Local helioseismology of high-latitude regions

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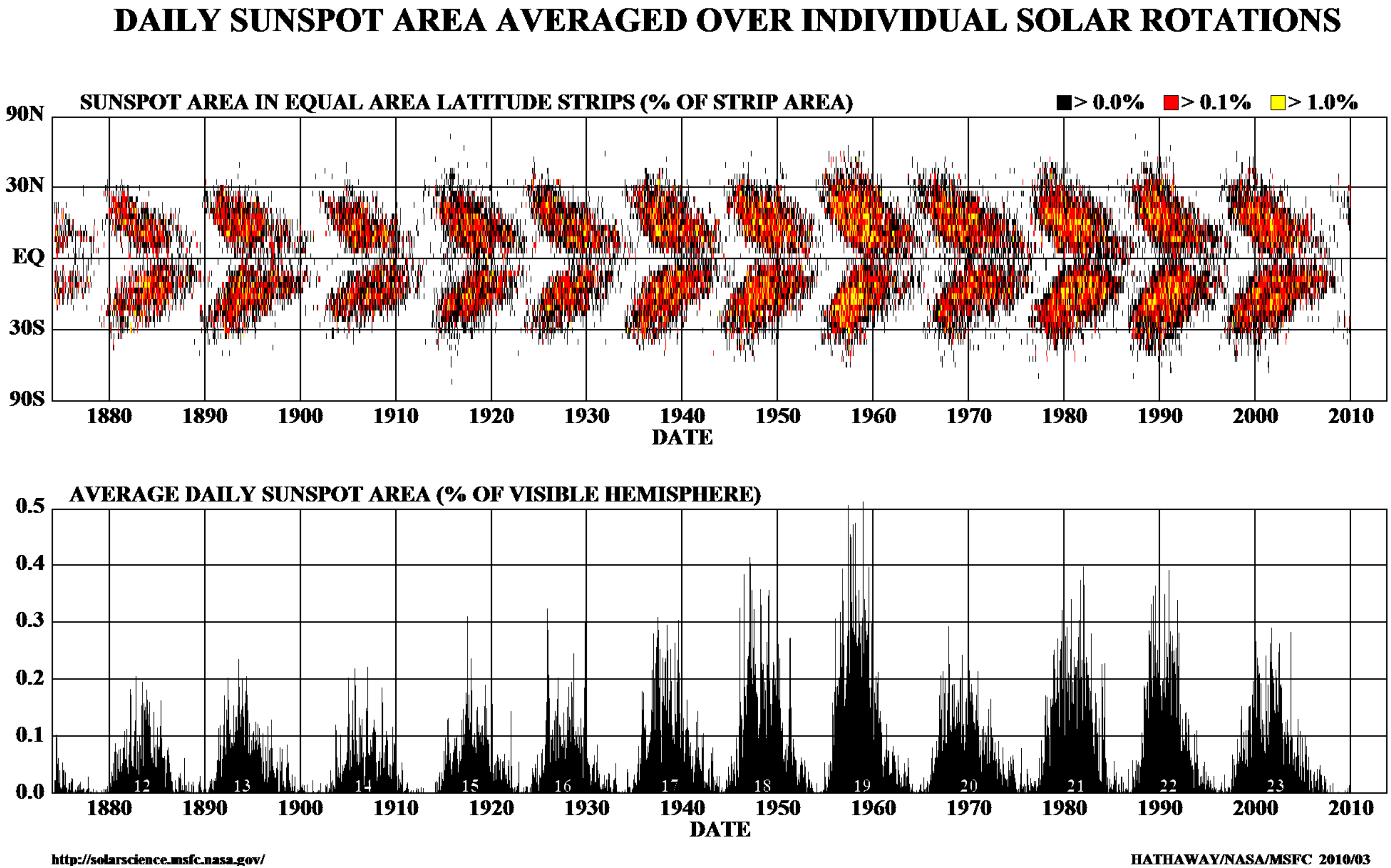
Stanford University
and SOLAR-C Plan-A sub-WG

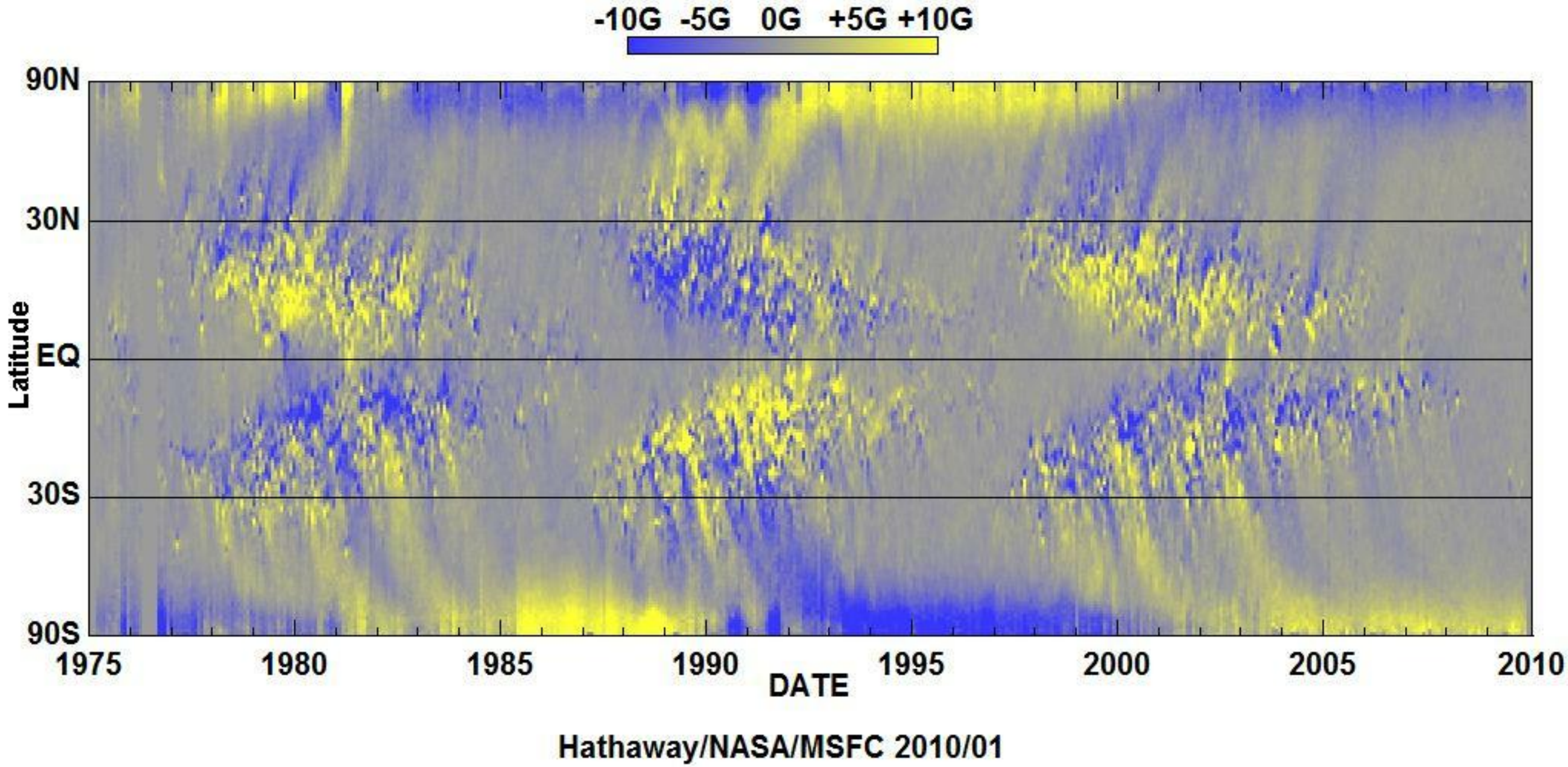
Outline

- Summary of the current status of the dynamo problem
- Key targets and helioseismology measurements
- Current status of local time-distance helioseismology
  - imaging active regions and sunspots
  - zonal and meridional flows and flux transport
  - imaging of the tachocline
  - observations of polar regions
- 4. Solar-C expected results and relations to SDO and Solar Orbiter
- 5. Instrument requirements

Solar sunspot cycle and the butterfly diagram



Magnetic Butterfly Diagram



The magnetic butterfly diagram. Axisymmetrical component of the line-of-sight magnetic field averaged over a full solar rotation as a function of time. Yellow and blue colors shows positive and negative magnetic fields

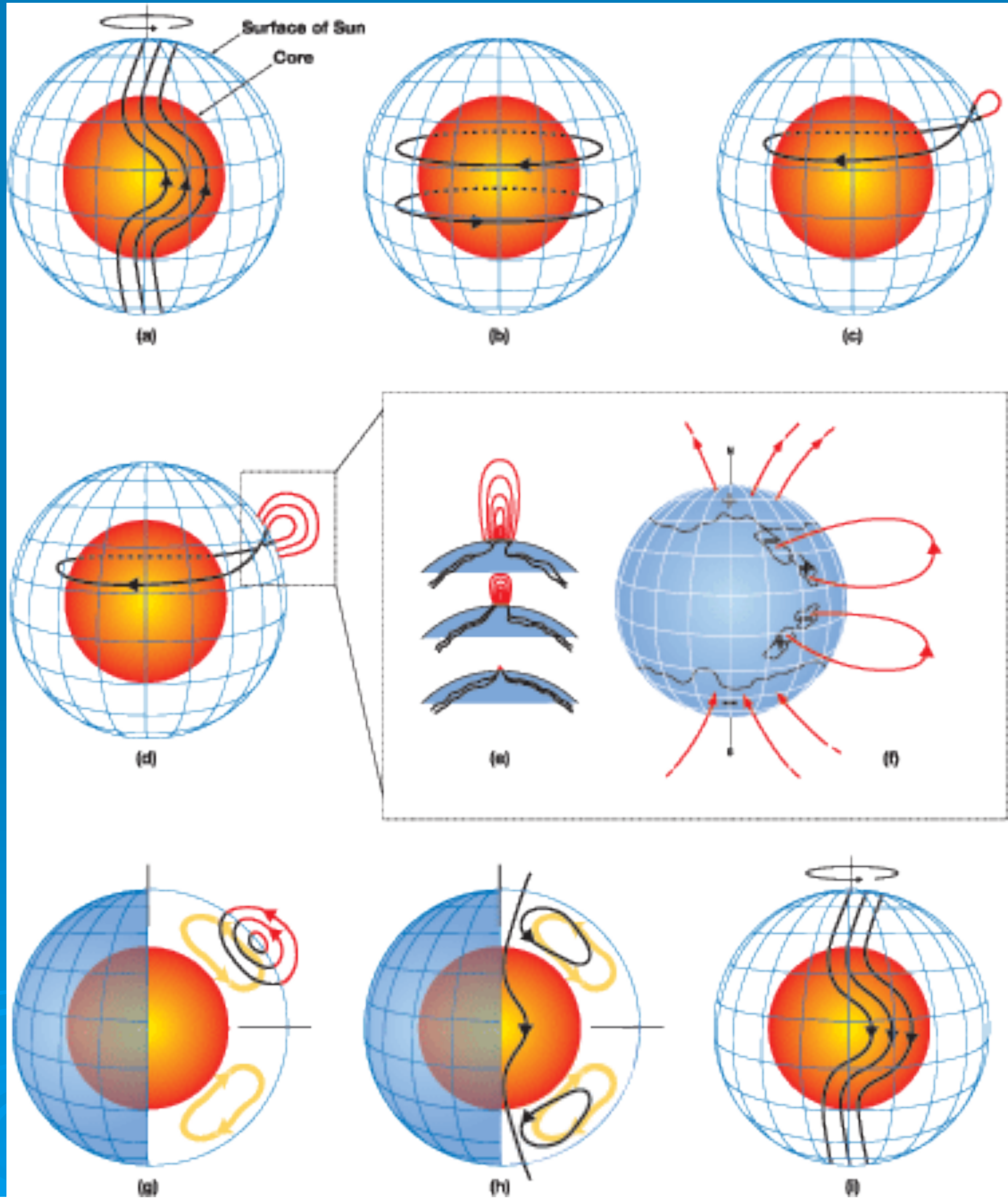
Schematic flux-transport dynamo model

1. Shearing of poloidal fields by differential rotation to produce new toroidal fields, followed by eruption of sunspots.

2. Spot-decay and spreading to produce new surface global poloidal fields.

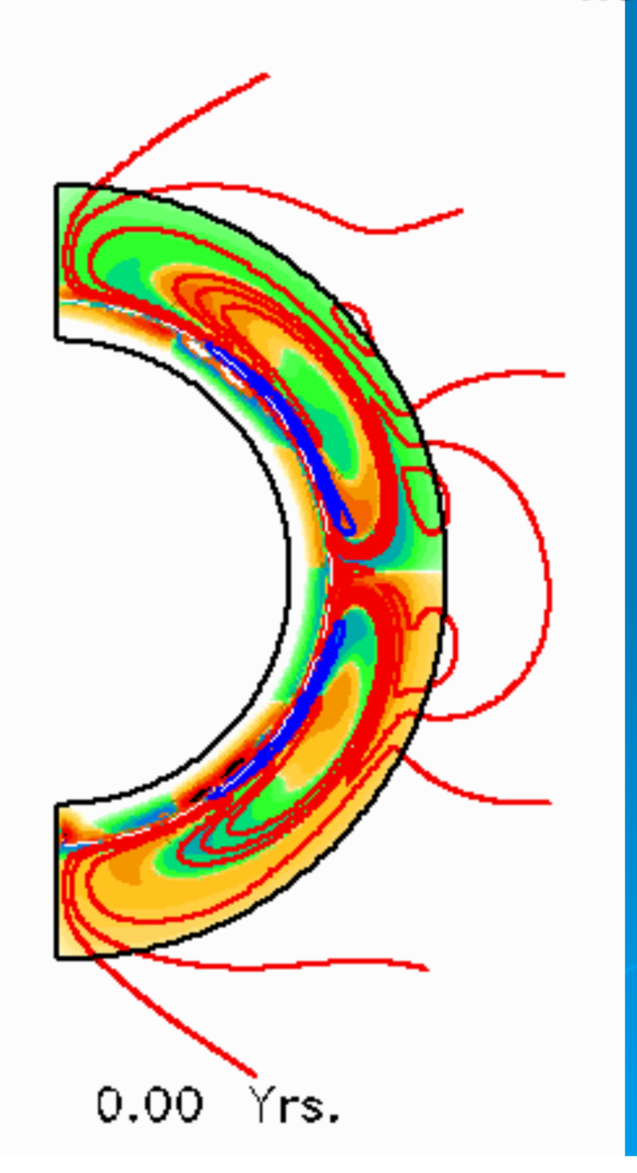
3.Transport of poloidal fields by meridional circulation (conveyor belt) toward the pole and down to the bottom, followed by regeneration of new toroidal fields of opposite sign.

Dikpati et al 2006

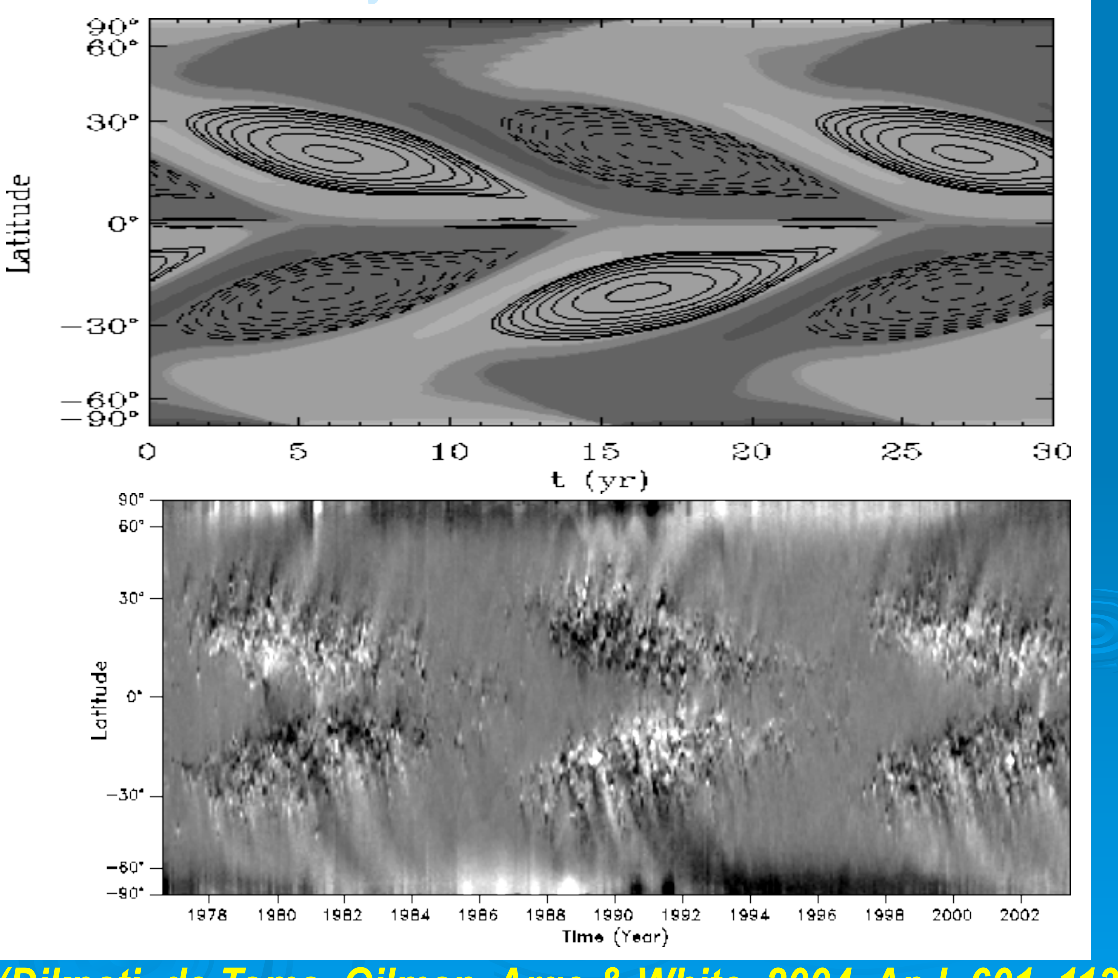


Calibrated flux-transport solar dynamo model:

numerical solution of 2D mean-field MHD equations
(differential rotation, meridional flow, supergranular diffusion, kinetic helicity are input parameters)

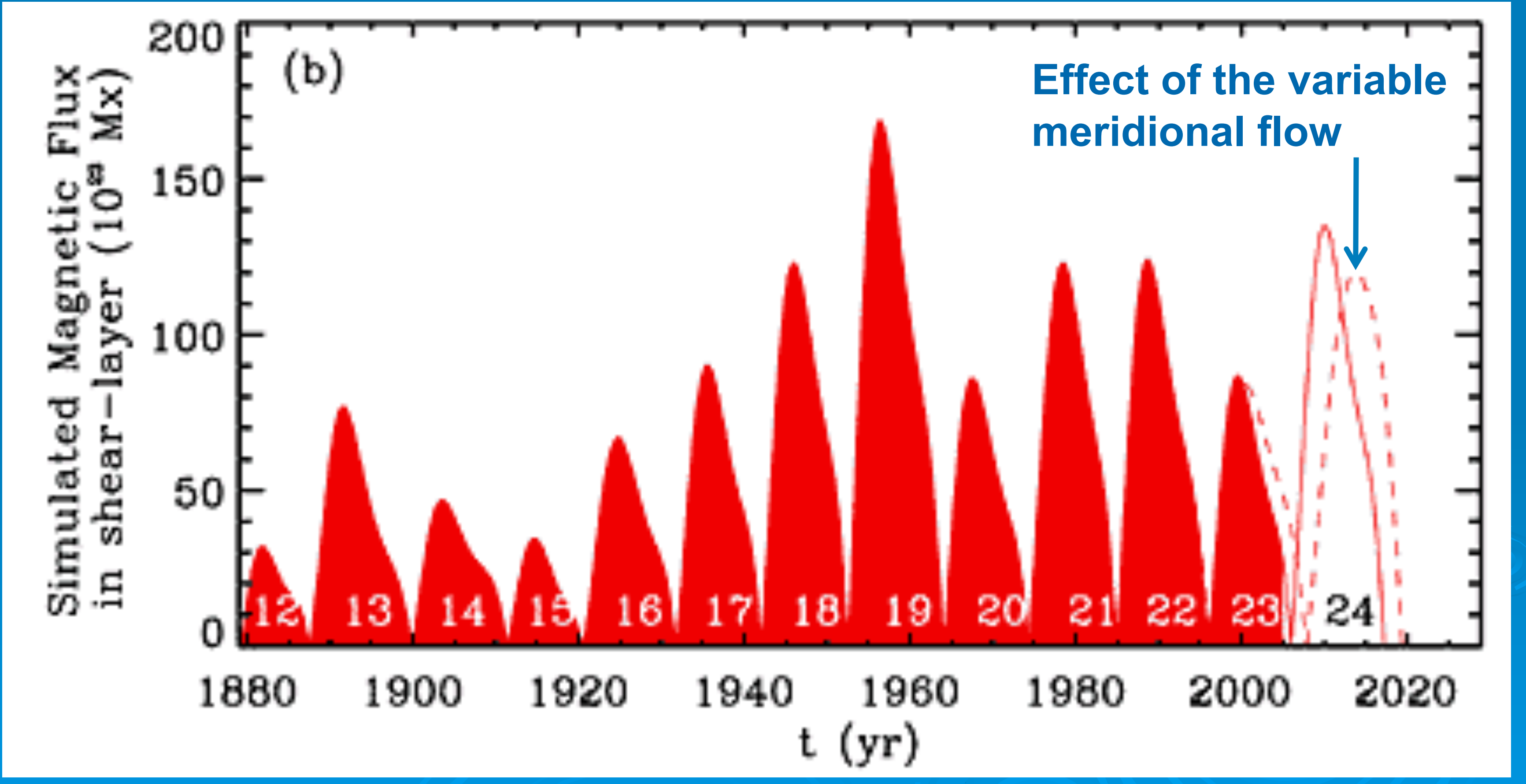


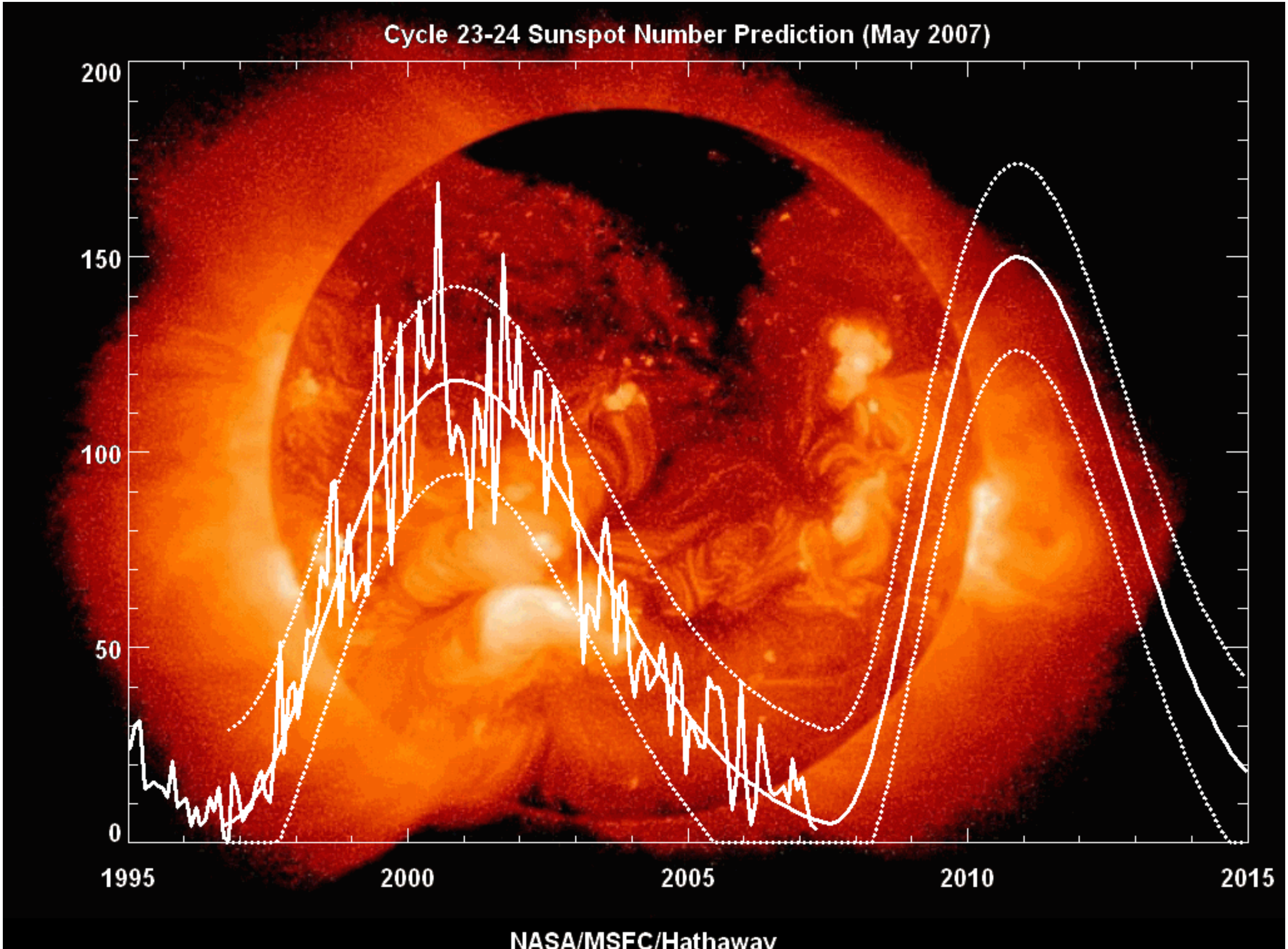
Contours: toroidal fields at CZ base
Gray-shades: surface radial fields



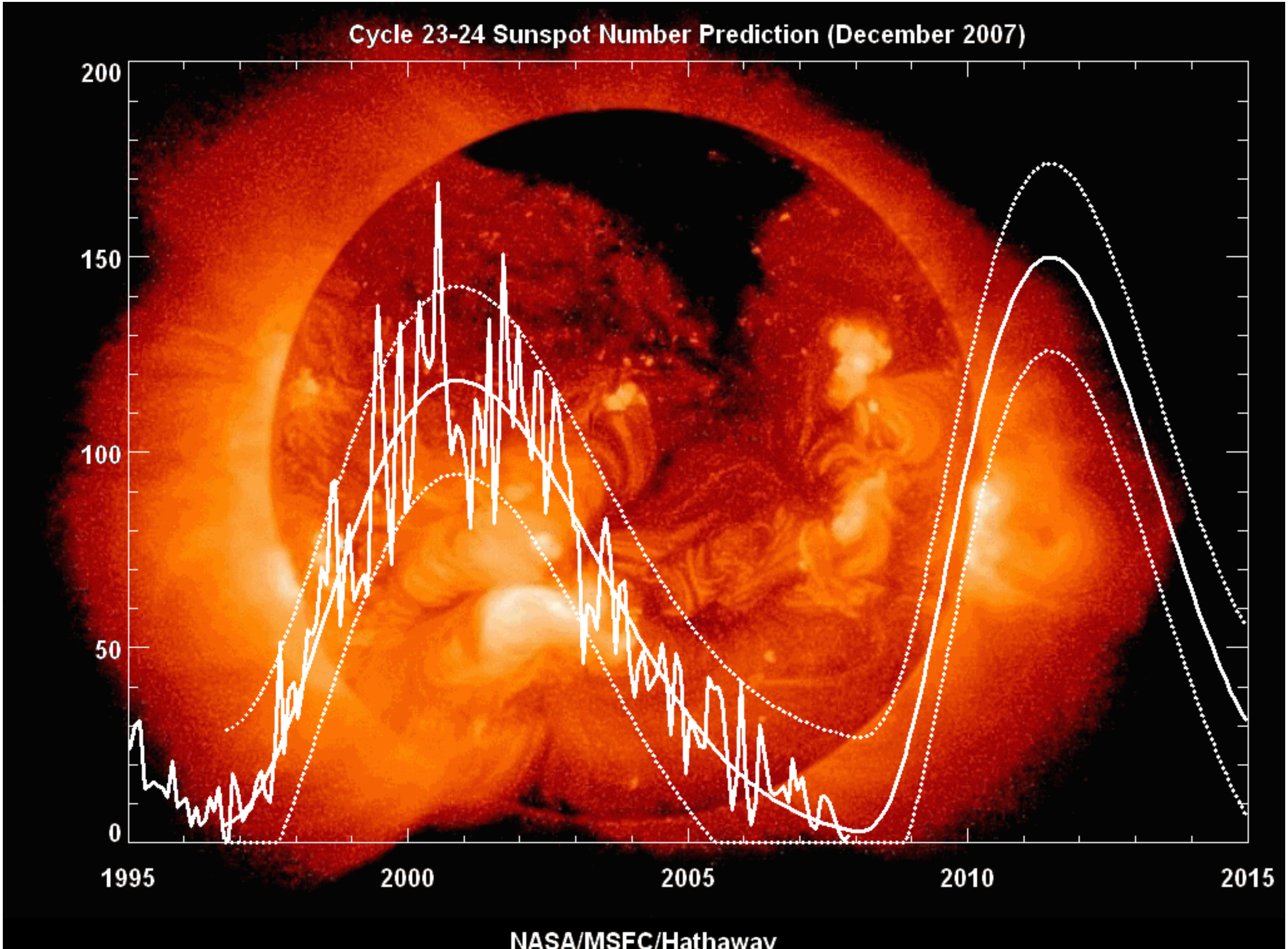
(Dikpati, de Toma, Gilman, Arge & White, 2004, ApJ, 601, 1136)

Flux-transport dynamo model predicts strong cycle 24 (Dikpati & Gilman 2007)

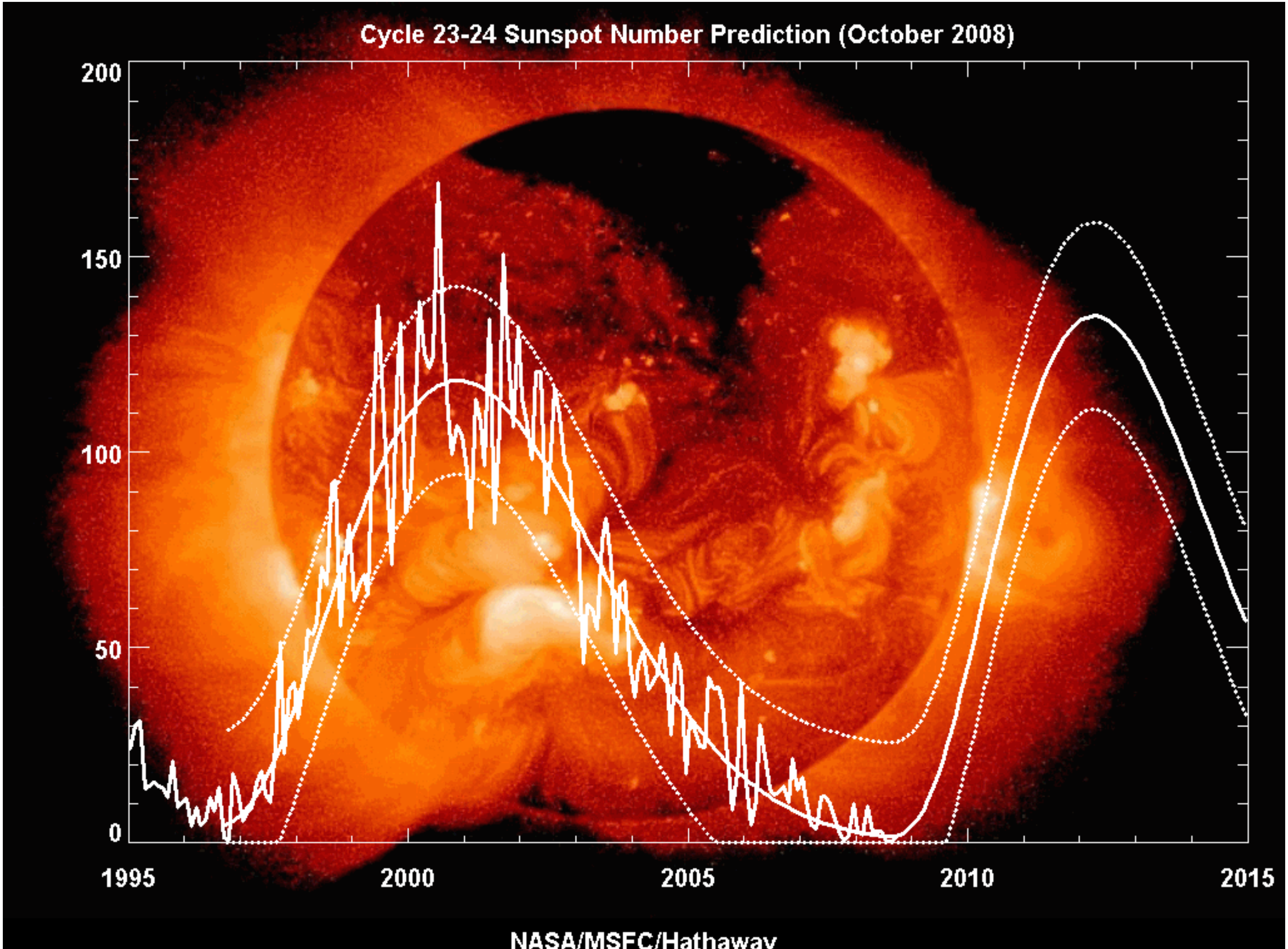


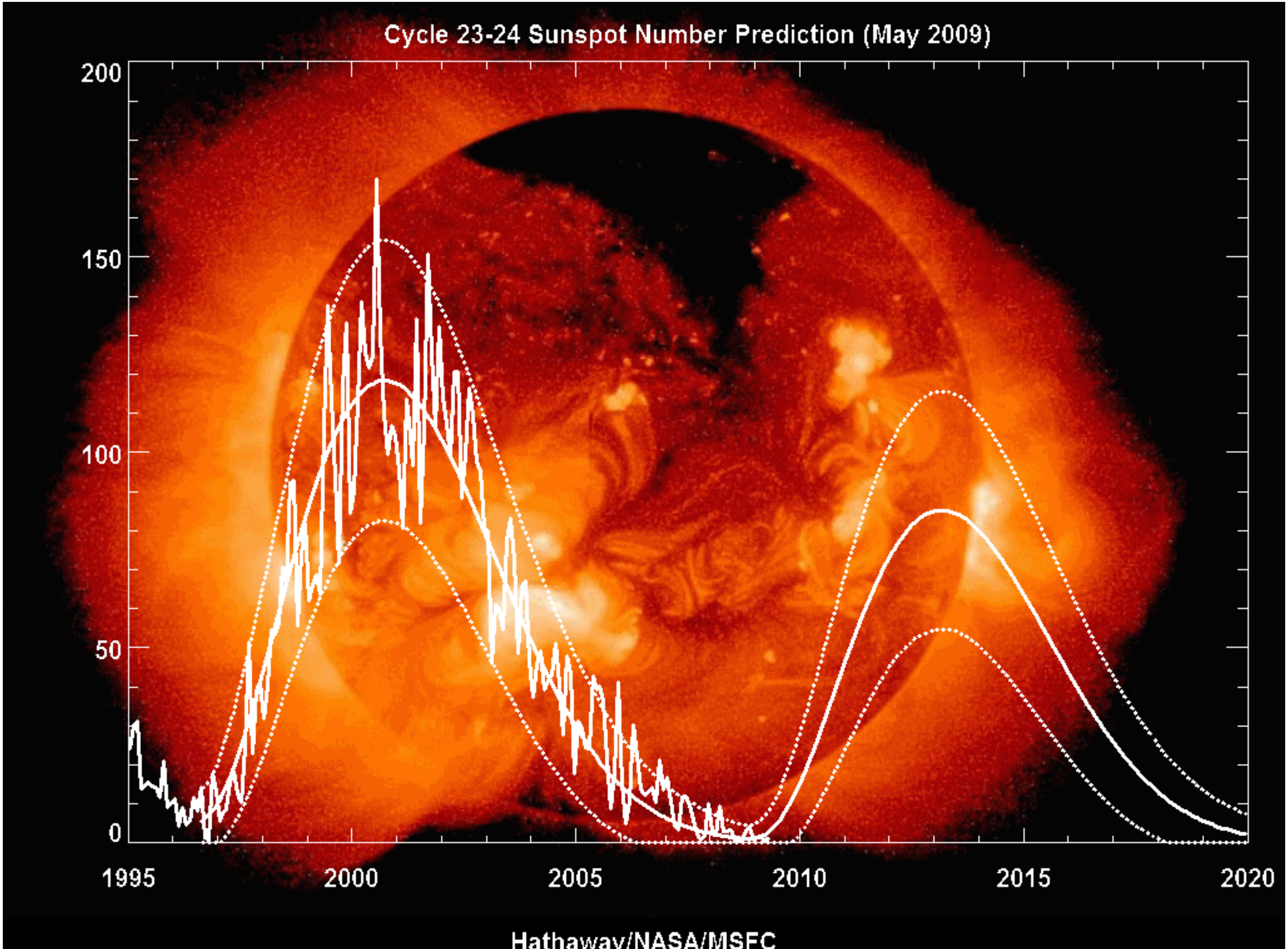


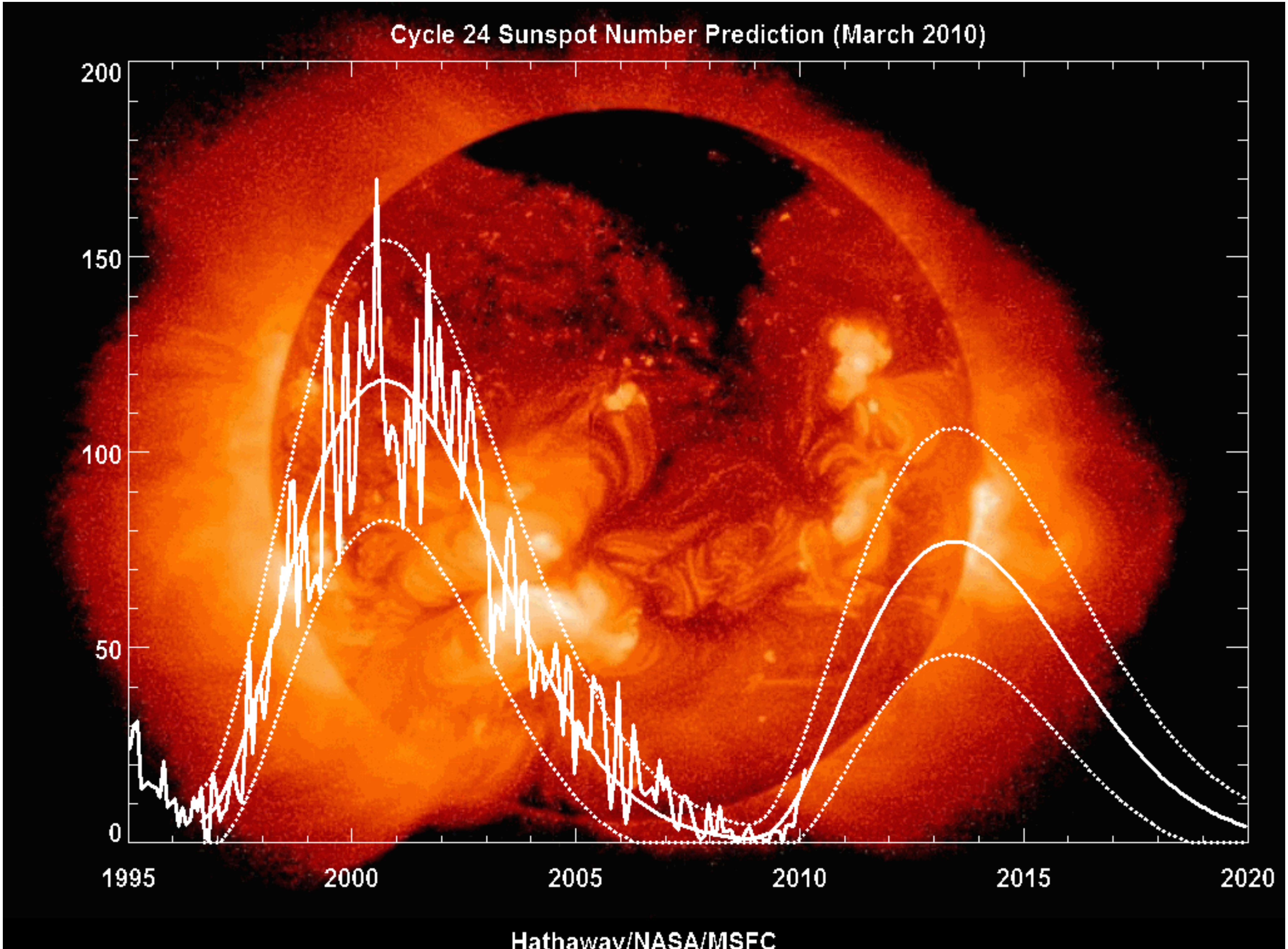
Cycle 23-24 Sunspot Number Prediction (May 2007)
200
150
100
50
0
1995
2000
2005
2010
2015
NASA/MSFC/Hathaway



Cycle 23-24 Sunspot Number Prediction (December 2007)
200
150
100
50
0
1995
2000
2005
2010
2015
NASA/MSFC/Hathaway

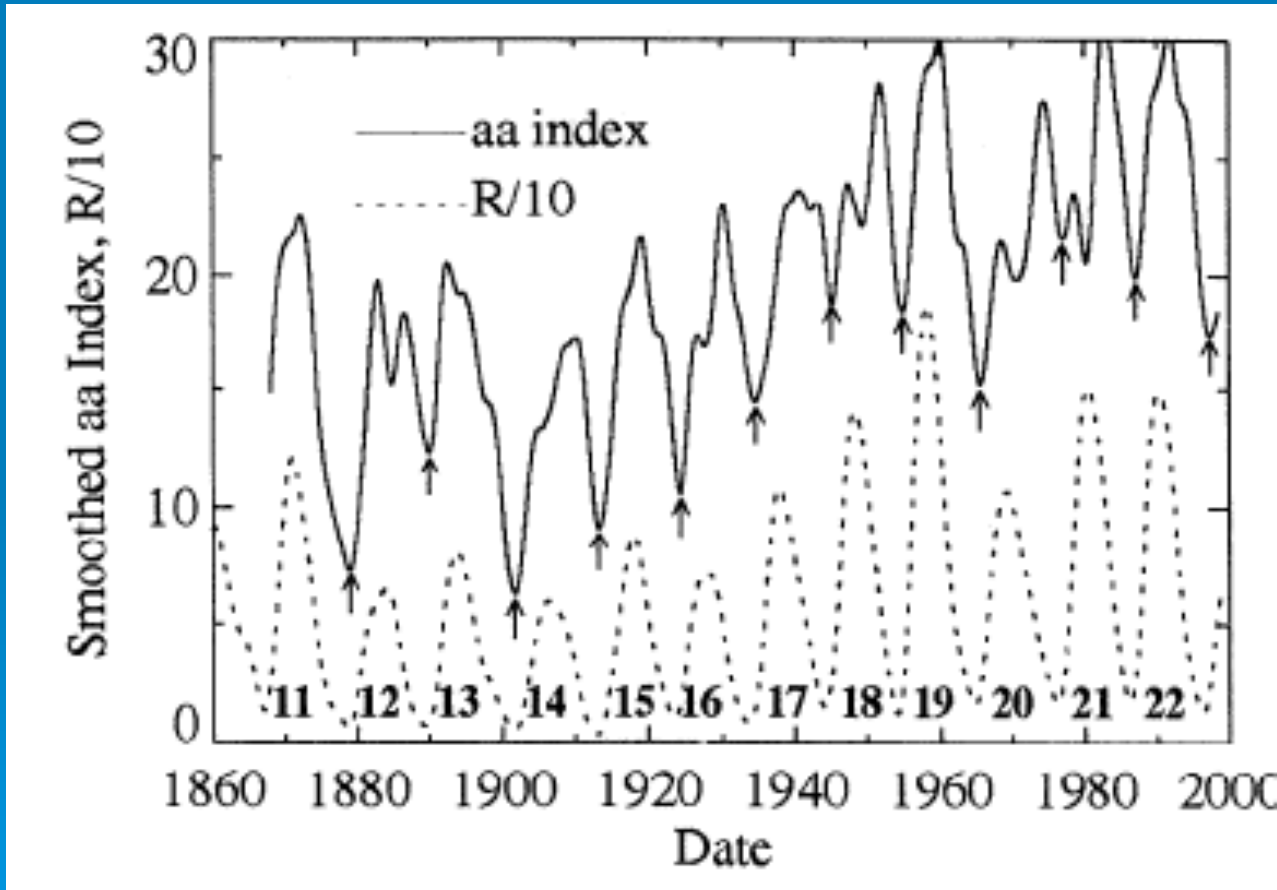

Cycle 23-24 Sunspot Number Prediction (October 2008)
200
150
100
50
0
1995
2000
2005
2010
2015
NASA/MSFC/Hathaway


Cycle 23-24 Sunspot Number Prediction (May 2009)
200
150
100
50
0
1995
2000
2005
2010
2015
2020
Hathaway/NASA/MSFC



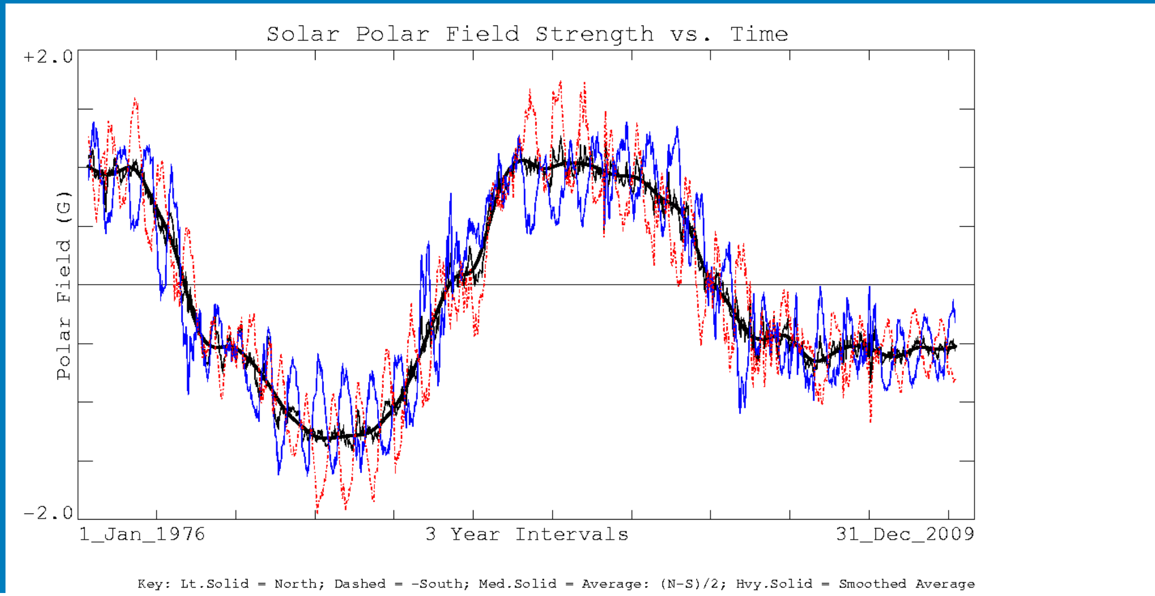
Cycle 24 Sunspot Number Prediction (March 2010)
200
150
100
50
0
1995
2000
2005
2010
2015
2020
Hathaway/NASA/MSFC

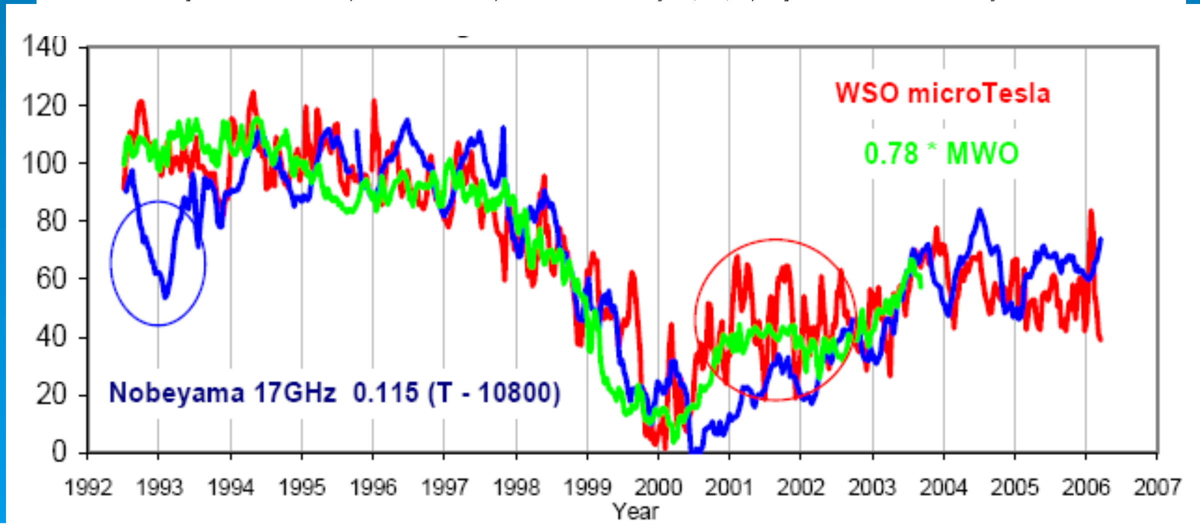
Geomagnetic aa index at the solar minimum is the best known indicator of the strength of the following solar cycle (Ohl, 1966)



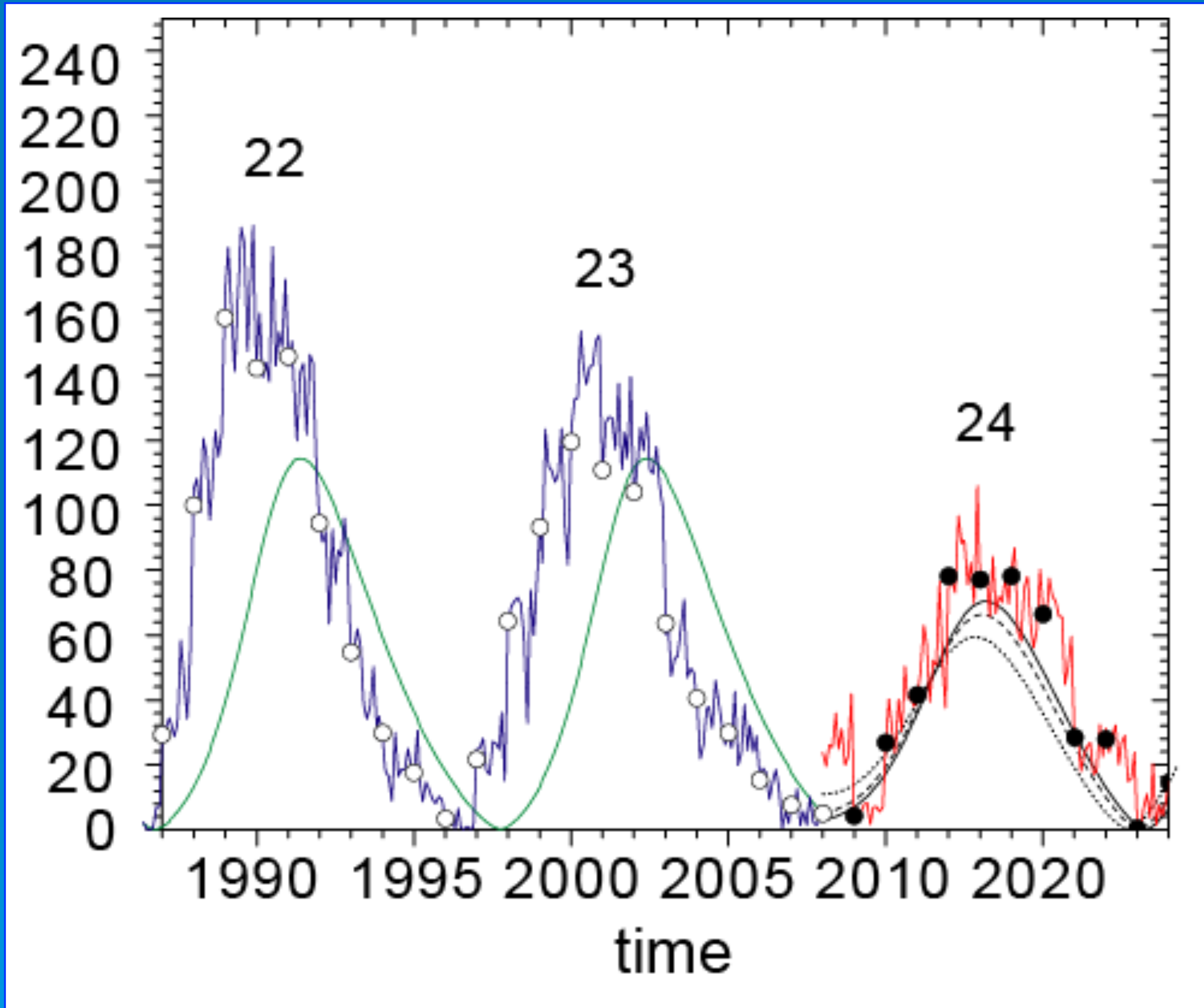
Hathaway, Wilson, Reichmann (1999)

Why? Because high-speed solar wind during the activity minima comes mostly from the polar regions.





Prediction of Solar cycle 24 by data assimilation method



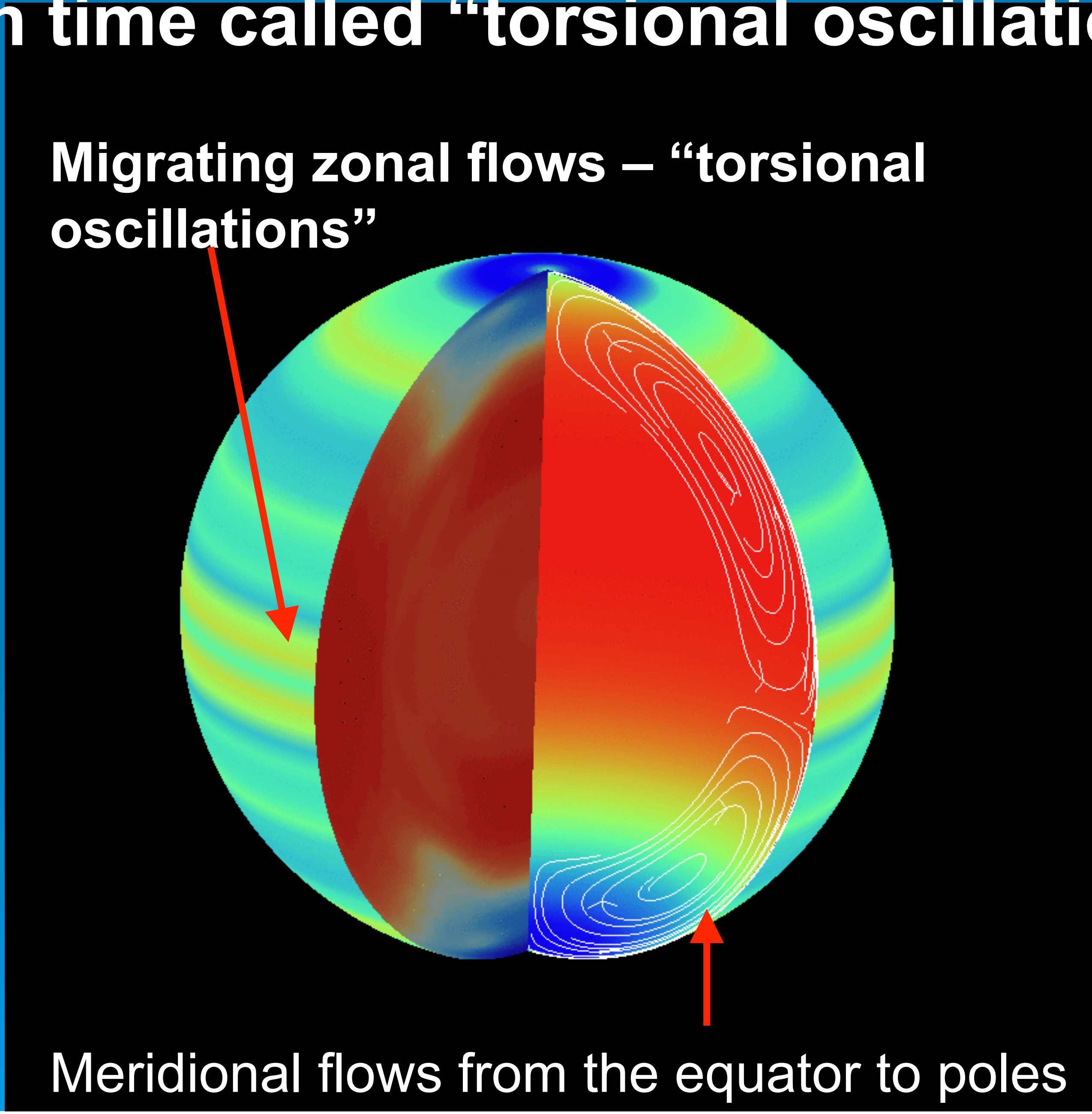
Kitiashvili & Kosovichev (2008)

Step 3: Prediction state of a system

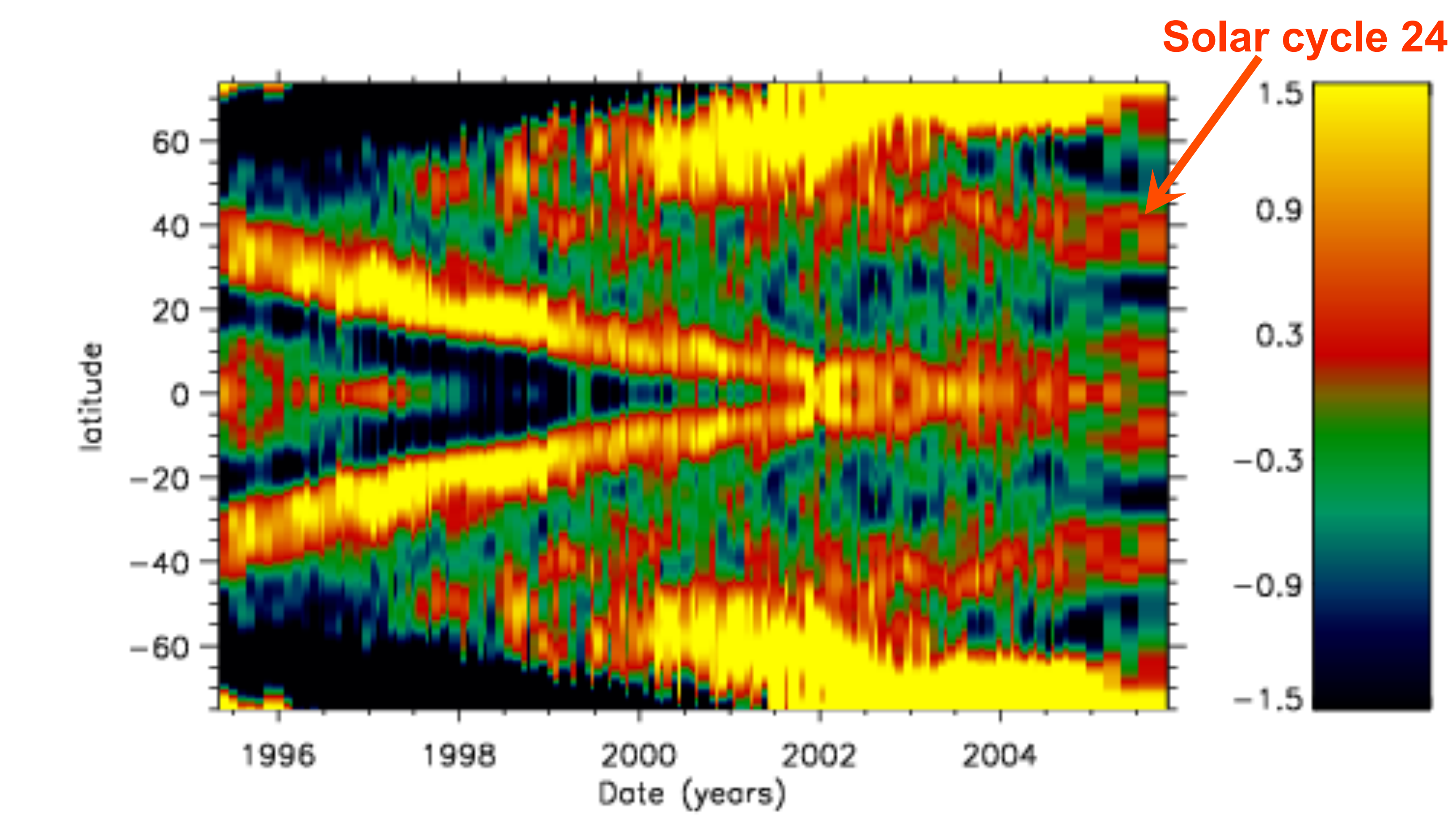
Key targets and helioseismology measurements

1. Torsional oscillations
2. Meridional flow
3. Flux transport (supergranular diffusion)
4. Complexes of activity
5. Flux emergence
6. Polarity reversals
7. Magnetic and kinetic helicity

Variations of the differential rotation with time called “torsional oscillations”

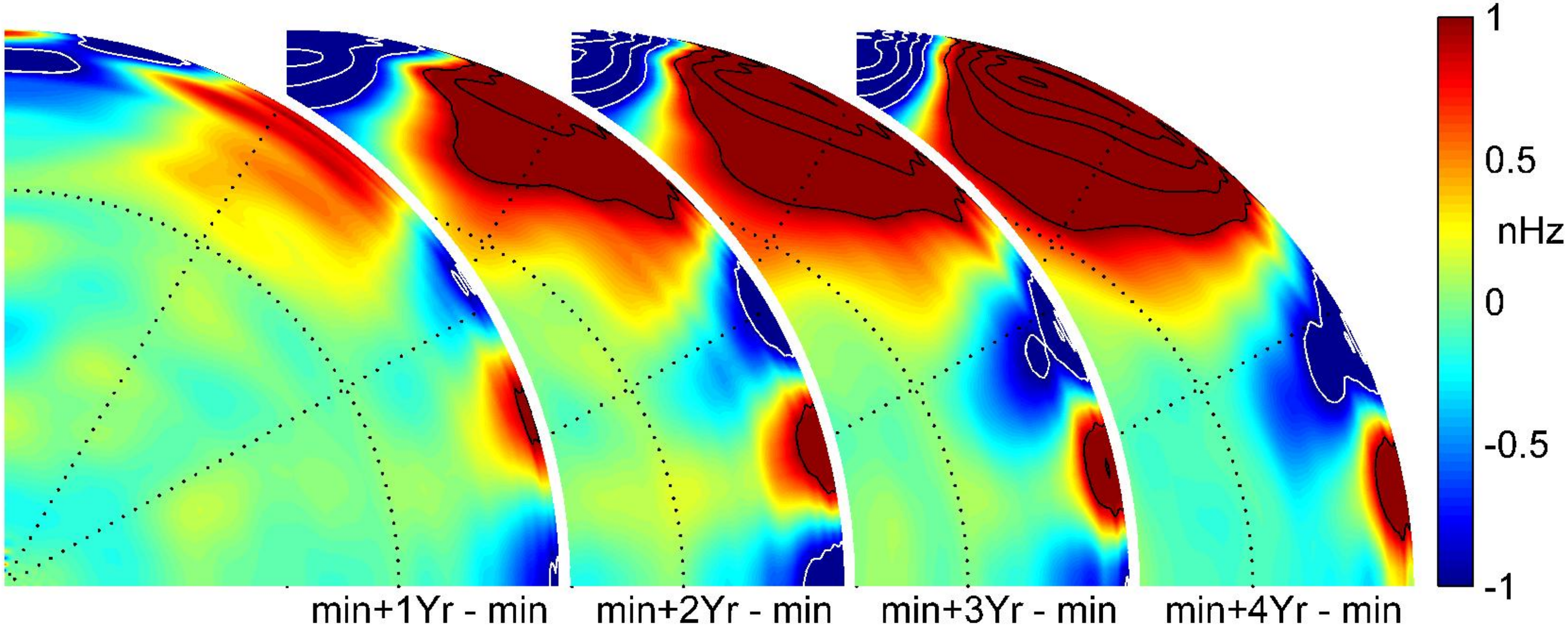


Magnetic fields emerge at the boundaries between fast and slow flows. Torsional oscillations show a start of the new cycle at high latitudes when there is no significant magnetic field on the surface



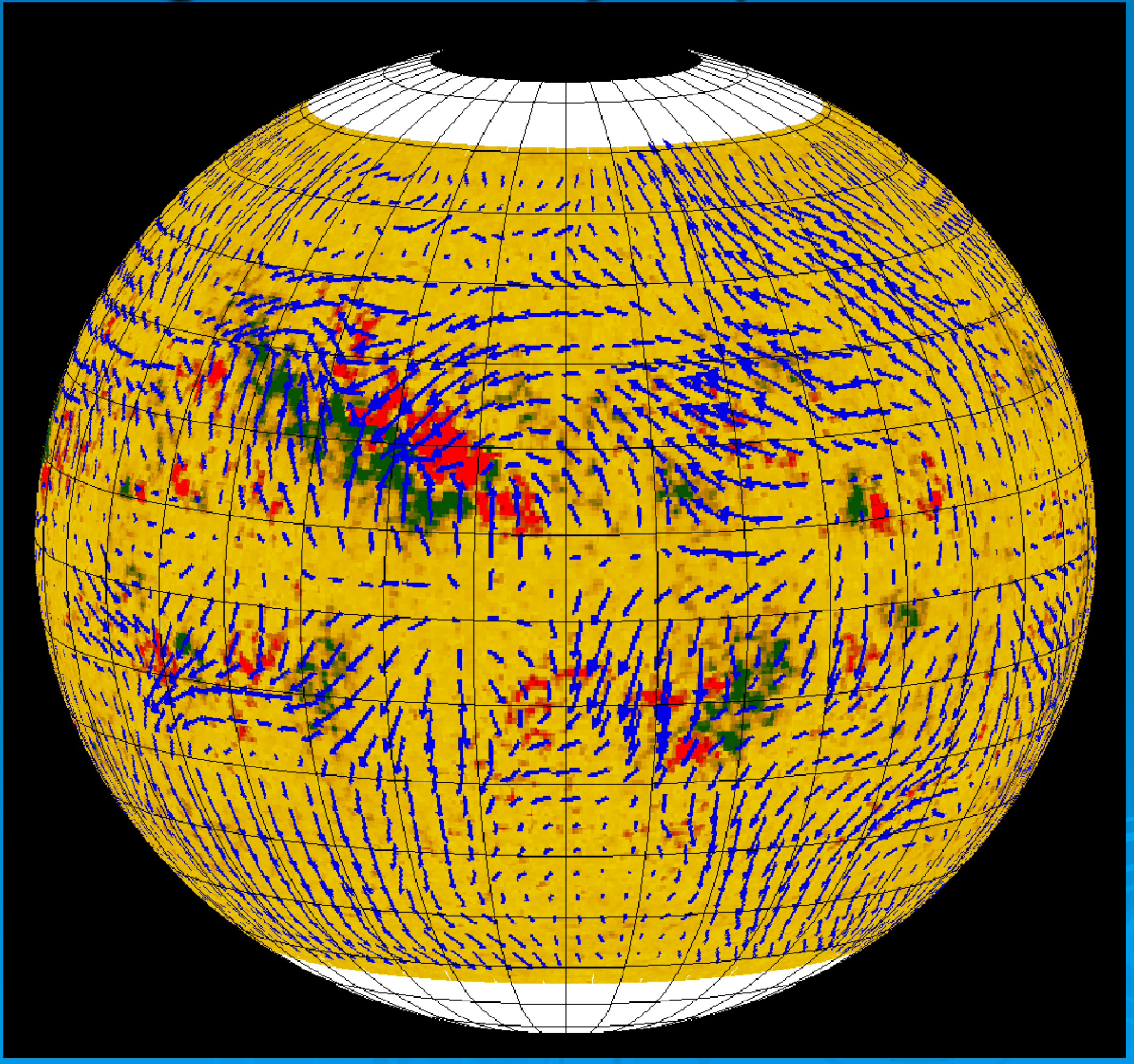
Howe et al (2006)

Strongest variations of the differential rotation are observed in high-latitude regions



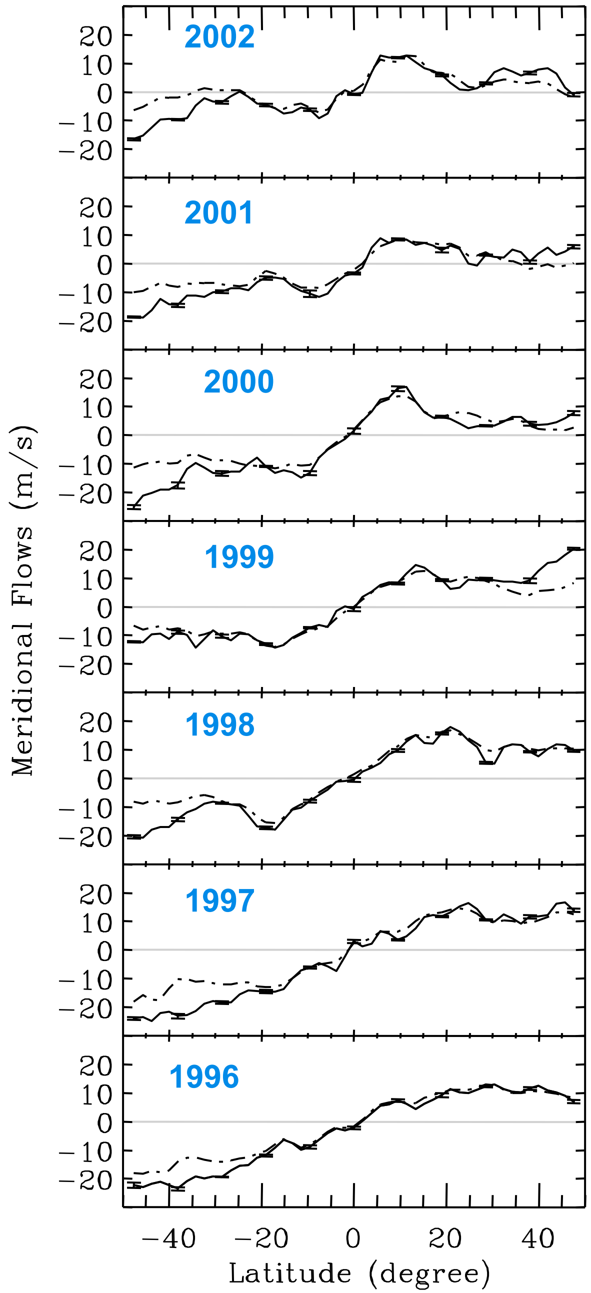
Vorontsov et al (2002)

Meridional flows can be measured from the large-scale synoptic flow maps



(Haber et al. 2002)

Solar-cycle variations of meridional circulation

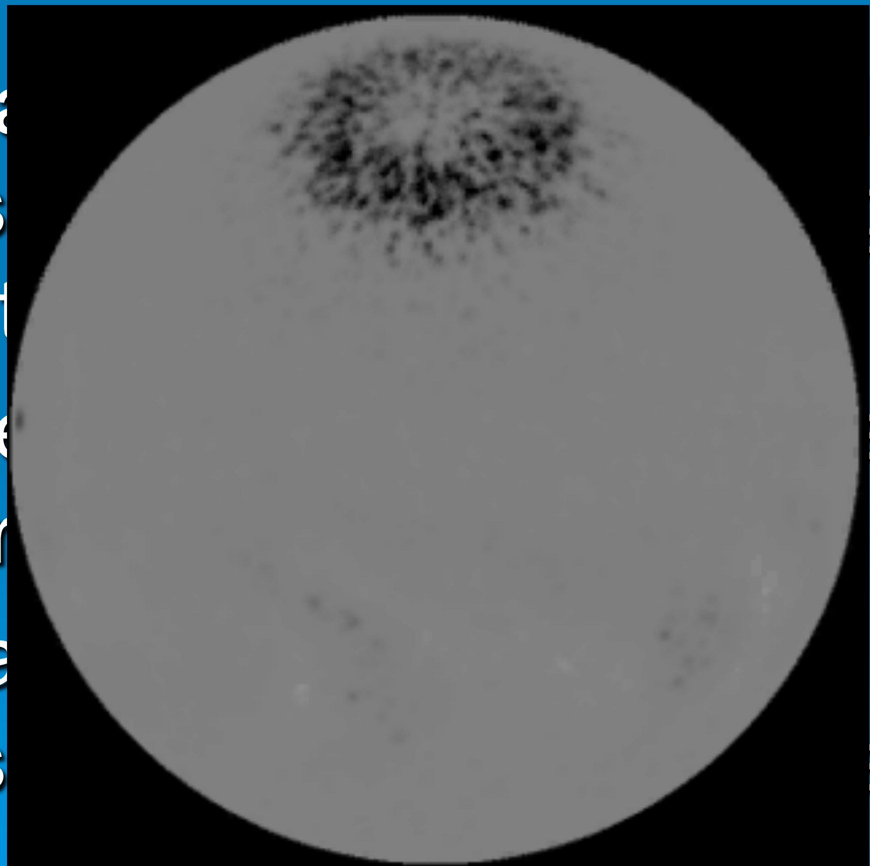


- In addition to the mean meridional flow from the equator to the poles we find extra meridional circulation cells converging towards the activity belts and migrating towards the equator as the solar cycle progresses

- Slowing meridional circulation at the solar maximum creates difficulties for flux transport dynamo models to explain reversals of the polar magnetic fields.

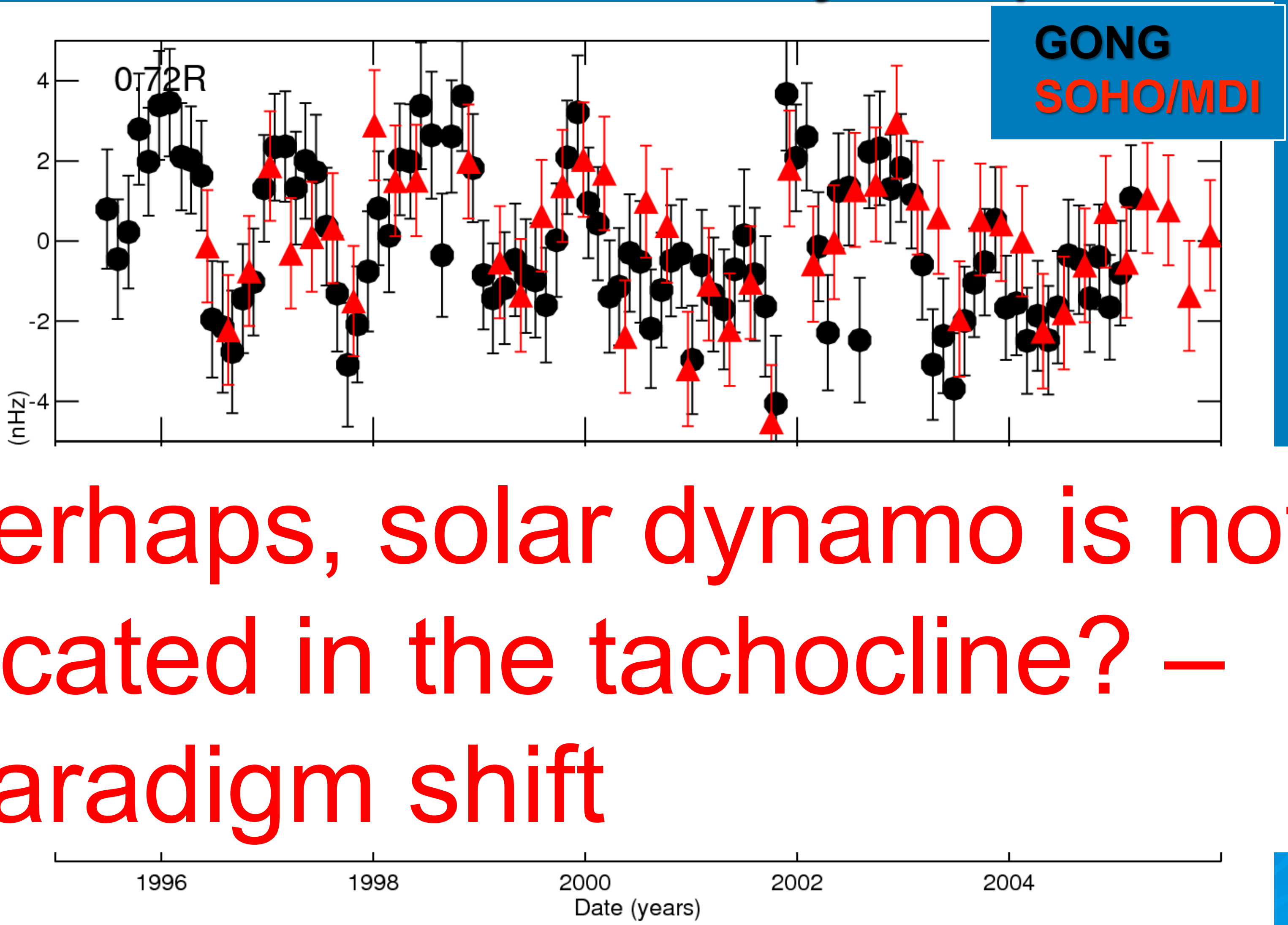
Zhao & Kosovichev (2004)

Relationship between the meridional flows and magnetic flux transport

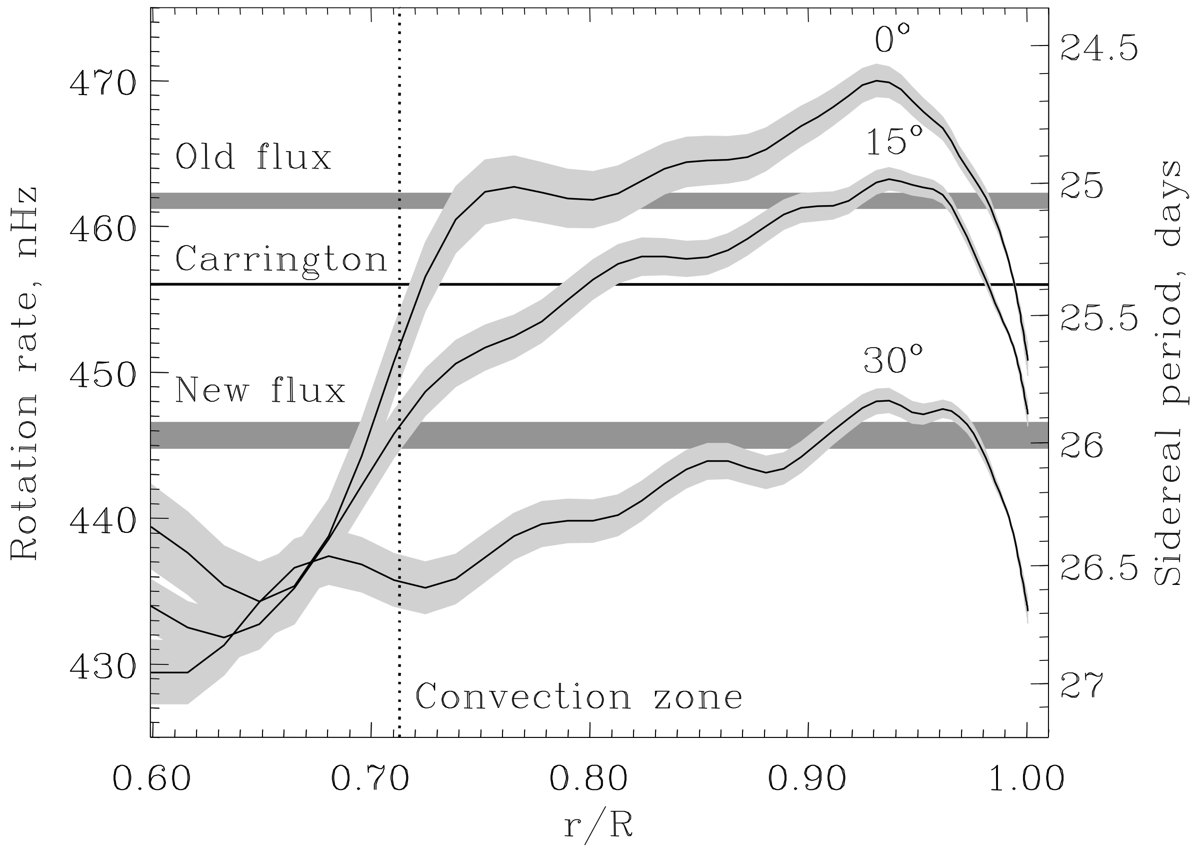


- The mea ional flow decreas gh activity at high lati
- How doe etic flux transpor
- What ha flux when it reaches es it sink into the

Rotation speed variations in the tachocline:1.3-year period?



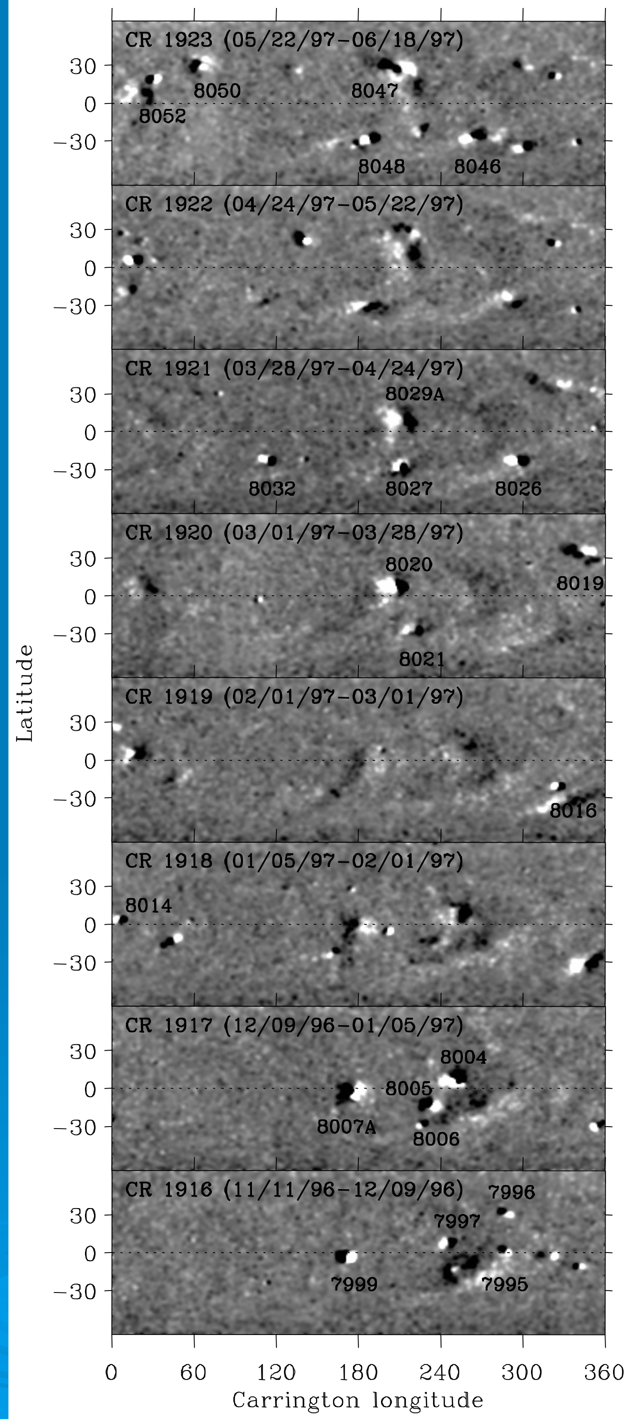
Perhaps, solar dynamo is not located in the tachocline? – Paradigm shift



What is the relationship between active longitudes and polar magnetic field?

Yohkoh and EIT observations revealed giants loop structure connecting active regions and polar regions.

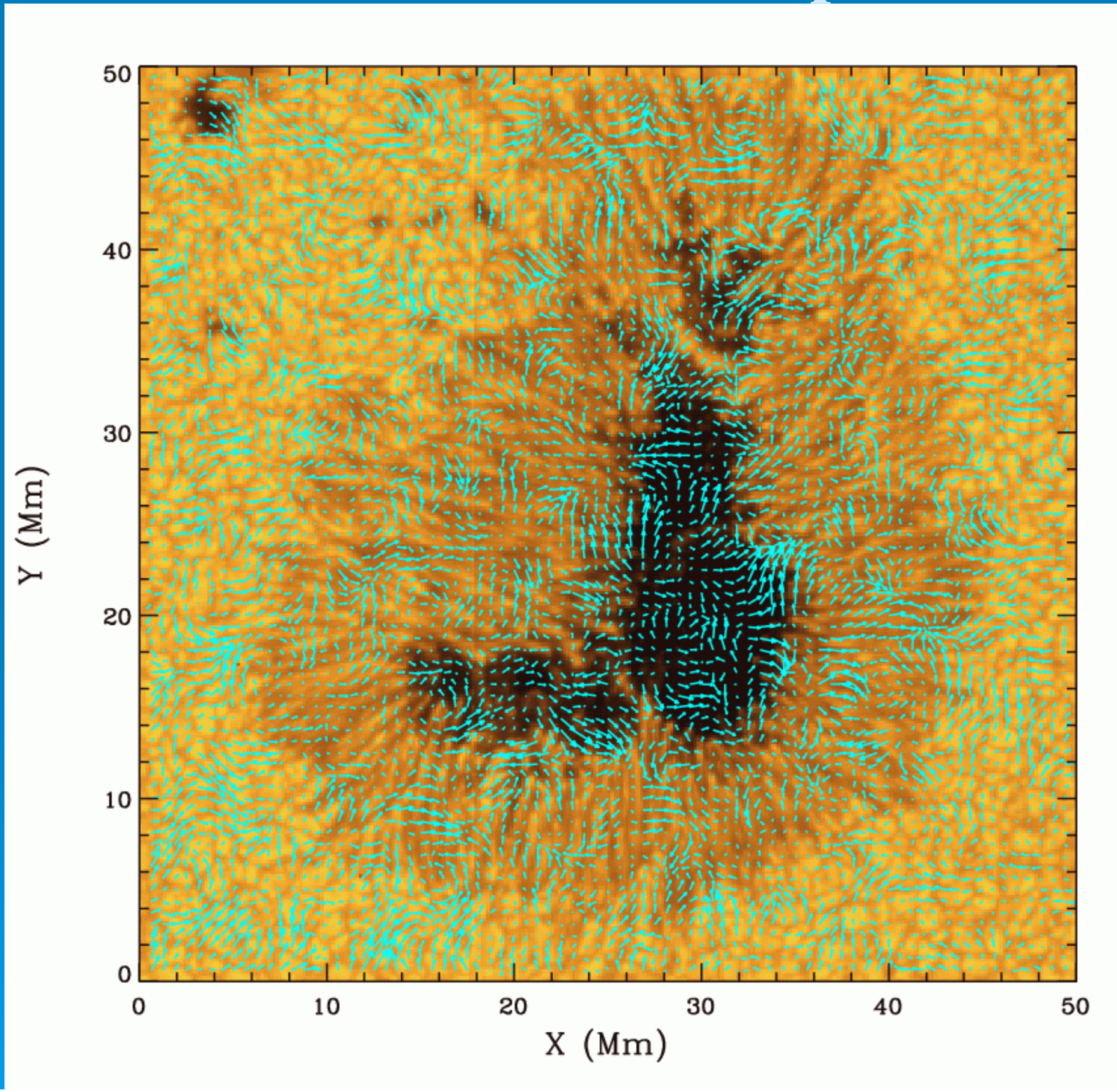
How deep is the link between plasma and flows in polar regions?



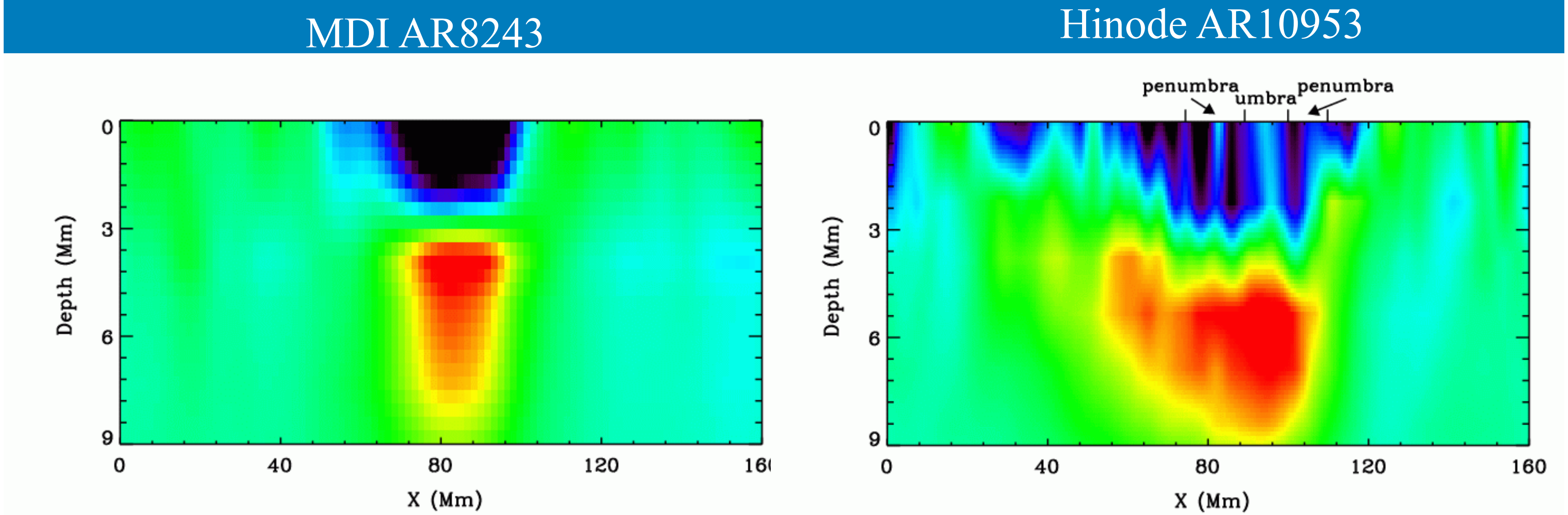
Current Status of Local Helioseismology

- Large-scale dynamics (supergranulation, large-scale flows around magnetic regions, zonal and meridional flows) are being investigated in details in the mid-latitude zone from -60 to 60 degrees in the upper convection zone, 30 Mm deep.

High-Resolution Subsurface Flow Fields inside the Sunspot

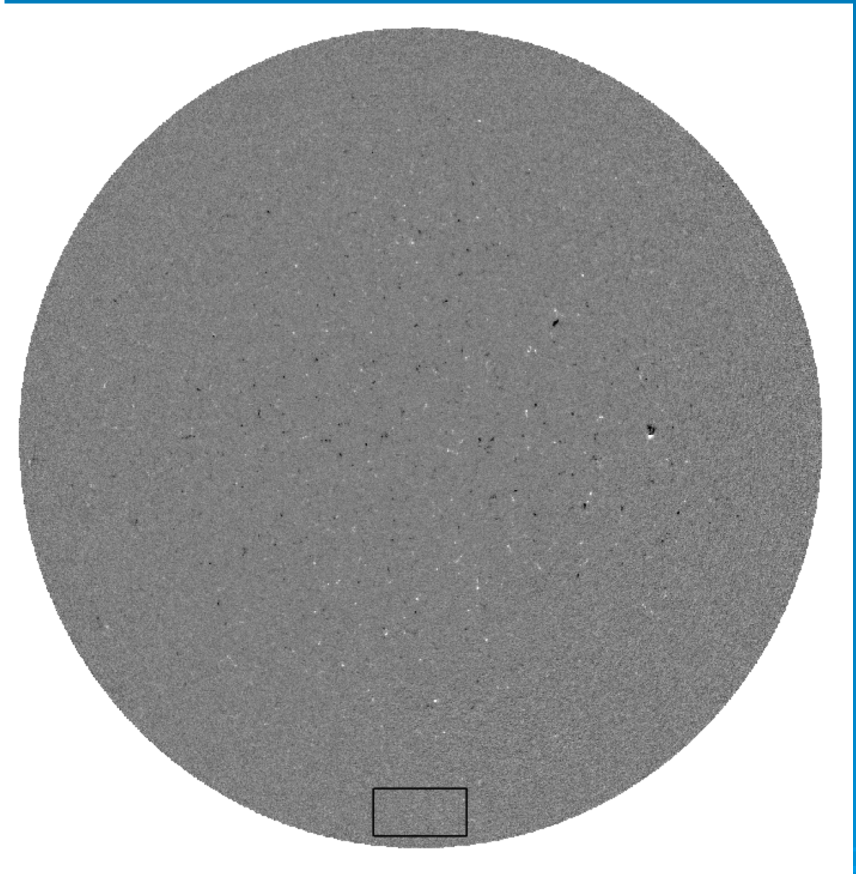


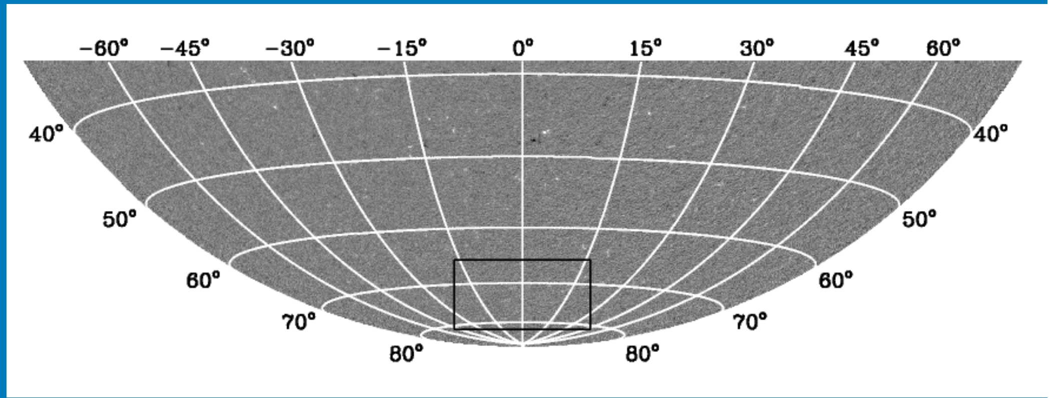
Comparing MDI and Hinode Sunspot Subsurface Structure



Note that the two studies are for two different active regions, and the sizes of sunspots are also different. However, the negative and positive sound speed perturbation structures look similar, and the conversion depth is similar.

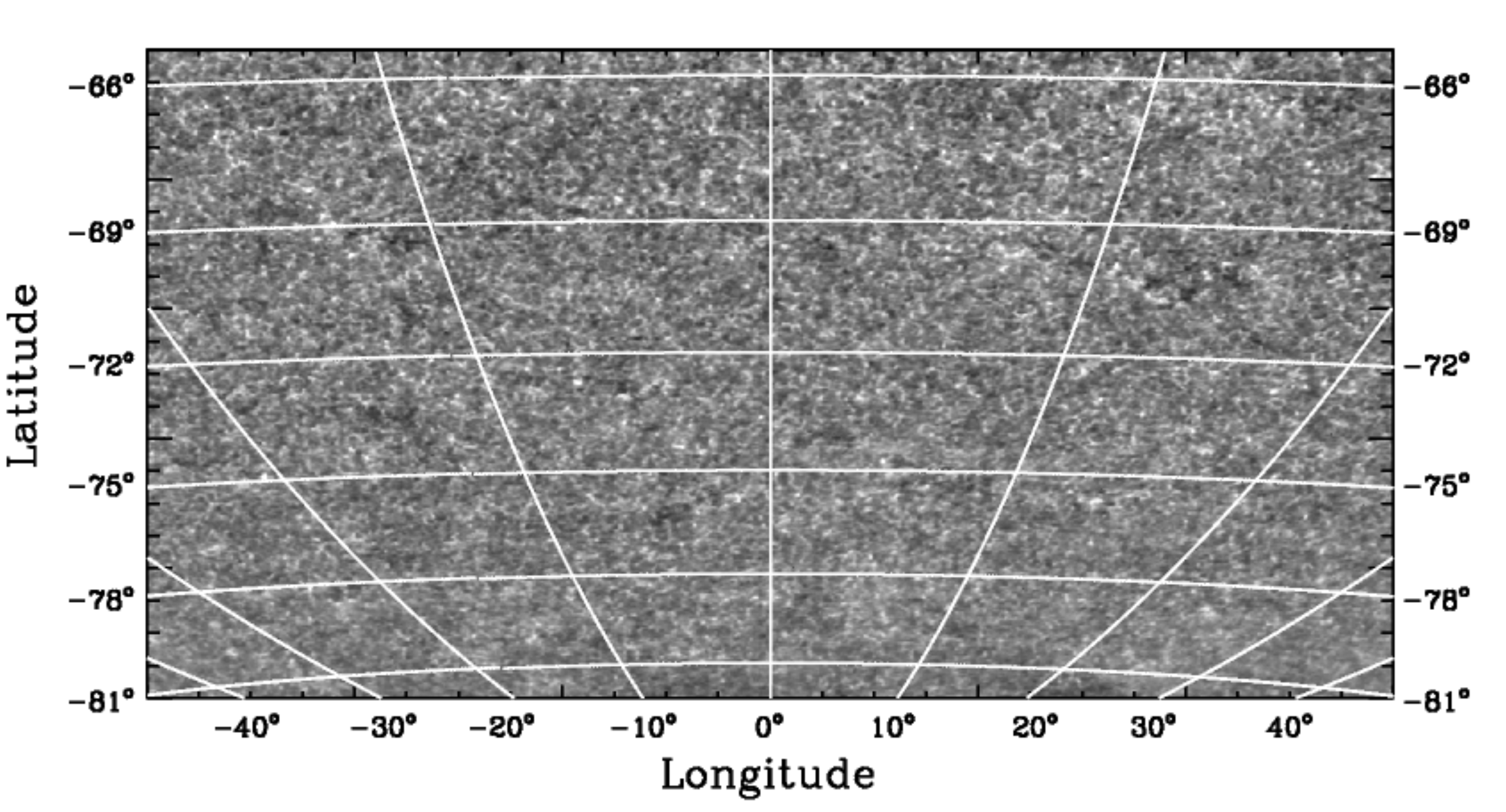
Hinode Observations of Solar South Pole Area





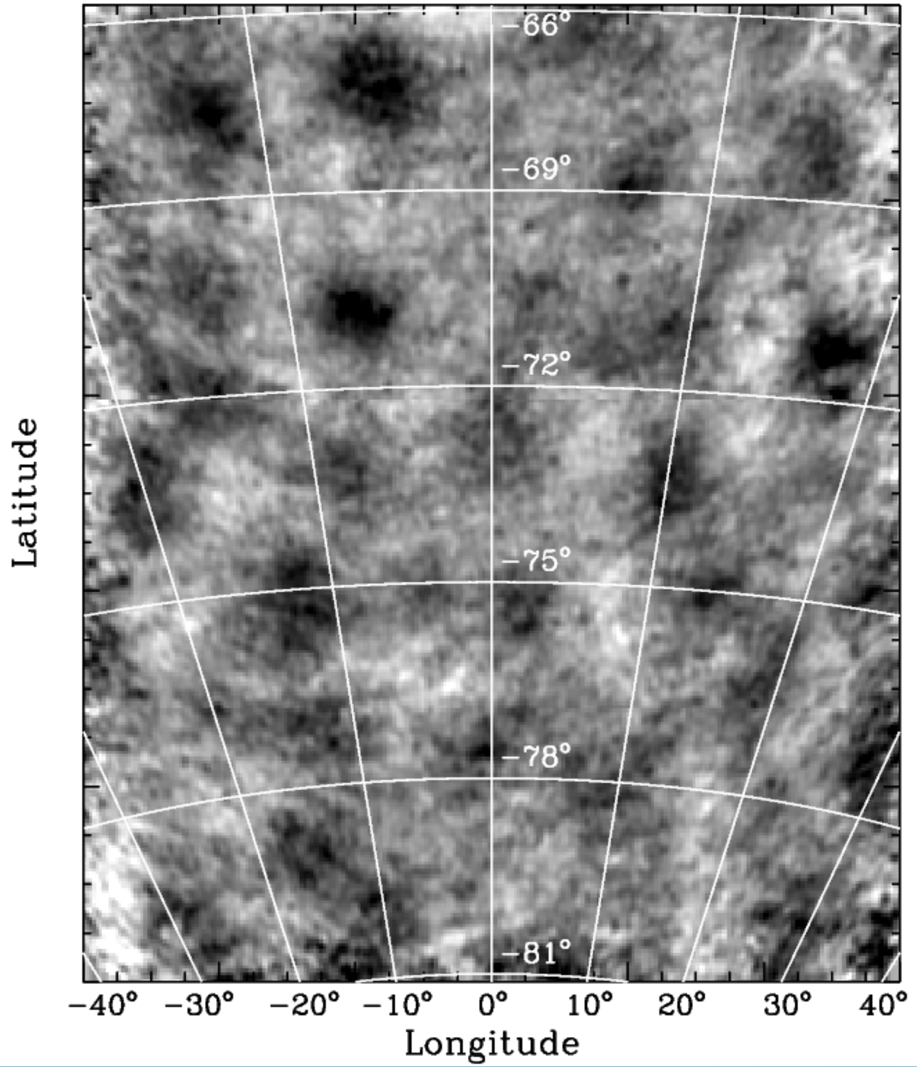
The observation was taken on March 15, 2008, when the solar south pole was pointing us with a B-angle of -7.17^{o}. The duration of observation was approximately 13 hours. We used the first 8.5 hours for this analysis.

A Closer Look at the Observation



The observation was made using Ca II H line, which has been demonstrated suitable for local helioseismology analysis (Sekii, Kosovichev, Zhao et al. 2007, PASJ). The FOV covers -65° to -82° or so in latitude.

Supergranular Structures Seen from Time-Distance Travel Time Measurement



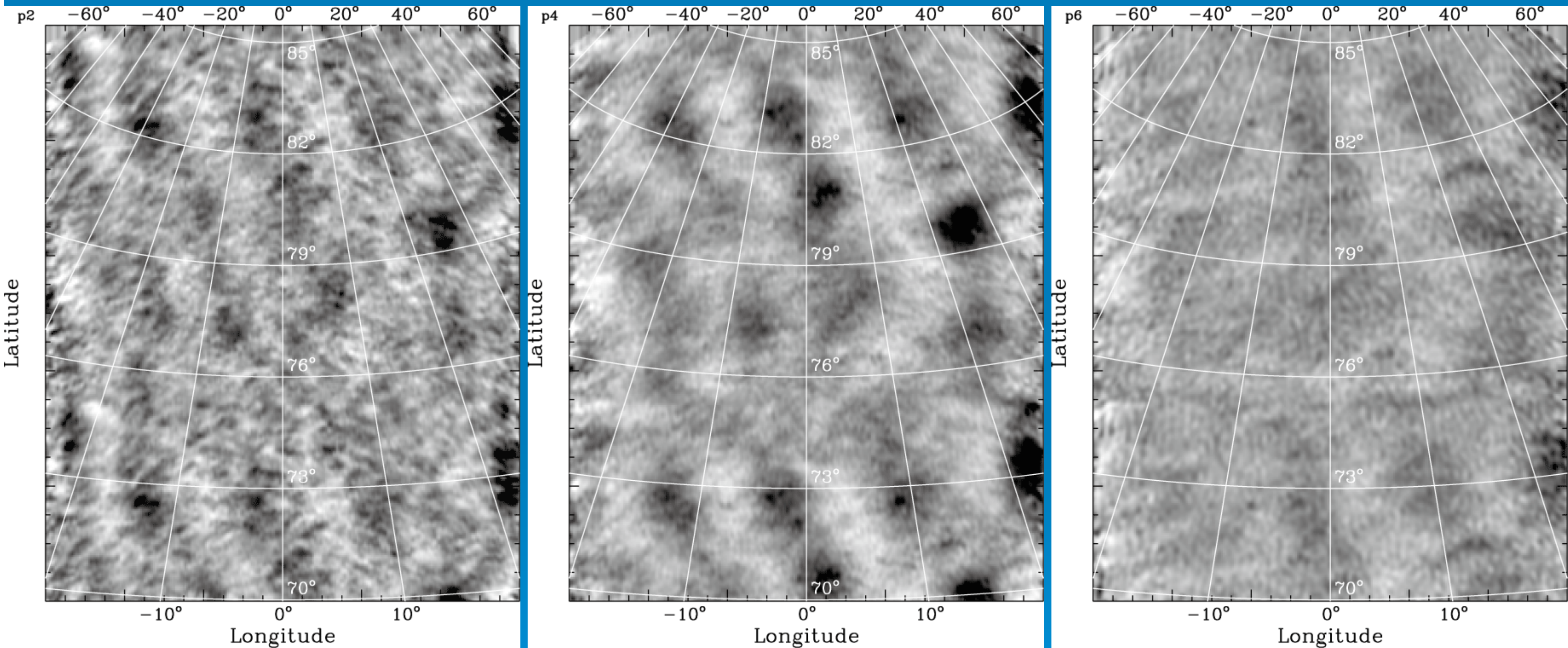
The measured acoustic travel time map using the time-distance helioseismology technique shows supergranular structures in this high latitude area. These structures are weaker in latitude higher than 75^{o}

Nagashima,Zhao, Kosovichev, Sekii (2009)

Outward – inward travel time difference maps with different annulus sizes

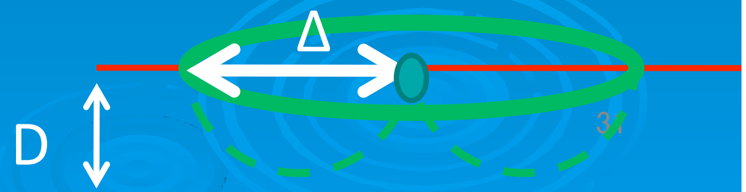
Δ=8Mm | Δ=14 Mm | Δ=21 Mm

max depth D= 2Mm | max depth D= 4.5Mm | max depth D= 8Mm

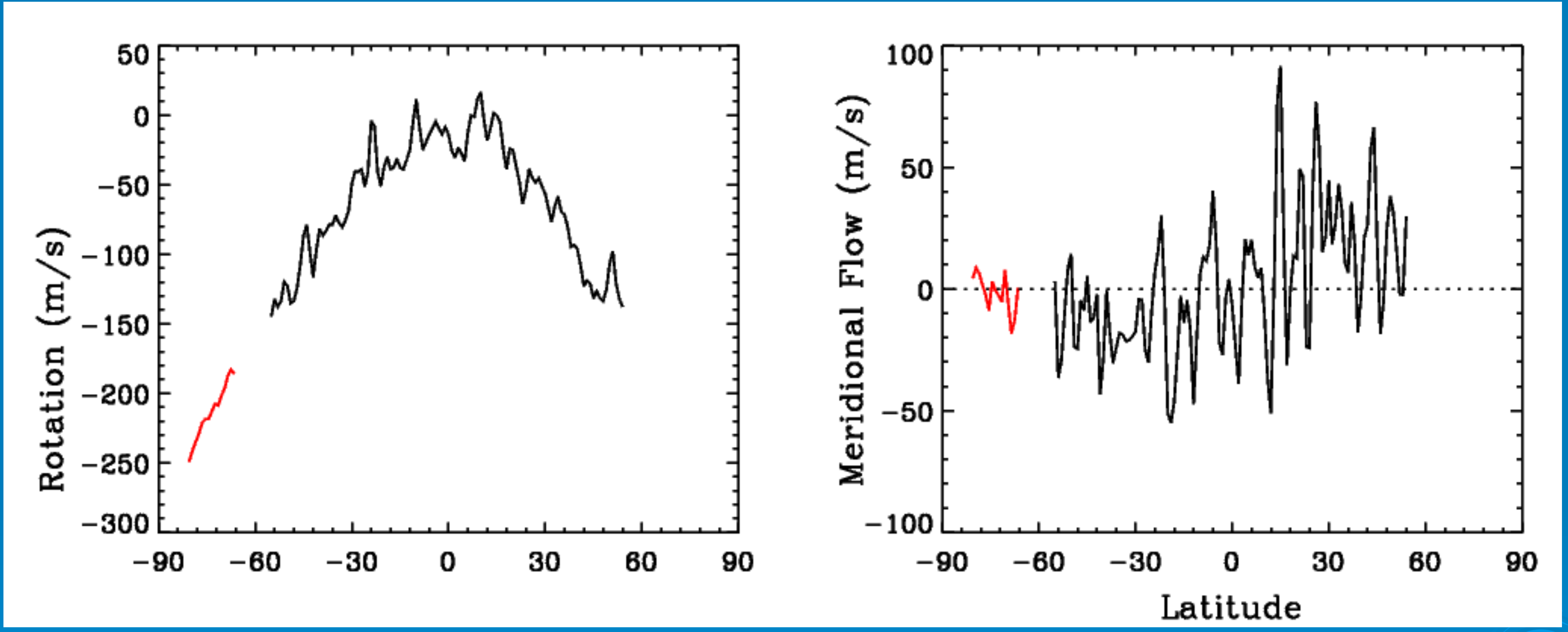


- The alignment is seen down to ~5Mm depth.

Nagashima, PhD thesis (2010)

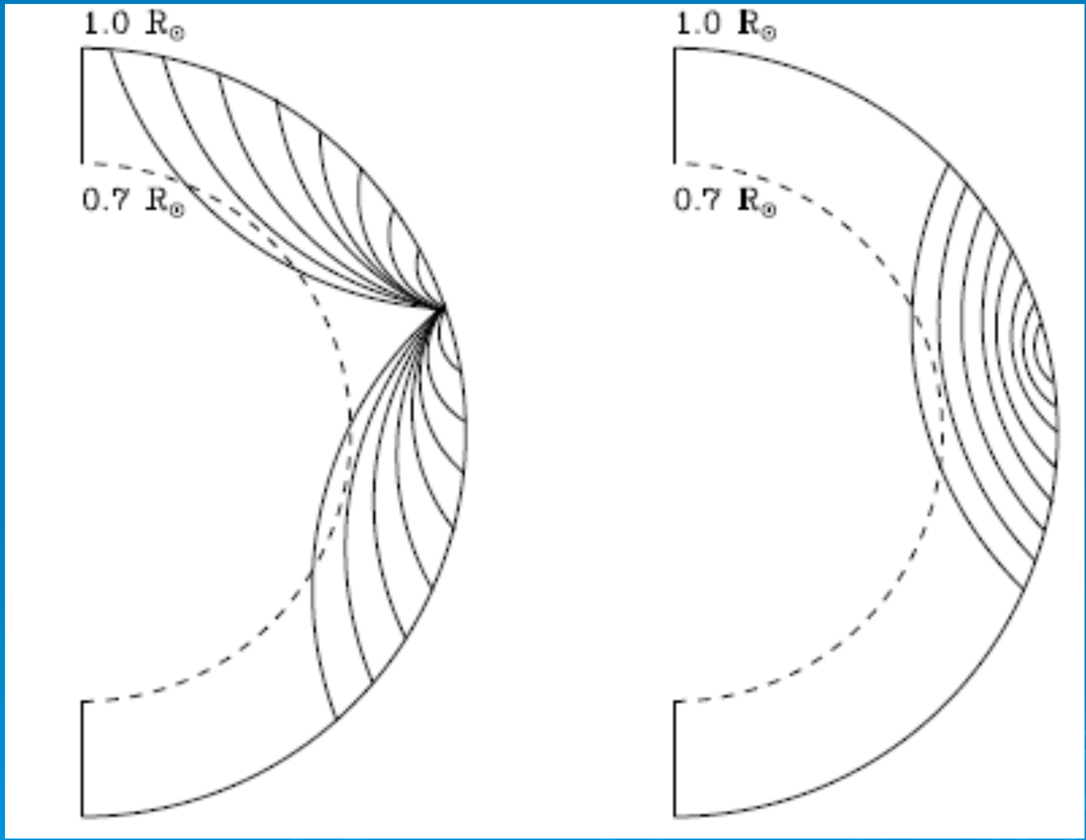


Combining MDI and Hinode Results



The Hinode results look consistent with the MDI results. Still, there is a data gap between results. We are working to fill up this gap.

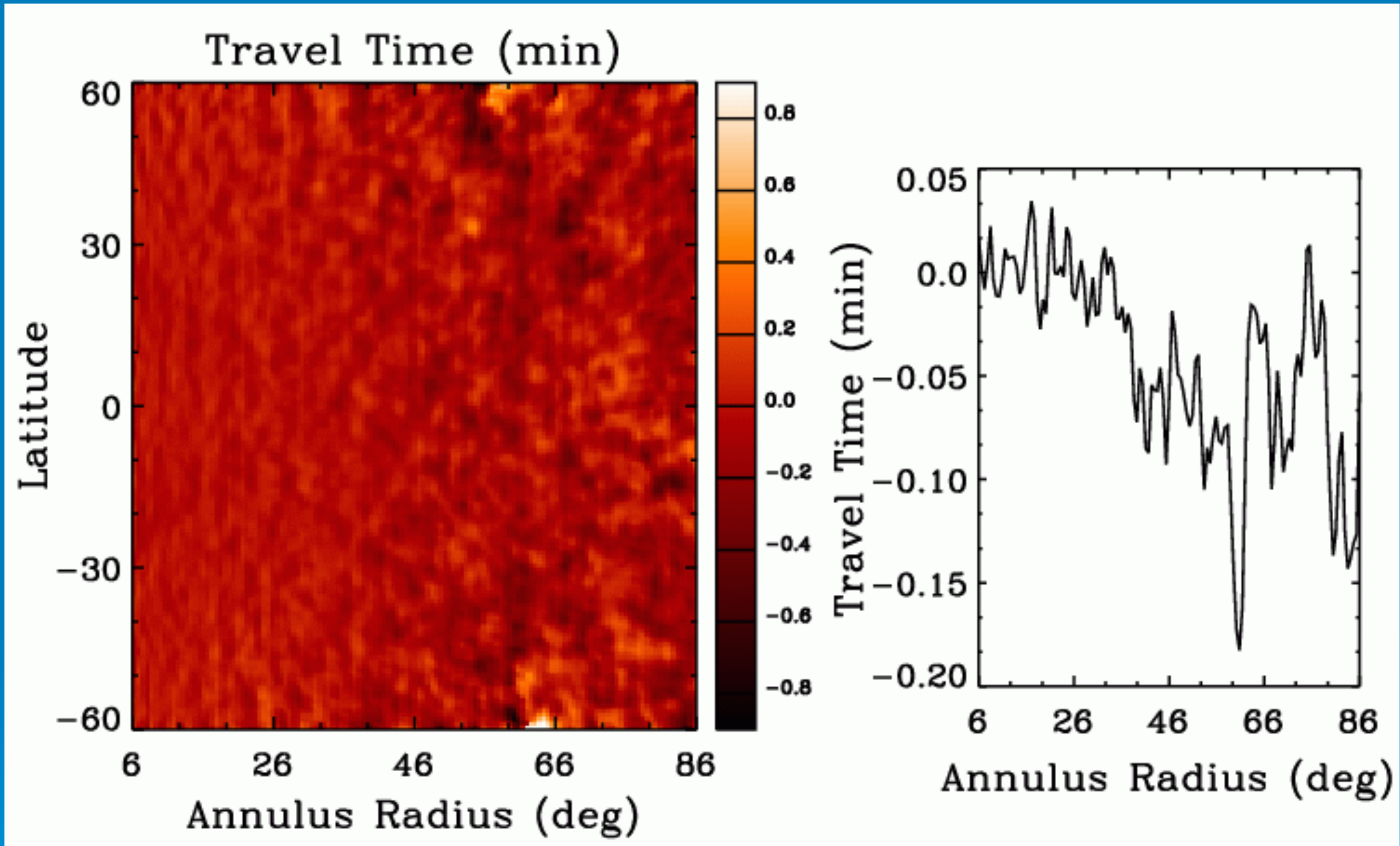
Time-distance helioseismology measurements schemes



Surface focusing

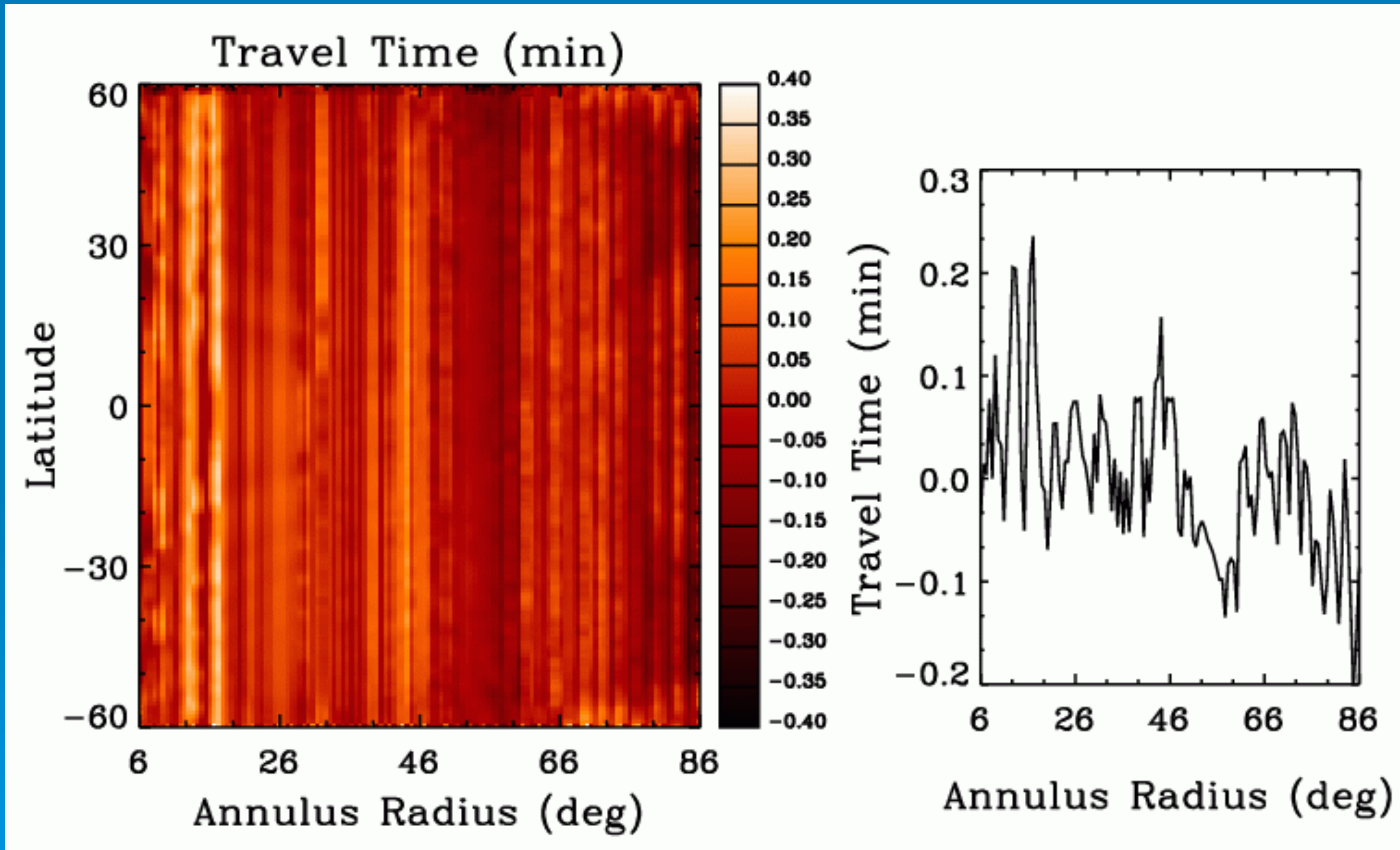
Deep focusing

Measured Travel Times



Measured travel times are displayed after a reference profile is subtracted. The reference profile is measured from a simulation that Thomas Hartlep made without perturbations.

Measurements from Real Sun: Surface Focusing

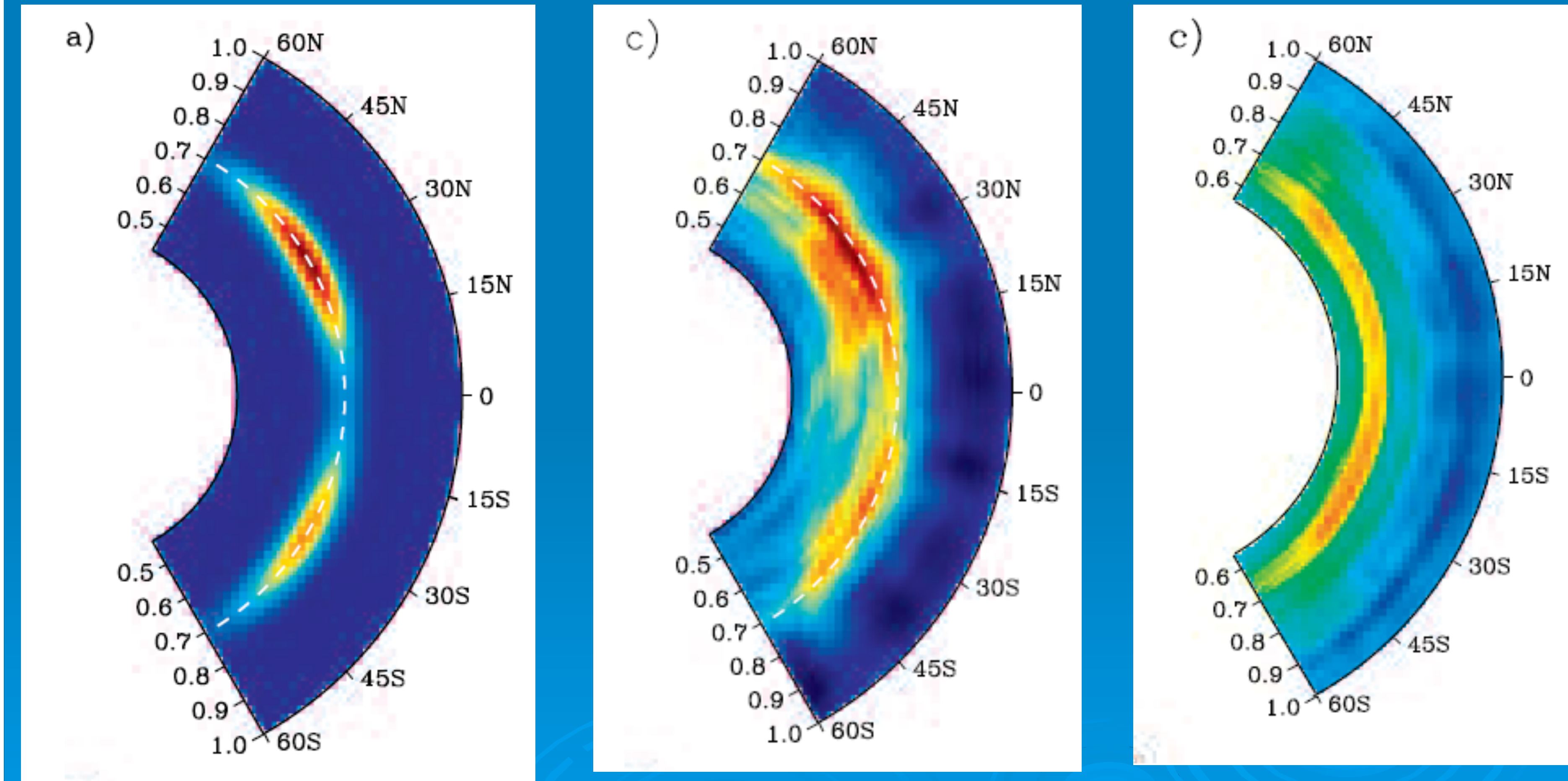


Tomographic imaging of the tachocline: inversions of test and MDI data

Artificial sound-speed profile

Inversion result using 18-hours of simulated oscillation signal

Inversion of 1-month of MDI data



MDI instrumental distortions may corrupt the results.
MDI was not designed for this type of measurements.

Major goal of the Solar-C mission:

Observations of high-latitude magnetic fields, meridional circulation, supergranulation dynamics and differential rotation.

These observations are crucial for understanding magnetic flux transport, polar field reversals, solar cycle models and predictions.

Solar-C will answer the basic science questions critical for understanding the solar dynamo and sunspot cycles

- What is the role of polar magnetism in the solar dynamo and cycle?
- What is the mechanism of the polar field reversals?
- How does the high-latitude field of the Sun evolve on a range of scales?
- What are the properties of the Sun's surface and subsurface meridional flow and differential rotation at high latitude, and how do these vary with time and position?
- How do the average properties of granular and supergranular flows depend on latitude?
- What are the properties of emerging flux at high latitudes?
- How is field removed from the solar surface around the high-latitude polarity inversion regions?
- What are the signatures of the solar dynamo action near the bottom of the convective envelope?

Solar-C Expected Helioseismology Results

1. Differential rotation and torsional oscillations at high latitudes, polar jets

    Global modes l=0-250

    Local helioseismology

2. Meridional circulation, latitudinal and longitudinal structures, secondary circulation cells, relationship to active longitudes, magnetic flux transport

    Local helioseismology

3. Supergranulation and large-scale convection patterns in polar regions (super-rotation, wave-like behavior, network, flux transport, relationship to coronal holes)

    Local helioseismology

4. Structure and dynamics of the high-latitude tachocline (oblateness, flows)

    Local helioseismology

5. Acoustic tomography of the deep interior: stereo-helioseismic observations (Solar Orbiter-SDO-GONG)

    Local Helioseismology (time-distance, holography)

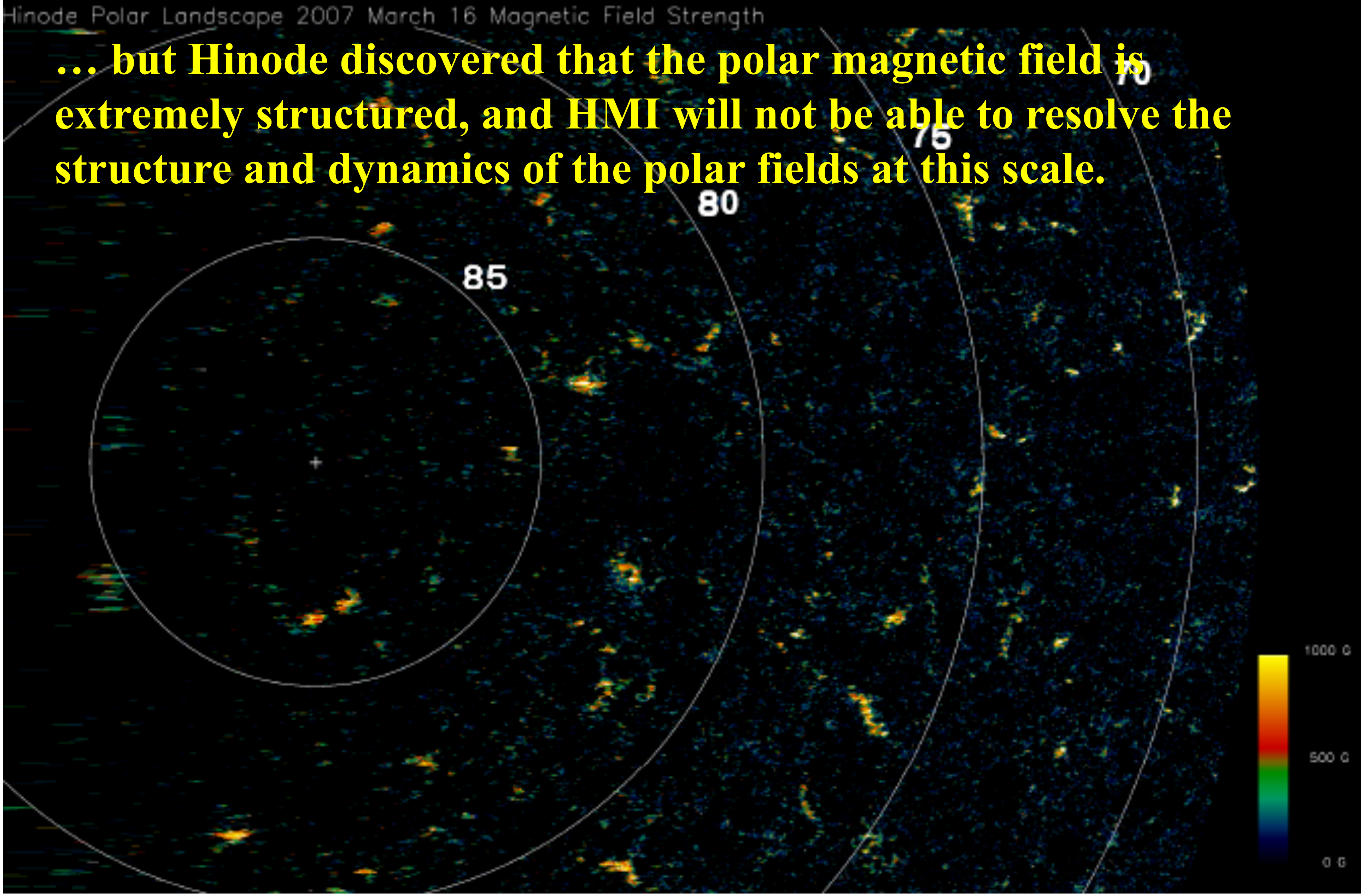
Relationship to Solar Orbiter and SDO

- Solar Orbiter will provide important support for the Solar-C mission by doing different out-of-ecliptic observations. It will reach 35 degrees latitudes after ~10 years after launch, in 2026-2028.
- SDO will provide uninterrupted observations of magnetic field and Doppler shift, and will cover the whole Sun except the polar regions. SDO was designed to “solve” the dynamo problem, but the Hinode discovery of the strong polar fields shows that the SDO alone will be insufficient.


ATLAS
USAF

Polar landscape kG field

… but Hinode discovered that the polar magnetic field is extremely structured, and HMI will not be able to resolve the structure and dynamics of the polar fields at this scale.

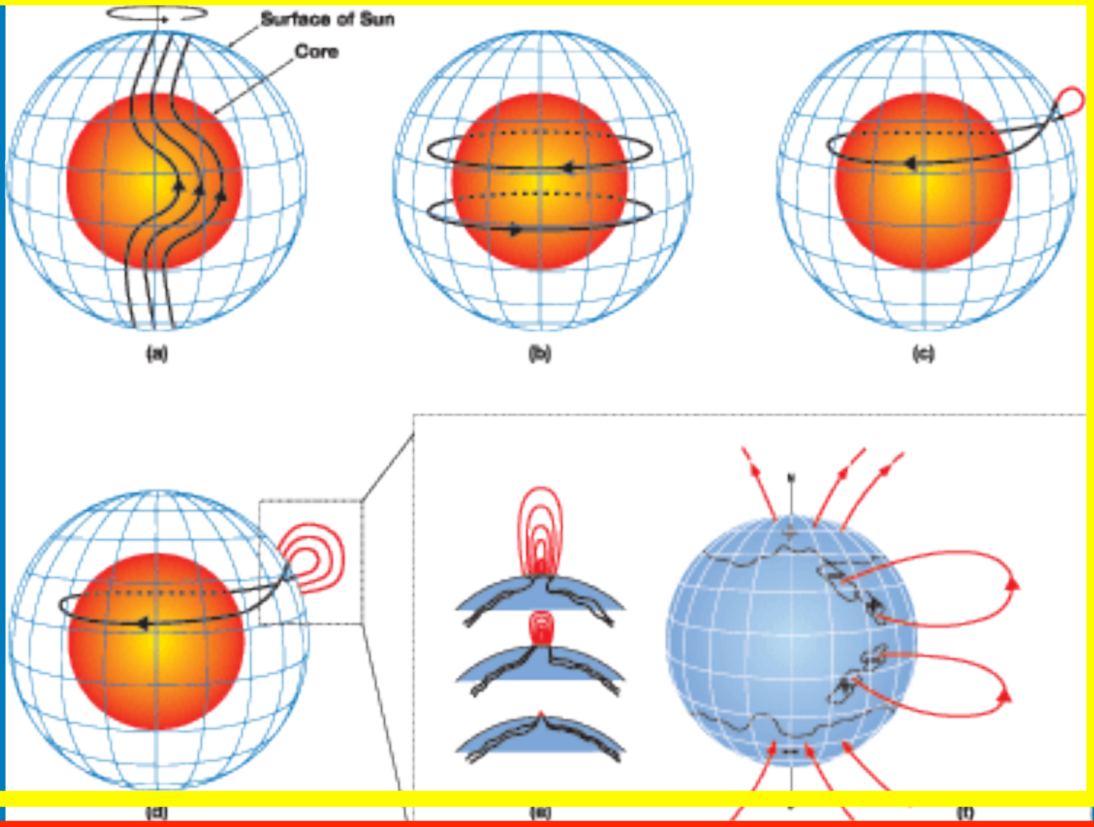


Schematic flux-transport dynamo model

SDO/HMI domain

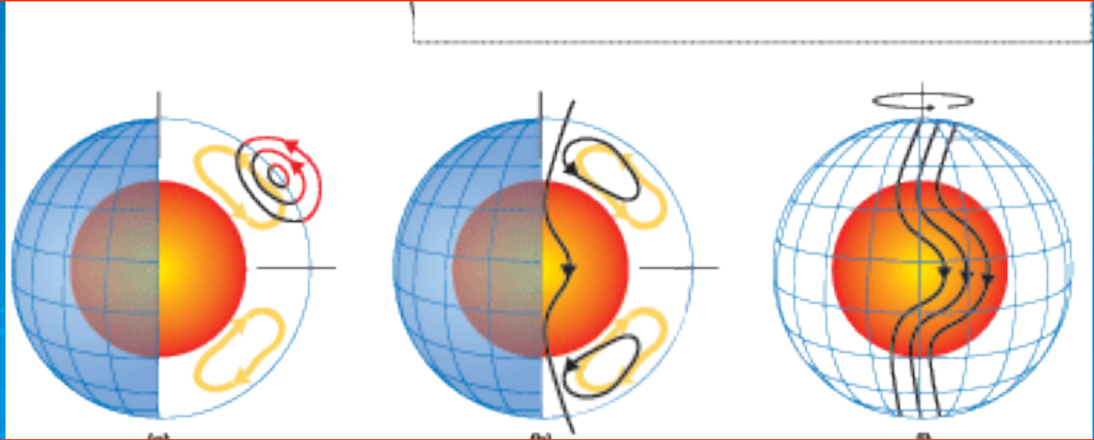
1. Shearing of poloidal fields by differential rotation to produce new toroidal fields, followed by eruption of sunspots.

2. Spot-decay and spreading to produce new surface global poloidal fields.



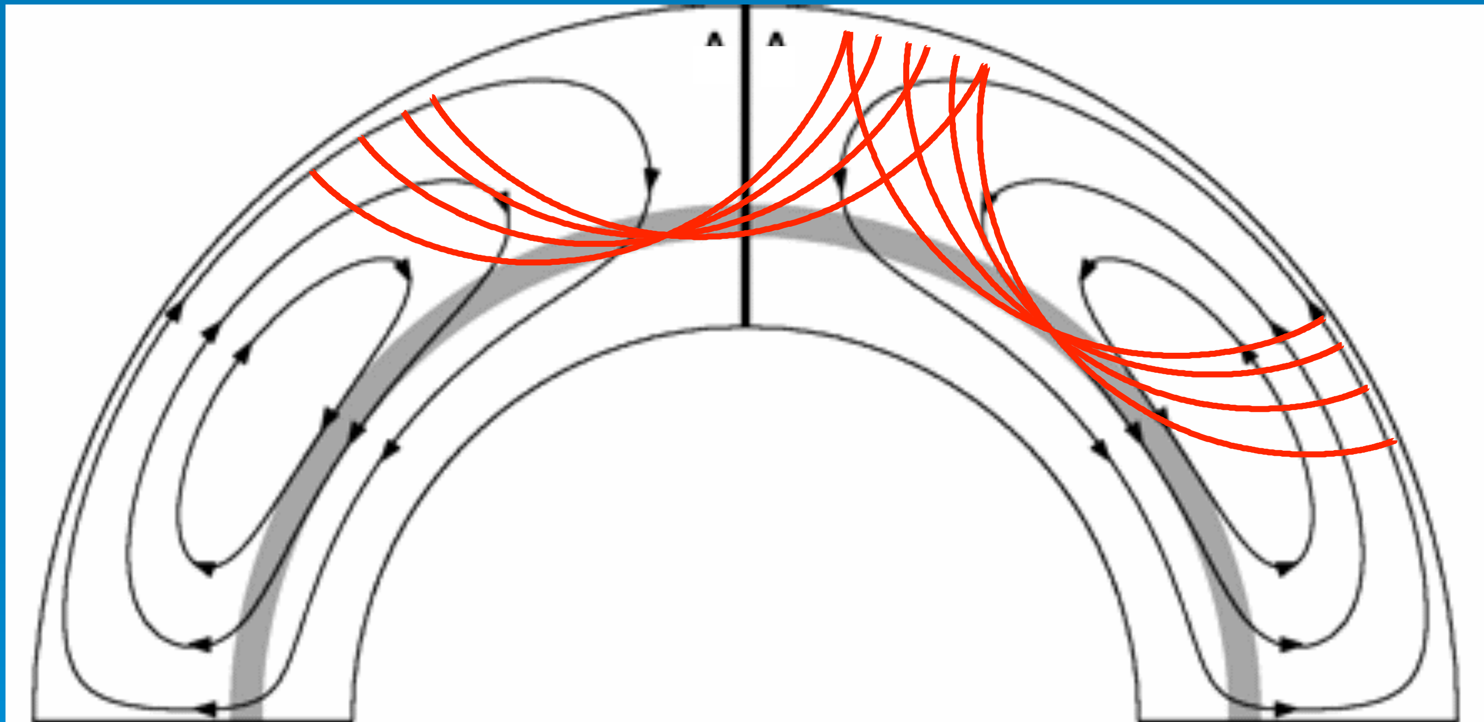
Solar-C domain

3. Transport of poloidal fields by meridional circulation (conveyor belt) toward the pole and down to the bottom, followed by regeneration of new toroidal fields of opposite sign.



Dikpati et al 2006

Stereo-helioseismology observations of the tachocline in polar regions



Data Requirements

- **Global helioseismology:**
  - 256x256 images,
  - 1-min cadence,
  - 36-72 days long time series
- **Local helioseismology:**
  - 1024x1024 images,
  - 1-min cadence,
  - 8-24 hour series for imaging the upper convection zone (depth 0-30 Mm);
  - 256x256 images, 1-min cadence, 36 days series for the tachocline and deep interior tomography.
- **Preferred observing periods:** solar maximum, during the polar field reversal process (2013-15, 2024-26)

Some key questions

- Are there multiple meridional cells predicted by numerical simulations?
- How fast is the polar rotation?
- How does the polar rotation changes with the solar cycle?
- Are there fast variations of the polar rotation?
- How deep are these variations?
- Is there a link to rotation of the radiative interior?
- How are these linked to the angular momentum loss?
- What are the structure, dynamics and variations with the solar cycle of the tachocline?

Conclusions

- The internal structure and dynamics of the near polar regions of the Sun are a key to our understanding of the solar dynamo and predicting of the solar activity cycles.
- Solar-C will provide a unique opportunity to directly observe and analyze magnetic fields, the differential rotation, supergranulation and meridional flows at high latitudes and near the solar poles.
- Synergy with a high-resolution helioseismology mission in the ecliptic plane or a ground-base network is critical.

Views of the Sun from the SPI orbit and the Earth