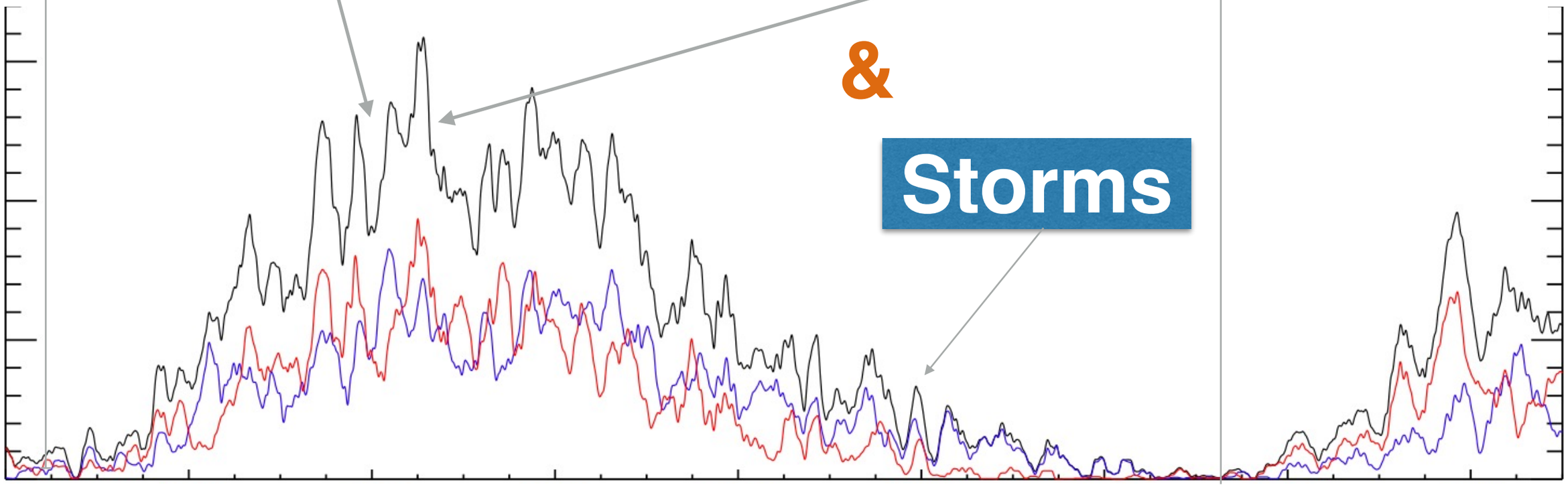
Cycles

Seasons

&

Storms



Scott W. McIntosh

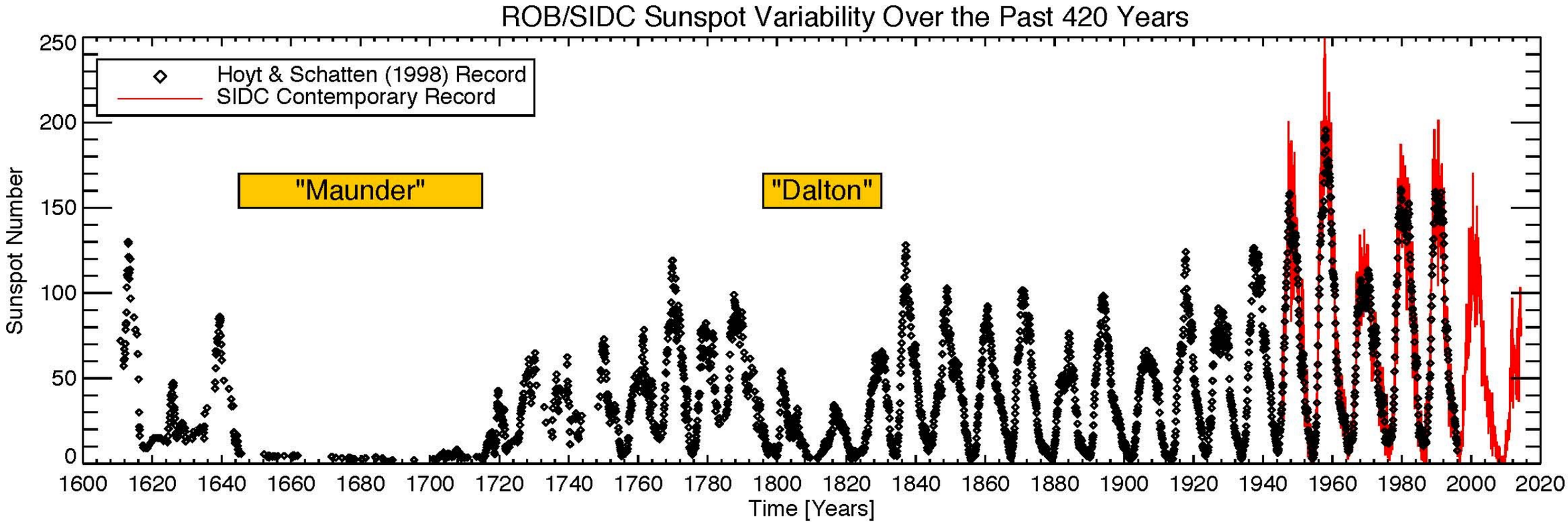
HIGH ALTITUDE OBSERVATORY

NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

Variability in Activity: Living With A Star

We live in the atmosphere of our star.

As a civilization* we take our star for granted.



A question that motivates us…..

….what will it do….

…over coming centuries?

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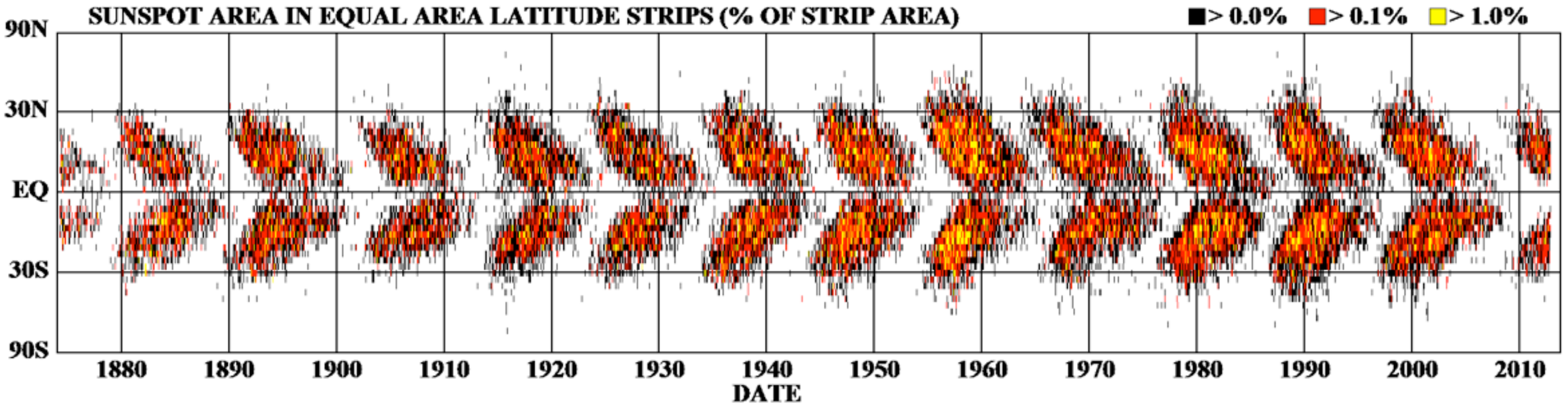

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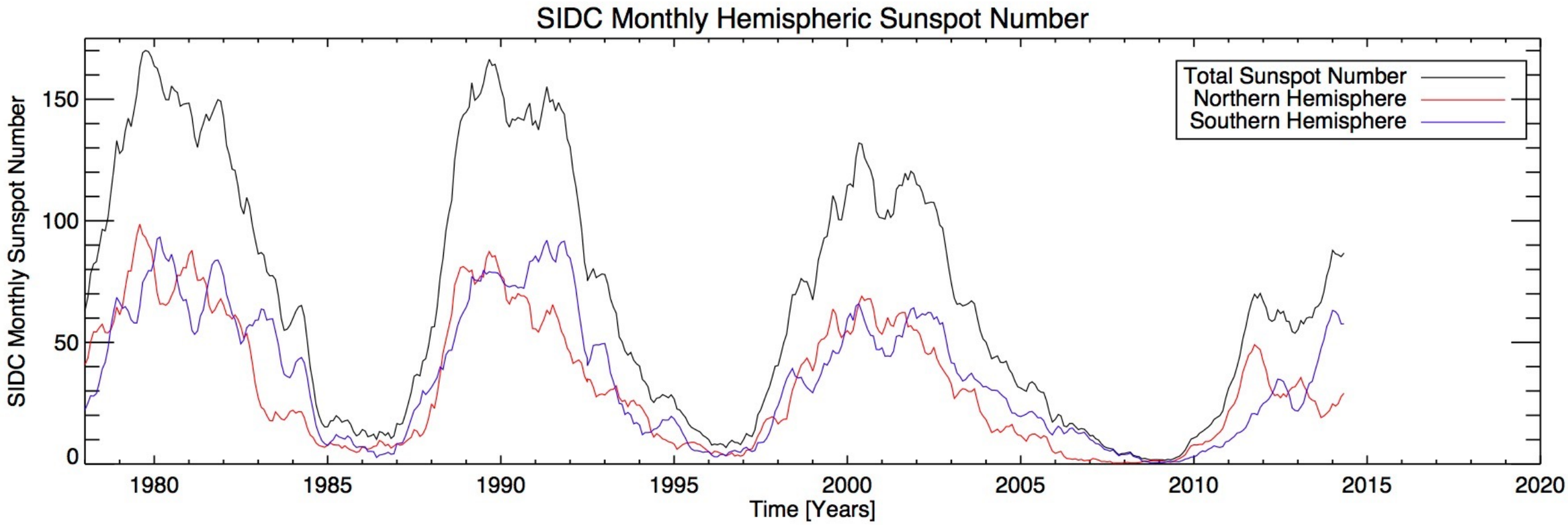

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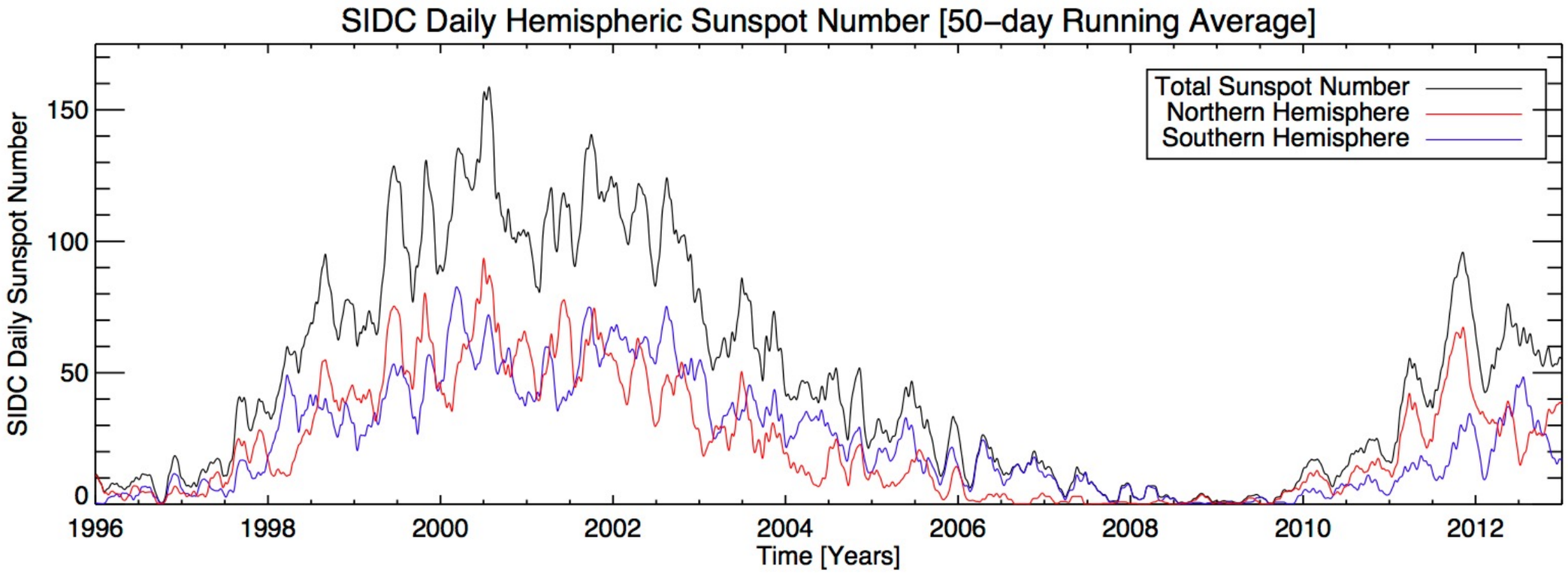

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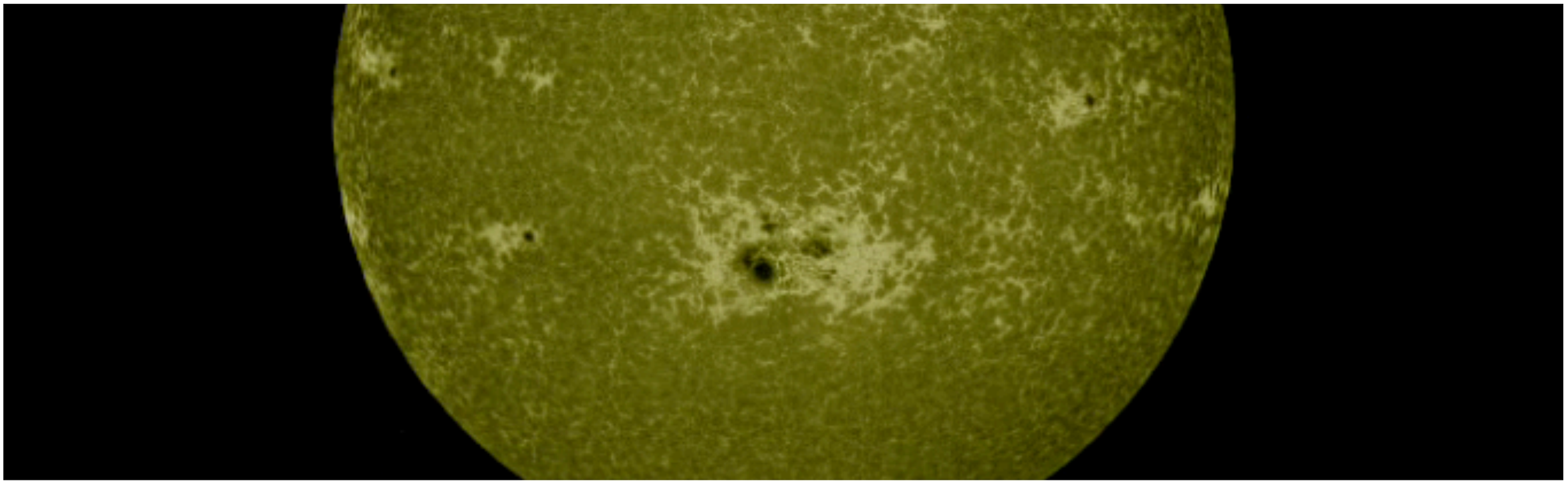


A question that motivates us…..

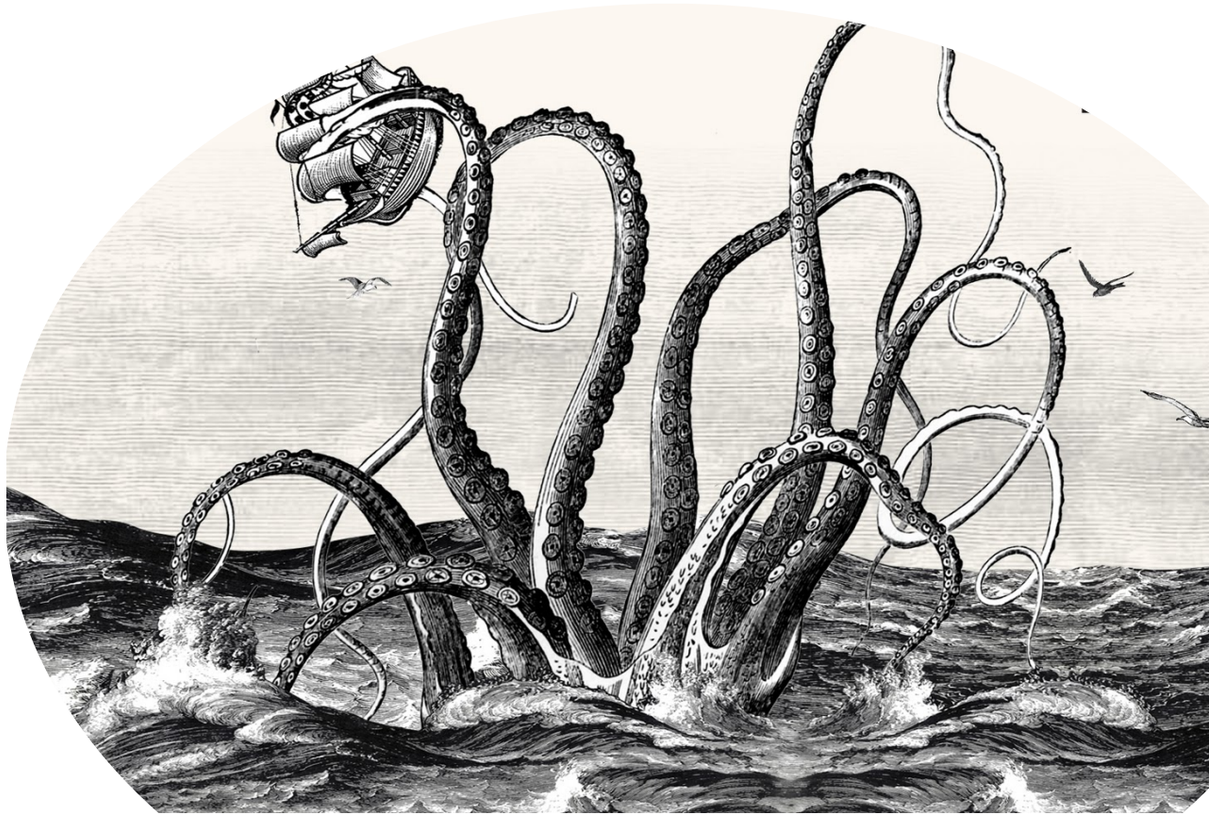
….what will it do….

…tomorrow?

The Grand [Central] Challenges

How does the Sun's internal magnetic machine produce the millennial, decadal, annual, and shorter-term solar variability?

Can the processes at play be observed?

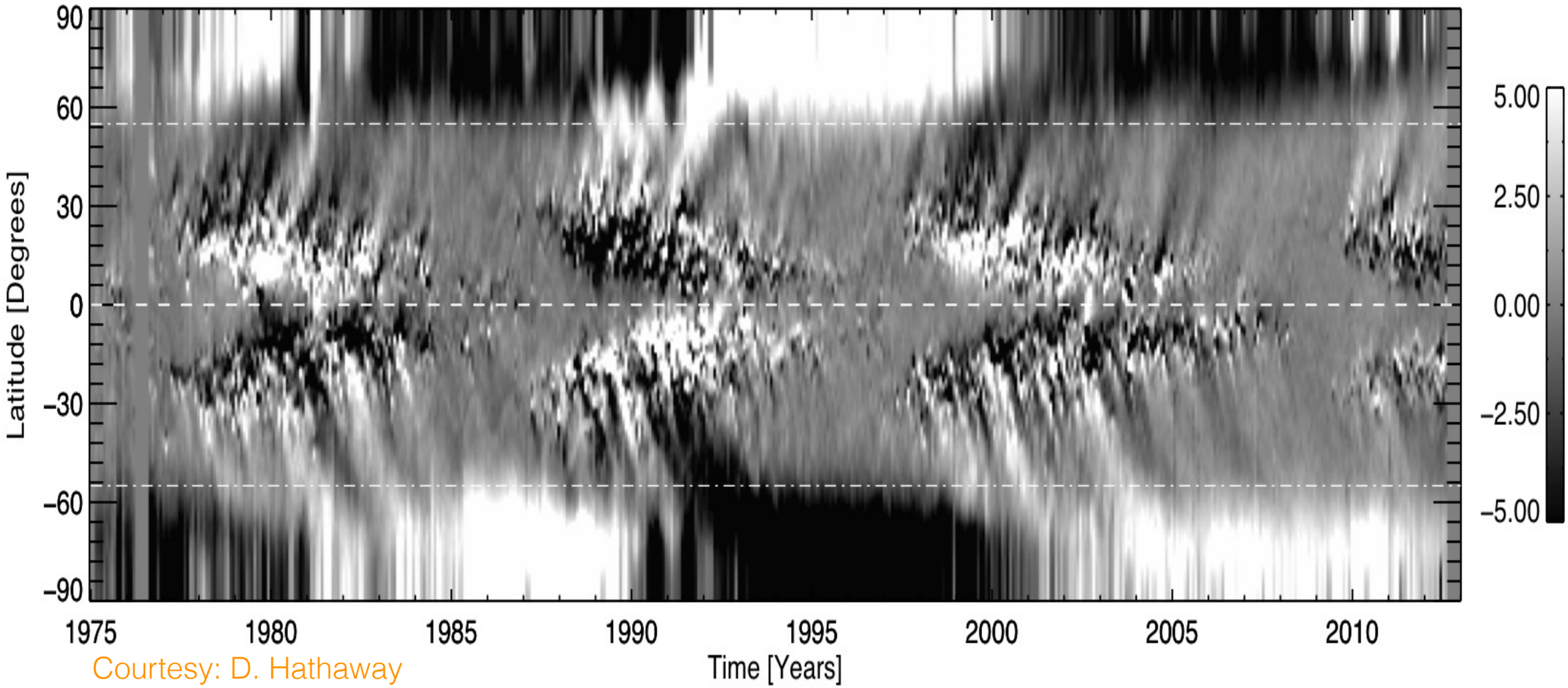


Do those observations permit a model where reliable hind- and fore- casts of activity over hours, days, weeks, months, years, decades, centuries (and millenia) to be developed?

How do we move forward?

Distracting/Misleading Butterflies

The key…



Courtesy: D. Hathaway

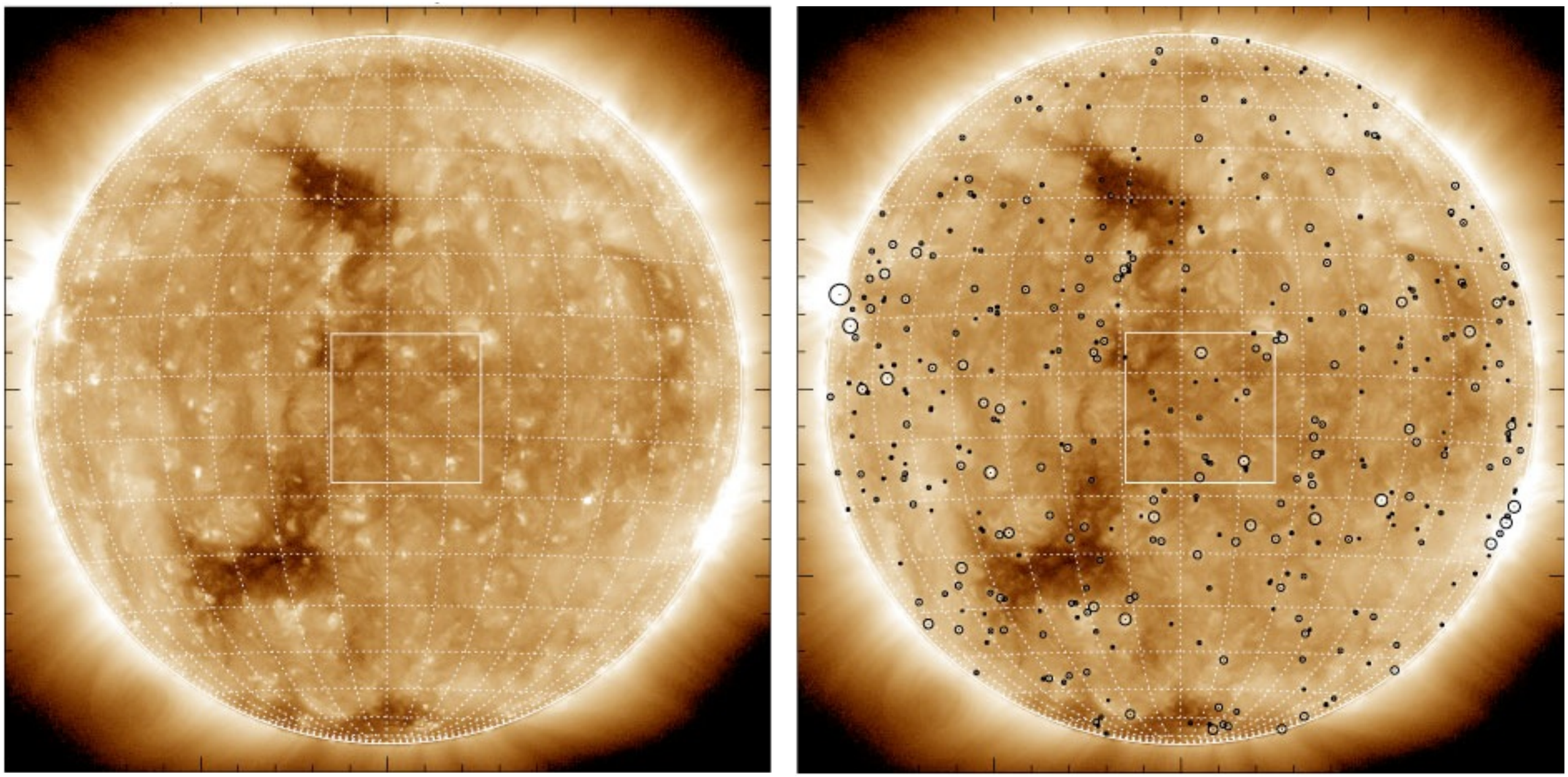
….lies in understanding the processes that govern solar magnetism

…unfortunately we only have the patterns that it produces….

…are those patterns complete and/or unique?

Decomposing Surface Magnetism

The coronal ever-present has a preferred location and formation (spatial) scale.



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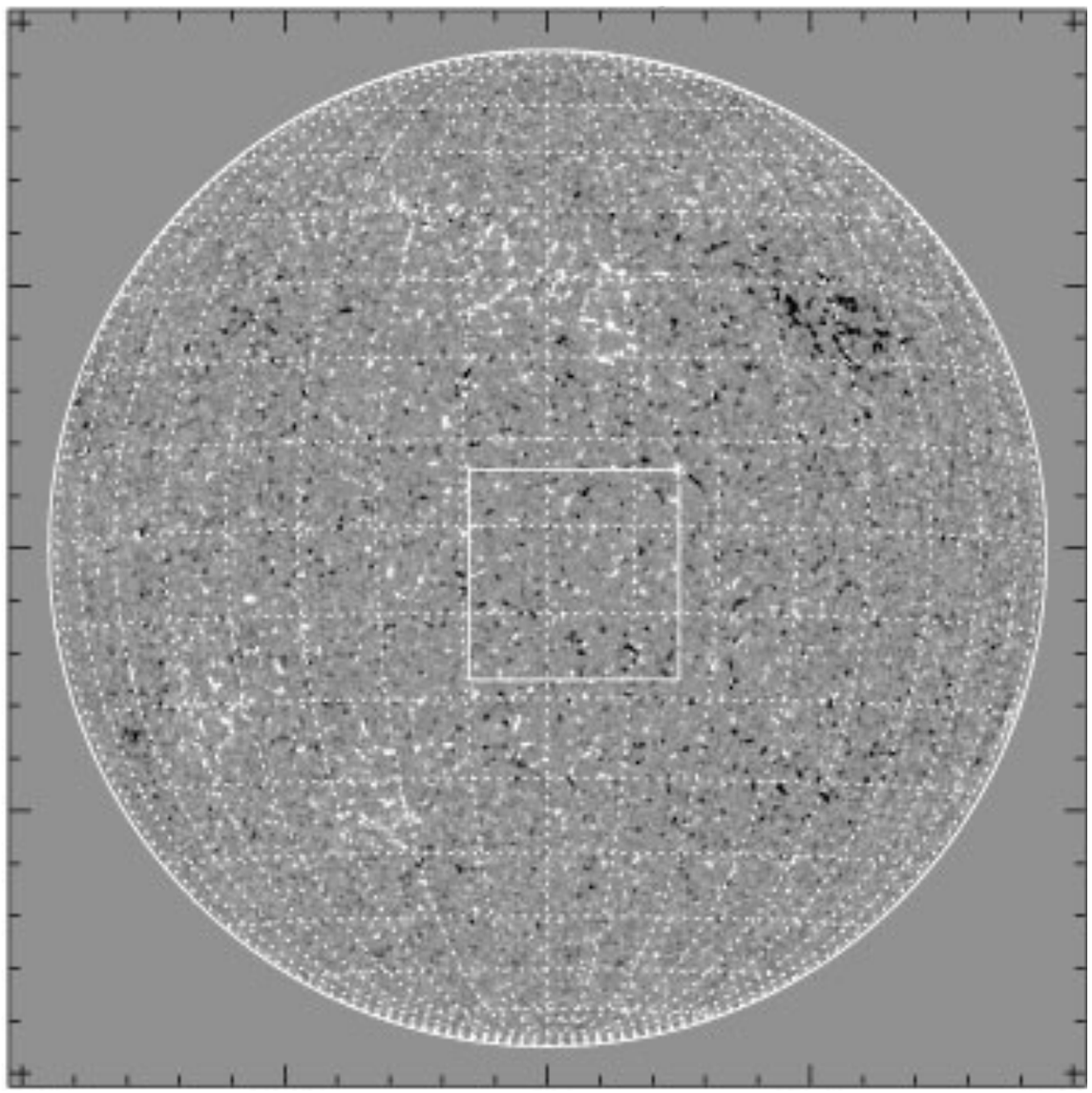
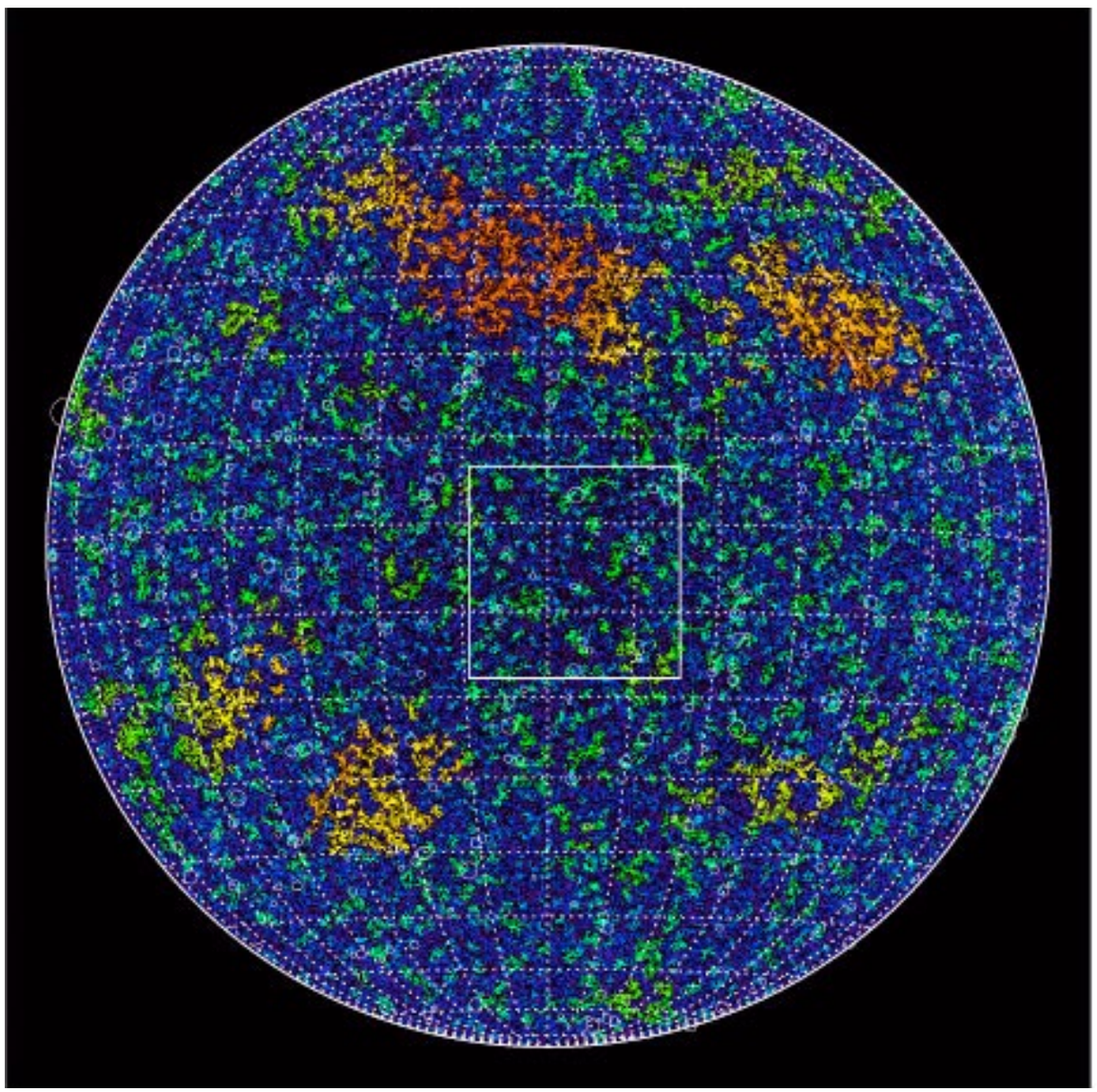
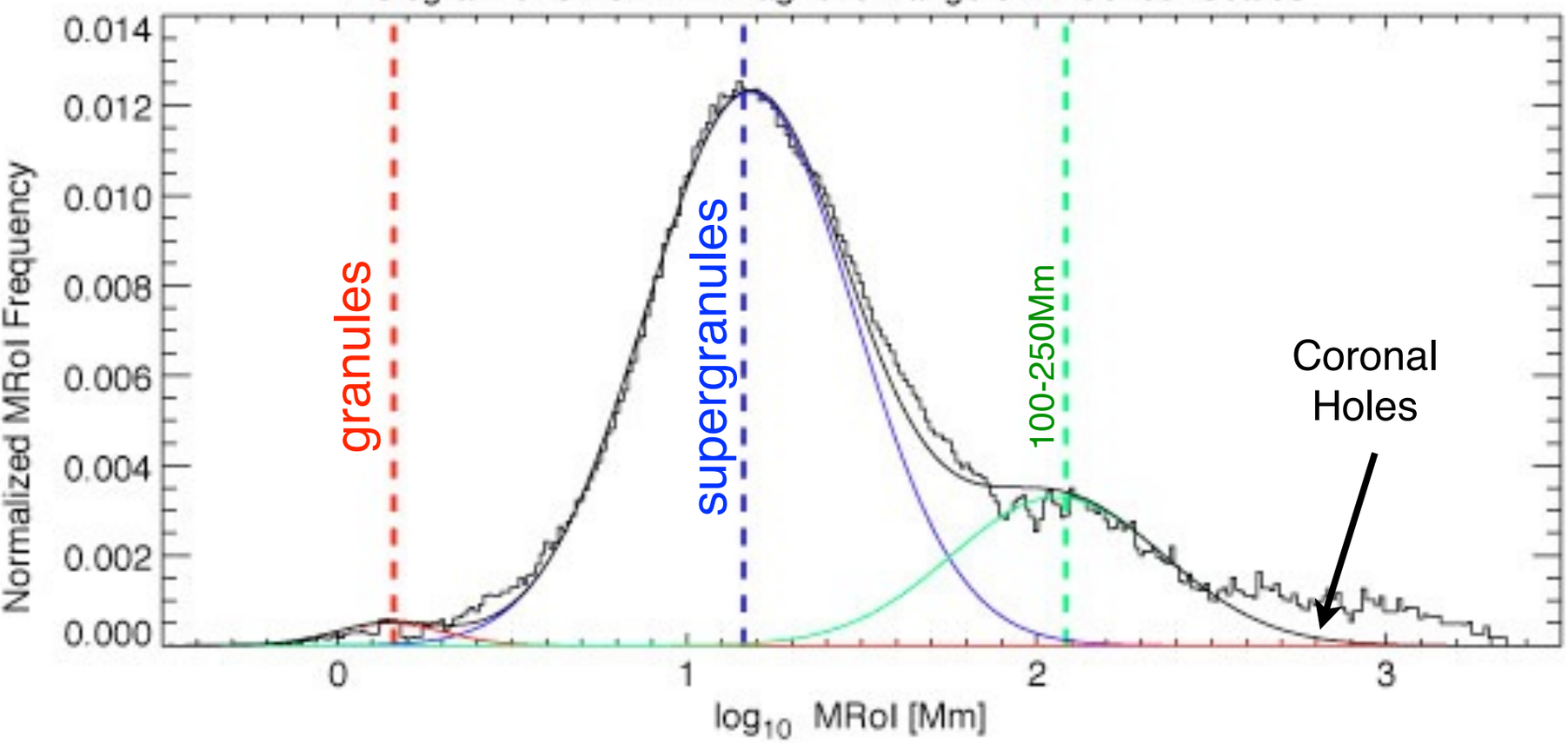
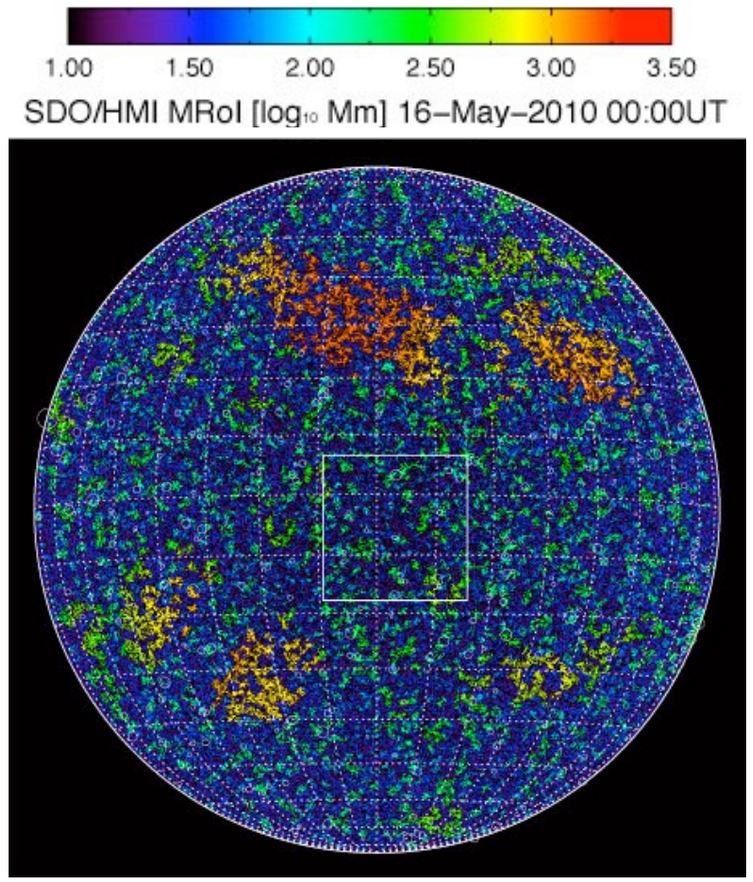




Decomposing Surface Magnetism

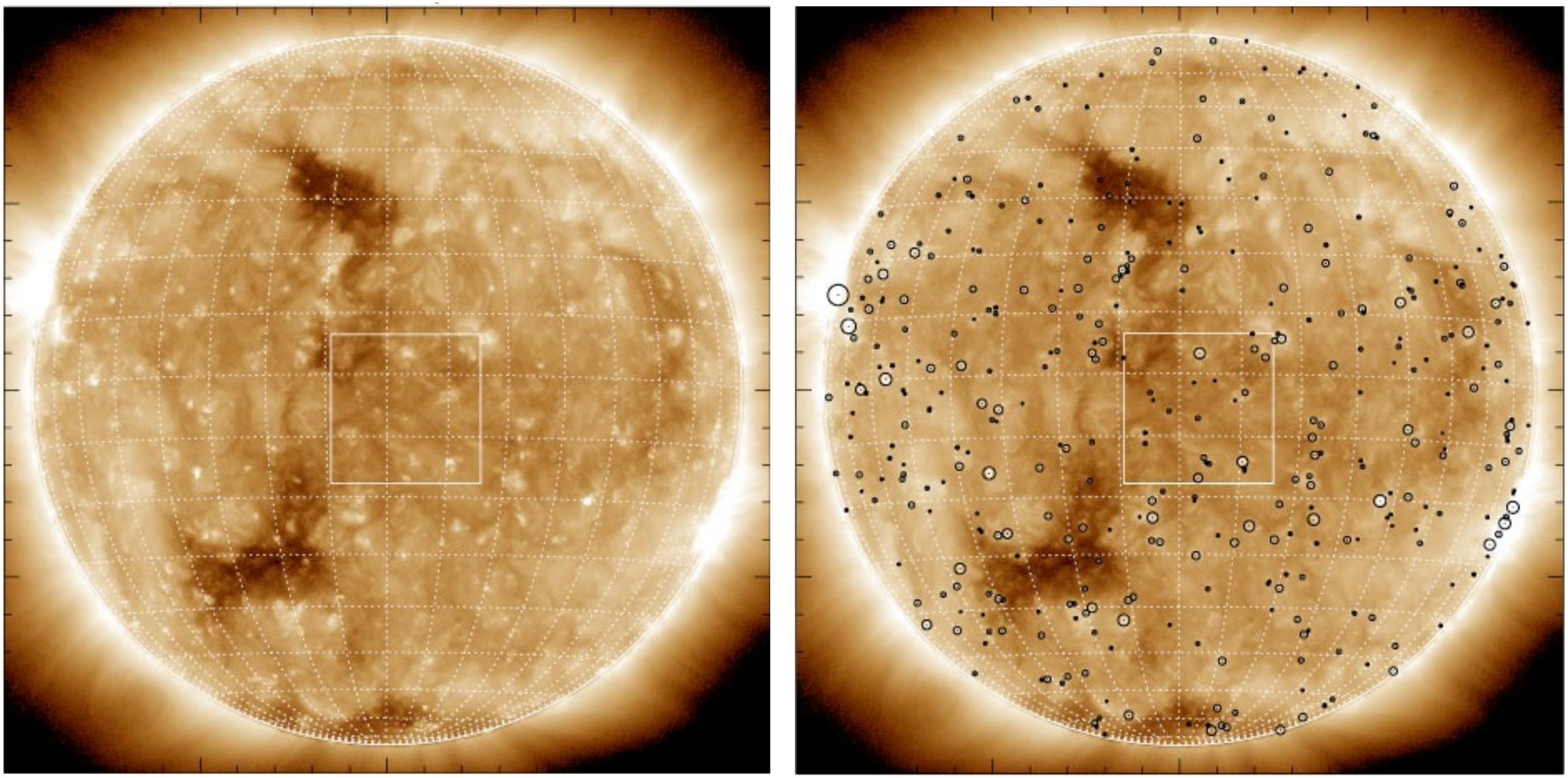




The apparent 100-250Mm MRoI scale is **consistent** with the that of **giant cell convection** [e.g., Miesch 2005]. A scale that was NOT readily observable.

Decomposing Surface Magnetism

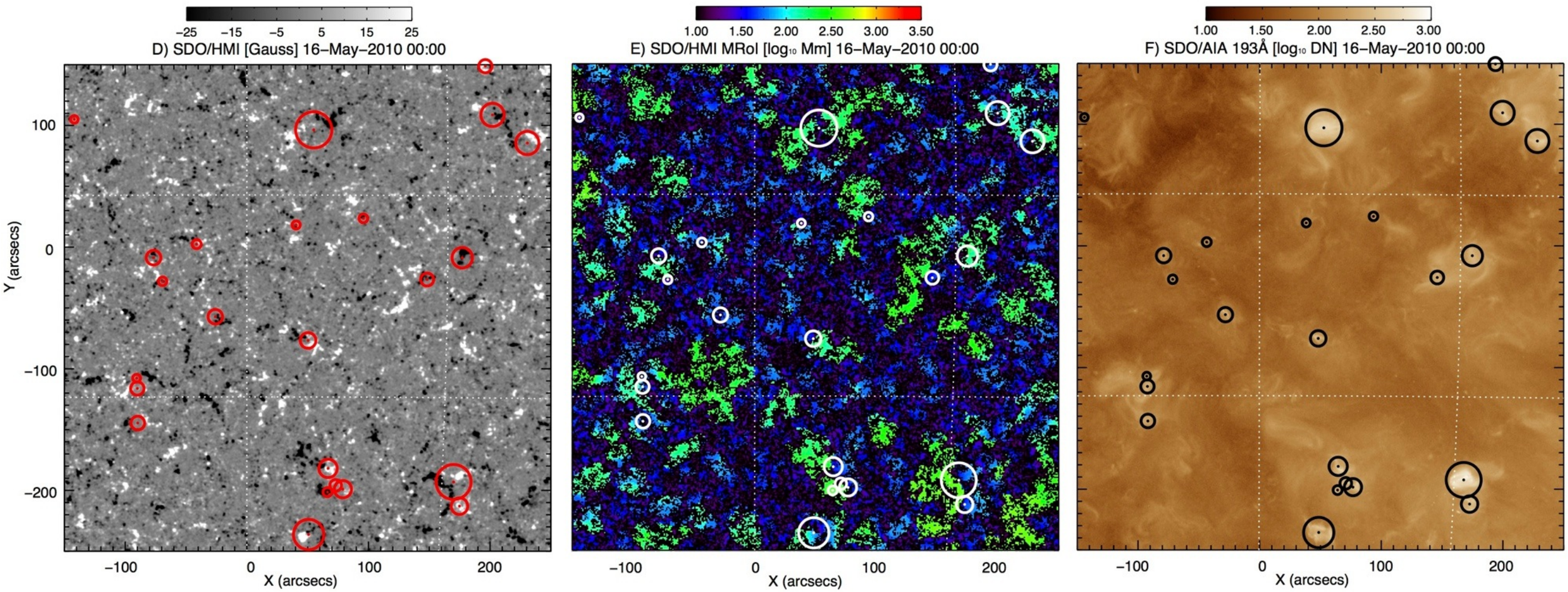
Identify coronal brightpoints (BPs) …an ubiquitous feature of the 1MK corona.



2002 - Original Hypothesis - BPs form at dipolar magnetic arrangements

Decomposing Surface Magnetism

BPs do NOT form at all dipolar regions - they have a preferred location and spatial scale.



They **form preferentially around** spatial concentrations of the 100-250Mm MRoI scale. **Unipolar** magnetic regions that we dub **“g-nodes”**.

Decomposing Surface Magnetism

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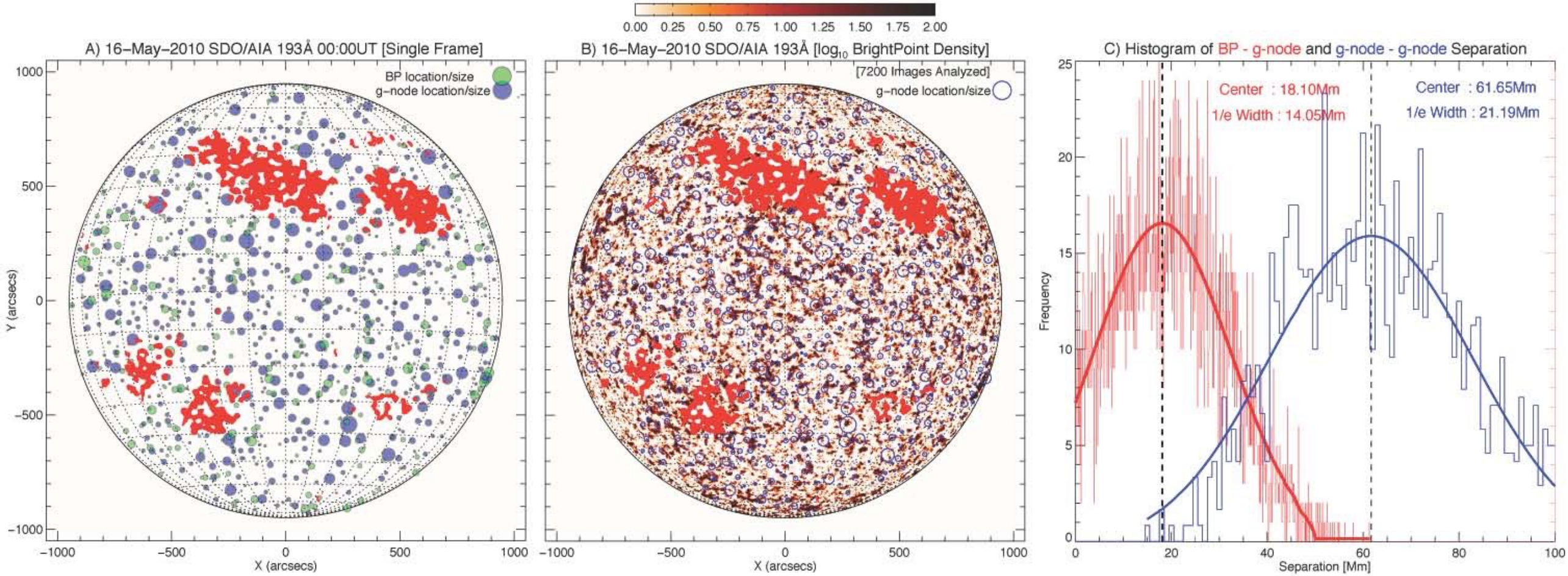


They **form (and reoccur) preferentially around** spatial concentrations of the 100-250Mm MRoI scale. **Unipolar** magnetic regions that we dub **“g-nodes”**.

Decomposing Surface Magnetism

- MRoI indicates the possible presence of four scales of magnetic influence in the outer solar atmosphere.

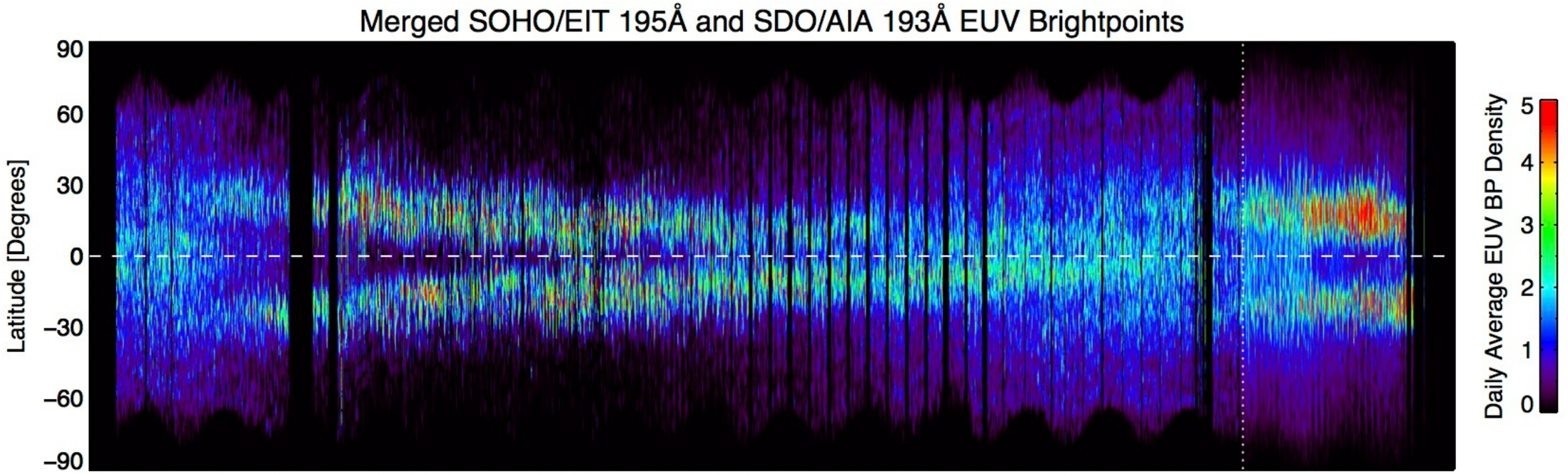
- The MRoI appears to illustrate the presence of a giant convective scale, one driven by the rotation of the star's radiative zone. That scale is an ever-present in the SOHO/MDI and SDO/HMI data archives.

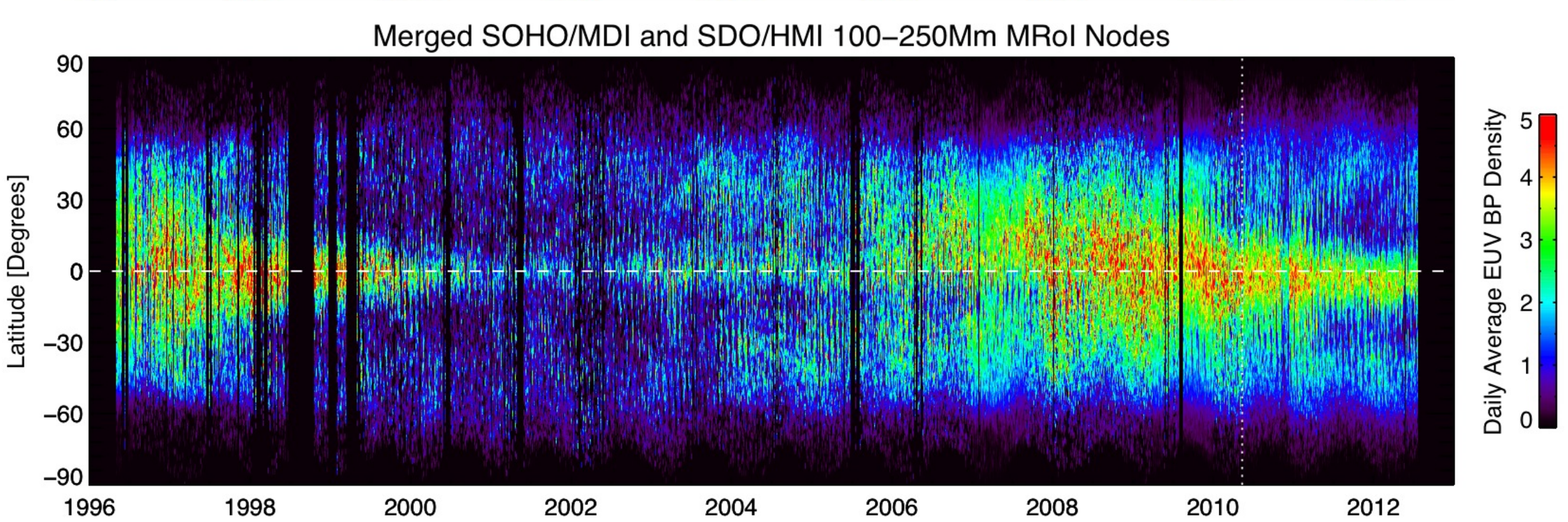
- Coronal Brightpoints do not form at all dipolar magnetic flux concentrations. Indeed, they appear to form in close proximity to the spatial concentrations of the giant scale - "g-nodes".

- Those locations rotate faster than the surface plasma. Consistent with magnetic flux rooted much deeper in the solar interior.

What do these features tell us about the evolution of the large scale magnetic field?

Cycles: Large Scale Temporal Evolution





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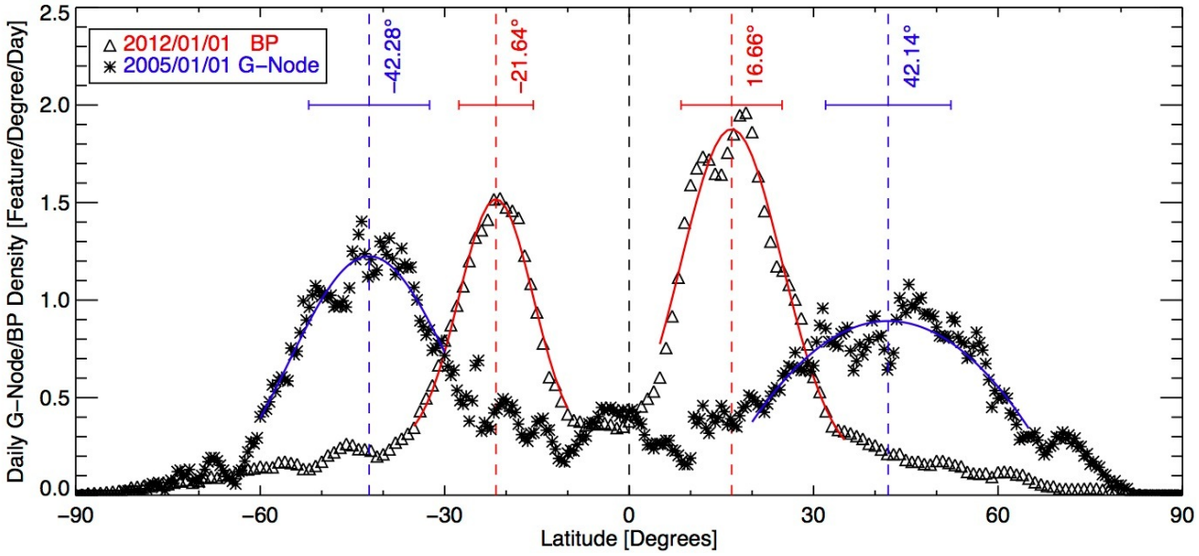
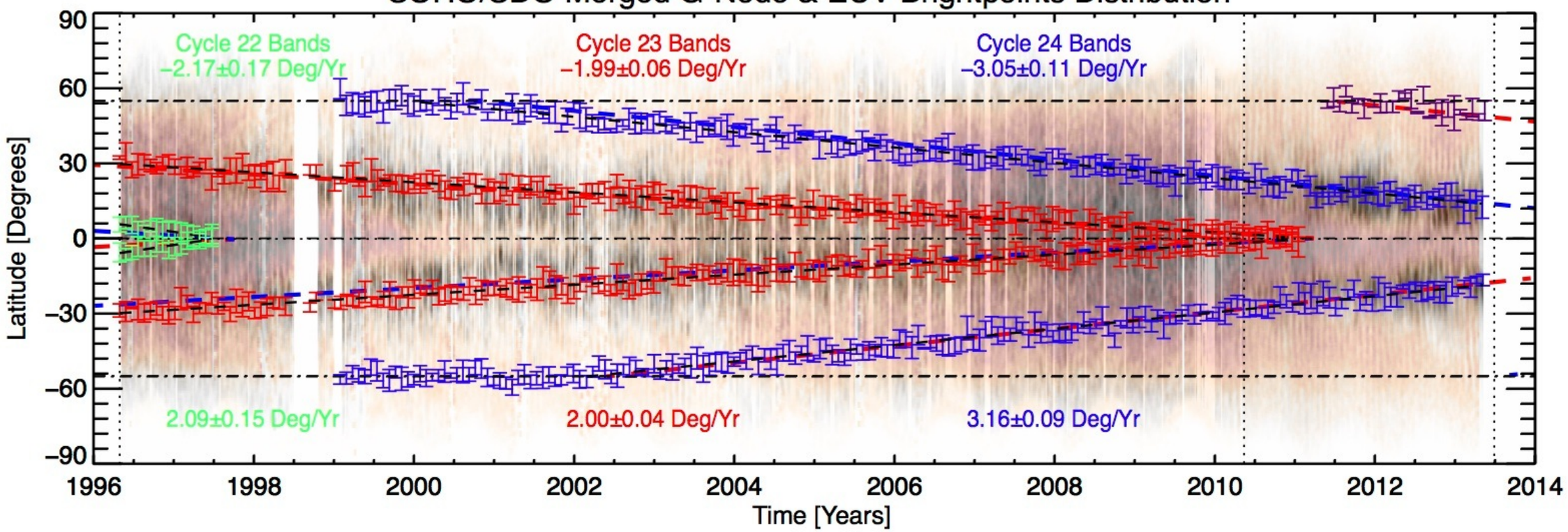
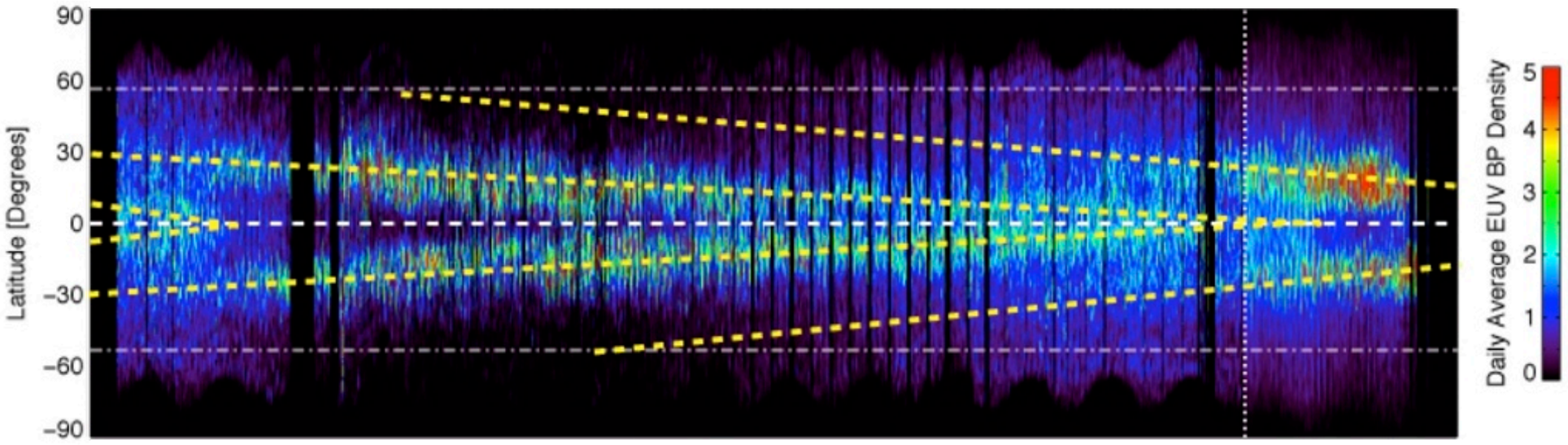


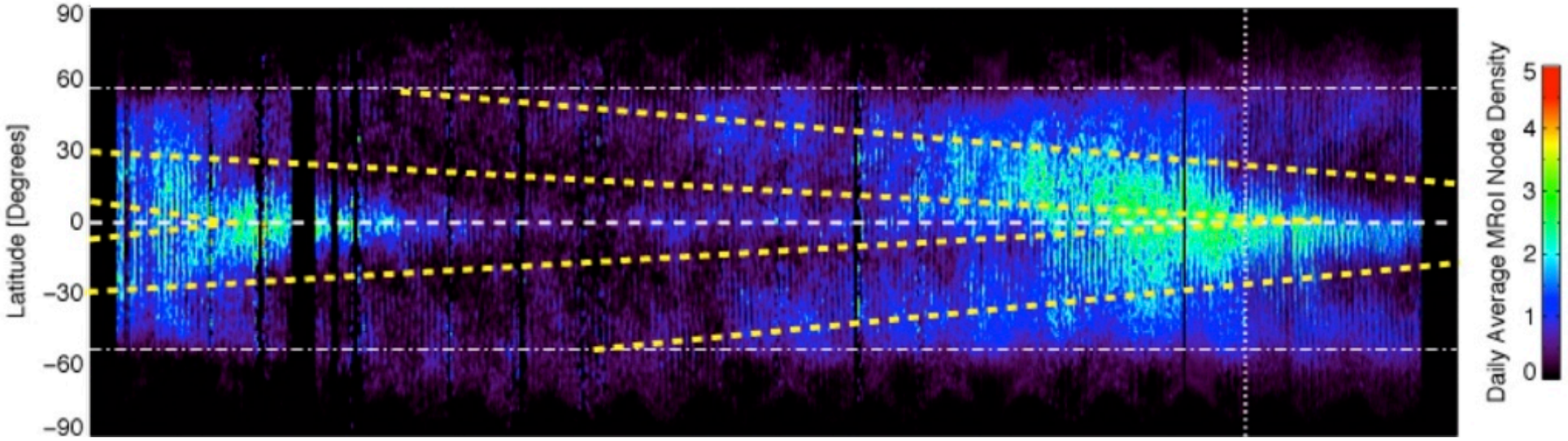
Gaussians fitted to peaks of g-node and BP latitudinal density distributions [cf. Golub et al. 1978] permit us to track motion of the bands with time.



Cycles: Large Scale Temporal Evolution

New diagnostics provide insight and add strong constraints on the origins and evolution of the solar (sunspot) cycle.





by extending the butterfly diagram in latitude and time…..

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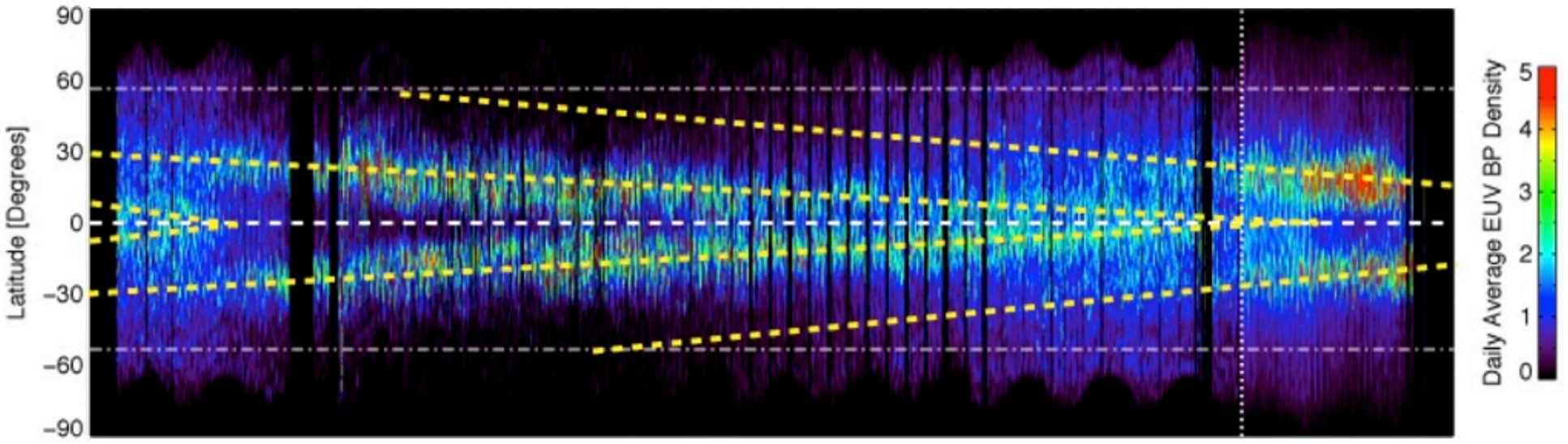

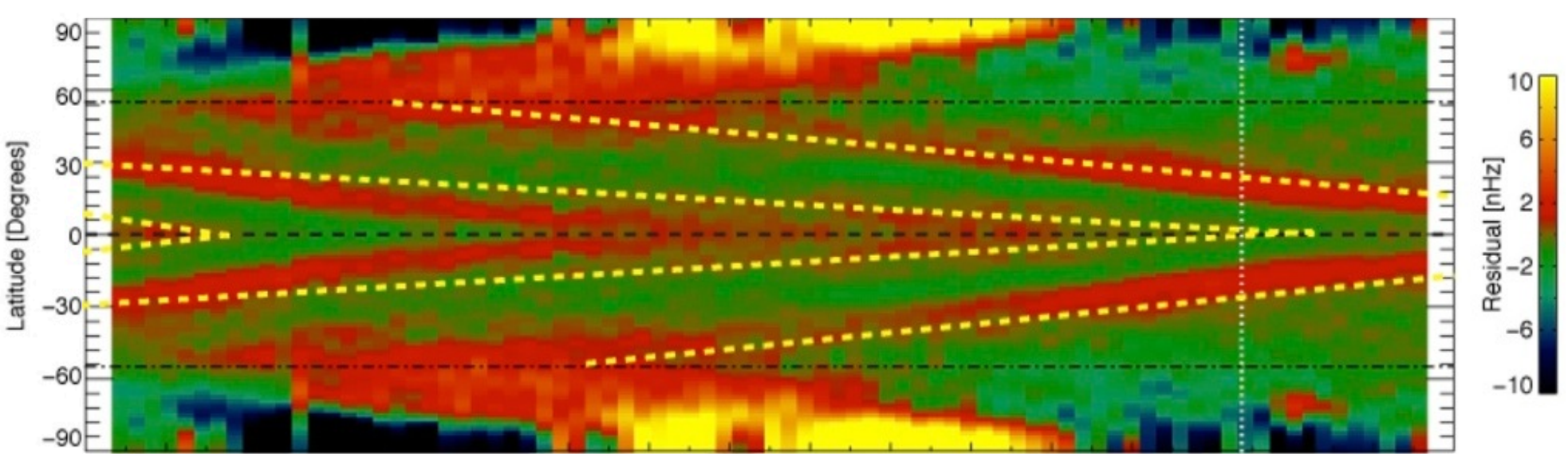

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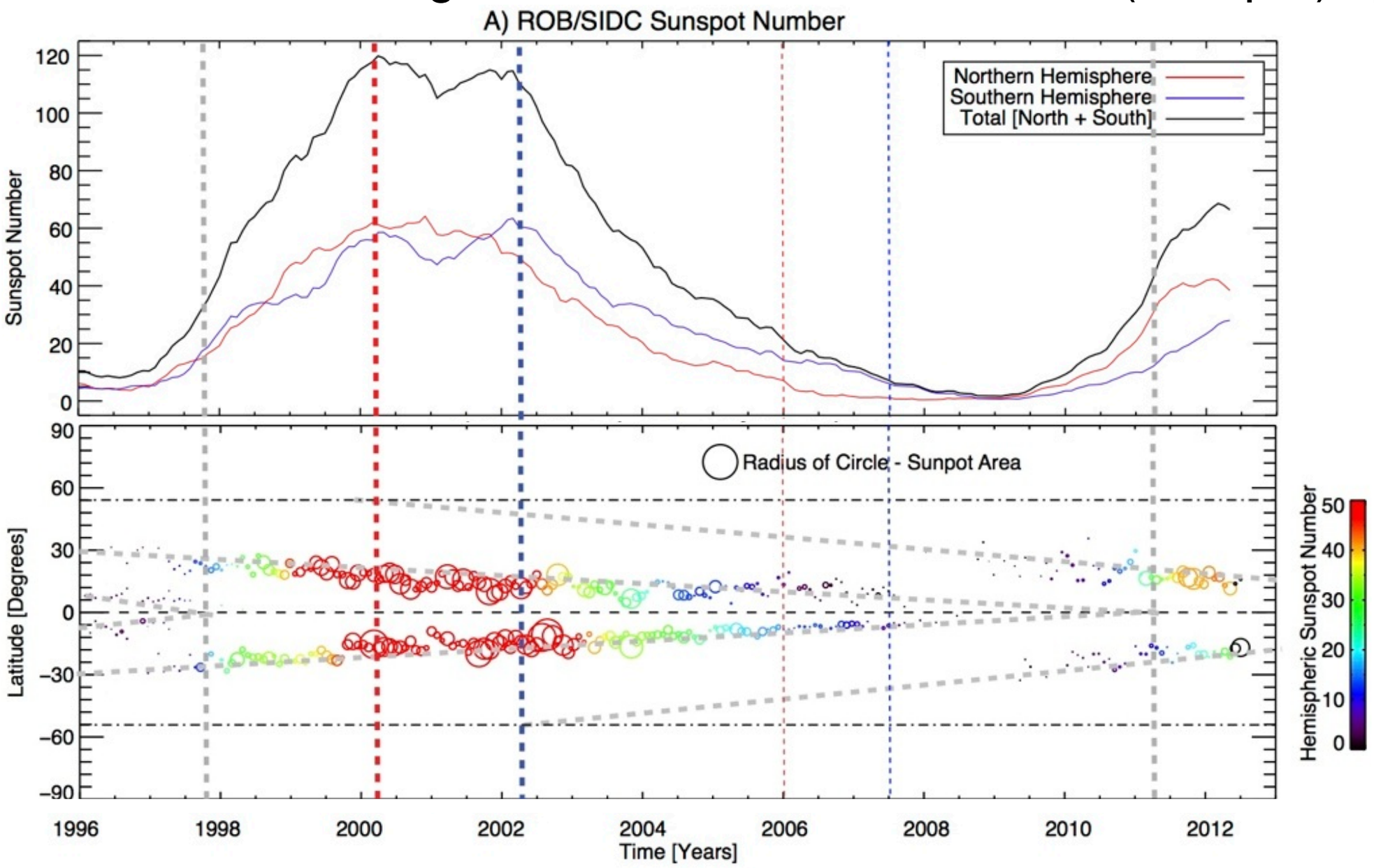

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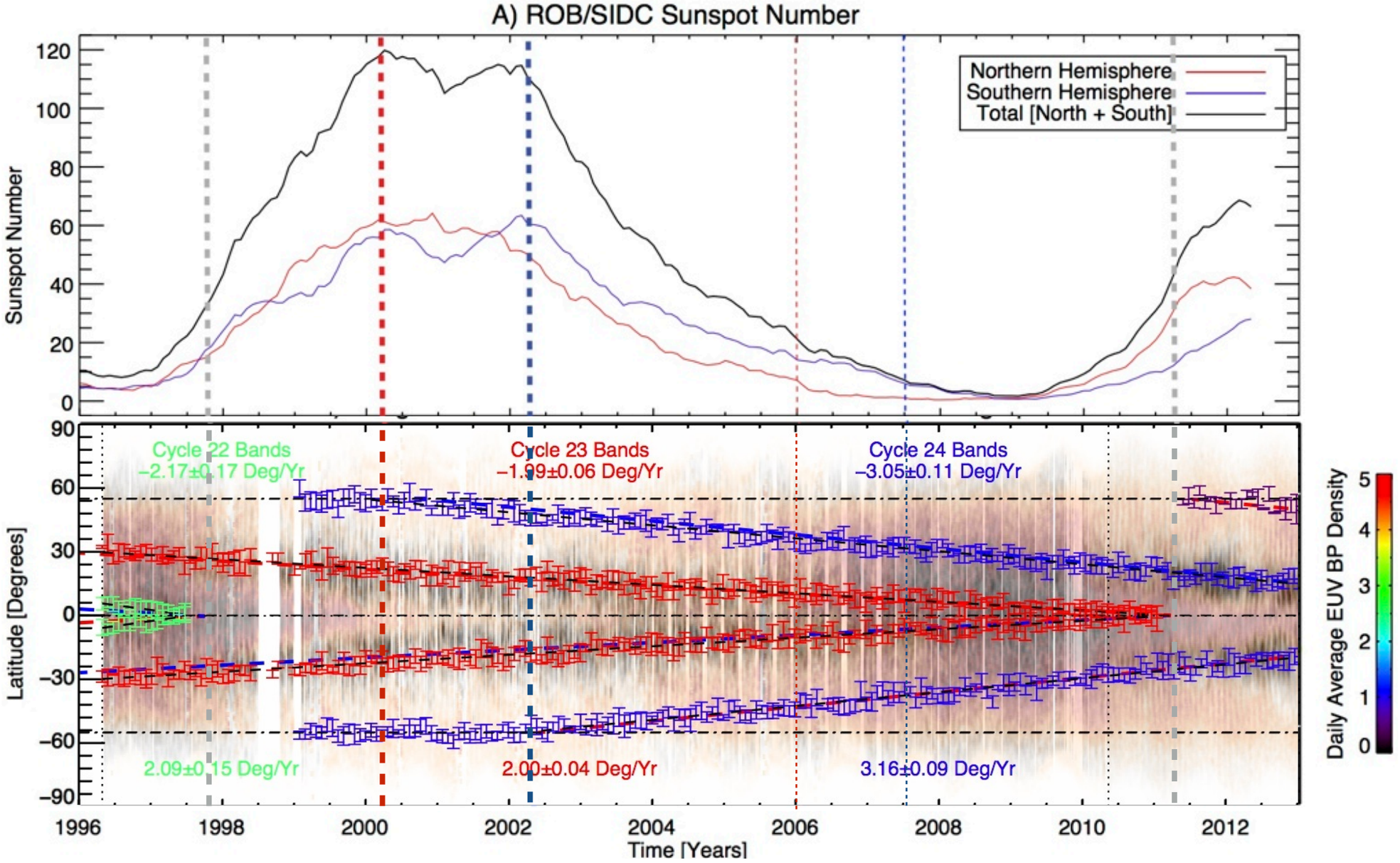

ID of small-scale magnetic features permit observation to 55° that **precede sunspot formation by >10yrs**

by extending the butterfly diagram in latitude and time…..

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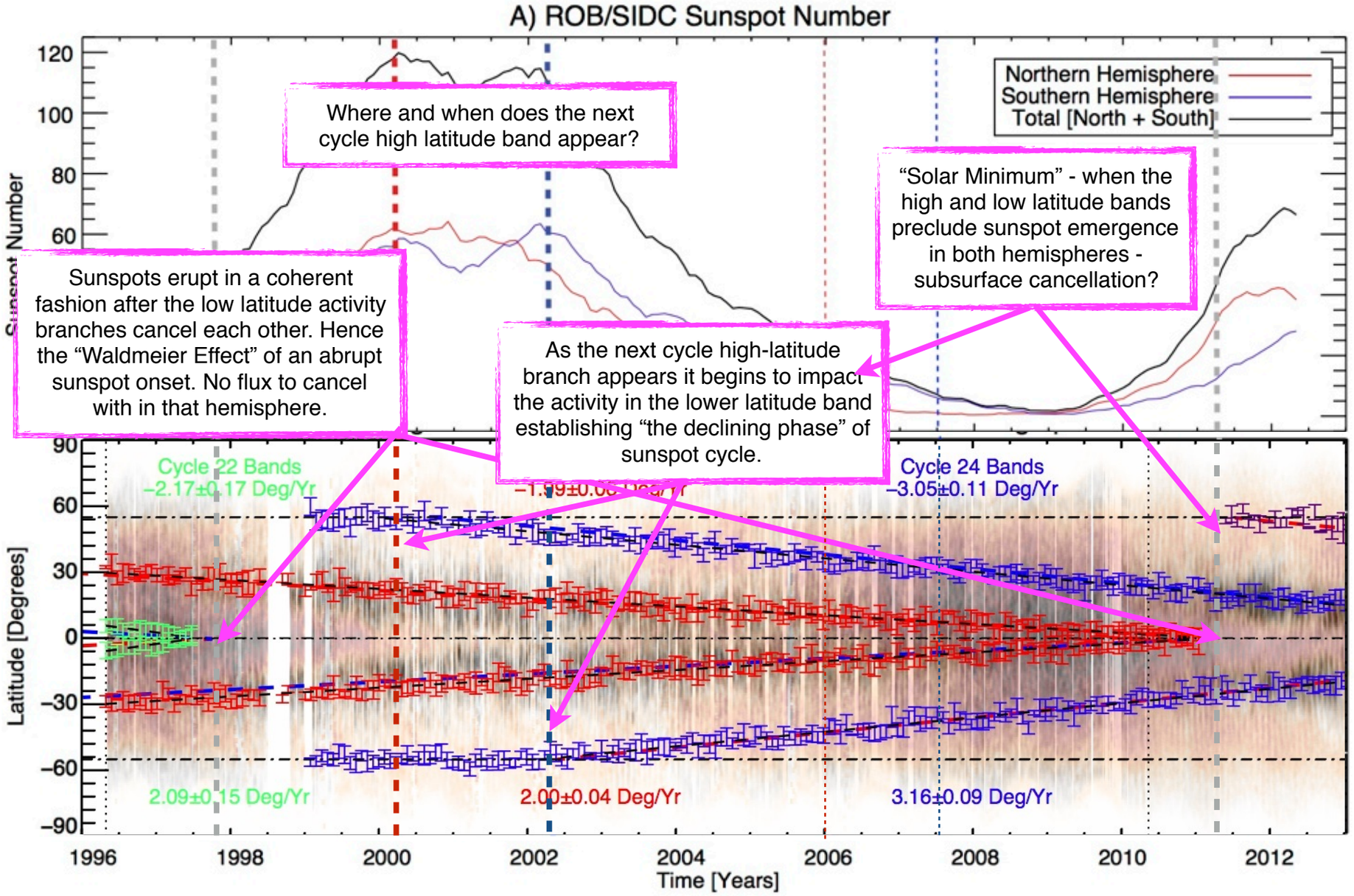

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sunspot evolution and cycle governed by **overlap of oppositely-signed activity bands?**

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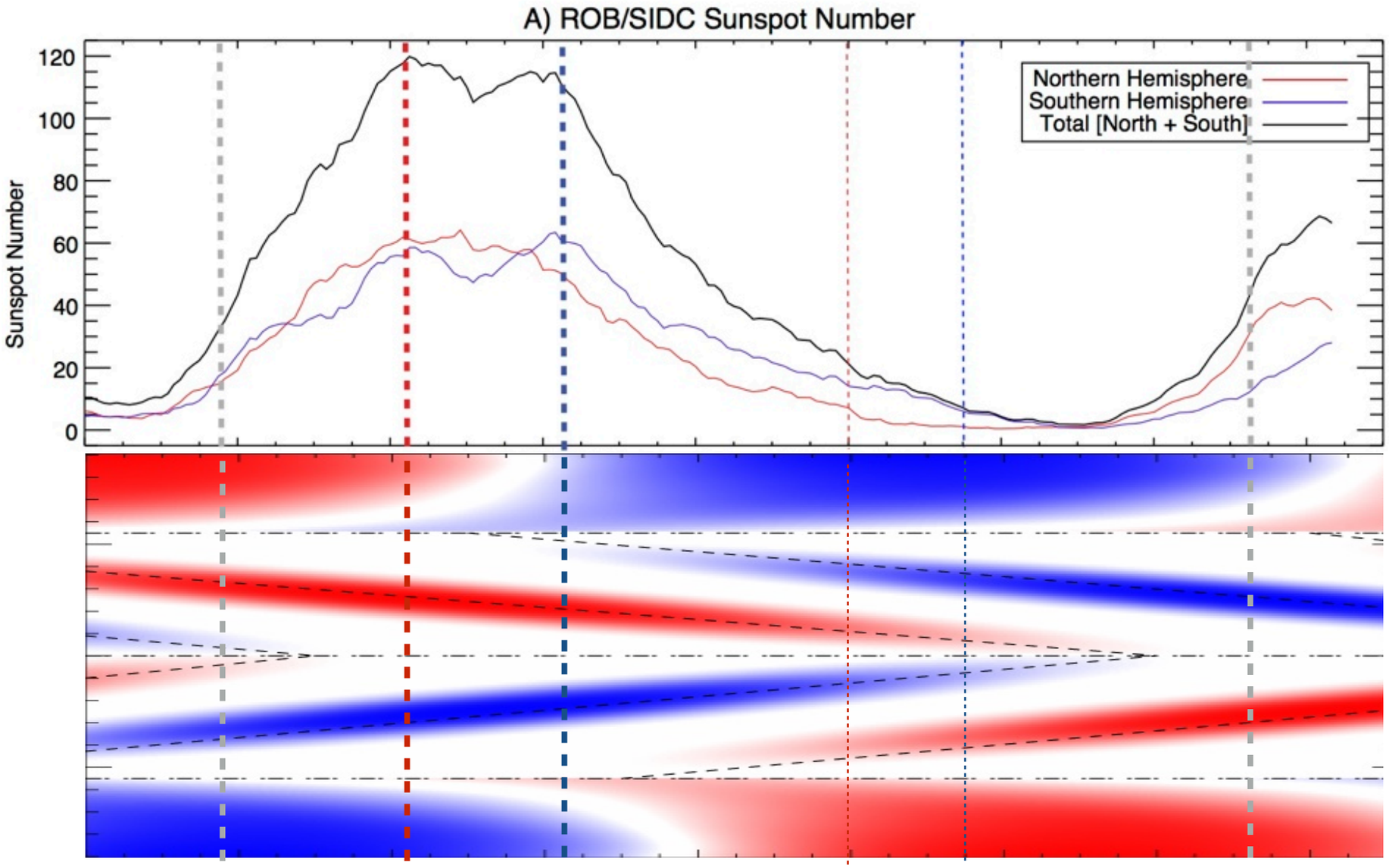

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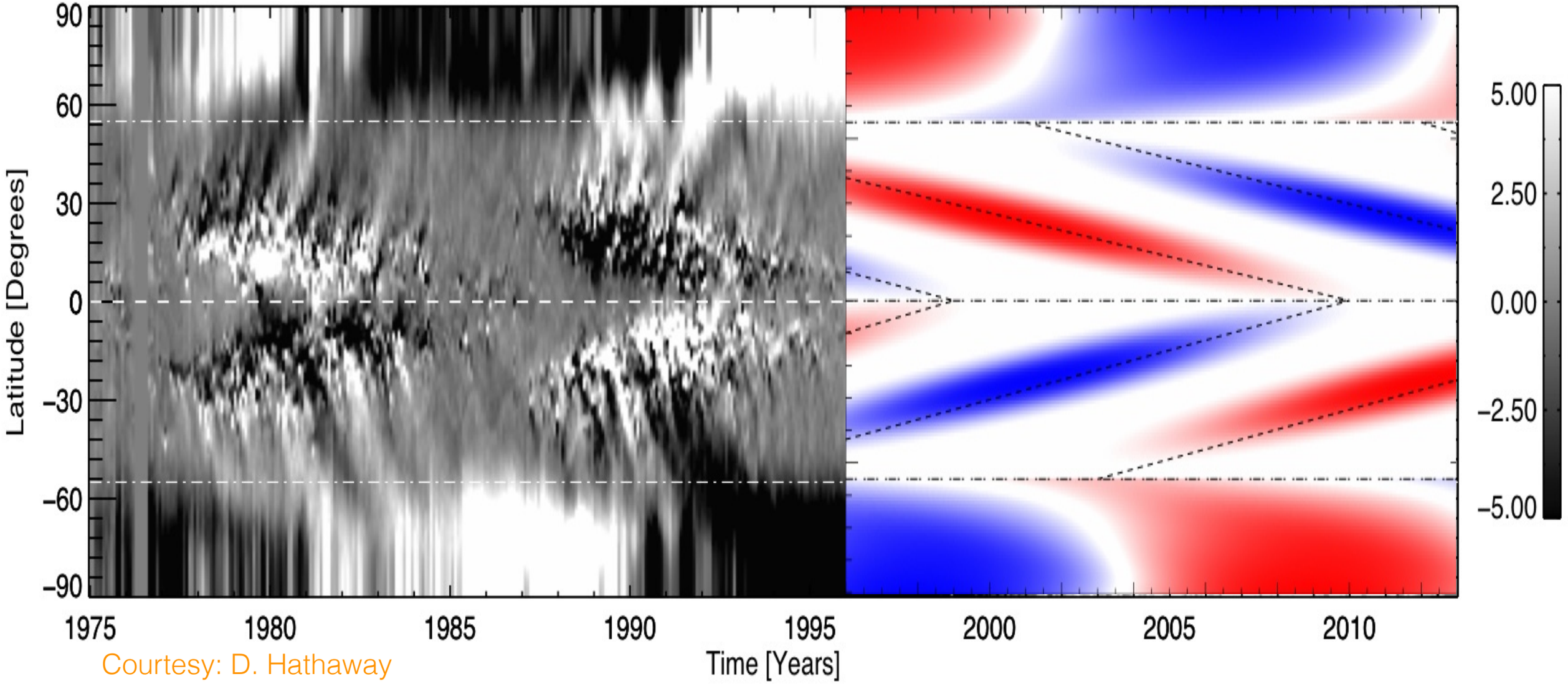
by extending the butterfly diagram in latitude and time…..

Distracting/Misleading/Extending Butterflies

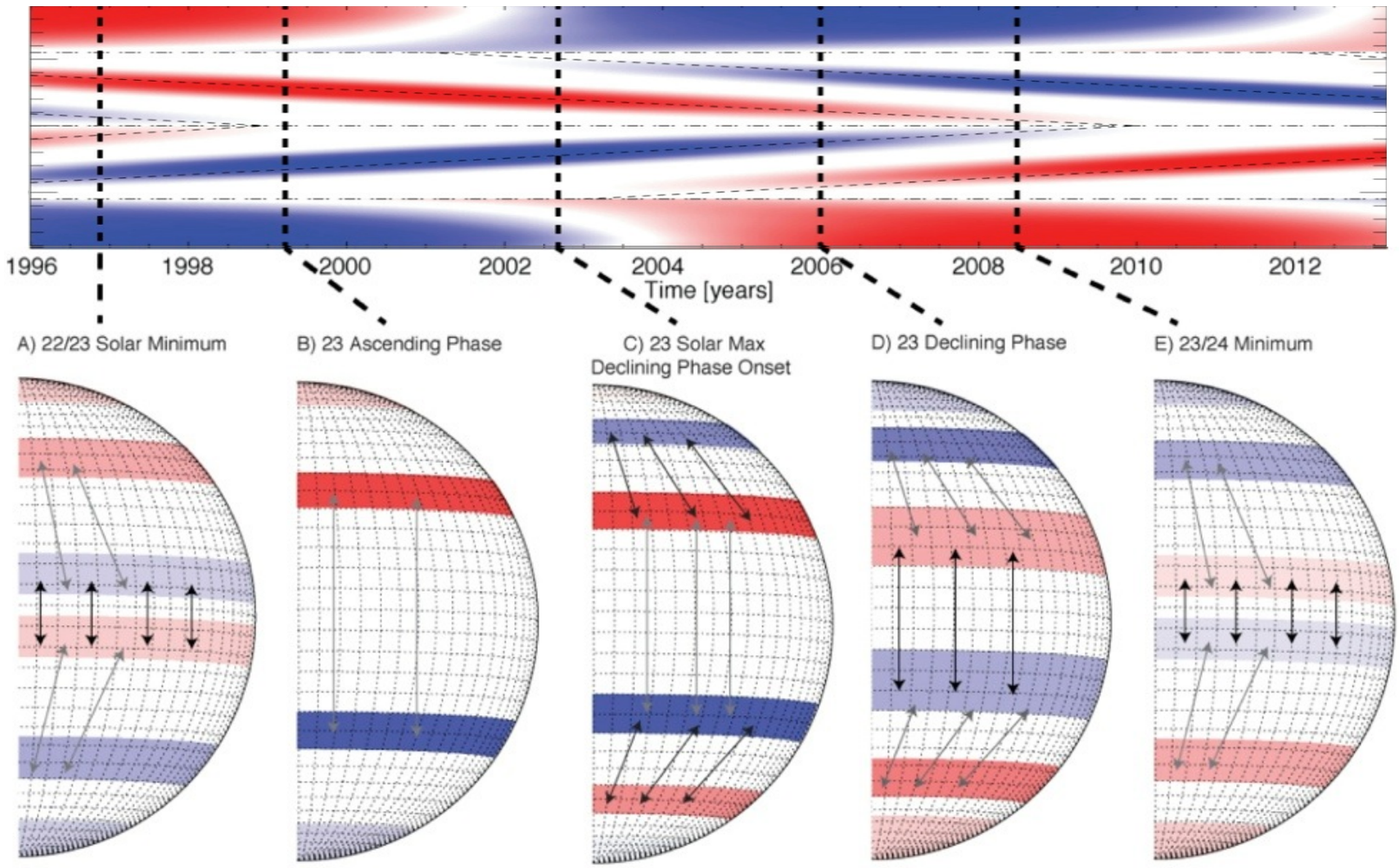
The activity bands on which sunspots form are “extended”!

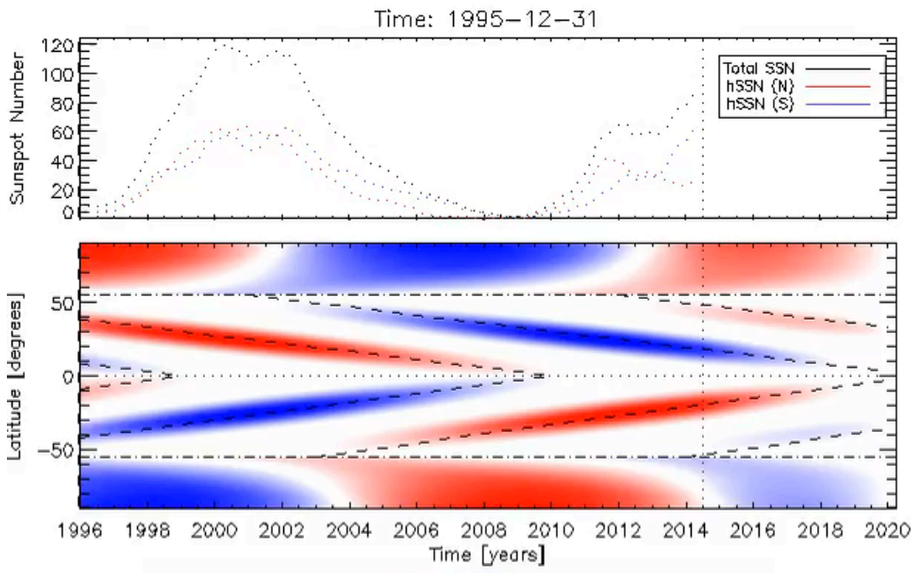


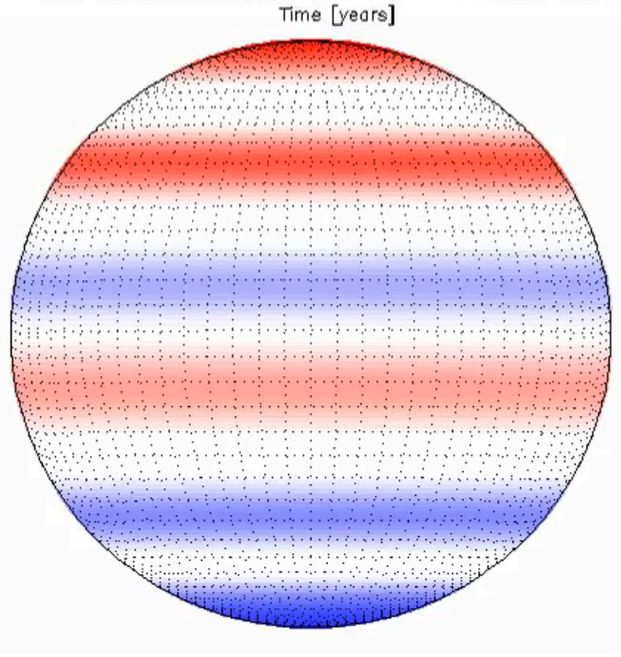
Courtesy: D. Hathaway

Cycles: Large Scale Temporal Evolution

Magnetic “telecommunication” appears to help modulate the appearance of the sunspot cycle?







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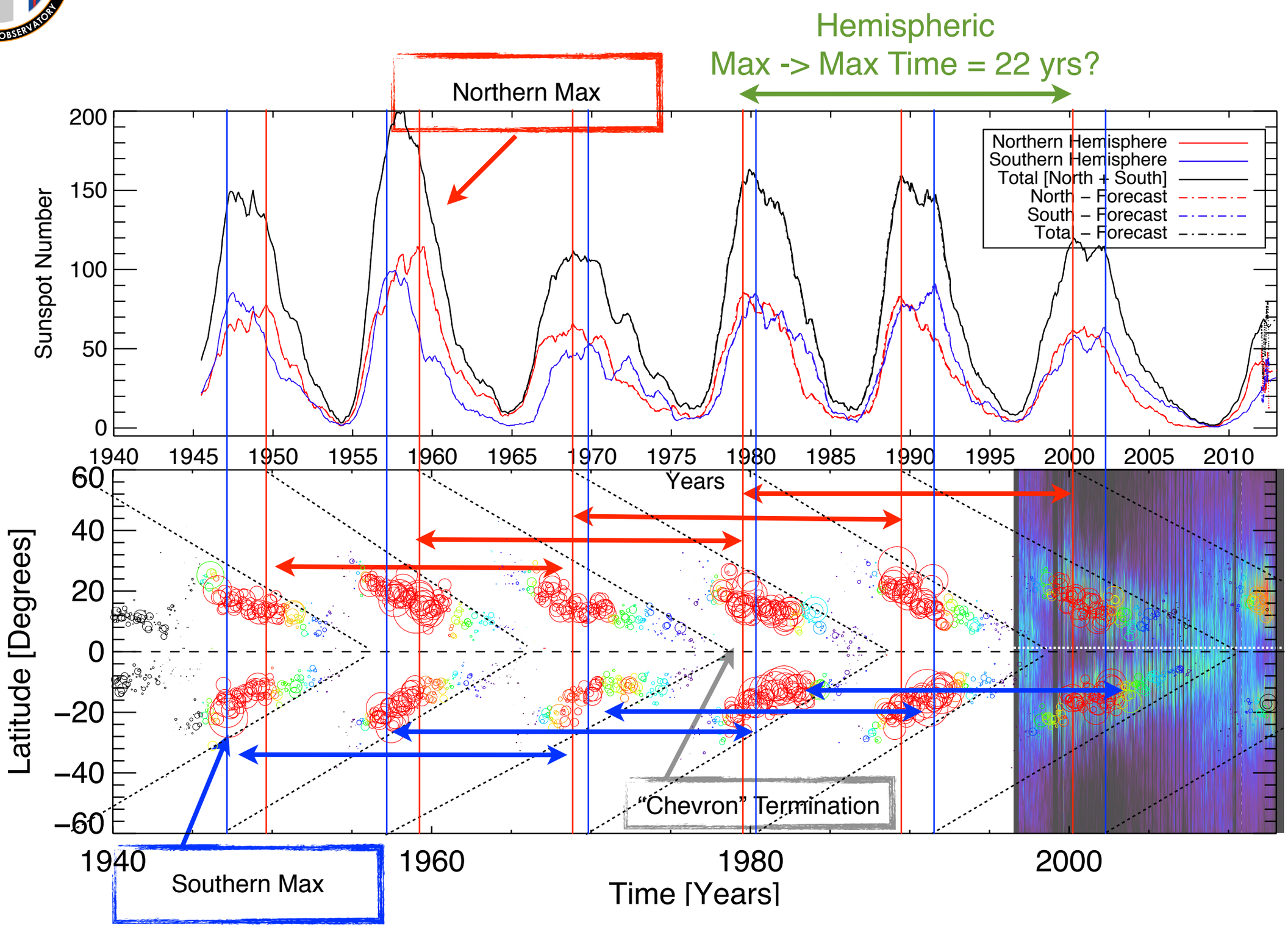

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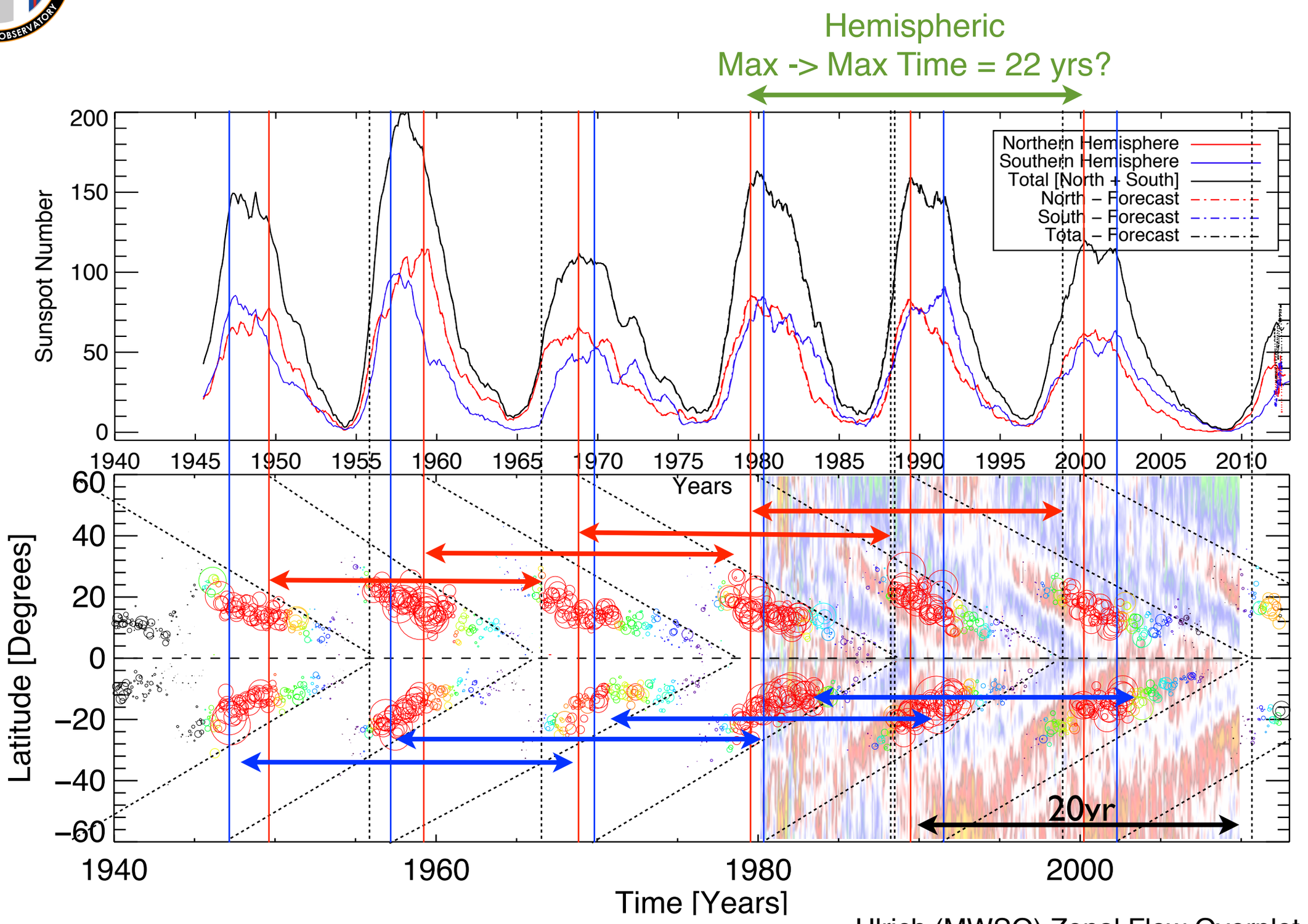


Ulrich (MWSO) Zonal Flow Overplot

Cycles: Large Scale Temporal Evolution

1. **Sunspot cycle appears to be a consequence of the interaction of latitudinally and temporally overlapping activity bands of the 22-year magnetic activity cycle.** An "interference pattern" of mutually canceling magnetic systems?

   Activity bands appear at high latitudes (~55°).
   Not Axisymmetric. Asymmetry is typical state.
   Bands don't always start migration at the same time.
   Degree of overlap linearly correlated with cycle length.
   Migratory speed correlated with cycle strength.

2. System seems to be **driven by the rotation of the radiative zone** and global-scale resulting (magneto-)hydrodynamics.

   Strong latitudinal dependence of all diagnostics.
   Evidence of "Critical Latitude" (~55°).

3. High latitude evolution seems to play a critical role in timekeeping and evolution of the system?

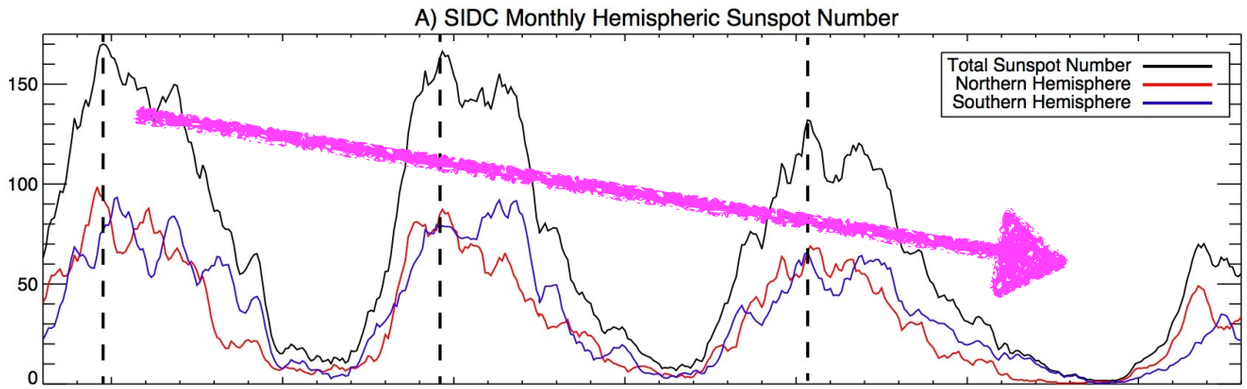
   Appearance at high-lat is almost like "clockwork", quasi-period is robust.

4. **FORECAST CAPABILITY**: Based on our ability to draw a straight line……

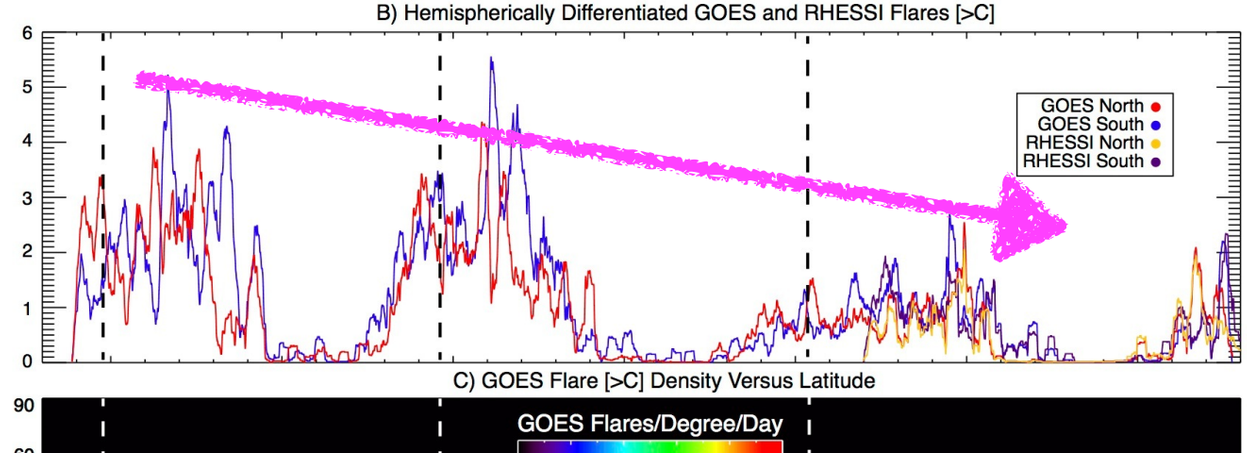
   ….. *possible insight into complex active region formation, grand minima entry and exit, and extreme event occurrence ……*

Seasons: Strong Episodic Variability

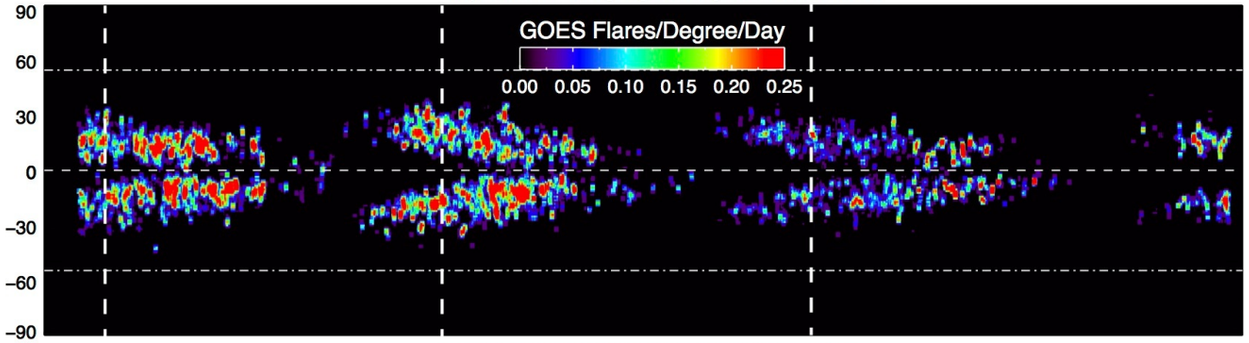
hSSN



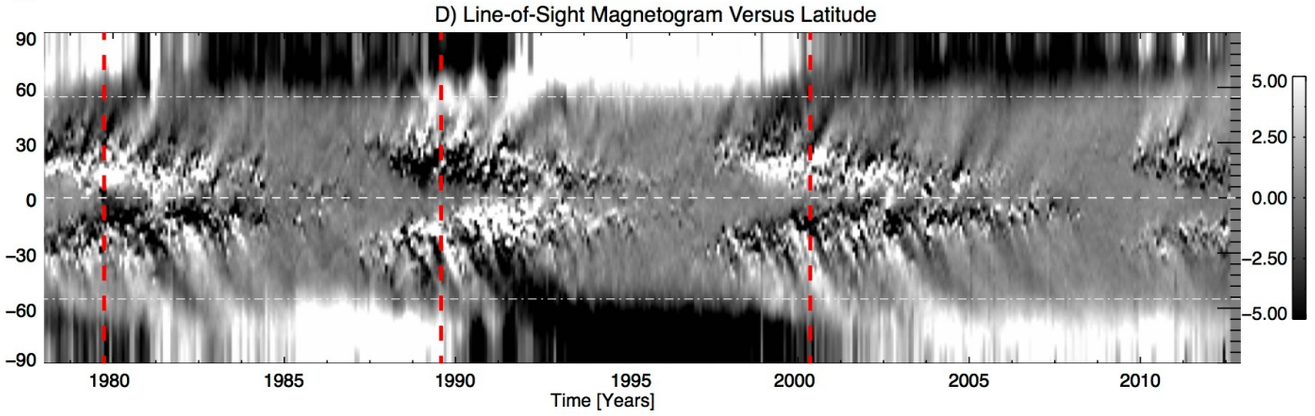
Flares >"C"



Flare "PDF"



B_{LOS}



Some process is modulating variability on those bands….

NOTE:
- Overall Decline in Magnetism
- Overall Decline in SSN
- Overall Decline in Flaring

Is significant contributor to "multi-peaked" SSN.

Hemispheric Phase Variance

$Flare_{MAX}$ later than SSN_{MAX}
- Follows by >1year
- The "Gnevyshev Gap"

Produces Clear Flare Clustering
- In Latitude AND Time

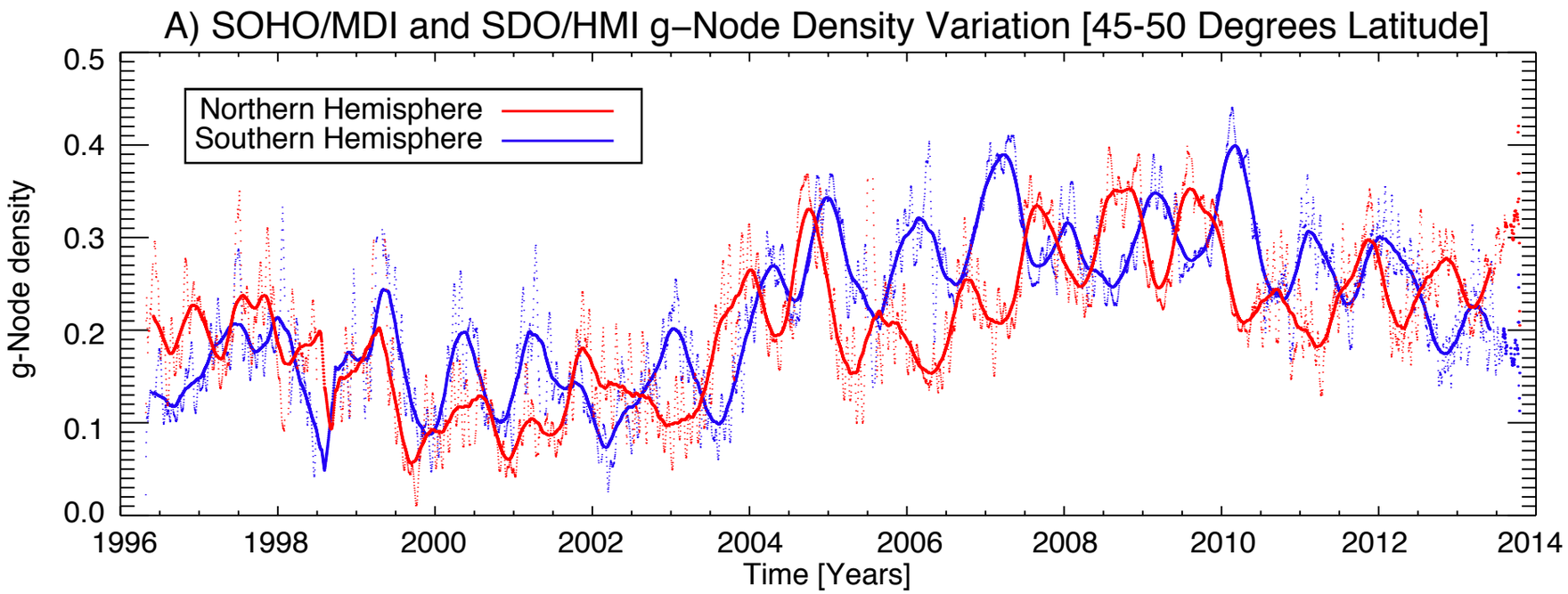
Seasons: Strong Episodic Variability

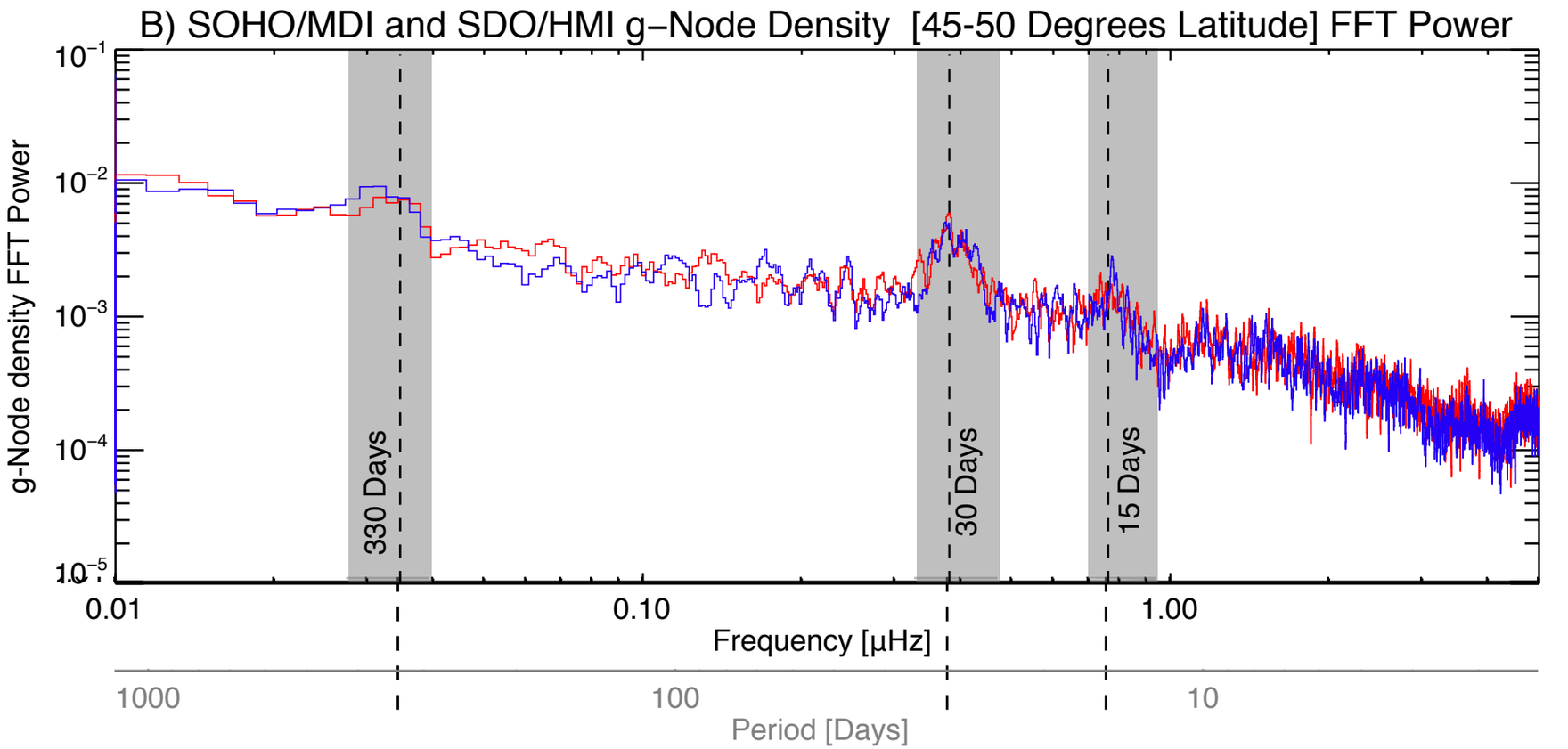
In addition to the apparent propagation of the bands with latitude the bands themselves display significant variation in feature density with time.

Hemispheric phase varies but periods are close.

Peak at ~330 days,

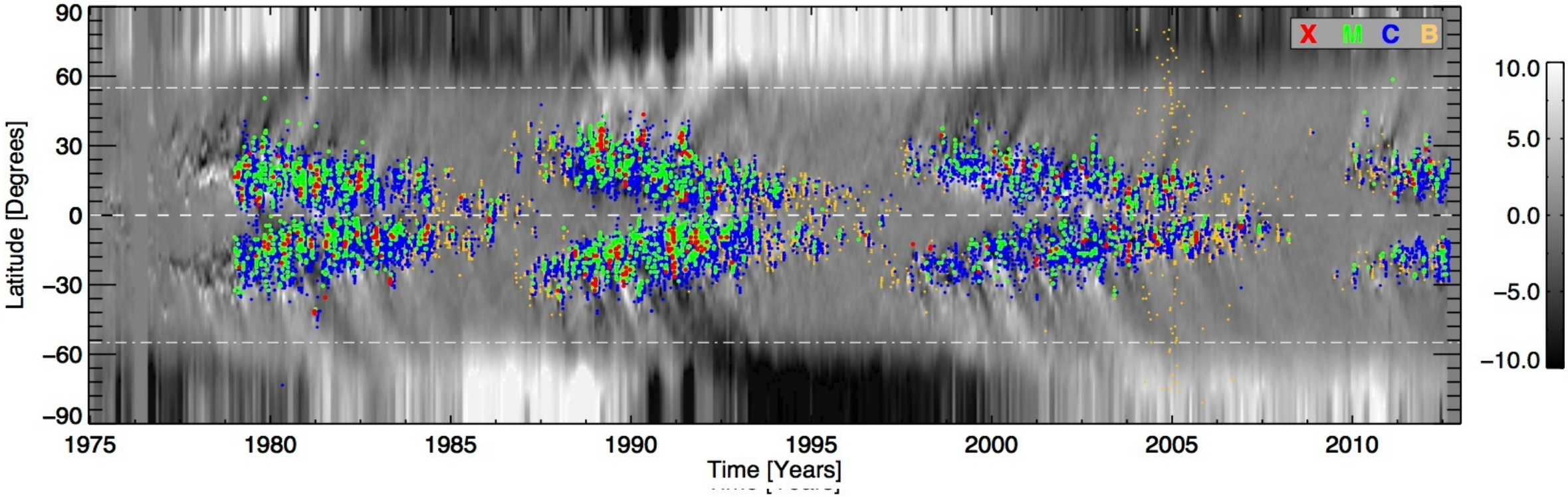
Global surges in magnetism?





Seasons: Strong Episodic Variability

McIntosh et al. (2014b)

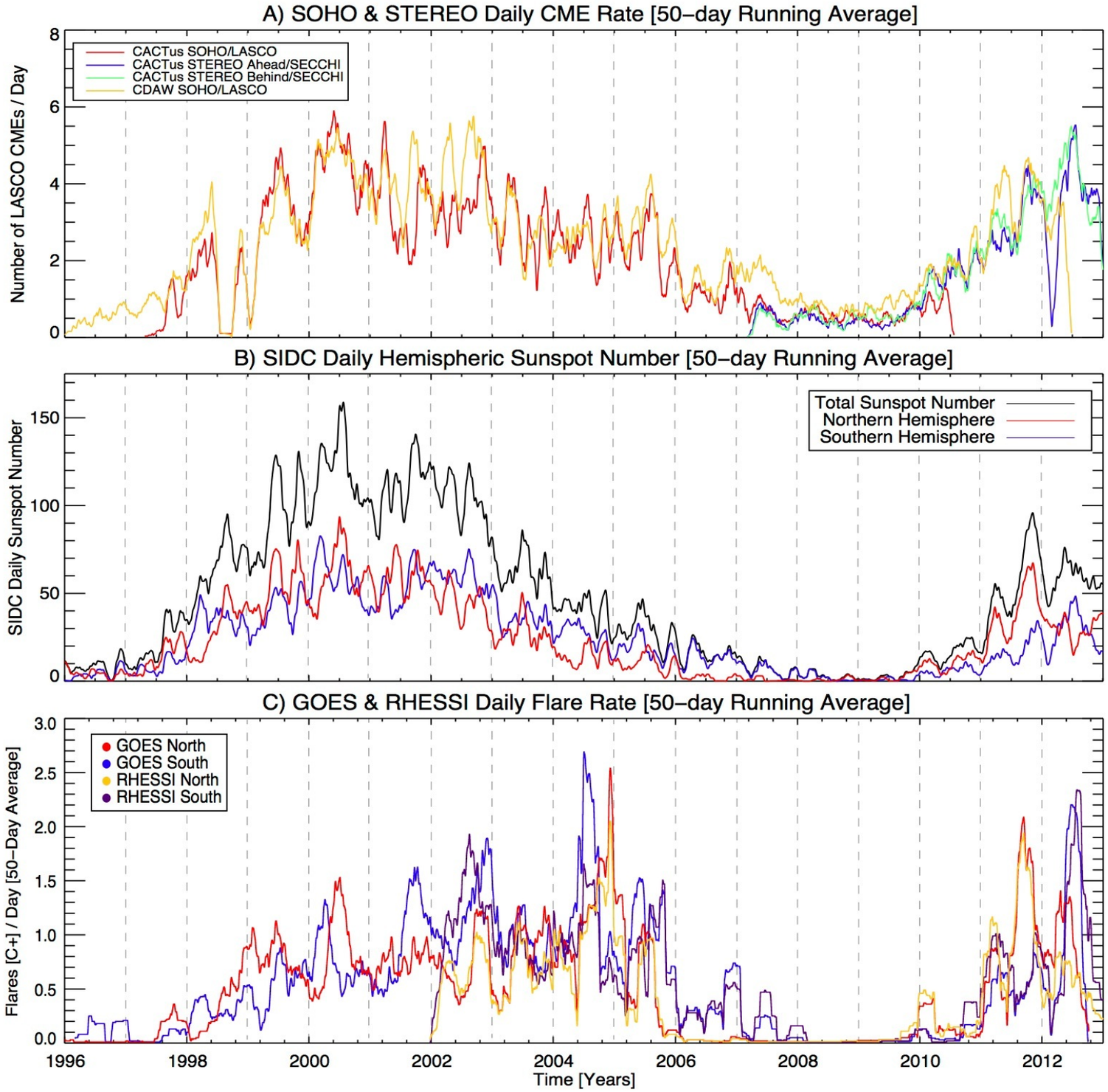


Low energy flares (<C) occur can at ANY phase of the sunspot cycle.
Related to latitudinal progression of sunspots, possible clustering.

Higher energy flares (~M) “cluster” in latitude and time.

Highest energy flares (~X) clearly “cluster”
(flares tend to appear on the periphery of the “butterfly”)

Seasons: Strong Episodic Variability

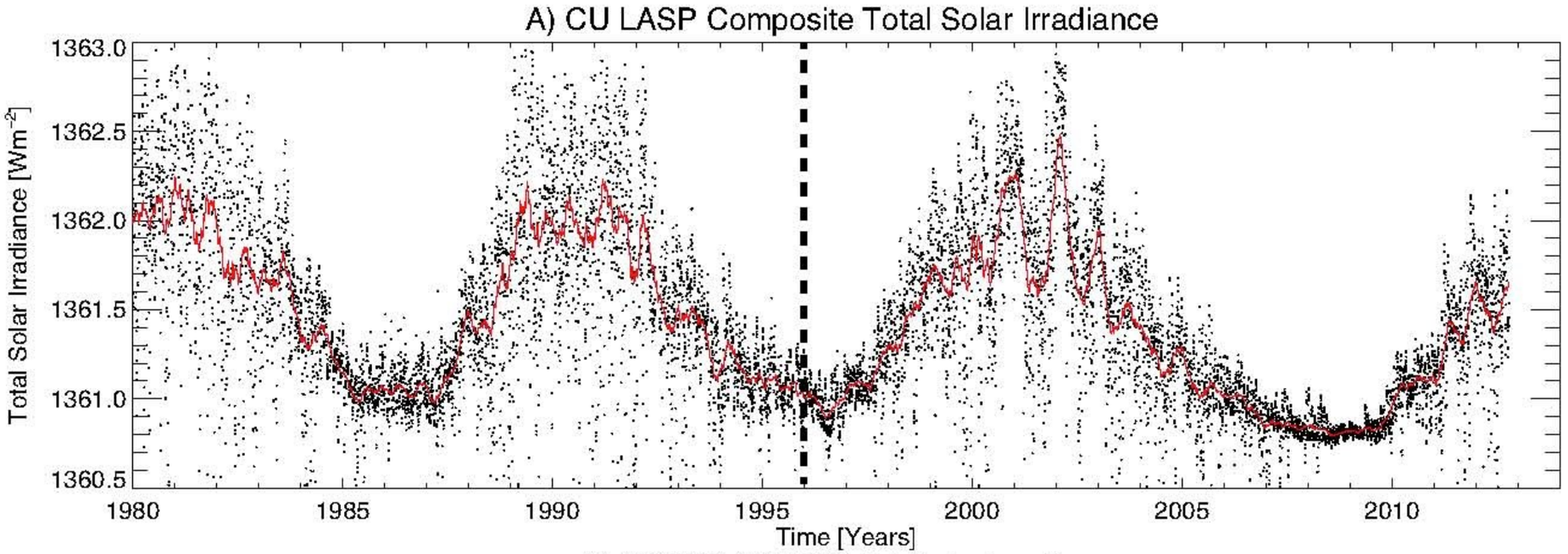


Coronal Mass Ejection
"CMEs"
Rate ~100% Increase

(h)SSN
Rate ~50-100% Increase

Flares
Rate >100% Increase

Seasons: Strong Episodic Variability



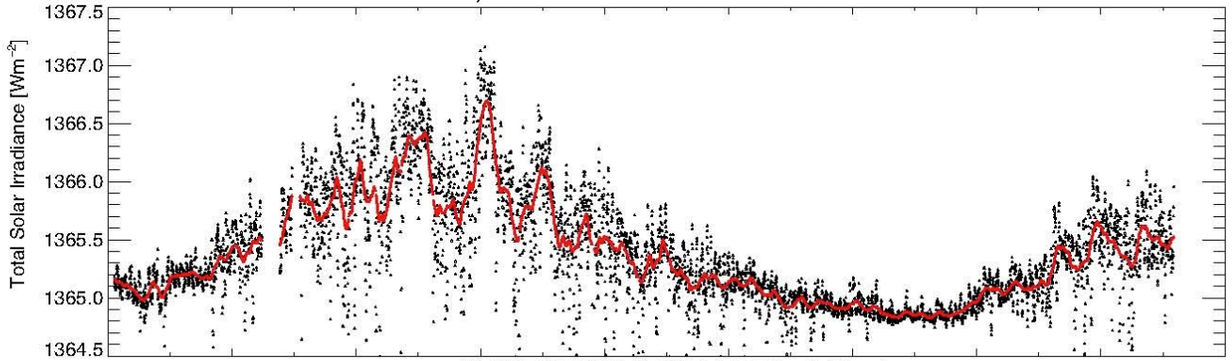
TSI ~1Wm^{-2}yr^{-1}

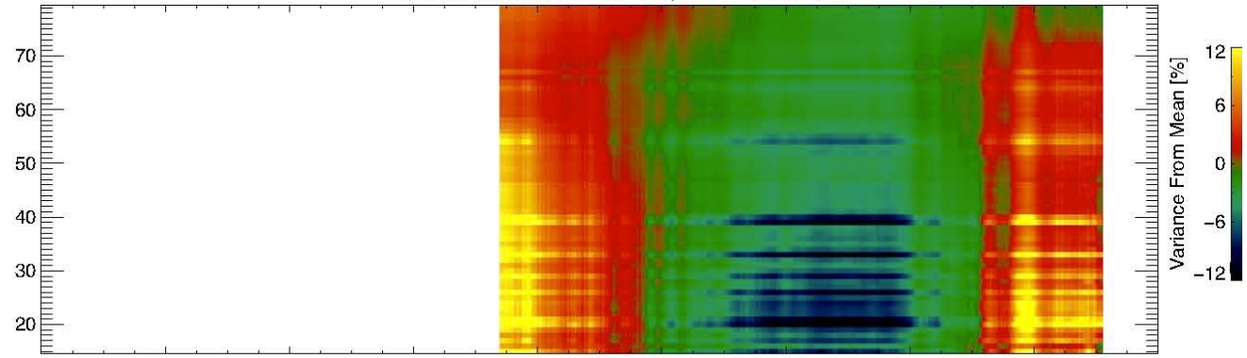
SSI_{UV} ±5%

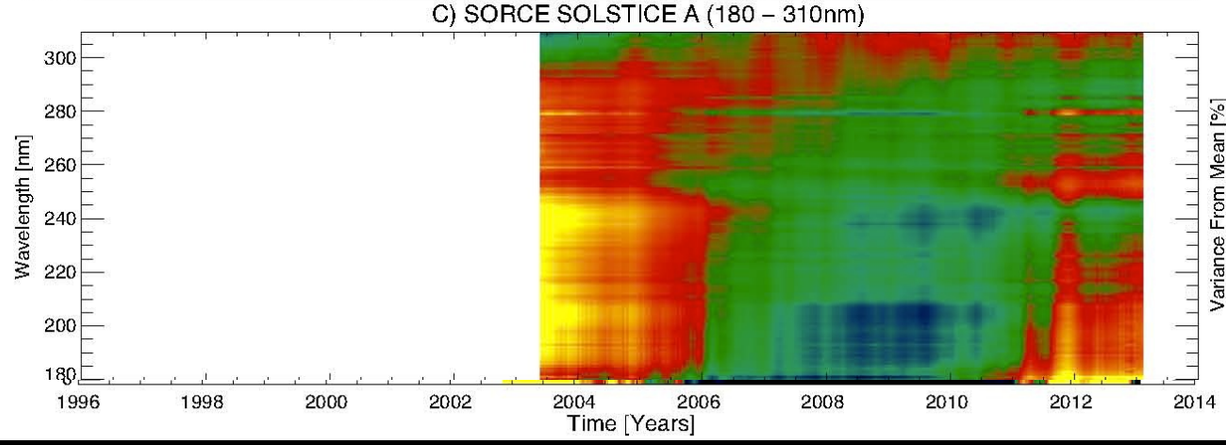
SSI_{EUV} ±15%

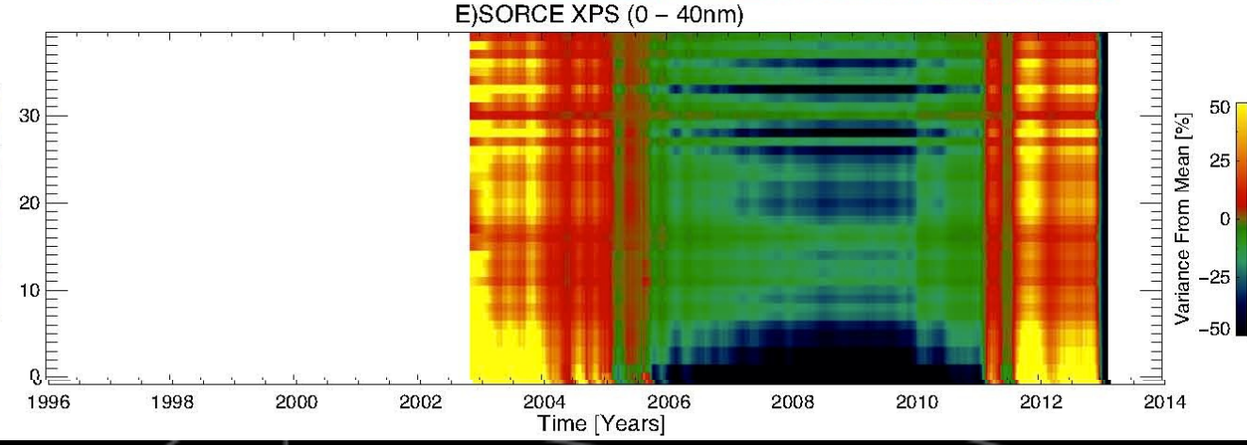
SSI_{XR} ±75%

$SSI_{Opt/IR}$ ±?

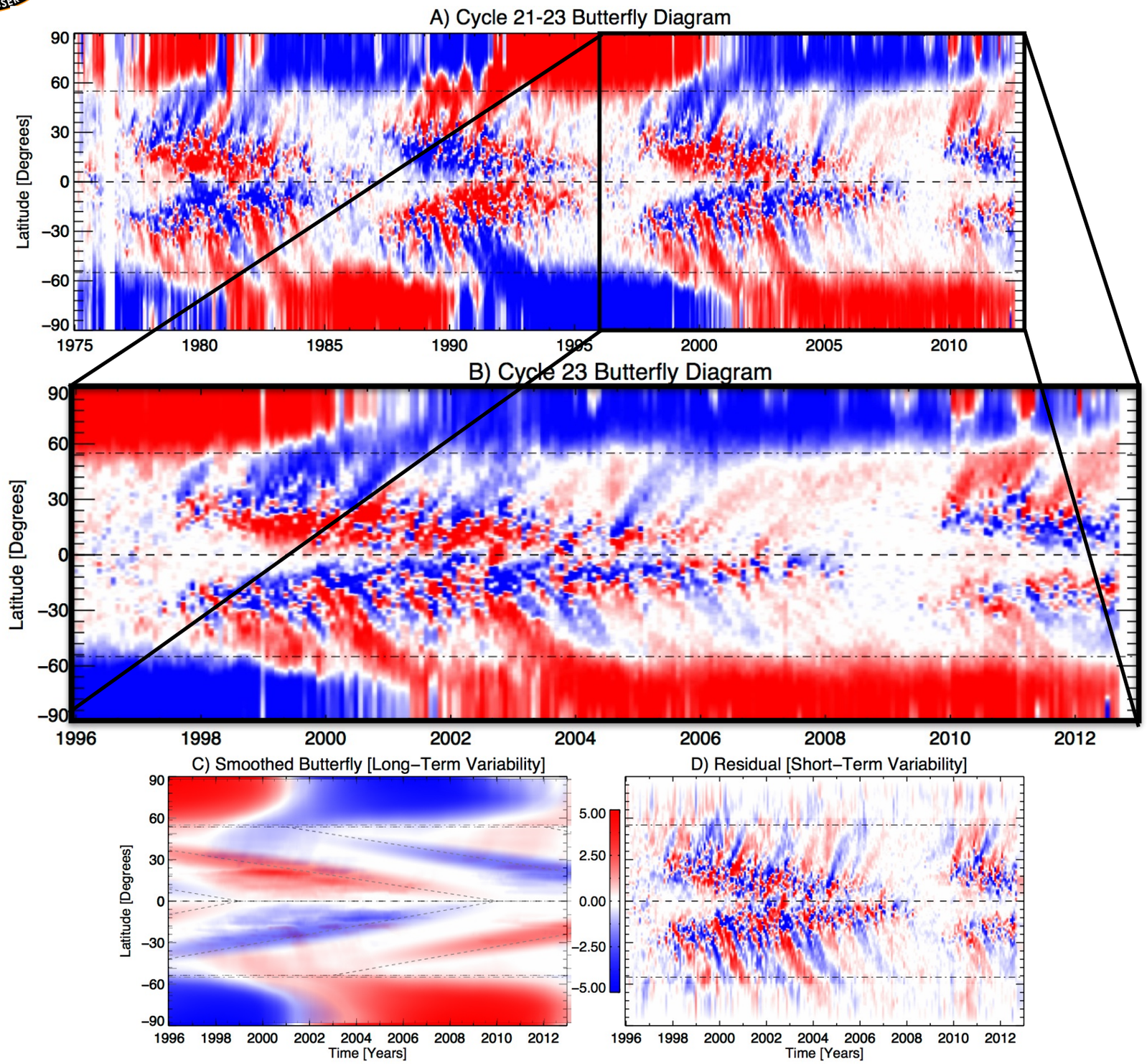








Seasons: The Roots of Strong Episodic Variability



Surges of Surface Magnetism

….apparent poleward motion of magnetic flux from the activity bands….

….apparent poleward motion is likely what happens when you feed the Sun's surface meridional circulation…..only a result of flux surge?

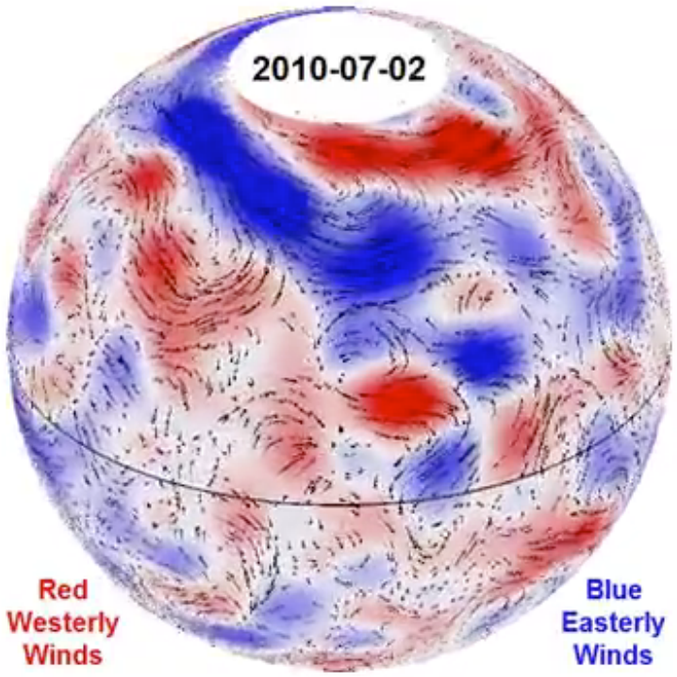
…..effect of global internal rotational dynamics rather than of the dynamo action itself?

What process drives these surges?

Brightpoints (and MRoI diagnostics) have revealed activity bands of the 22-year magnetic activity cycle.

- Bands rooted at (or near) the bottom of the solar convection zone.
- The 11-ish year sunspot (/solar) cycle - the result of an “interference” pattern?
- Different interpretation of stellar activity cycles?

“Giant Cells”



Courtesy: D. Hathaway

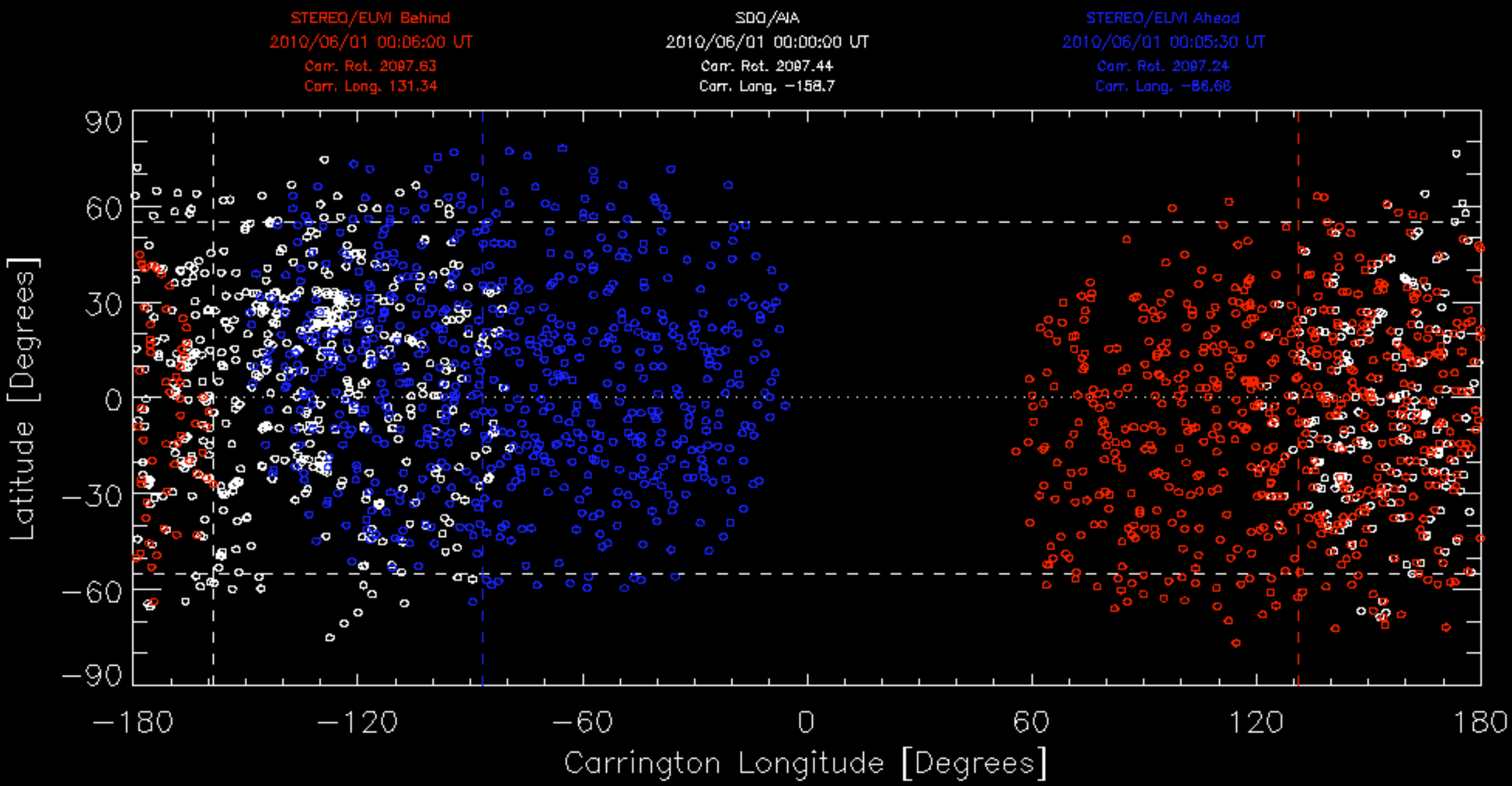
Activity Band Interaction:

- Decadal envelope of solar activity
  - sharp rise - single band per hemisphere in ascending phase
  - shallow decline - two bands per hemisphere in declining phase & mixing
- Band mixing can give rise to hybrid active regions and extreme events.
  - Hale-Nicholson Law Violators
  - Delta-Spots?
  - Equatorial Deltas of Mixed Helicity & Polarity lead to Extreme Events?

Activity bands exhibit a strong instability. Instabilities drive large (global) surges of flux emergence:

- Massive increases in radiative, particulate, and eruptive output. **THE** driver of space environment variability incl. thermosphere and radiation belts.
- Surges and band interaction zones can lead to very powerful storms.
- Different Interpretation of “Secondary” stellar cycles?

Next Steps - Observation: 360° Sampling



Combining STEREO/EUVI [A & B] and SDO/AIA reveals the 360° picture. Surges in magnetism occur at “hot” longitudes. We have the knowledge to motivate next-generation explorer - the “Solar Meteorology Mission”.

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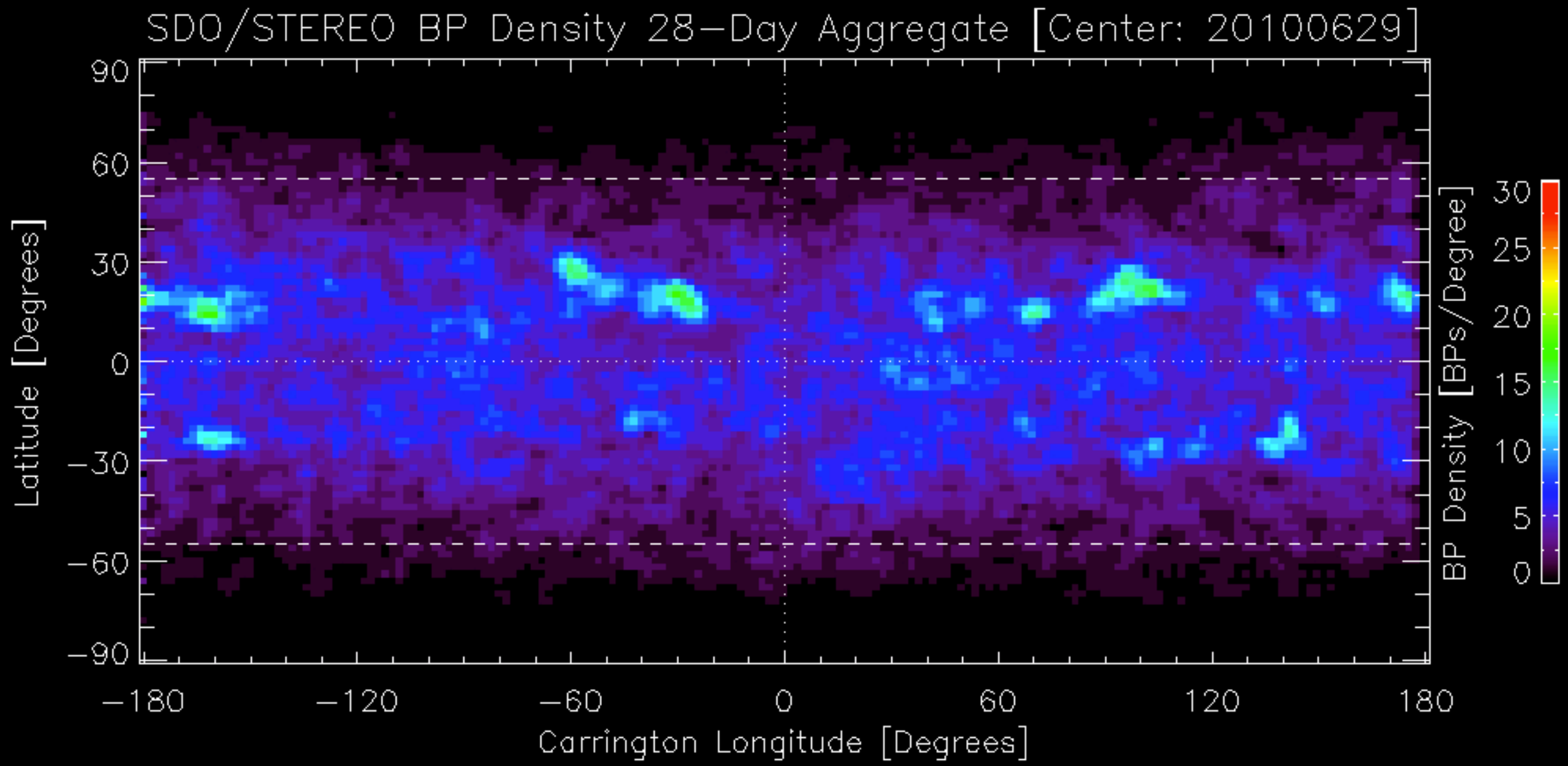
Observation: [modified] Rossby Modes?



Integrated BP Density: Lon, Lat, Time

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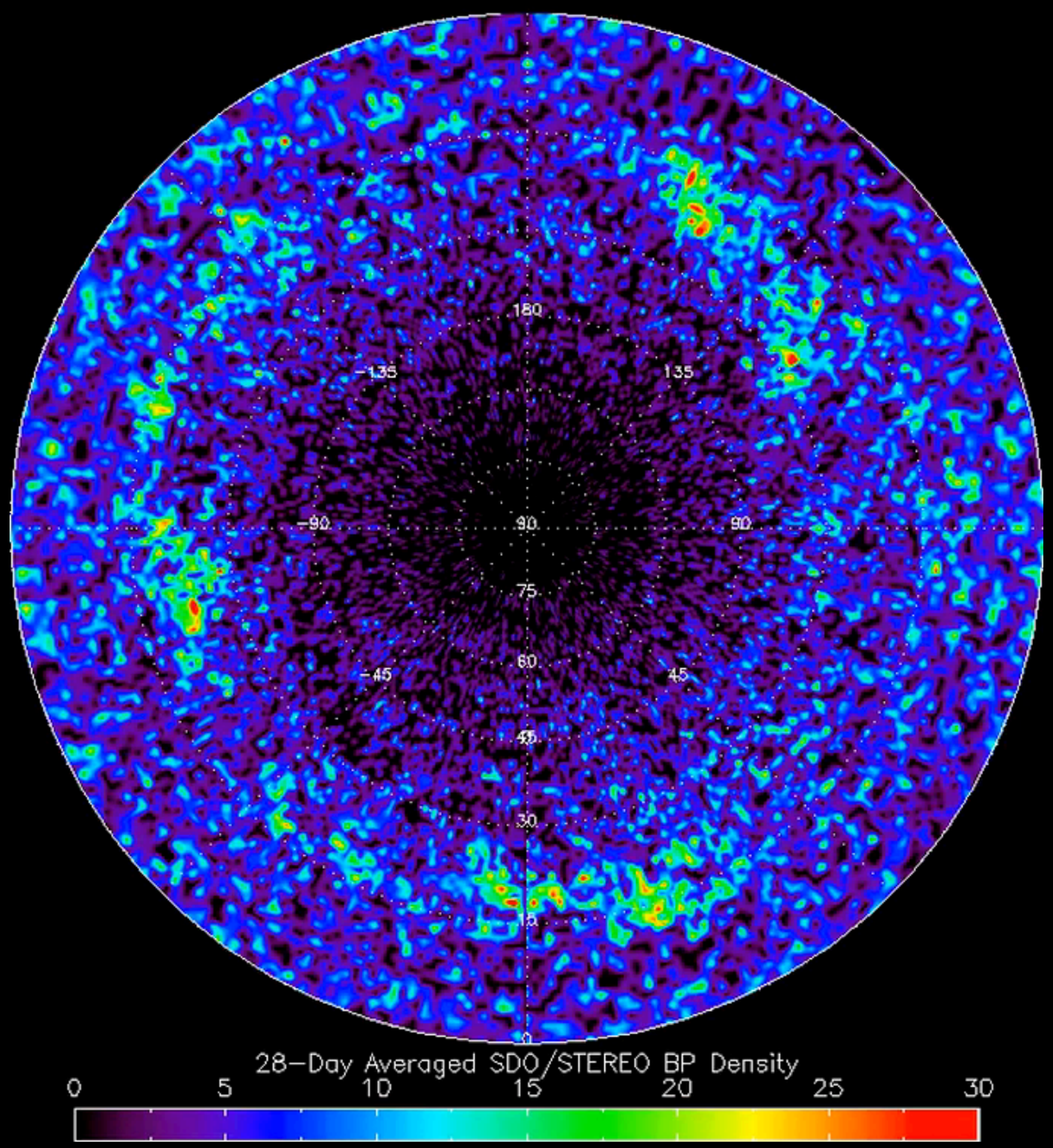
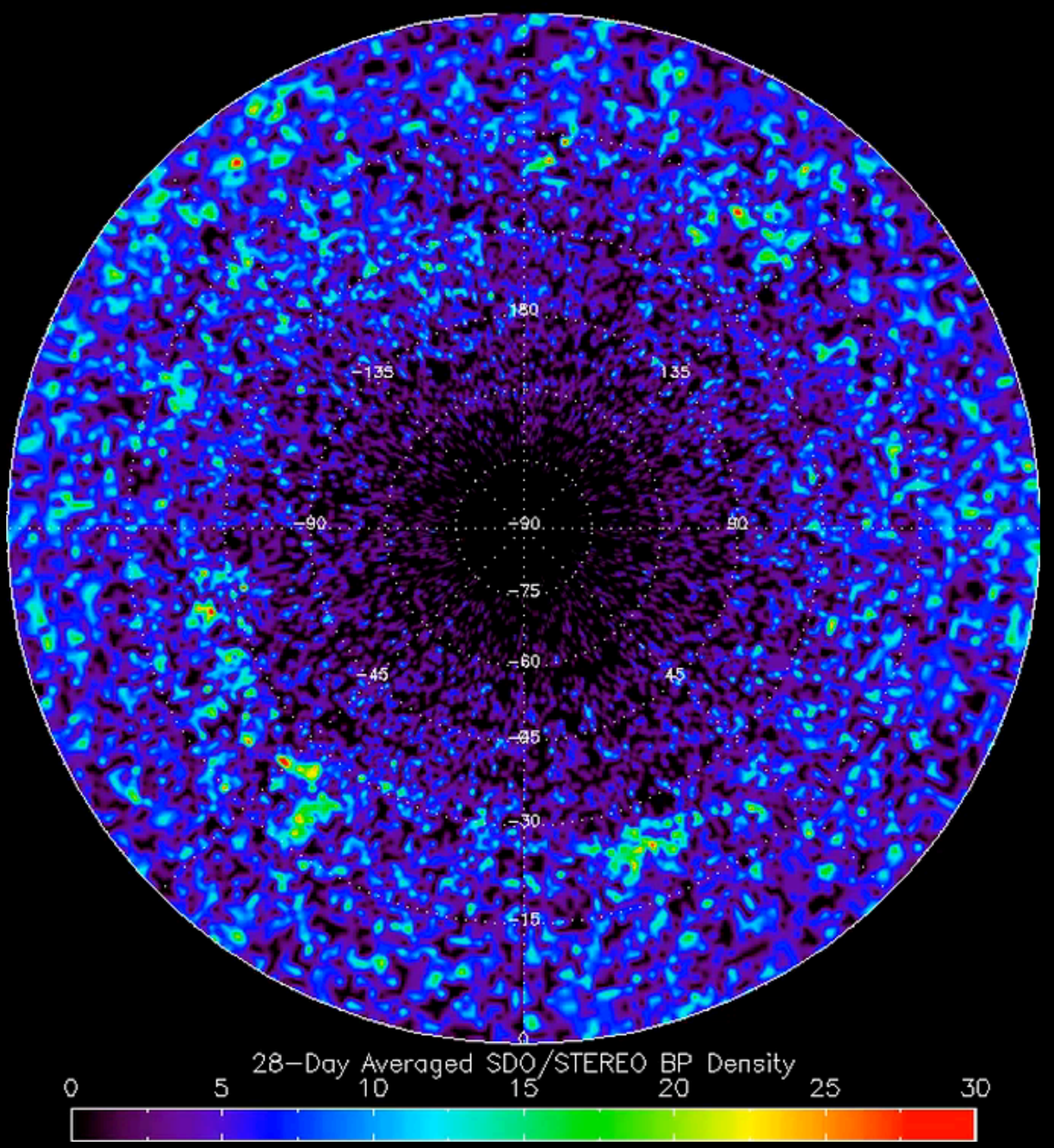
Observation: [modified] Rossby Modes?

Polar Plots of BP Density





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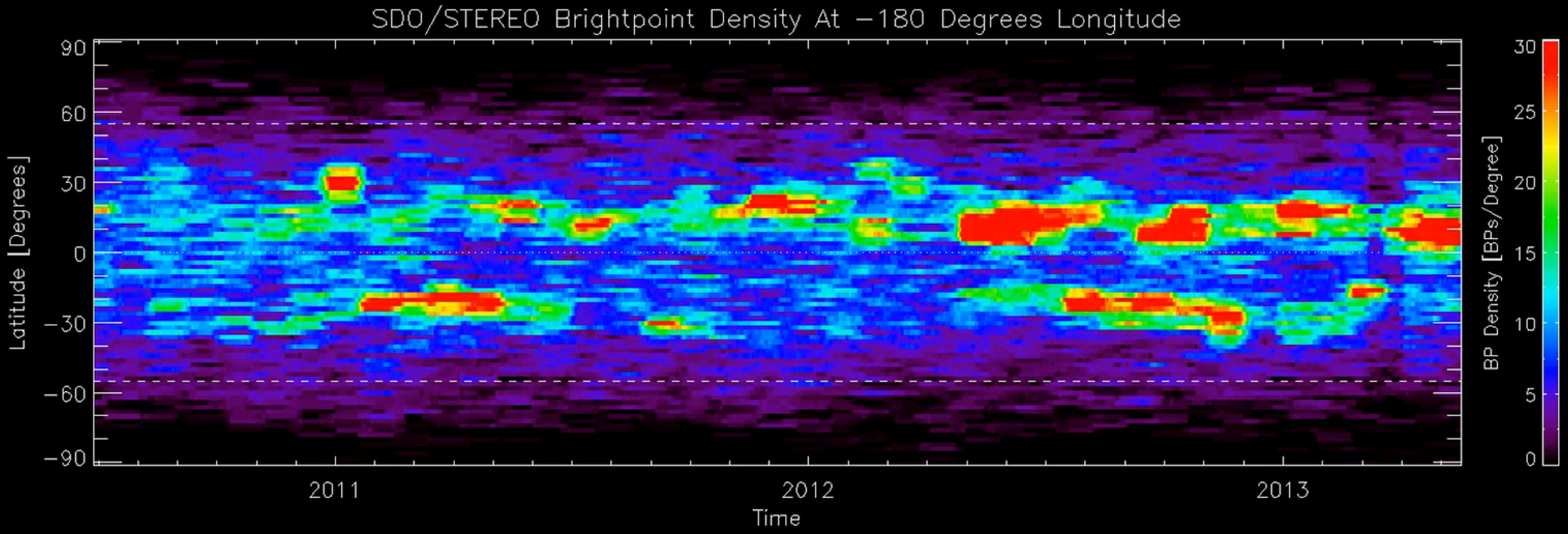
Observation: [modified] Rossby Modes?

Integrated BP Density: Lat Vs. Time Vs. Longitude



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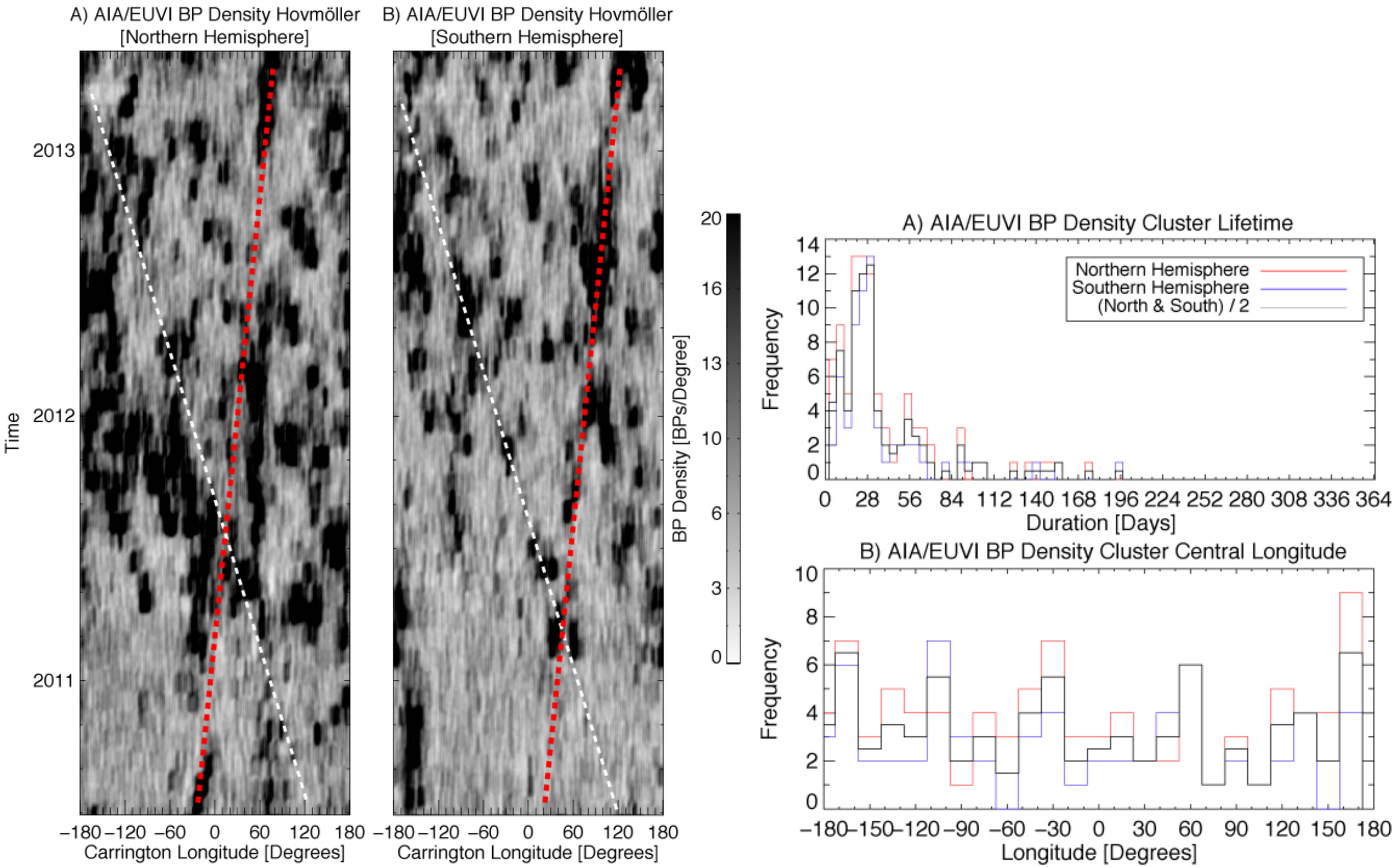
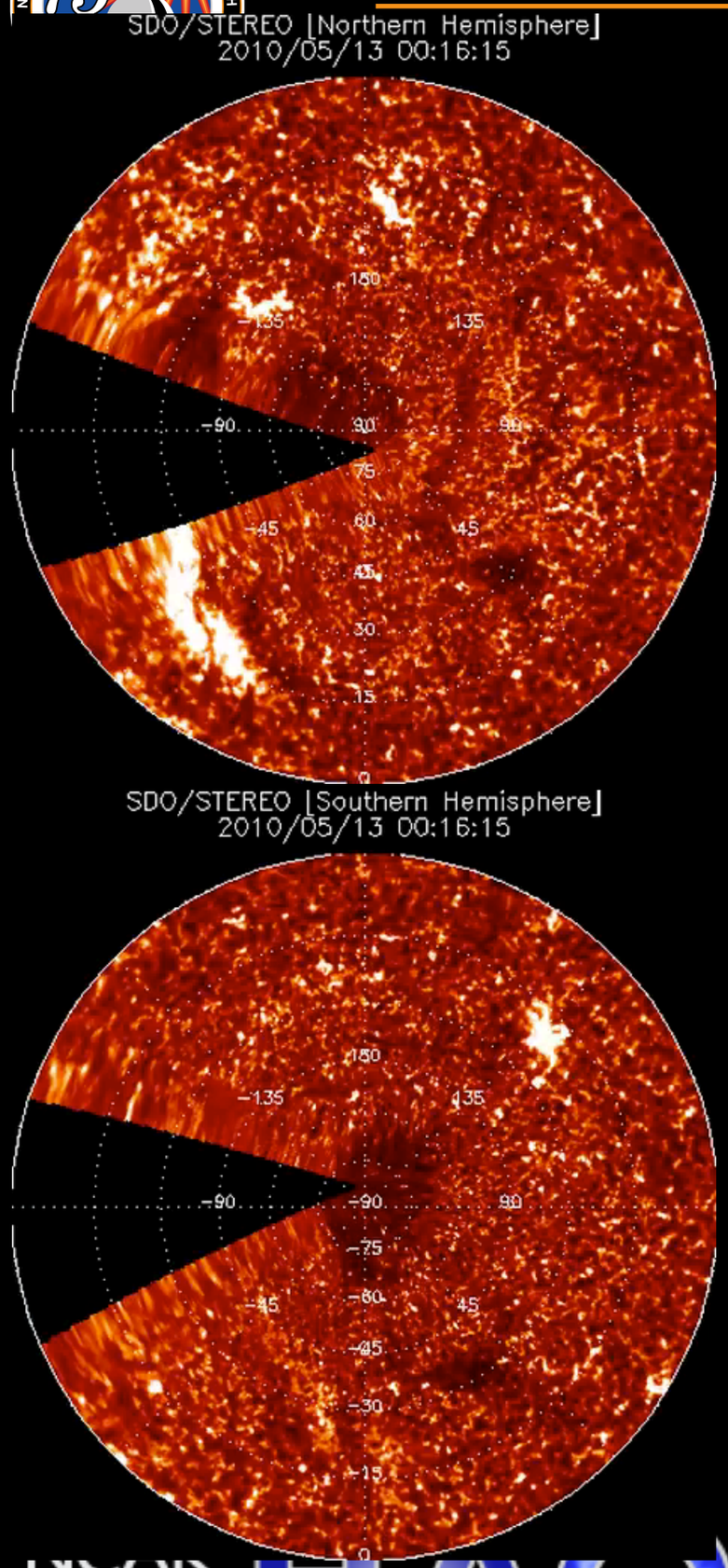
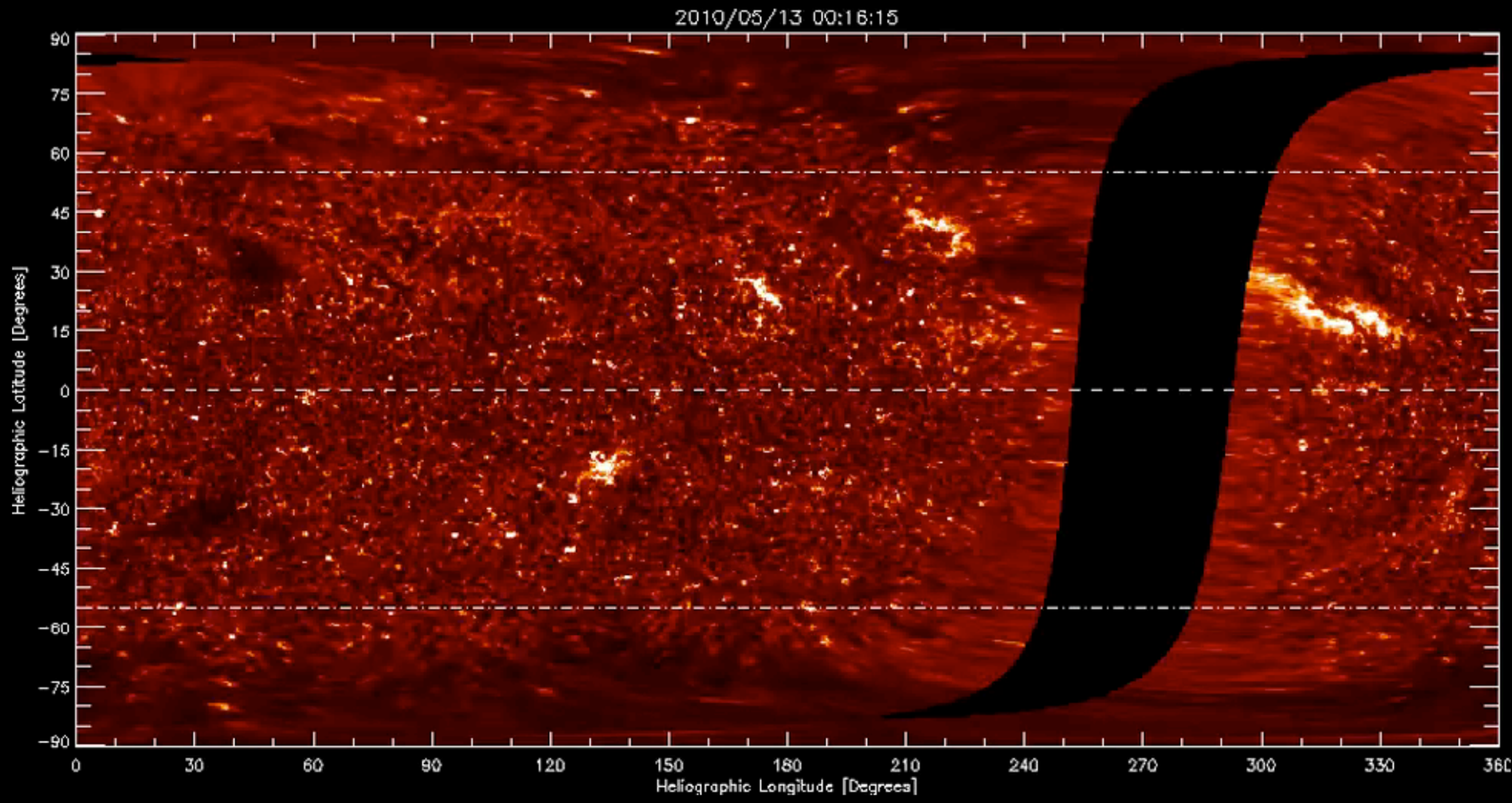
Observation: [modified] Rossby Modes?

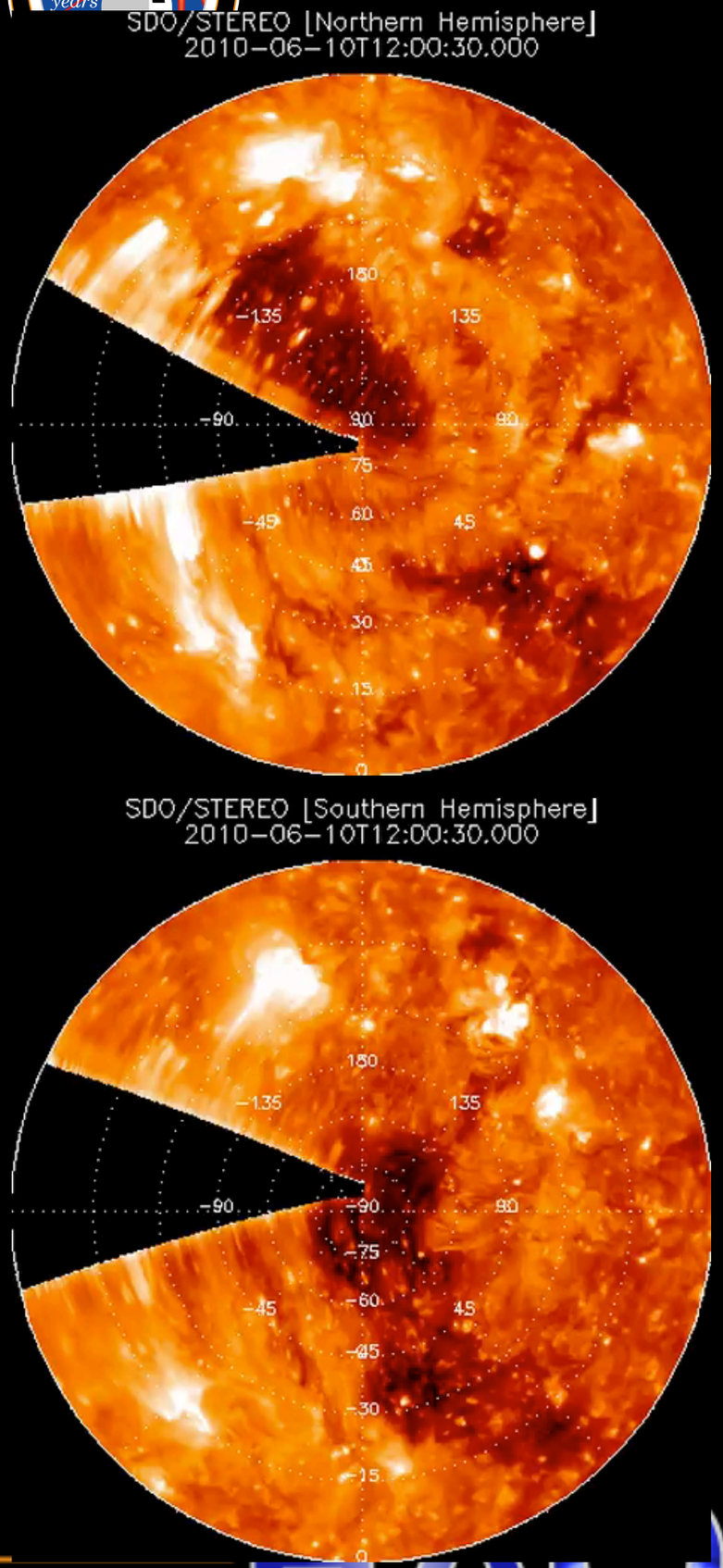


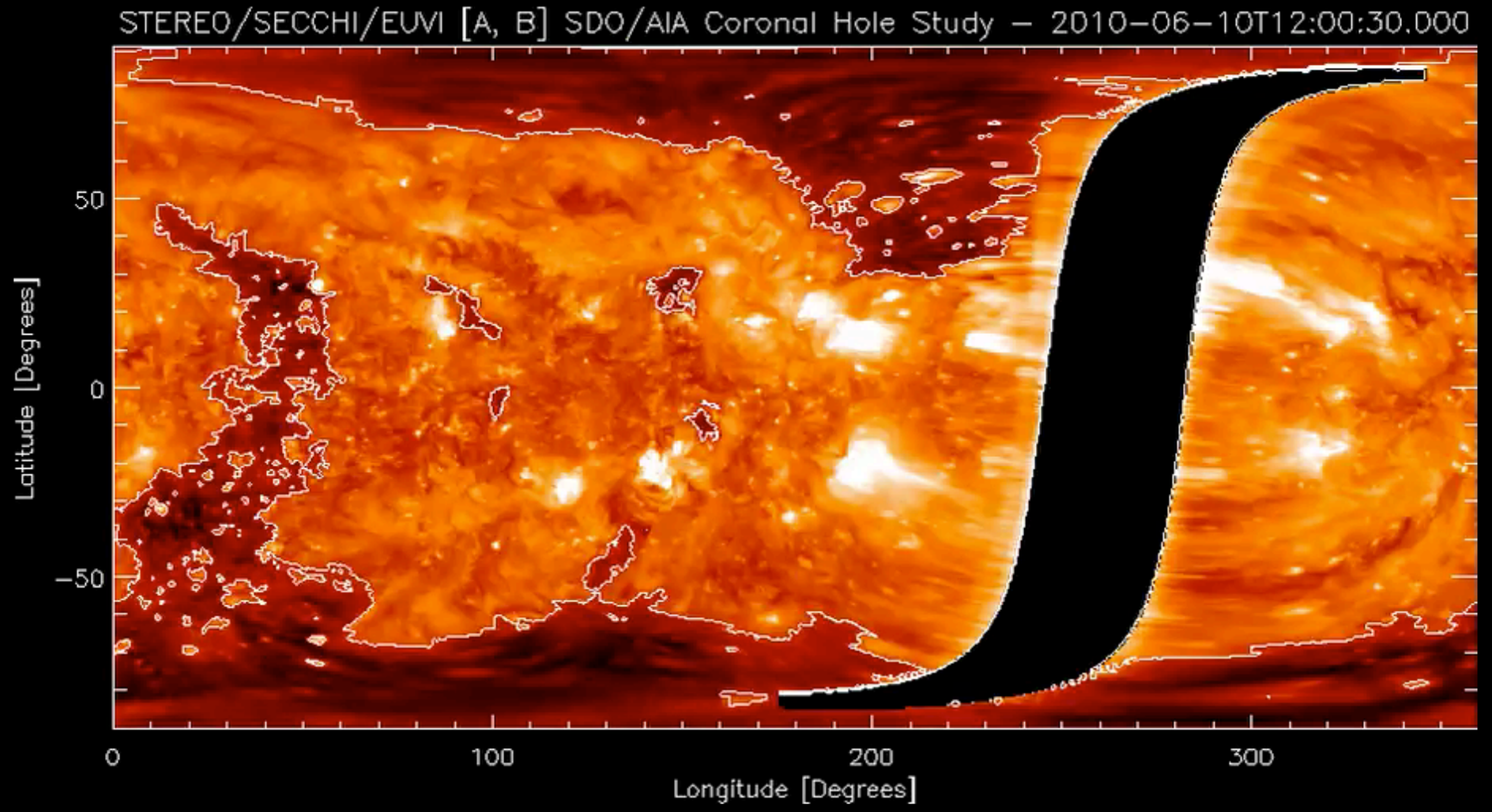
Octal Diabetes



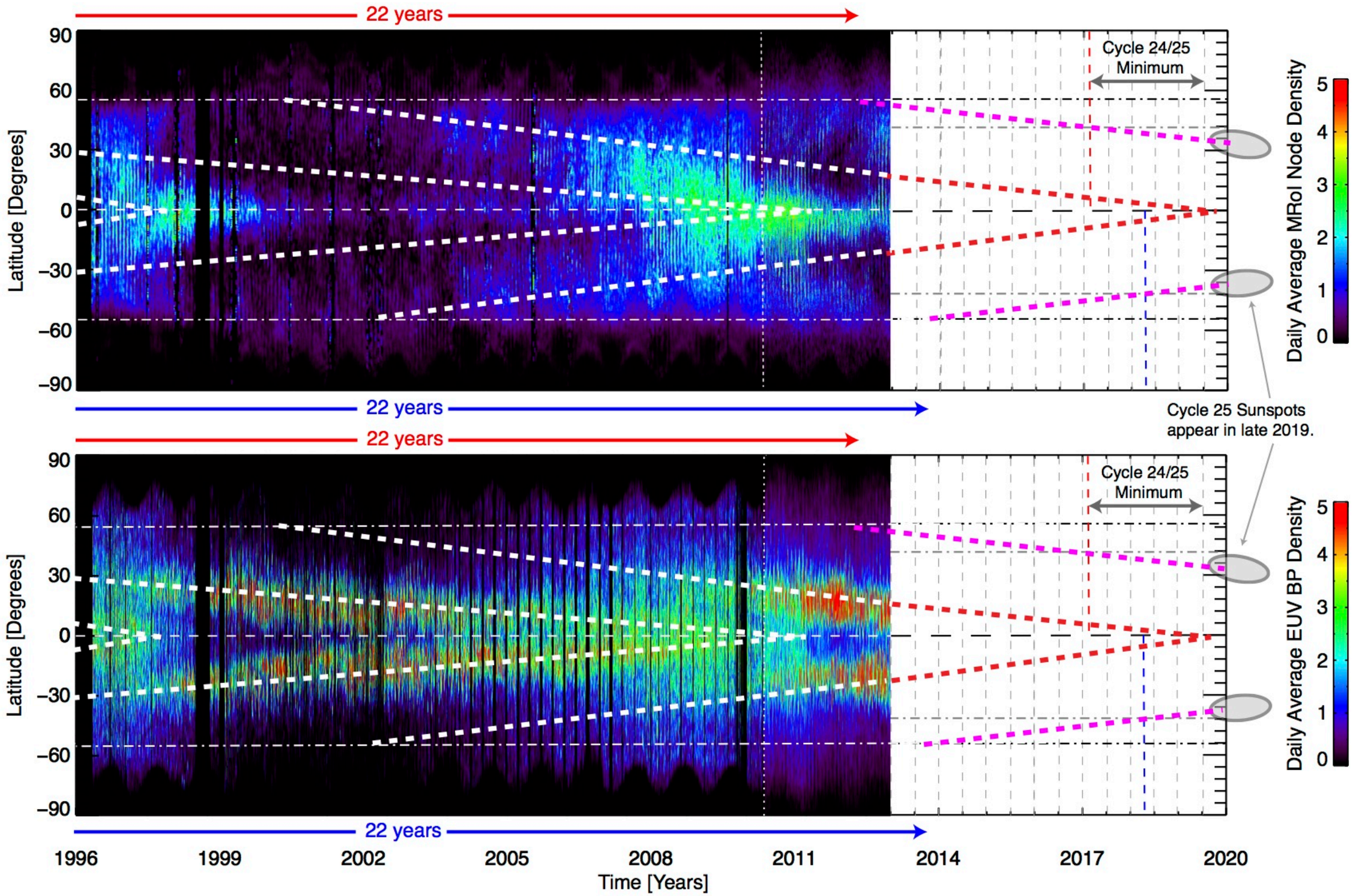


Octal Diabetes

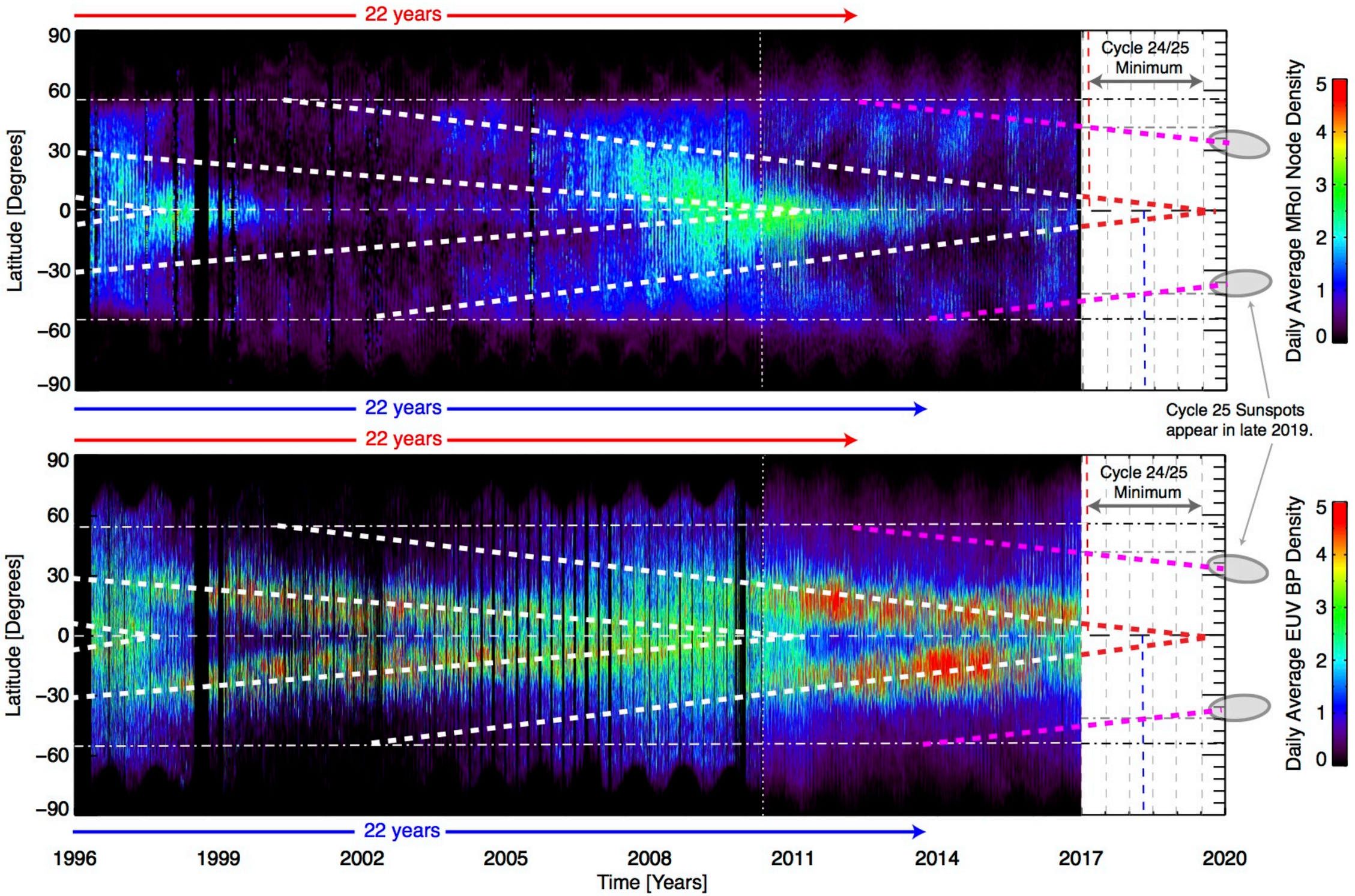




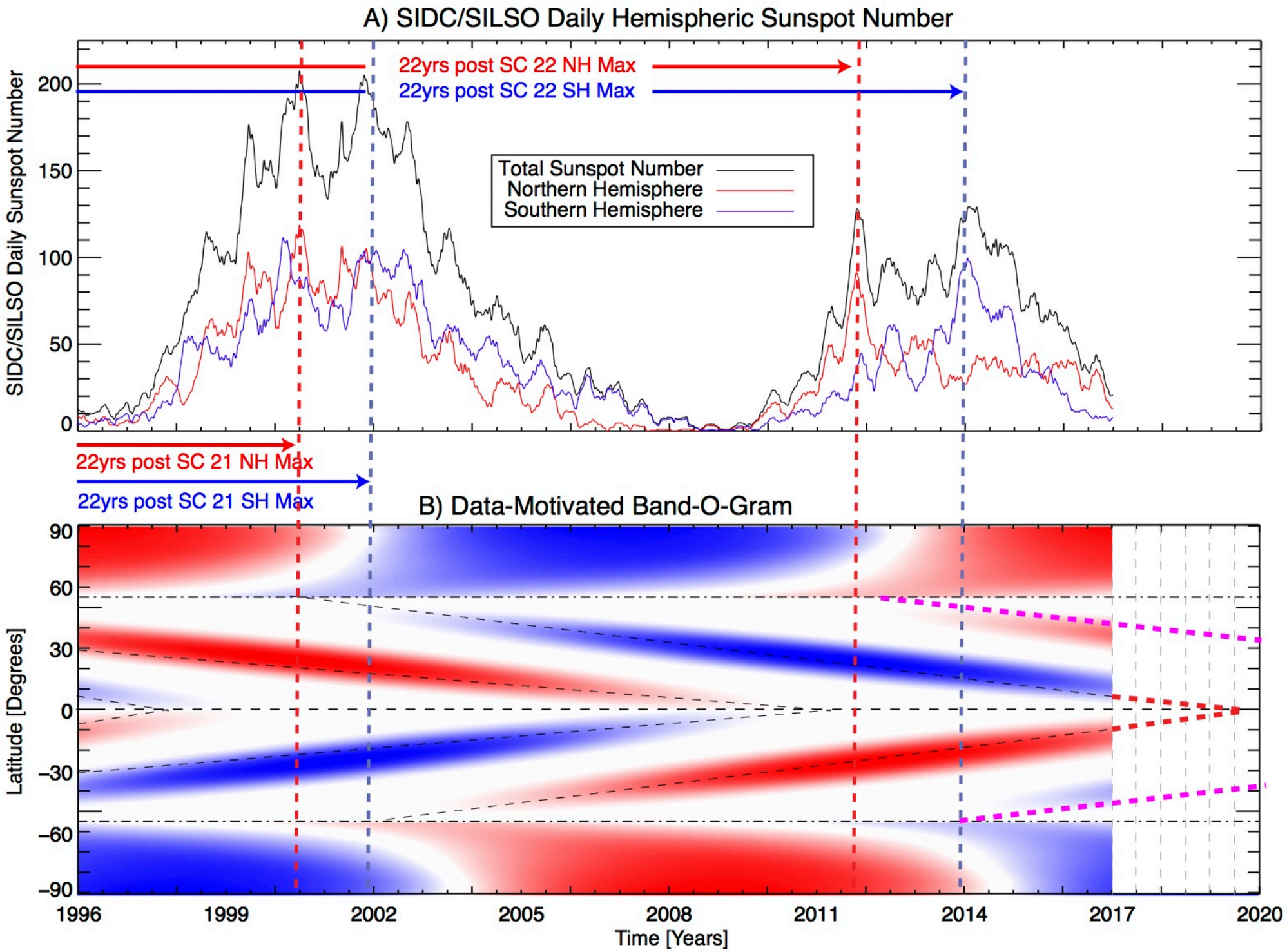
Where Are We Now?



Where Are We Now?

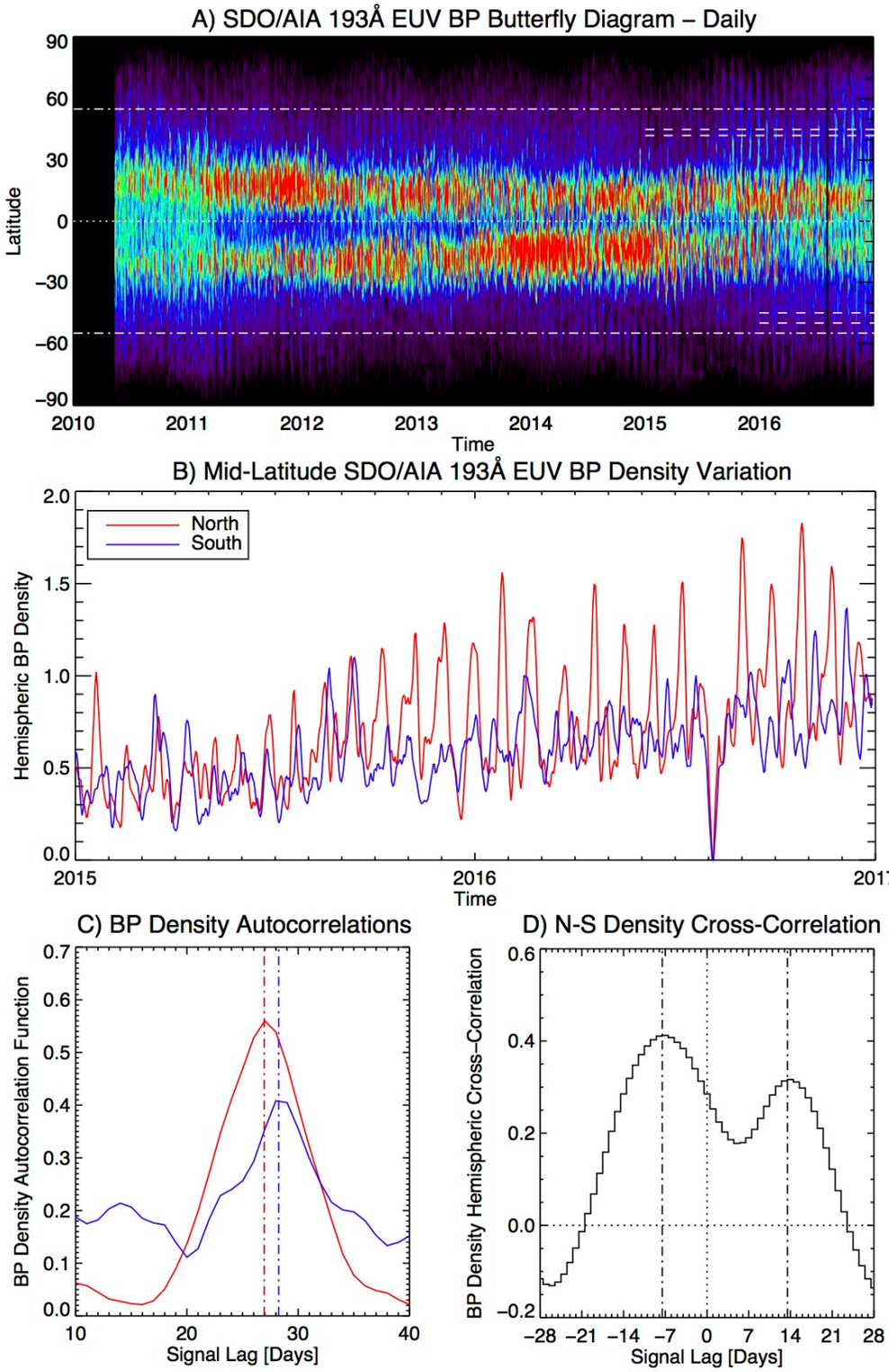


Where Are We Now?



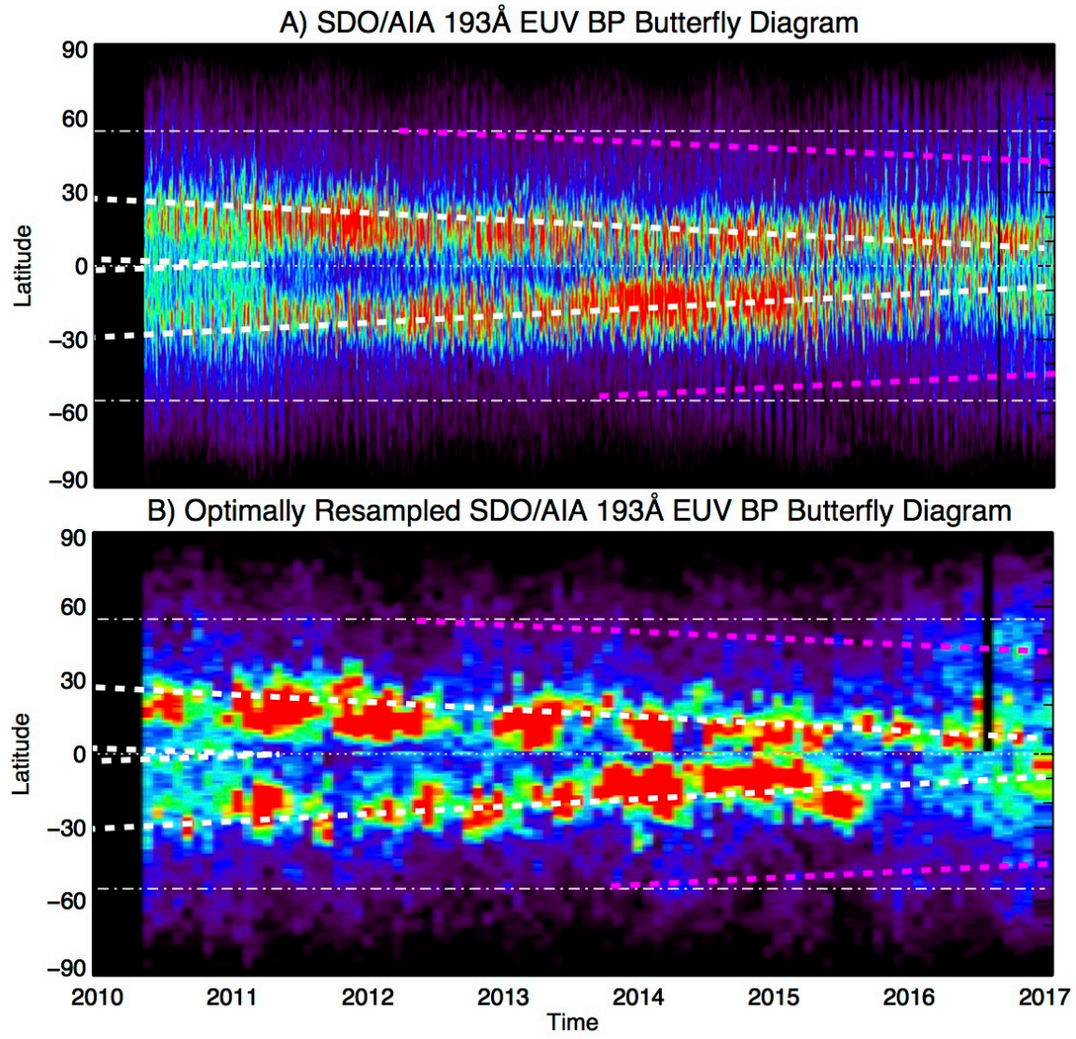
Should we have been braver?

Where Are We Now?



Cycle 25 is VERY visible….

So…..



Take Home

1. **Sunspot cycle appears to be a consequence of the interaction of latitudinally and temporally overlapping activity bands of the 22-year magnetic activity cycle.** An "interference pattern" of mutually canceling magnetic systems?

2. System seems to be **driven by the rotation of the radiative zone** and global-scale resulting (magneto-)hydrodynamics.
    - High latitude evolution seems to play a critical role in timekeeping and evolution of the system?

3. **Strong variability** (**of similar magnitude to cycle) of the activity bands** on timescales much shorter (~11 months) than the solar cycle:
    - Drives STRONG modulation in radiative, particulate and eruptive solar output
    - We tend to ignore it, but shouldn't!

….. this work yields potential insight into complex active region formation, grand minima entry and exit, and extreme event occurrence ……

★**NEED to observe solar magnetism from all perspectives to capture the global scale evolution of the magnetic field. Need new observing strategy and platforms for task.**

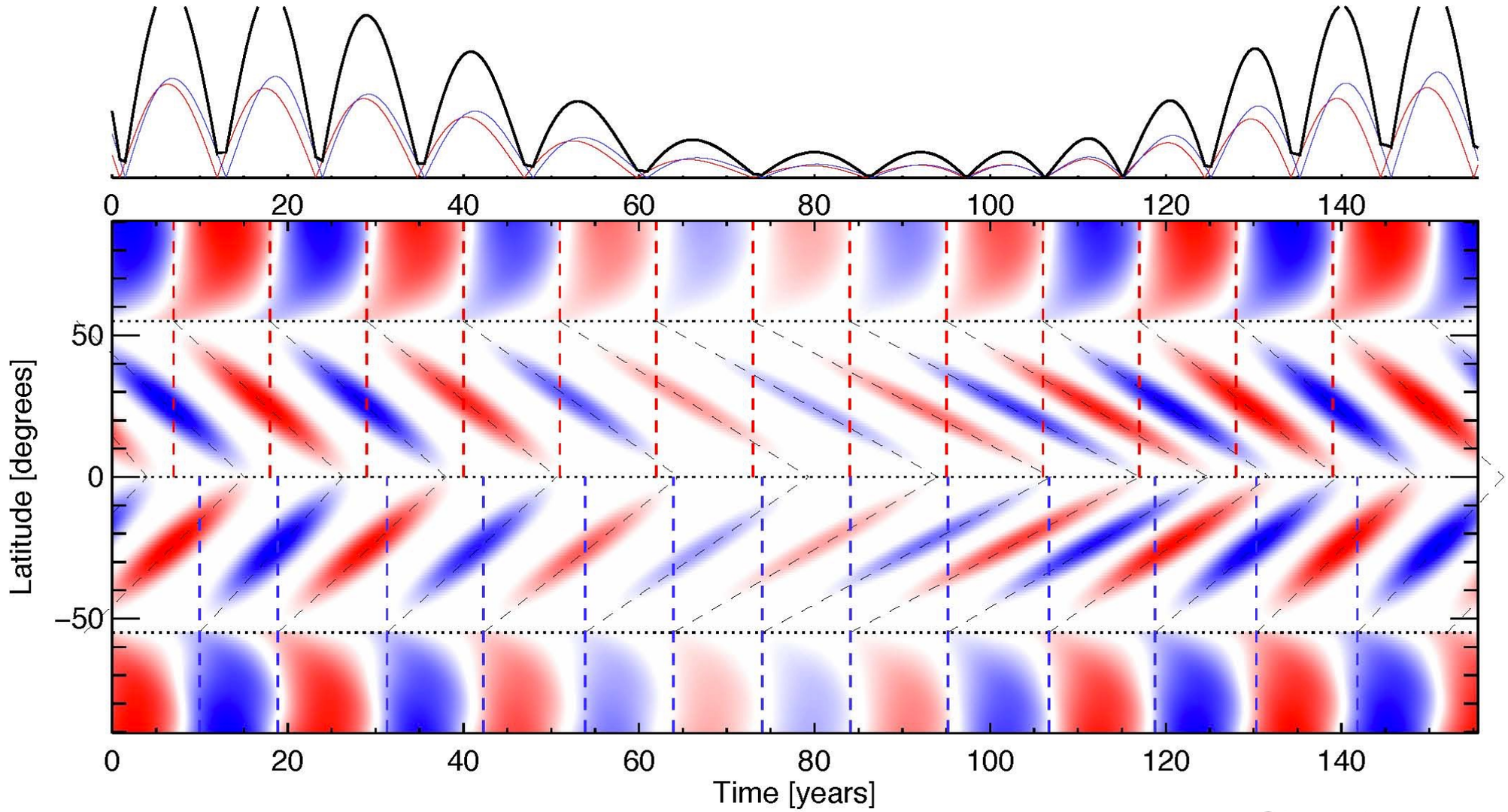
★**What is the solar dynamo?** Clearly we are **missing/overlooking/ignoring some vital observational clues** that can help to constrain the problem and drive a break through in understanding of our star (and others).

Are our models of the Sun's interior really "up to snuff". If not, what do we do?

Extra Slides

Grand Minimum: Entry & Exit

Can we naturally explain the progression into, and out of, grand minima?



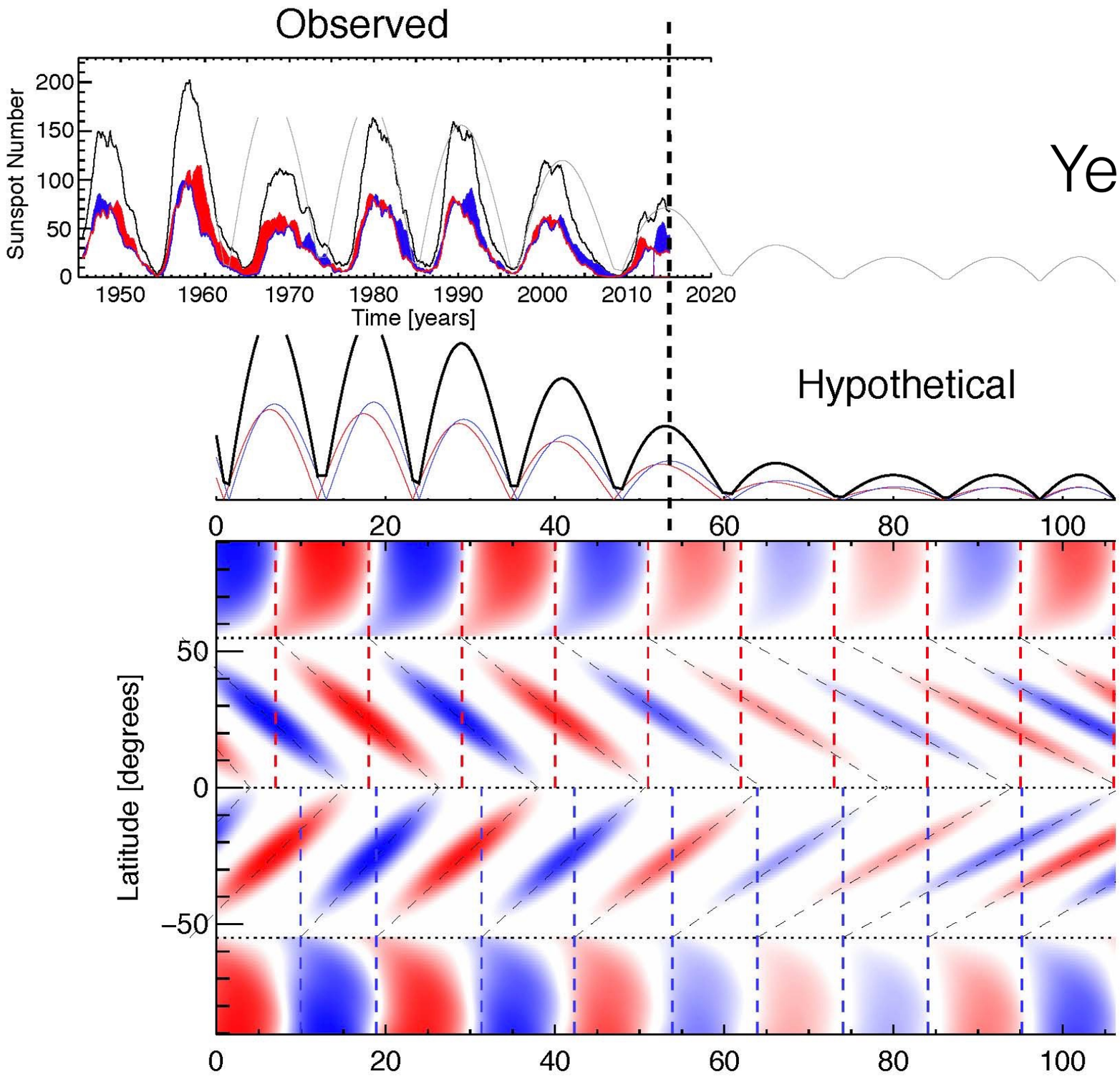
Impose a 22-year “clock”

Increase Overlap
Low SSN - Longer Cycles

Clock “catches up”
driving extra band and gets system back in phase.

Representing the progression of solar cycle variation into, and out of, a grand minimum state. The northern hemisphere has a fixed 22-year period while the southern hemisphere has a 22-year period that is randomly perturbed in a ±2 year range to reduce the north-south symmetry. The termination points of the equatorial branches are then stretched out from 20 years using a Gaussian perturbation 30 years wide centered on 75 years.

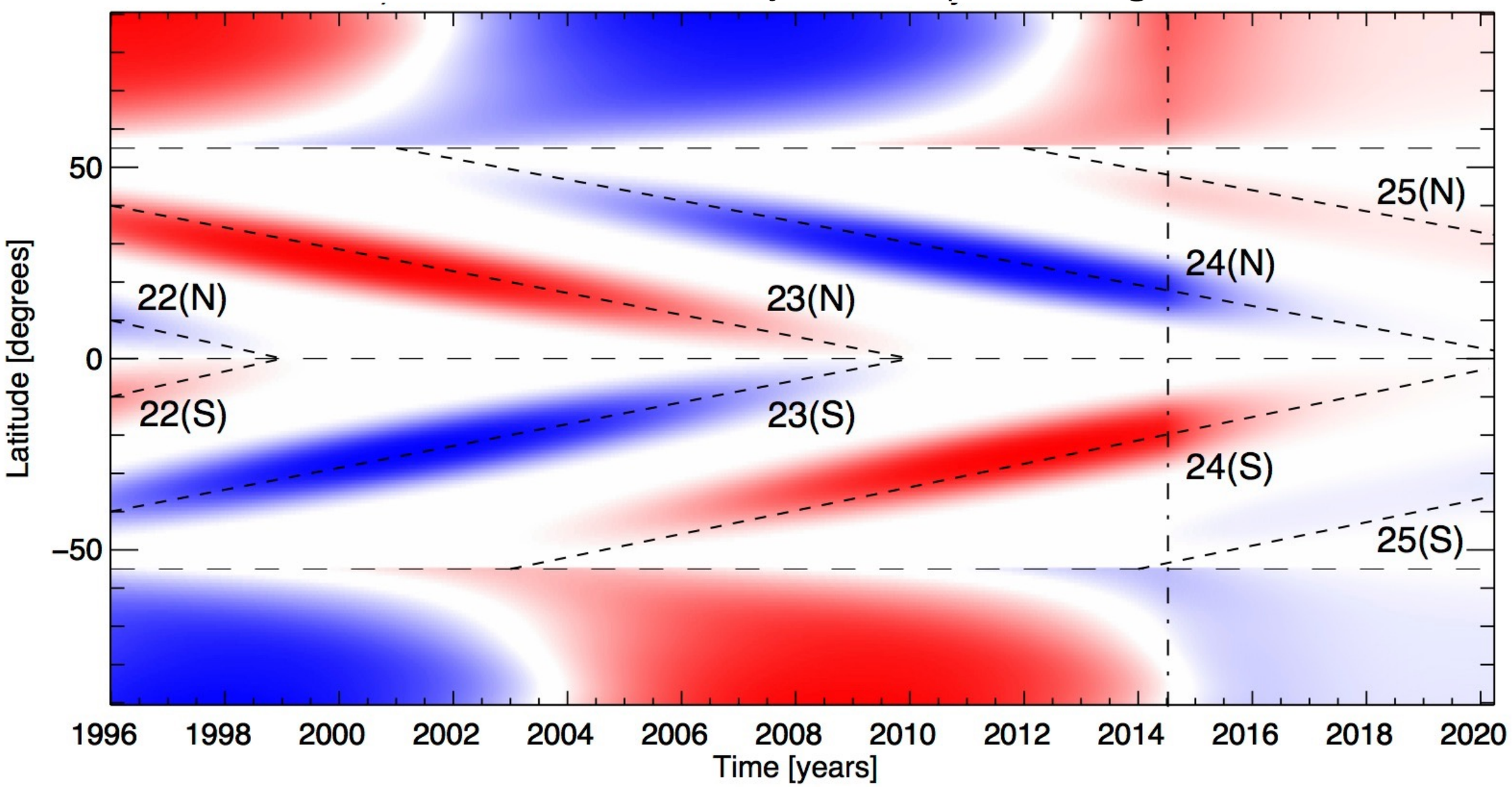
Grand Minima: Where Are We Now?



Year 52……

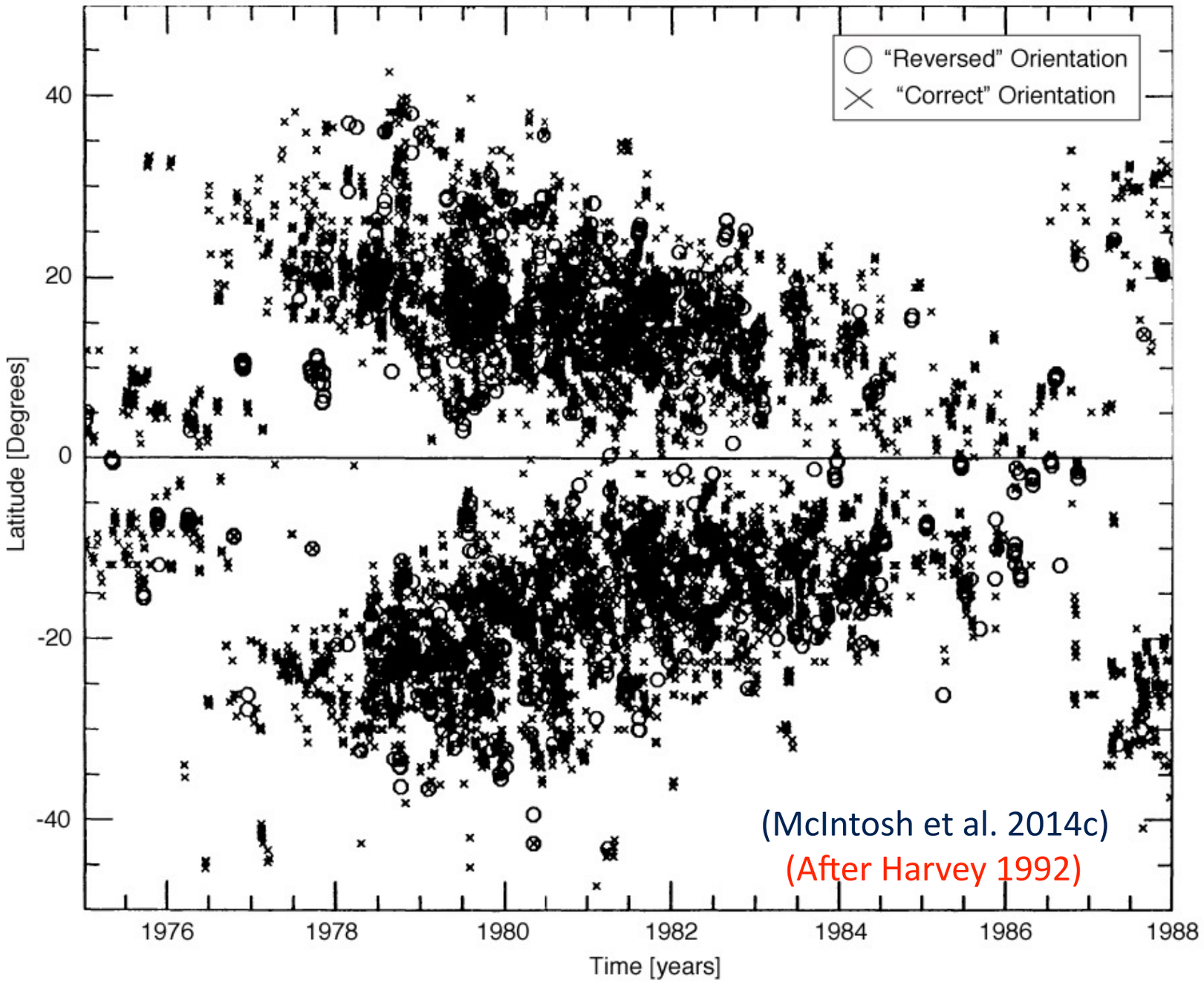
Storms: Band Interaction

The activity bands of the 22-year magnetic activity cycle can help frame the decadal activity envelope through their interaction



Storms: Driving Deltas

Open Circle - Delta Spot



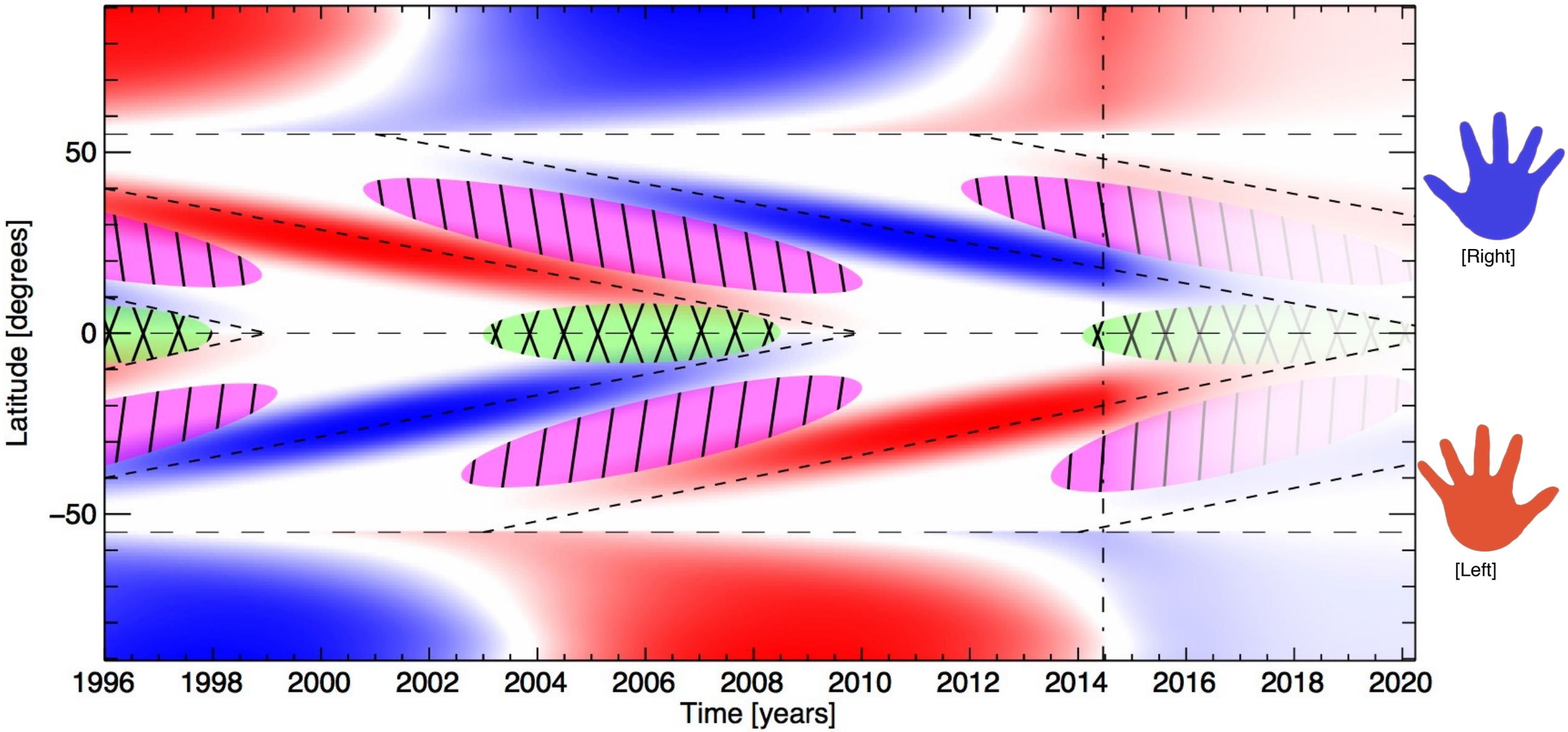
(McIntosh et al. 2014c)
(After Harvey 1992)

Delta spots are more abundant in the declining phase of the 11-yr solar cycle and on the periphery of the sunspot "butterfly diagram" [left].

5% of the spots responsible > 90% of M/X Class flares.

Storms: To The X-treme?

The activity bands of the 22-year magnetic activity cycle can help frame the decadal activity envelope through their interaction



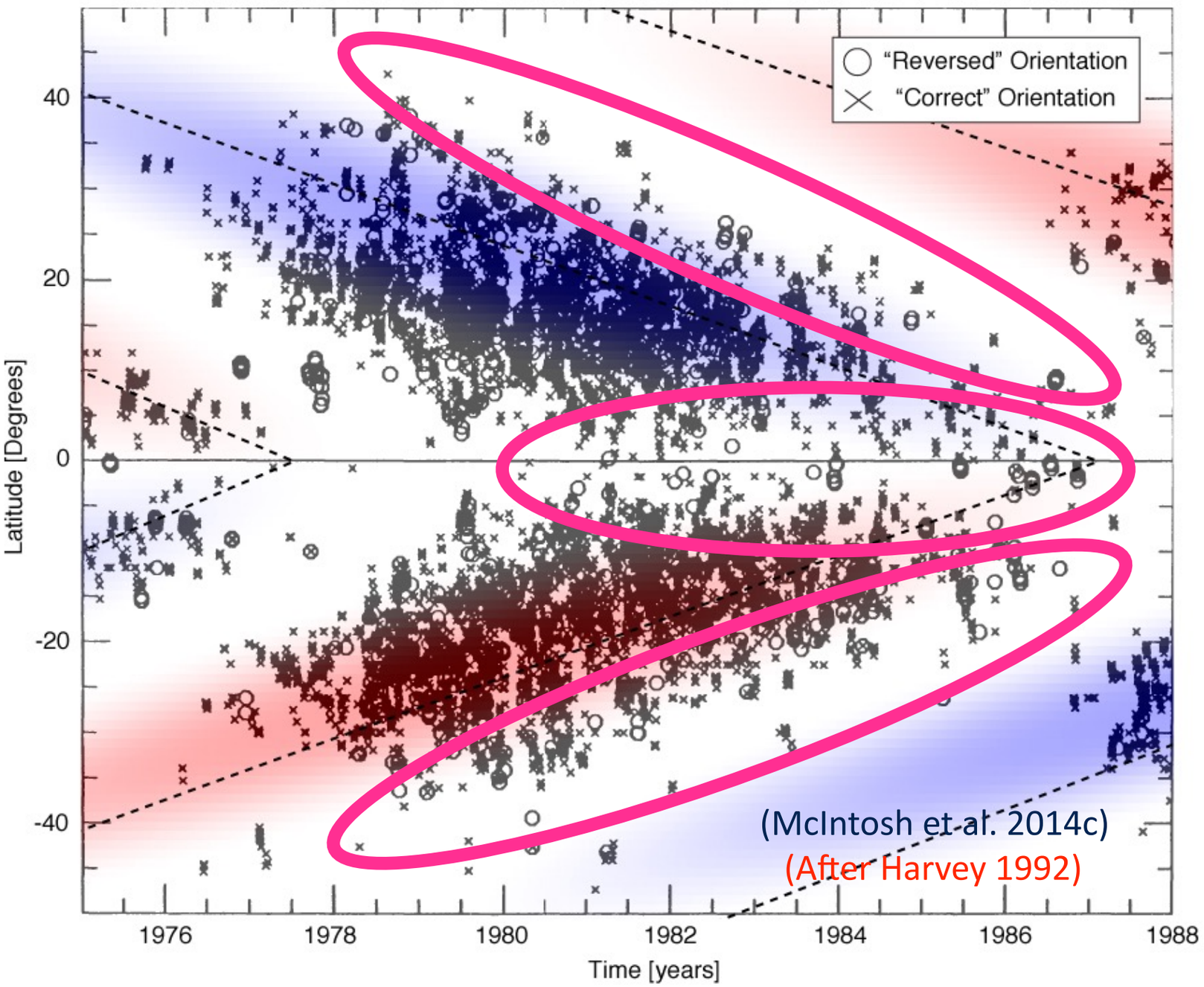
Interaction complicated by hemispheric helicity?

Mixed-Helicity Region/Time - Linton (2000) - Rapid/Efficient Energy Release

Storms: Driving Deltas

22-yr Activity Bands

Delta Formation Zone



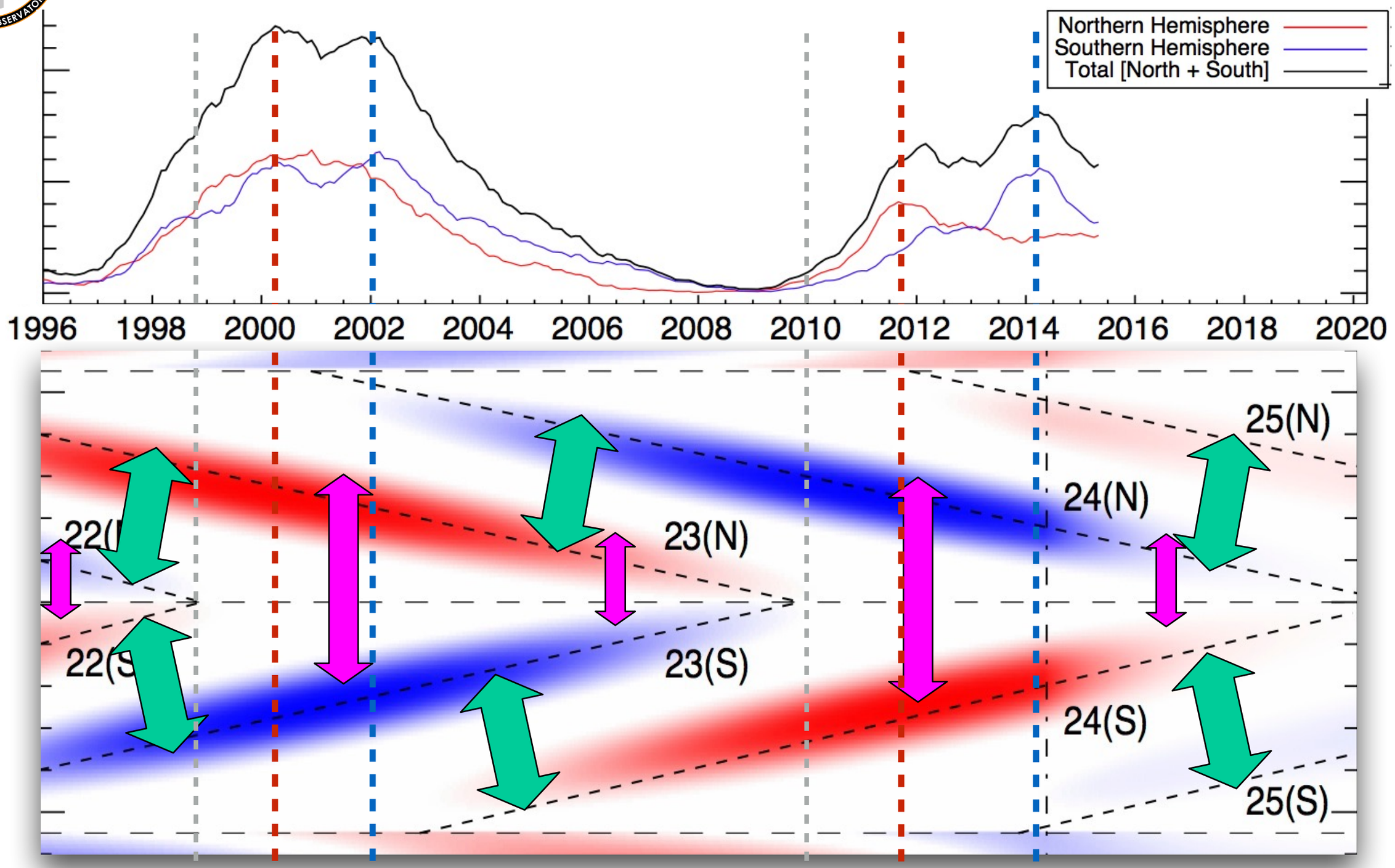
Delta spots are more abundant in the declining phase of the 11-yr solar cycle and on the periphery of the sunspot "butterfly diagram" [left].

5% of the spots responsible > 90% of M/X Class flares.

Signature of mixing between oppositely signed (and/or) twisted magnetic flux systems belonging to 22-yr (magnetic) solar polarity cycle in the solar interior?

Gaining rapid insight into the strongest possible solar storms, when, where and why they occur.

The Current State



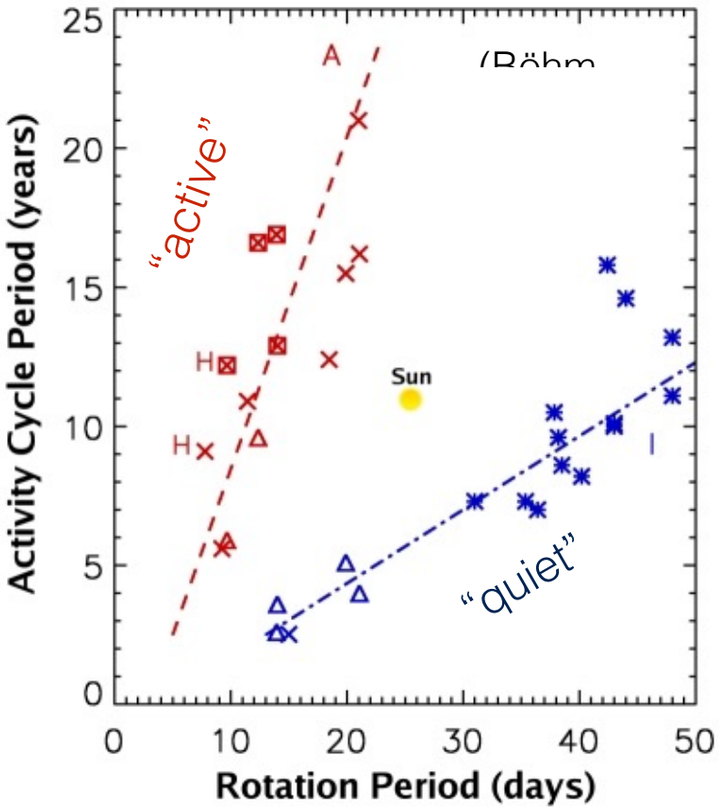
Extra-Hemispheric Interaction

Intra-Hemispheric Interaction

The Sun Vs. Stars

We live in the atmosphere of our star.

As a civilization* we take our star for granted.



"If the Sun didn't have a magnetic field, then it would be as boring a star as most astronomers think it is."

(Bob Leighton circa 1965)

"..the Sun is special…"

Stars live on active **and** quiet branches!

Bohm-Vitense (2007)

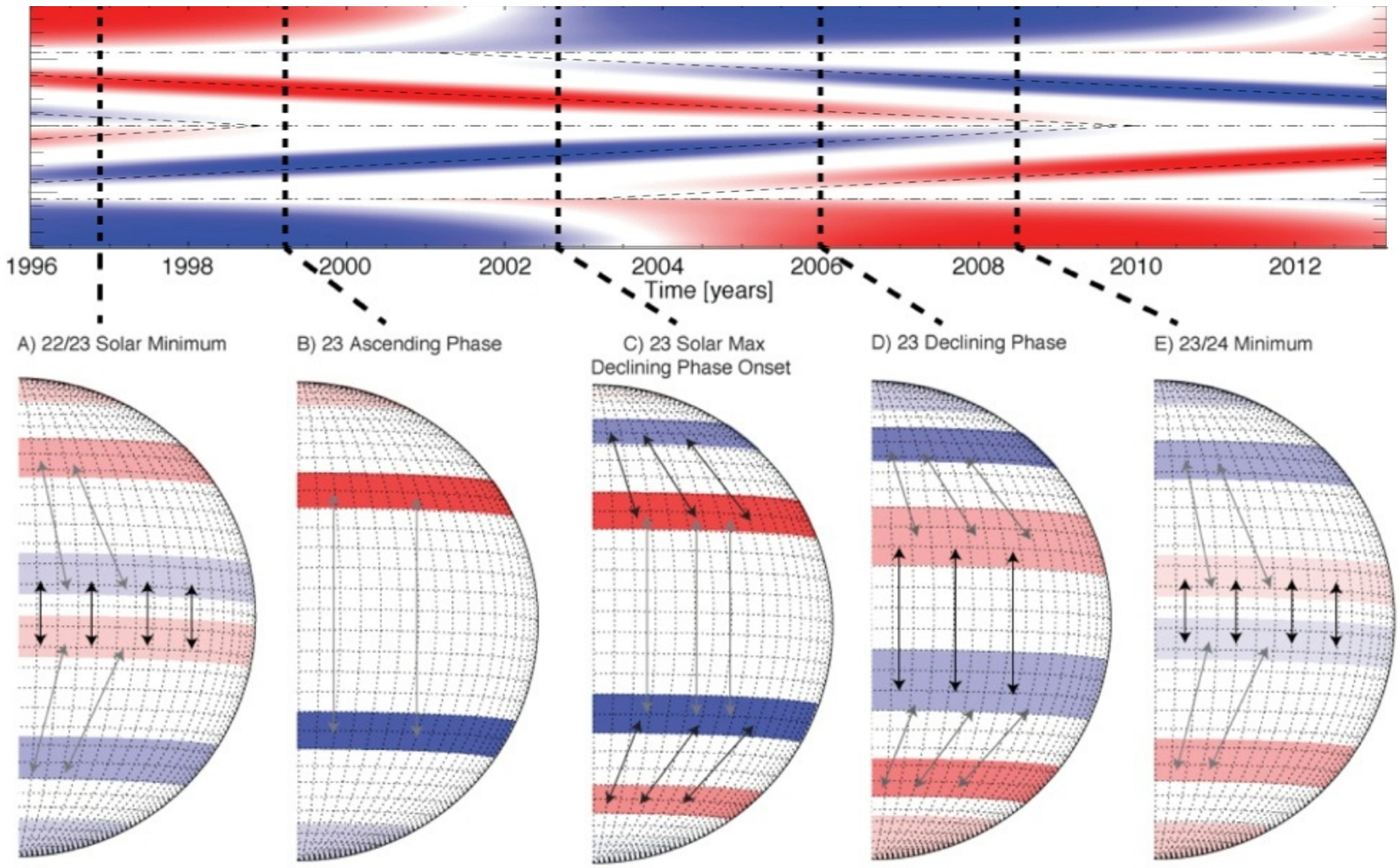
One question that motivates HAO's place in NCAR…..

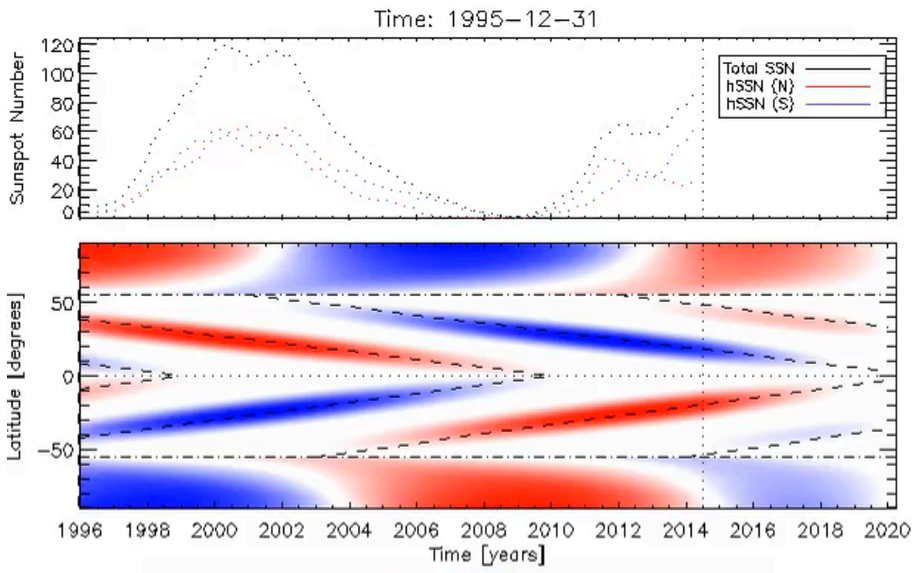
….what will it do….

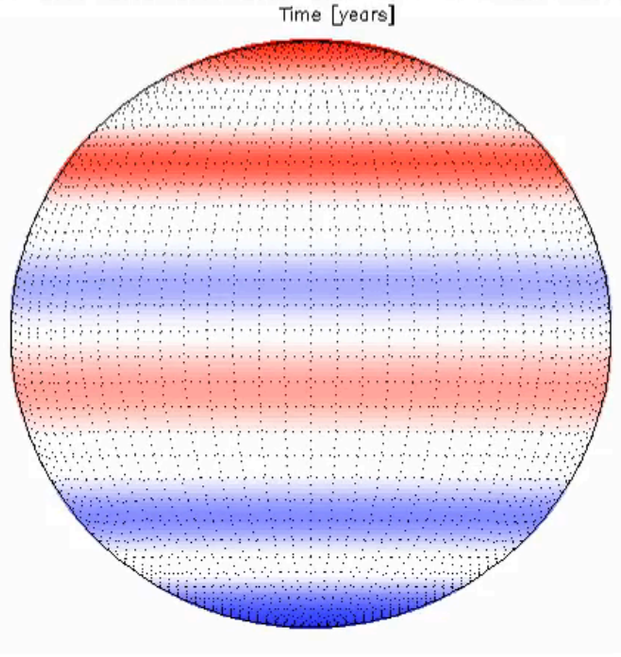
…compared to other stars?

Cycles: Large Scale Temporal Evolution

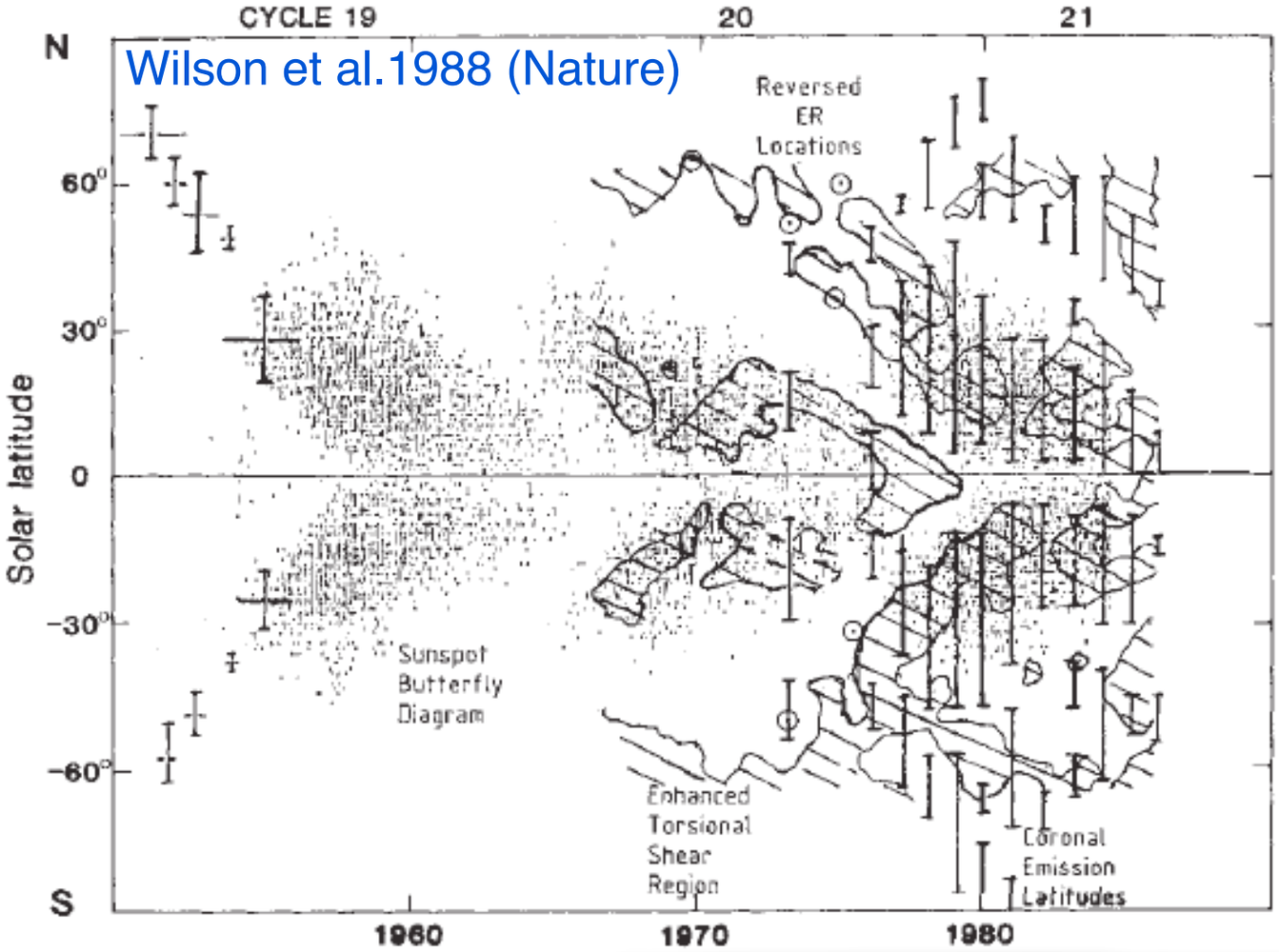
Magnetic “telecommunication” appears to help modulate the appearance of the sunspot cycle?

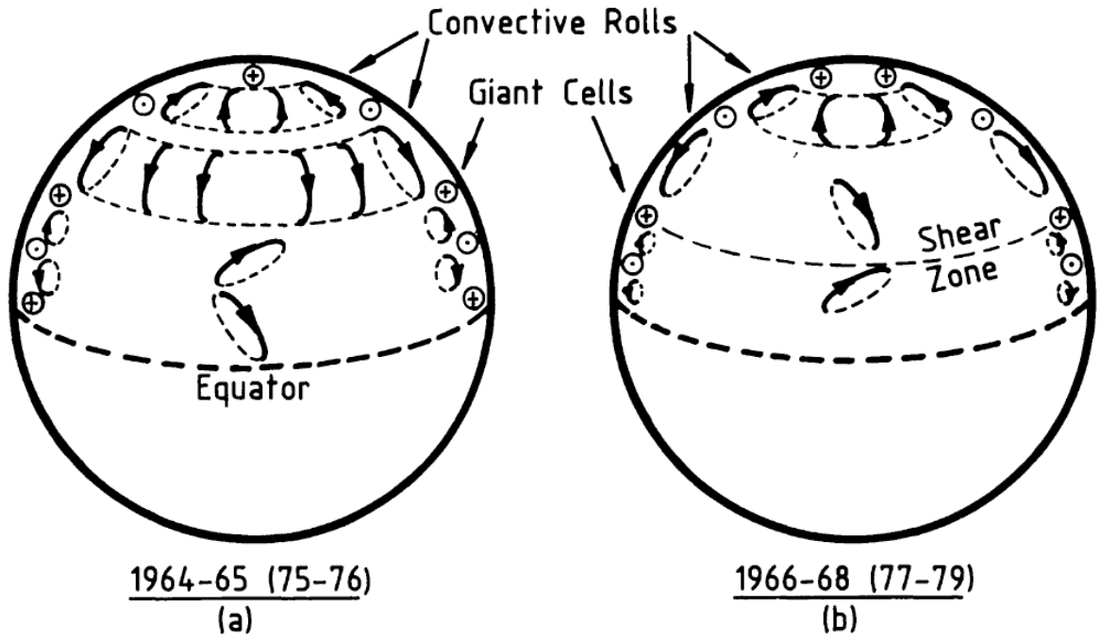






NOTHING is ever new!





Azimuthal Rolls
NOT Banana Cells

> Recently (Wilson, 1987) it has been shown that the current concept of the solar cycle is incomplete and that the torsional-oscillation signal is closely involved with activity phenomena. Beginning at the poles every 11 yr just prior to solar maximum, the faster-than-average band of rotation is associated with high-latitude ephemeral regions, for which the predominant orientation is that of the next cycle rather than the current one (Martin and Harvey, 1979), and with peaks in the coronal green line emission which progress with it to the sunspot latitudes (Altrock, presentation at this workshop). Snodgrass (1987) has shown that, as it progresses into sunspot latitudes, this faster-than-average zone matches well with the butterfly diagram for the next cycle, and thus the faster-than-average band of the torsional oscillations represents a natural extension of the 'butterfly diagram' into a 'herringbone diagram'.

NOTHING is ever new!

Golub et al. (1974)

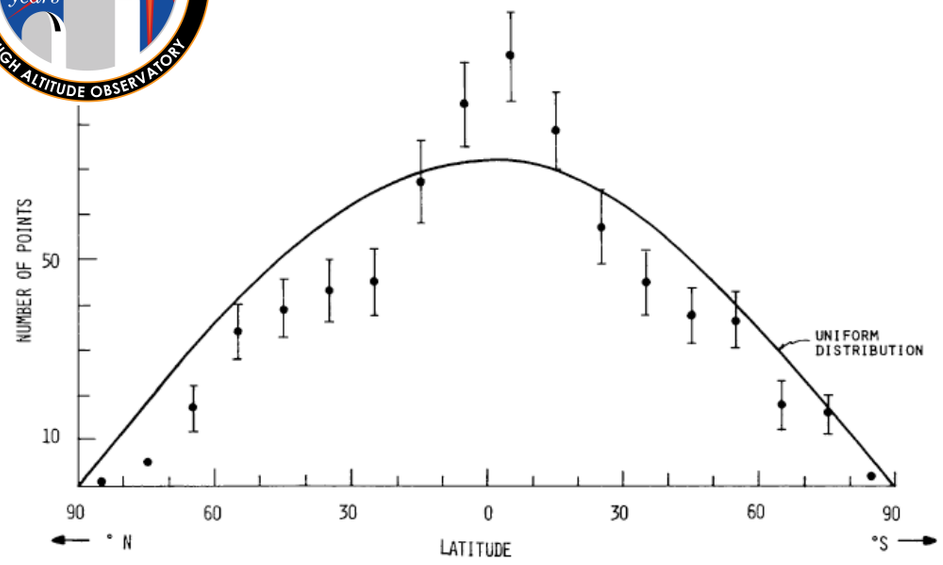
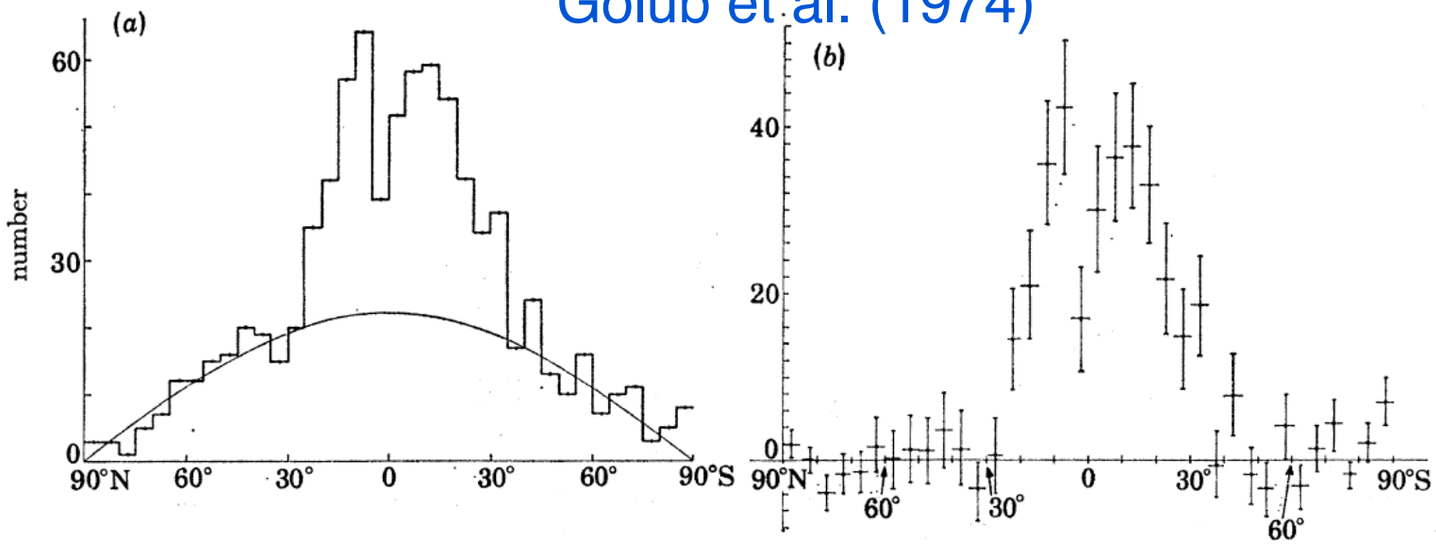


FIG. 4.—Latitude distribution of bright points



1974ApJ...185

From preliminary measurements of temperature and density, we estimate from the equipartition argument that the average magnetic field of these points is ~10 gauss. This agrees with estimates of the longitudinal field in bright points obtained by comparison with Kitt Peak magnetograms (J. Harvey, private communication; also Harvey and Martin 1974). With an average area of 10^{18} cm^2 and 1500 points emerging per day, the magnetic flux brought to the surface would be ~10^{22} Mx per day. This estimate leads us to the surprising conclusion that X-ray bright points contribute more emerging flux than do active regions at this time in the solar cycle. If this flux is dispersed over the solar surface, e.g., by a process similar to that for major active regions (Leighton 1964), then bright points not only are major contributors to the solar magnetic field, but may be the dominant contributors. Thus, an explanation of X-ray bright points may be of fundamental importance to our understanding of solar dynamo theories and of the solar cycle.

The flaring behavior, the similarity in structure of the bright points to active regions, and the association with bipolar magnetic field regions suggest that the X-ray bright points may be miniature active regions. On the other hand, their uniform distribution across the solar surface indicates that they are not produced in exactly the same way as active regions. The association with the supergranulation cells is probably the key to their origin. As a working hypothesis we are suggesting that while active regions are produced as an amplification of subsurface magnetic field by the differential rotation of the Sun, bright points are due to the amplification of subsurface field by turbulence in the convection zone.

We would like to thank Richard Chase of AS&E for help with statistical analysis and Wallace Tucker of Fallbrook Strawberry Farms and Bruno Rossi of MIT for useful discussions. We are thankful to J. W. Harvey and Wm. Livingston of Kitt Peak National Observatory for their magnetic field data.

This work has been funded by NASA, Marshall Space Flight Center, under contracts NAS5-9041 and NAS8-27758.

NOTHING is ever new!

Harvey (1992)

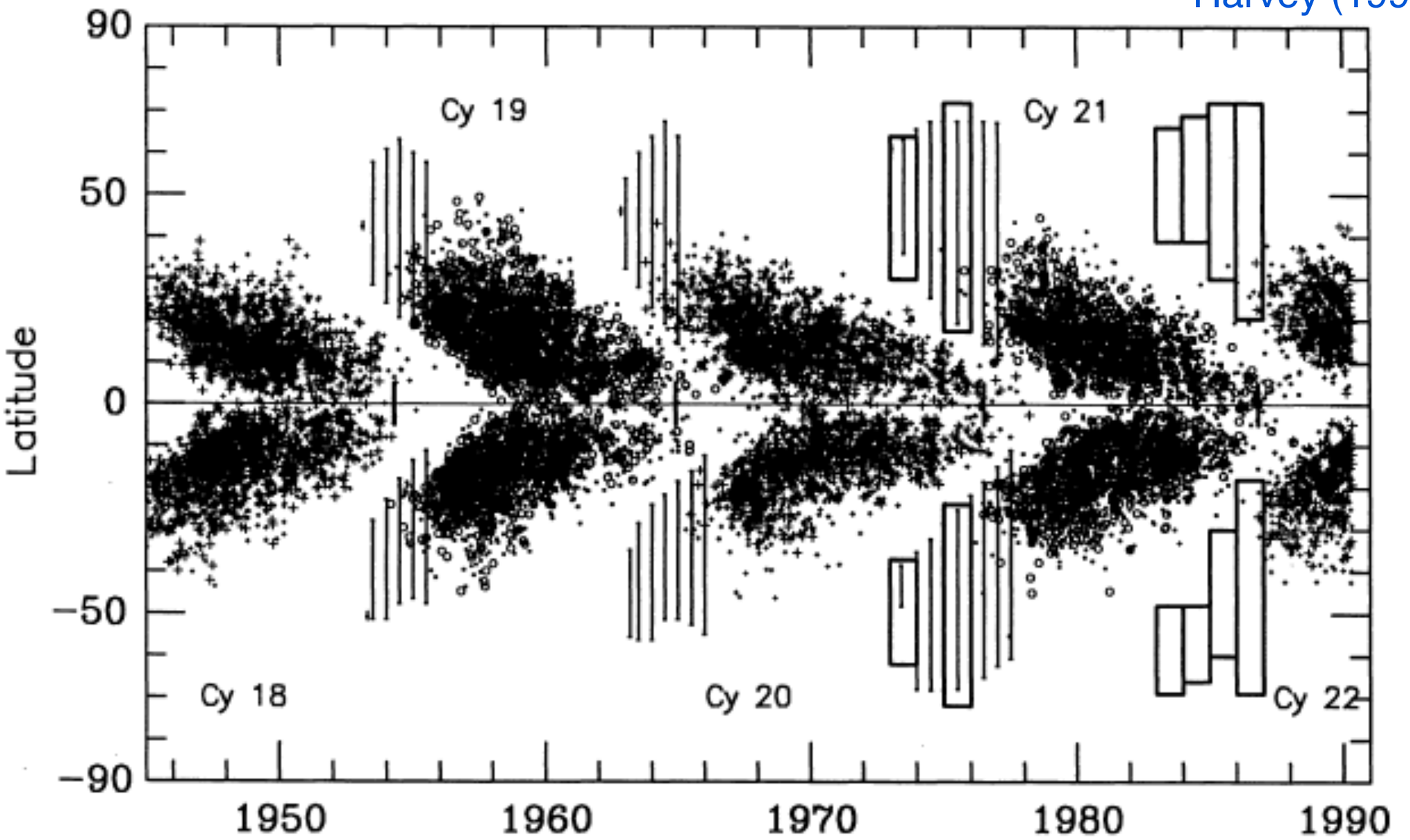
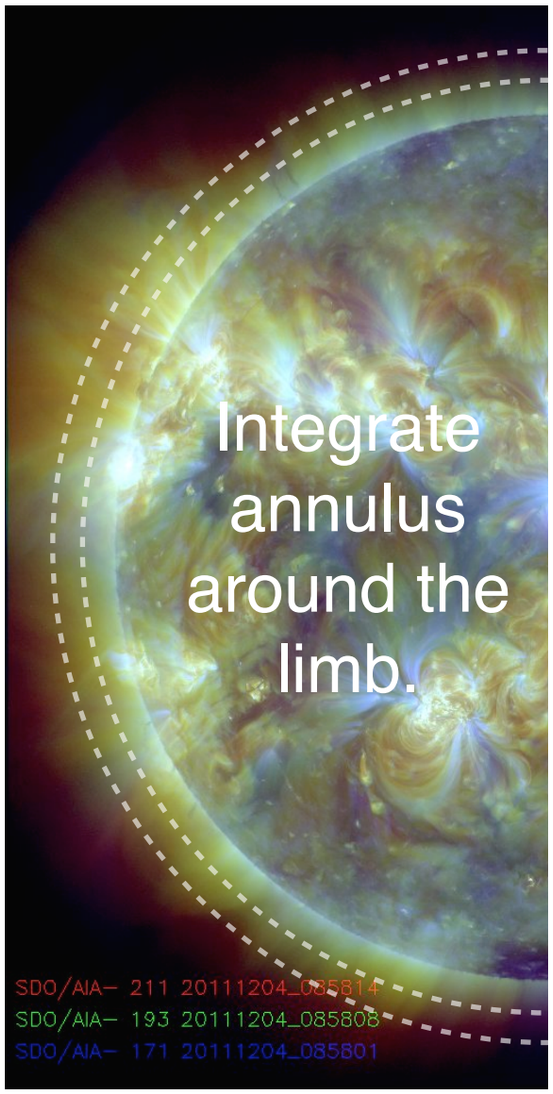
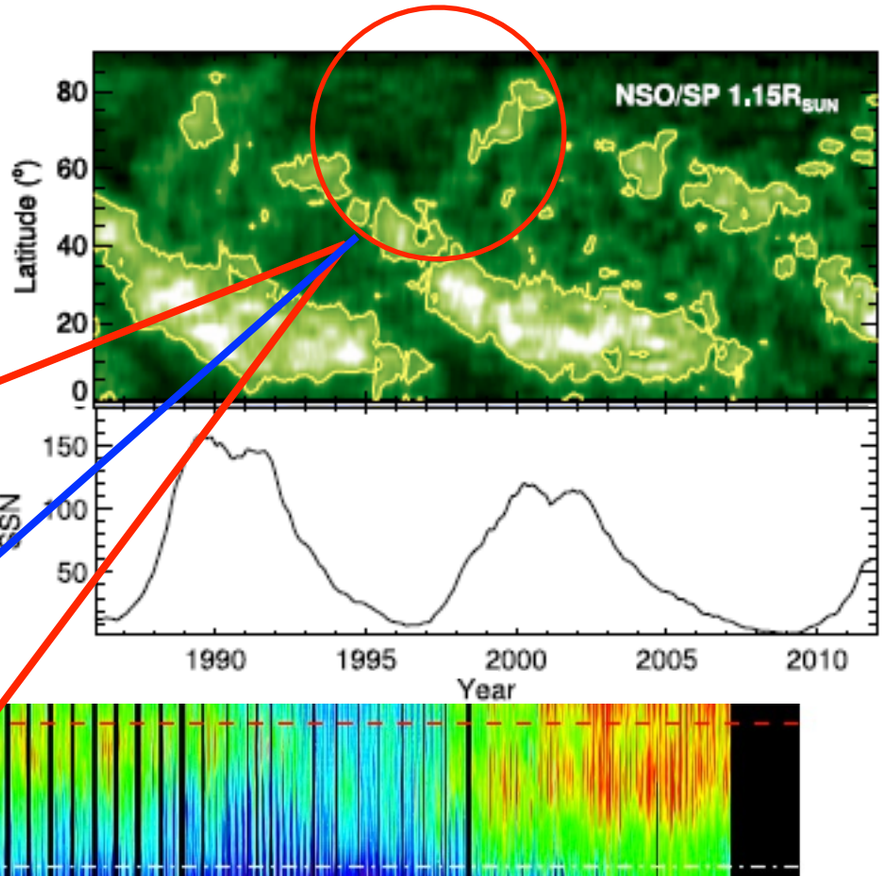
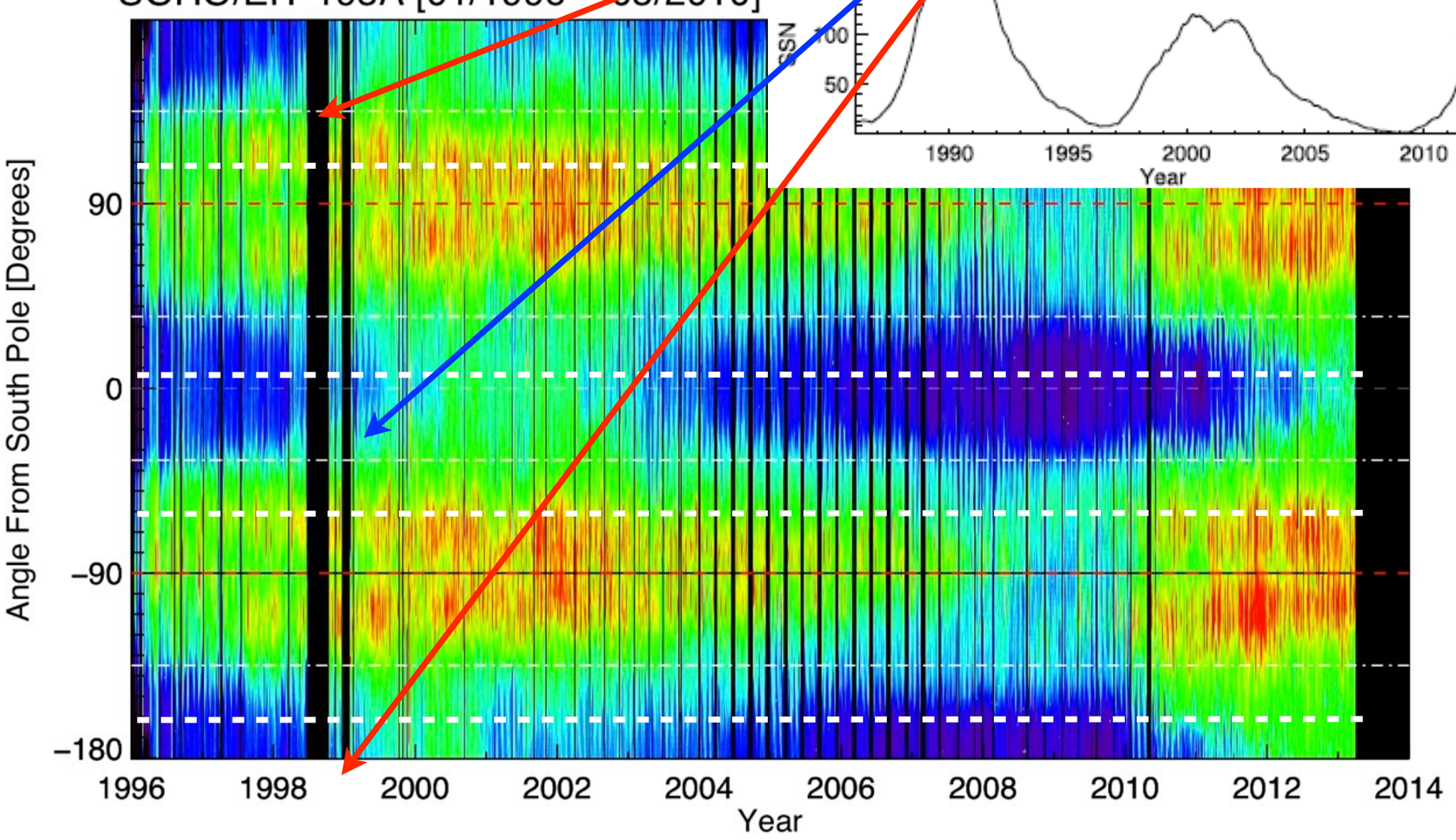


Fig. 15. Butterfly diagram of sunspot regions from 1945 to 1991 combined with latitudinal extent of Ca^+ plage regions (vertical lines) and ephemeral regions (boxes) identified with new cycle. The cycle minima are indicated by vertical lines. Active regions with sunspot areas greater and less than 80 10^{-6} $H_\odot$ are indicated by larger and smaller symbols, respectively. Successive sycles are indicated by different symbols.

NOTHING is ever new: “Altrock-o-grams”

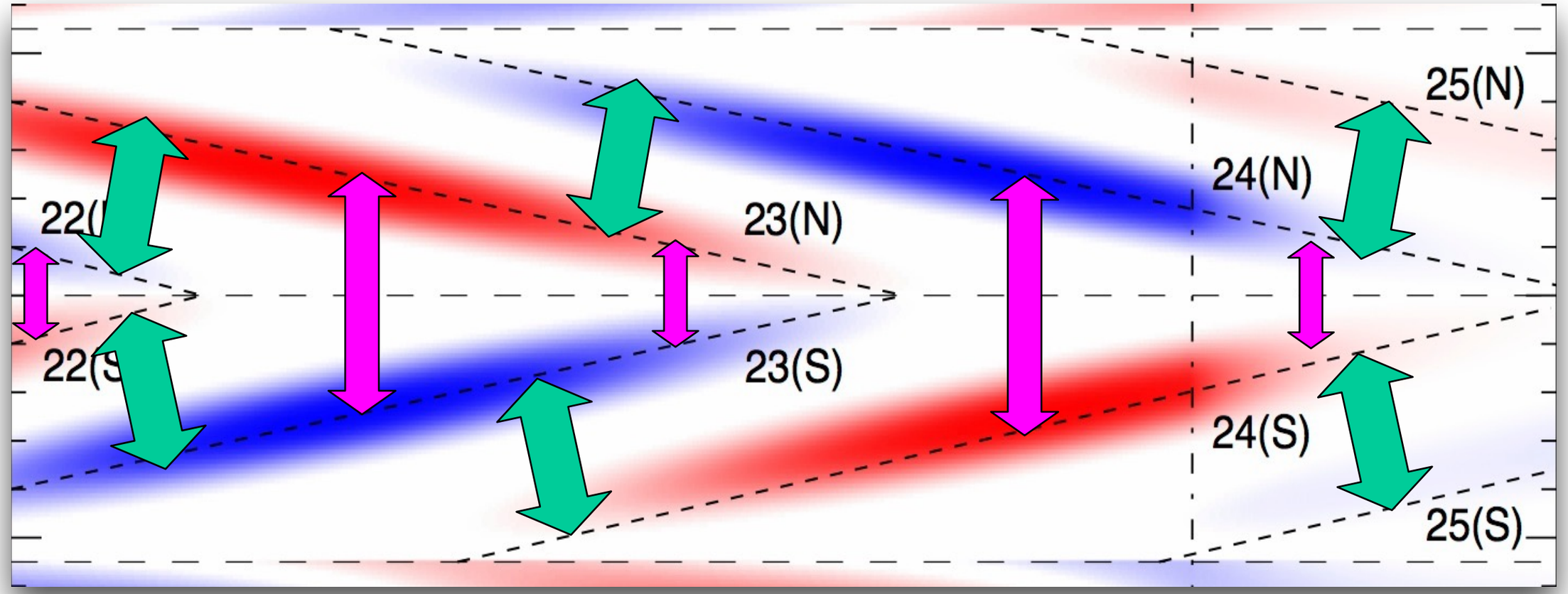






Storms: Band Interaction

The activity bands of the 22-year magnetic activity cycle can help frame the decadal activity envelope through their interaction



Activity Bands Oppositely Signed
&
Long-Lived (~19yrs)

Intra-Hemispheric Interaction

Extra-Hemispheric Interaction

Activity band overlap "shapes" decadal-scale activity envelope……