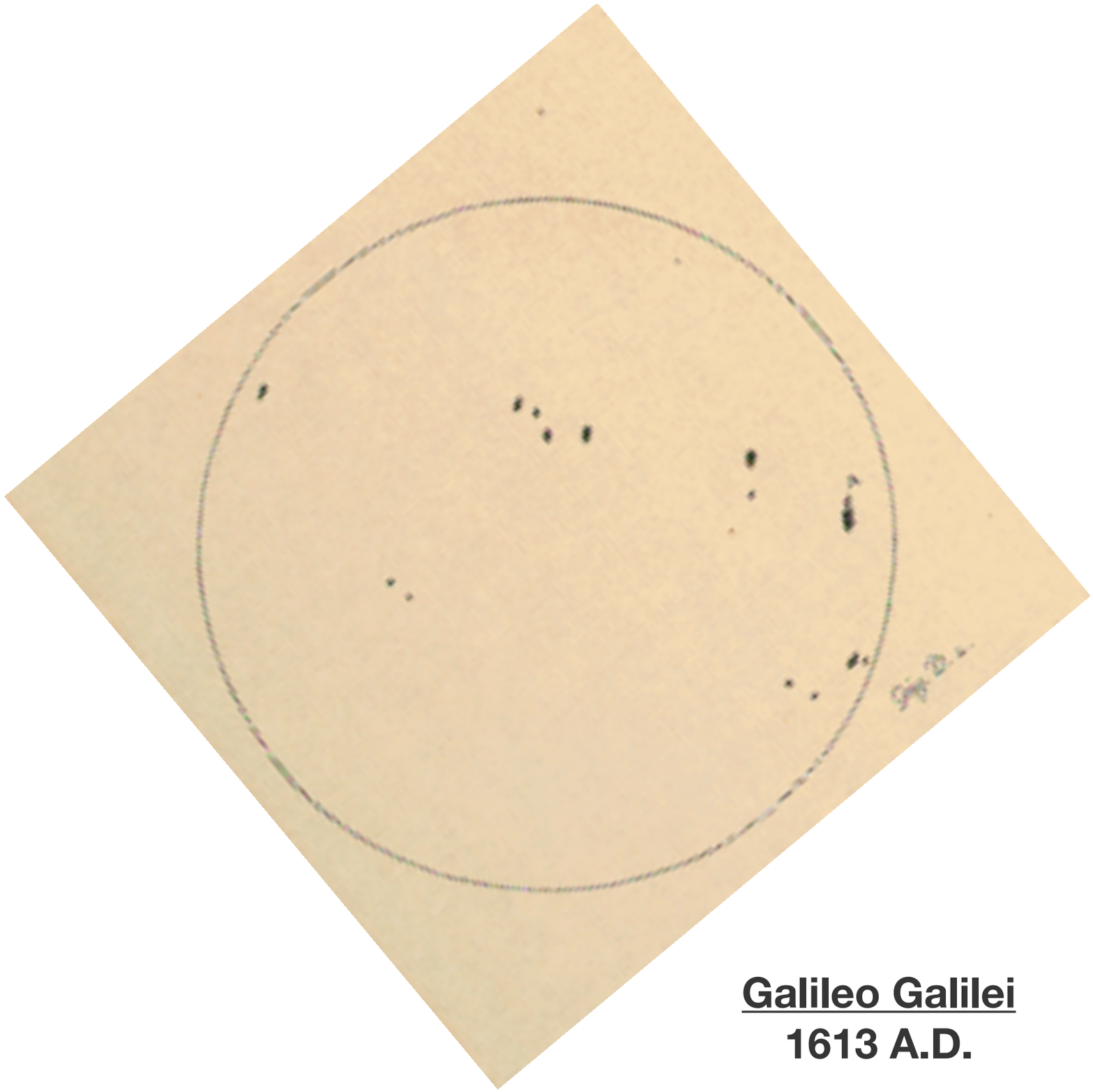
Solar Cycle Prediction

Scott W. McIntosh [Leamon, Chapman, Watkins & Egeland]

Thanks to R. Altrock, D. Banerjee, S. Chatterjee, E. Cliver, A. Srivastava

This material is based upon work supported by the National Center for Atmospheric Research, which is a major facility sponsored by the National Science Foundation under Cooperative Agreement No. 1852977.

Sunspots……



Galileo Galilei
1613 A.D.

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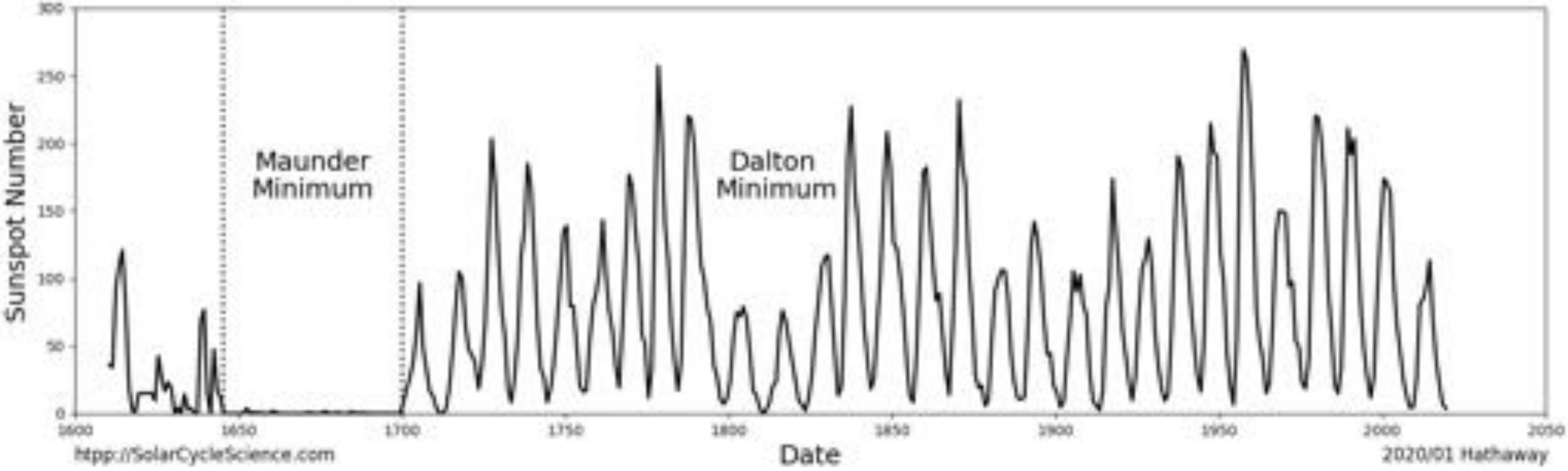
Sunspots……

How many times have you seen this plot so far this week?



[QUASI-] Cyclic Sunspot Evolution : Average Period 11-Years

Except when there are NONE.

Jack Eddy: The Sun continued to cycle even though there were no spots!
[NOTE: Not Covered Here]

The Challenge: Understand the underlying process/physics well enough to project what the system will do in the future!

http://solarcyclescience.com/index.html

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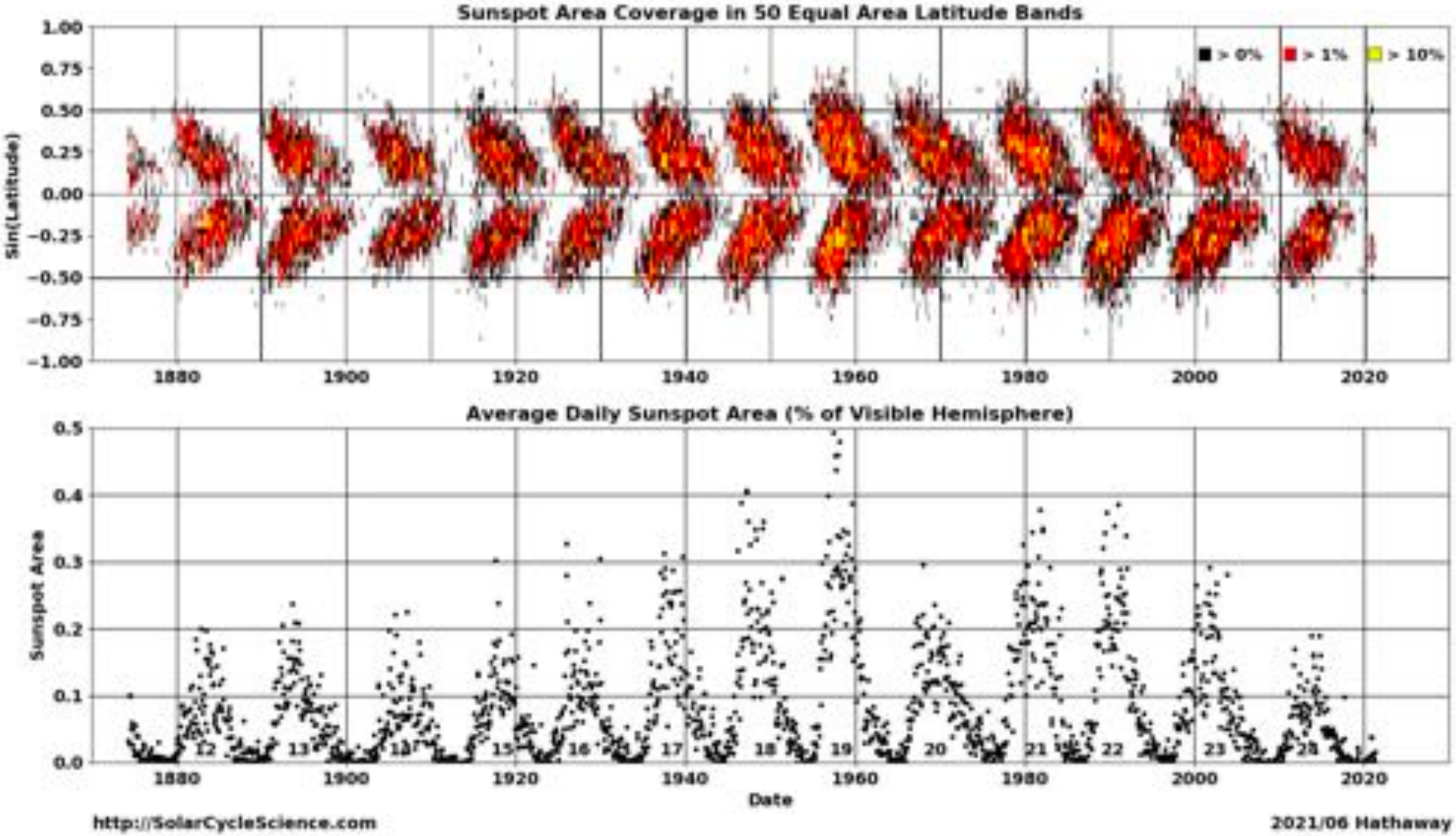
Sunspots……



Maunder - 1904: **“Butterfly”**

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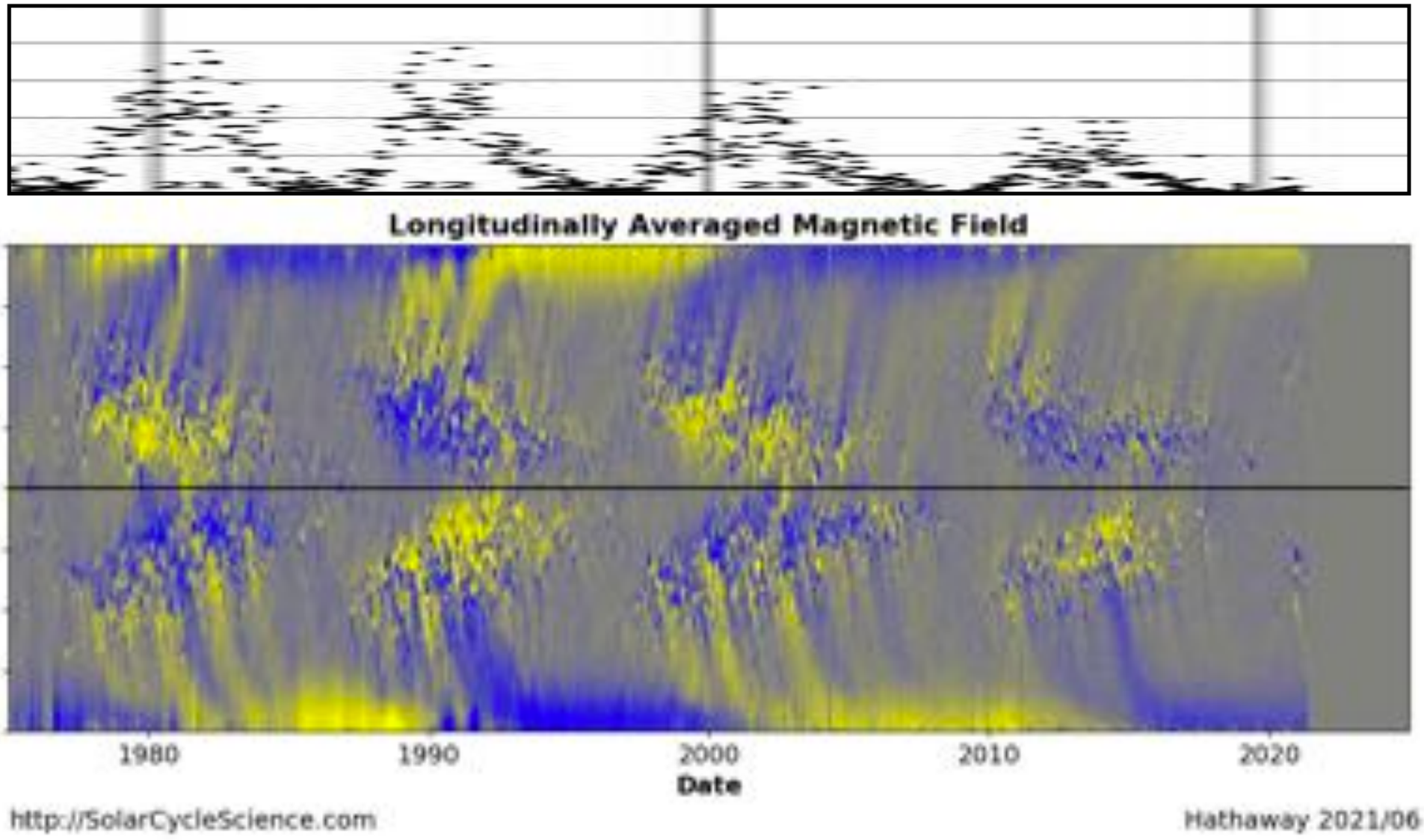
Sunspots……

Hale - 1913-1919: Sunspots are magnetic objects

Hale - 1925: Sunspots obey a 22-year magnetic polarity law



“Magnetic Butterfly”

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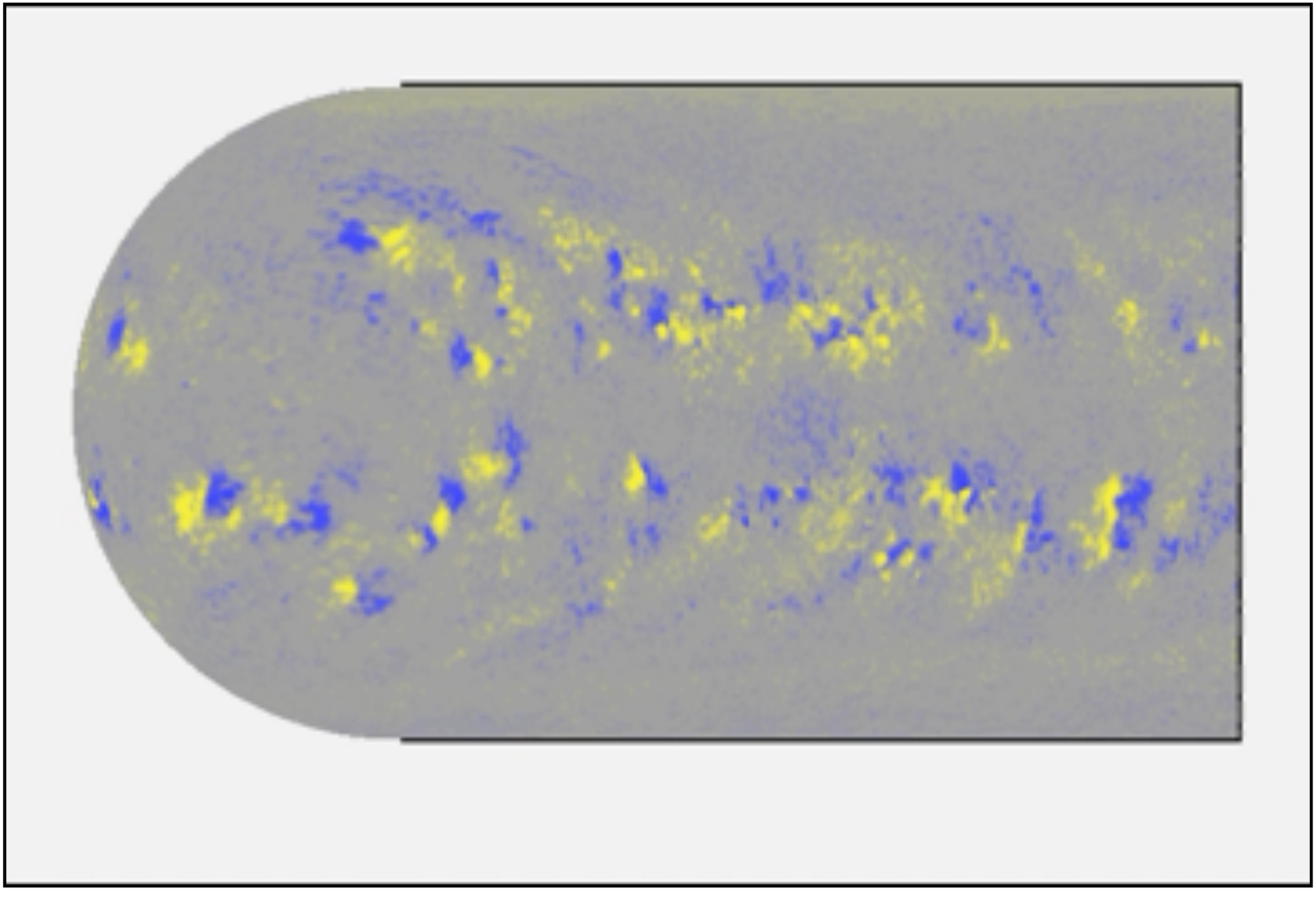
“Building A Magnetic Butterfly”



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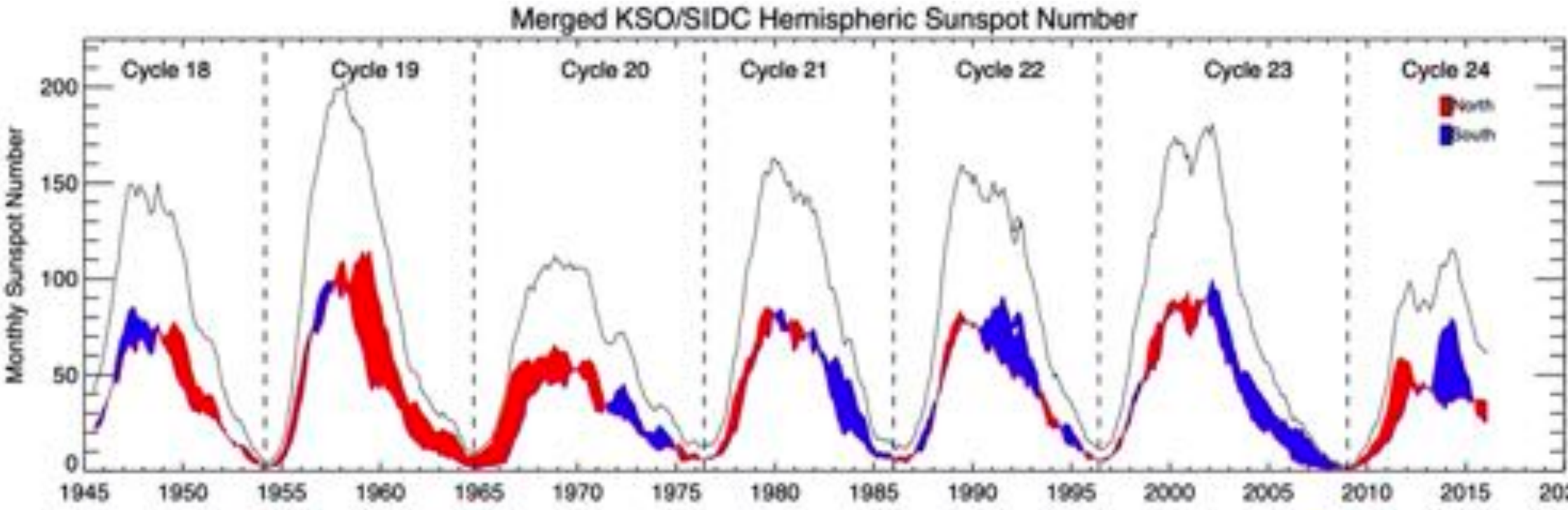
Sunspots……



SUNSPOT CYCLES ARE NOT SINUSOIDAL

CYLES MORE OFTEN THAN NOT DOUBLE PEAKED

HEMISPHERIC ACTIVITY NOT SYMMETRIC

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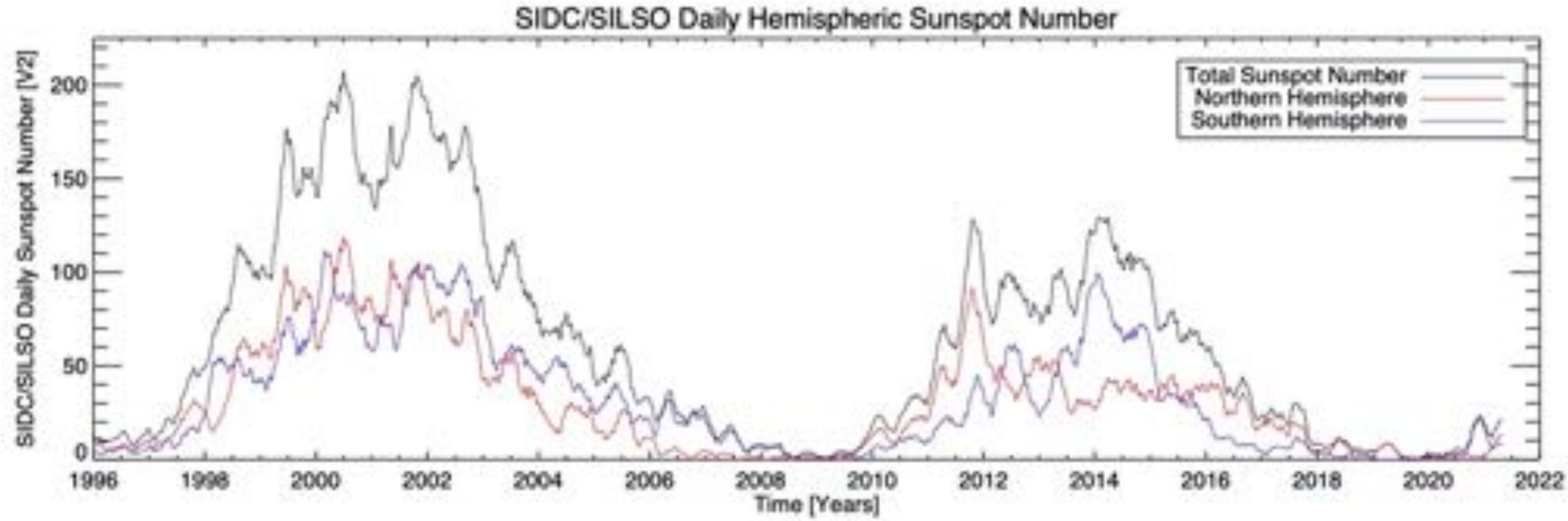
Sunspots……



SUNSPOT CYCLES ARE NOT SINUSOIDAL

CYLES MORE OFTEN THAN NOT DOUBLE PEAKED

HEMISPHERIC ACTIVITY NOT SYMMETRIC

The Sun exhibits periods of enhanced spot formation

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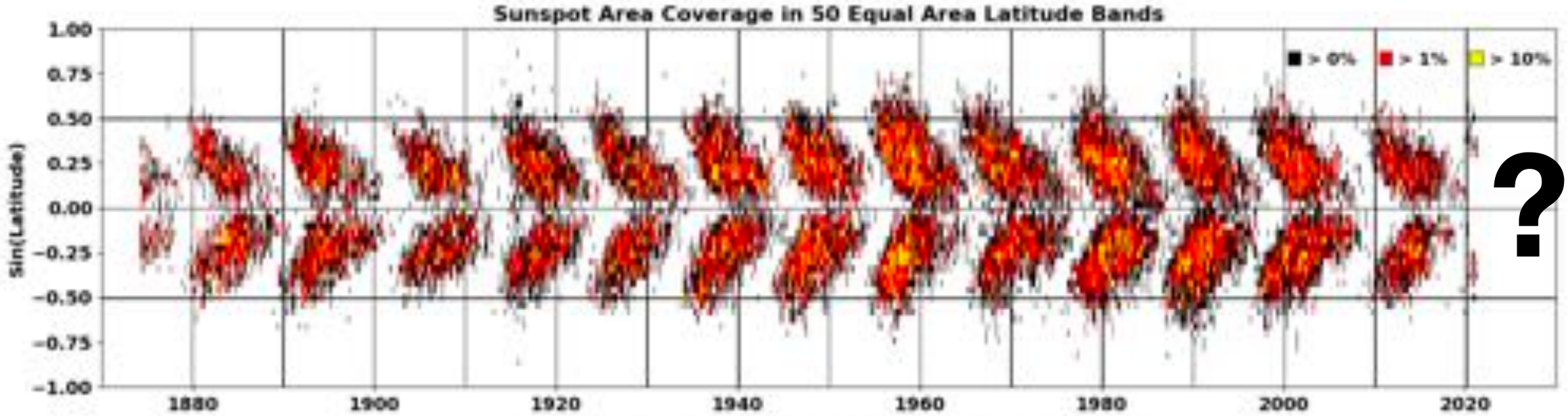

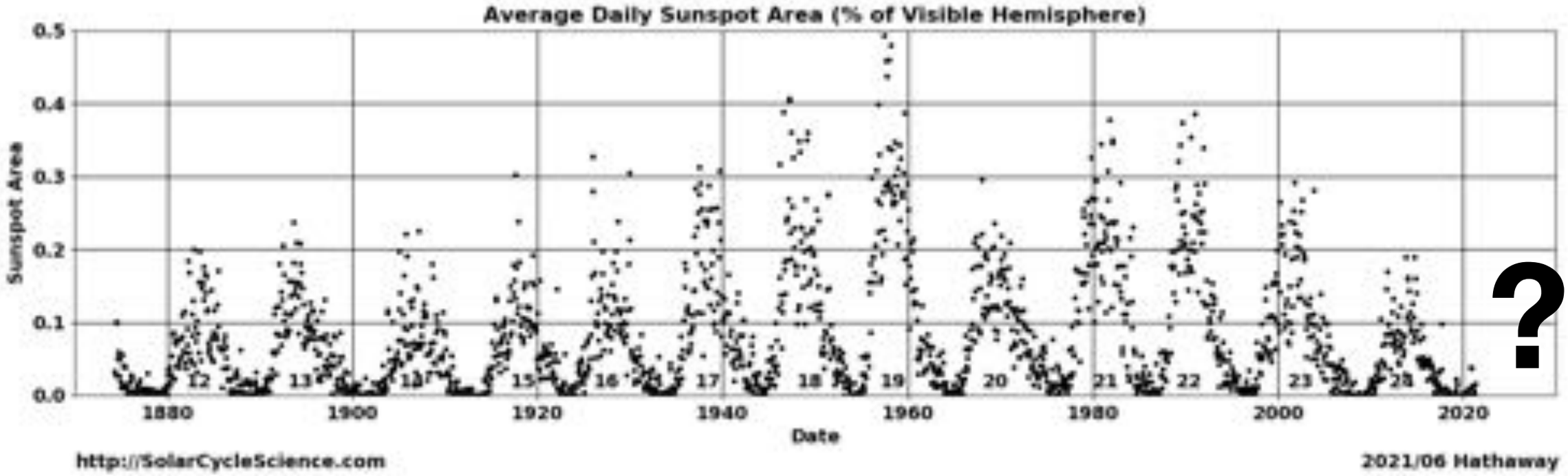

400+ years of the sunspot number?

100+ years of the magnetic data

∞ potential solutions to the puzzle

250+ ‘predictions’ of sunspot cycle 25?

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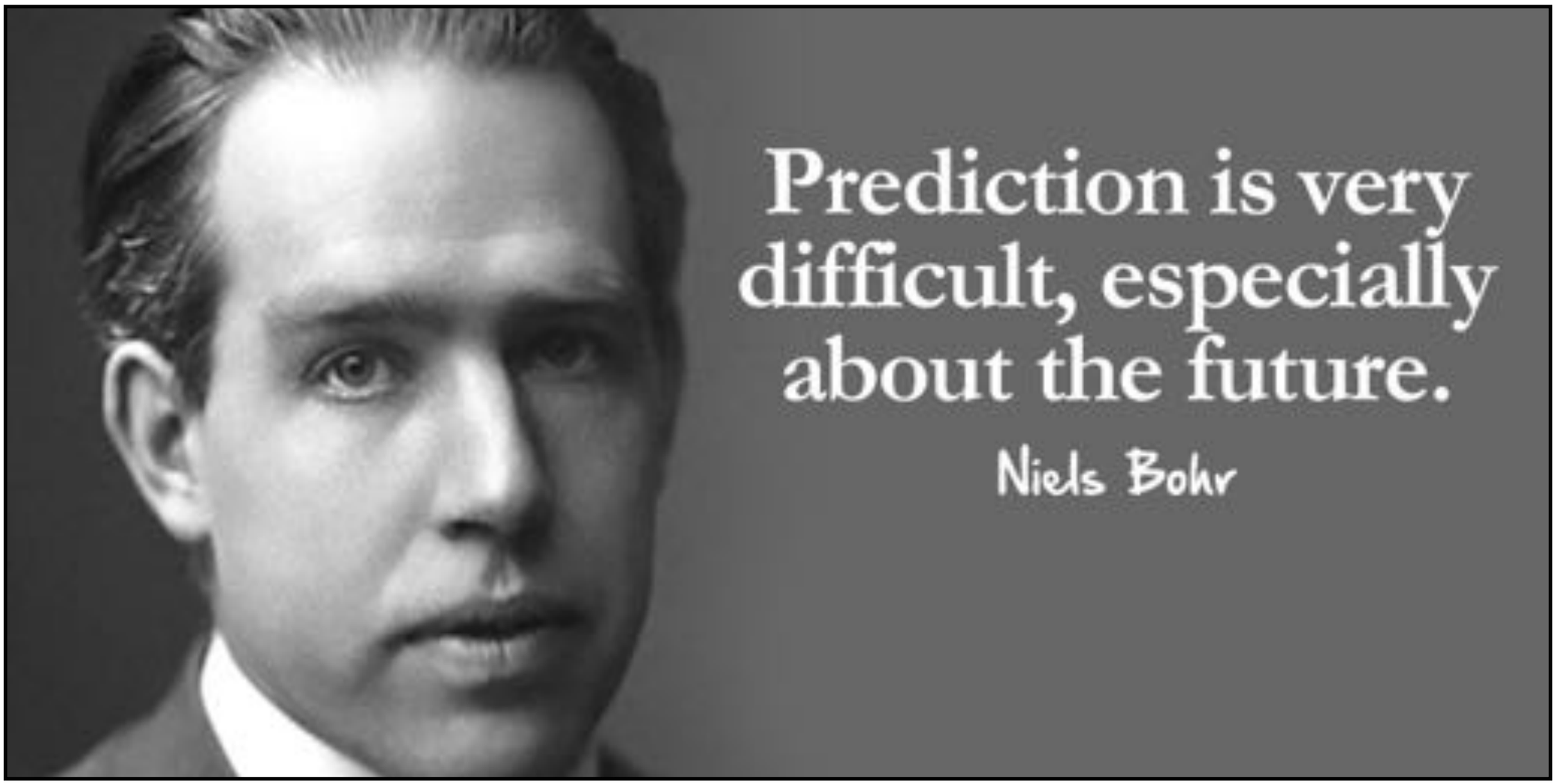
A Warning



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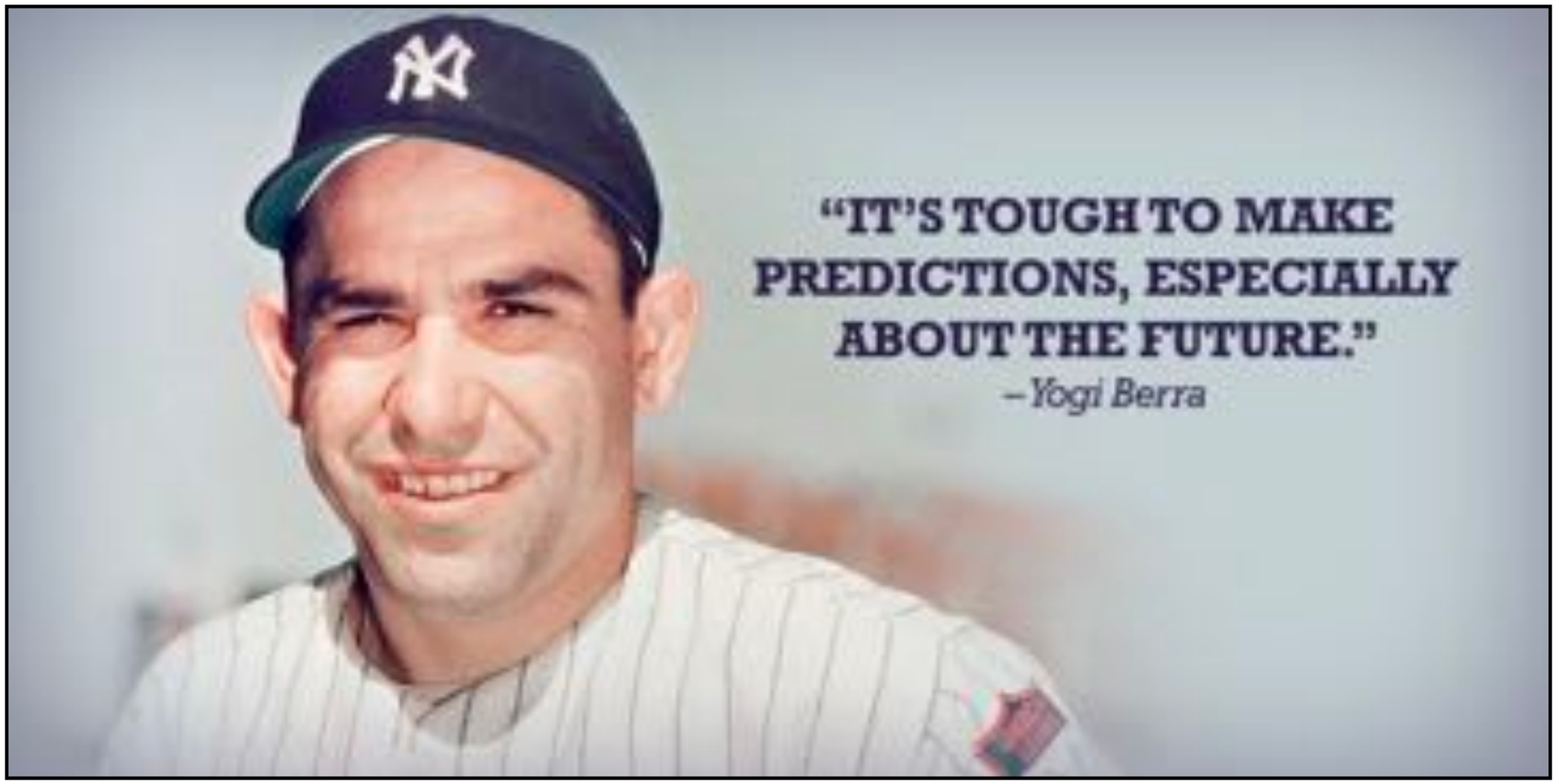
A Warning



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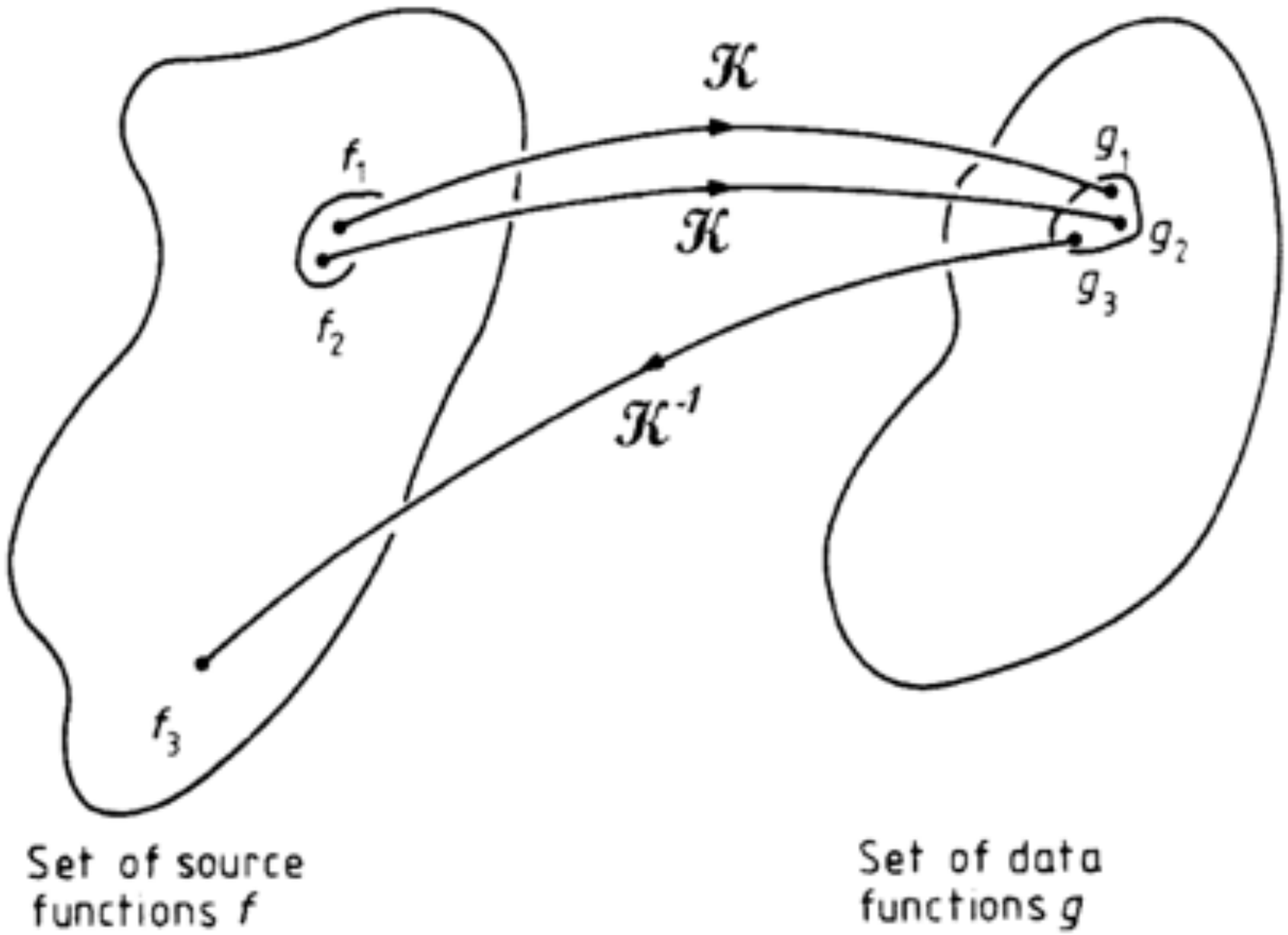
Another Warning

The Challenge: Understand the underlying process/physics well enough to project what the system will do in the future!



Observe Spots ⇒ Infer Physics

[Only works in a "well-posed" problem]

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Predicting Sunspot Cycle.....

23

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Eos, Vol. 78, No. 20, May 20, 1997

Panel Achieves Consensus Prediction of Solar Cycle 23

Jo Ann Joselyn, Jeffrey B. Anderson, Helen Coffey, Karen Harvey, David Hathaway, Gary Heckman, Ernie Hildner, Werner Mende, Kenneth Schatten, Richard Thompson, A. W. P. Thomson, and Oran R. White

are considered in "Climatology (all)."

While four of the six techniques are in general agreement, the panel gave the greatest weight to precursor methods because they have proven to be most successful for solar activity predictions in the past. Precursor methods use the concept of an "extended solar cycle"—the idea that the imminent solar cycle actually starts in the declining phase of the previous cycle. In the declining phase and at solar minimum, the coming cycle manifests itself in structures such as coronal holes and in the strength of the solar polar magnetic field. High-speed solar wind streams from low-latitude coronal holes give rise to recurrent geomagnetic disturbances that are used to predict the strength of the next cycle [*Thompson*, 1993]. Precursor methods invoke a solar dynamo concept in which the polar field in the declining phase and at minimum is the seed of future toroidal fields within the Sun that will cause solar activity [*Schatten and Pesnell*, 1993]. The hypothesized dependence of future cycle activity on the solar polar field strength at cycle minimum also explains why geomagnetic precursors serve as proxies for predicting the solar cycle—that is, a physical connection exists between the polar field, coronal holes, the interplanetary field, and geomagnetic activity.

The prediction technique based on the

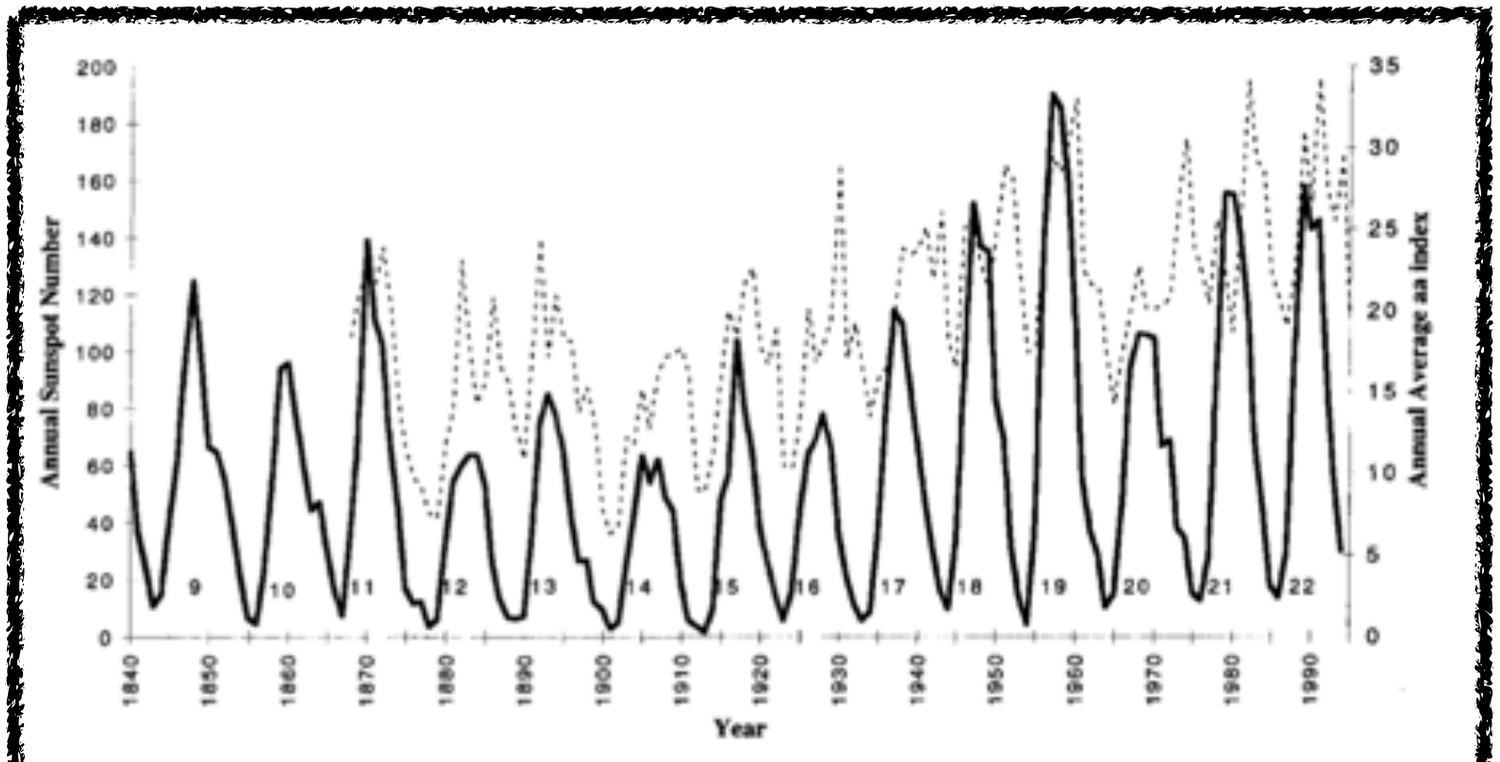

Fig. 1. Annual sunspot numbers, 1840–1995 (cycles are labeled with their associated numbers), and annual average aa *geomagnetic index, 1868–1995 (dotted line).*

28 Forecasts

Methods

- "Precursor" Methods
- Empirical
- Climatology
- "Recent Climatology"
- Neural Networks
- "Spectral" Methods

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The “Consensus” Forecast: Joselyn

Table 1. Combined Forecasts of Maximum Smoothed Sunspot Number for Classes of Prediction Techniques, and the Consensus Forecast

Technique	Low End of Range		Maximum
Even/Odd Behavior	165	200	235
Precursor		140	160
Spectral		135	155
Recent Climatology	125	155	185
Neural Networks	110	140	170
Climatology (all)	75	115	155
Consensus: Smoothed Monthly Sunspot Number	130	160	190

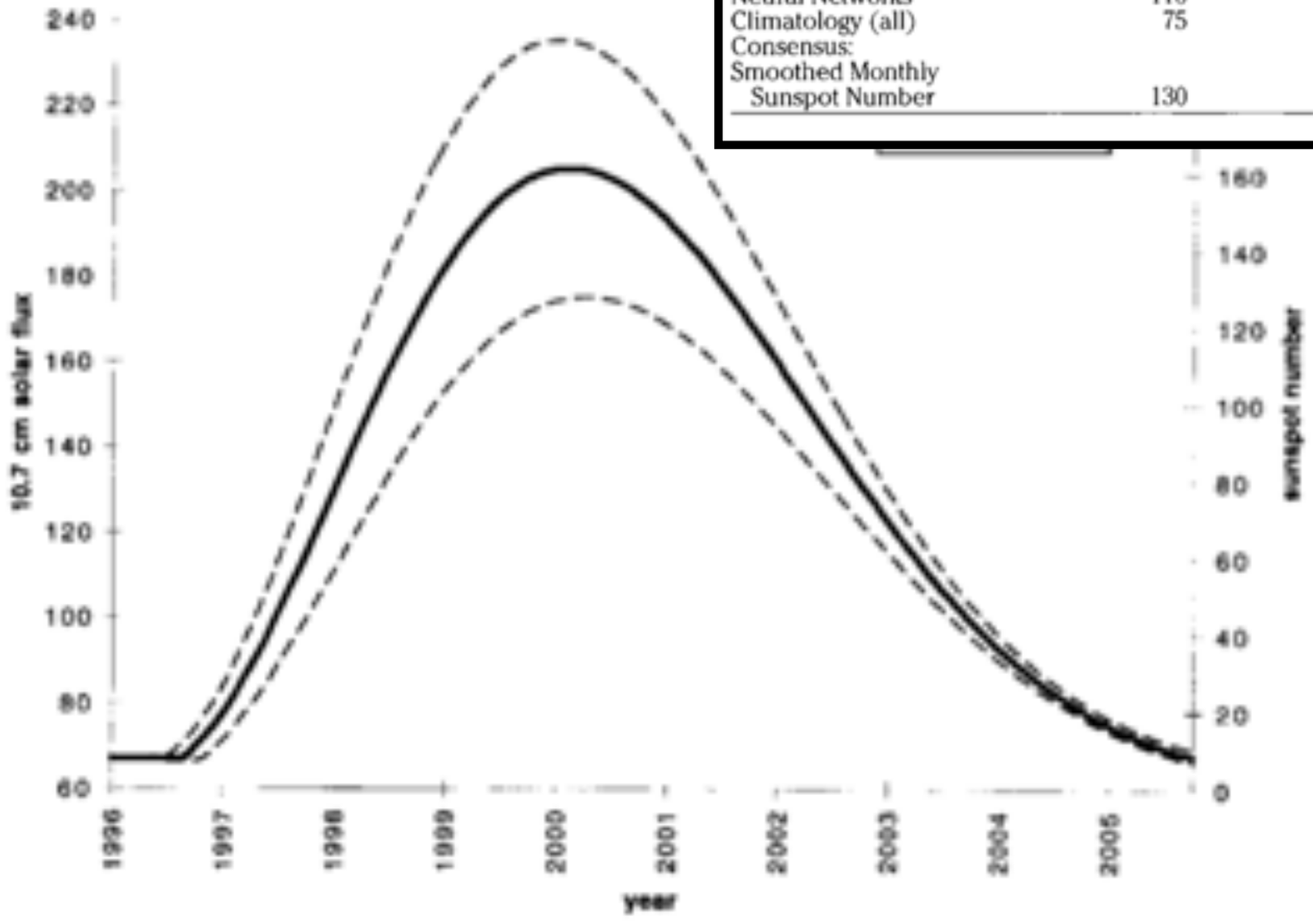

Fig. 2. The estimated profile for Cycle 23 of sunspot number and 10.7-cm solar flux.

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The Product: Joselyn Vs. Reality

Amplitude: Not Bad
Timing: Off

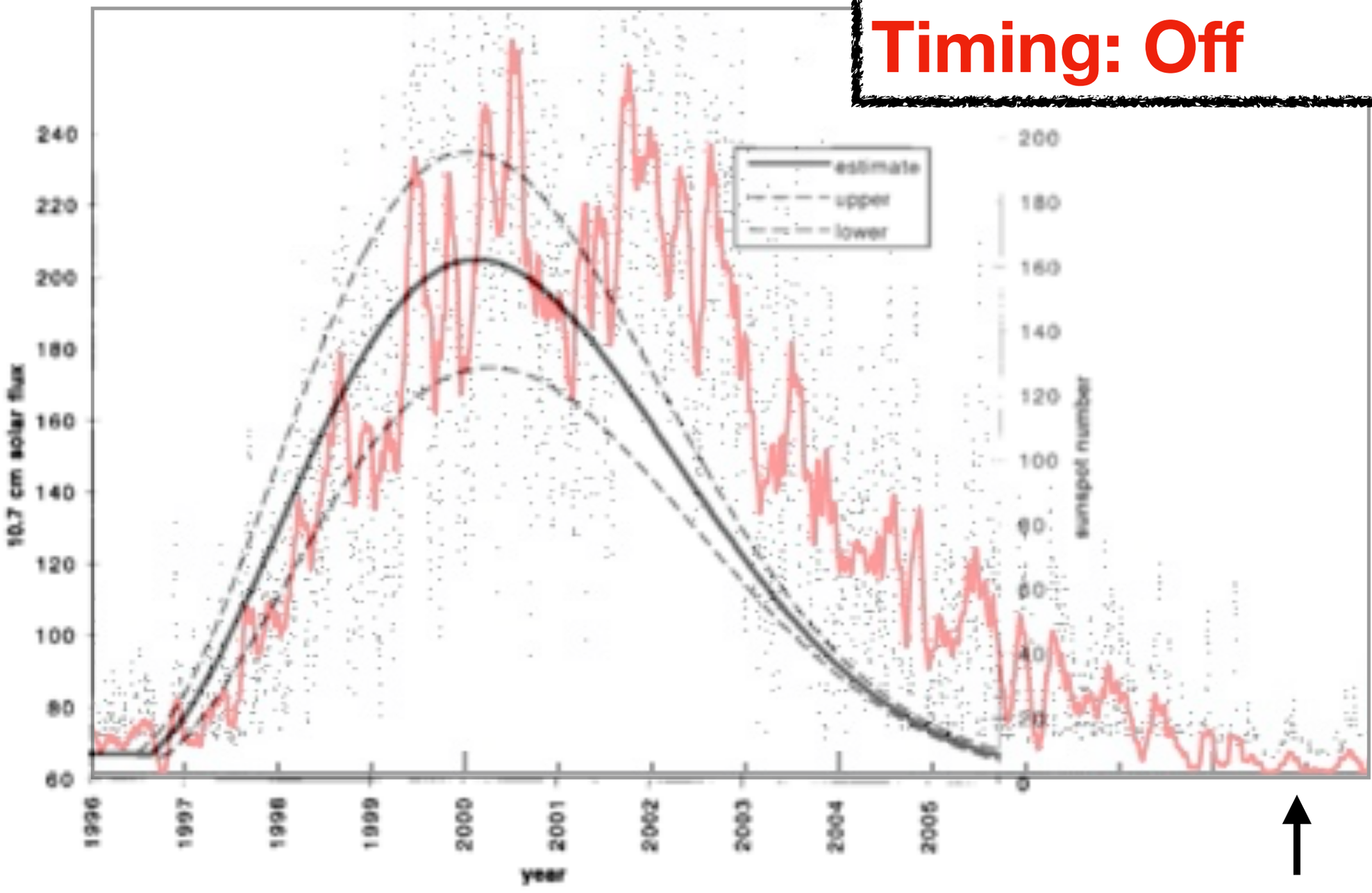

Fig. 2. The estimated profile for Cycle 23 of sunspot number and 10.7-cm solar flux.

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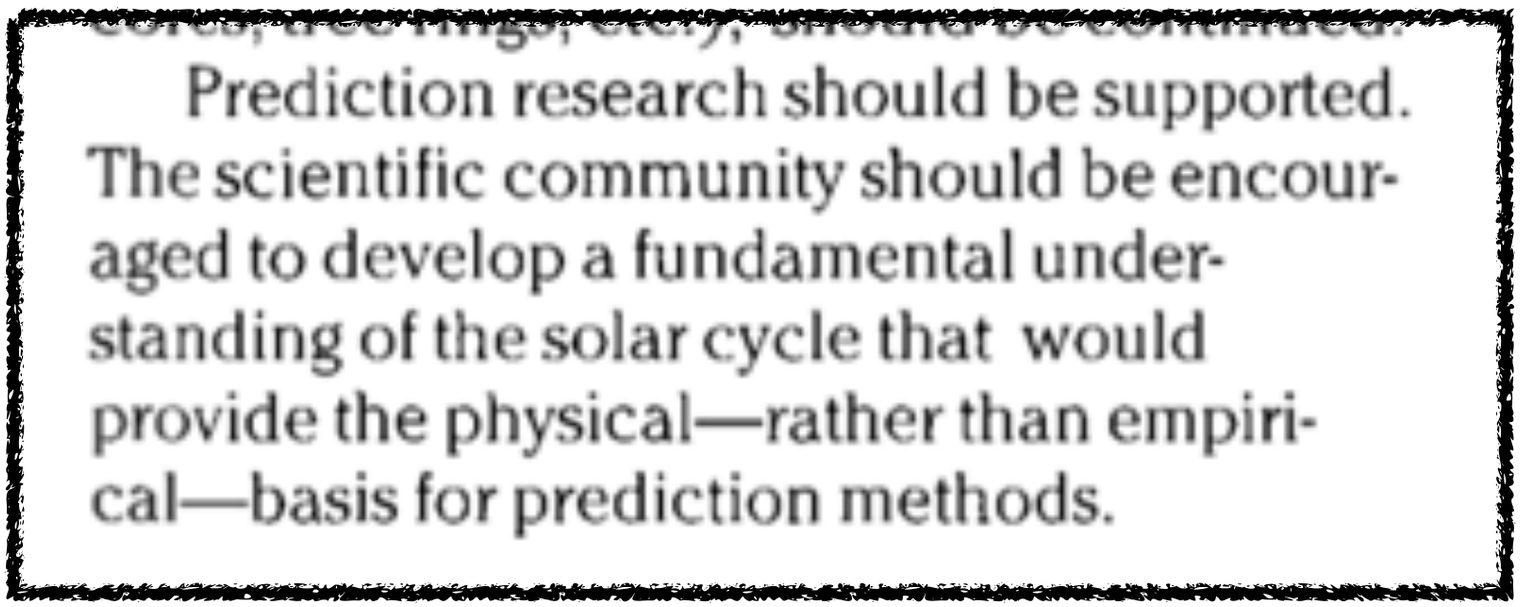
Key Recommendation: Joselyn



Prediction research should be supported. The scientific community should be encouraged to develop a fundamental understanding of the solar cycle that would provide the physical—rather than empirical—basis for prediction methods.

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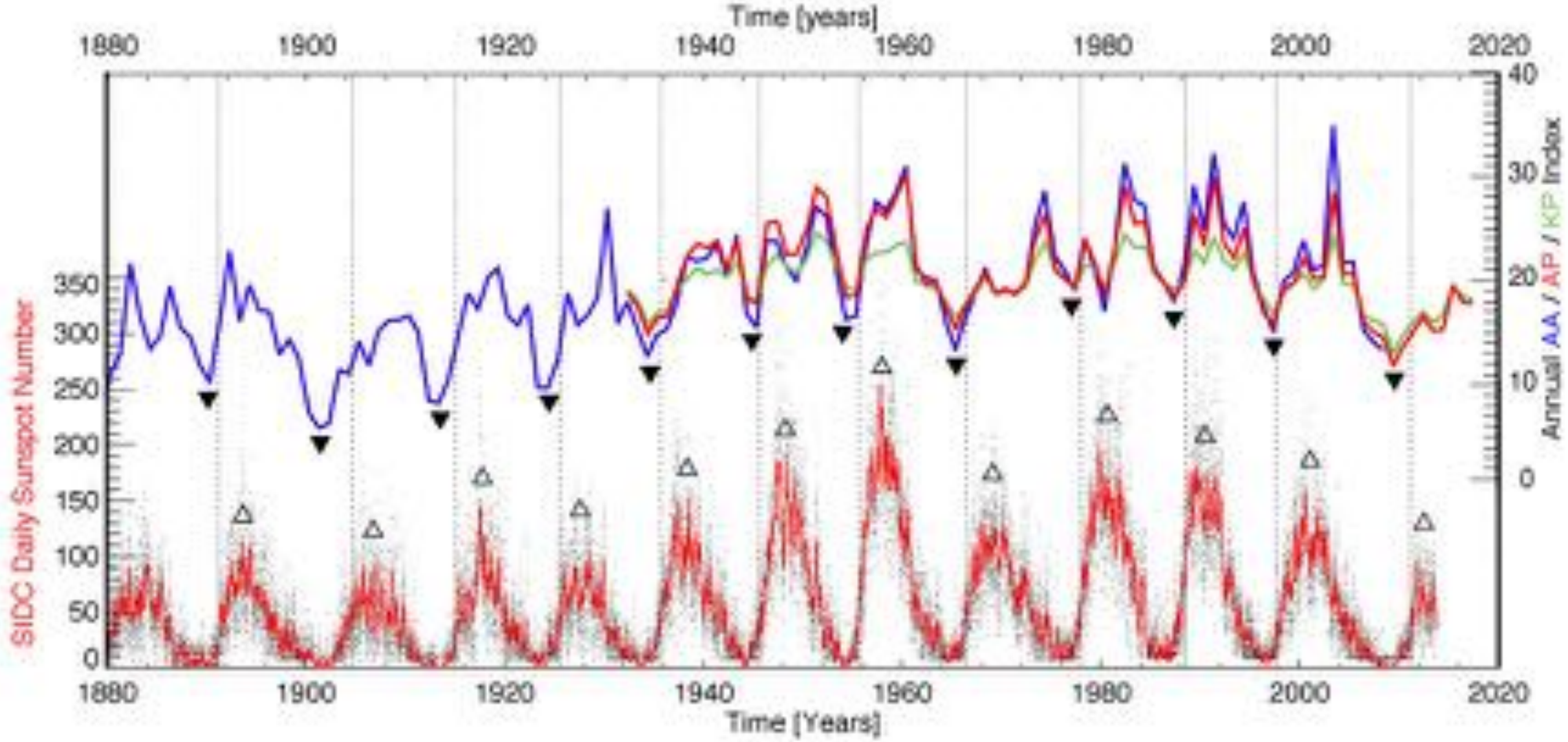
An Interesting “Precursor”



What do you see in this record?

[Feynman, Legrand, Mayaud, Others]

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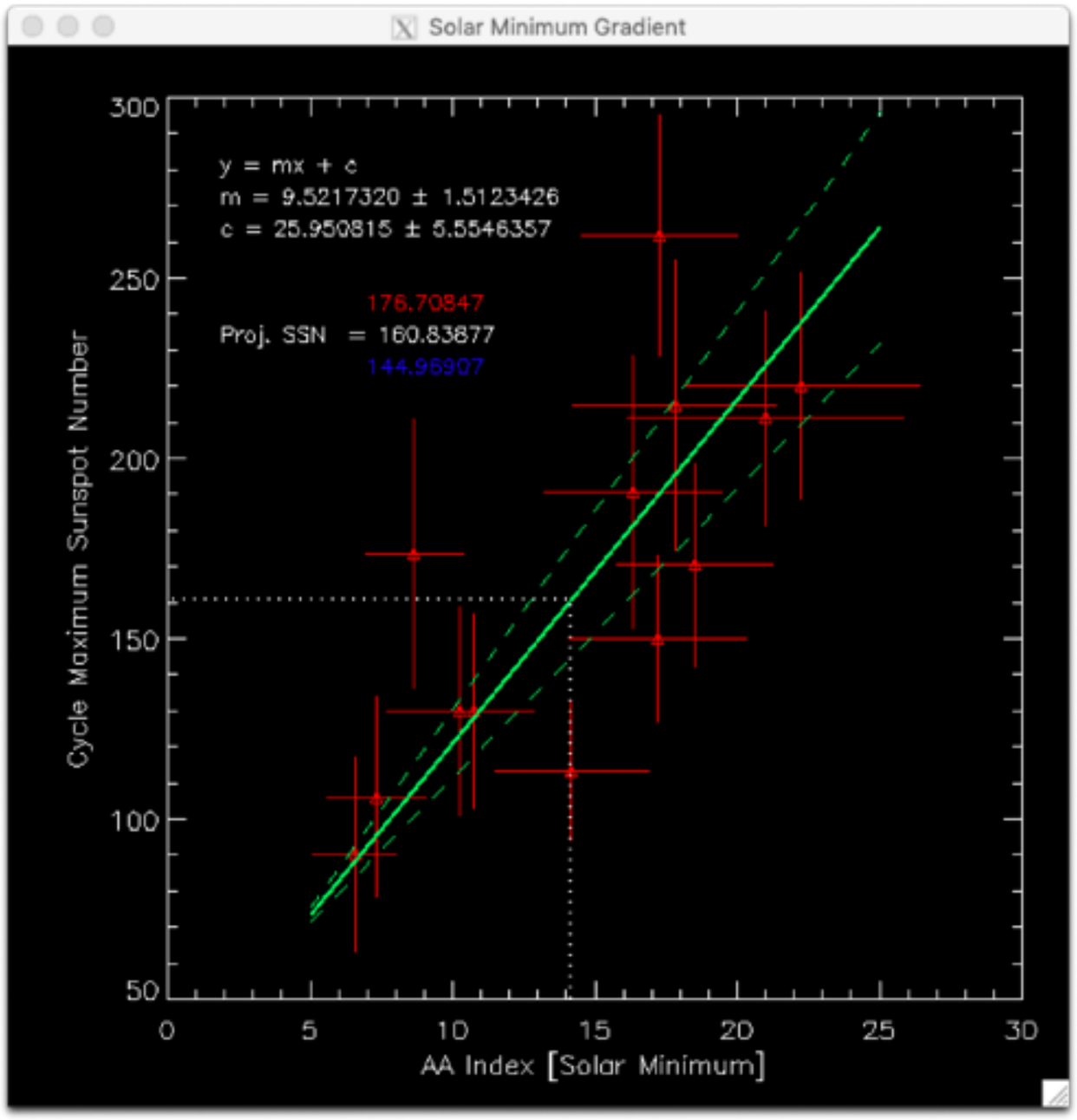
An Interesting “Precursor”



What do you see in this record?

[Feynman, Legrand, Mayaud, Others]

Why might this be SO good? [Physics]

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Predicting Sunspot Cycle.....

24

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Solar Phys (2008) 252: 209–220
DOI 10.1007/s11207-008-9252-2

Predictions of Solar Cycle 24

William Dean Pesnell

Table 2 Summary of predictions for Solar Cycle 24.

Category	Number	Average	Range
All	54	117 ± 33	40 – 185
Climatology (C)	13	111 ± 36	40 – 185
Recent climatology (R)	2	140 ± 30	120 – 160
Dynamo models (D)	3	131 ± 45	80 – 168
Spectral (S)	12	100 ± 33	42 – 180
Neural network (N)	2	145	145 – 145
Precursor (P)	22	124 ± 30	70 – 180
Geomagnetic (mostly aa)	12	137 ± 20	111 – 180
aa	7	140 ± 14	120 – 160
Ap	5	134 ± 28	111 – 180
Solar	10	110 ± 30	70 – 175
Polar fields	3	88 ± 24	70 – 115
Other solar	7	116 ± 32	74 – 175

50+ Forecasts

Methods

- "Precursor" Methods
- Empirical
- Climatology
- "Recent Climatology"
- Neural Networks
- "Spectral" Methods
- Dynamo Models

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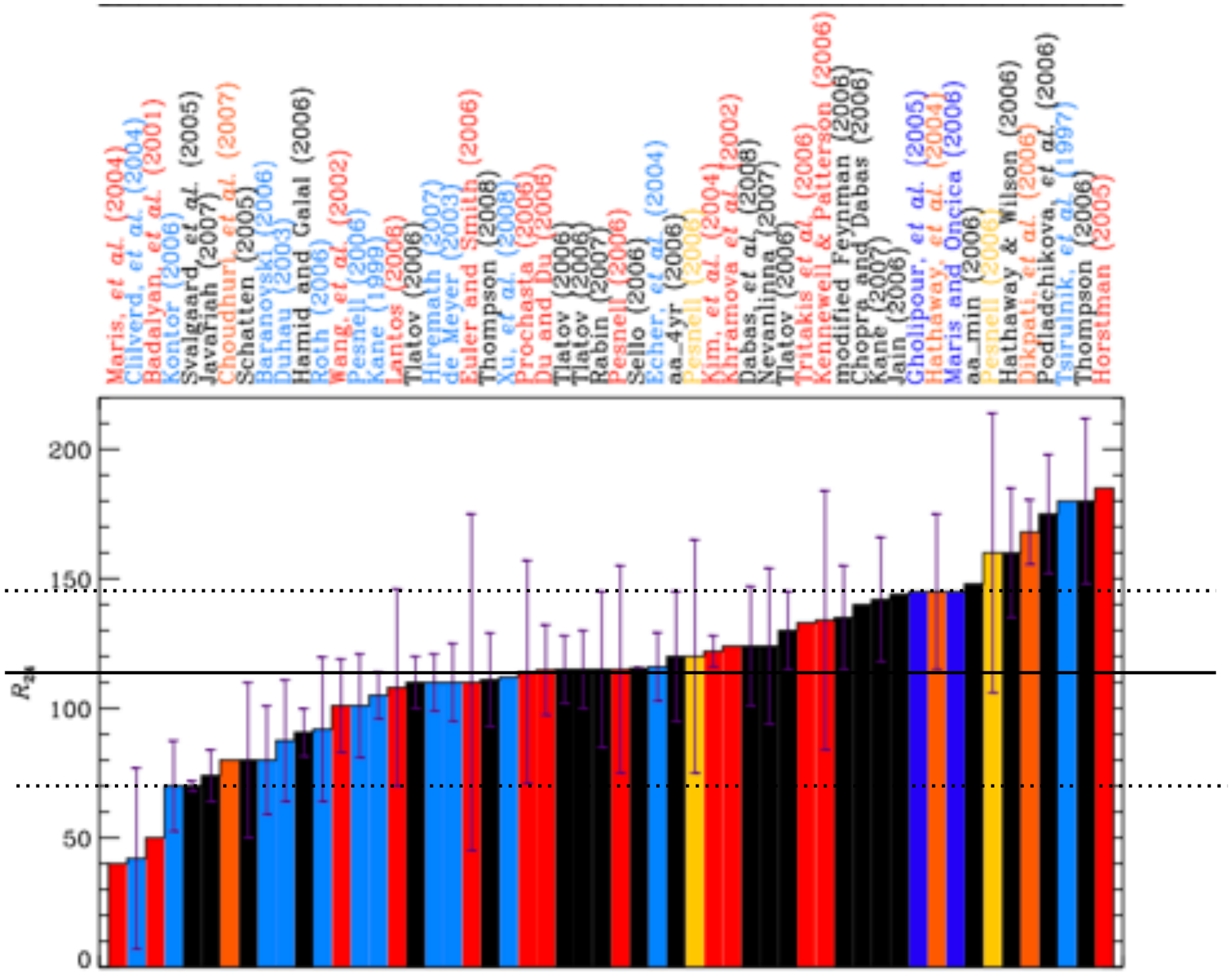

Figure 1 The predictions from Table 1, plotted in order of increasing predicted maximum for Cycle 24. The prediction categories are color coded as in the top panel. The upper plot is the significance of the difference from the climatological average of 115 ± 40 for those predictions that included an error bar. The dashed line shows the estimated "highly significant" level, which one prediction reaches. Two other predictions are statistically significant at the 90% level.

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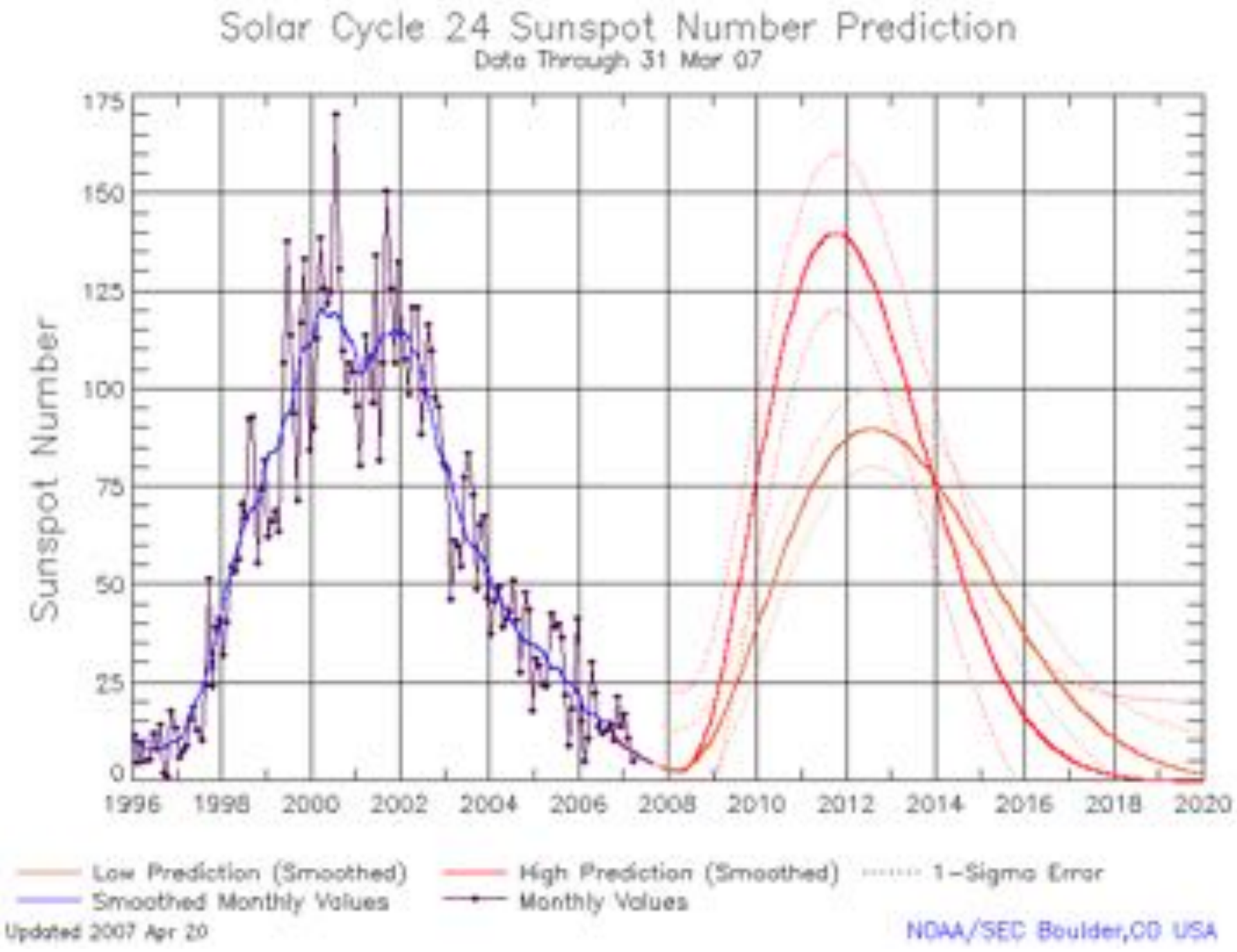
The “Consensus” Forecast: Pesnell



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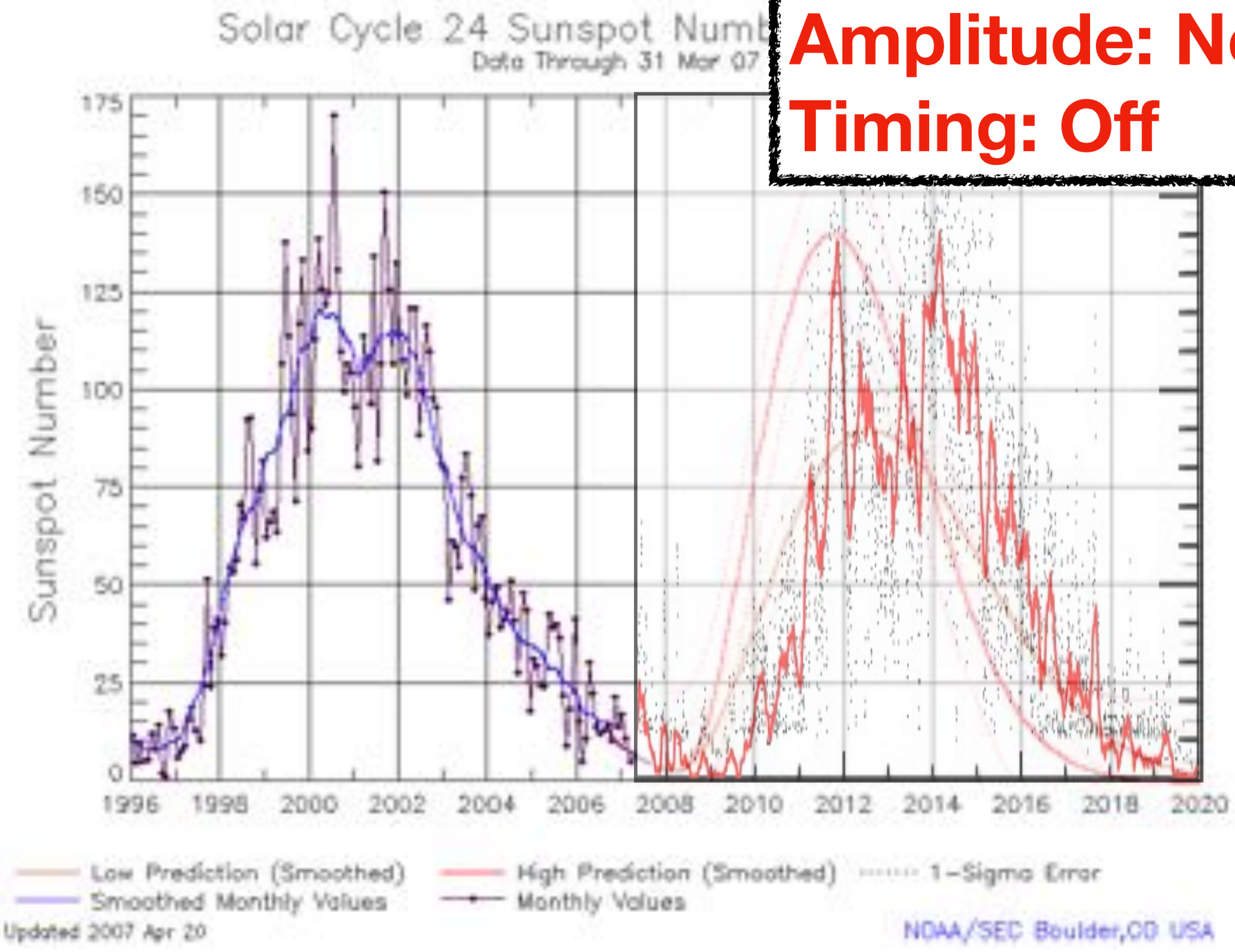
The Product: Pesnell Vs. Reality



Amplitude: Not Bad
Timing: Off

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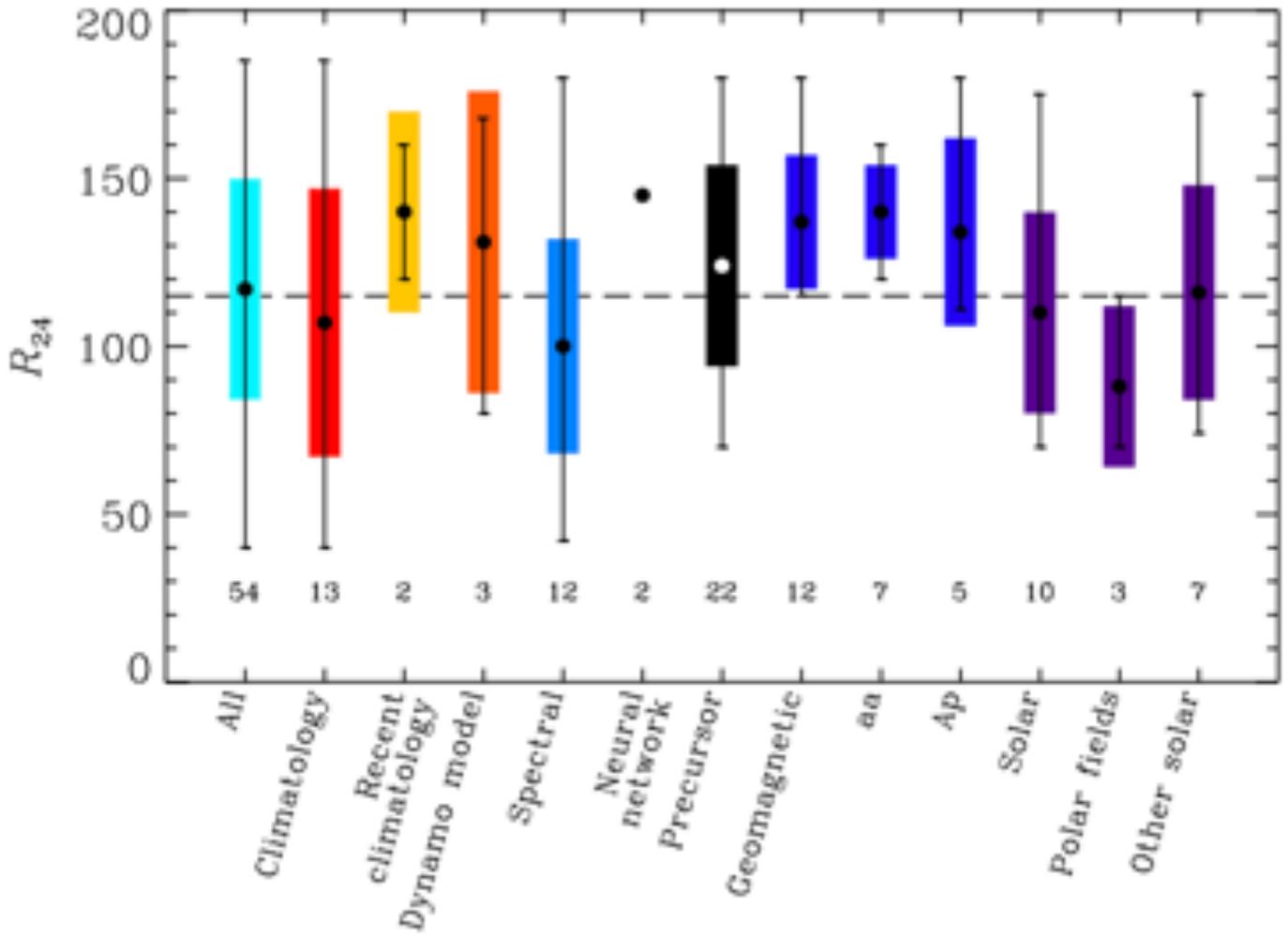

The Poles In Play

5. Summary and Conclusions

The convergence of the climatology predictions to $R_{2,ave}$ is not surprising, but the large discrepancy in the dynamo models shows that those models do not as yet possess a predictive capability. The precursor category must be further broken out into solar and geomagnetic to produce equivalent classes, illustrating the poor overlap of the two techniques. Precursors were a major contributor to the consensus prediction of Solar Cycle 23 (Joselyn *et al.*, 1997) and their growing discrepancy is worrisome for future work. As a consequence of this divergence, the solar and geomagnetic precursors should be considered as separate categories.

3.3. Precursor

Precursor forecasts, which look for leading indicators of solar activity, were the most common category of predictions. Two types of precursors dominate this category:

1. Solar polar magnetic field at minimum ≈ level of activity at next maximum: The three predictions in this category tend to be near or below average for Cycle 24.
2. Geomagnetic activity near minimum ≈ level of activity at next maximum. Seven of the 12 geomagnetic precursor predictions in Table 1 used aa as their indicator of geomagnetic activity, four used Ap, and one used both. All of the predictions were for average to above average levels of activity in Solar Cycle 24.

The remaining precursor predictions used solar properties such as global magnetic field and have a wide divergence in their forecasts.

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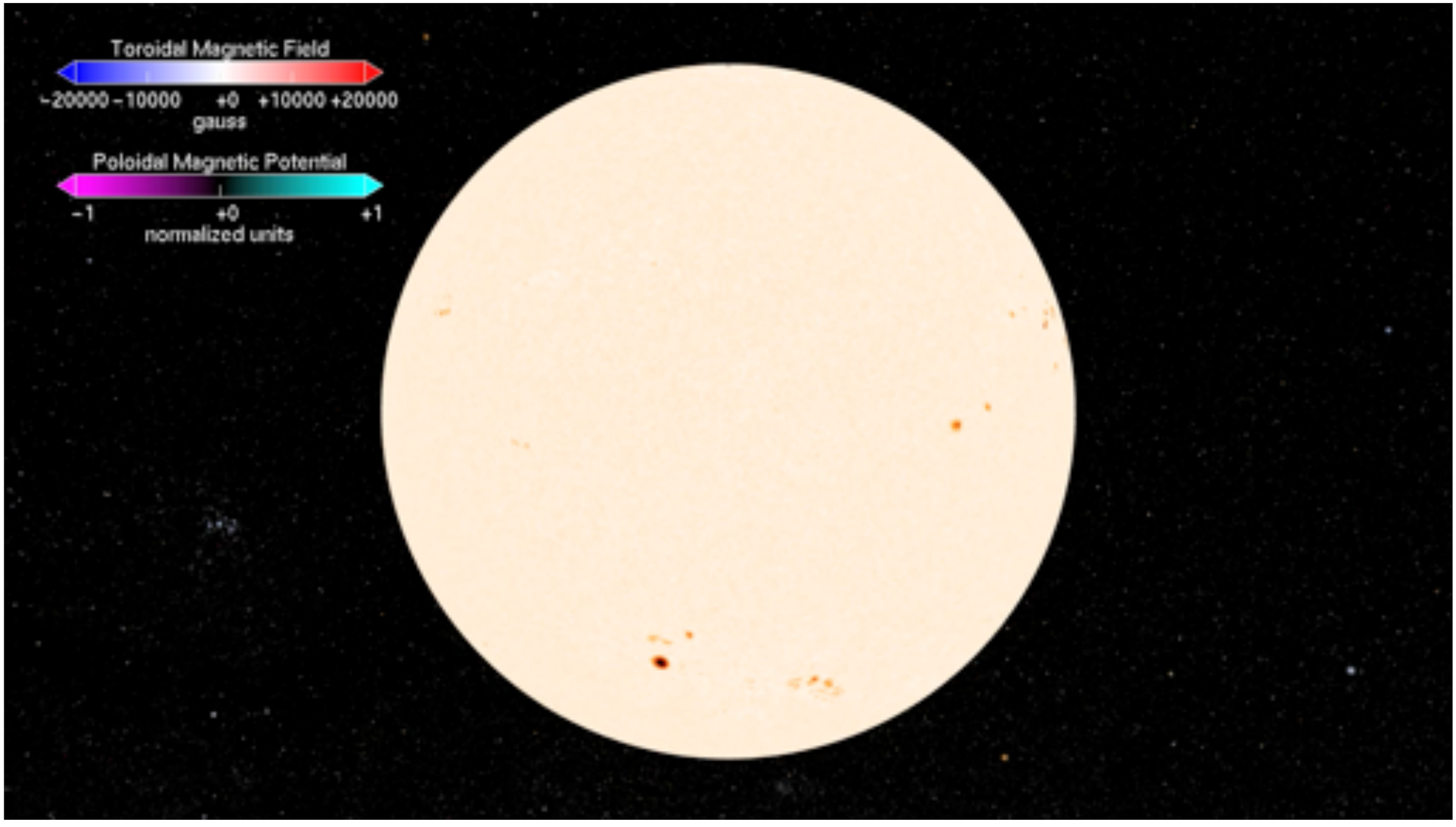
The Rise of the Physical Model



https://svs.gsfc.nasa.gov/3521

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Predicting Sunspot Cycle.....

25

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Solar Physics
DOI: 10.1007/•••••-•••-•••-••••-•

Progress in Solar Cycle Predictions: Sunspot Cycles 24–25 in Perspective

Dibyendu Nandy[1,2]

Abstract
The dynamic activity of the Sun – sustained by a magnetohydrodynamic dynamo mechanism working in its interior – modulates the electromagnetic, particulate and radiative environment in space. While solar activity variations on short timescale create space weather, slow long-term modulation forms the basis of space climate. Space weather impacts diverse space-reliant technologies while space climate influences planetary atmospheres and climate. Having prior knowledge of the Sun's activity is important in these contexts. However, forecasting solar-stellar magnetic activity has remained an outstanding challenge. In this review, predictions for sunspot cycle 24 and the upcoming cycle 25 are summarized, and critically assessed. The analysis demonstrates that while predictions based on diverse techniques disagree across solar cycles 24–25, physics-based predictions for solar cycle 25 have converged and indicates a weak sunspot cycle 25. It is argued that this convergence in physics-based predictions is indicative of progress in the fundamental understanding of solar cycle predictability. Based on this understanding, resolutions to several outstanding questions related to solar cycle predictions are discussed.

Keywords: Solar Activity; Sunspots; Solar Cycle Prediction; Magnetohydrodynamics; Solar Dynamo

80+ Forecasts

Methods

- "Precursor" Methods
- Empirical
- Climatology
- "Recent Climatology"
- Neural Networks / Machine Learning
- "Spectral" Methods
- Dynamo Models

"Dynamo"
- Assimilative: Polar Field -> SSN
- Surface Flux Transport
- Full MHD

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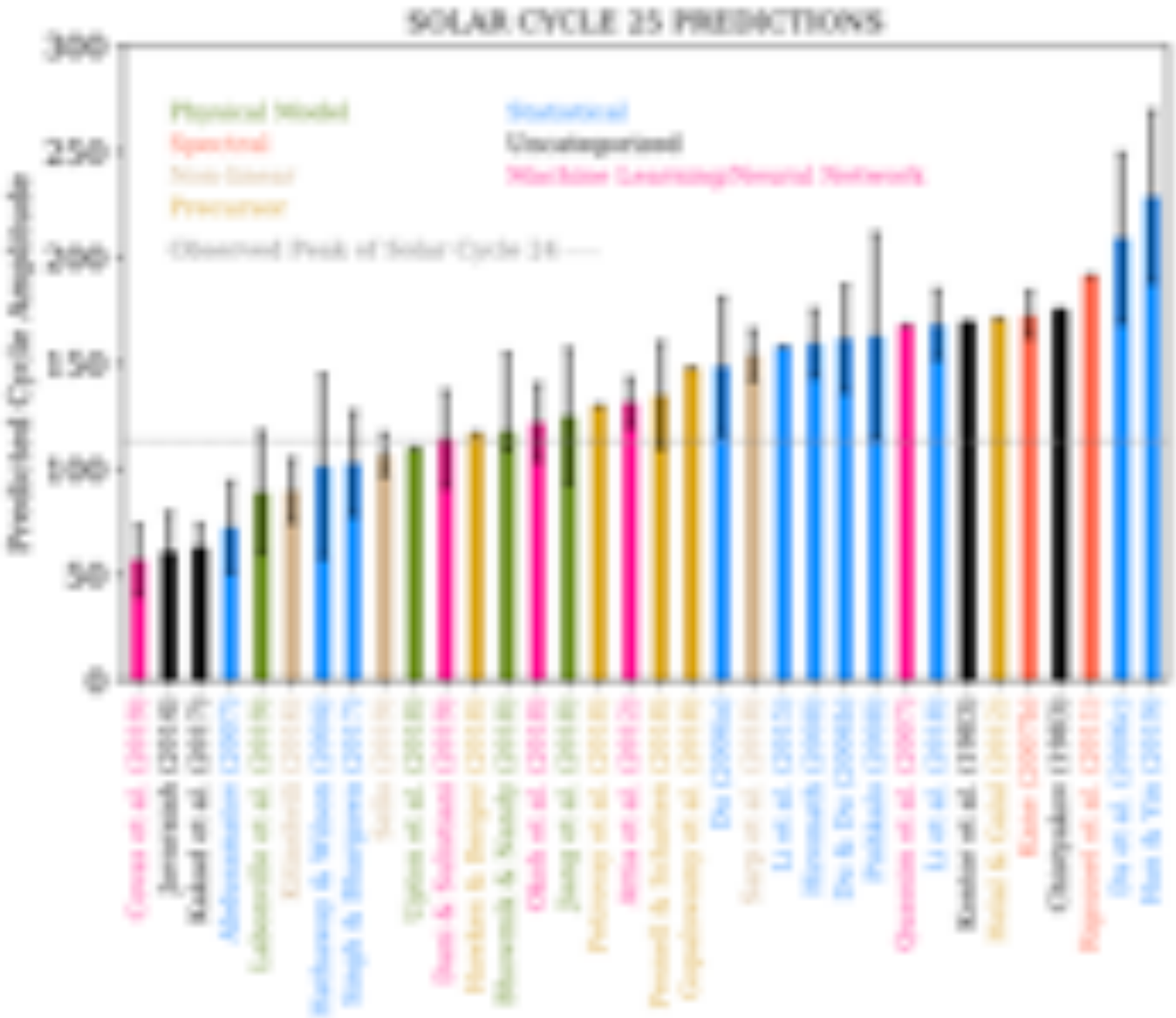

Figure 3. Predictions of solar cycle 25 by different groups based on diverse methodologies (indicated in the plot and represented through distinct colour bars). The height of the bars indicates the predicted peak strength (scaled to conform to the new, revised sunspot time series). The mean ($\pm$ 1σ) of all cycle 25 predictions is 135.88 $\pm$ 39.27 (SSN). The dashed line denotes the observed peak of solar cycle 24 (113.3 SSN in the revised scale) for comparison. Details of the utilized methodologies can be found in the references cited below the corresponding predictions; these are available in the bibliography.

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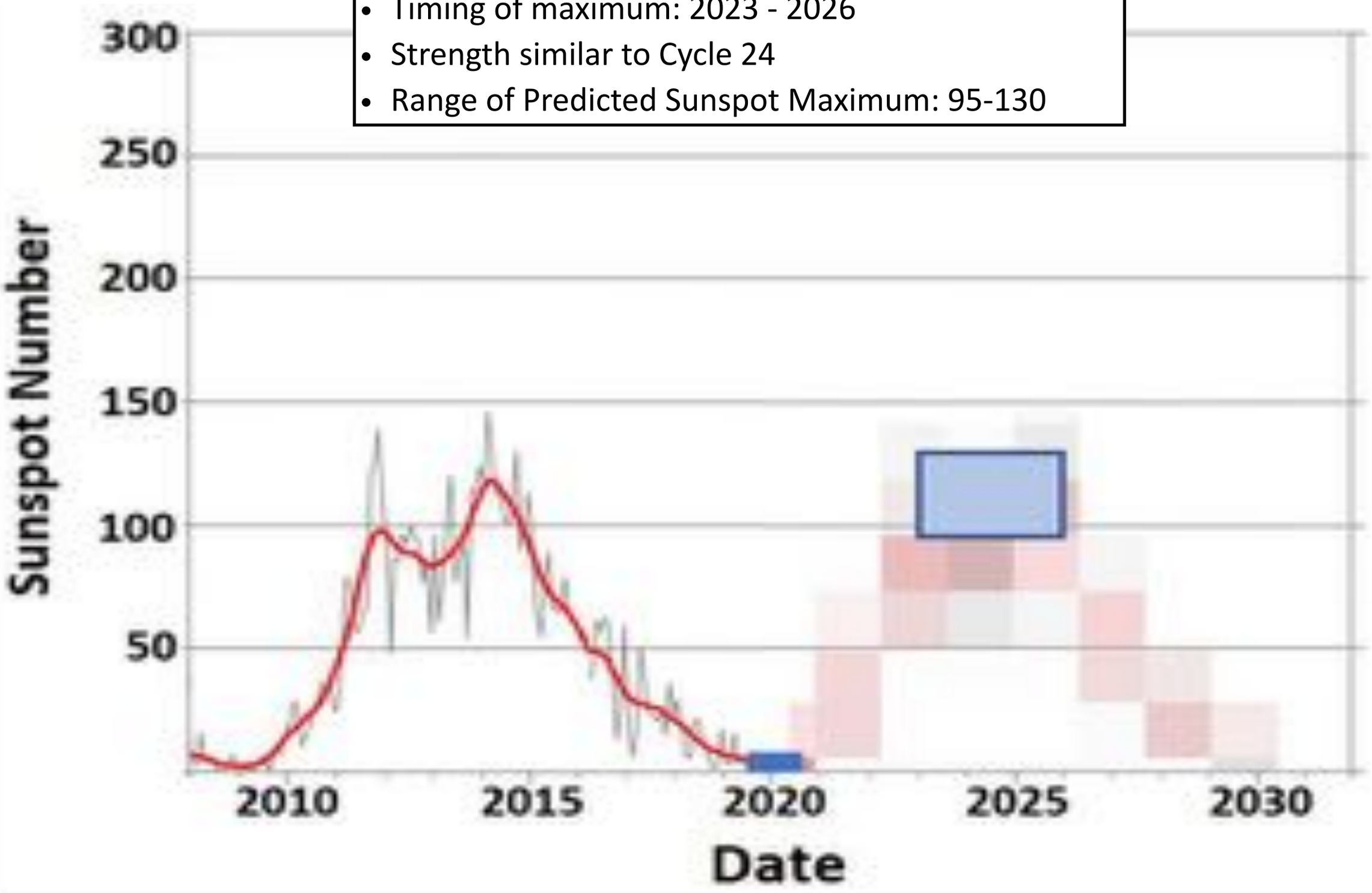
The “Consensus” Forecast 2020

- Timing of minimum: 2019.5 - 2020.75
- Timing of maximum: 2023 - 2026
- Strength similar to Cycle 24
- Range of Predicted Sunspot Maximum: 95-130



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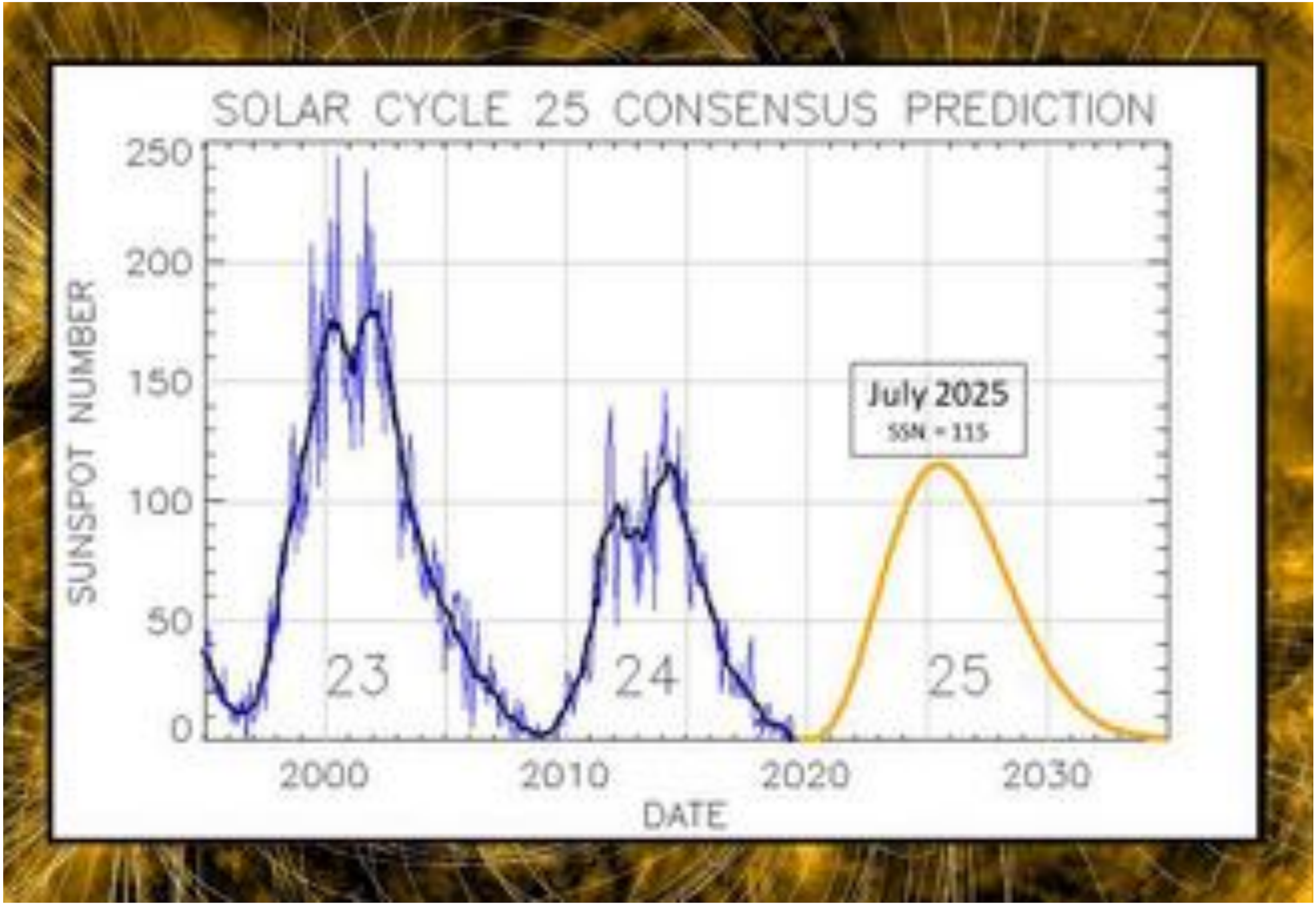
The “Consensus” Forecast 2020



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We’re caught up……

….or are we?

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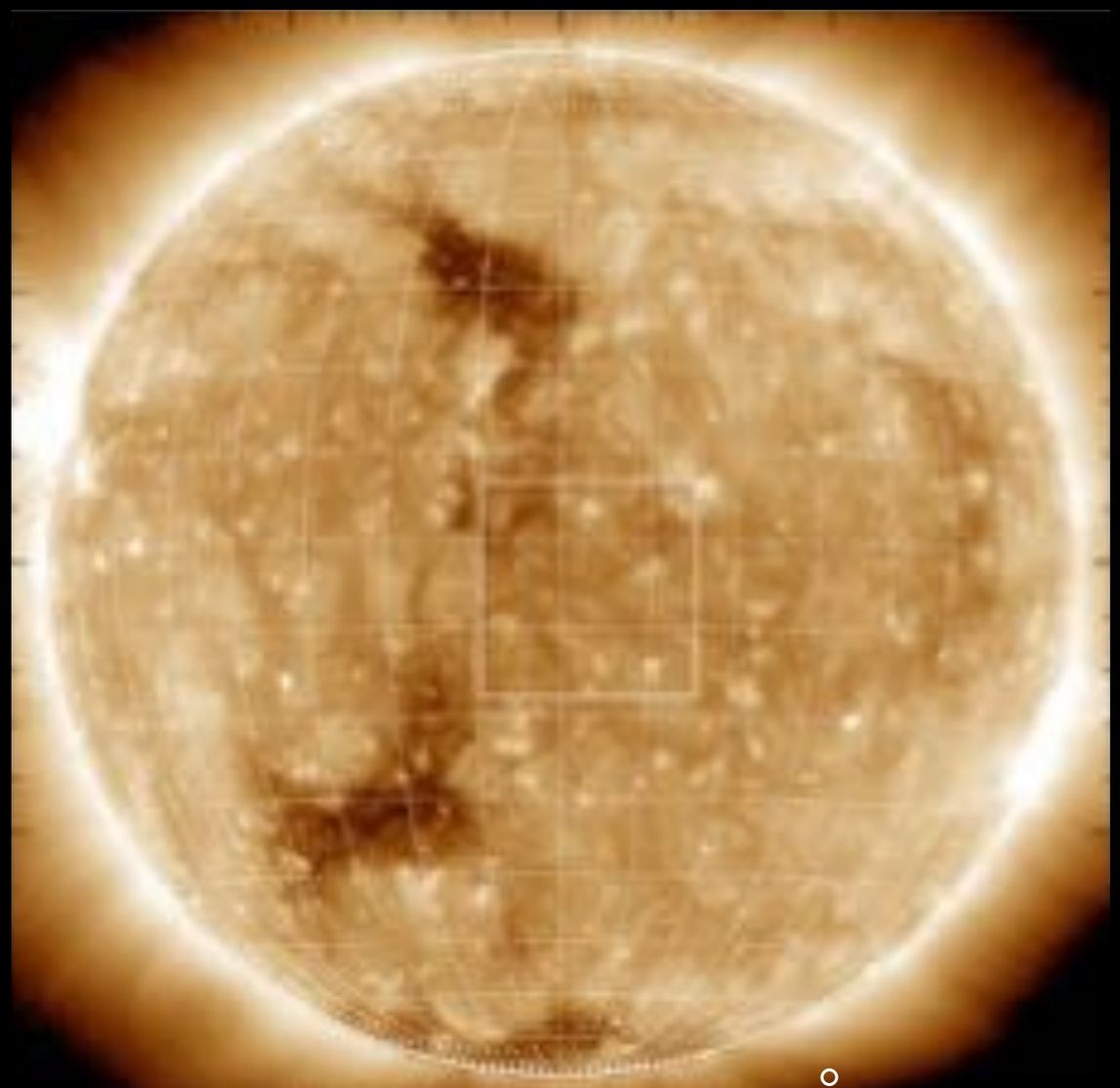
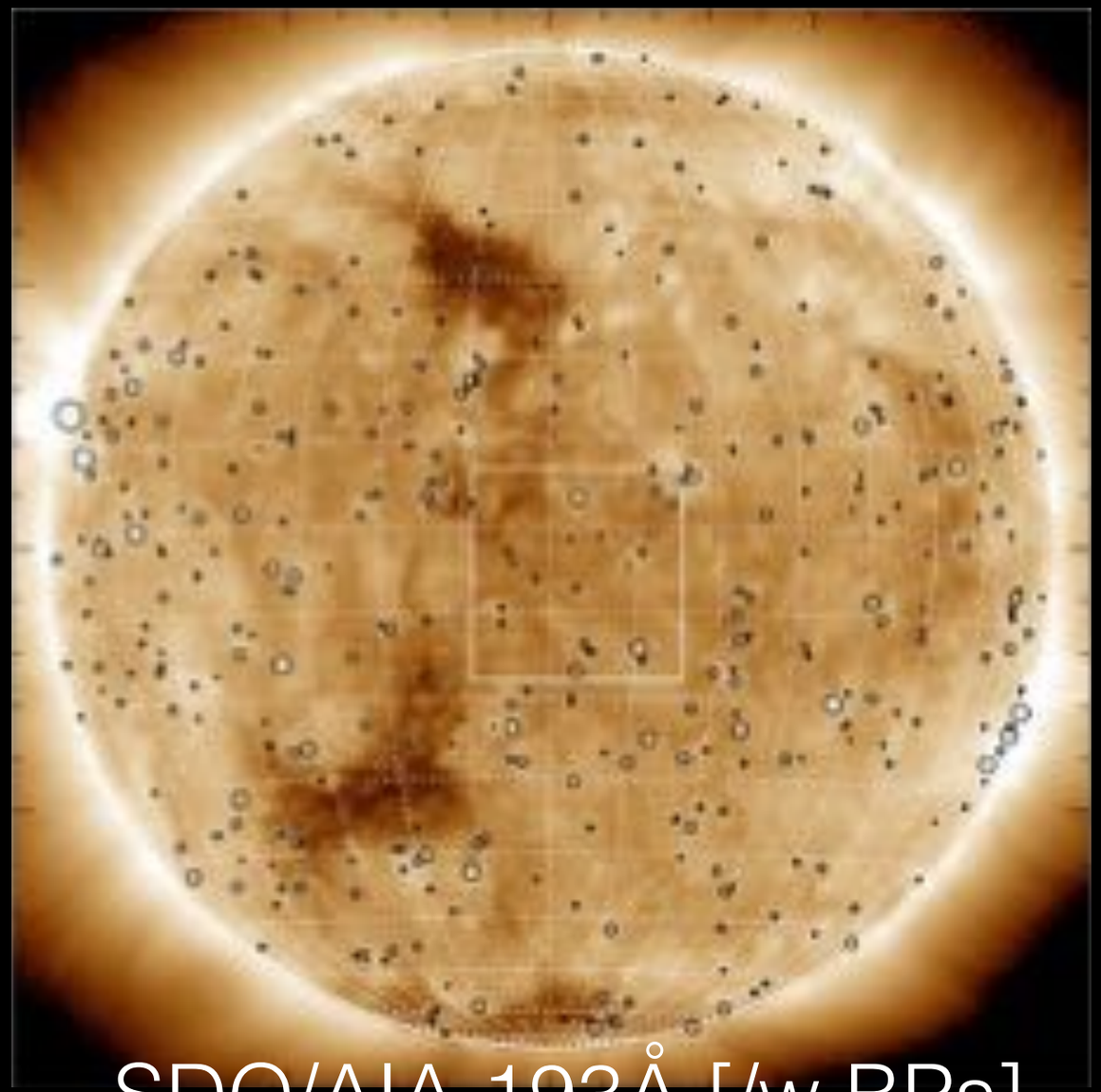
Brightpoints Everywhere

Brightpoints: ubiquitous, concentrated, distributed, long-lived, bright patches of coronal emission.

[McIntosh & Gurman (2005), Sol Phys, 228, 285]



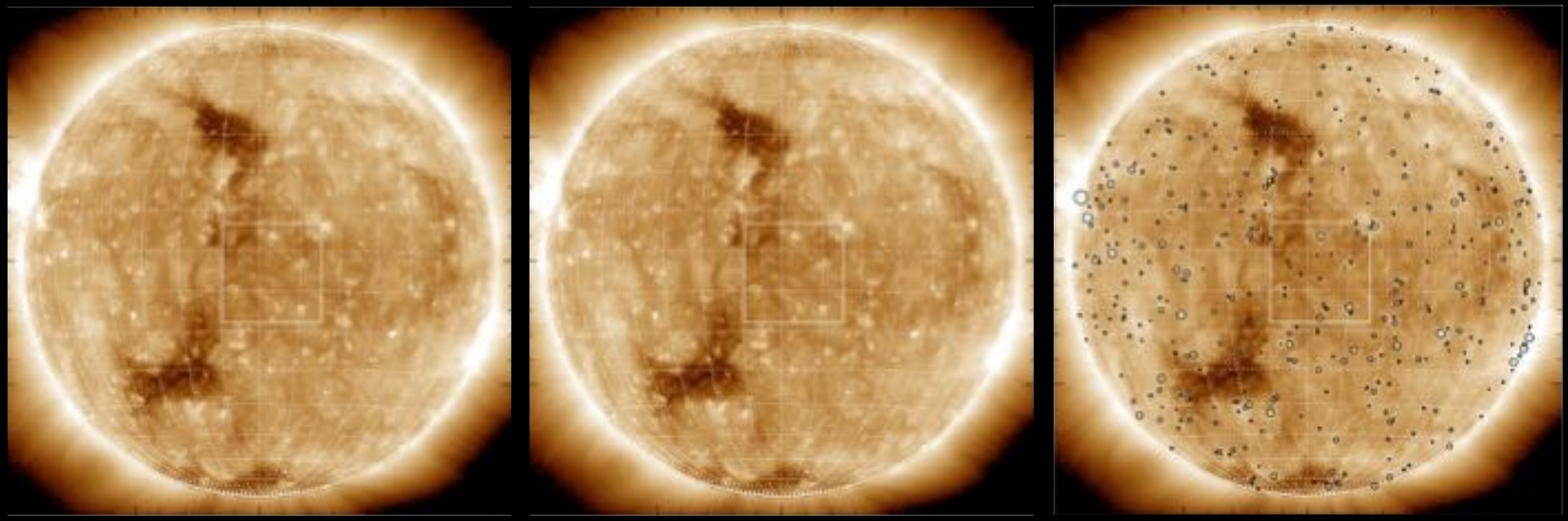
SDO/AIA 193Å



SDO/AIA 193Å [/w BPs]

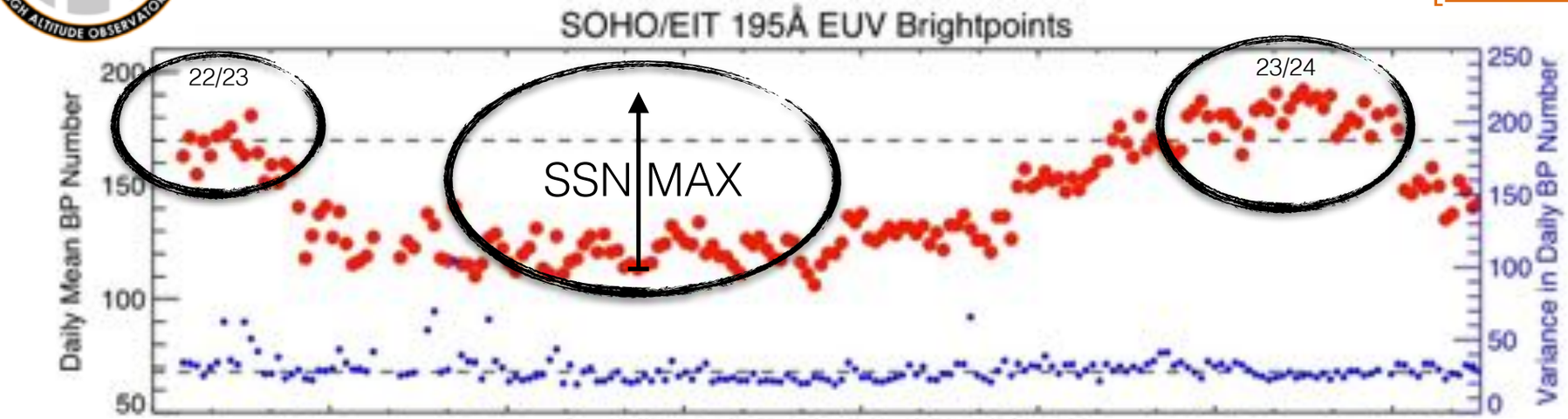
Brightpoints Everywhere

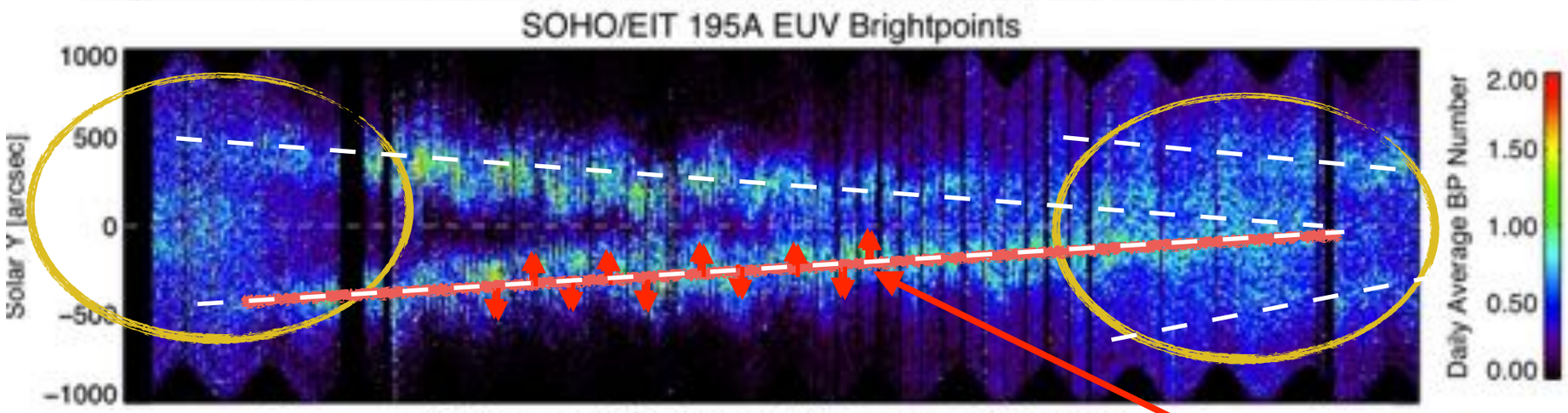
Brightpoints: ubiquitous, concentrated, distributed, long-lived, bright patches of coronal emission.

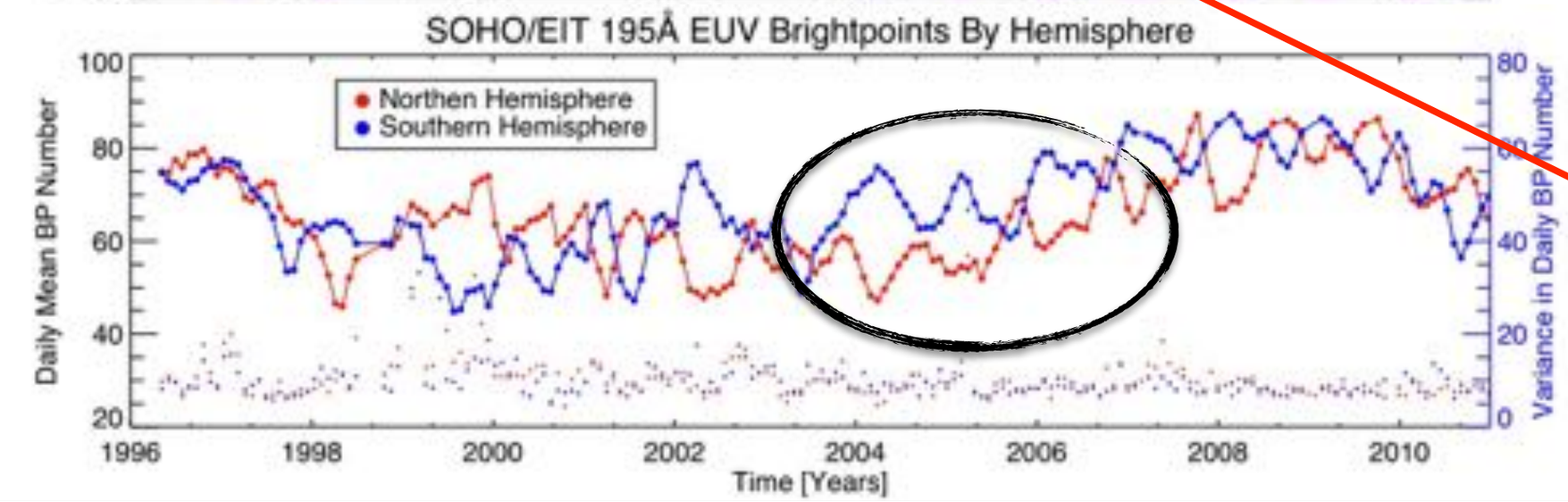


BP Temporal/Spatial Variability

[McIntosh et al. (2013), ApJ, 765, 146]







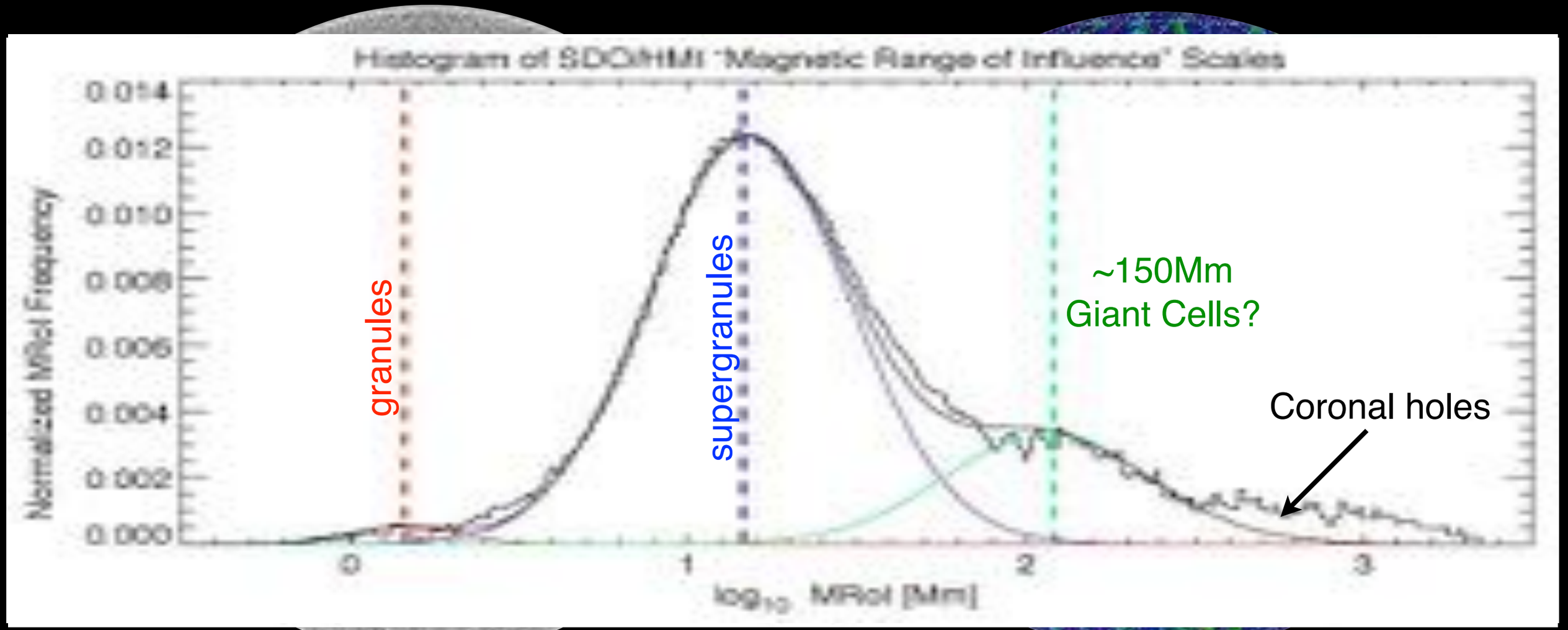
Features

- ★ Anti-correlated with SSN [2010 > 1996]
- ★ Linear "Migrating" Bands
- ★ Significant Overlap in Latitude/Time > 4 years visible
- ★ Quasi-Periodic Variability in Number
- ★ Meandering?

Decomposing Surface Magnetism

Brightpoints: ubiquitous, concentrated, distributed, long-lived, bright patches of coronal emission.

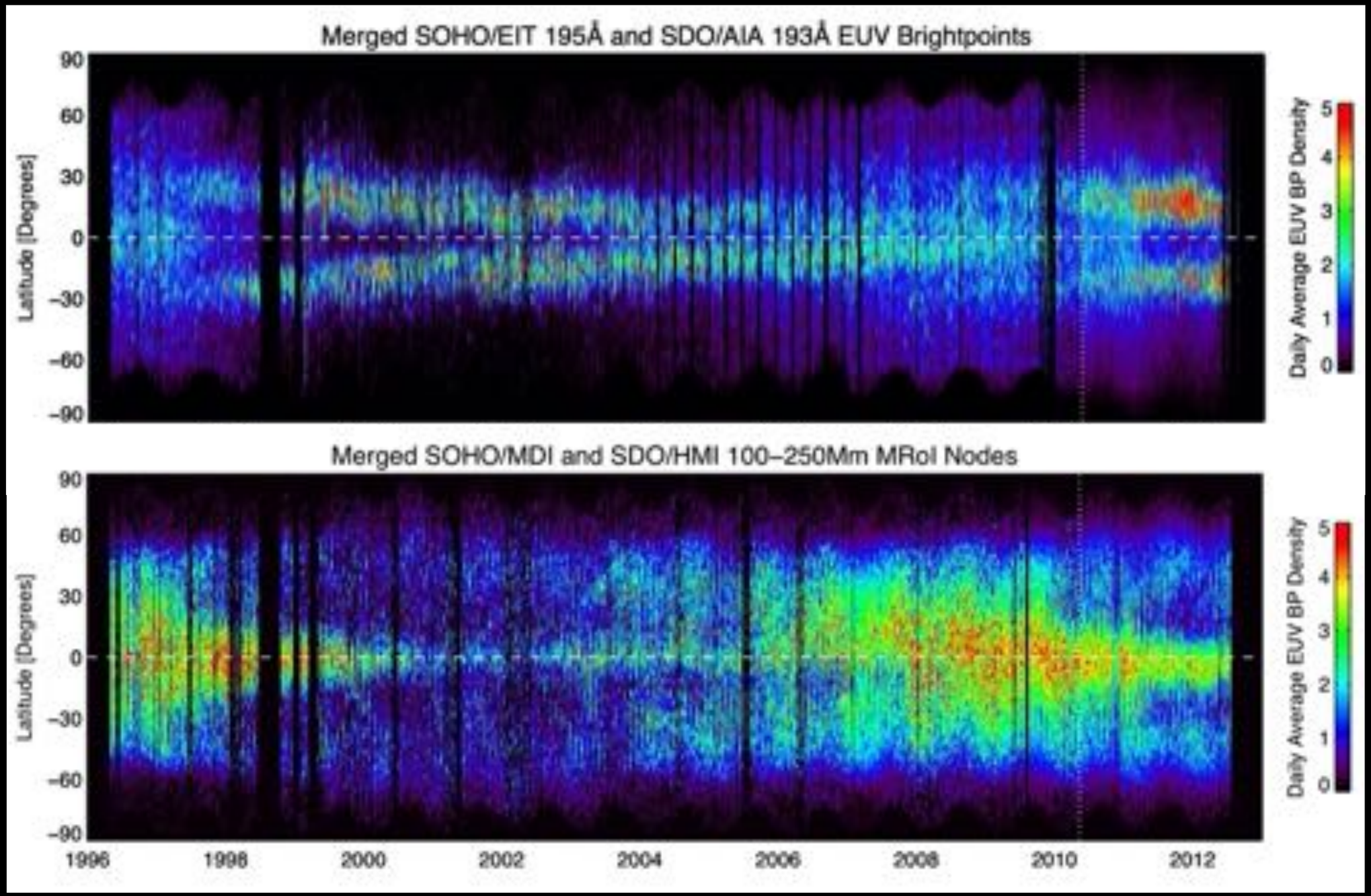
BPs appear to have a preferred location and formation (spatial) scale. Possibly that of the “giant” convective scale.



[McIntosh et al. 2014, ApJ, 784, 32]

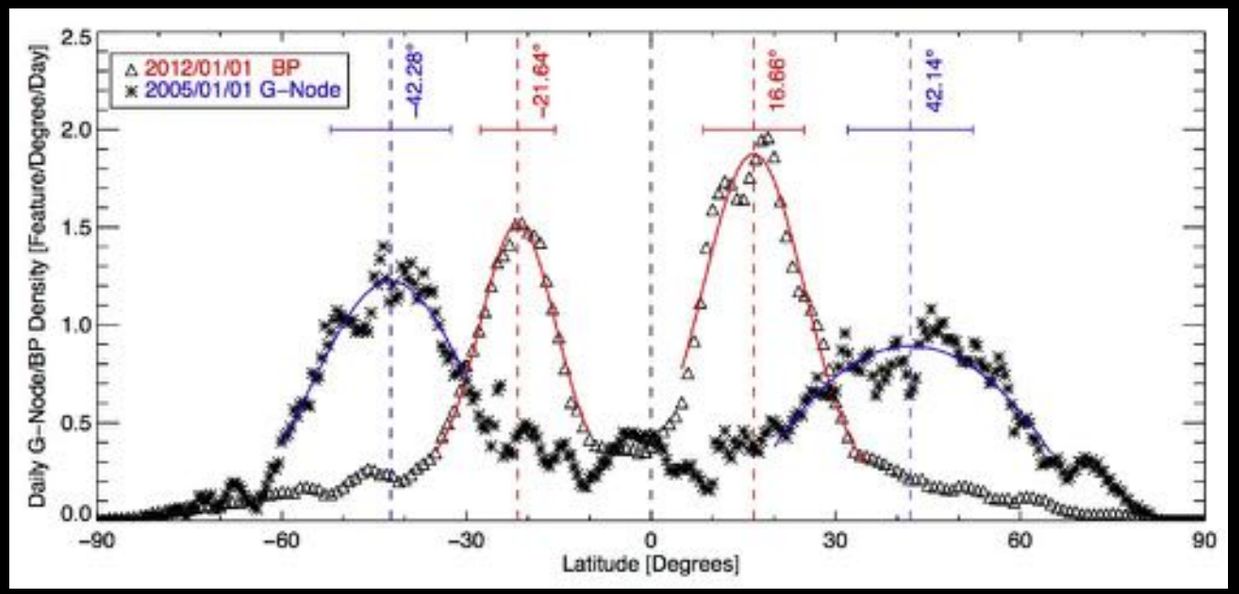
Tracking Scales in Latitude & Time

Extending the bands….to the “extended solar cycle”



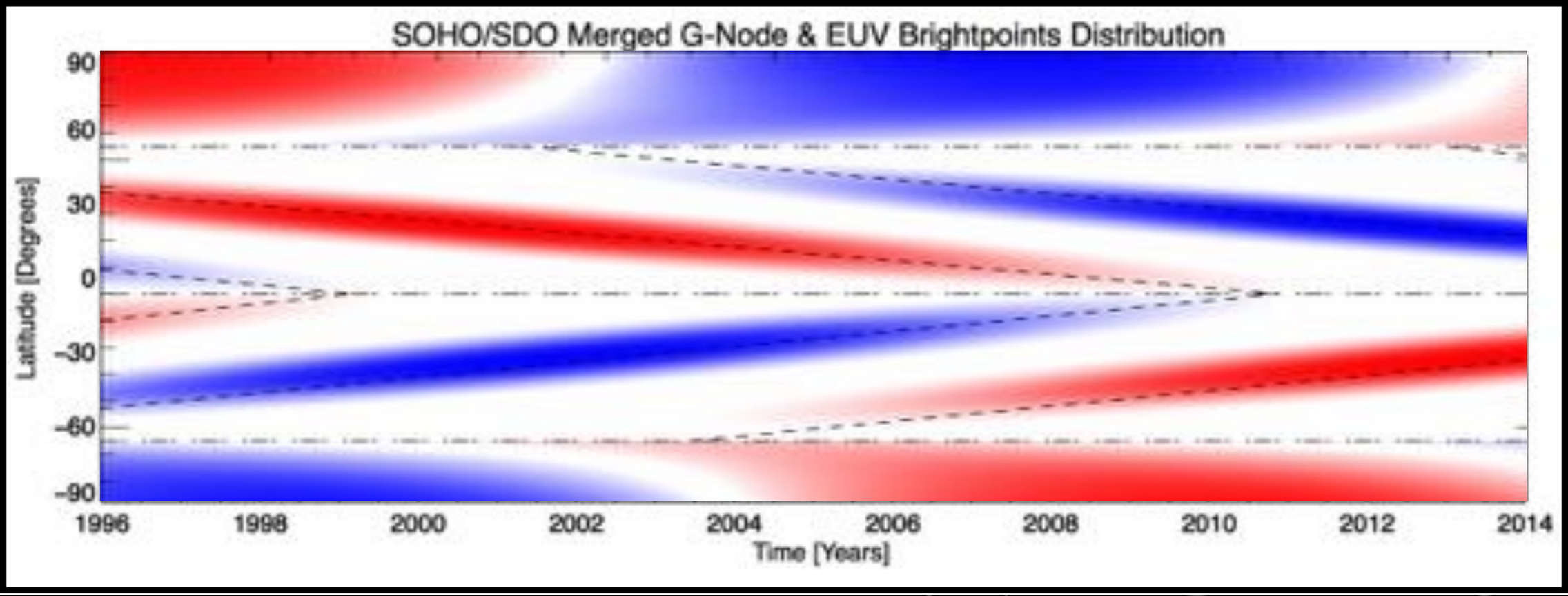
[McIntosh et al. 2014, ApJ, 792, 12]

Activity Band Tracking



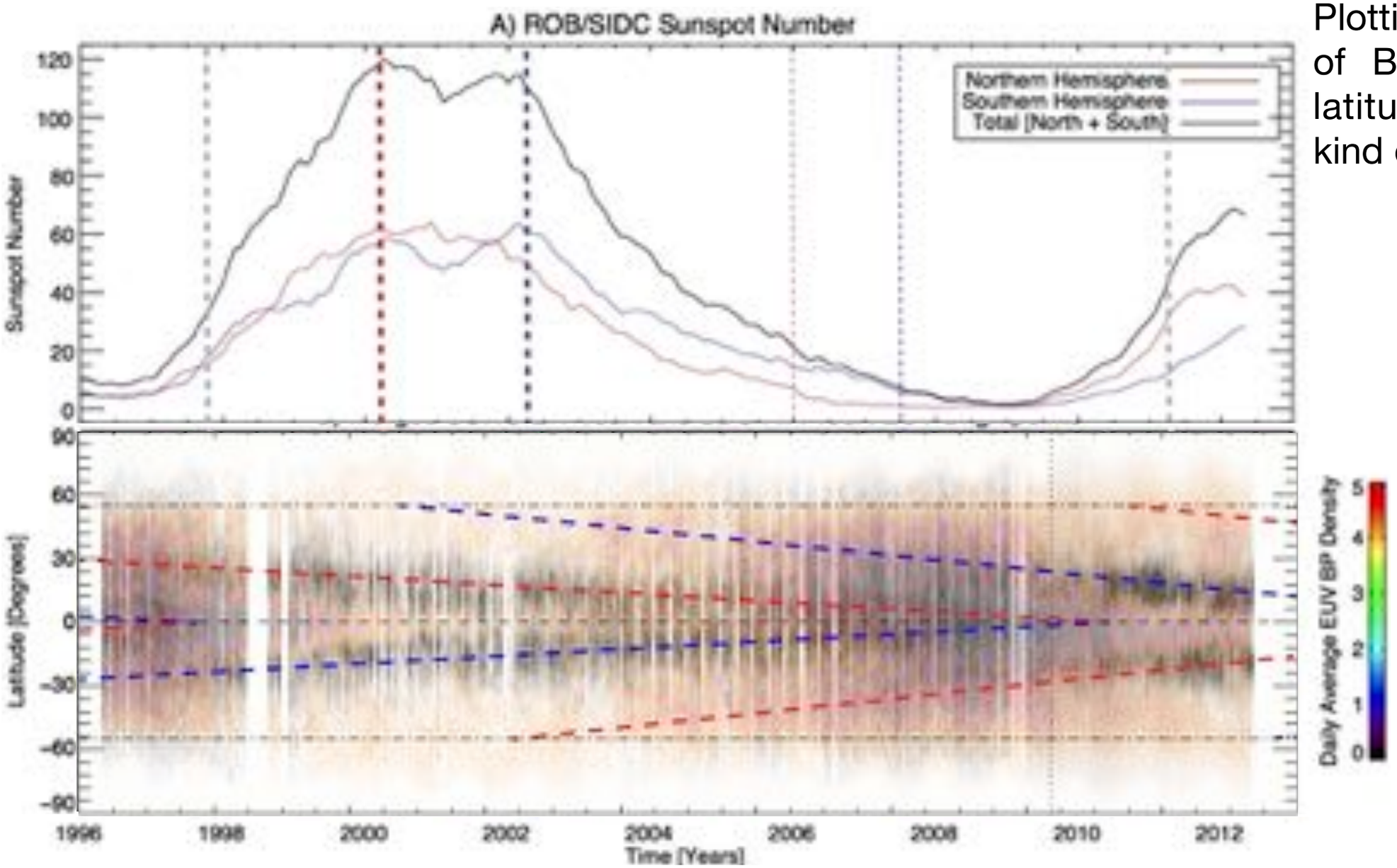
[McIntosh et al. 2014, ApJ, 792, 12]

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.



“Bright Points” [1996 - 2014]

A project to identify and track coronal brightpoints (BPs) started in 2002 while I was an external fellow for the European Space Agency at NASA/GSFC and an instrument scientist on the Solar and Heliospheric Observatory.



Plotting the daily distribution of BPs density with solar latitude yields a different kind of butterfly diagram.

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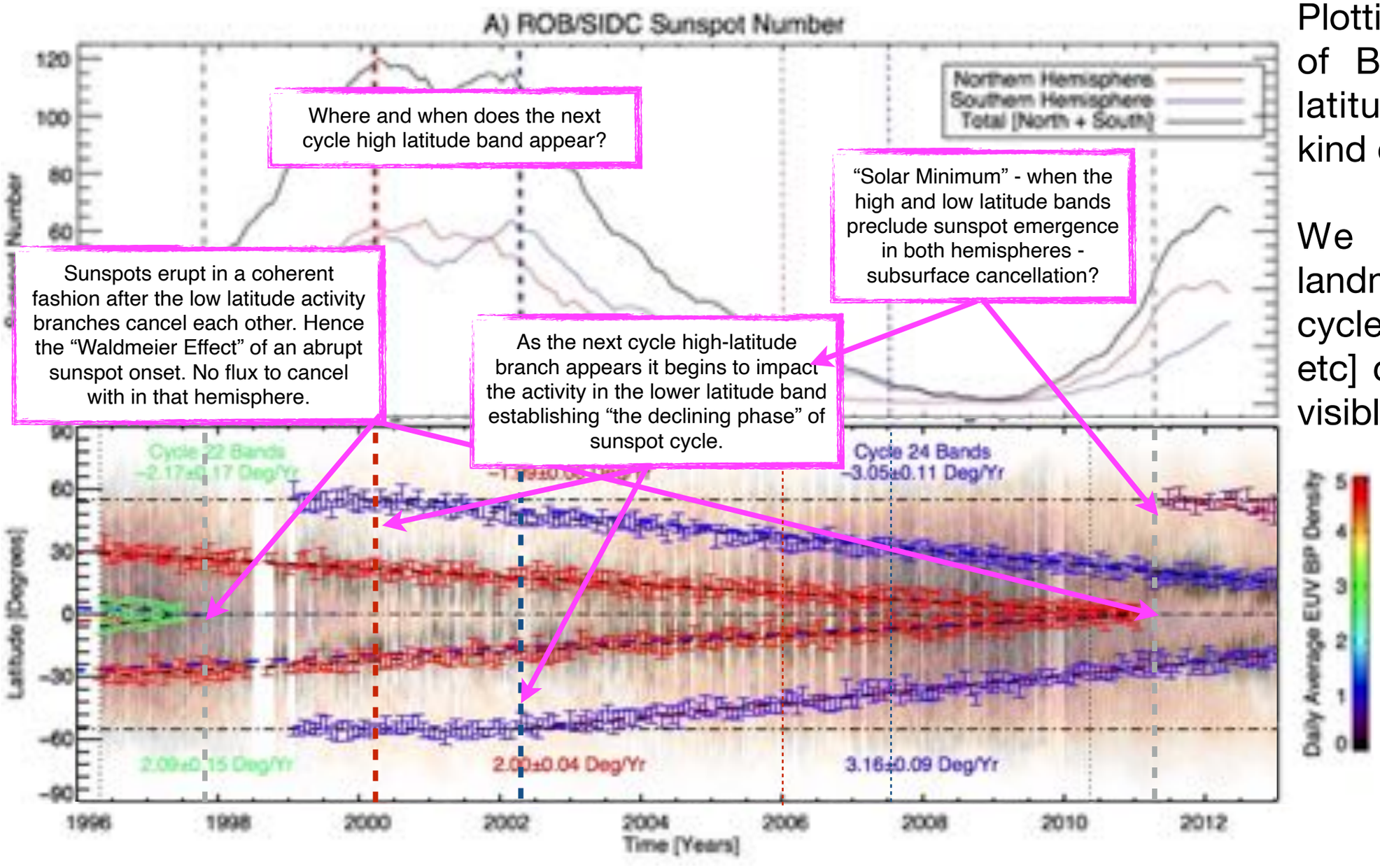

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We identified that the landmarks of the sunspot cycle [minimum, maximum, etc] coincided with patterns visible in the BP variation.

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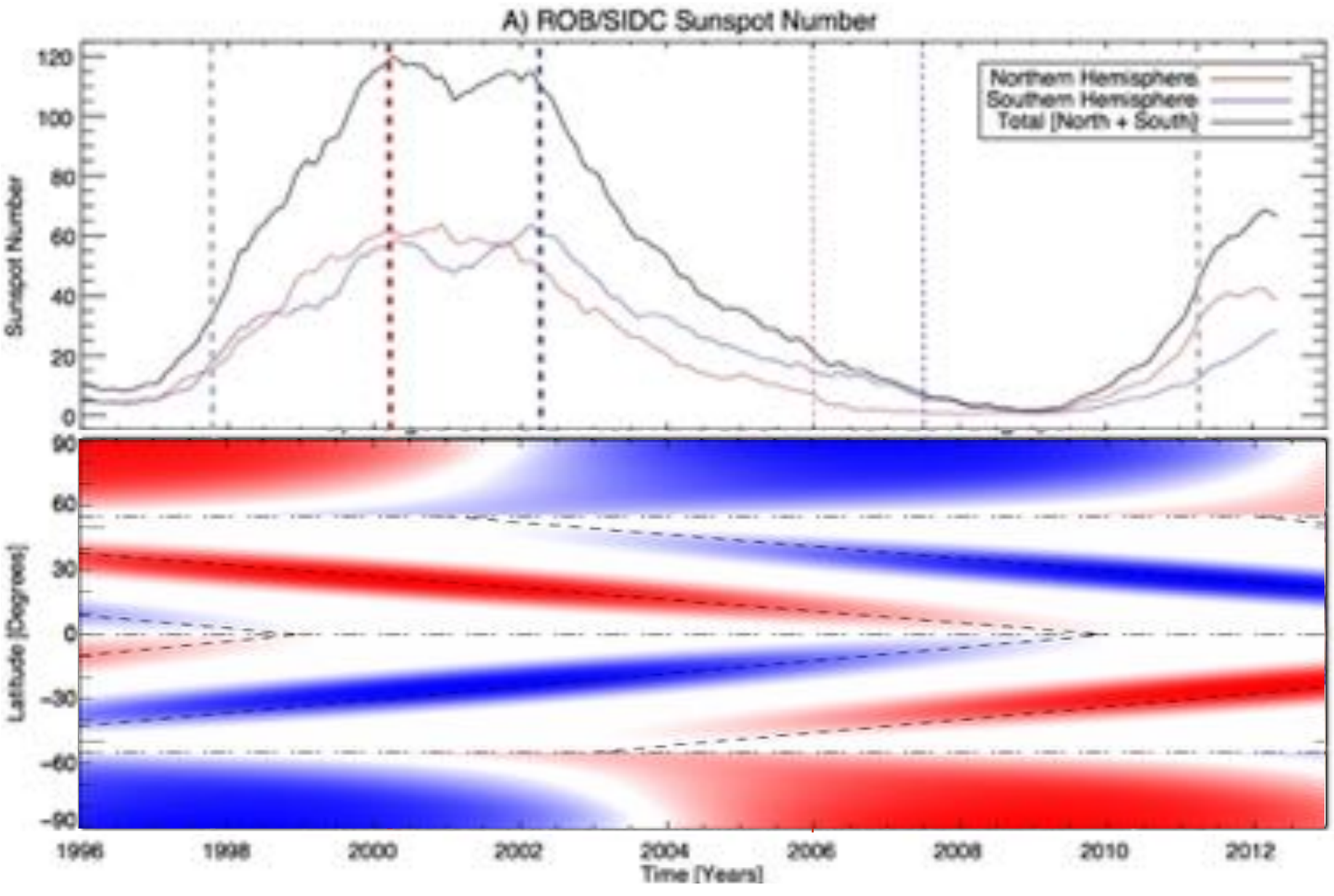


Plotting the daily distribution of BPs density with solar latitude yields a different kind of butterfly diagram.

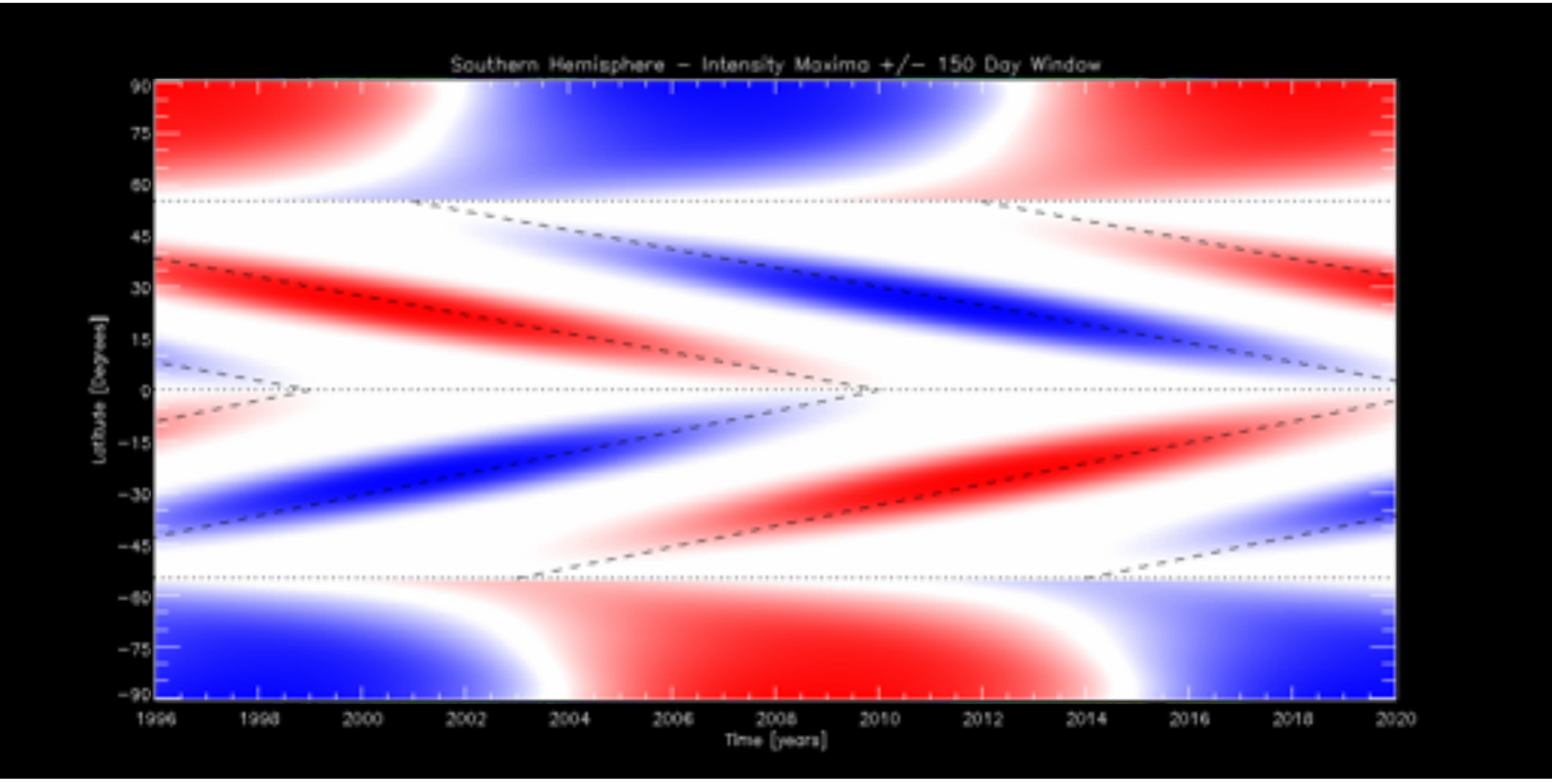
We identified that the landmarks of the sunspot cycle [minimum, maximum, etc] coincided with patterns visible in the BP variation.

Interaction of the magnetic cycle bands - the Sun’s 22-year magnetic polarity cycle - dictates sunspot behavior!

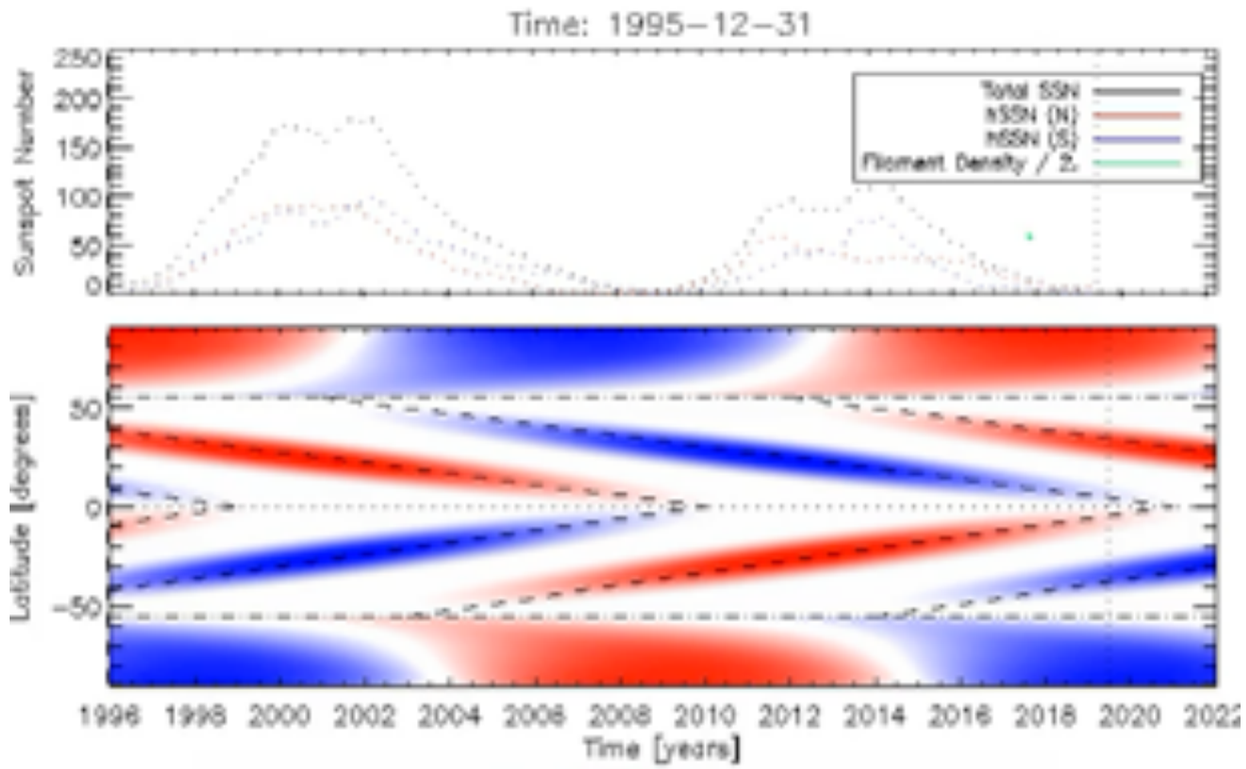
Based on 18-years of data: the sunspot cycle appears to be the result of an “interference pattern” - if correct there’s predictive skill.

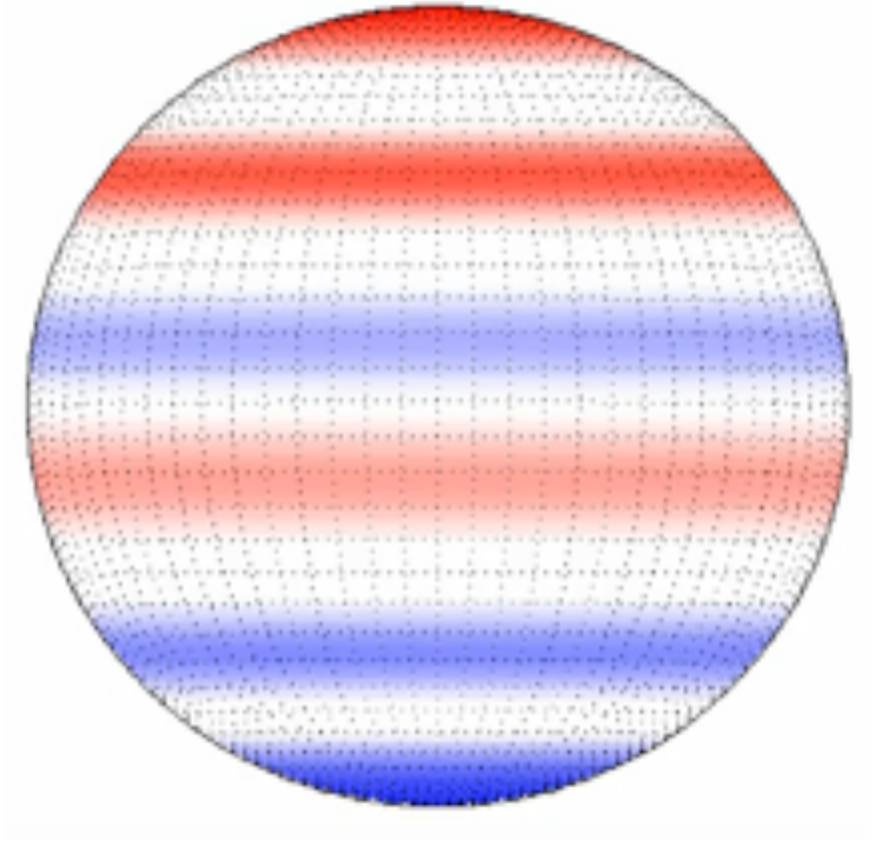
Coronal Scan [1996 - Present]

SoHO [1996 - Present] STEREO “A” [2007 - Present] STEREO “B” [2007 - 2014] SDO [2010 - Present]



Does that pattern look familiar?





The "22-year" Hale (magnetic polarity) Cycle of the Sun is traceable.

The bands of the Hale Cycle have a definitive end, the "terminator", at the equator.

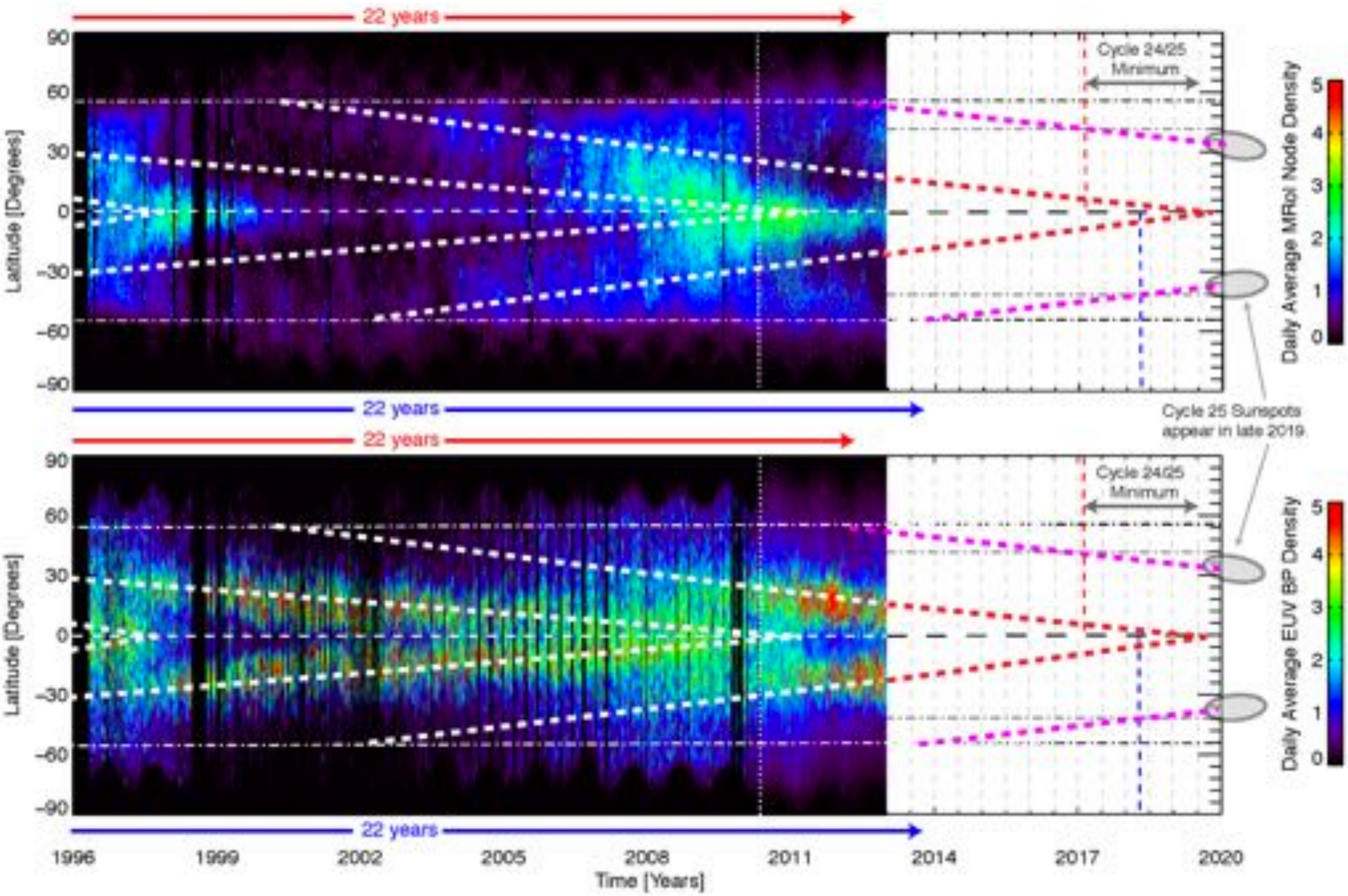
This terminator rapidly triggers growth and emergence of magnetism at mid (30-35°) and high (~55°) latitudes - within one solar rotation. Over the course of one/two rotations, at many longitudes.

M2014 Hypothesis: the bands of the Hale Cycle contrive to modulate the sunspot pattern and amplitude.

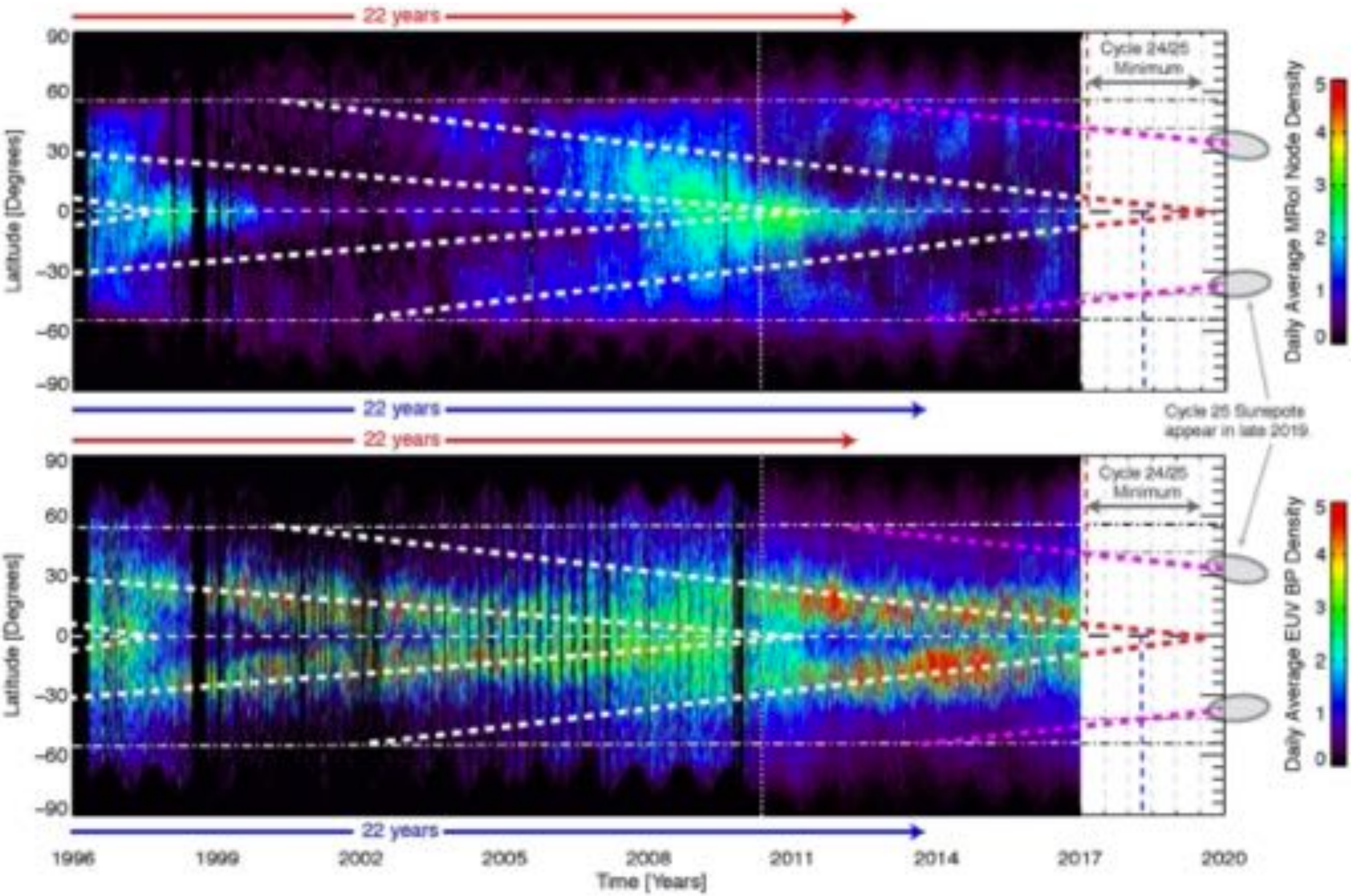
Terminator separation is one measure of the interplay of the Hale Cycle bands.

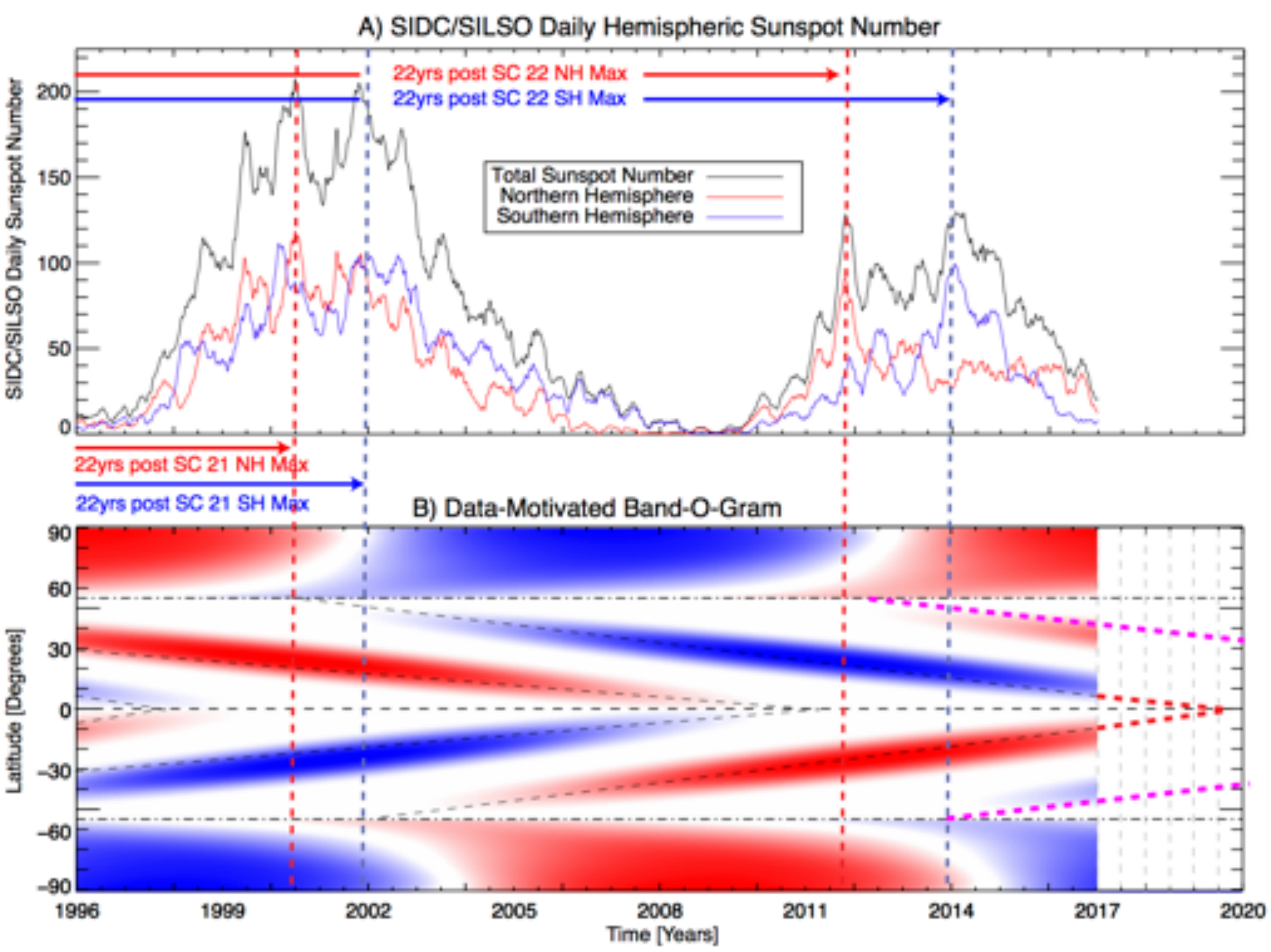
Concept: Long terminator separations yield small upcoming cycles and vice versa.

“Bright Points” [FastForward] 2014



“Bright Points” [FastForward] 2017





Solar Minimum Now - Solar Cycle 25 is Present and Will be weak. Are we heading for an extended solar minimum, maybe a grand minimum?

So, now we're caught up……

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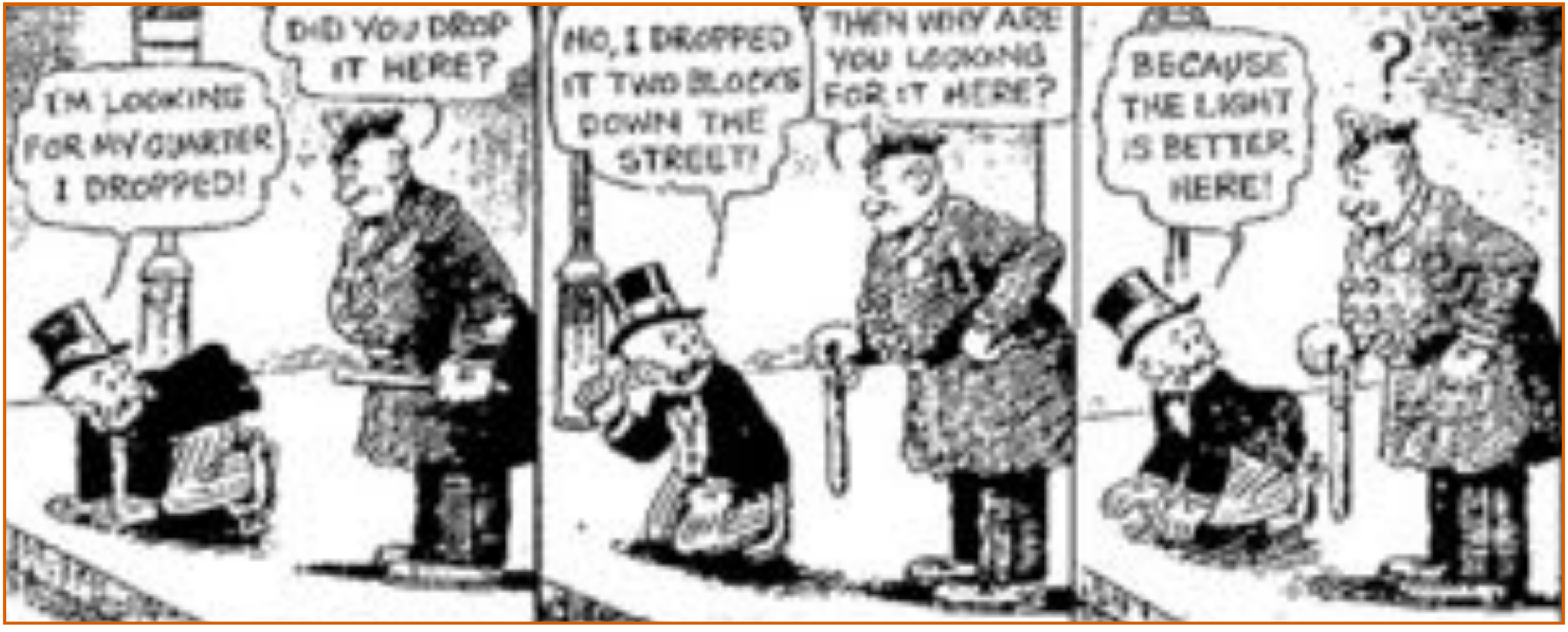
A critical part of the scientific method is making critical assessments of the agreement between hypothesis, model and experimental observation



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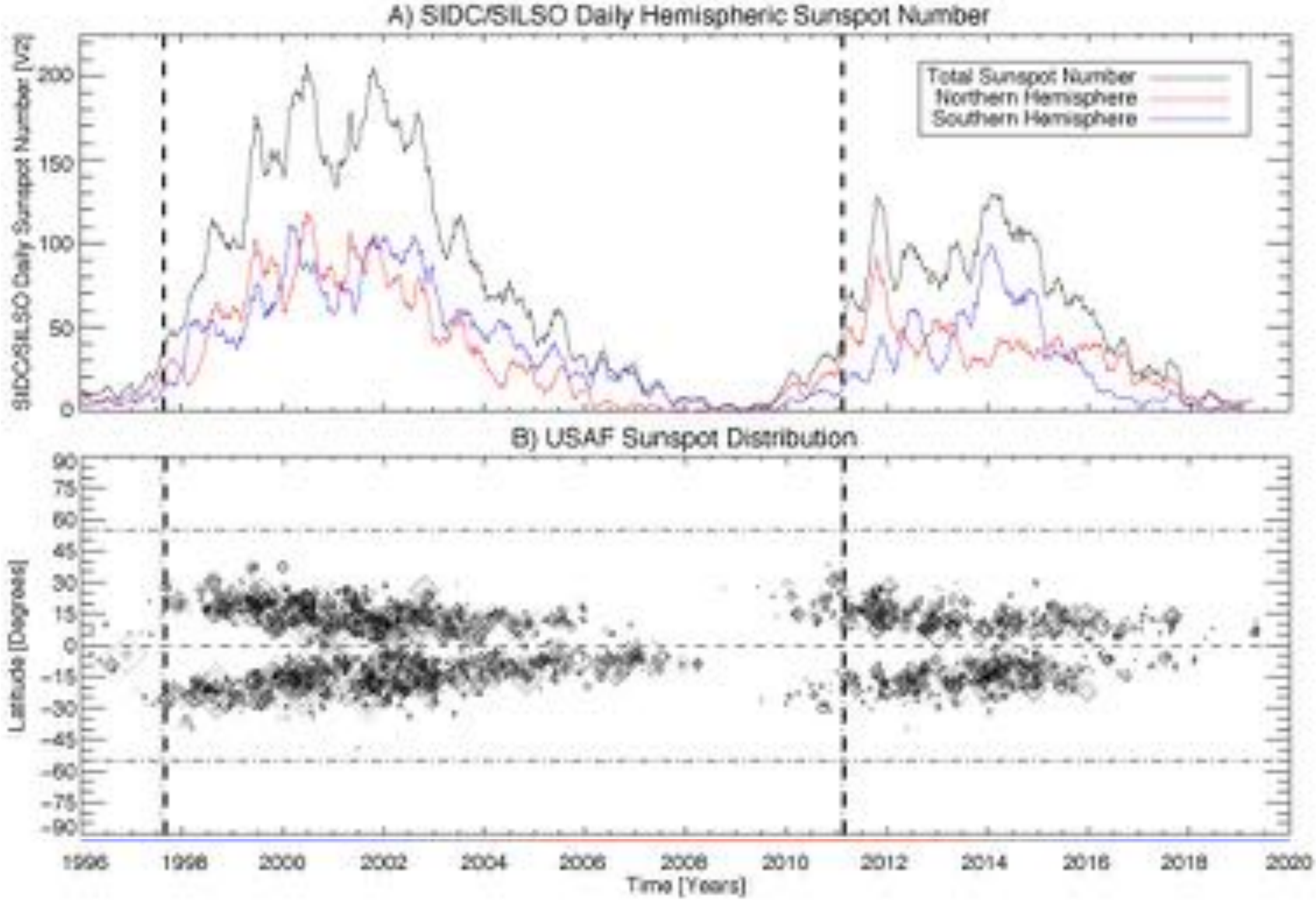

Agree: We are in sunspot/solar minimum?

How does minimum end?

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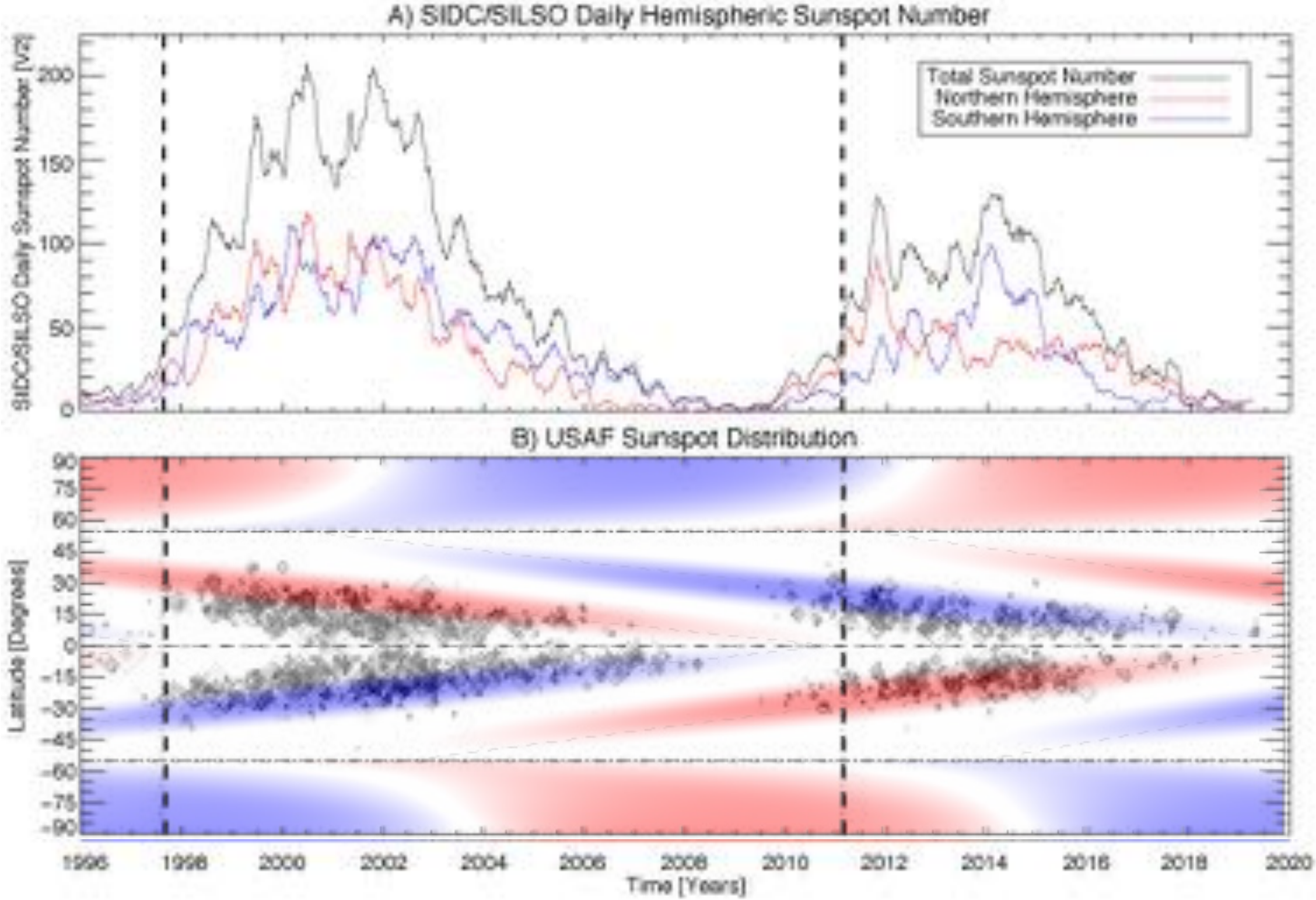

What is minimum?
How does minimum end?
Minimum ends when a Hale magnetic cycle ends!

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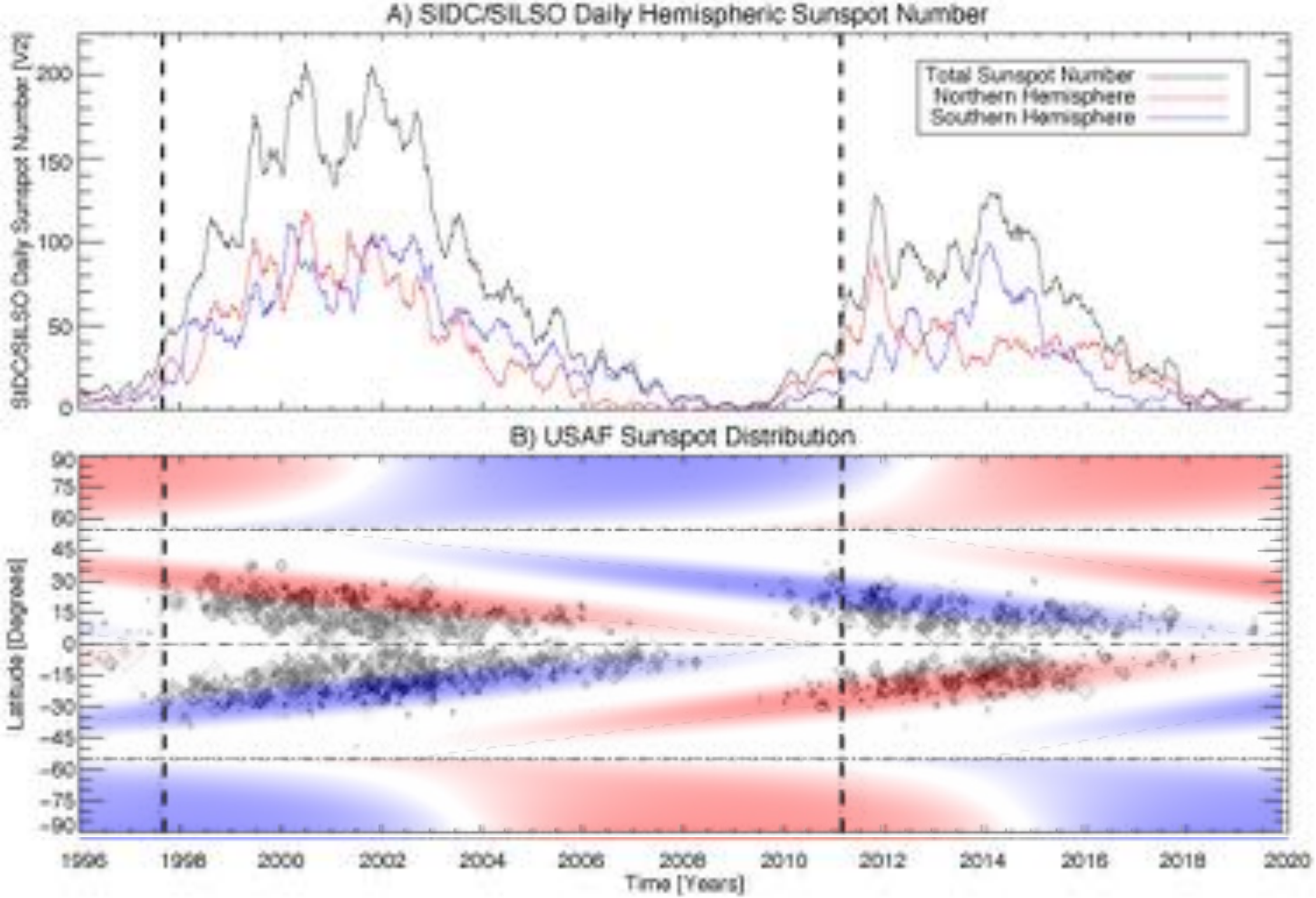

Minimum ends when a Hale magnetic cycle ends!

Interaction of Hale cycles shapes the sunspot cycle.

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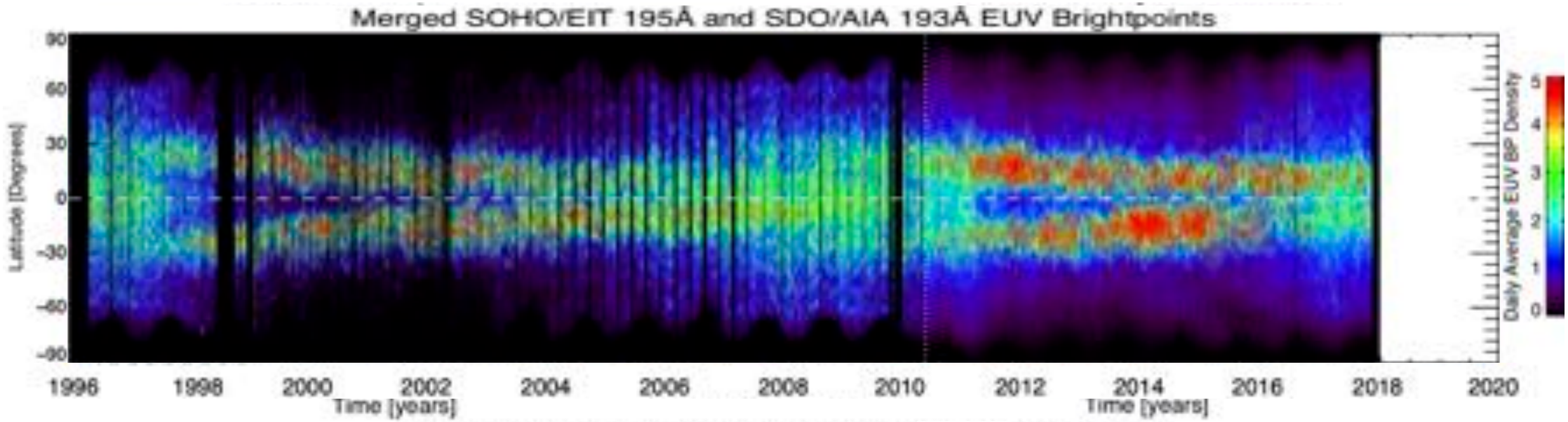

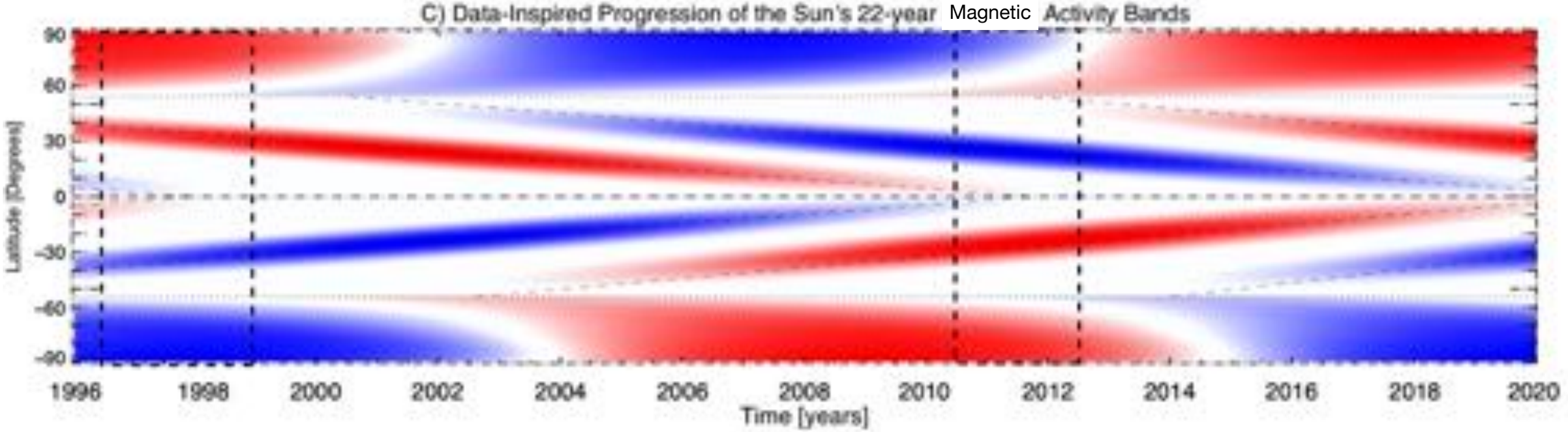

The magnetic environment of the Sun changes in a "heartbeat"

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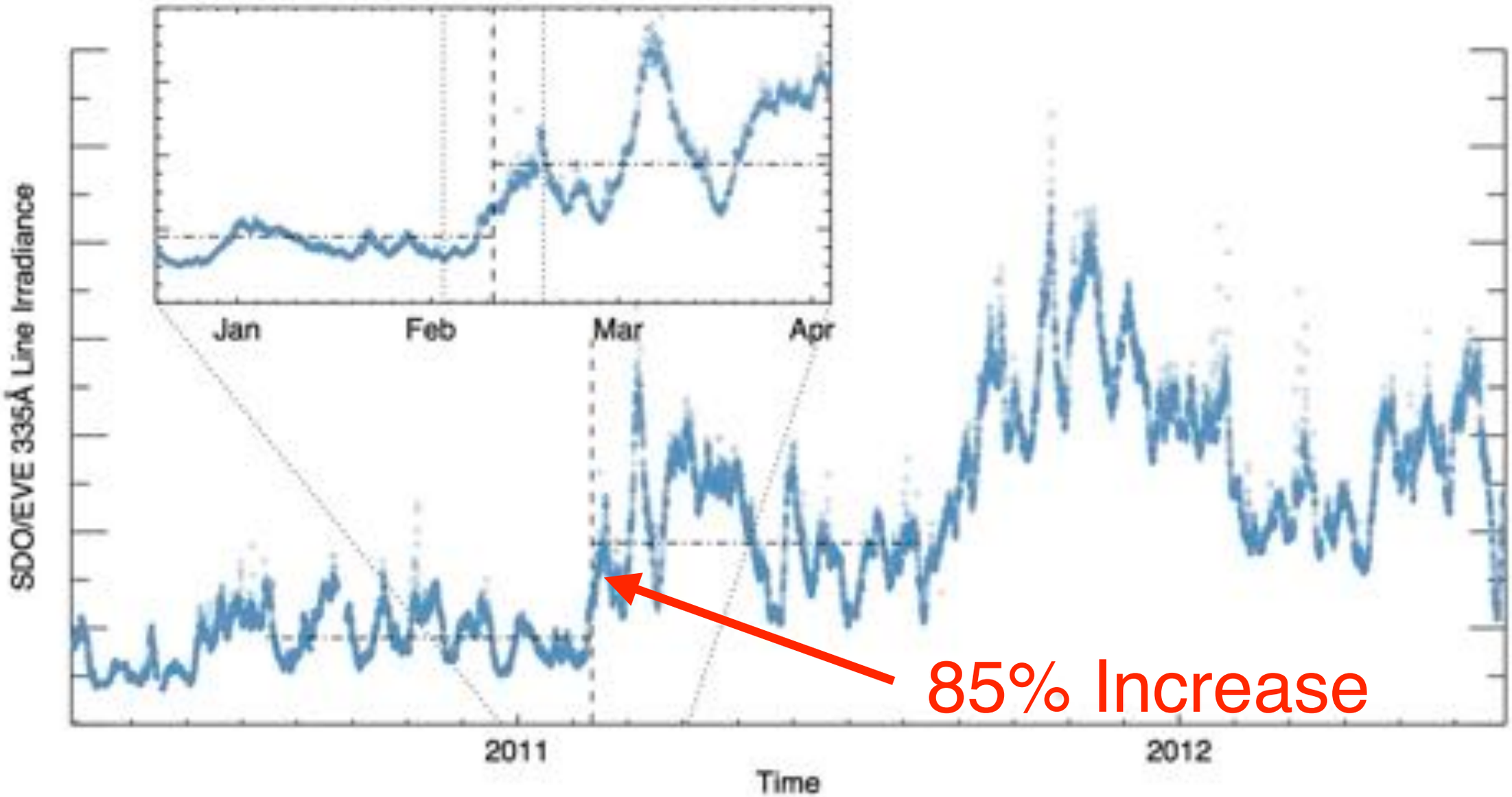

The radiative environment of the Sun changes in a “heartbeat”

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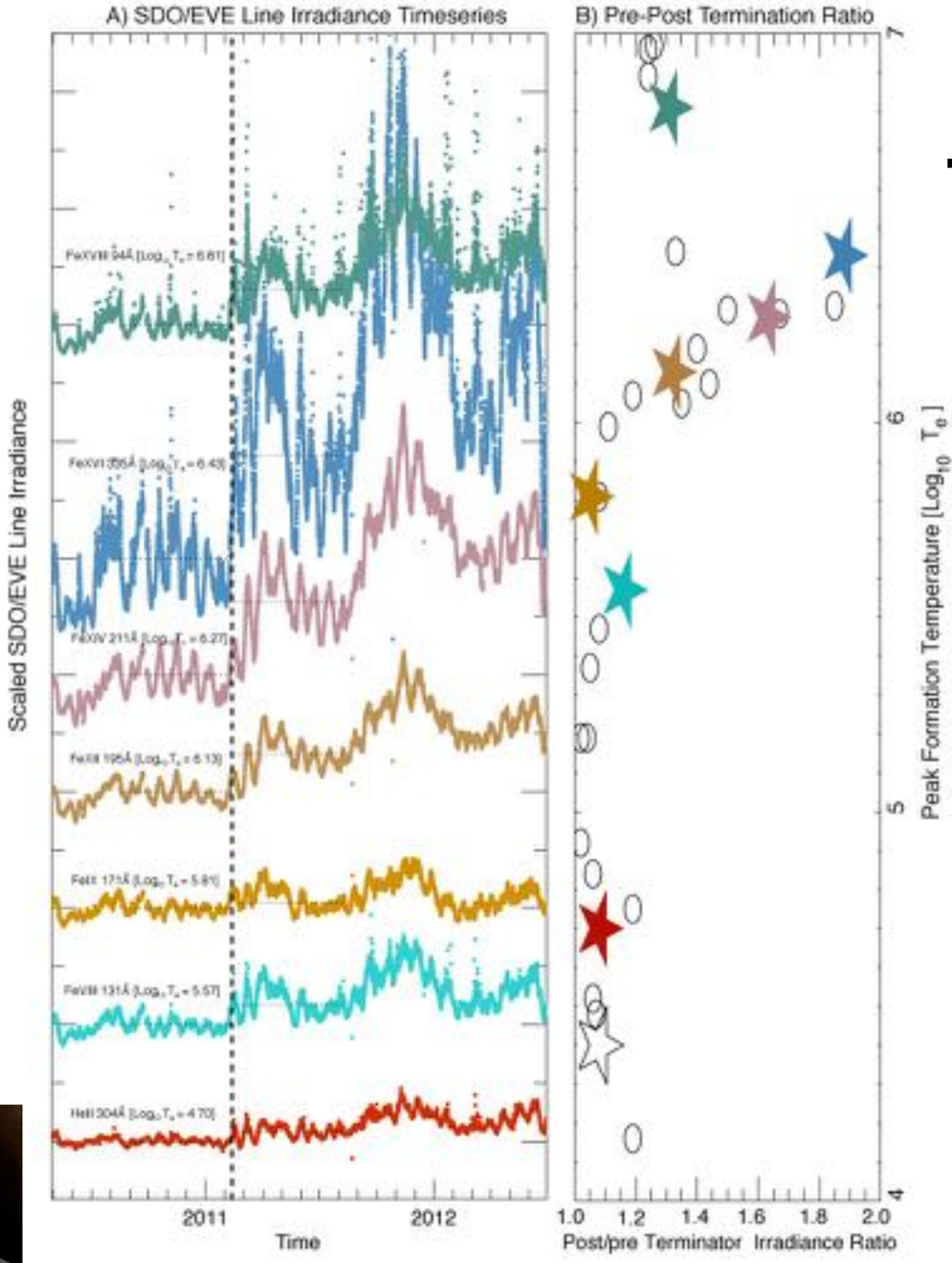

The radiative response to the end of a Hale cycle shows a strong temperature dependence.

The corona, in response to the magnetic environment beneath, undergoes a rapid metamorphosis.

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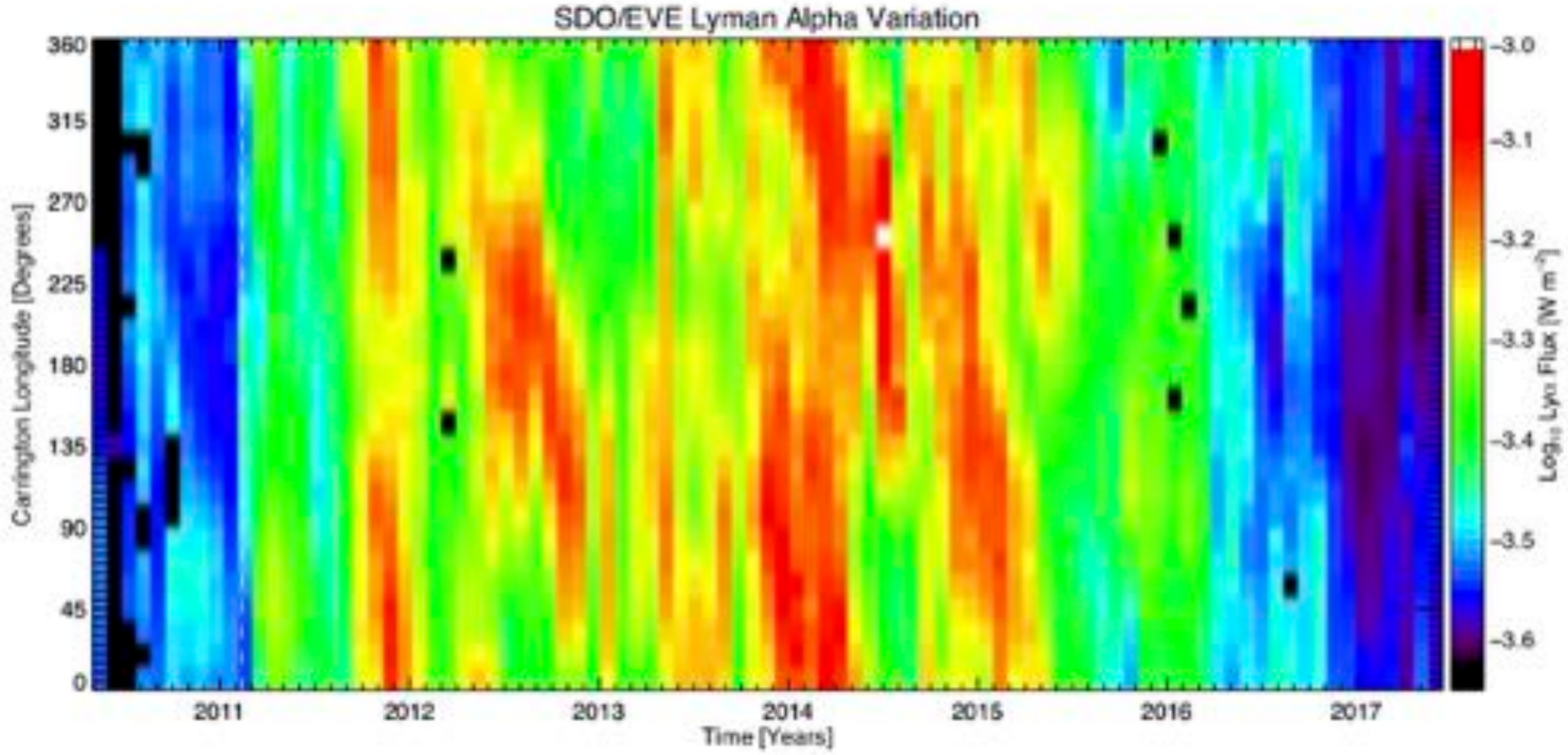
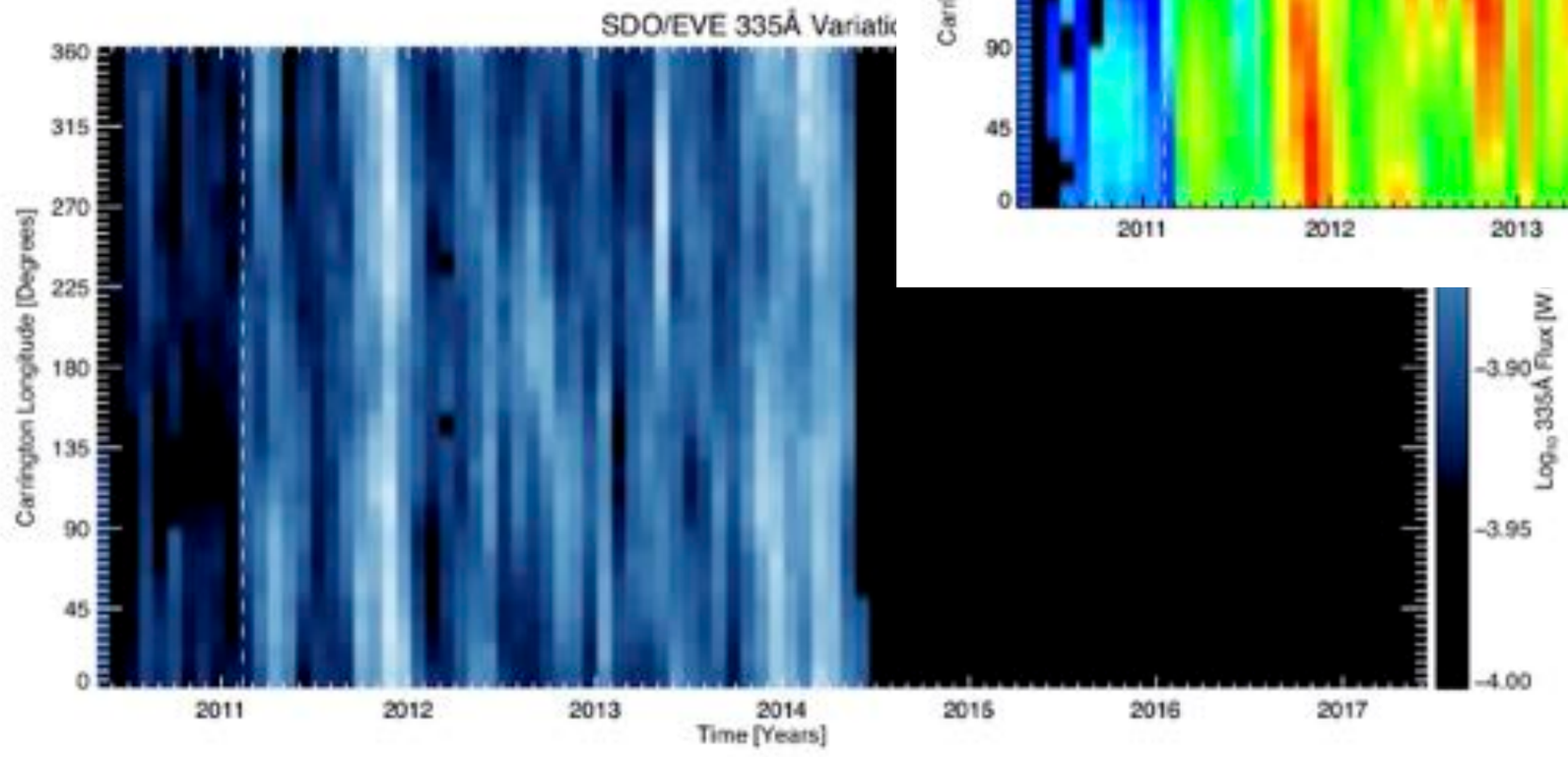
Rearranging the SDO/EVE data by a rotational period of 28 days to mimic longitudinal behavior, here is what Lyman Alpha and the Fe XIV 335Å look like. Can you spot Feb 11, 2011?





Almost immediately after Feb 11, 2011 there is a strong longitudinal "switch on" of activity.

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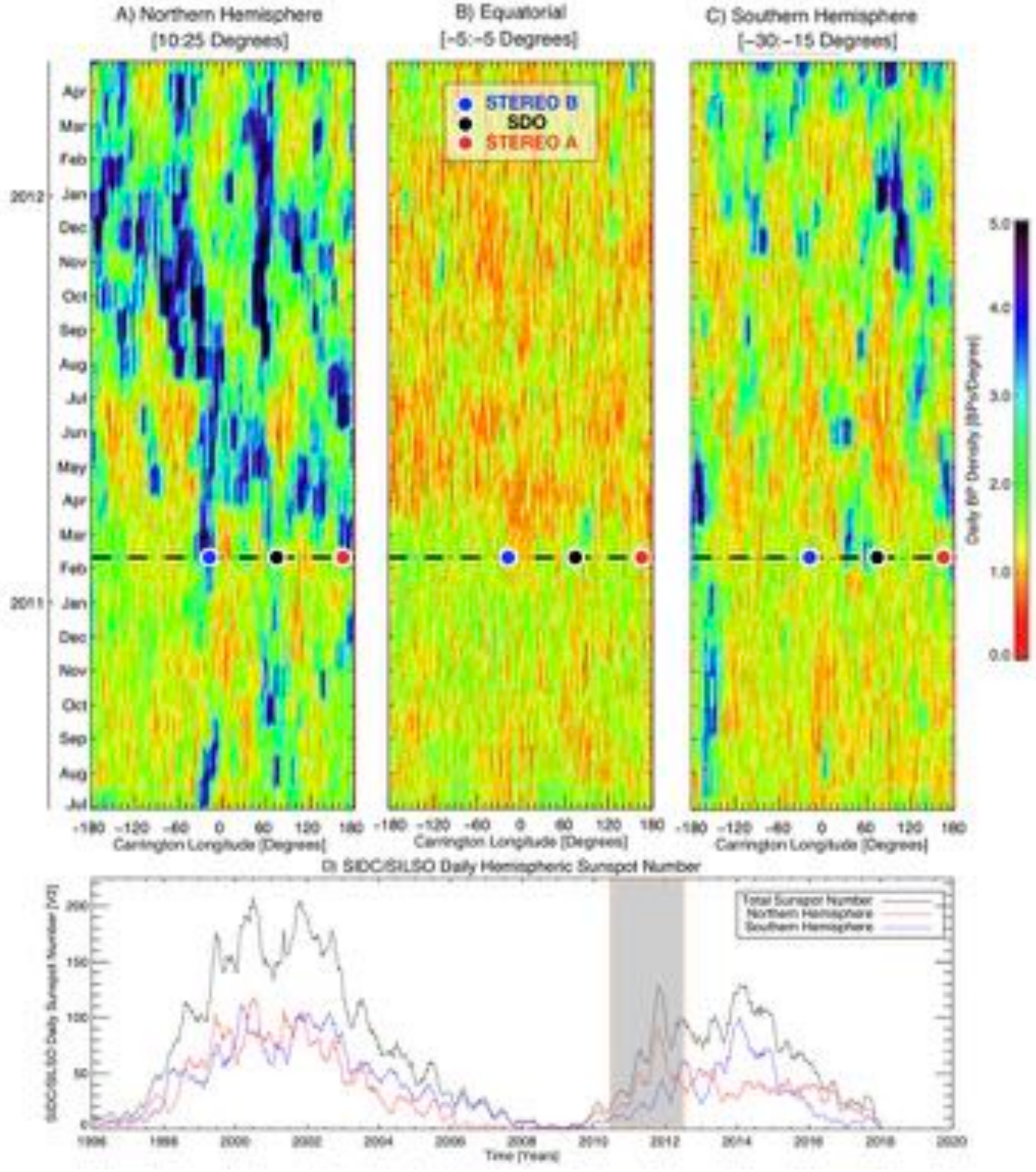

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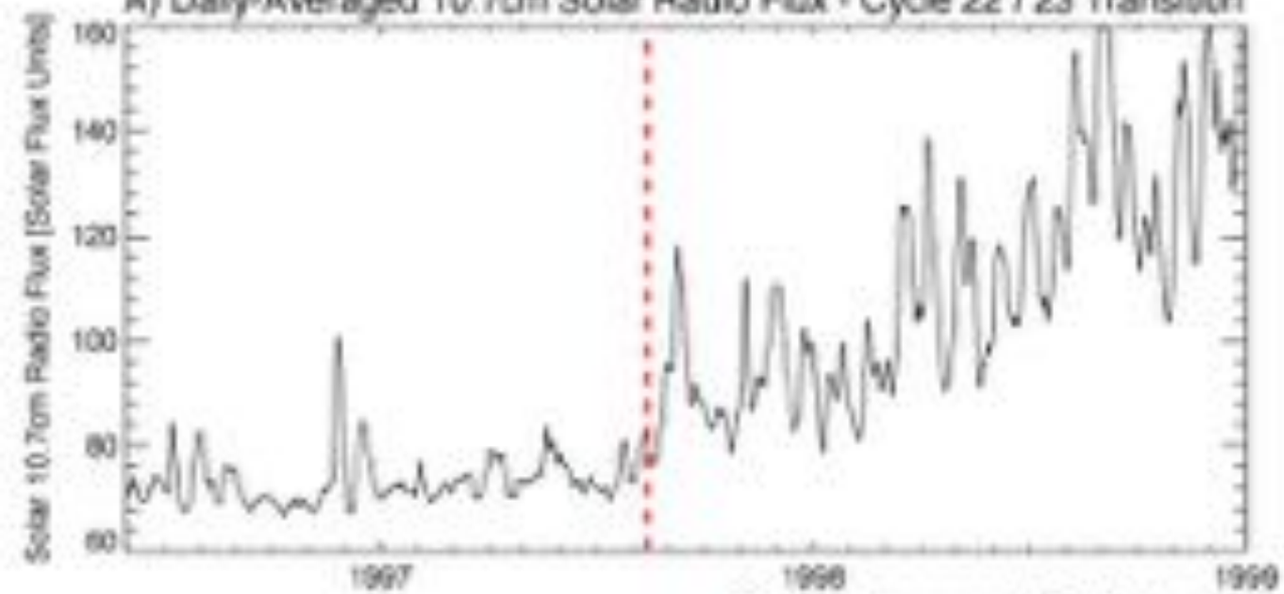

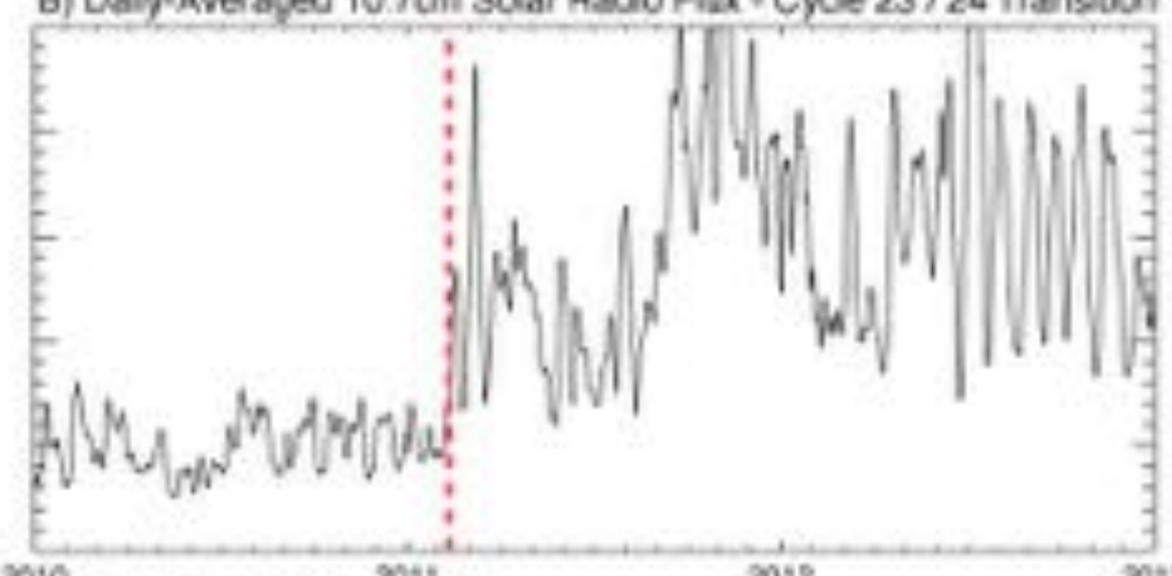

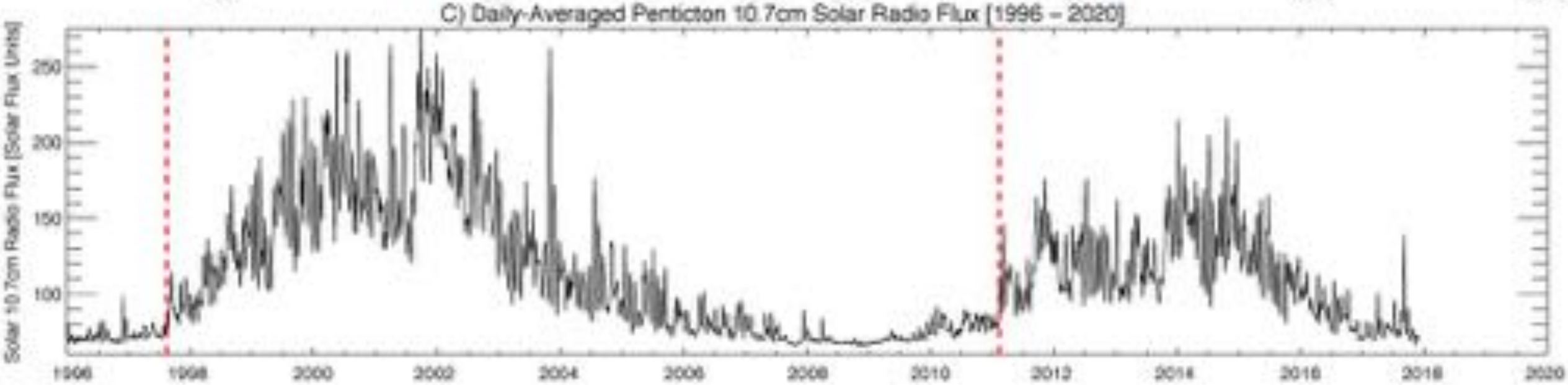

Cycles 23 and 24 are NOT distinct

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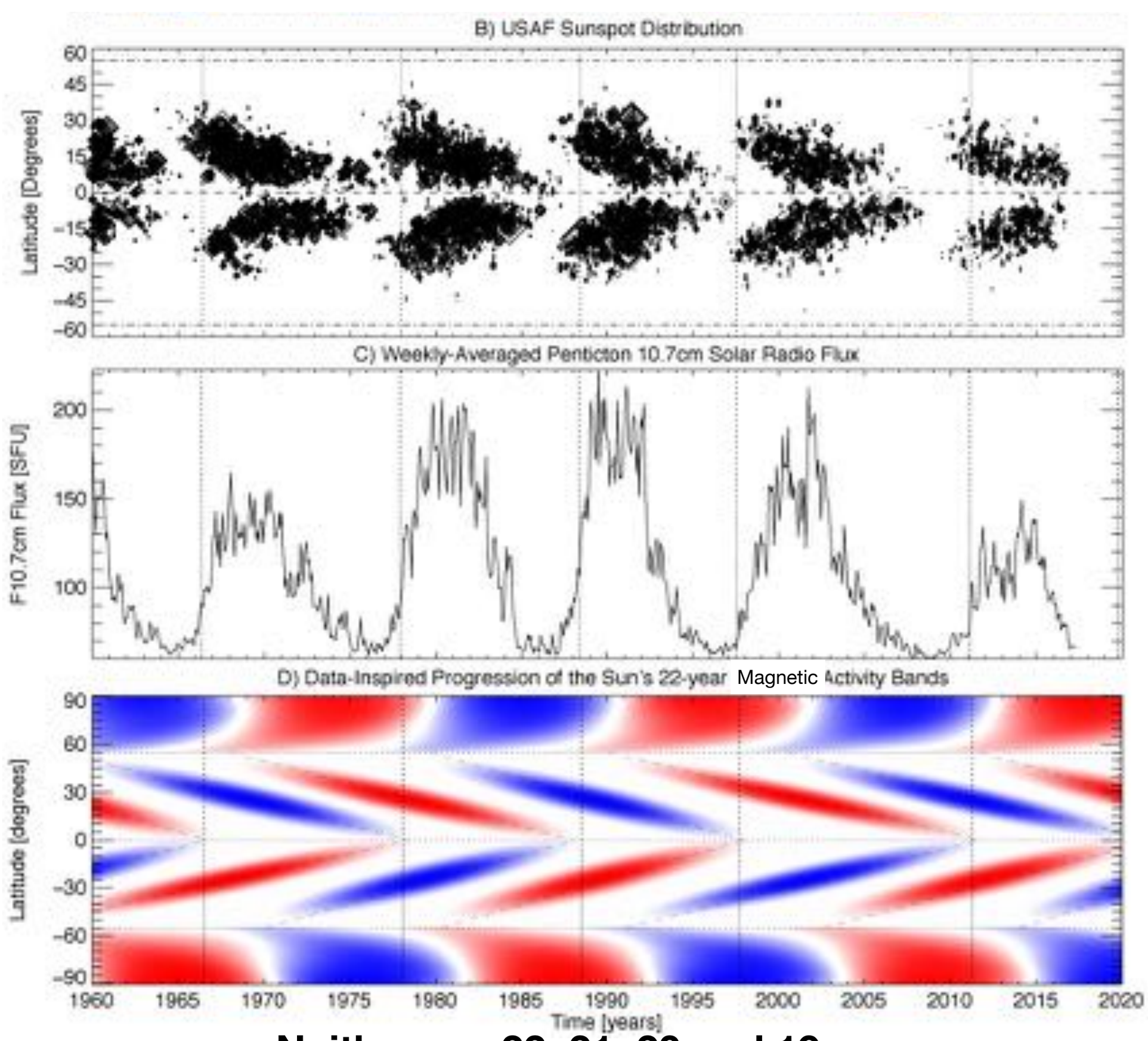

Neither are 22, 21, 20 and 19…..

Step-functions in f10.7 coincident with 100μH transition

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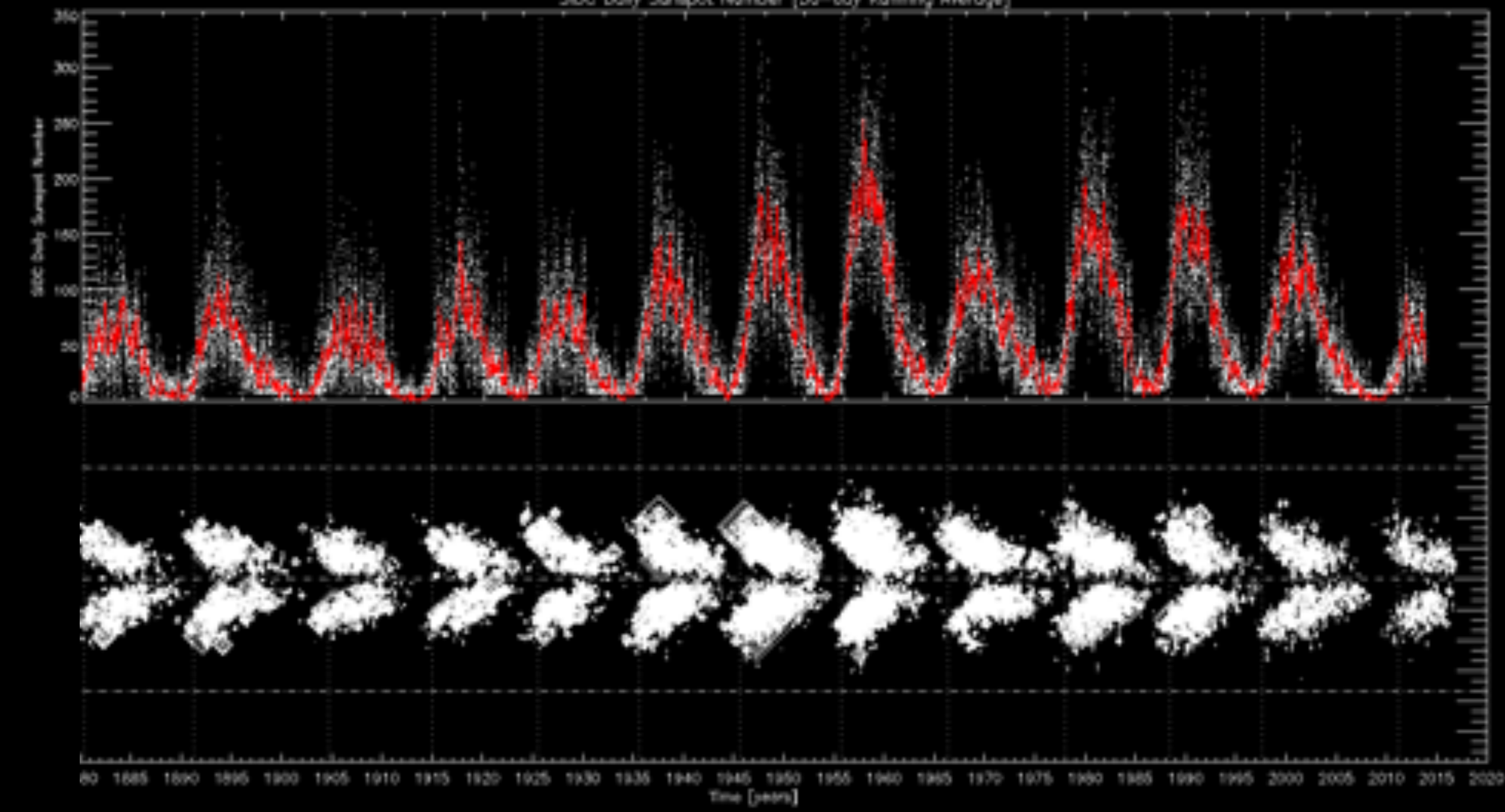
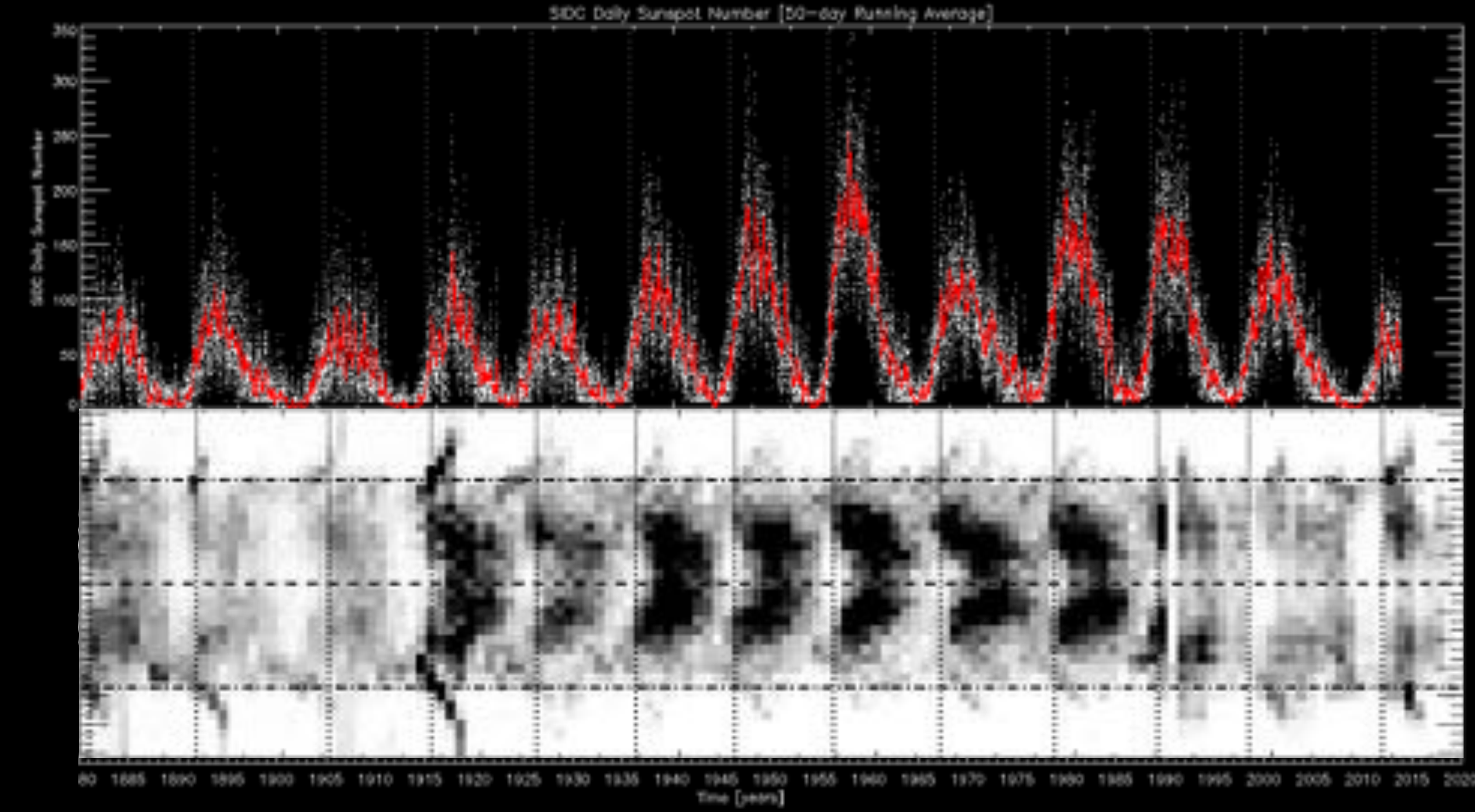


Going back 140 years one notices something odd when you look at filaments.



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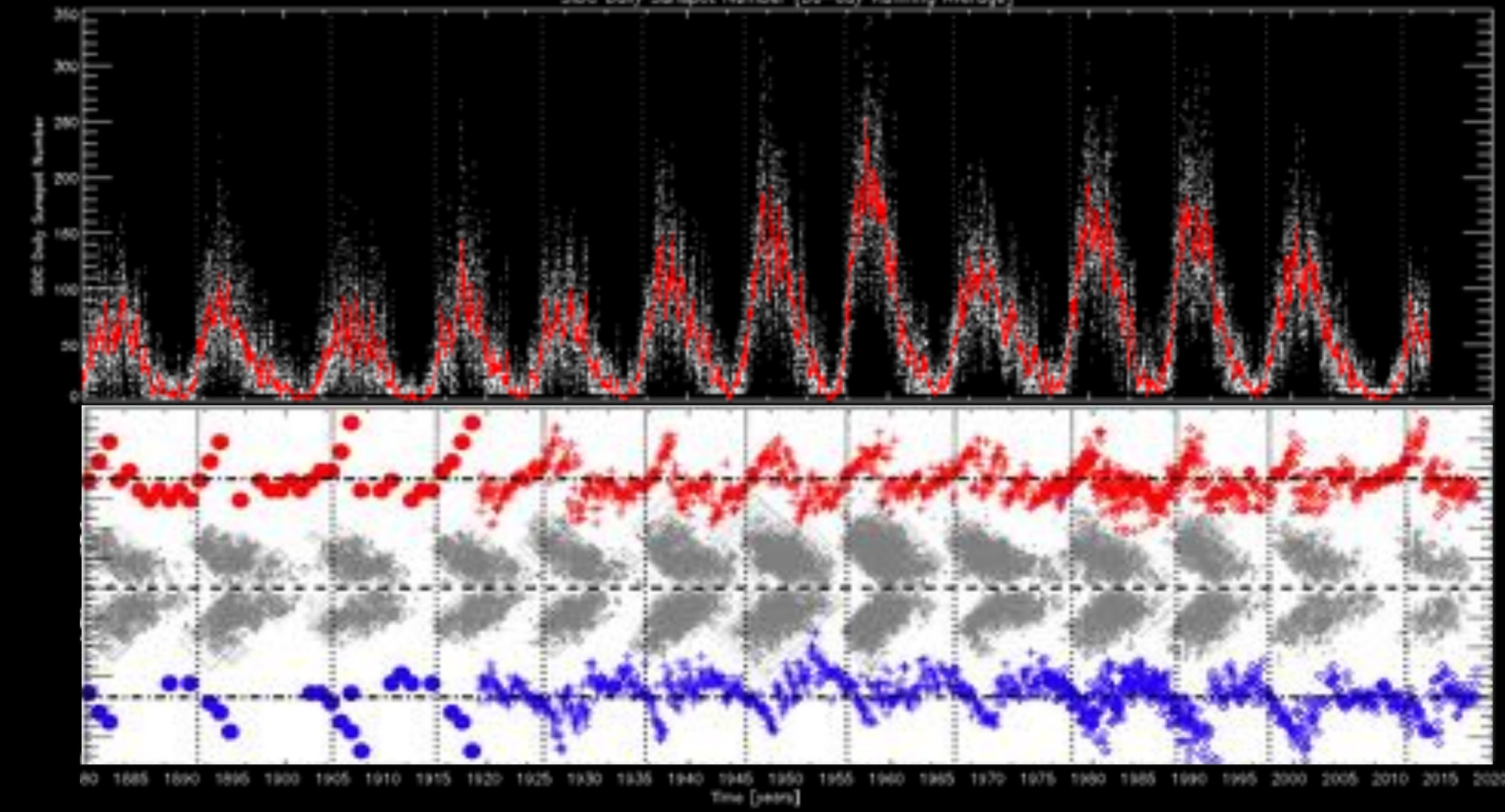
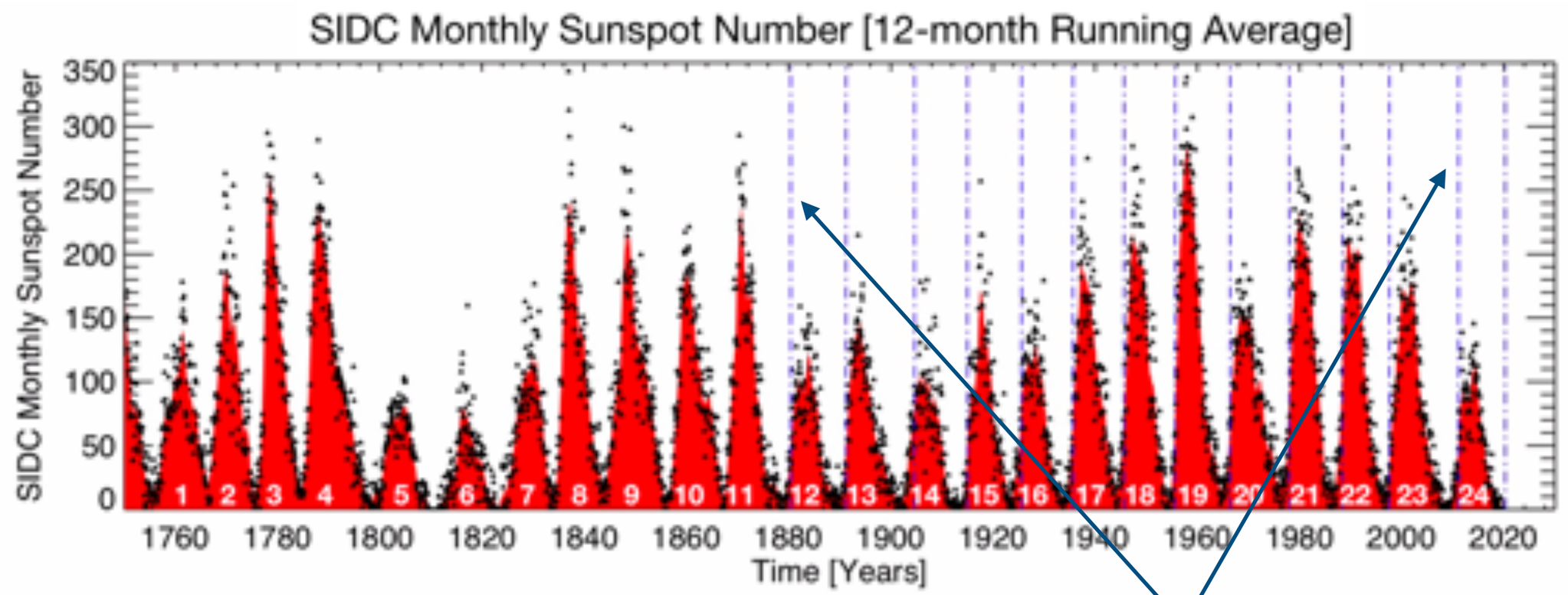


The end of Hale cycles occurs in (very) close conjunction with the emergence of the sunspot pattern at mid-latitudes AND the start of the polar reversal process (~55°).

14 Hale Cycle Terminations - 14 cycles of information - 14 coincidences



Three things to establish:

SUBJECTIVE: Is there an algorithmic approach to terminator detection?

When will the next termination occur?

Does the separation of the termination points give a sense of Hale cycle interaction and predictability of cycle strength?

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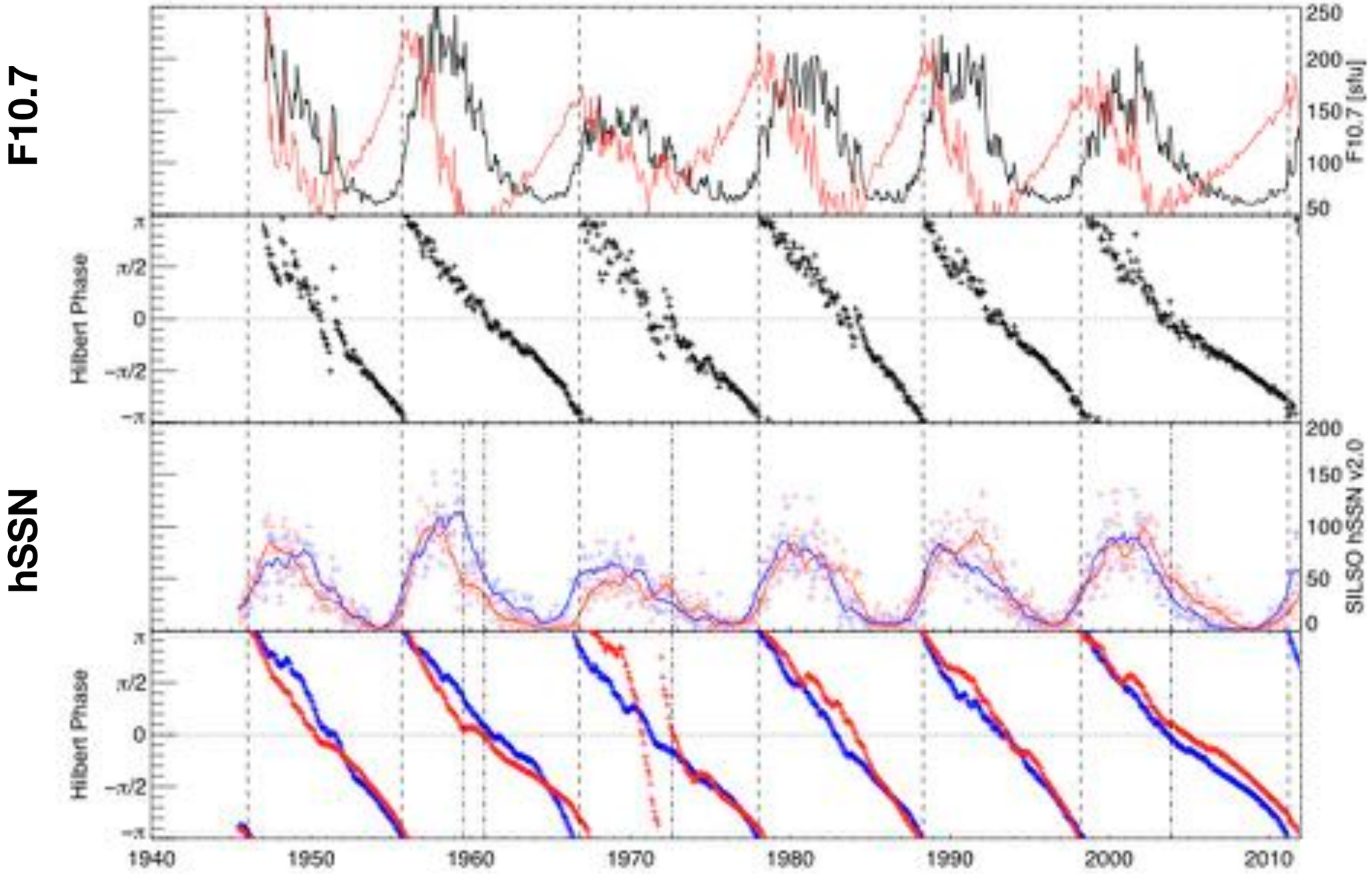
Hilbert Transforms To The Rescue

The Hilbert Transform is an excellent tool for diagnosing phase transitions in timeseries.

Terminators present a unique signature!

H(t) Expresses time series in terms of time dependent amplitude and phase functions



HT-based methodology validates earlier “ad-hoc“ determination of terminator times based on sunspot area with accuracy of ~3 months.

https://arxiv.org/abs/1909.06603

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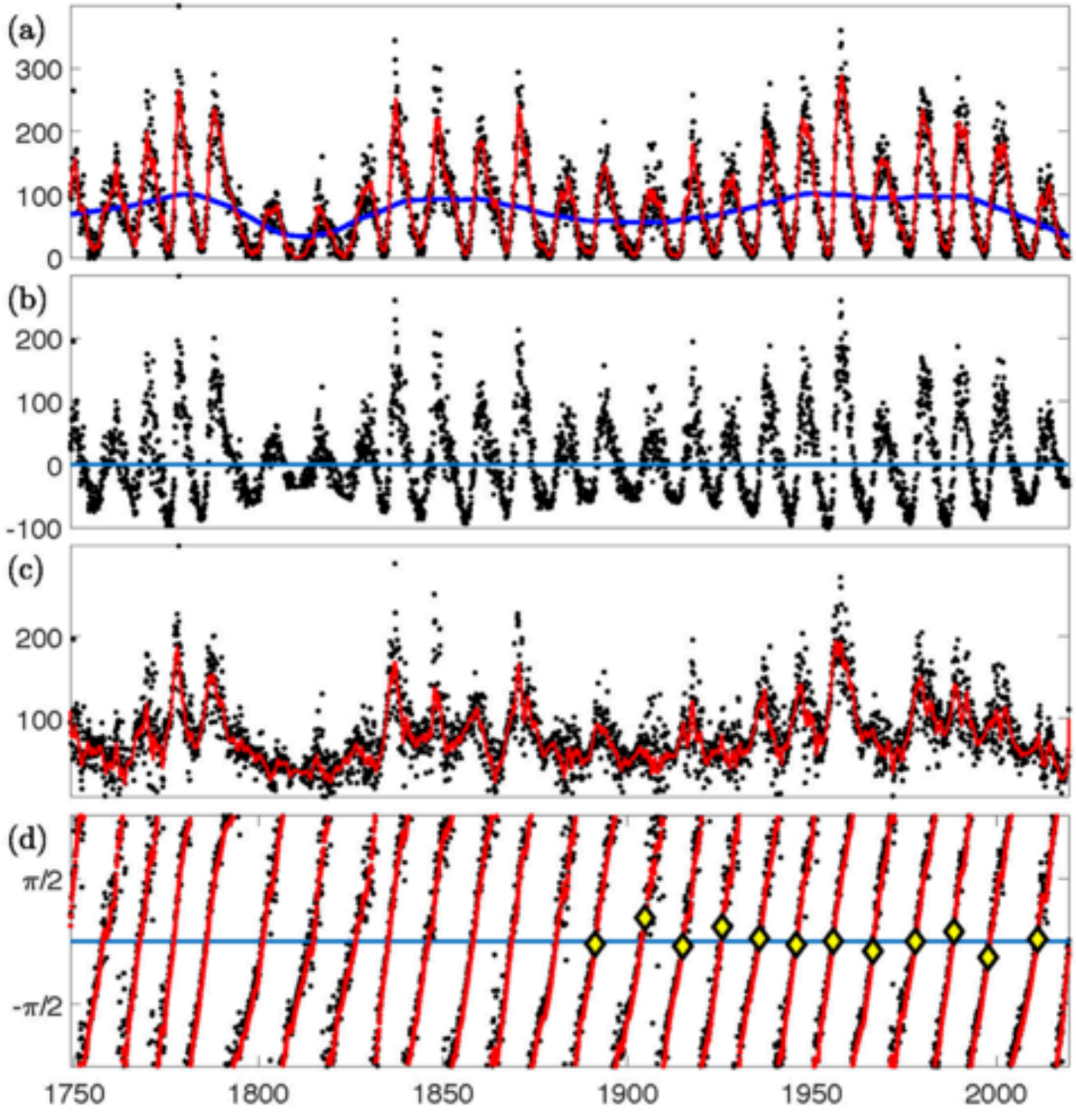
Statistics - Damn Statistics

Apply H(t) to longest baseline data - what pattern do you see?



MONTHLY SUNSPOT NUMBER

[TREND]

DETRENDED MONTHLY SUNSPOT NUMBER

H(t) Amplitude

H(t) Phase

Terminator

Offsetting phase function by π such that the terminators are now zero-crossings

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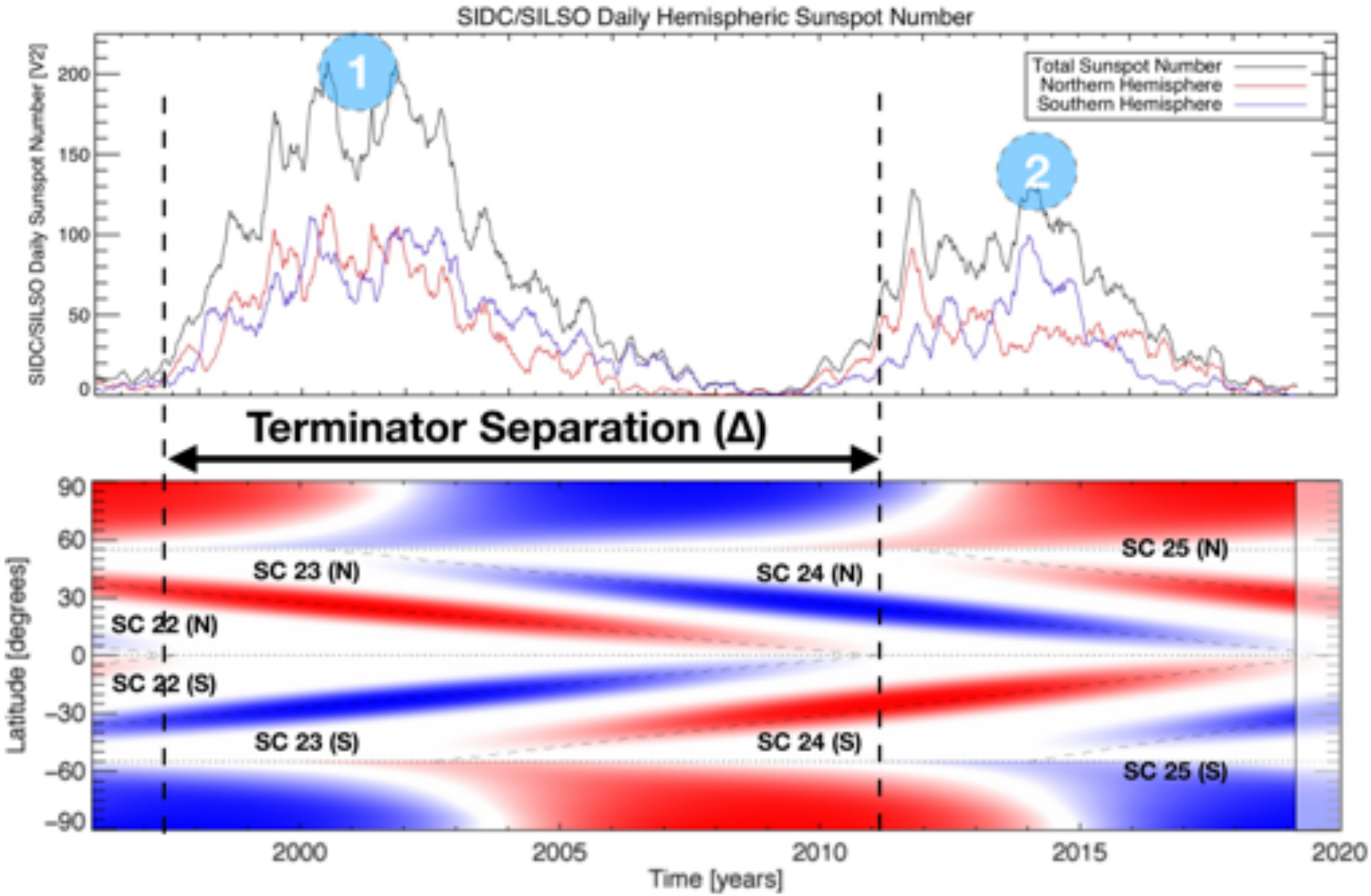

From the 24 sunspot cycles since 1750 look at relationships:

1) terminator separation and **INTERMEDIATE** cycle strength

2) terminator separation and **UPCOMING** cycle strength

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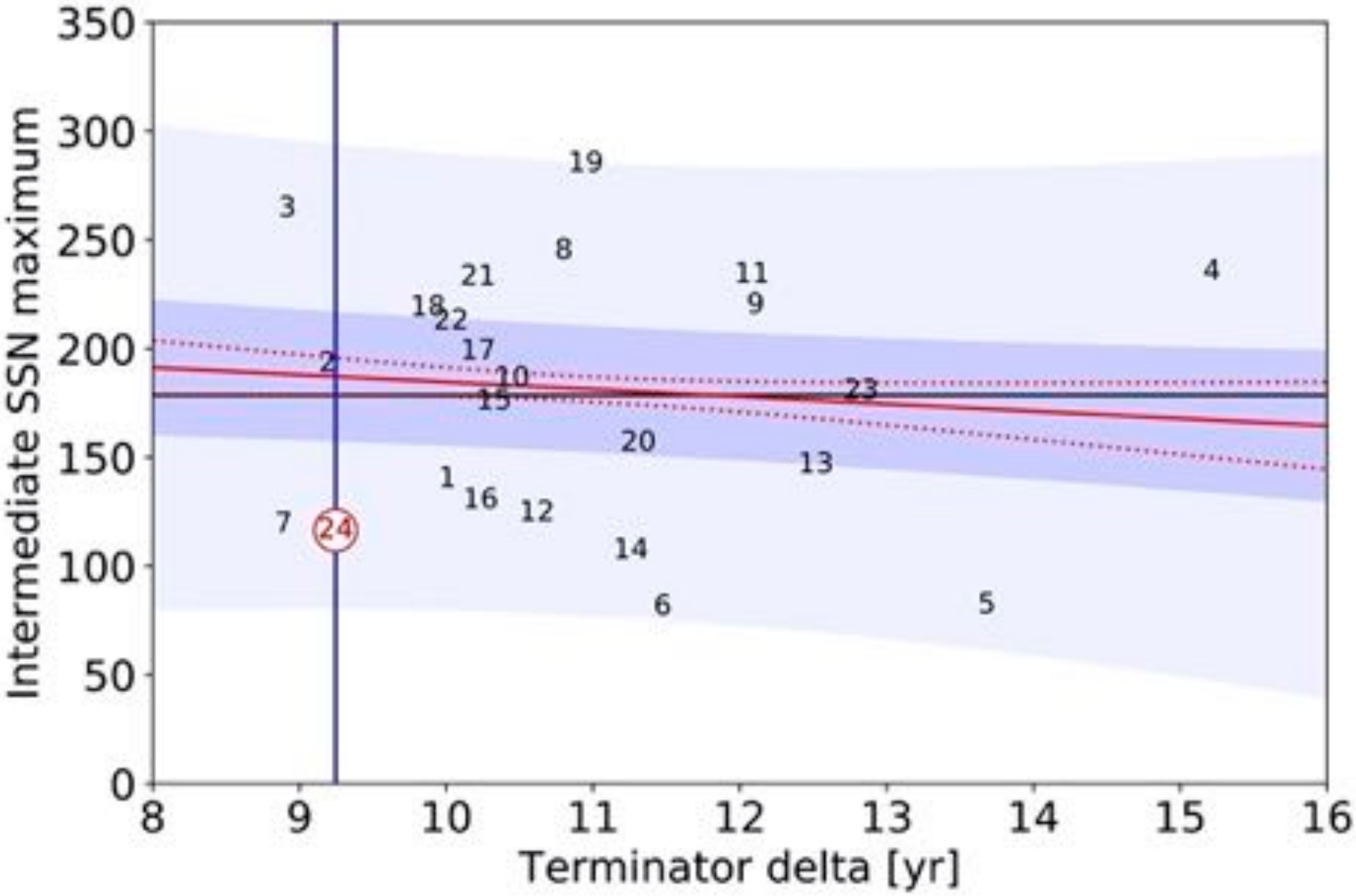
Terminator separation Vs. INTERMEDIATE cycle strength



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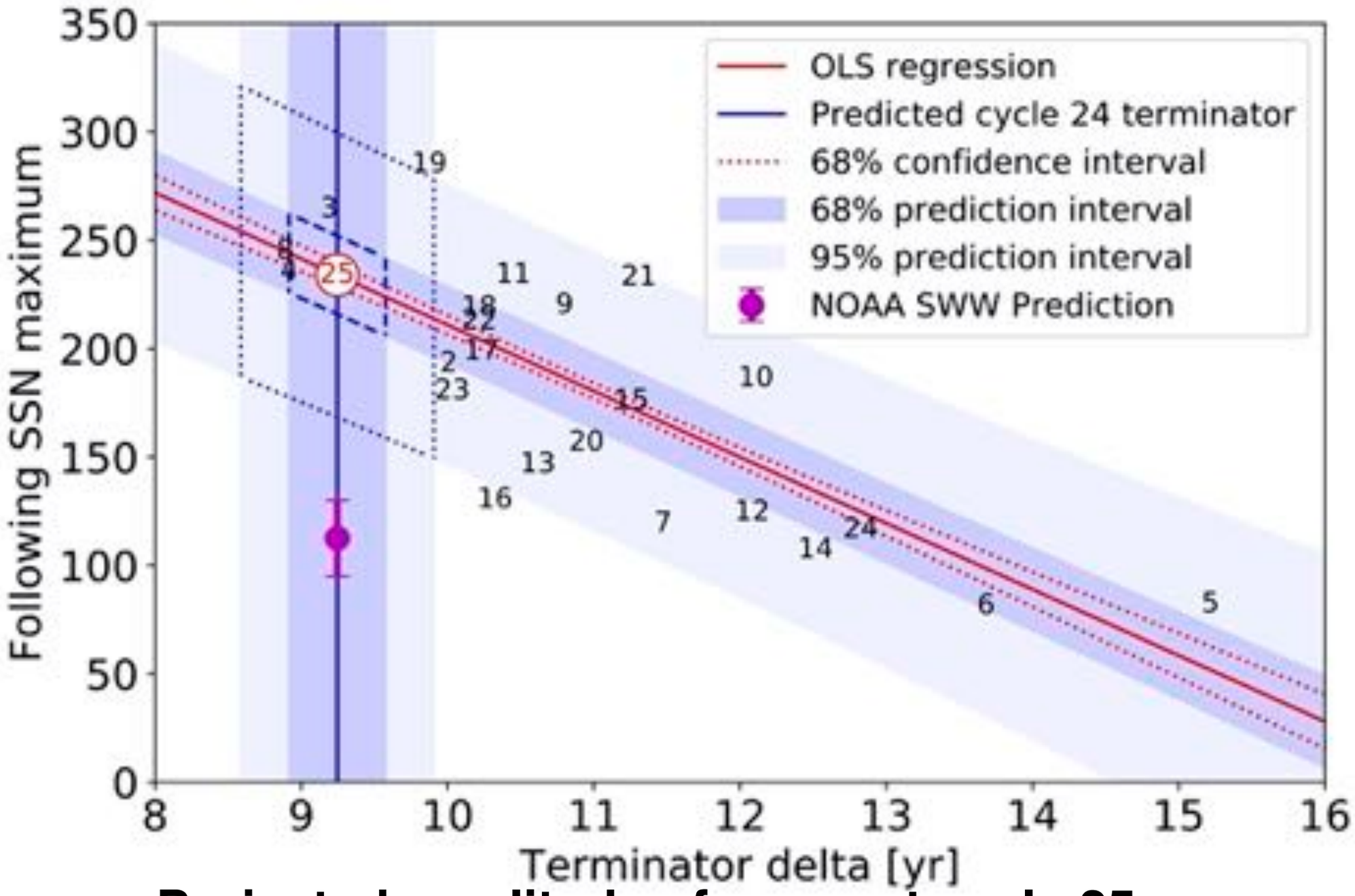
Terminator separation Vs. UPCOMING cycle strength



Projected amplitude of sunspot cycle 25

@ 68% confidence: 233 spots (211 - 257)

@ 95% confidence: 233 spots (159 - 310)

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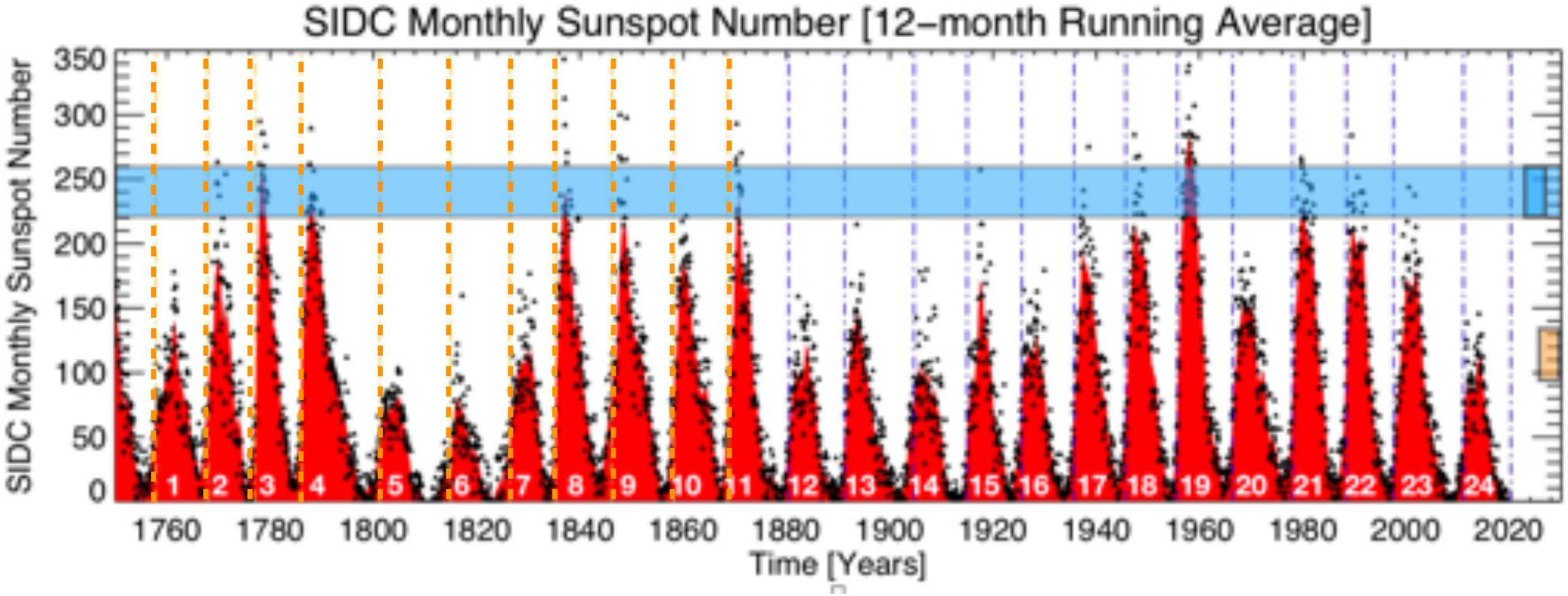

Hale cycles overlap and interfere

Hale cycles end - the end is a “trigger”

Death of one cycle and VERY rapid growth of activity on the bands of the upcoming cycle

The corona responds almost instantly to the ramp up in global flux emergence

Hilbert Transforms verify observational analysis 1860 - Present

Hale Cycle End is Pending - May 2020 **+4.0 months** **-1.5 months**

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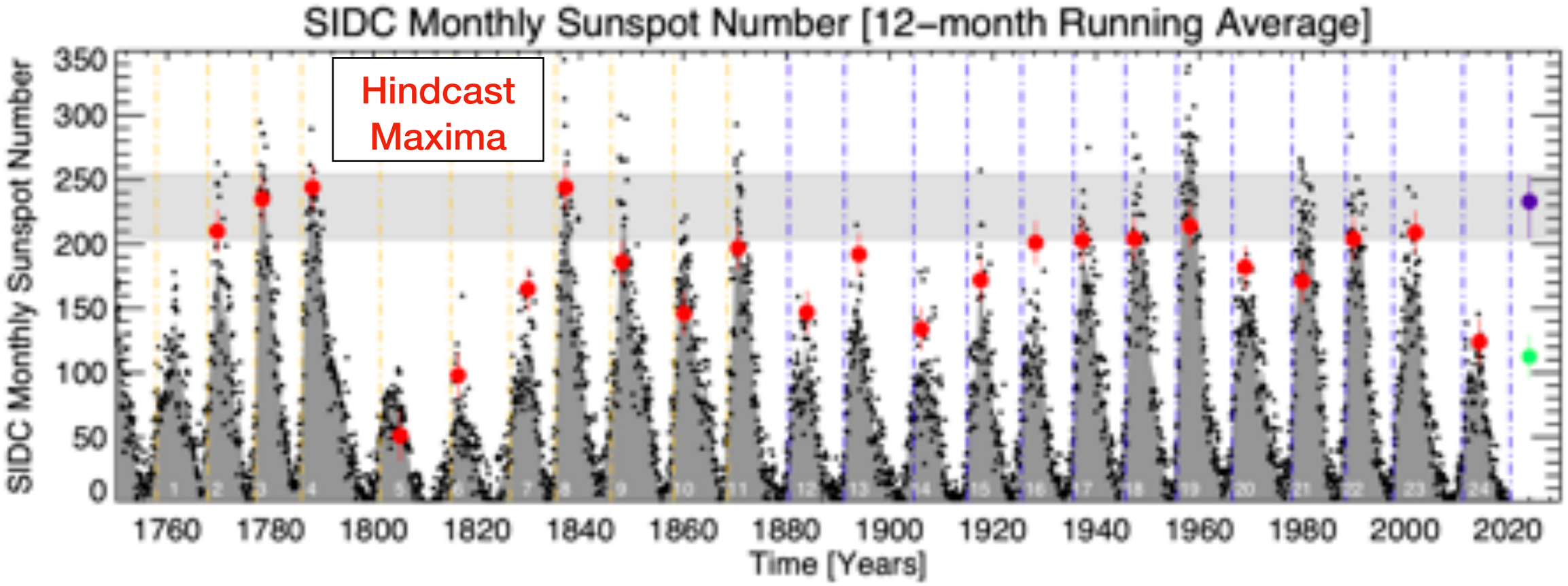

Projected amplitude of sunspot cycle 25

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Are we ready for a large sunspot cycle?

PSP will fly through the next terminator - if things pan out - at perihelion, what will it see/feel?

As the cycle grows rapidly - the coronal WILL respond as will other things modulated by the Sun's magnetism. Significant ramp up!

How will the Earth's atmosphere respond?

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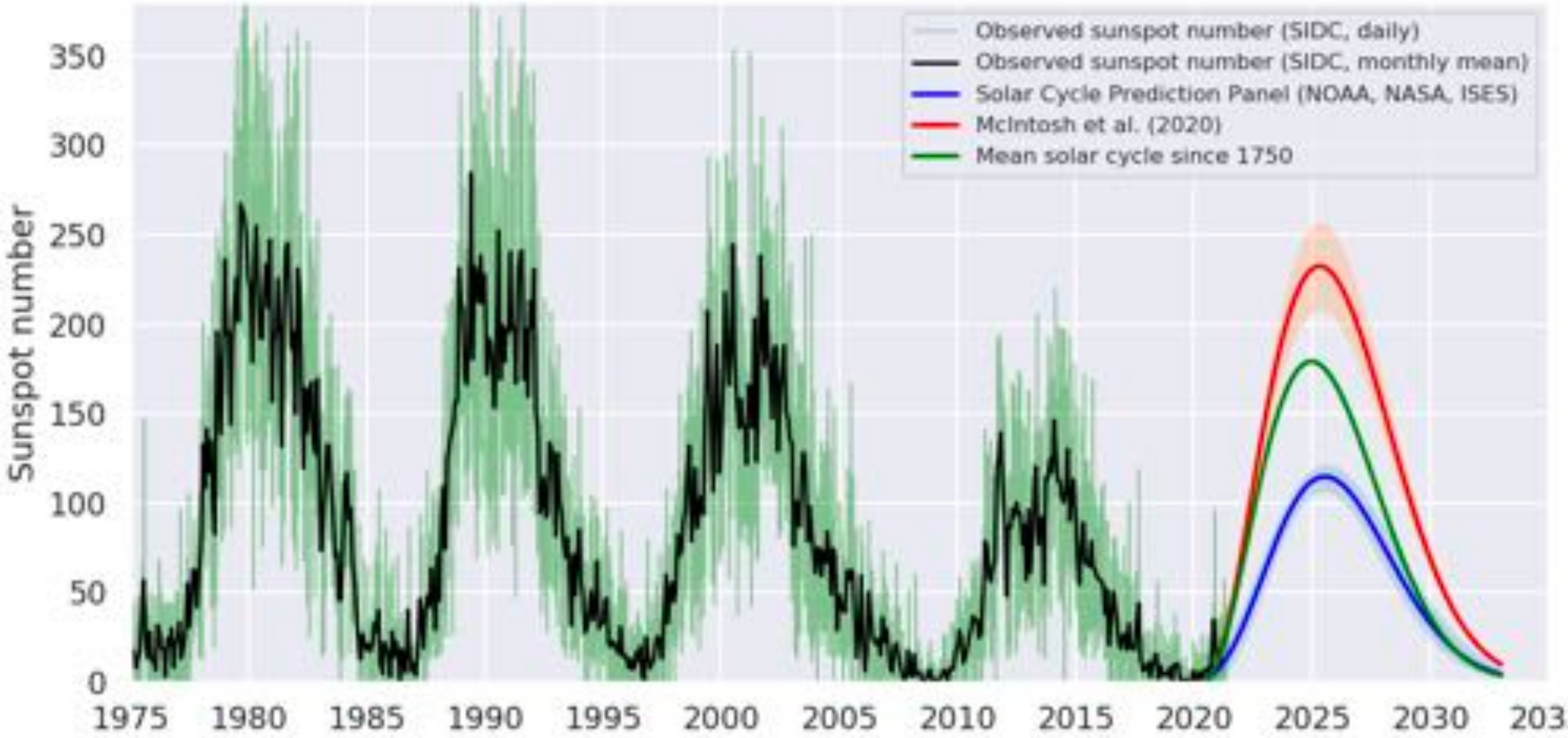
Comparing “Forecasts”



Contrast could not be greater?

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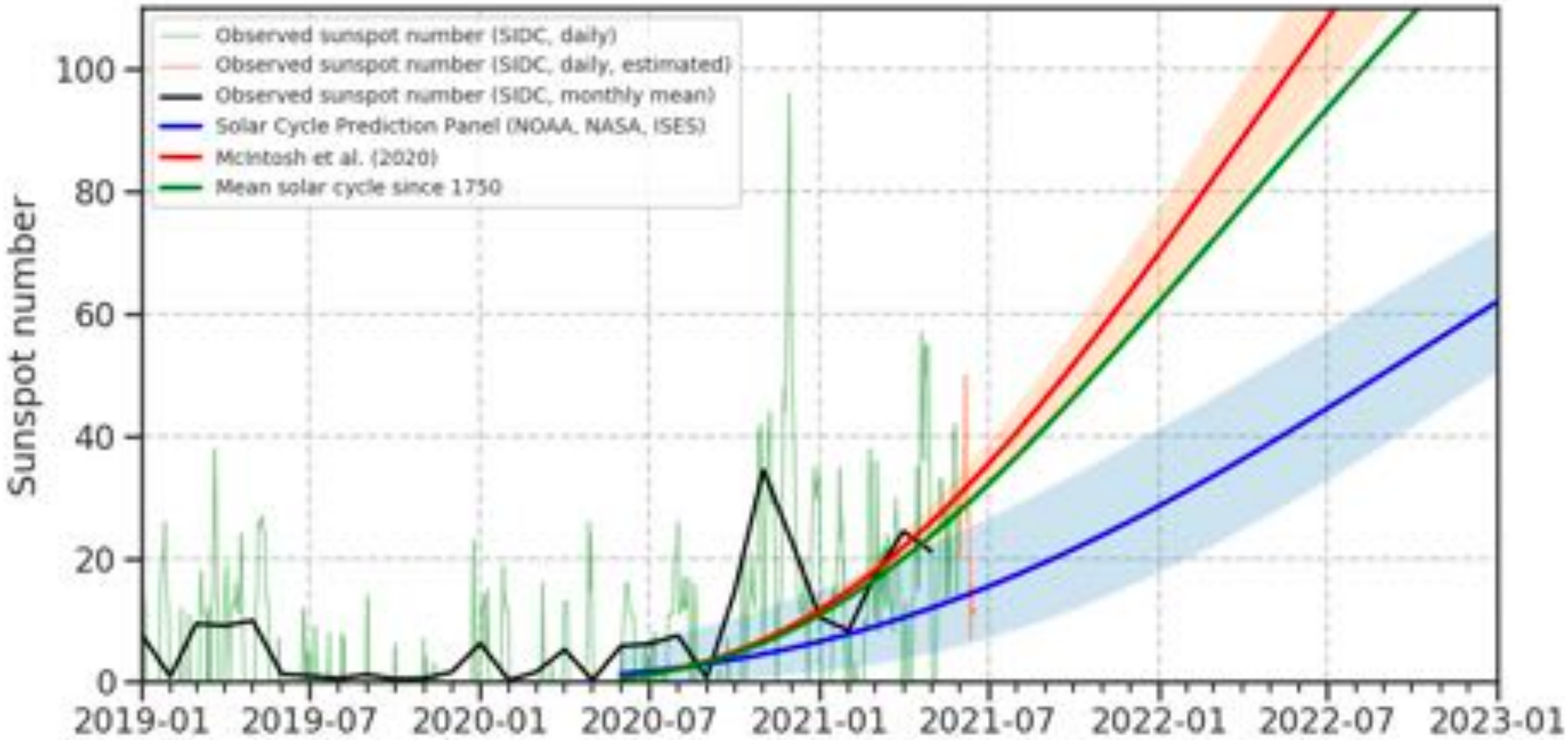
Comparing “Forecasts”



Contrast could not be greater?

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“Clocking The Sun”

Part Deux:

Now that I have terminators what else might I be able to do?

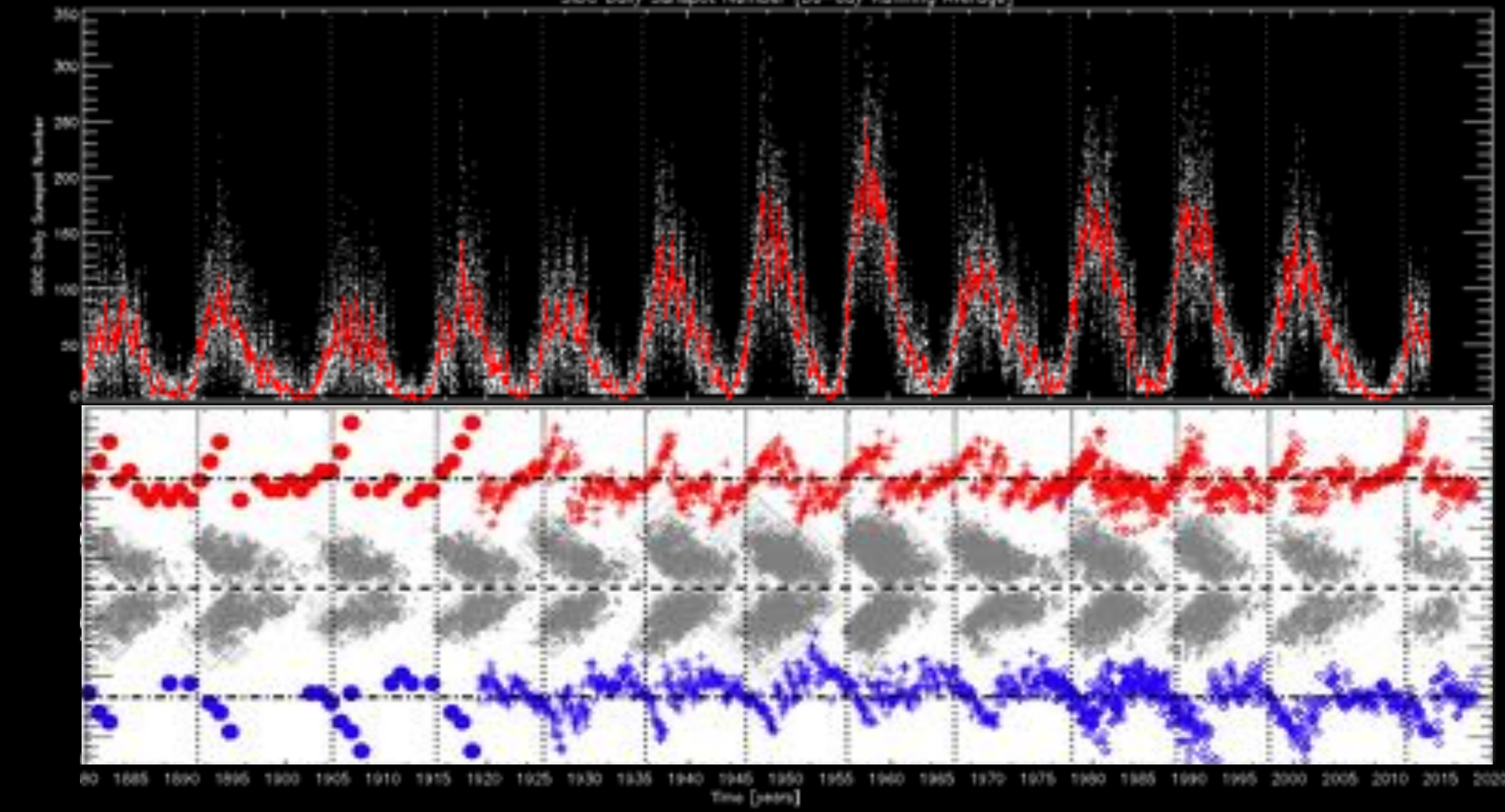
Developing Climatology

III. *Some Phenomena of Sunspots and of Terrestrial Magnetism at Kew Observatory.*

By C. Chree, *Sc.D., LL.D., F.R.S., Superintendent of Kew Observatory.*

Received March 30,—Read May 9, 1912.

mscott@ucar.edu



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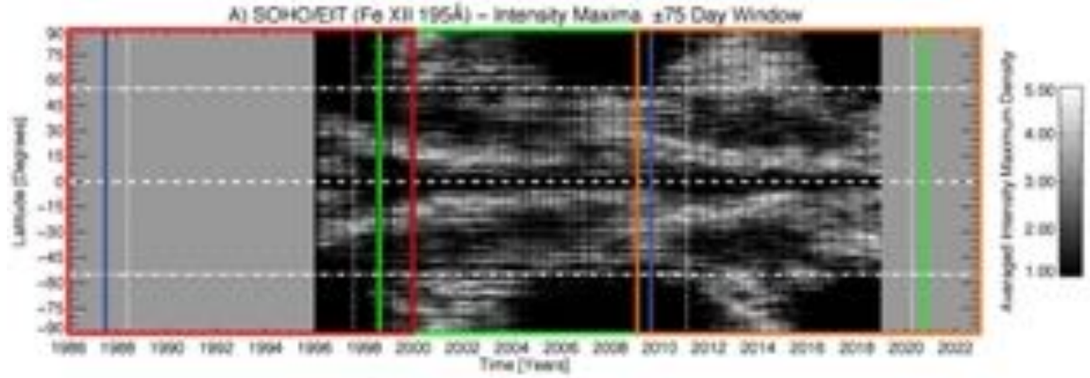

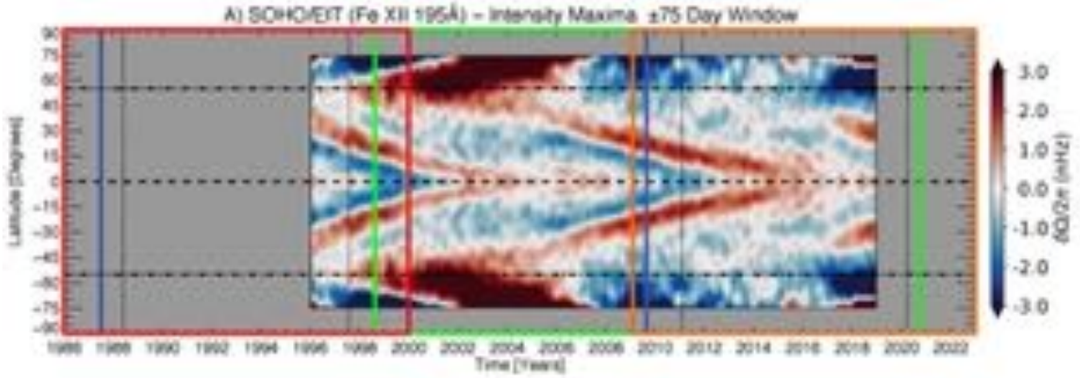

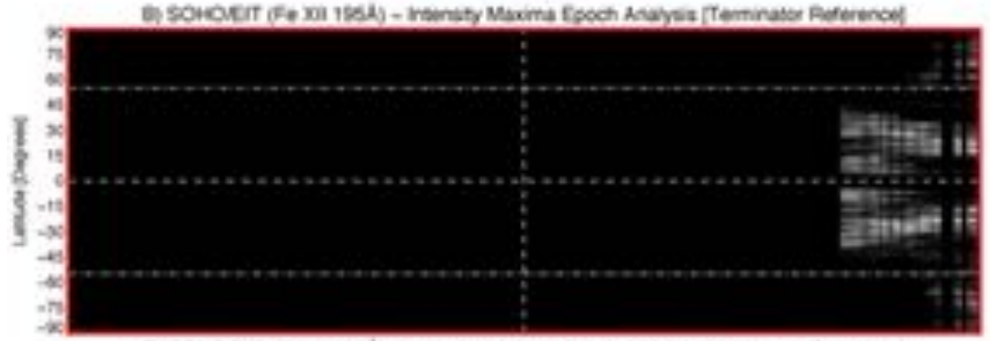

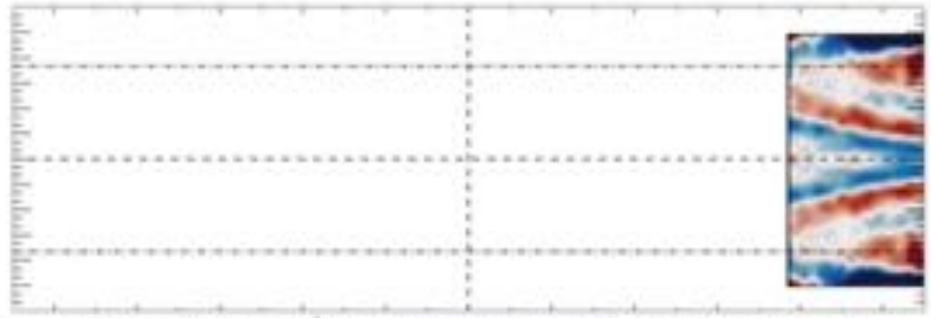

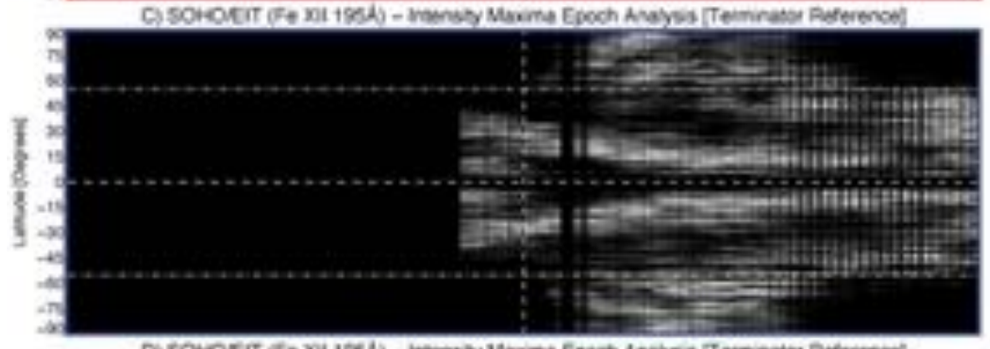

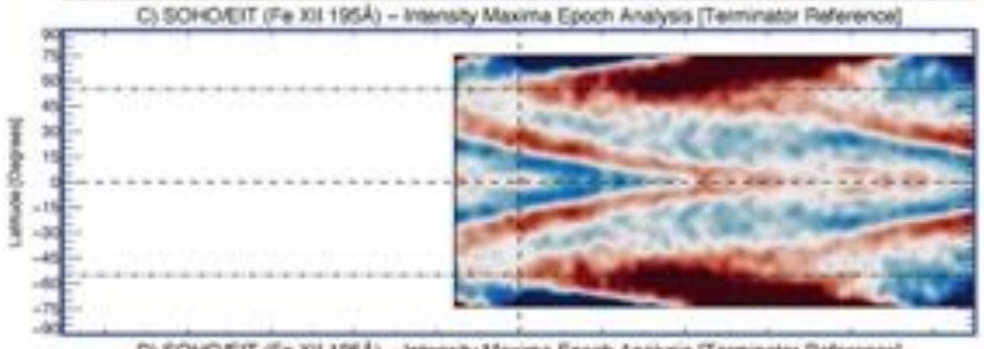

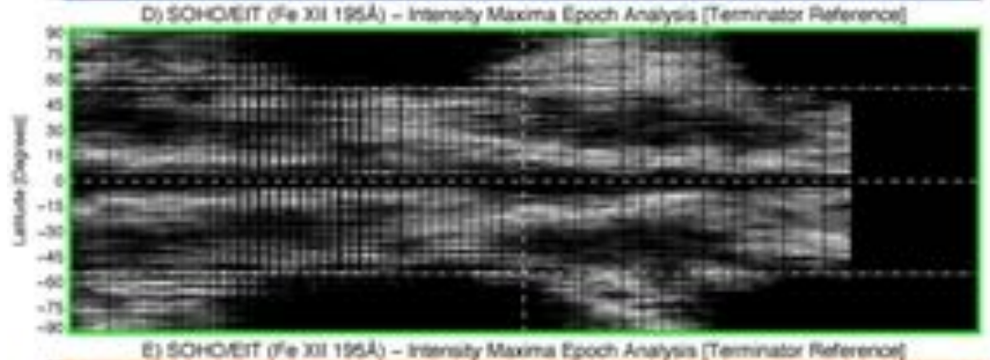

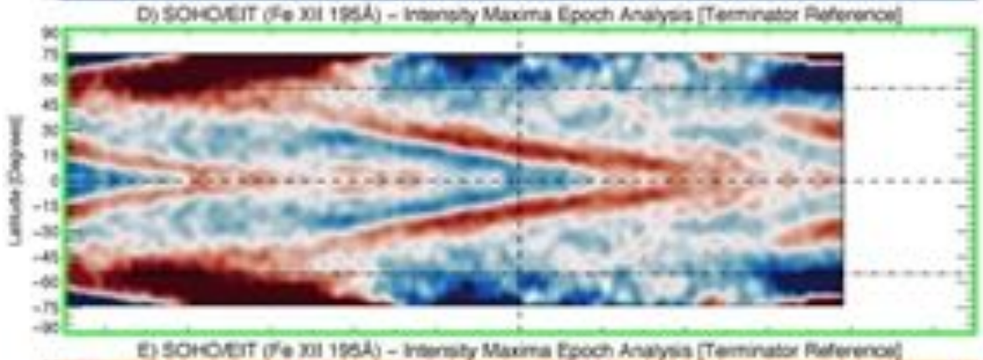

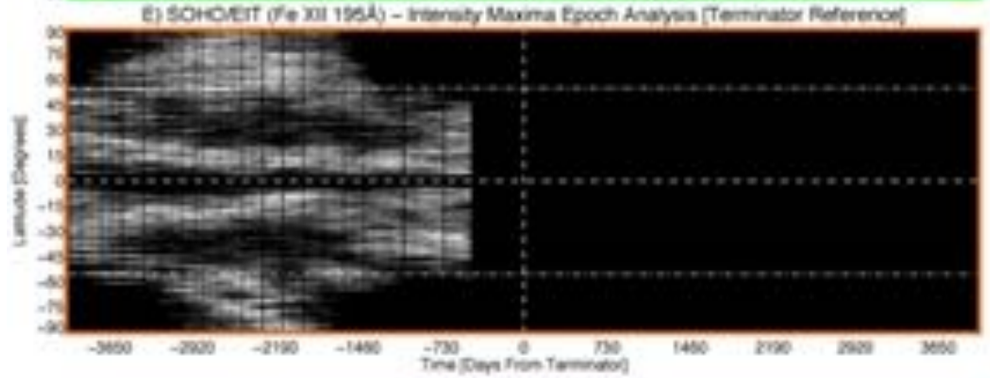

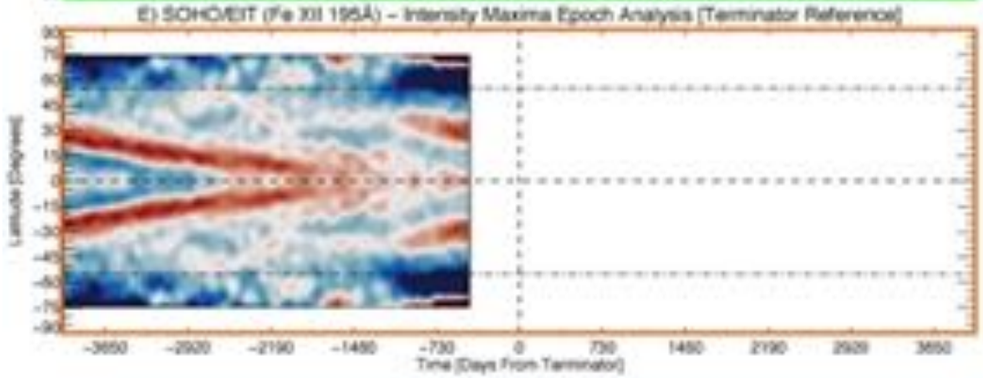

Corona: Intensity Maximum Distribution

Interior: “Torsional Oscillation”

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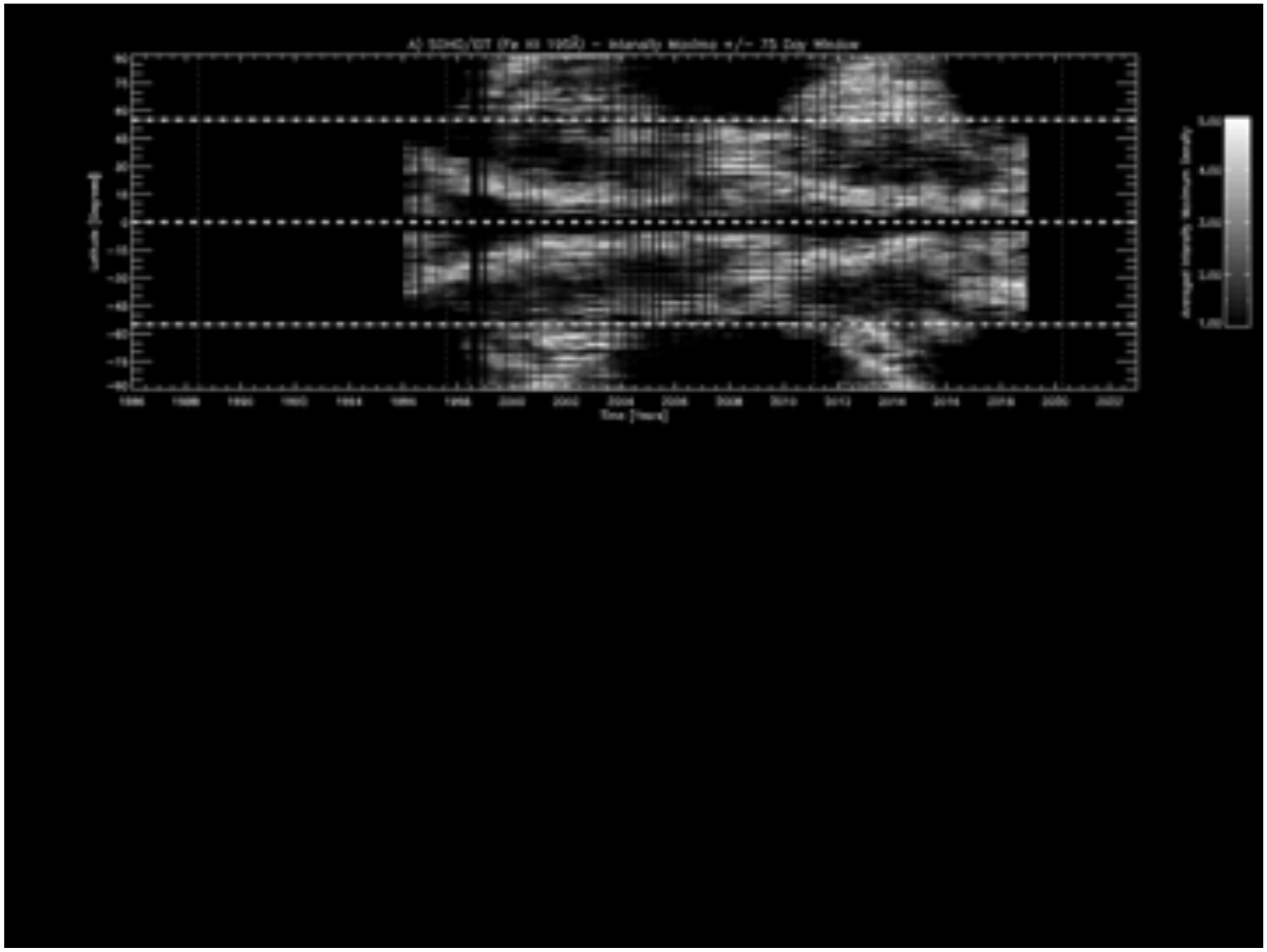
Superposed Epoch Analysis: 24 Years of SOHO/EUV



Terminator Key Time

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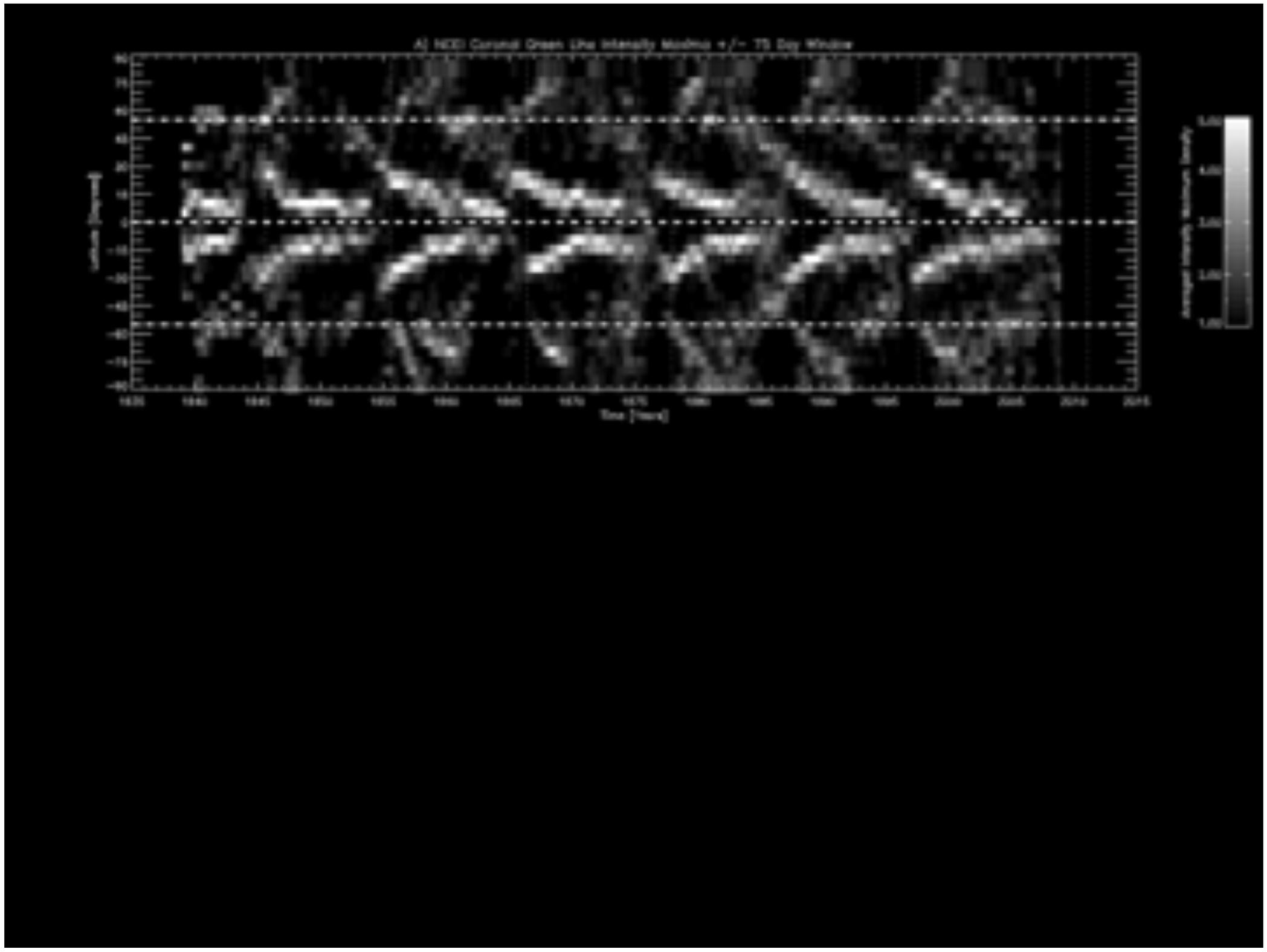
Superposed Epoch Analysis: 70 Years of Green Line



Terminator Key Time

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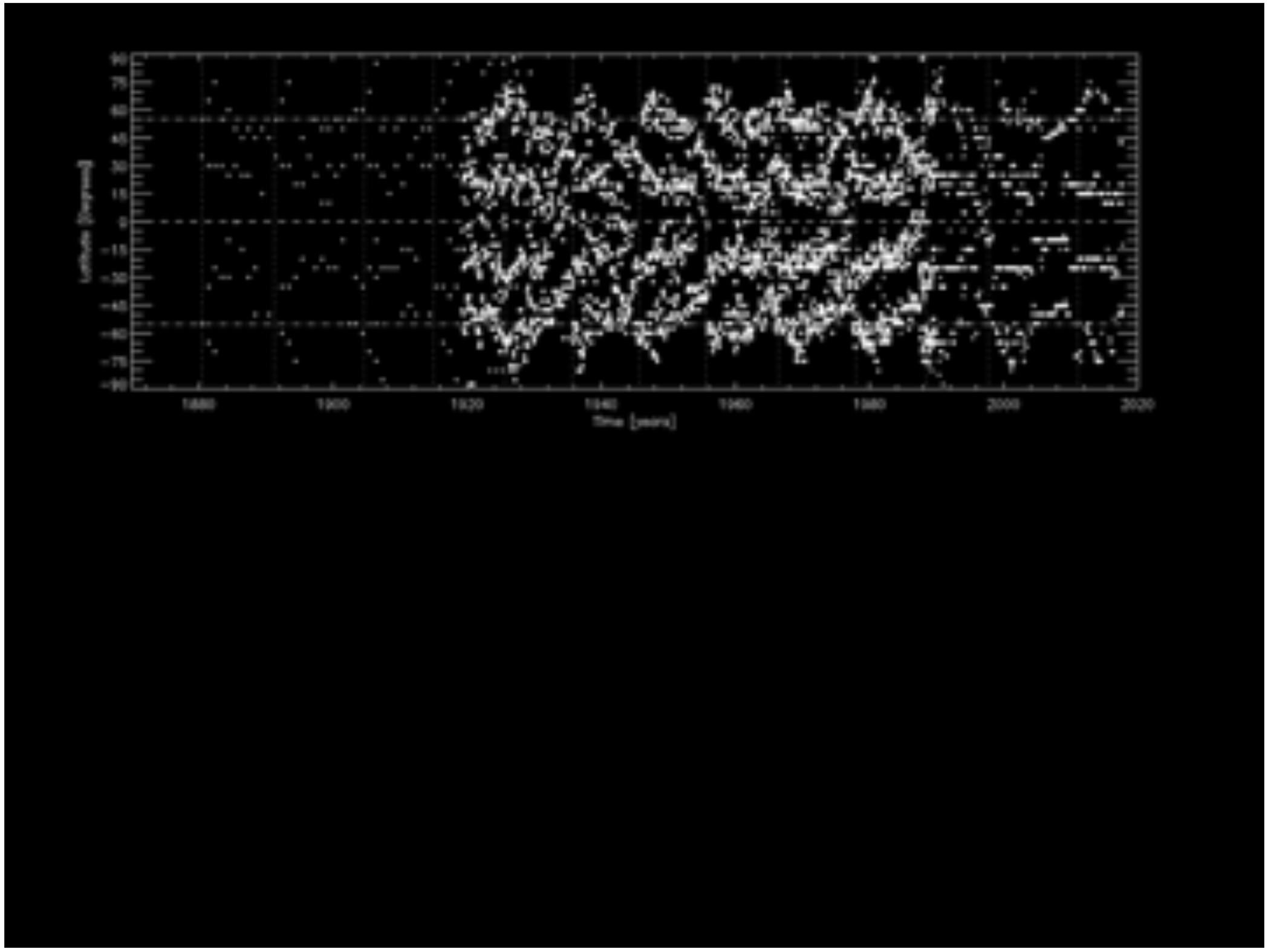
Superposed Epoch Analysis: 140 Years of Filaments



Terminator Key Time

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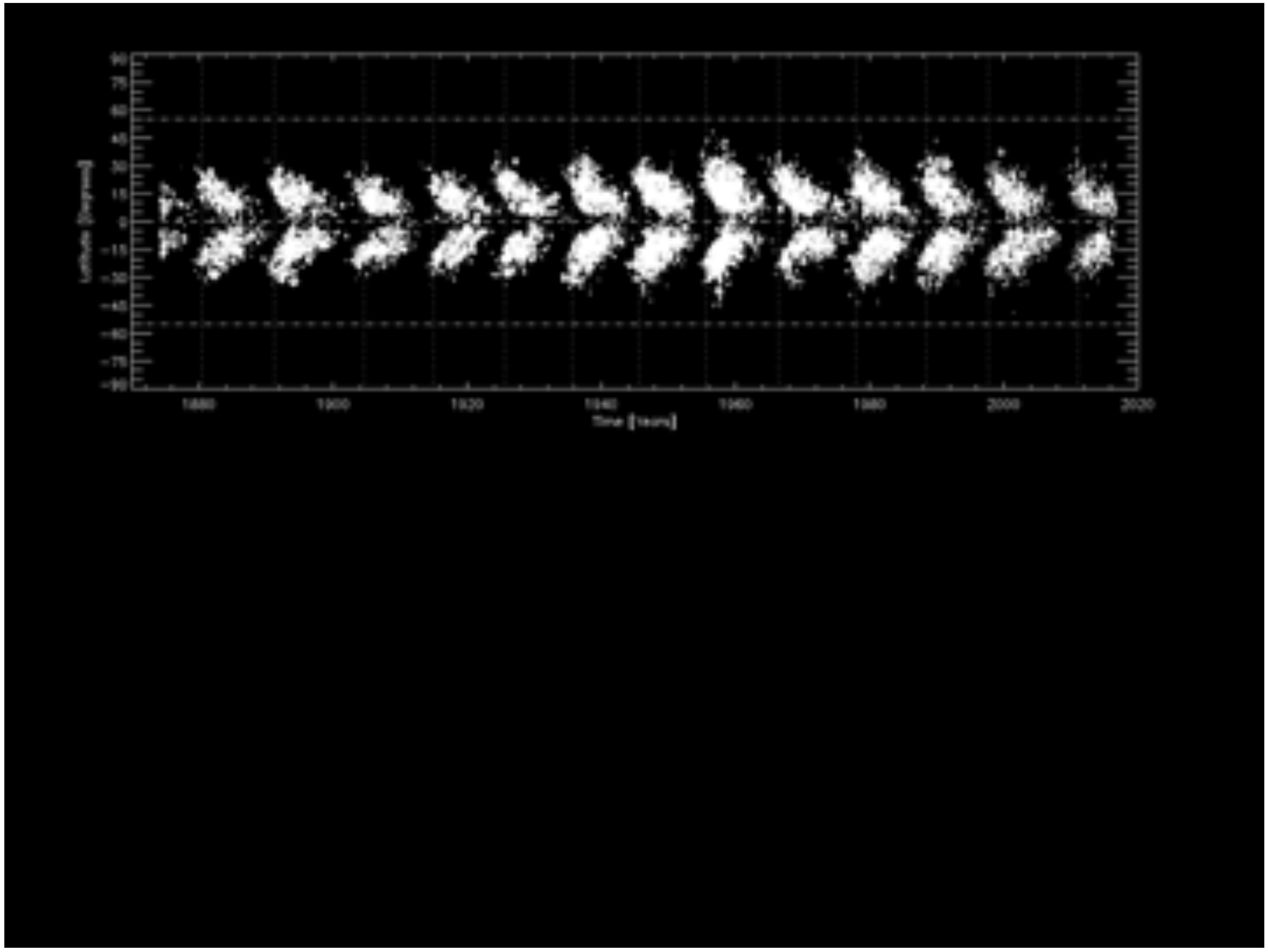
Superposed Epoch Analysis: 140 Years of Sunspots



Terminator Key Time

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Comparing Superposed Epoch Analyses (SEA)

The Extended Solar Cycle - Comparison to Sunspot Variation

SEA Reference Time: "Terminator"

Baseline of Observations Compared:

USAF Sunspots - [1880-2020]

Combined International Filament Record - Density Distribution Maxima [1880-2020]

NCEI Coronal Green Line - Intensity Maxima [1939-2019]

SOHO/EIT, STEREO SECCHI/EUVI, SDO/AIA 195Å - Intensity Maxima [1996-2019]

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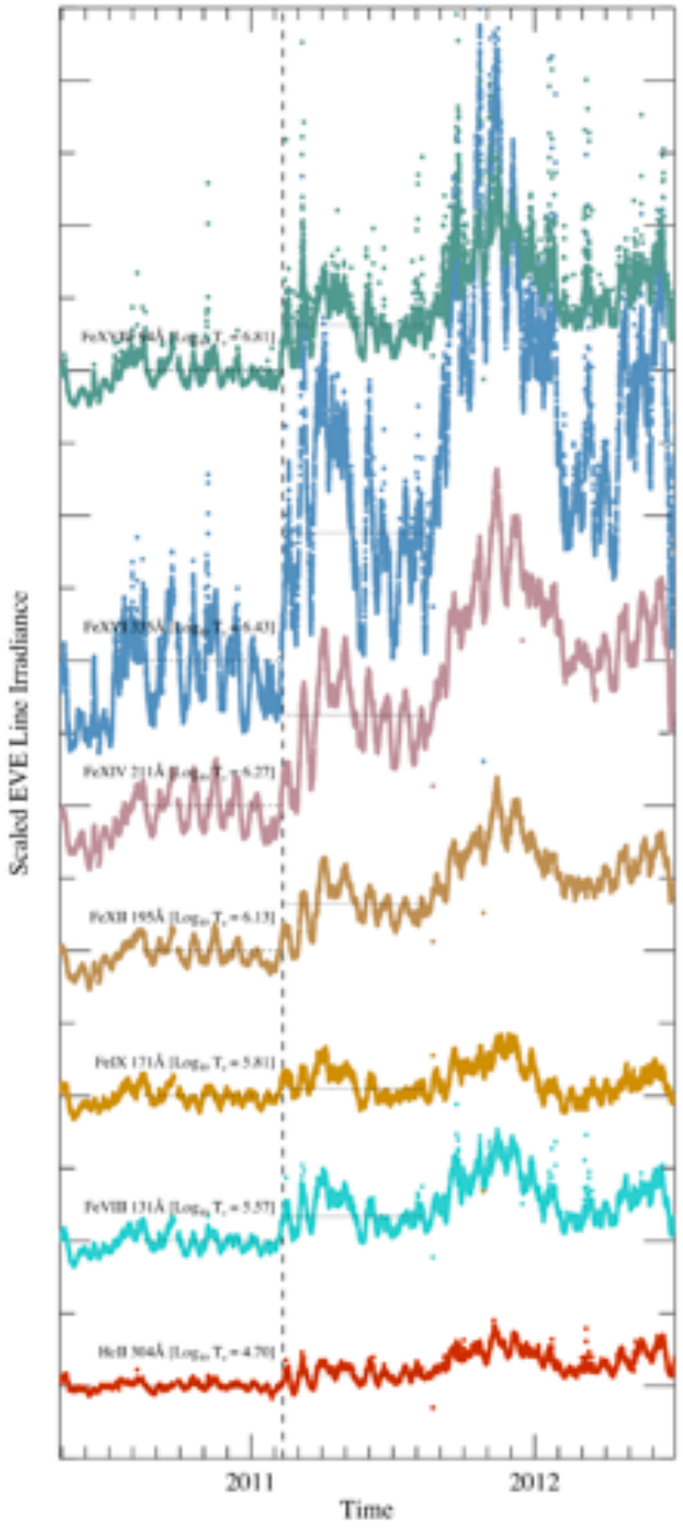
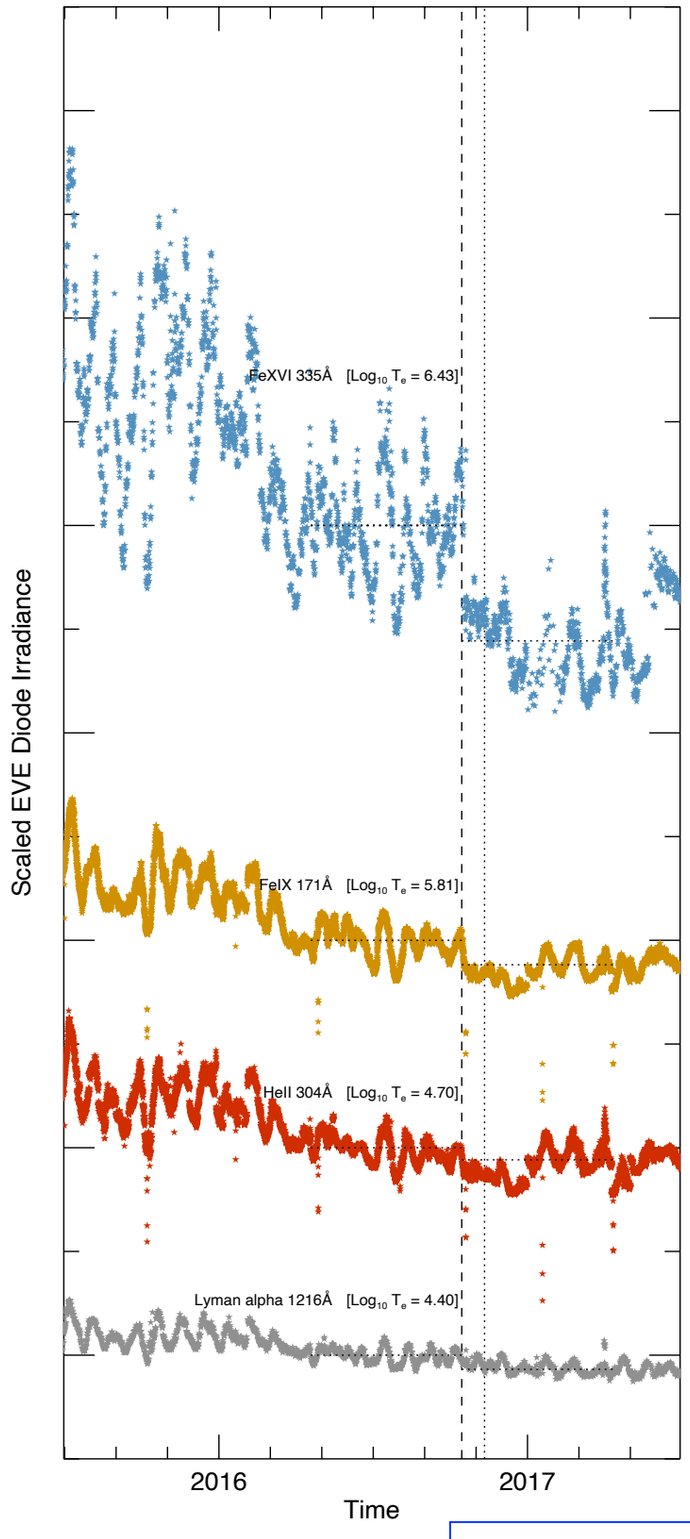
This Hale cycle pattern is recurrent throughout the entire record since photographic observations were available, ~1860. The sunspot "butterfly" is only a subset of that recurrent pattern.

Curious-ER





“Clocking the Solar Cycle II”
Leamon et al. (2020).

Comparing 2011 and 2016 in SDO/EVE

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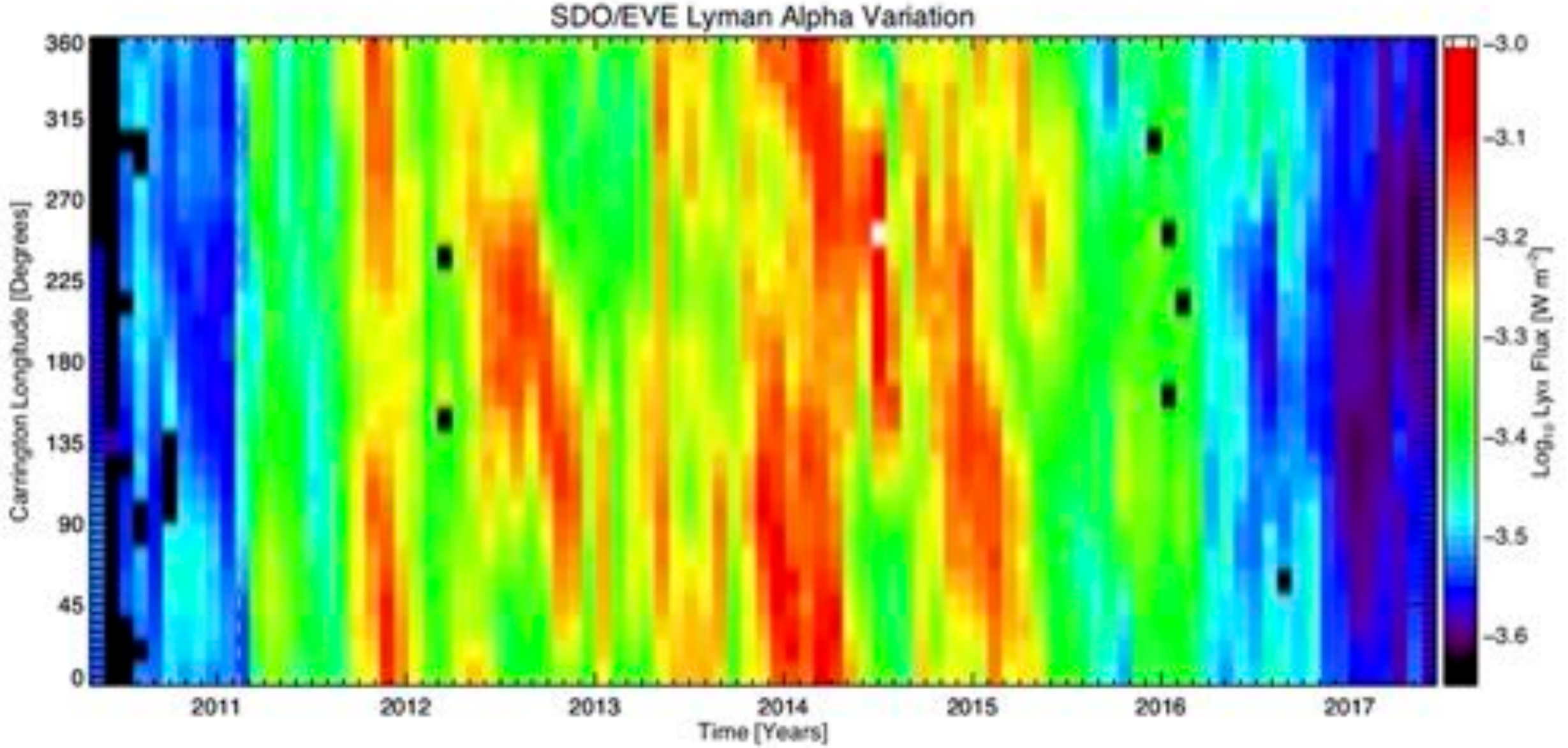
More Curious-ER



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Where are we now?

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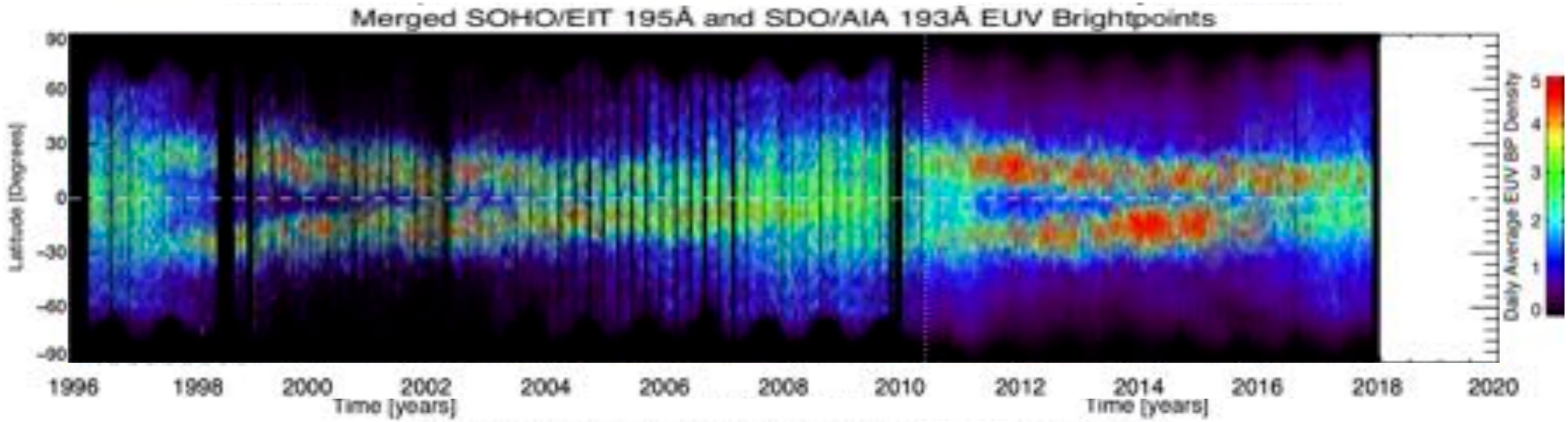

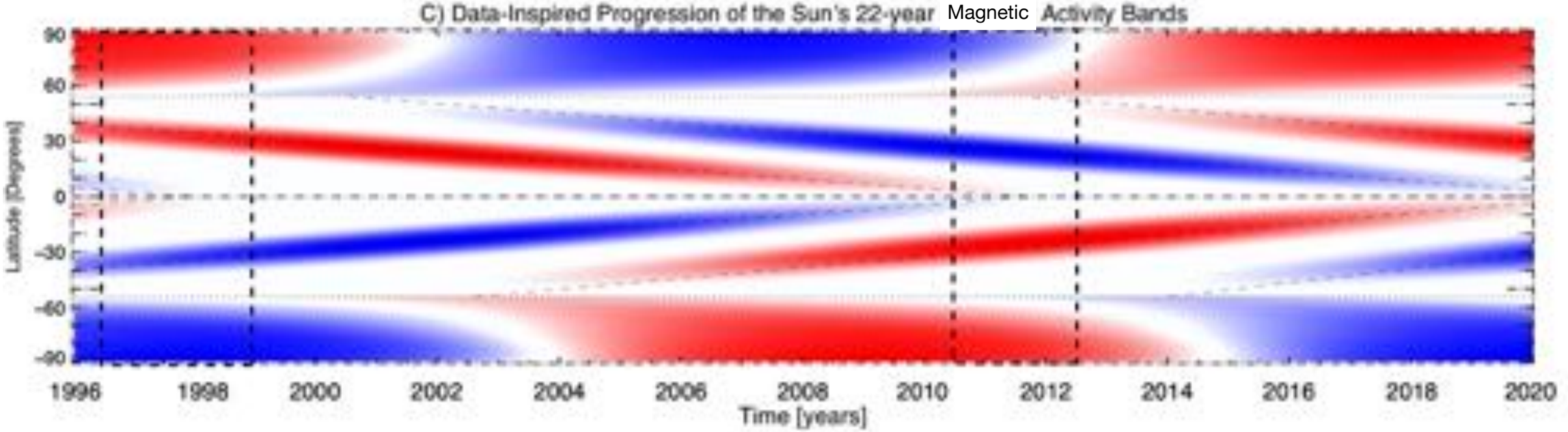

Recalling!!

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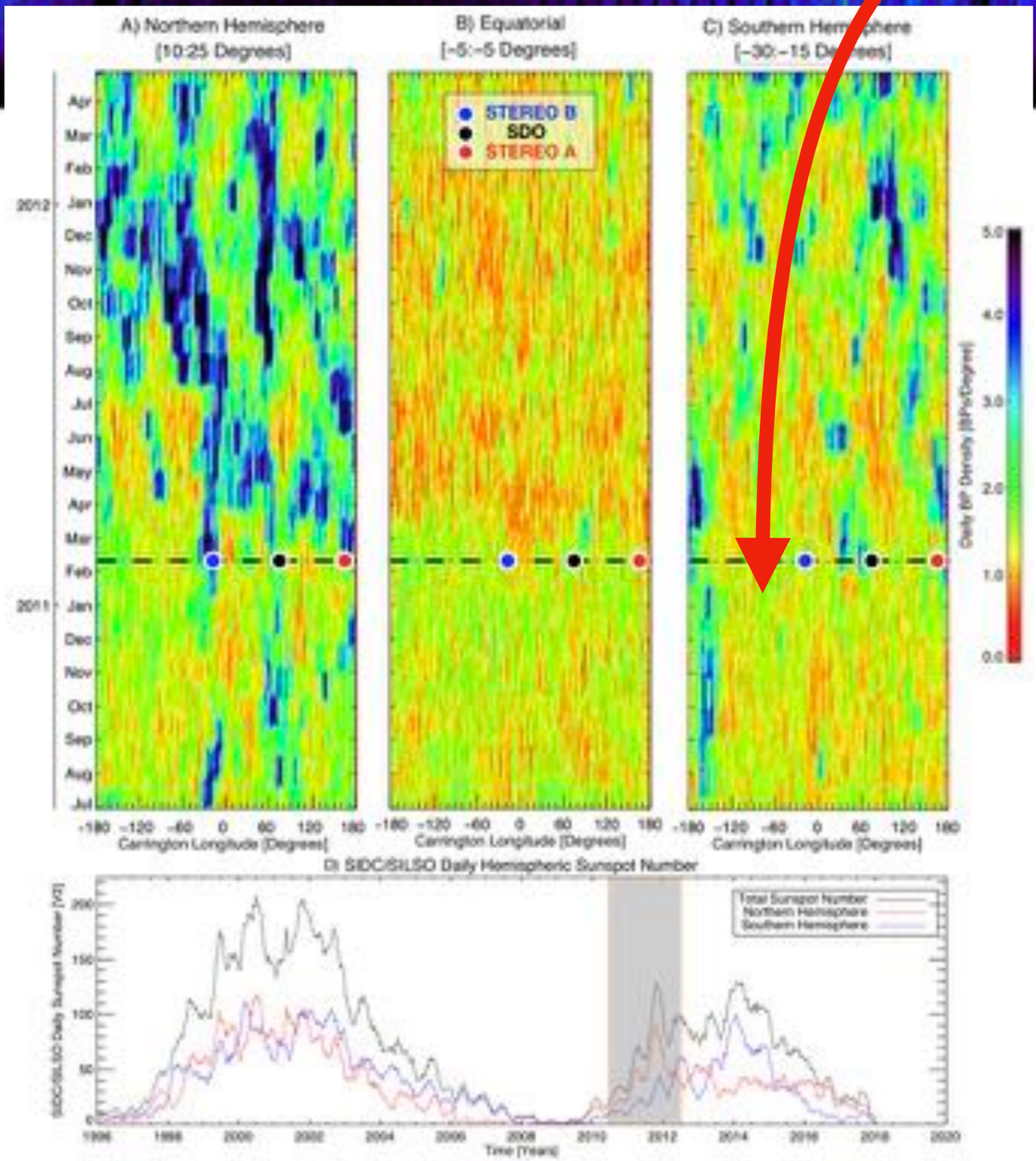

Activity is Longitudinal

Mapping Longitude
Vs
Time @ Fixed Latitude

The #terminator washes AROUND the Sun

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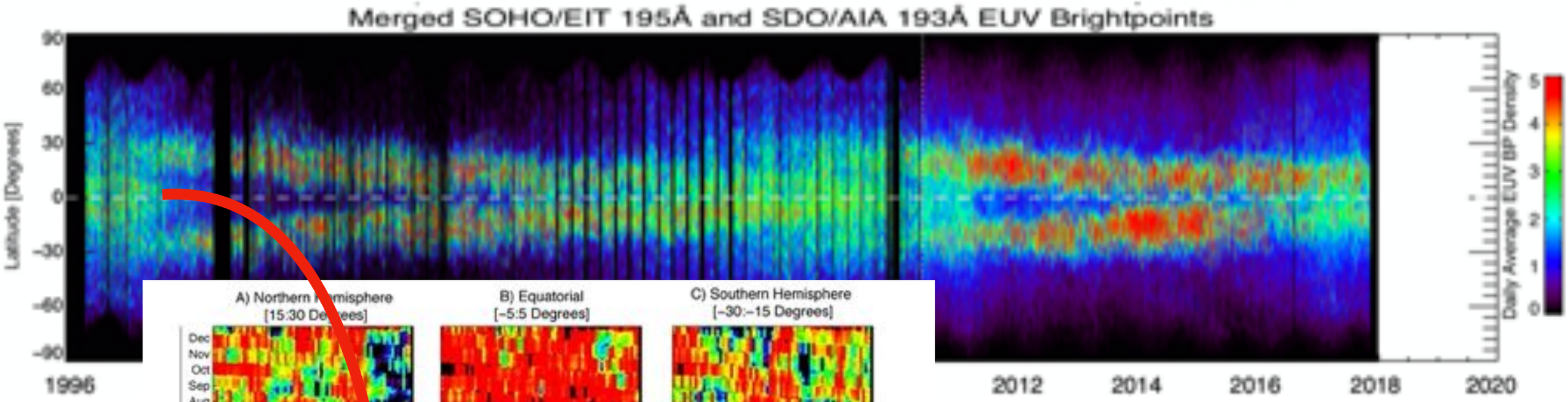

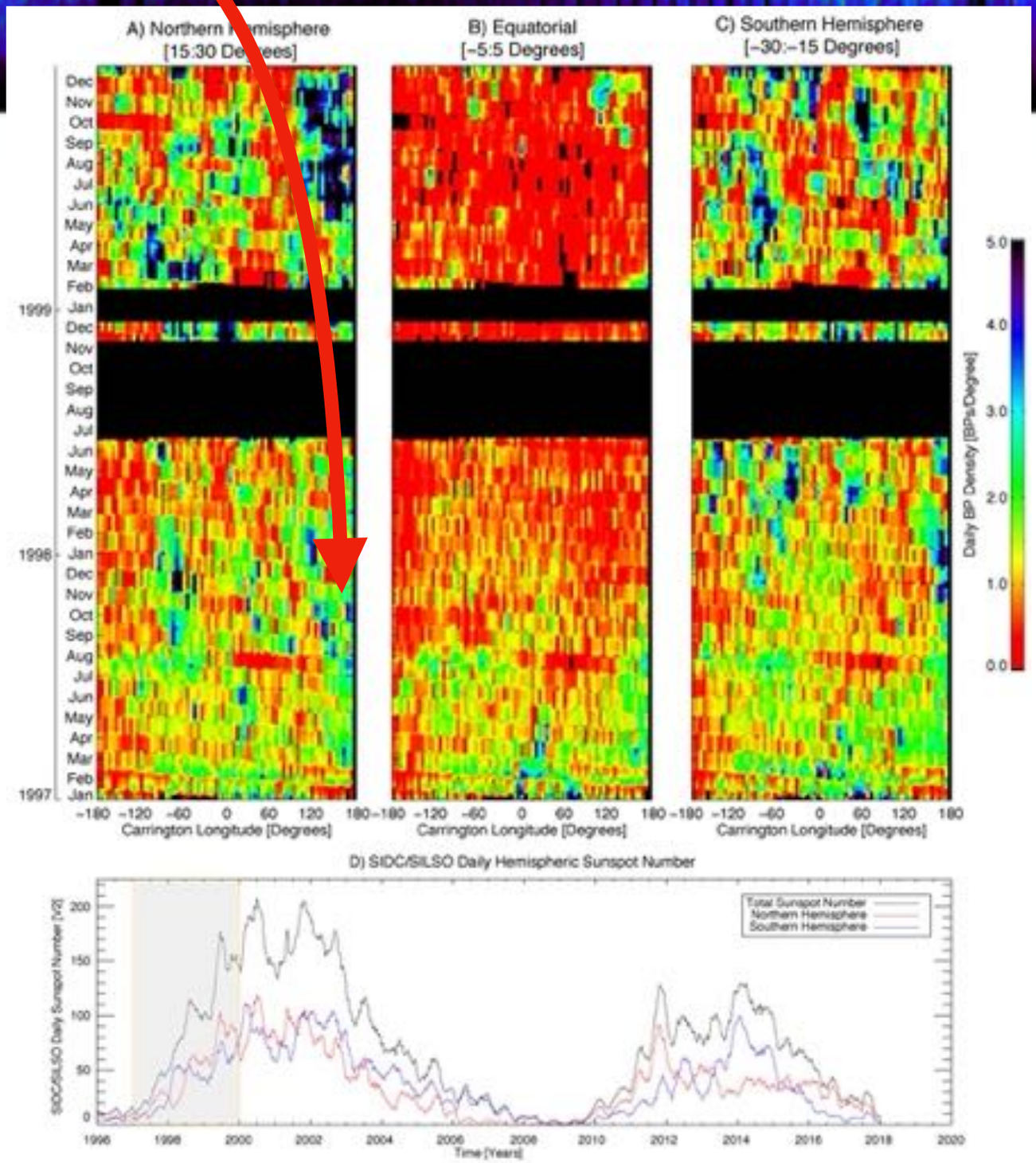

Activity is Longitudinal

Mapping Longitude
Vs
Time @ Fixed Latitude

The #terminator washes AROUND the Sun

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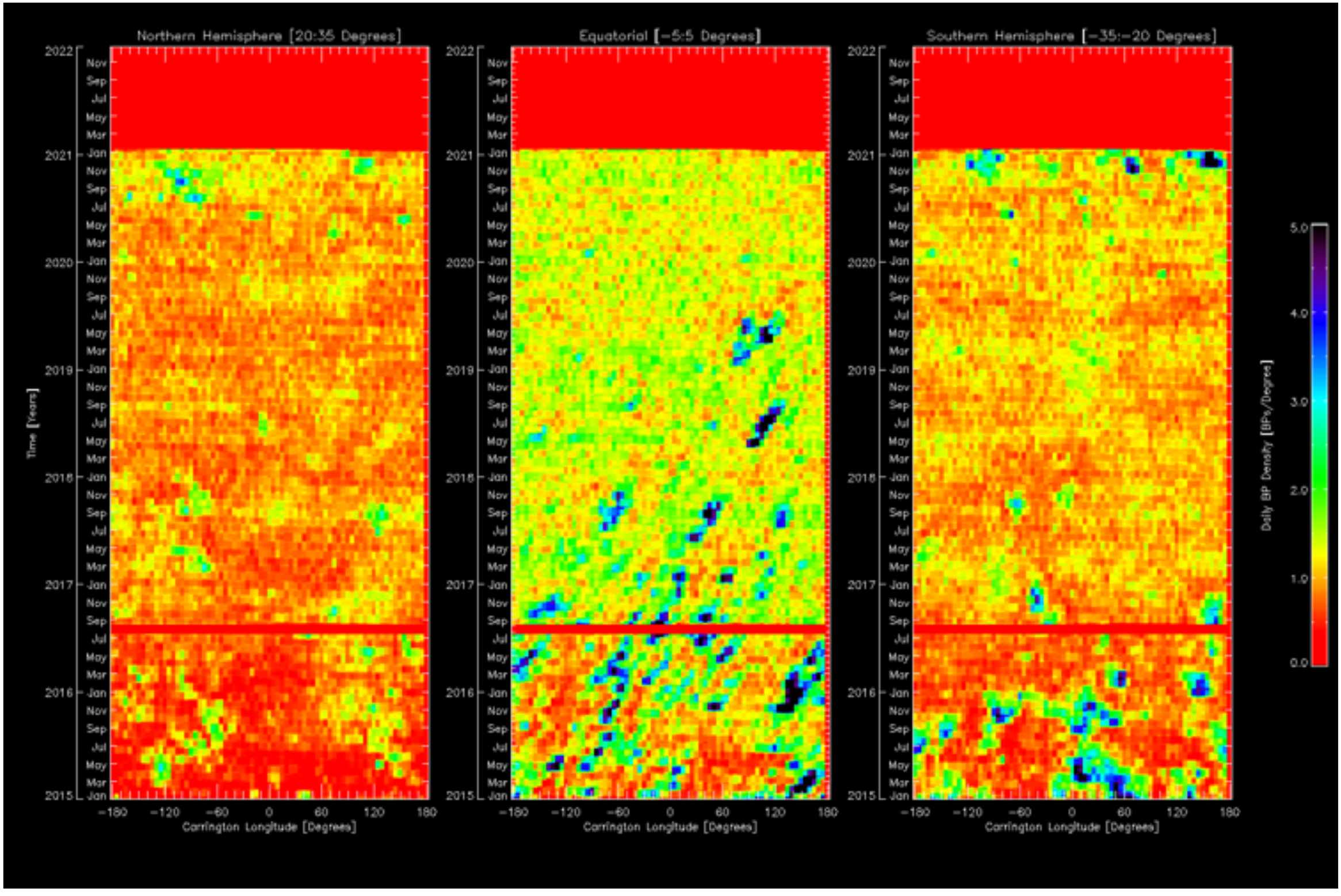
The #terminator washes AROUND the Sun

Late 2020: We saw growth at mid-latitudes [ESPECIALLY IN THE SOUTH] but not the drop at the equator. The #terminator is not here yet!



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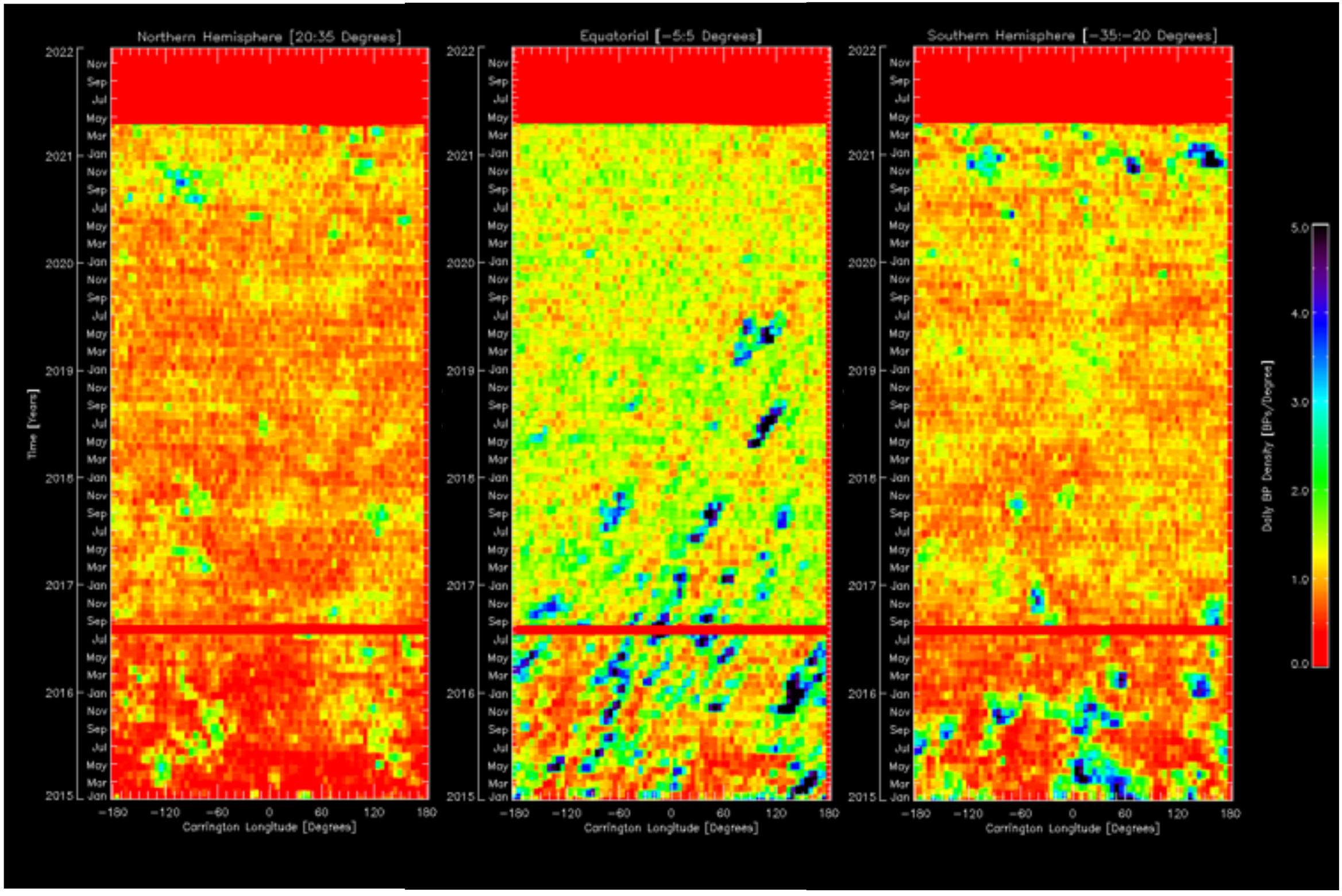
The #terminator washes AROUND the Sun

April 2021: We see growth at mid-latitudes but not the drop [YET] at the equator.
The #terminator is not here yet!



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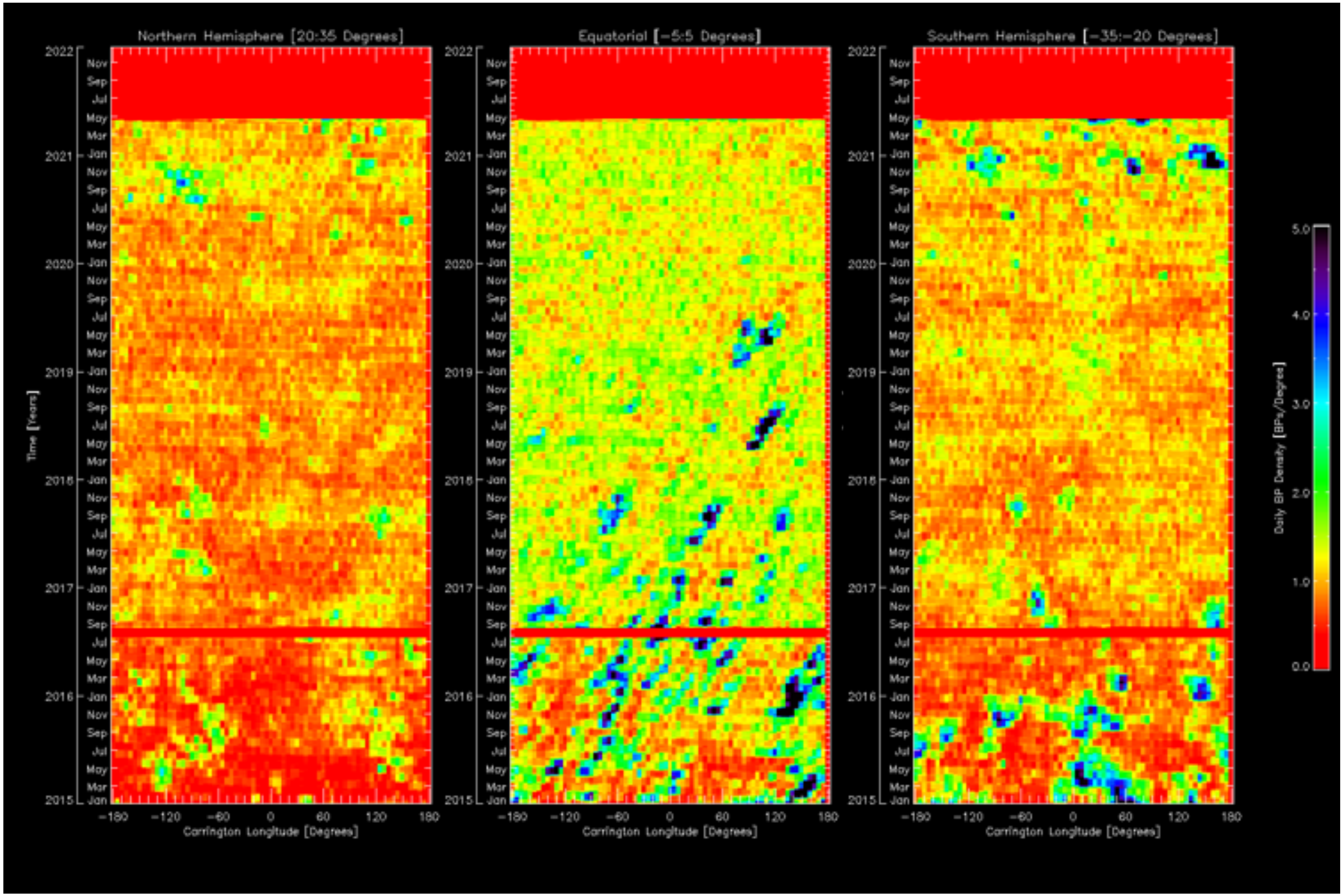
The #terminator washes AROUND the Sun

May 2021: We see growth at mid-latitudes but not the drop [YET] at the equator.
The #terminator is not here yet!



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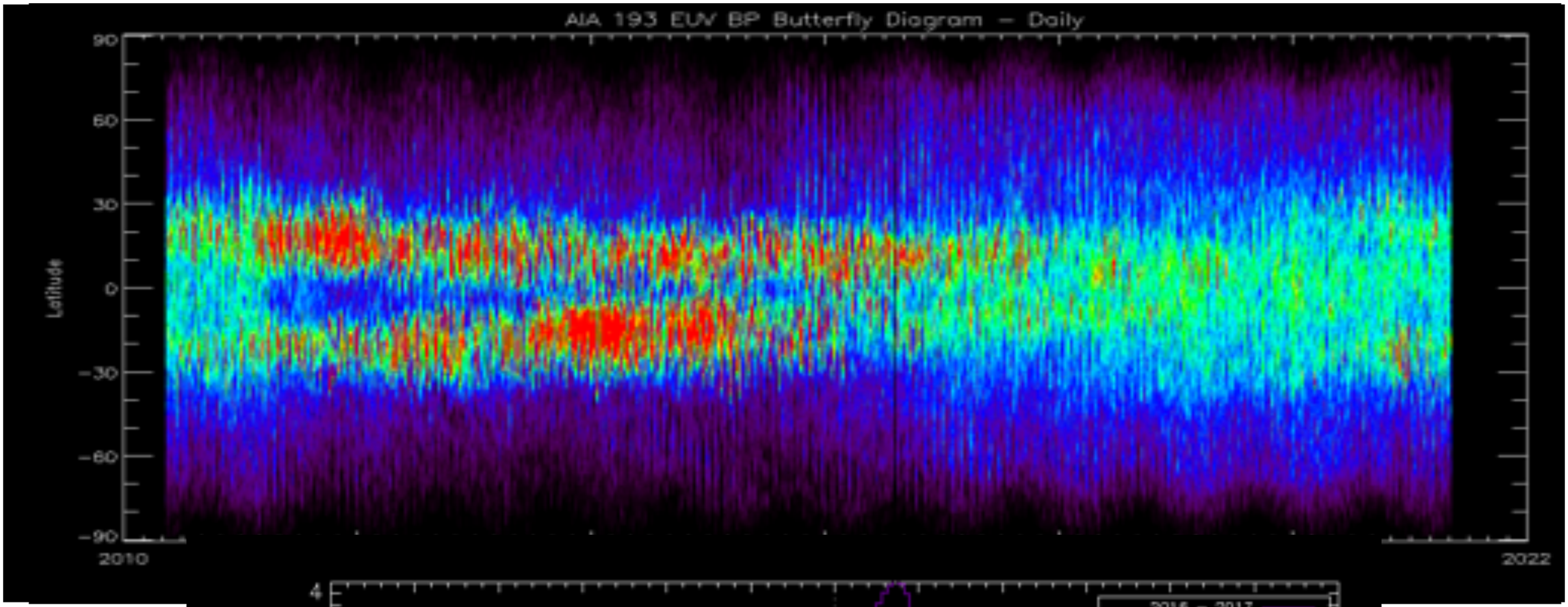
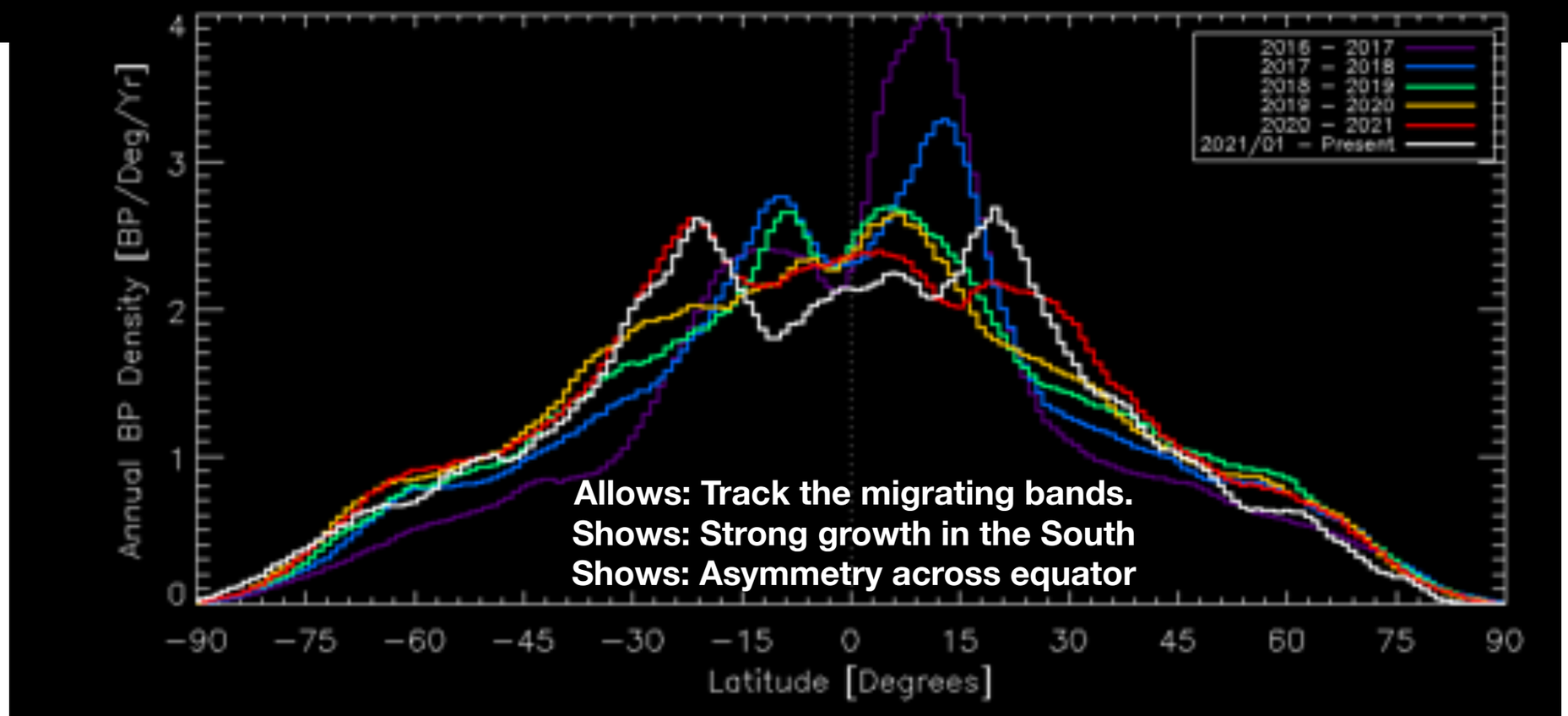
BP Density Slices through latitude over time





Allows: Track the migrating bands.
Shows: Strong growth in the South
Shows: Asymmetry across equator

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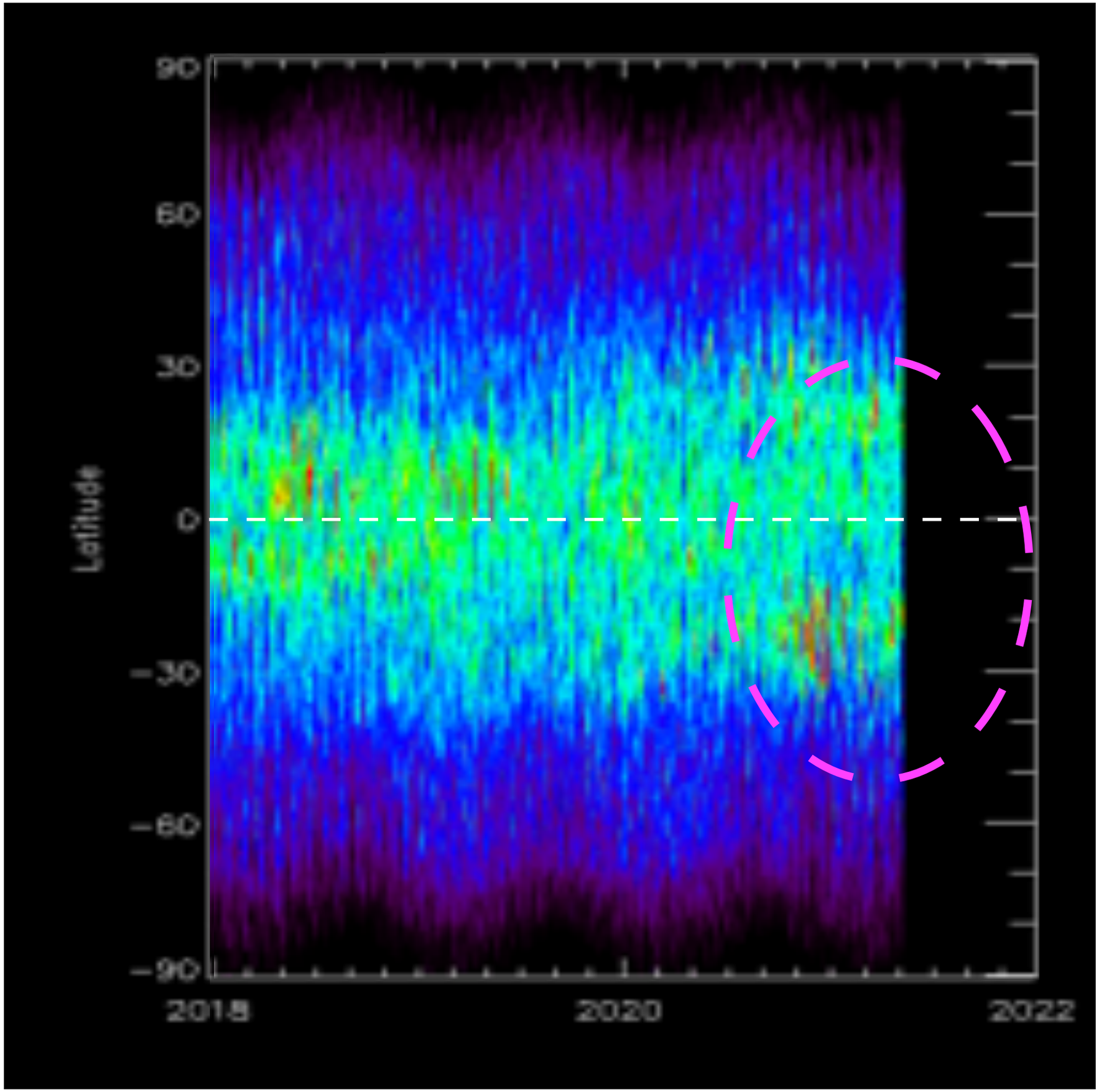

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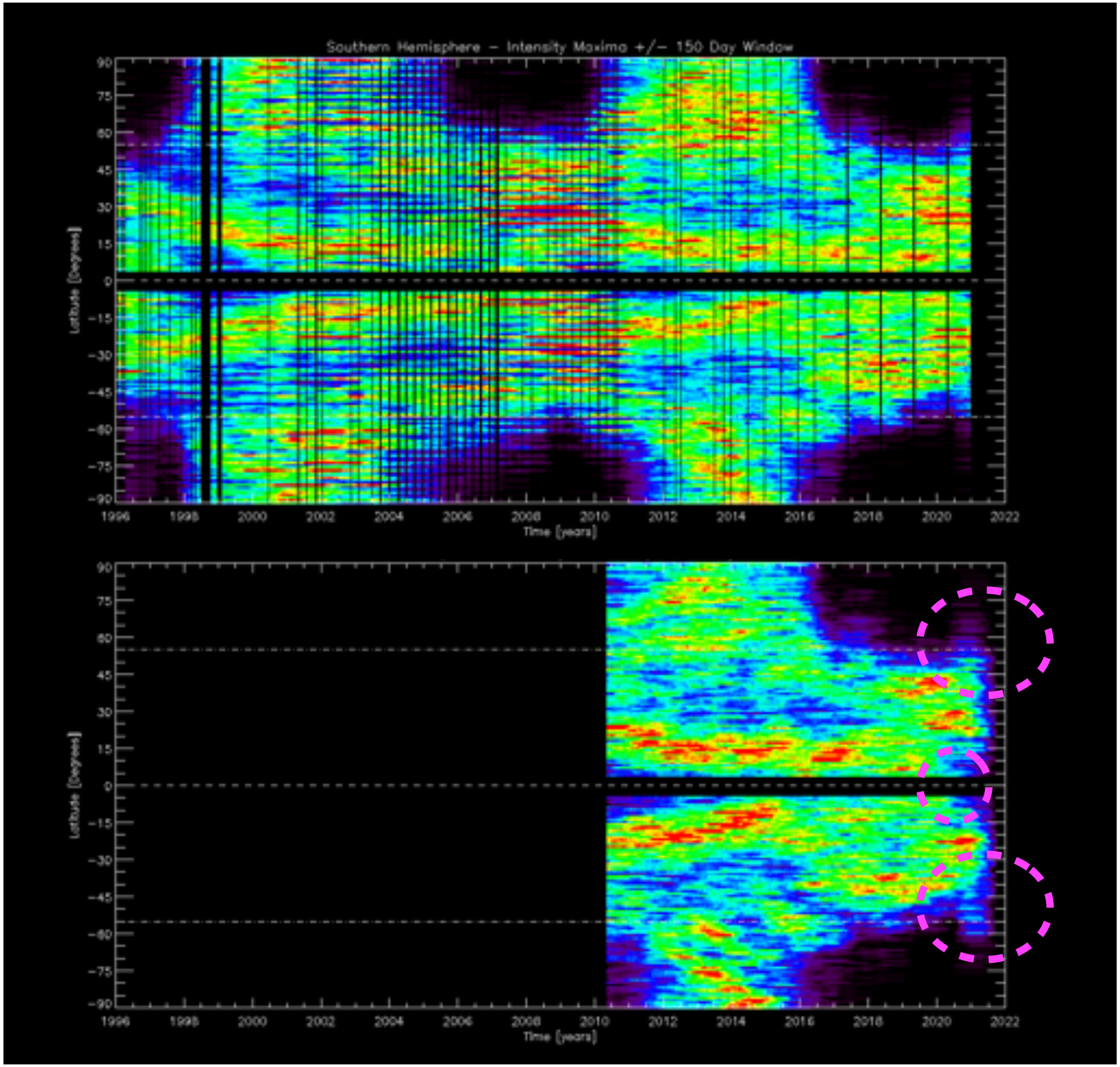
SOHO/EIT

SDO/AIA



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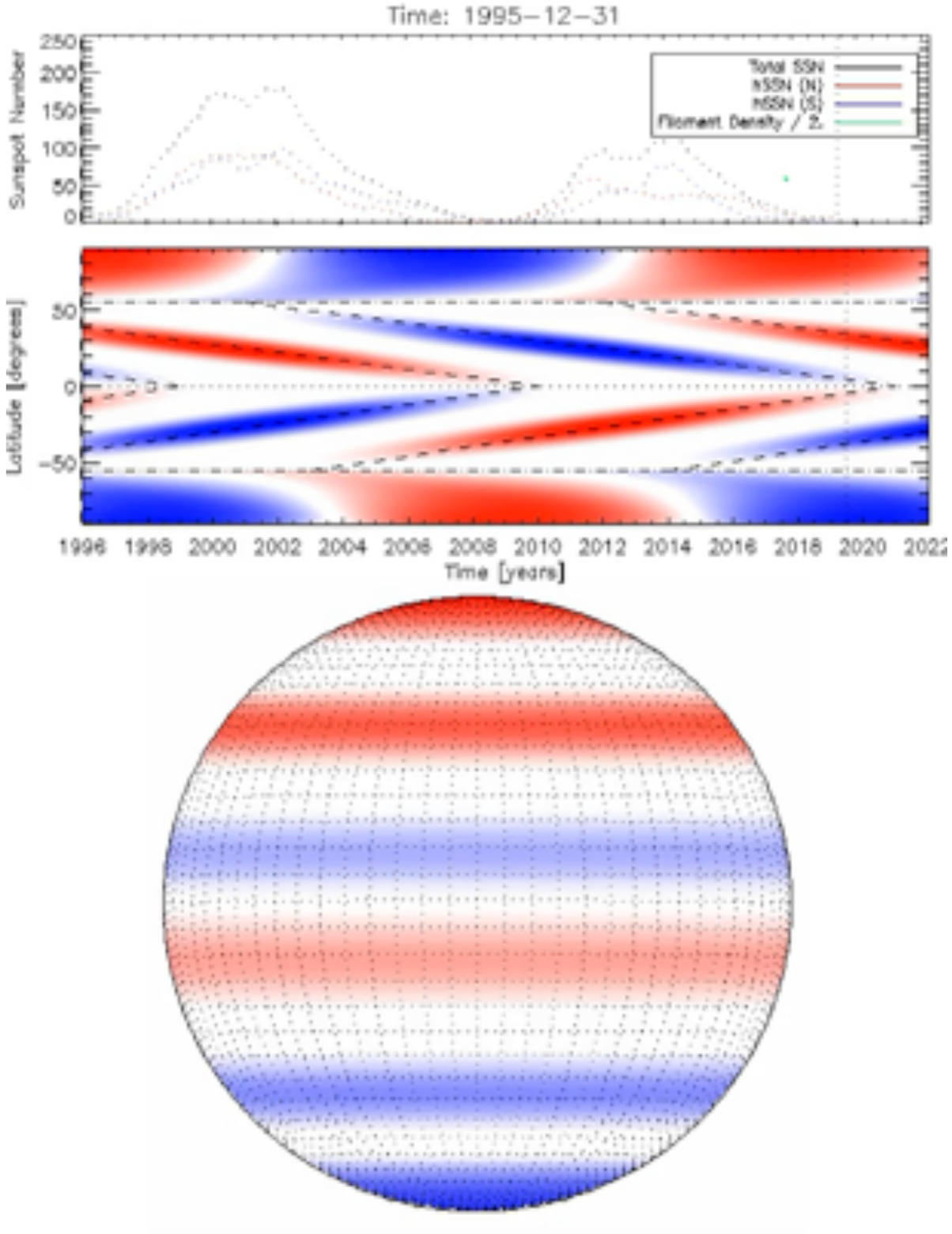
Conclusions



The "22-year" Hale (magnetic polarity) Cycle of the Sun is recurrent and robust.

The bands of the Hale Cycle have a definitive end, the "terminator", at the equator.

This terminator rapidly triggers growth and emergence of magnetism at mid (30-35°) and high (~55°) latitudes - within one solar rotation. Over the course of one/two rotations, at many longitudes.

The terminator sees a rapid jump in solar proxies throughout the upper atmosphere - most profound changes in corona.

M2014 Hypothesis: the bands of the Hale Cycle contrive to modulate the sunspot pattern and amplitude.

Terminator separation is one measure of the interplay of the Hale Cycle bands.

Long terminator separations yield small upcoming cycles and vice versa.

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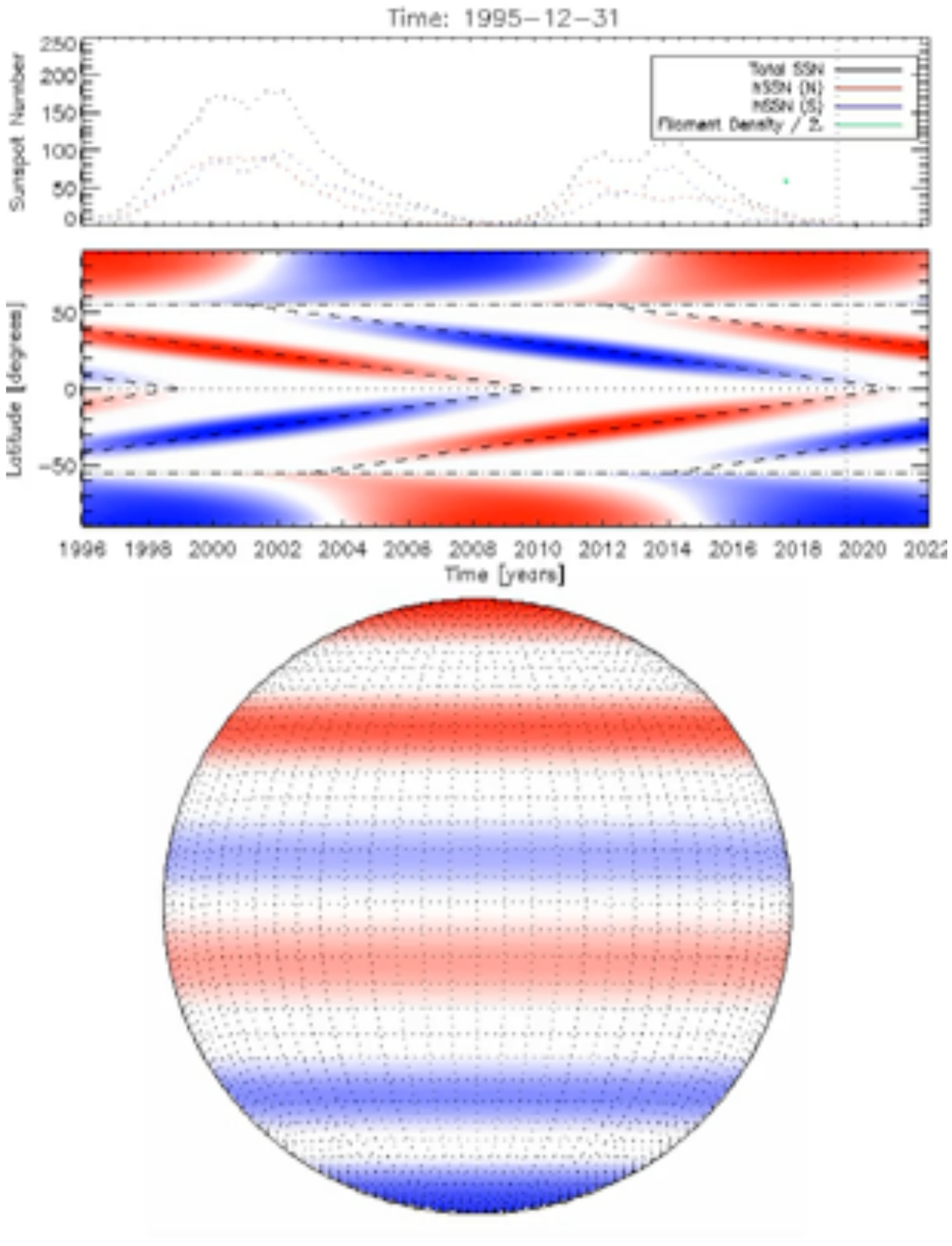
Conclusions



#Terminator separation at 10.25 years

If #Terminator occurs - SC25 will be of significant amplitude based on this relationship spanning 24 cycles. Possibly in the top 5 since the record began.

The derived relationship under-estimates big cycles.

Terminators, as much as possible, provide a robust fiducial to study the recurrence of a host of phenomenology.

What comes next?

Are we ready?

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