	
Hinode	space	○	○	
SUNRISE	balloon	○		
CLASP	sounding rocket	○		
FOXSI	sounding rocket		○	
ALMA	ground-based	○	○	
Nobeyama Radio	ground-based			○
Mitaka Flare	ground-based	○	○	○
Hida DST	ground-based	○	○	
Hida SMART	ground-based		○	○
Nagoya IPS	ground-based	○	○	○
Yamagawa Radio	ground-based		○	
ngGONG	ground-based		○	○
NIRTF	ground-based	○	○	
SciCRT	ground-based		○	
AMATERAS	ground-based		○	
Simulations		○	○	○

Orange: Future plan

Hinode/SOT (Solar Optical Telescope)

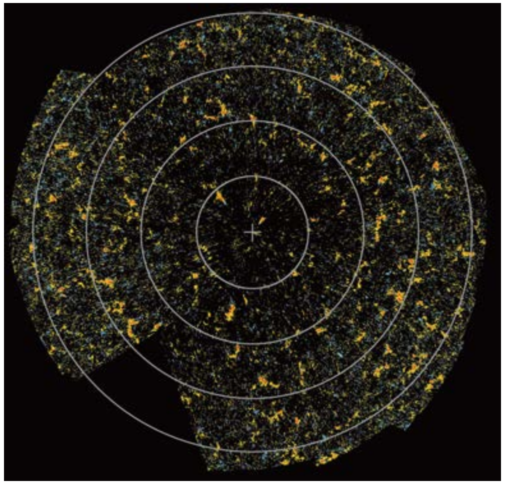
✓ **Measurement of *B* in the photosphere**

Ubiquitous granular-scale loops (hG)



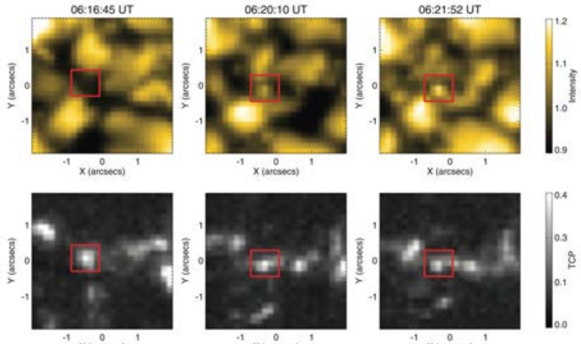
Ishikawa+2008, Lites+2008

kG patches viewed from pole



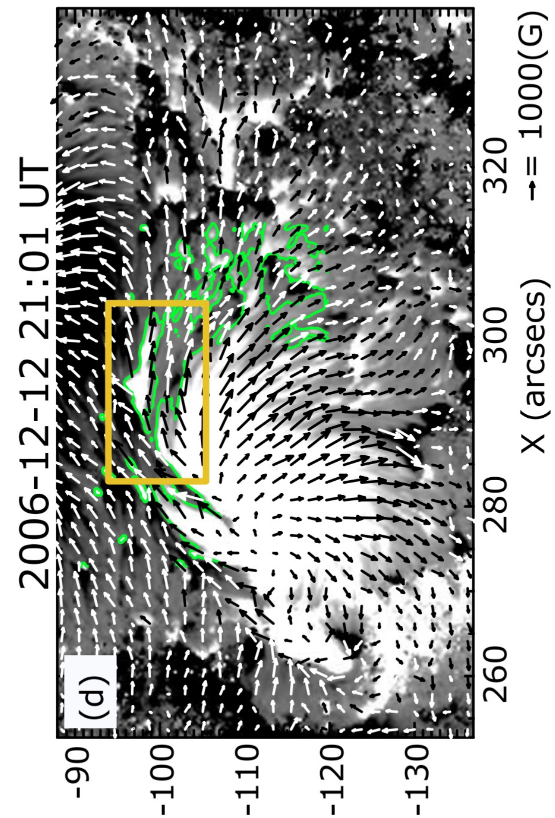
Tsuneta+08, Shiota+12

Formation of super-equipartition (kG) field



Nagata+08

B **shear (flare trigger)**

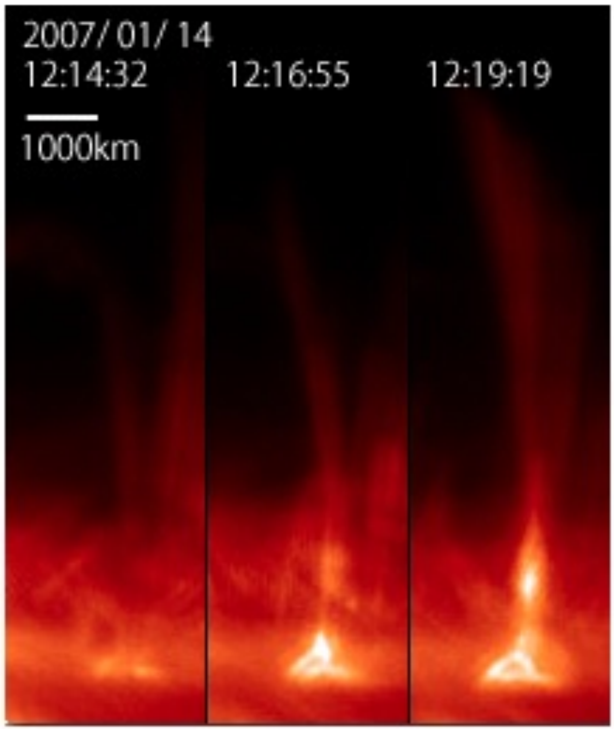


Bamba+13

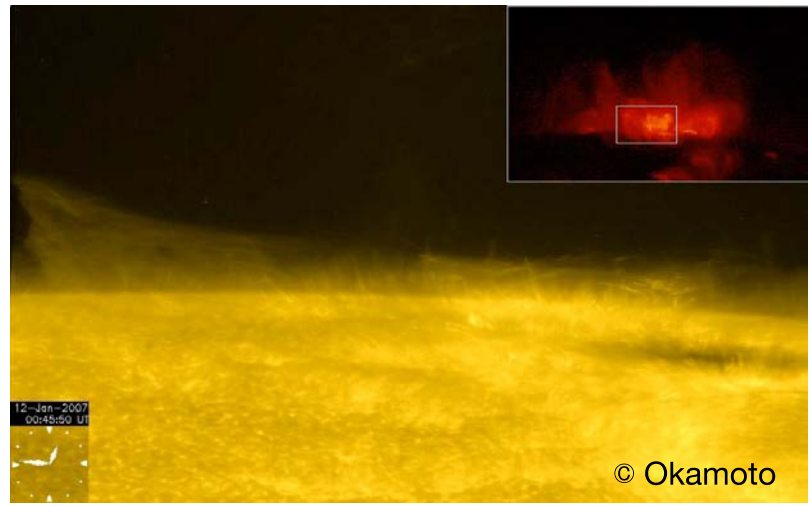
Hinode/SOT (Solar Optical Telescope)

✓ **Dynamic activities in the chromosphere**

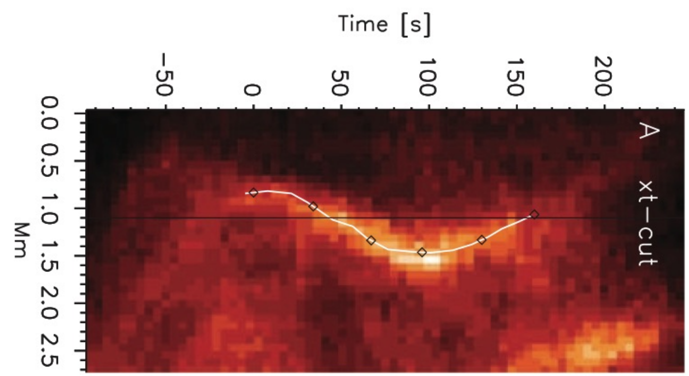
Ubiquitous jets



Shibata+07



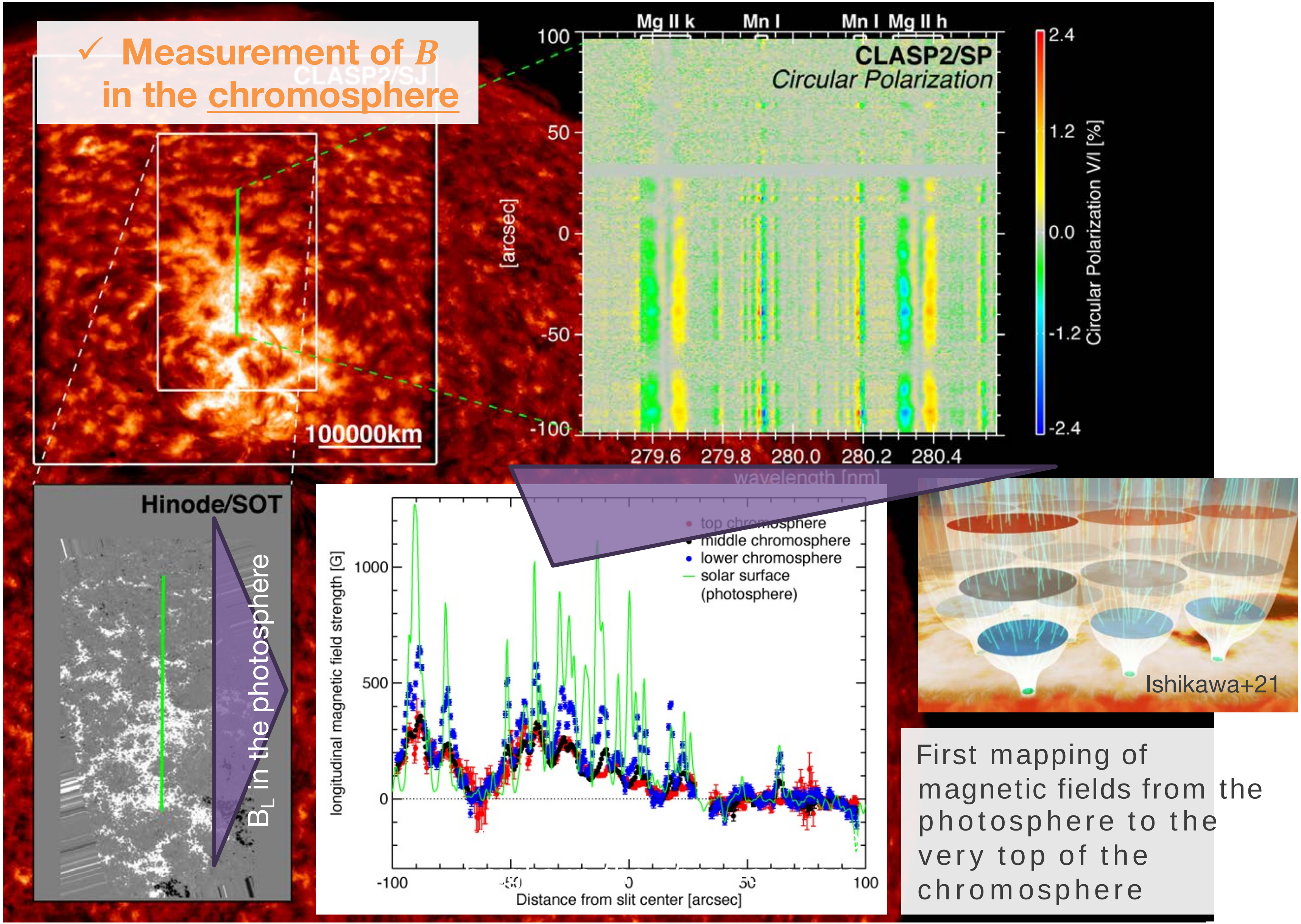
MHD waves



De Pontieu+07

Okamoto+07

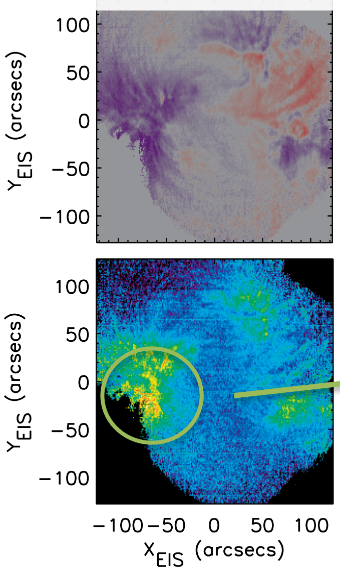
CLASP rocket experiment
Chromospheric LAyer Spectro-Polarimeter

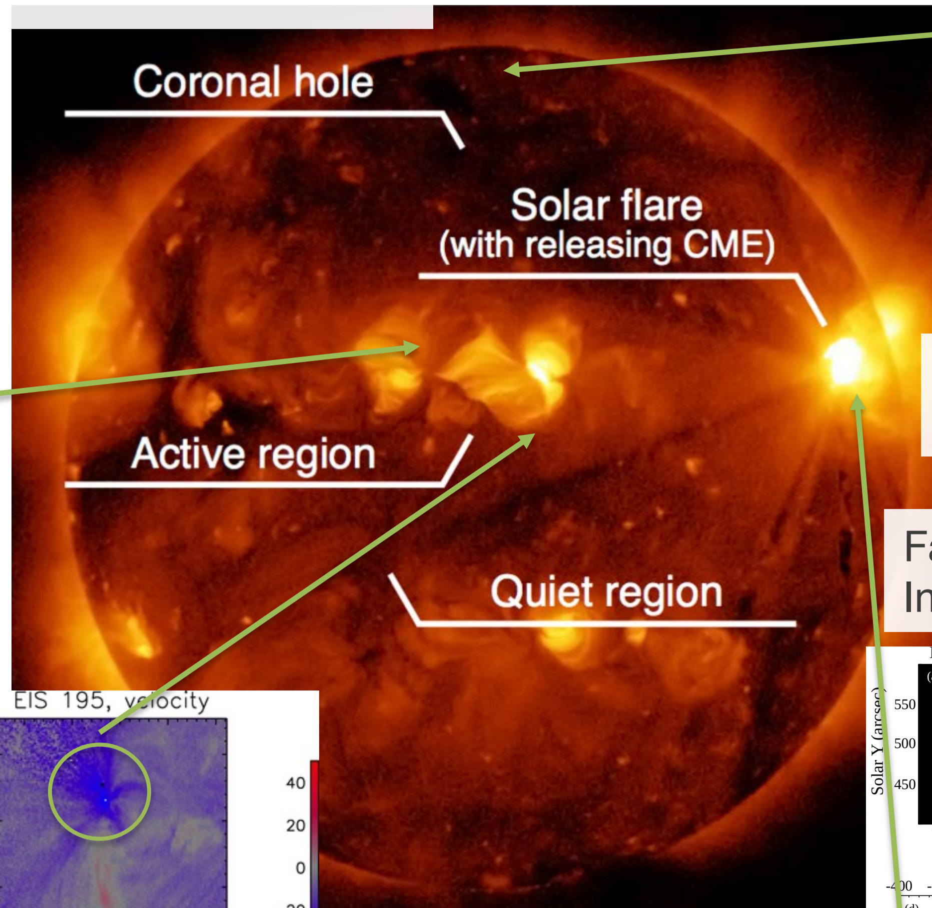


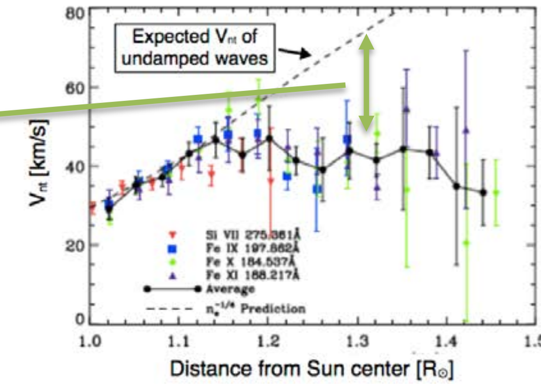
First mapping of magnetic fields from the photosphere to the very top of the chromosphere

Hinode/EIS (EUV Imaging Spectrometer)

Turbulent motion at the foot point of AR
Hara et al. 2008

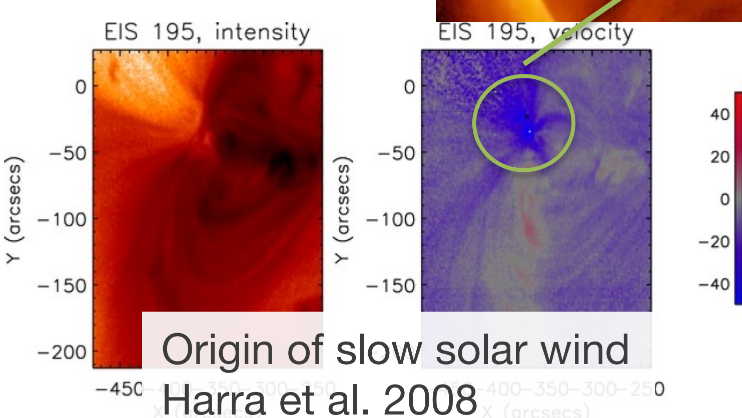




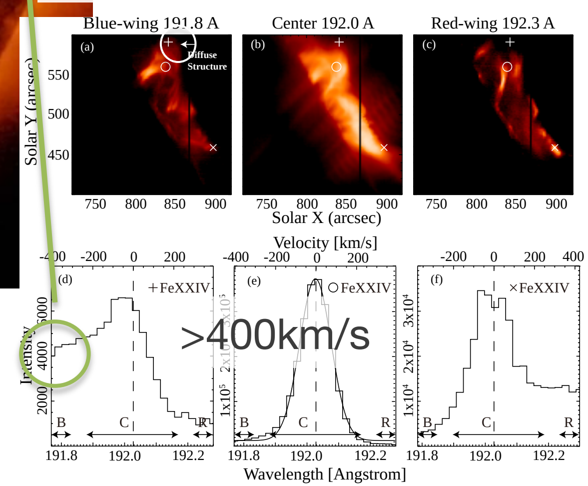


Fast solar wind acceleration
Hahn & Savin 2013

Fast flows from reconnection
Imada et al. 2013



Origin of slow solar wind
Harra et al. 2008



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Solar-C_EUVST

Launch 2027

JAXA Epsilon M-class mission

EUV High-throughput Spectroscopic Telescope

Science objectives:

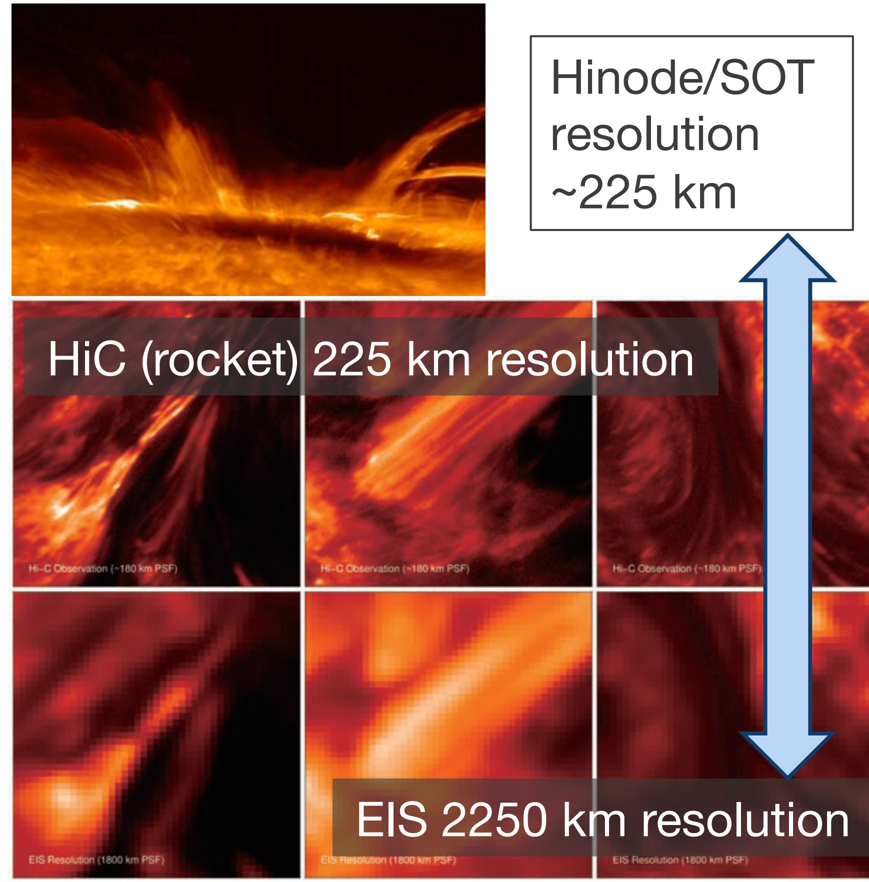
1. Chromospheric and coronal heating, Solar wind
2. Mechanism for solar flares, i.e., energy release and eruption.

Key features:

A) Wide T-coverage (10^4-10^7 K)
Observe the whole regimes of the solar atmosphere as a single coupled system

B) High resolution
(spatial ~ 0.4”, temporal ~ 1 sec)
Capture the dynamic evolutions of elementary structures

C) Spectroscopy
Determine the physical states of the targets (v, ρ, T, composition, ionization)

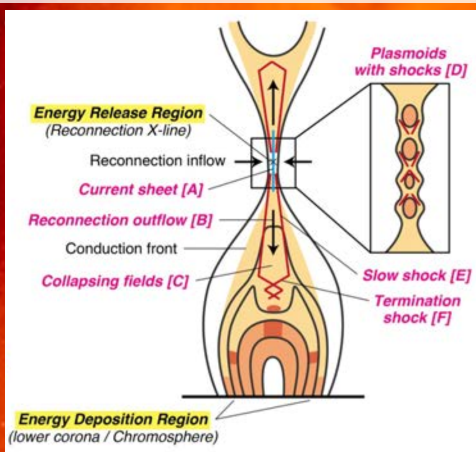


Hinode/XRT (X-Ray Telescope)

Solar Observations in X-rays can evaluate

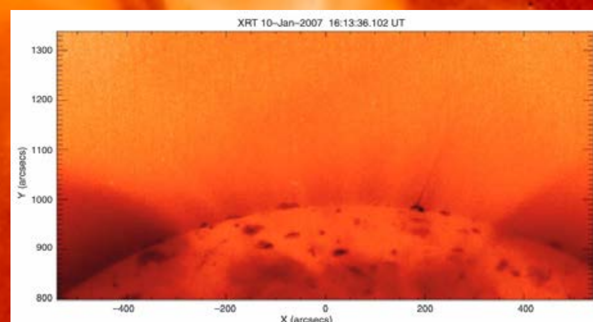
- Physical quantities of **hot thermal plasma** (~ 1 MK to > 10 MK) from soft X-ray observations, e.g., Hinode/XRT
- Physical quantities of **non-thermal (accelerated) electrons** hard X-ray observations e.g., RHESSI

caused by magnetic reconnection.



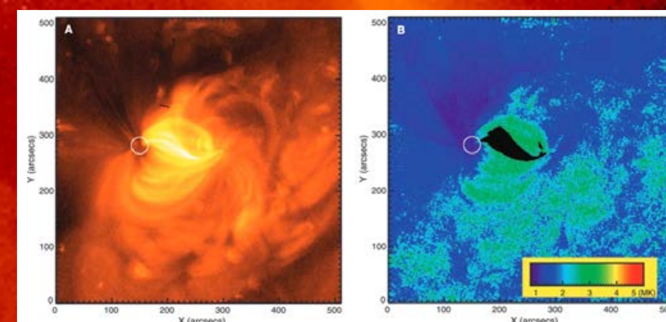
Alfvenic waves

(e.g., Cirtain et al. 2007)



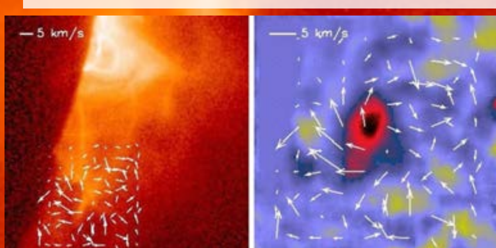
Outflows from active regions

(e.g., Sakao et al. 2007)



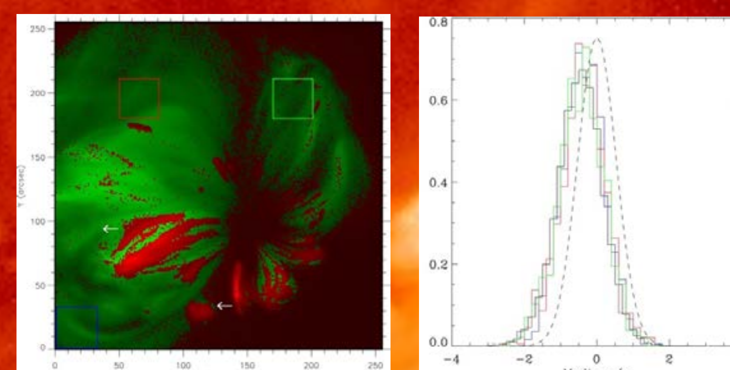
Turbulence

(e.g., McKenzie et al. 2013)



Nano-flare heating

(e.g., Terzo et al. 2011)



PhoENiX

Physics Of Energetic and Non-thermal plasmas in the X-region

PhoENiX in 2030s –
Imaging spectroscopy in soft and hard X-rays
- ➢ High dynamic range to evaluate entire flaring region
- ➢ High spatial, temporal, and energy resolutions

For the understandings of energetics in solar flares including particle acceleration.

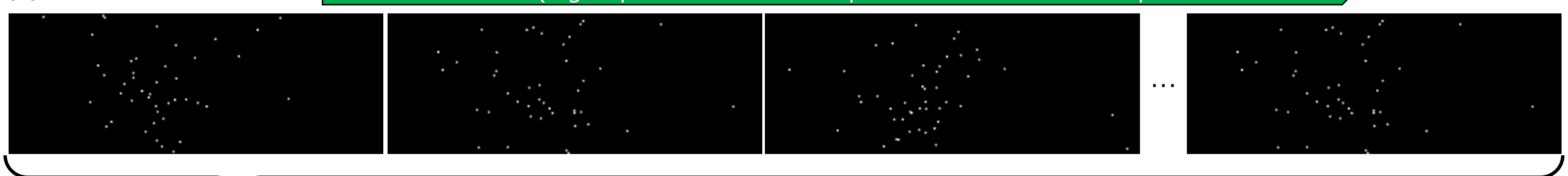
PhoENiX WG

Demonstrations with Sounding Rocket FOXSI series

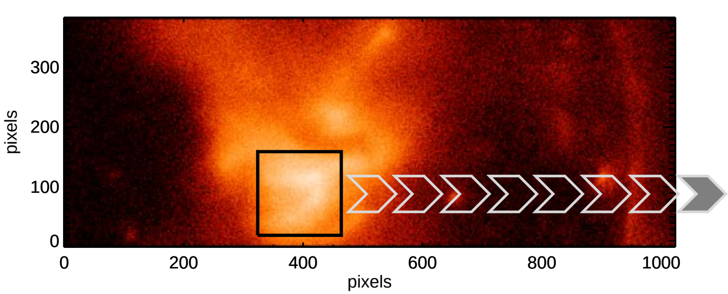
FOXSI-3 WG

(a) Observational data

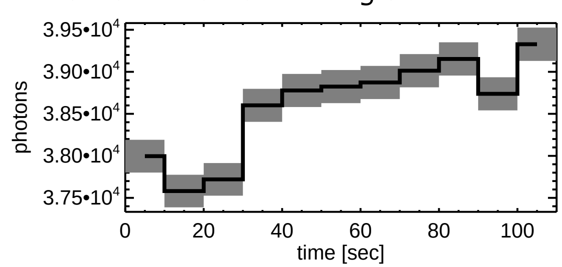
Flow of time (high-speed continuous exposure with 250 frames per second)



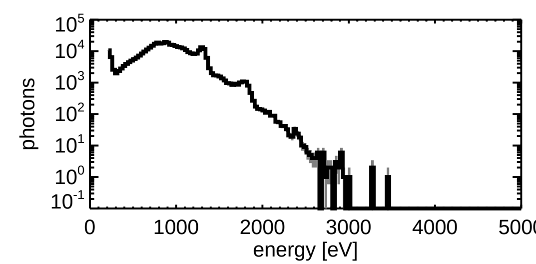
(b) Solar Image with integrated X-ray photons



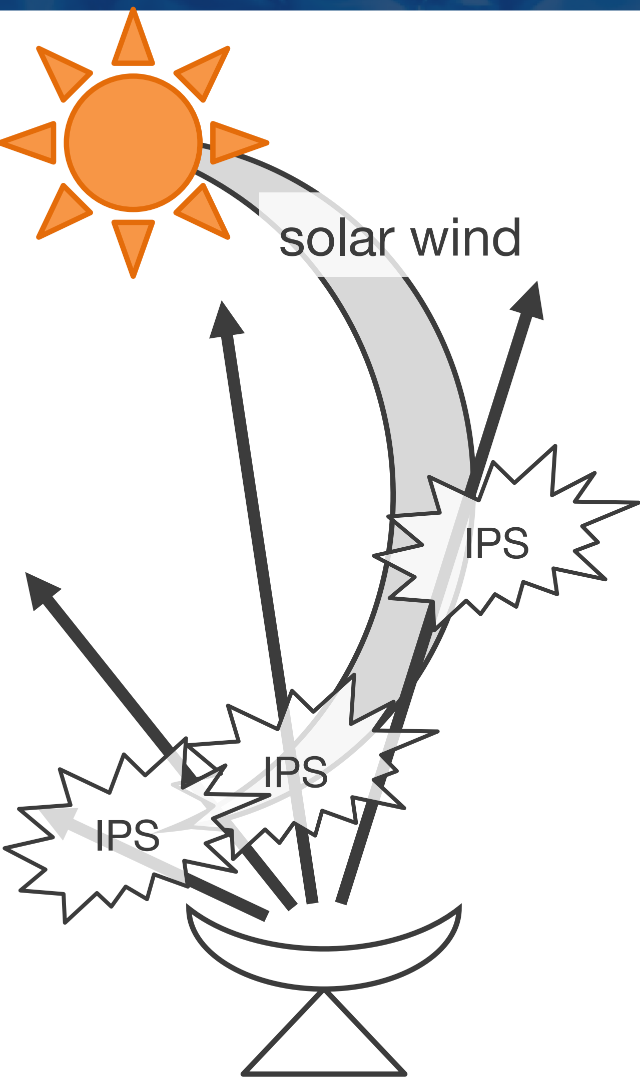
(c) Time variation of X-ray photon number in an active region



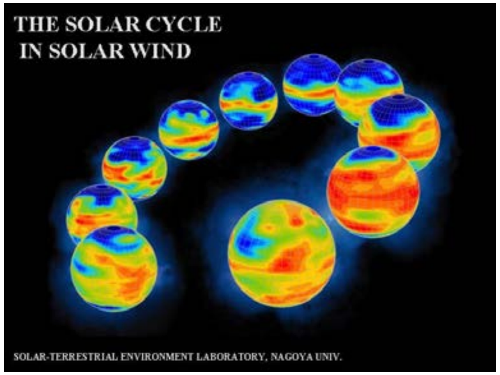
(d) X-ray spectrum of an active region

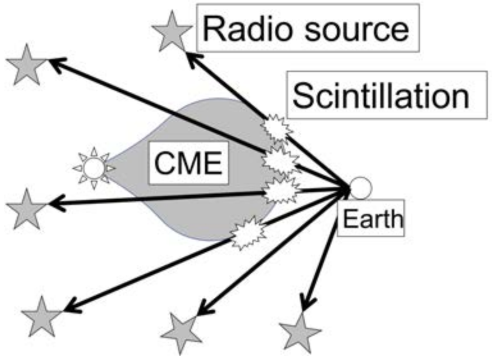


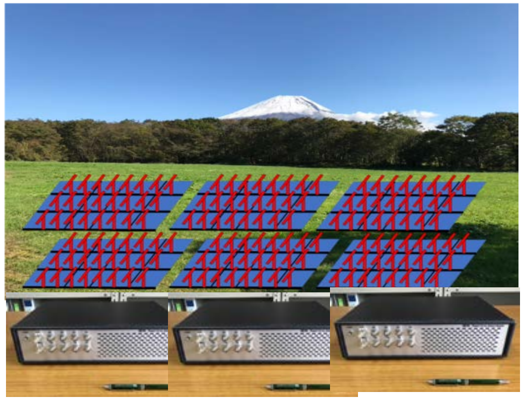
Nagoya-U IPS (InterPlanetary Scintillation)



IPS: Radio scattering by the solar wind







Solar wind observation for more than 30 years
Global structure of the solar wind and its solar cycle variation
Fujiki+2015, Tokumaru+2018

Detection of the CMEs and their real-time analysis system are also used for space weather forecasting.
Iwai+2019, 2021

New IPS observation system (MP2023 submitted)
- x10 IPS observations.
- Resolve the global spatial scale of the solar wind

Japanese projects for solar cycle, dynamo and interior

		Chromosphere/coronal heating and solar wind	Solar flare and CME	Solar cycle and dynamo
Solar-C_EUVST	space	○	○	
PhoENiX	space		○	
Hinode	space	○	○	
SUNRISE	balloon	○		
CLASP	sounding rocket	○		
FOXSI	sounding rocket		○	
ALMA	ground-based	○	○	
Nobeyama Radio	ground-based			○
Mitaka Flare	ground-based	○	○	○
Hida DST	ground-based	○	○	
Hida SMART	ground-based		○	○
Nagoya IPS	ground-based	○	○	○
Yamagawa Radio	ground-based		○	
ngGONG	ground-based		○	○
NIRTF	ground-based	○	○	
SciCRT	ground-based		○	
AMATERAS	ground-based		○	
Simulations			○	○

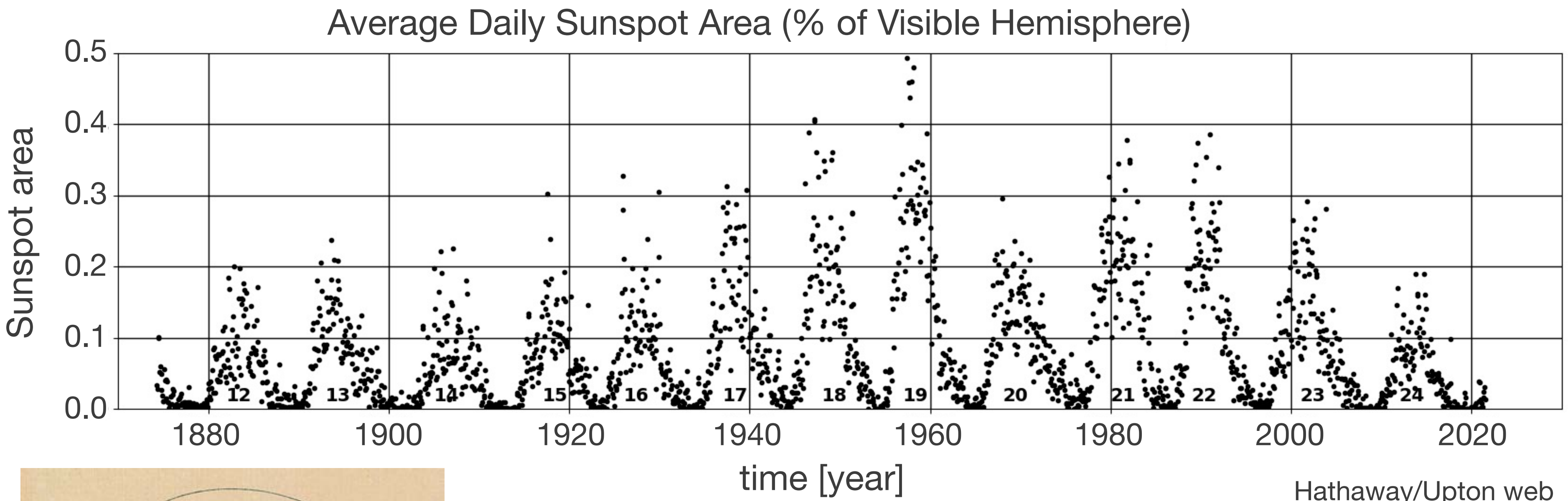
There is almost no observational project for the understanding the solar cycle and solar interior.
→We need it.

Observe long term evolution of solar status
(flare, solar wind, etc)

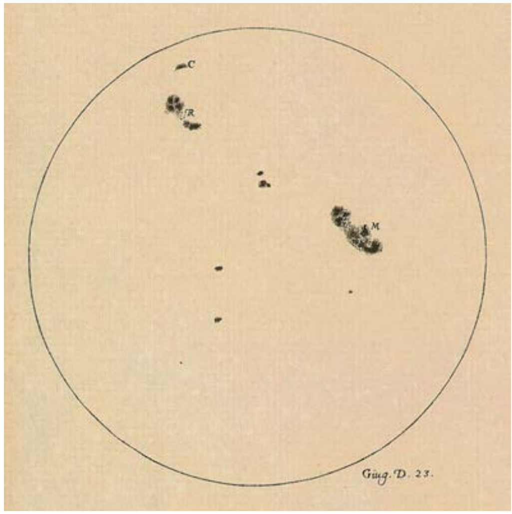
ngGONG includes science goal for the solar interior but main motivation of Japan's contribution is space weather

As for the theory for the solar interior, Japan has been doing world leading large-scale project.

Solar cycle



Hathaway/Upton web

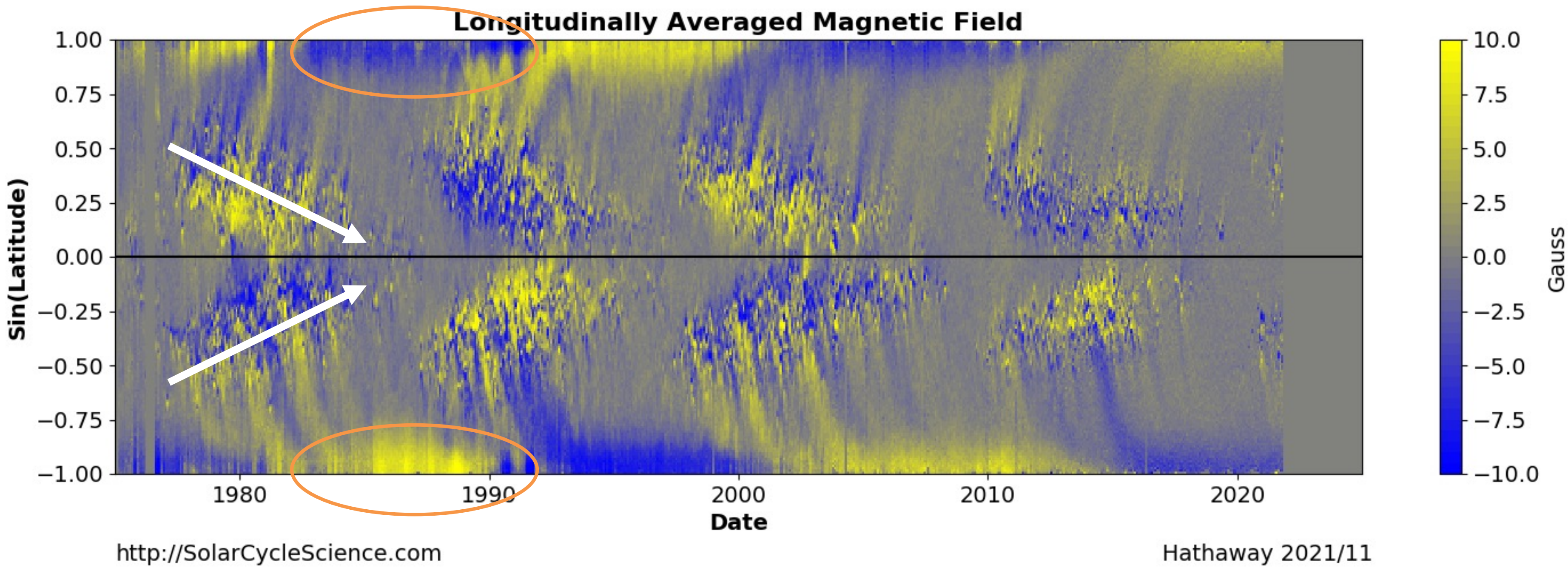


Galileo’s sunspot drawing
[The Galileo Project]

Number of sunspots varies with the 11-year cycle. This is confirmed with several hundred years of observations.

Physical mechanism to maintain the cycle has not been understood yet.
One of the most important problems in the solar physics.

Features in solar cycle: Butterfly diagram



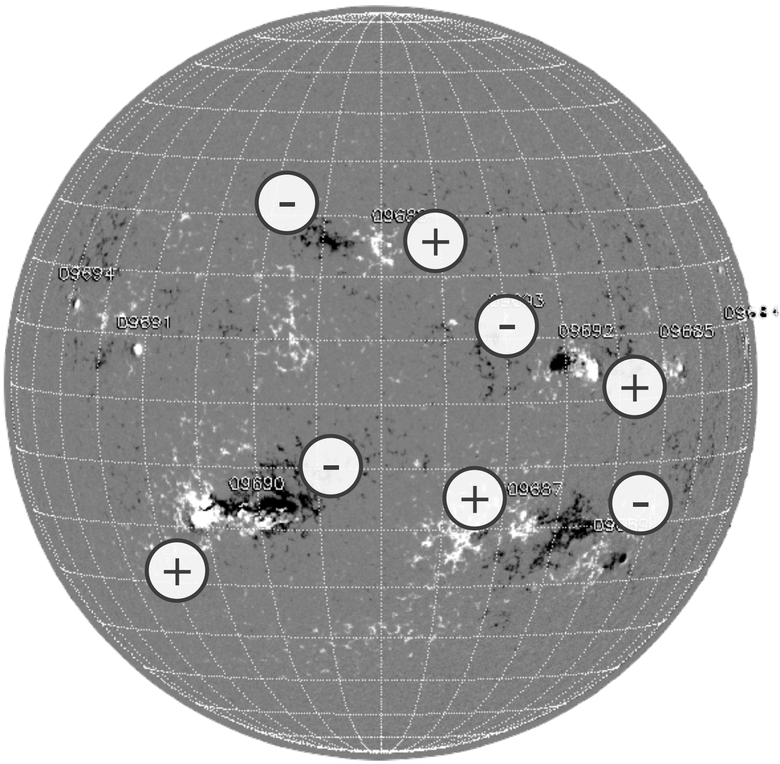
The solar cycle is not a simple oscillation in the 11-year cycle.
There are several interesting features:

✓ The sunspot latitude (active latitude) migrates from mid-latitudes to low latitudes during each cycle.

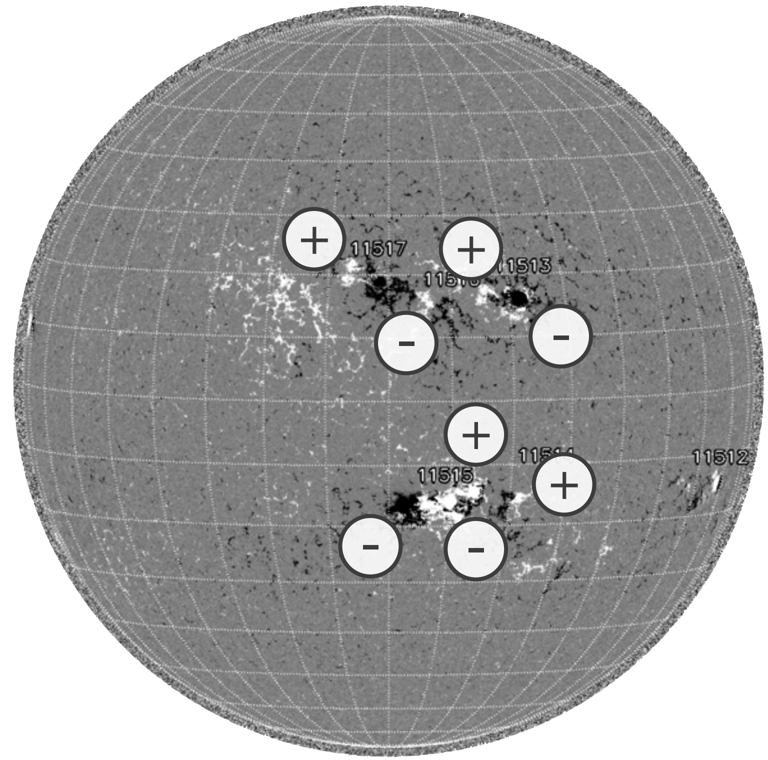
✓ The solar global field has a dipolar field. The polarity of the dipole reverses in every cycle.

Features in solar cycle: Hale's law

SOHO/MDI, 2001 (cycle 23)



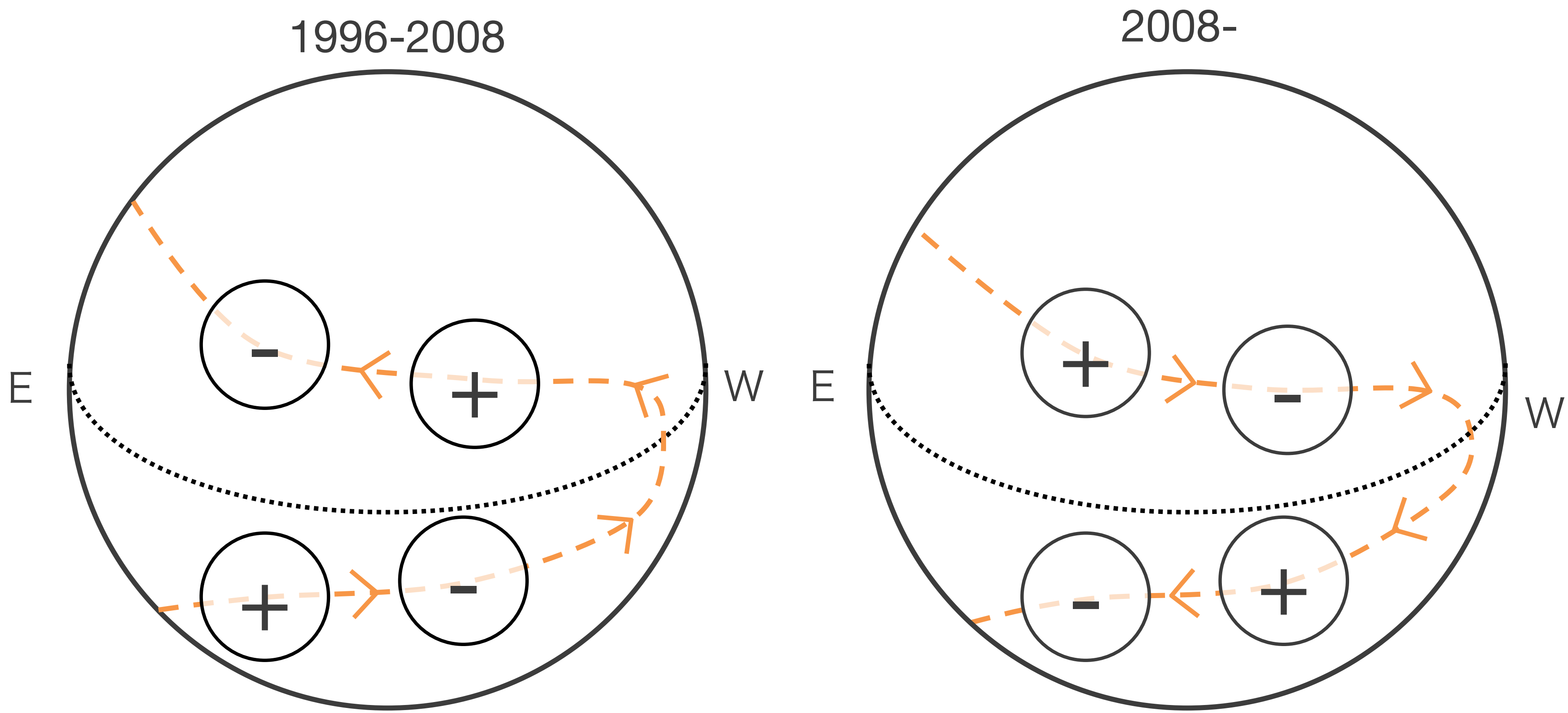
SDO/HMI, 2012 (cycle 24)



<u>More than 90% of sunspot pairs obey coherent polarity rule</u>

- ✓ In a cycle, proceeding spots in a hemisphere always has one polarity.
- ✓ The polarity in the other hemisphere is opposite.
- ✓ The relation is reversed in every 11-year cycle.

Features in solar cycle: Hale's law



Hale's law indicates large-scale magnetic fields in the solar interior.

Magnetic field evolution (1/2)

We need to explain the reasons why:

✓ the sunspot number varies in 11 years.

✓ the large-scale magnetic field is constructed in the solar interior

Faraday's law in high conductivity limit

$$\frac{\partial \boldsymbol{B}}{\partial t} = -c\nabla \times \boldsymbol{E}$$

$$\boldsymbol{E} = -\frac{1}{c}\boldsymbol{v} \times \boldsymbol{B}$$

$\longrightarrow$

Magnetic induction equation

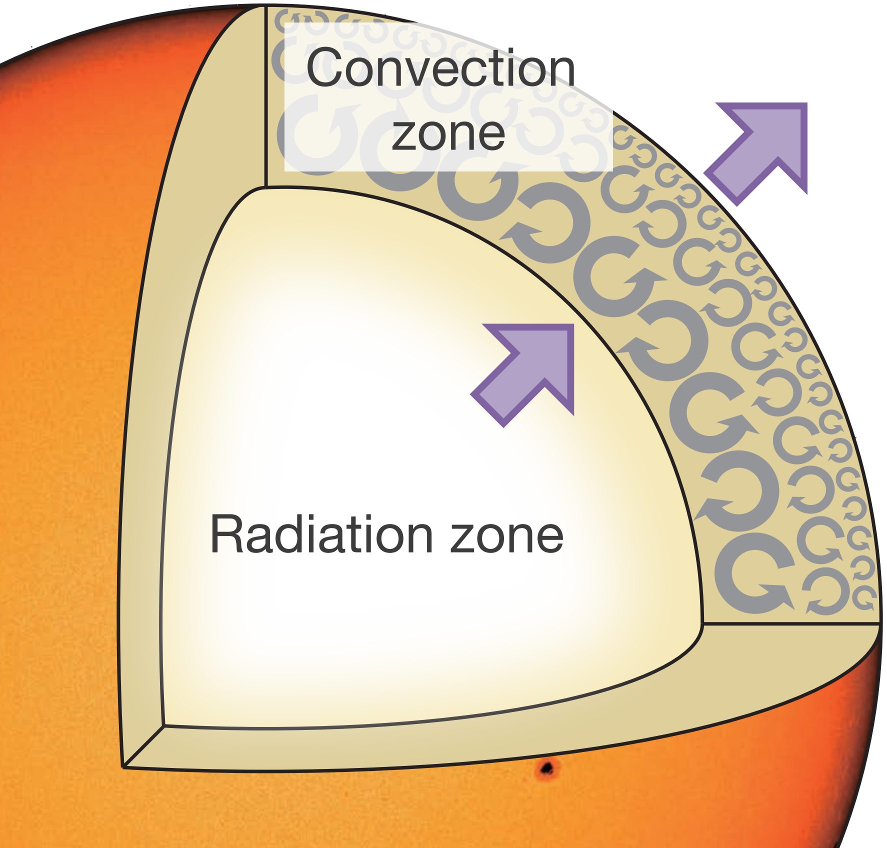
$$\boxed{\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B})}$$

We want to know "large" scale magnetic field and we divide the field and flow to large $\langle\quad\rangle$ and small scale $'$ as $\boldsymbol{B} = \langle \boldsymbol{B} \rangle + \boldsymbol{B}'$ and $\boldsymbol{v} = \langle \boldsymbol{v} \rangle + \boldsymbol{v}'$. Then the induction equation for large-scale fields becomes

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

Magnetic field evolution (2/2)

$$\frac{\partial \langle \boldsymbol{B} \rangle}{\partial t} = \underbrace{\nabla \times (\langle \boldsymbol{v} \rangle \times \langle \boldsymbol{B} \rangle)}_{\text{Effect by large-scale flow}} + \underbrace{\nabla \times \langle \boldsymbol{v}' \times \boldsymbol{B}' \rangle}_{\text{Effect by small-scale flow}}$$



We need to understand at least:

- ✓ Large-scale flow $\langle \boldsymbol{v} \rangle$
- ✓ Correlation between flow and magnetic field $\langle \boldsymbol{v}' \times \boldsymbol{B}' \rangle$

in the convection zone.

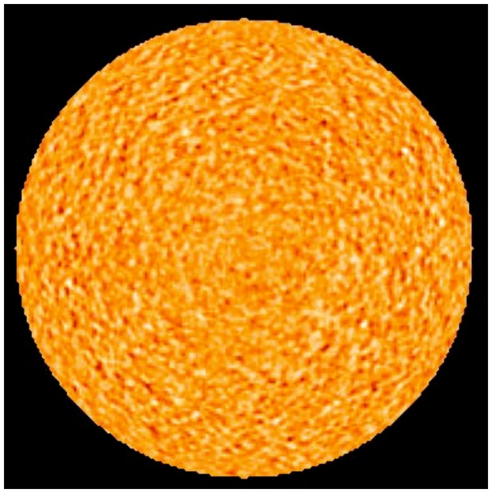
In the outer 30% of the solar interior, the convection transports the energy generated by nuclear fusion in the center of the sun.

This is turbulent.

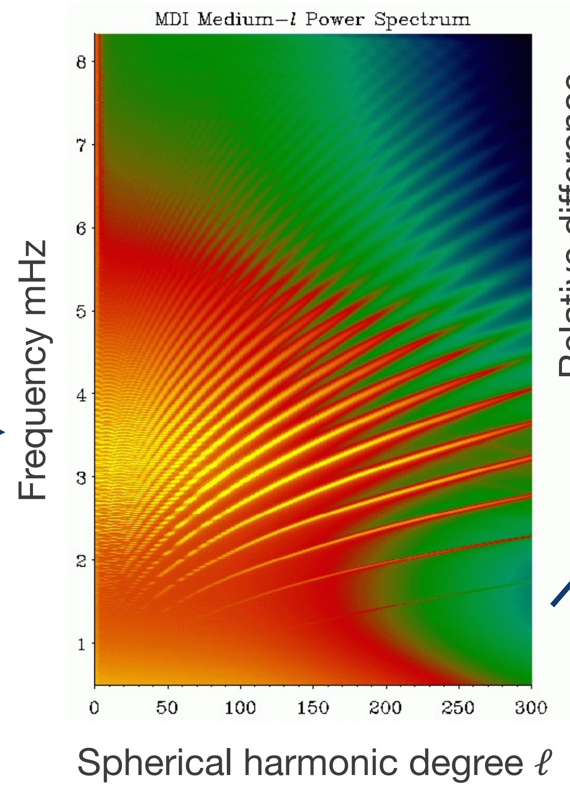
Technique to evaluate the internal flow: Helioseismology (1/2)

<u>Global helioseismology</u>:

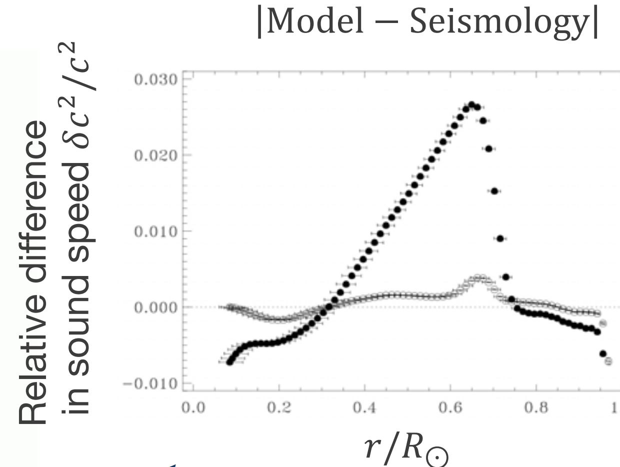
Solar oscillation observed with SOHO/MDI



“Fourier” transform in time and space



Inversion



Christensen-Dalsgaard+2009

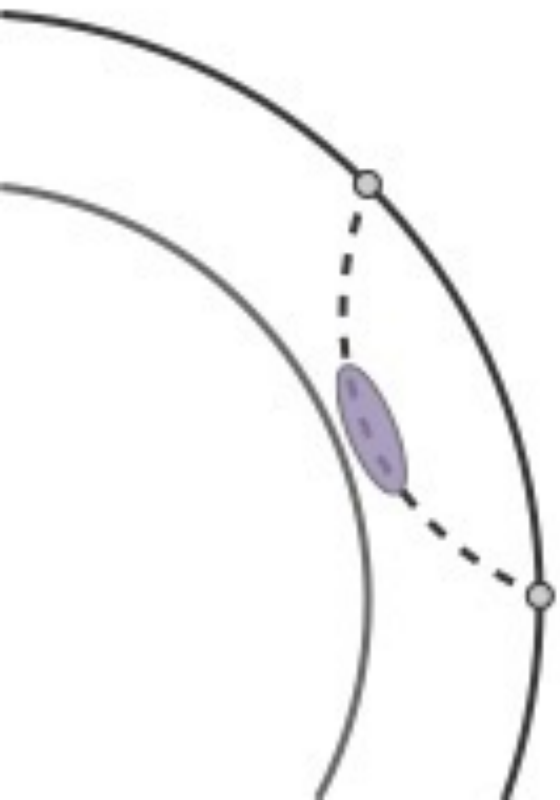
Acoustic wave in the solar convection zone constructs eigenmode.
Eigenmode must reflect solar internal structure (temperature, rotation, and flow).
Inversion of eigenmode observation leads to understandings of the solar interior.

Technique to evaluate the internal flow: Helioseismology (2/2)

<u>Local helioseismology</u>:

In travel time method, travel time in two points is evaluated.

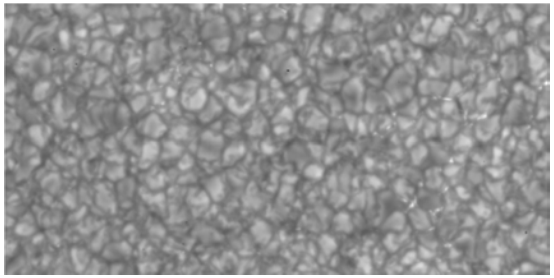
- ➢ Mean travel time → Temperature or ***B***
- ➢ <u>Travel time difference → Flow</u>



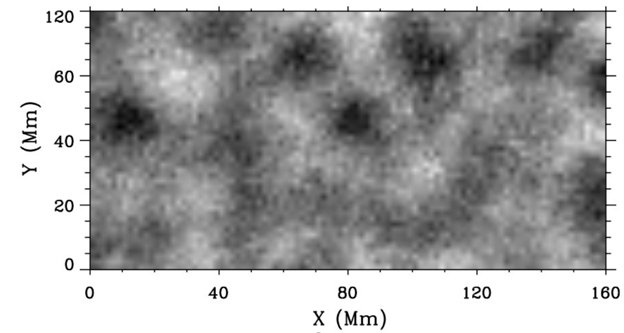
e evaluate the travel time multiple layers and carry t inversion to obtain ysical quantities.

we want to evaluate the antities in the deep layer, e need to observe two ints apart long enough r a long duration.

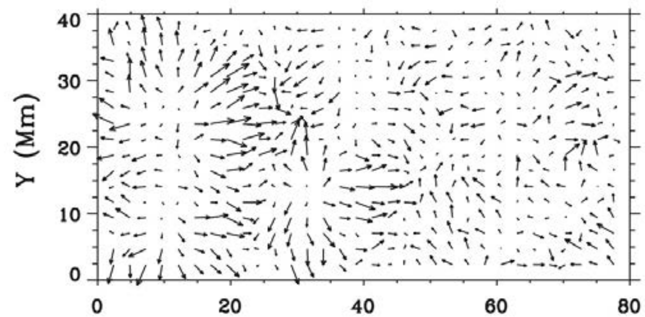
G-band intensity



Travel time difference



Inverted flow structure



Sekii+2007

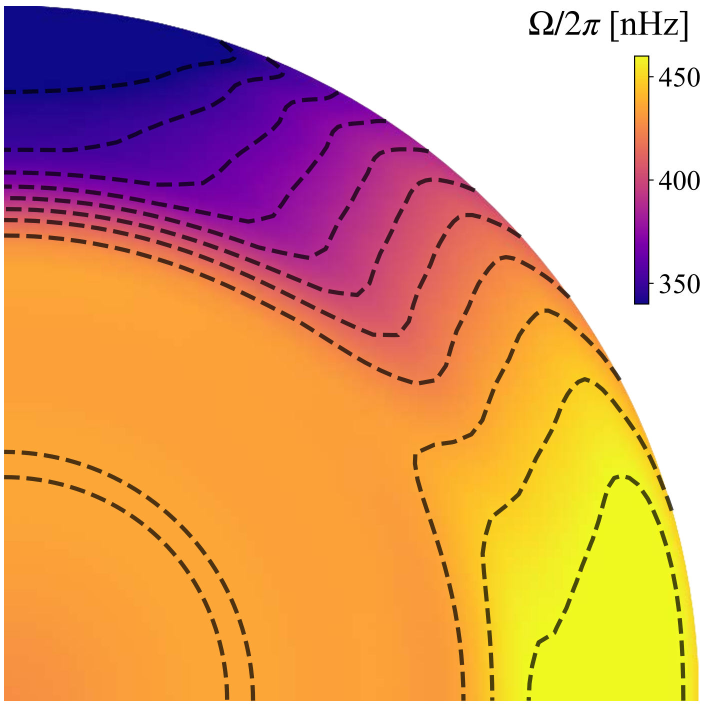
Large-scale flow: Differential rotation

$$\frac{\partial\langle \boldsymbol{B}\rangle}{\partial t} = \underbrace{\nabla \times \left(\langle \boldsymbol{v}\rangle \times \langle \boldsymbol{B}\rangle\right)} + \nabla \times \langle \boldsymbol{v}' \times \boldsymbol{B}'\rangle$$

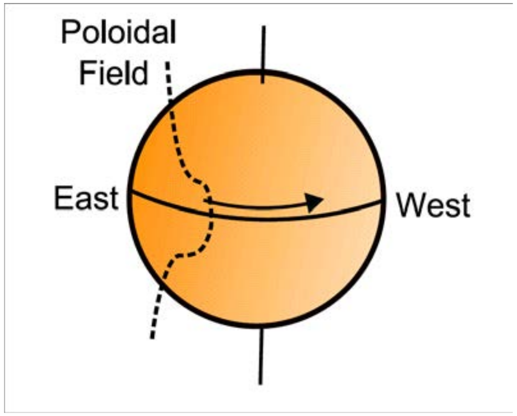
stretching

$$\longrightarrow \quad \nabla \times \left(\langle \boldsymbol{v}\rangle \times \langle \boldsymbol{B}\rangle\right) = \boxed{\left(\langle \boldsymbol{B}\rangle \cdot \nabla\right)\langle \boldsymbol{v}\rangle} - \nabla \cdot \left(\langle \boldsymbol{v}\rangle\langle \boldsymbol{B}\rangle\right)$$

Result of global helioseismology



Data provided by R. Howe



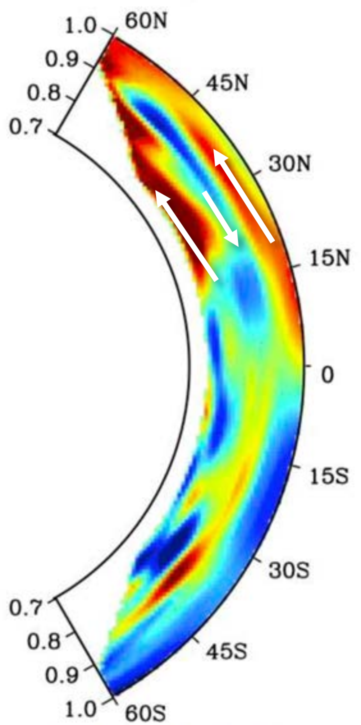
The details of the differential rotation have been revealed by helioseismology.
Error in pole and radiation zone is large, but the distribution in most of the convection zone has reached a consensus.
(see solar orbiter mission)

Large-scale flow: Meridional flow

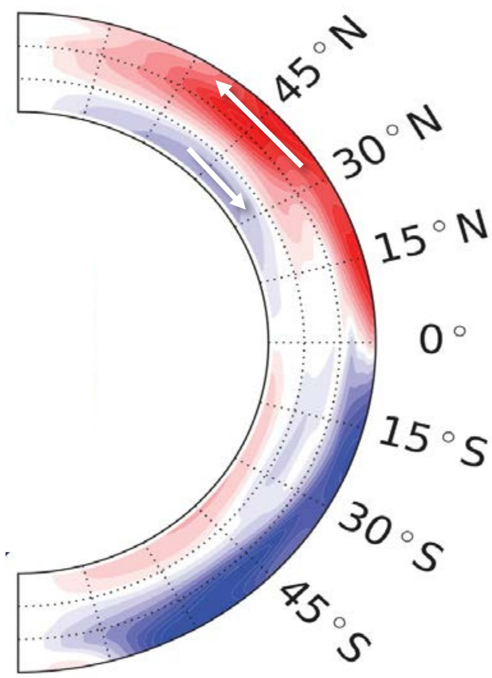
$$\frac{\partial \langle \boldsymbol{B} \rangle}{\partial t} = \underline{\nabla \times (\langle \boldsymbol{v} \rangle \times \langle \boldsymbol{B} \rangle)} + \nabla \times \langle \boldsymbol{v}' \times \boldsymbol{B}' \rangle$$

flux transport

$$\longrightarrow \quad \nabla \times (\langle \boldsymbol{v} \rangle \times \langle \boldsymbol{B} \rangle) = (\langle \boldsymbol{B} \rangle \cdot \nabla) \langle \boldsymbol{v} \rangle \boxed{- \nabla \cdot (\langle \boldsymbol{v} \rangle \langle \boldsymbol{B} \rangle)}$$



Zhao+2013
SDO



Gizon+2020
SoHO, GONG

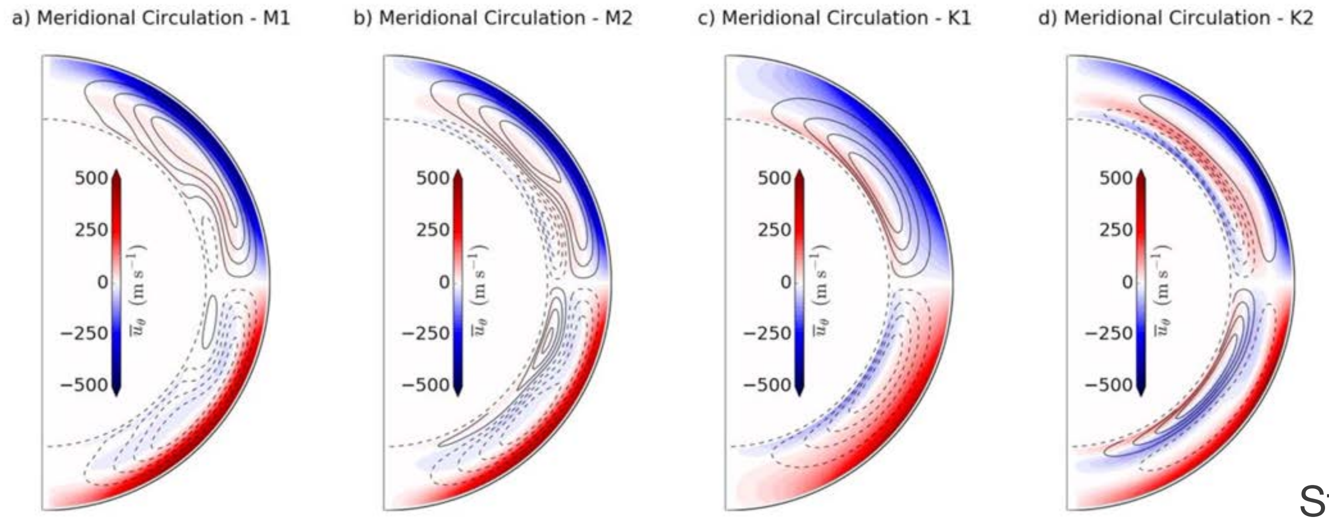
Different observations show different results
(Zhao+2013, Rajaguru+2015, Jackiewics+2015, Rajaguru+2015, Chen+2017, Gizon+2020)

The flow at the base of CZ is expected to be several m/s and it is difficult to detect it in 200 km/s sound speed.

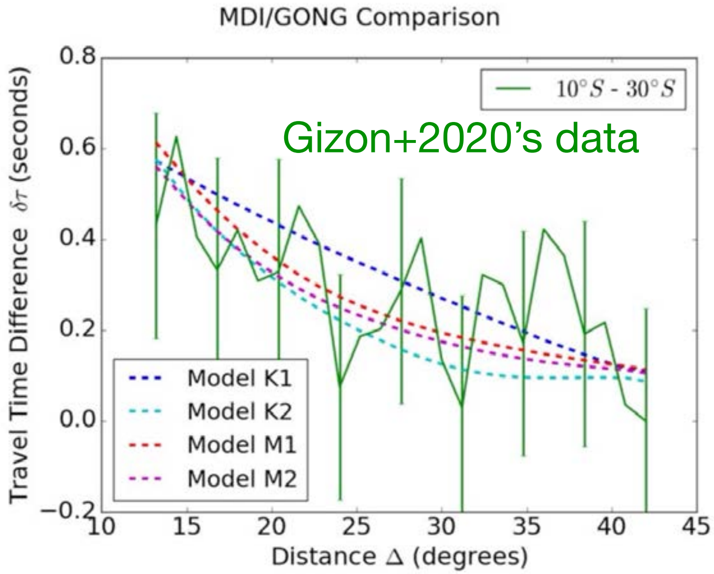
Currently we cannot distinguish even poleward and equatorward flow at the base of the convection zone.

Current status of meridional flow

Prepared meridional flow by mean-field simulation



Stejko+2021



- ✓ Local helioseismology is applied to the simulation data
- ✓ Travel time difference is evaluated for single and multiple cell flow.
- ✓ <u>It is concluded that Gizon+2020 does not have the precision to determine the flow direction at the base of CZ.</u>

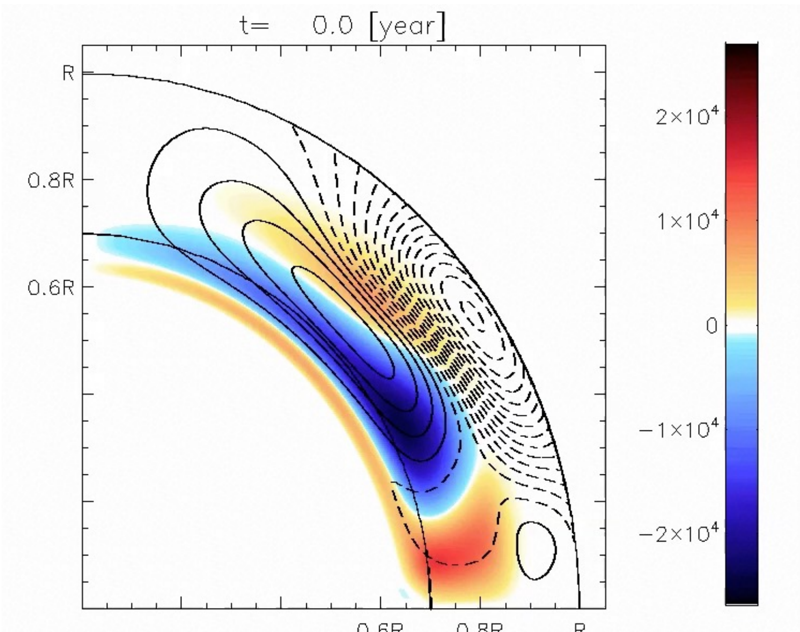
→Longer observation + α is needed.

Importance of meridional flow

1. Meridional flow determines cycle length (11-year) in flux transport dynamo.
2. Information on turbulence (convection) in the solar convection zone.

Cycle length: $T = 56.8 v_0^{-0.89} s_0^{-0.13} \eta_{\mathrm{T}}^{0.22}$, v_0: meridional flow velocity, s_0: α-effect, η_{T} : turbulent diffusivity (Dikpati & Charbonneau, 1999)

Ex. of flux transport dynamo



Hotta & Yokoyama, 2010

$$\underbrace{\left(\rho_0 \langle \boldsymbol{v}_{\mathrm{m}} \rangle \cdot \nabla\right) \langle \mathcal{L} \rangle}_{\text{transport by meridional flow}} = \underbrace{-\nabla \cdot \left(\rho_0 \lambda \langle \boldsymbol{v}'_{\mathrm{m}} v'_{\phi} \rangle\right)}_{\text{transport by turbulence}}$$

Angular momentum transport by the turbulence and the meridional flow should be balanced.

The distribution of the meridional flow directly reflects the turbulent status.

Small-scale flow: Turbulence
Mean field theory

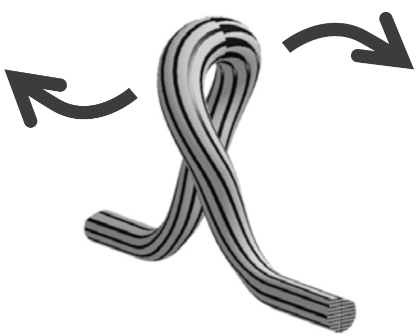
$$\frac{\partial\langle \boldsymbol{B}\rangle}{\partial t} = \nabla\times(\langle\boldsymbol{v}\rangle\times\langle\boldsymbol{B}\rangle) + \underbrace{\nabla\times\langle\boldsymbol{v}'\times\boldsymbol{B}'\rangle}$$

It is difficult (almost impossible) to observe small-scale flow and $\boldsymbol{B}$ simultaneously in the deep convection zone. We use theories to evaluate it. Mean-field theory suggests the electromotive force is written as (see Krause & Rädler, 1980 textbook)

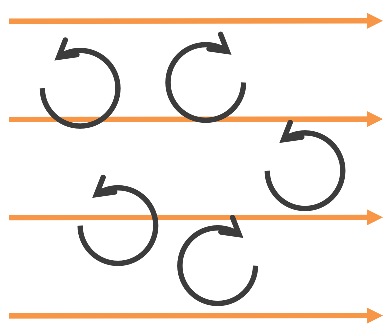
$$\langle\boldsymbol{v}'\times\boldsymbol{B}'\rangle = \alpha\langle\boldsymbol{B}\rangle - \beta\nabla\times\langle\boldsymbol{B}\rangle$$

$$\alpha = -\frac{\tau}{3}\langle\boldsymbol{v}'\times(\nabla\times\boldsymbol{v}')\rangle\,,\ \ \beta = \frac{\tau}{3}\left\langle|\boldsymbol{v}'|^2\right\rangle$$

α-effect

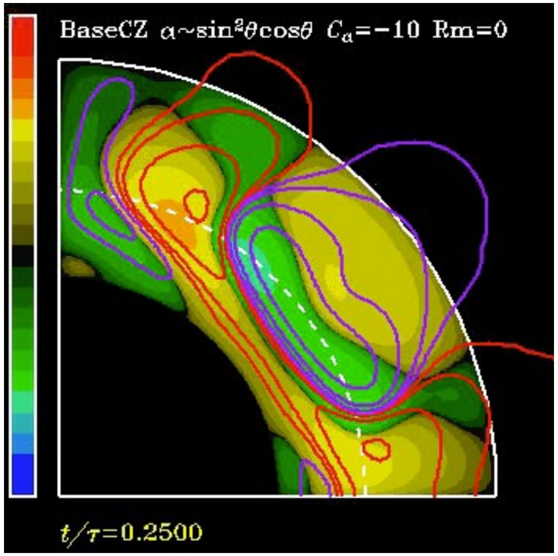


β-effect



Helical flow leads to construction of large-scale $\boldsymbol{B}$. Cause of helical flow is rotation (Coriolis force). Relation between rotation and convection flow determines the helicity.
$\rightarrow$ We need to at least determine **convection velocity**

Importance of turbulent flow



Charbonneau, 2005

In $\alpha\Omega$ dynamo, the cycle period (11 years) is determined by the value of β (turbulent diffusivity).

The turbulence directly determines the cycle period.

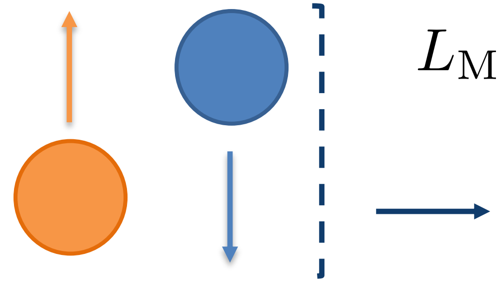
$$T \sim \left(\frac{\alpha}{2L}\frac{dv_\phi}{dL}\right)^{-1/2} \sim L^2/\beta \text{ (Parker, 1955)}$$

In addition, turbulence is also important for the construction of the large-scale flow (differential rotation and meridional flow) due to angular momentum transport.

$$\begin{aligned}
\frac{\partial}{\partial t}\left(\rho_0\langle\mathcal{L}\rangle\right) &= -\nabla\cdot\langle\rho_0\boldsymbol{v}_\mathrm{m}\mathcal{L}\rangle \\
&= -\nabla\cdot\left(\rho_0\langle\boldsymbol{v}_\mathrm{m}\rangle\langle\mathcal{L}\rangle\right) - \nabla\cdot\left(\rho_0\lambda\langle\boldsymbol{v}'_\mathrm{m}v'_\phi\rangle\right) \\
&= \underbrace{-\left(\rho_0\langle\boldsymbol{v}_\mathrm{m}\rangle\cdot\nabla\right)\langle\mathcal{L}\rangle}_{\text{transport by meridional flow}} \boxed{\underbrace{-\nabla\cdot\left(\rho_0\lambda\langle\boldsymbol{v}'_\mathrm{m}v'_\phi\rangle\right)}_{\text{transport by turbulence}}}
\end{aligned}$$

Small-scale flow: Turbulence
Mixing length theory (MLT) and simulation

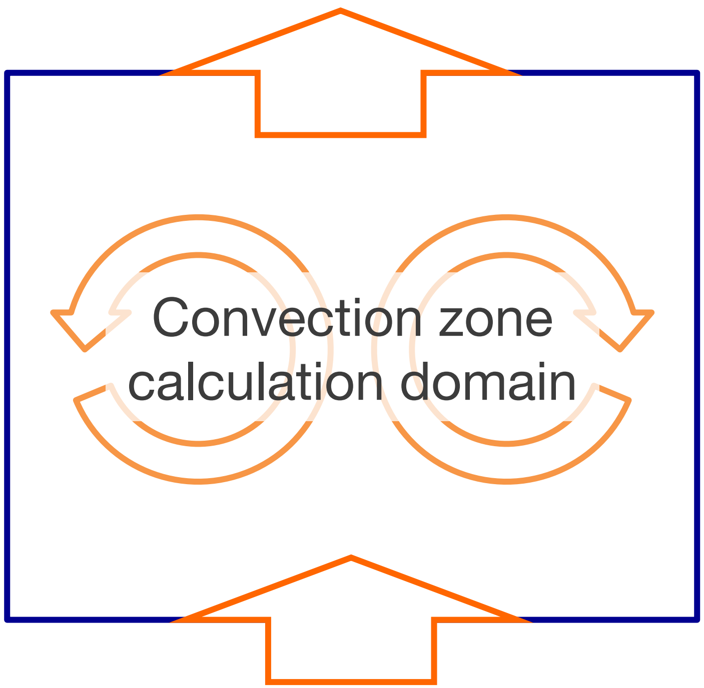
$$L_\odot = 3.84 \times 10^{33}\ \mathrm{erg\ s^{-1}}$$



$$L_{\mathrm{MLT}} = \alpha_{\mathrm{MLT}} H_p$$

Evaluate typical temperature perturbation

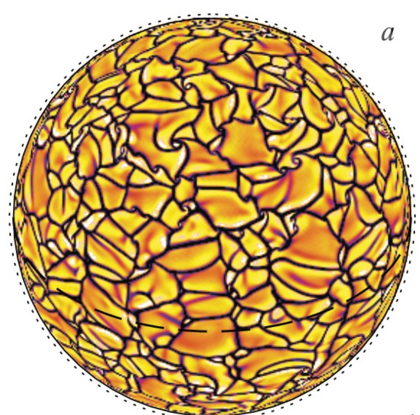
Radiation energy flux



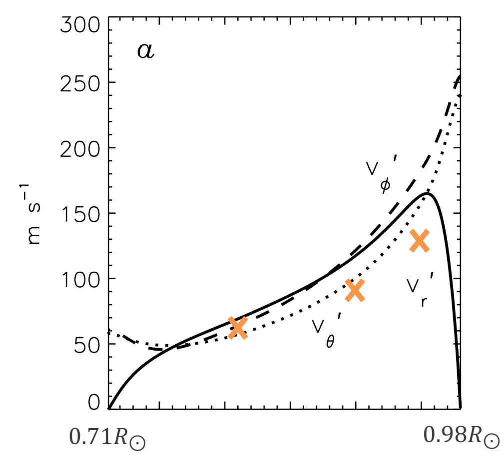
Radiation energy flux (well known value)

$$\frac{L_\odot}{4\pi r^2} = \langle \rho c_p \Delta T v_r \rangle \sim \langle \rho v_r^3 \rangle$$

Comparison with numerical simulation

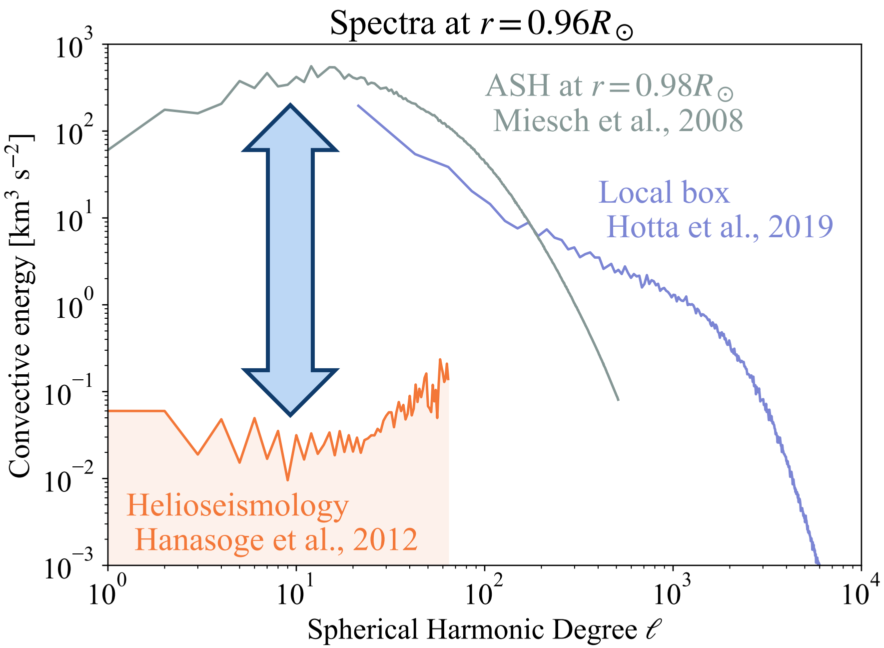


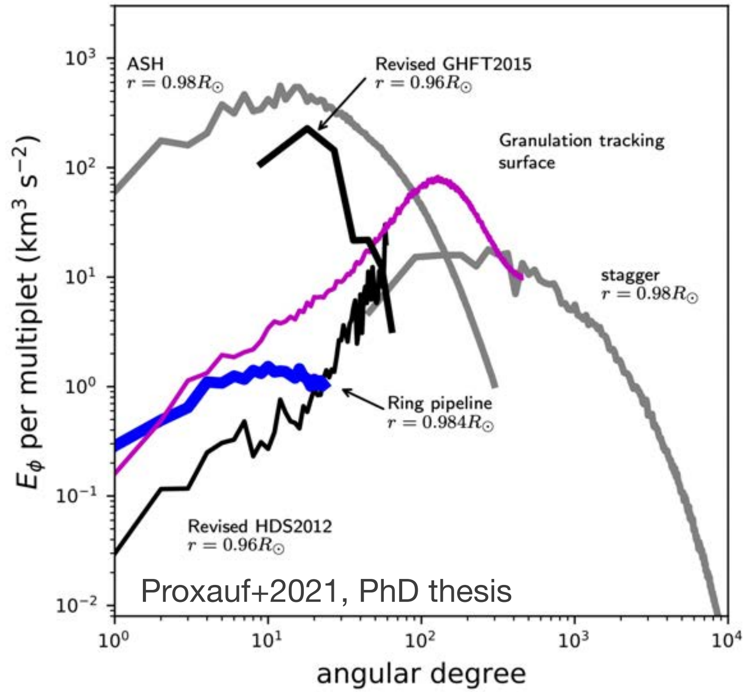
Miesch+2008



MLT and simulations are consistent

Current problems: Convective conundrum

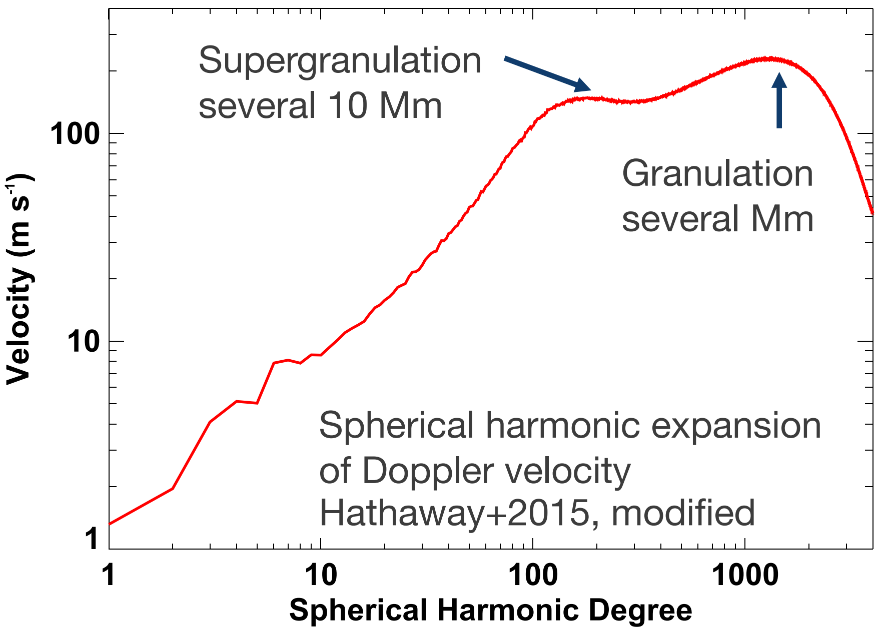




Travel time measurement by helioseismology possibly is able to evaluate the convective amplitude. Hanasoge+2012 suggest that the numerical simulations overestimate it order of magnitude larger.

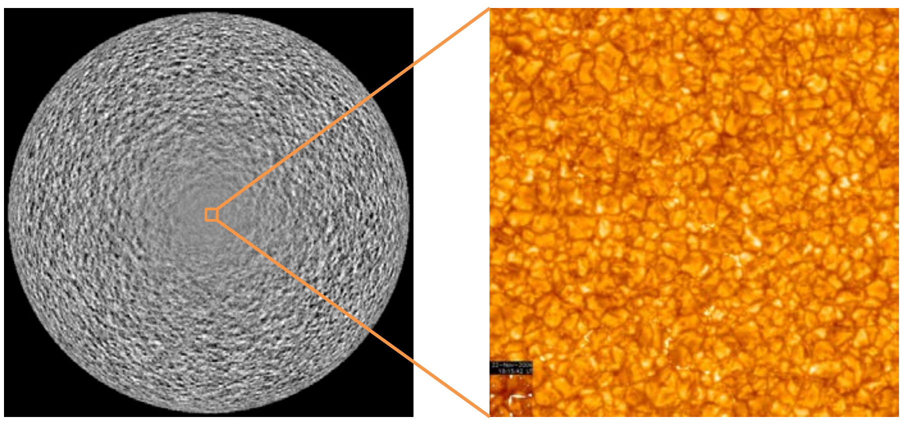
The observation is still controversial, but since then there have been a lot of doubts on the convective amplitude in theory and numerical simulations→**Convective conundrum**

Convective conundrum: Supergranulation

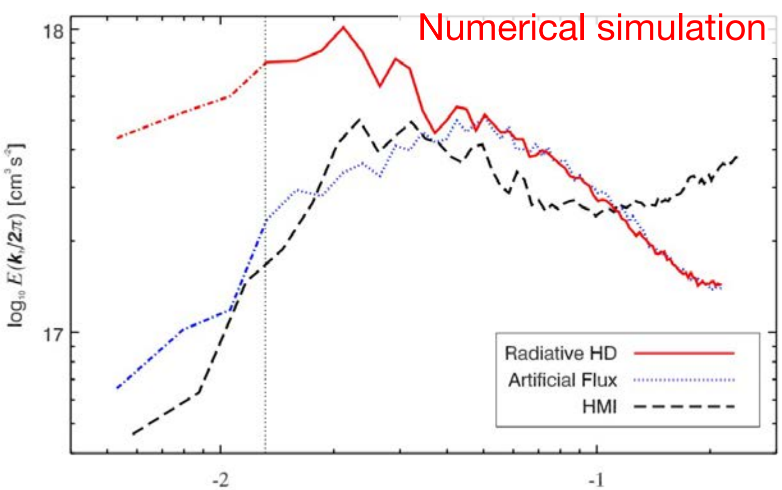


There are typical two convection scales

Supergranulation | Granulation



SOHO/MDI | Hinode/SOT

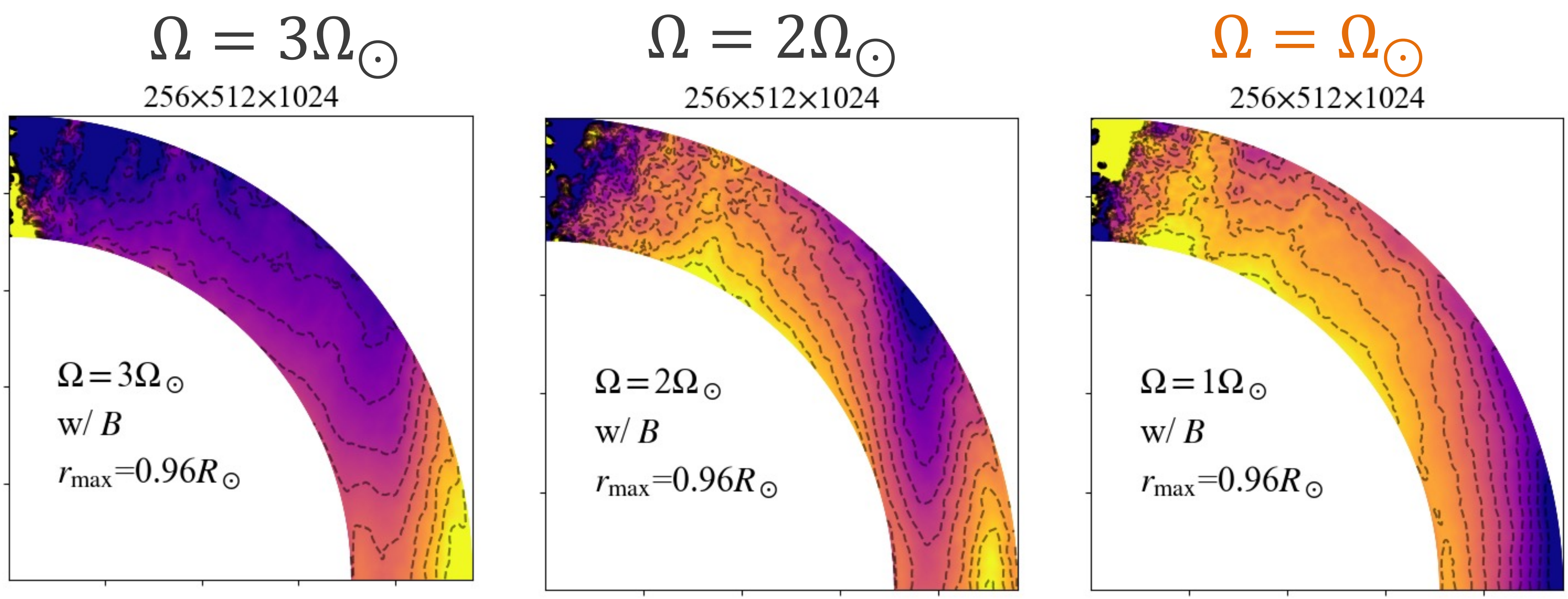


Lord+2014

Numerical simulations cannot reproduce supergranulation peak. A larger calculation shows the peak in the largest scale determined by calculation box size.

Convective conundrum: Differential rotation

We cannot reproduce the solar differential rotation with solar parameters



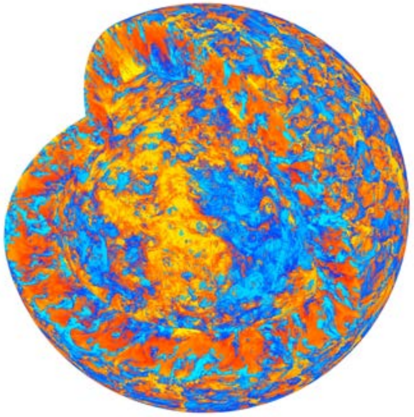
In the numerical simulation, the convection automatically transports angular momentum and construct the differential rotation. Recent high-resolution simulation falls into “anti-solar” differential rotation.
Convective amplitude in the simulations is too large.
(see O’Mara+2016)

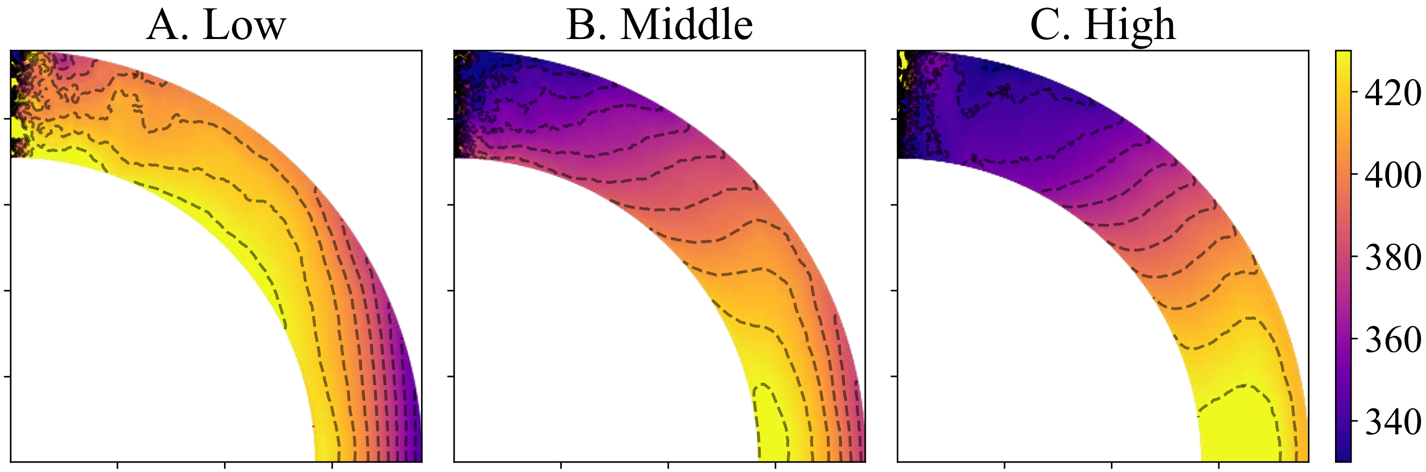
Summary of convective conundrum

The solar convective conundrum is summarized as:

- ✓ Huge discrepancy between observation and simulations
  - ➢ Observations is controversial
  - ➢ Simulations are consistent with each other (consistently wrong?)
- ✓ Supergranulation cannot be reproduced with simulations
- ✓ Solar-like differential rotation is not reproduced.
  - ✓ Recently solved with super high resolution simulation in Fugaku.

Our understanding of the thermal convection with a high Reynolds number is highly premature.





Hotta & Kusano, 2021, Nature Astronomy

Summary of solar observation

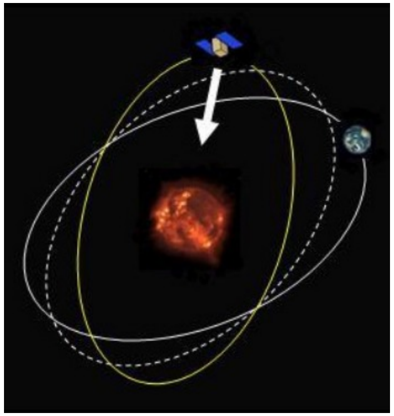
$$\frac{\partial \langle \boldsymbol{B} \rangle}{\partial t} = \underbrace{\nabla \times \left(\langle \boldsymbol{v} \rangle \times \langle \boldsymbol{B} \rangle \right)}_{\text{Effect by large-scale flow}} + \underbrace{\nabla \times \langle \boldsymbol{v}' \times \boldsymbol{B}' \rangle}_{\text{Effect by small-scale flow}}$$

- ✓ Large scale flow $\langle \boldsymbol{v} \rangle$ part:
  - ➢ Differential rotation has reached a consensus
  - ➢ Meridional flow in the deep layer is highly controversial
- ✓ Small scale flow $\boldsymbol{v}'$ part:
  - ➢ Observation is controversial
  - ➢ Theory and simulation may be wrong.

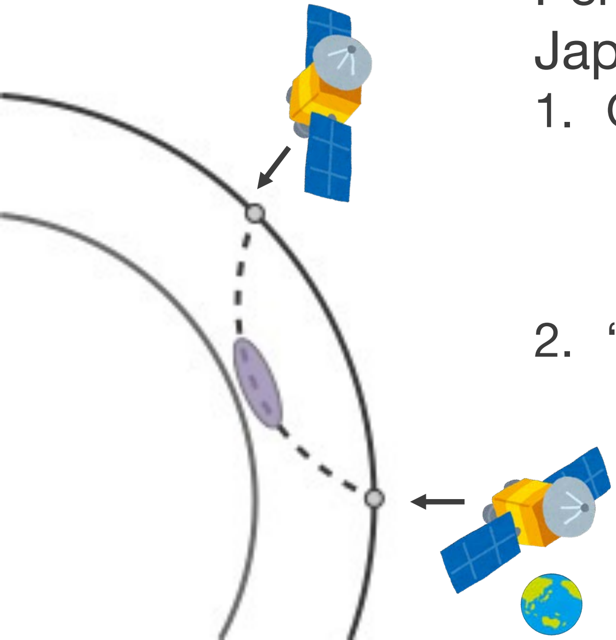
We have finally reached a status “I know that I know nothing (無知の知)”.

We have defined the problem. The next 10-20 years must be exciting for the solar interior study, but no Japanese mission challenges the problem…

Future perspective of solar interior research



Solar-C Plan-A WG



Solar-C Plan-A was planed 10 years ago.
Solar-C planned to be out-of-ecliptic orbit to observe the solar polar region. This type of mission is needed to understand the solar interior.

Solar-C Plan-A
Plan-B → (part of Plan-B) → Solar-C EUVST

Perspective to contribute the solar interior research from Japan

1. Observation from multiple points is necessary
   - Acoustic wave ray pass the deep layer.
   - Long stable observation is required.
   - Out-of-ecliptic orbit or L5 point is preferable
2. "Reliable" numerical simulation is needed.
   - Strong point of Japan
   - Useful for inversion
   - Definition of reliable: solar cycle, large-scale flow, travel time are consistent with observations.

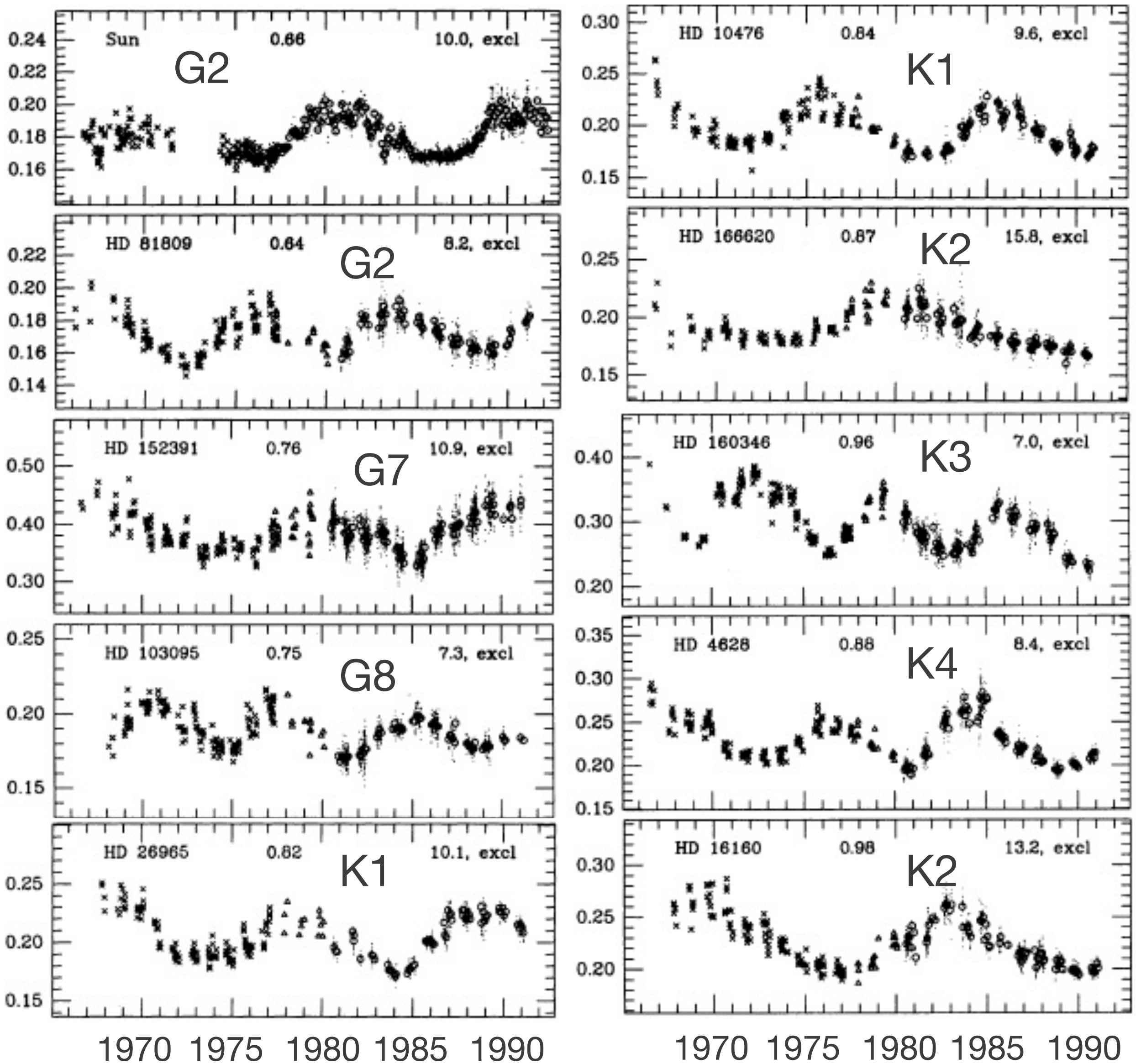
Future perspective of solar interior research

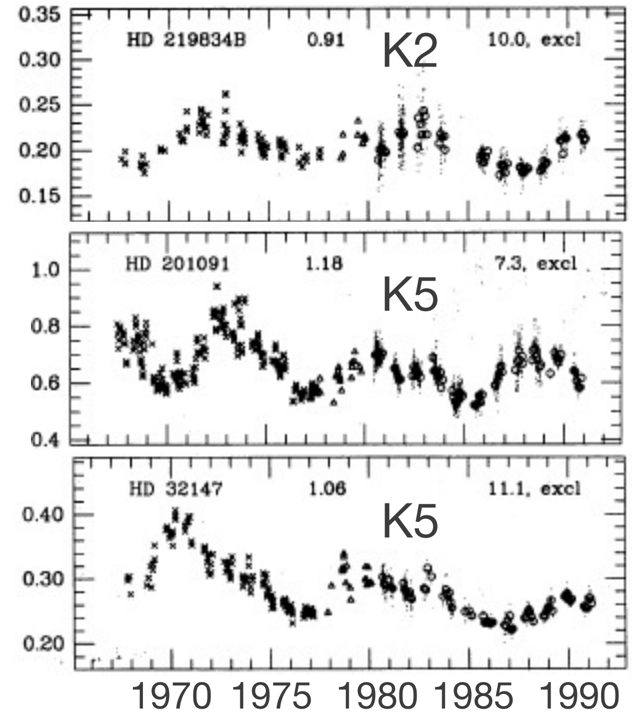
We should observe:

- ✓ Convection (turbulence)
  - ➢ Angular momentum transport: Differential rotation and meridional flow
  - ➢ $\boldsymbol{B}$ generation: Though the turbulent α- and β-effect
  - ➢ The cycle period is determined by turbulence itself in the $\alpha\Omega$ dynamo.
  - ➢ Convective amplitude in scales is important and then we can use theoretical approaches.

- ✓ Meridional flow
  - ➢ The cycle period is determined by the meridional flow in the flux transport dynamo (Dikpati & Charbonneau, 1999)
  - ➢ Meridional flow directly reflects the turbulent angular momentum transport → Important information on turbulence.
  - ➢ At least direction at the base of the convection zone should be determined.

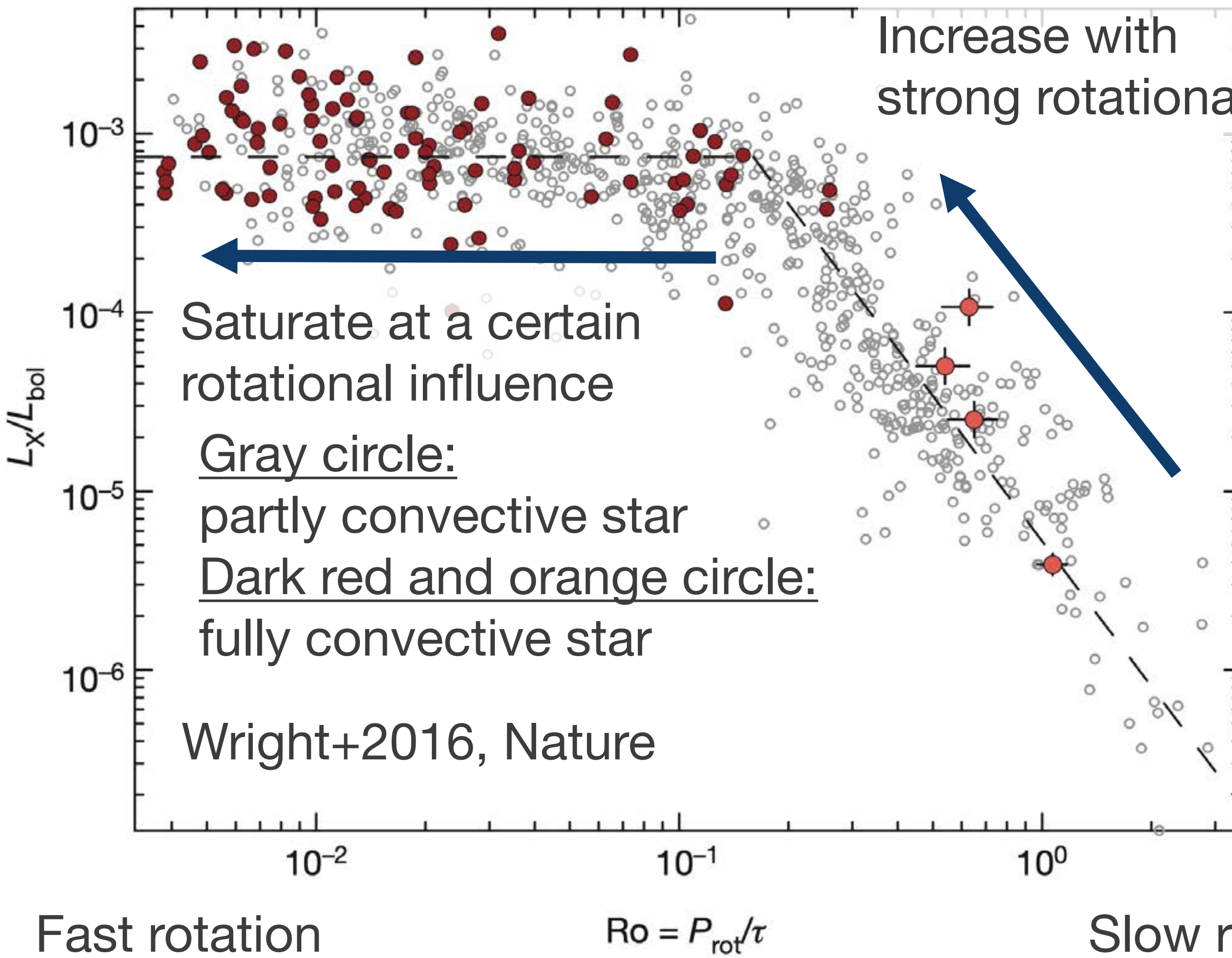
Stellar magnetic field cycle





The decade scale stellar activity cycle is also confirmed with the chromospheric activity.
(Baliunas+1995)

Rotation, convection, magnetic field in stars



X ray luminosity

Increase with strong rotational influence

Saturate at a certain rotational influence

Gray circle:
partly convective star

Dark red and orange circle:
fully convective star

Wright+2016, Nature

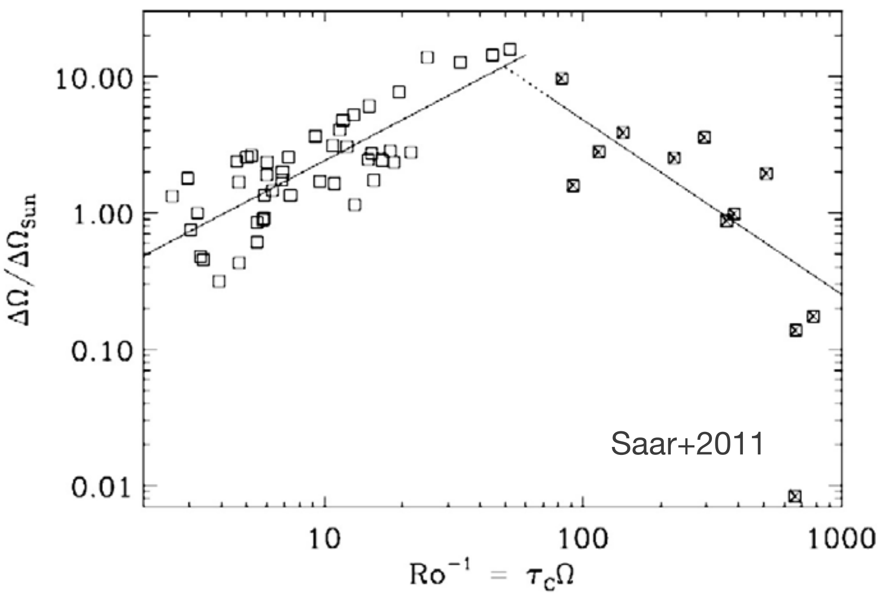
Fast rotation

Slow rotation

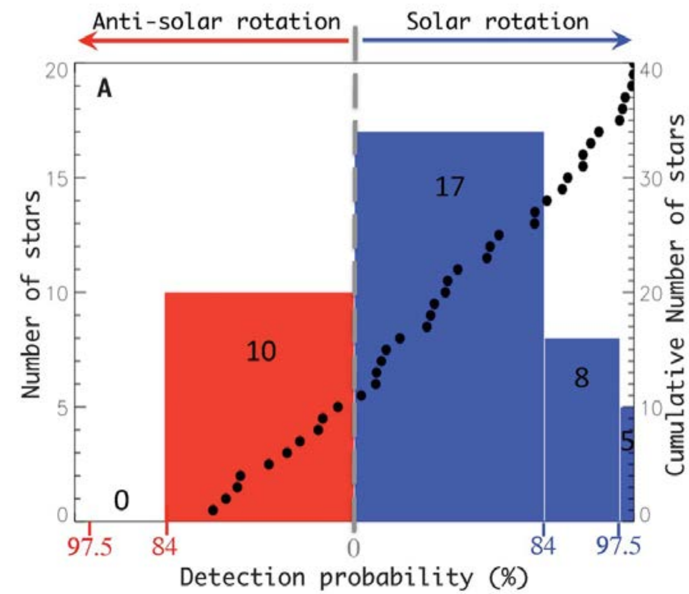
$$\text{Rossby number} = \frac{\text{Rotation time scale}}{\text{Convection time scale}}$$

Differential rotation (DR) in stars

Evaluation of DR with light curve



Evaluation of DR with asteroseismology

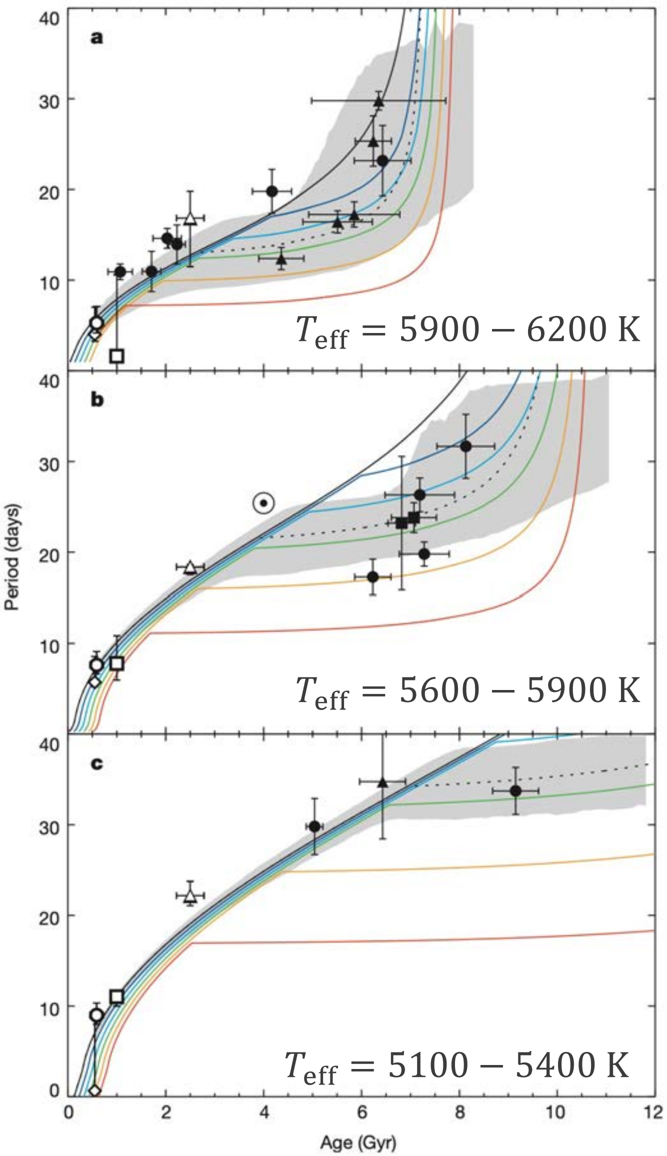


Benomar+2018, Science

We begin to evaluate the differential rotation $\Delta\Omega$ for stars with different Rossby number (Rotation/Convection).

This must be explained to understand the stellar magnetic activity.

Rotation evolution depend on magnetic field



van Saders+2016, Nature

Stars lose mass and angular momentum during their life and becomes slow down.

Age-rotation relation is used for evaluate the stellar age (gyrochronology).

Recent observation indicates that some older stars have rapid rotation rate than expected (van Saders+2016, Metcalf+2017).

The configuration of the magnetic field in these stars have changed significantly and stop losing further angular momentum.

The dynamo is also the key to understand it.

Summary

- ✓ The current and planed solar project in Japan
  - ➢ There are a lot of projects to investigate:
    - Phospheric dynamics
    - Chromospheric/Coronal heatings
    - Magnetic reconnection
    - Solar wind/Coronal Mass Ejection
  - ➢ The central issue is the magnetic field
- ✓ Solar interior research
  - ➢ Unfortunately, Japan has no mission for this topic except for the numerical simulation
  - ➢ Differential rotation has reached a consensus
  - ➢ Meridional flow and convective amplitude have big uncertainty.
  - ➢ Japan should join observational project with multiple point helioseismology with taking advantage of the leading position of the numerical simulation project.
- ✓ Connection stellar research
  - ➢ Stars have cyclic activity variation
  - ➢ Convection-rotation relation (Rossby number) is important to understand the stellar activity and the differential rotation
  - ➢ Rotation evolution is significantly constrained by the magnetic field (dynamo)
  - ➢ Stelar activity is also important for habitability in exoplanet.