

# Sunspot Cycle 25 and the 'Rogue' Forecast

ALSO

## Testing A Hypothesis In Real Time

Scott W McIntosh

X @swmcintosh

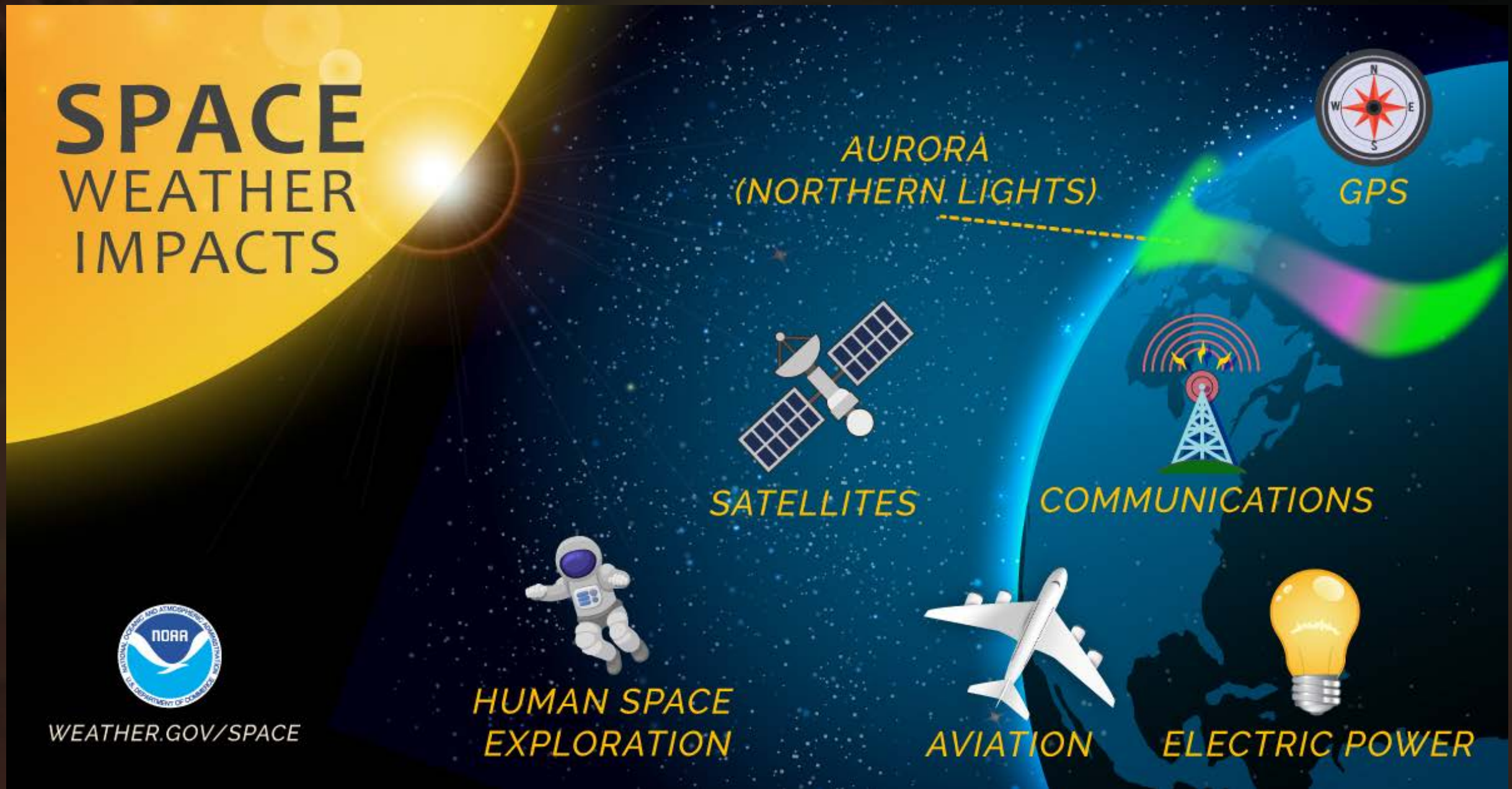
Presented by Tom Berger  
University of Colorado Boulder



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.



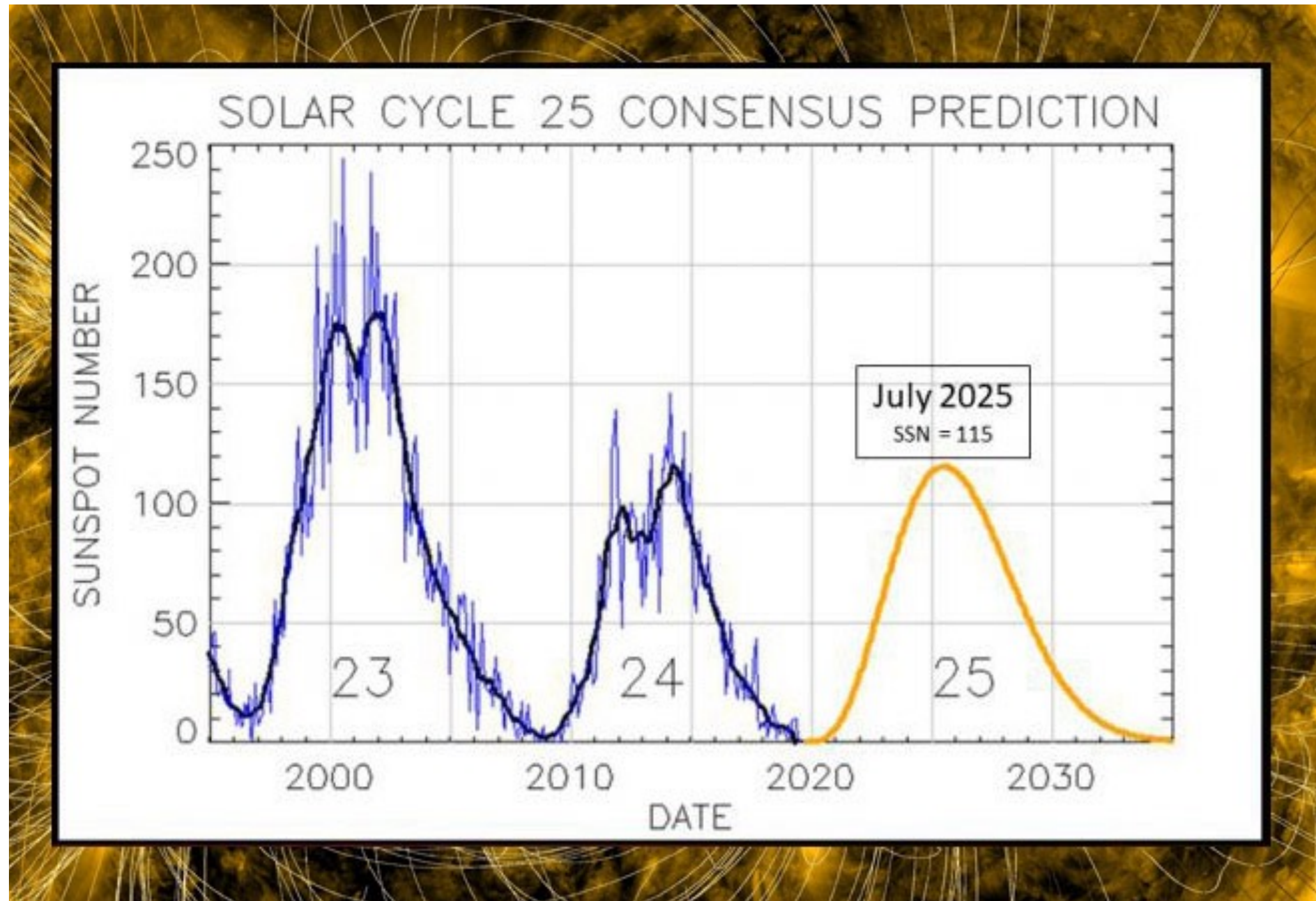
# Why is predicting solar activity important?



**RECALL:** Forecasts of solar activity **drive** the models that protect lives and assets in space and utilities on the ground? If those forecasts are wrong...  
....it is our mission to have high a “skill” as possible to protect these assets.

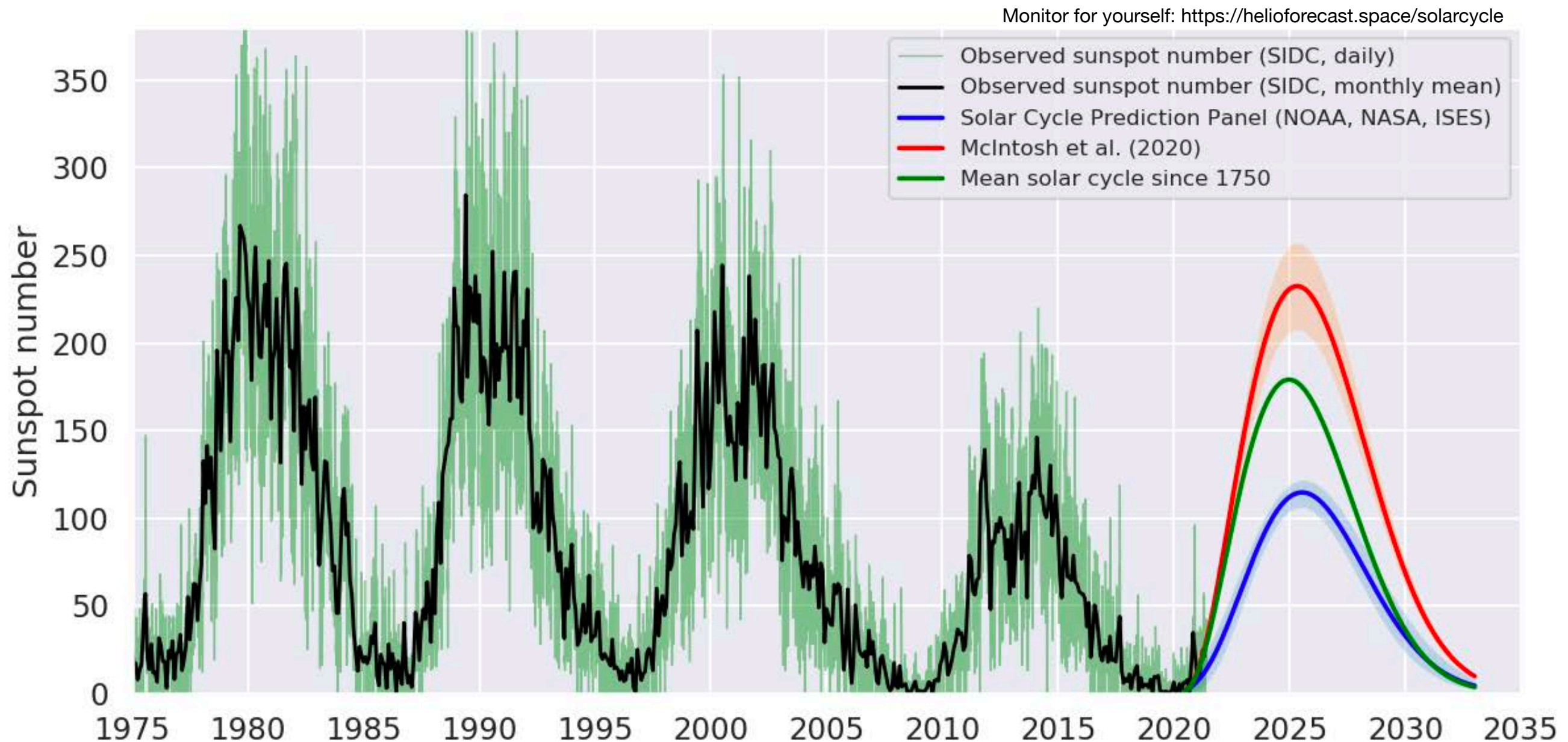


# The SC25 “Consensus” Forecast 2020



Are there [real world] risks associated with adopting this model for Sunspot Cycle 25?

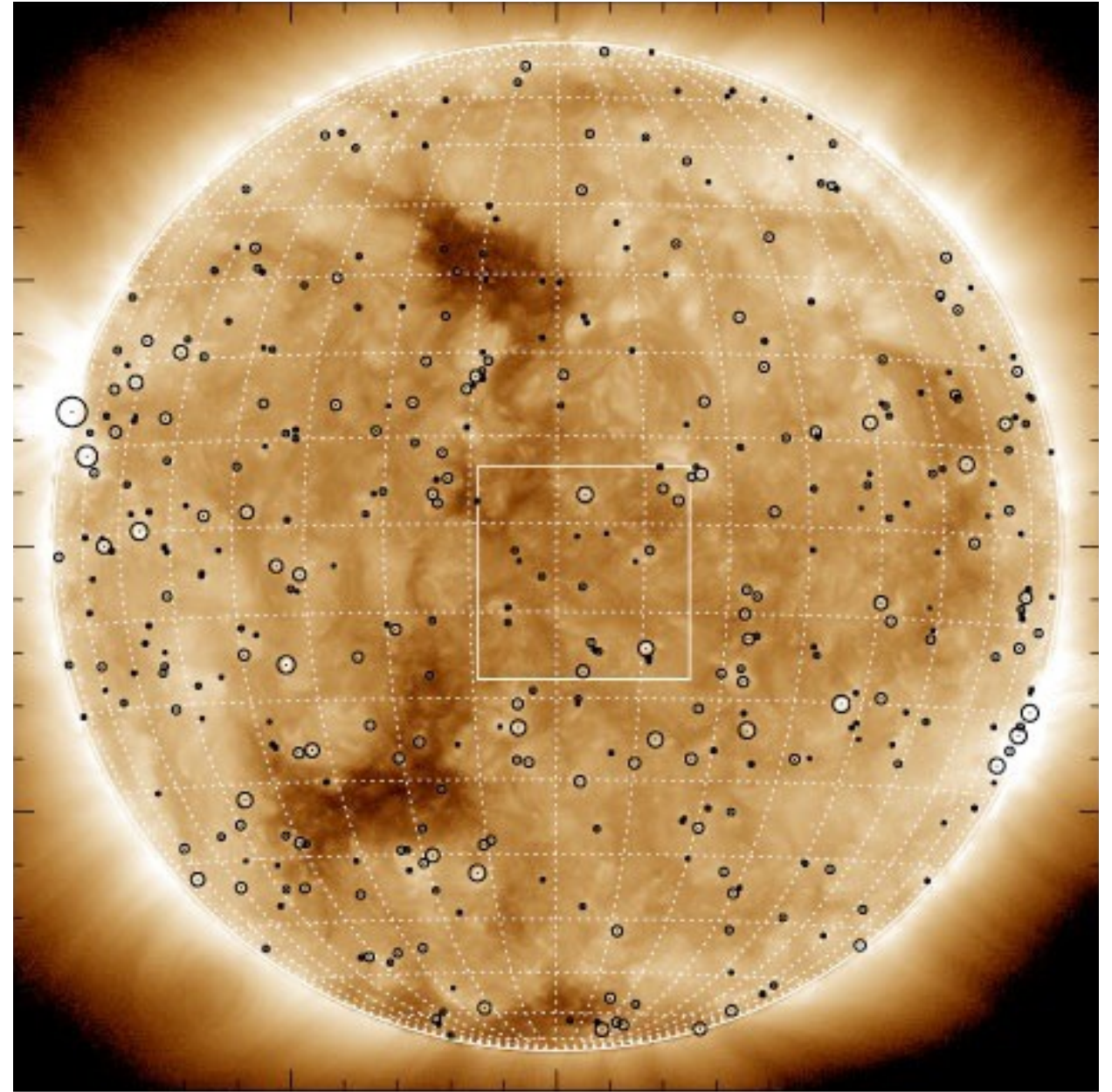
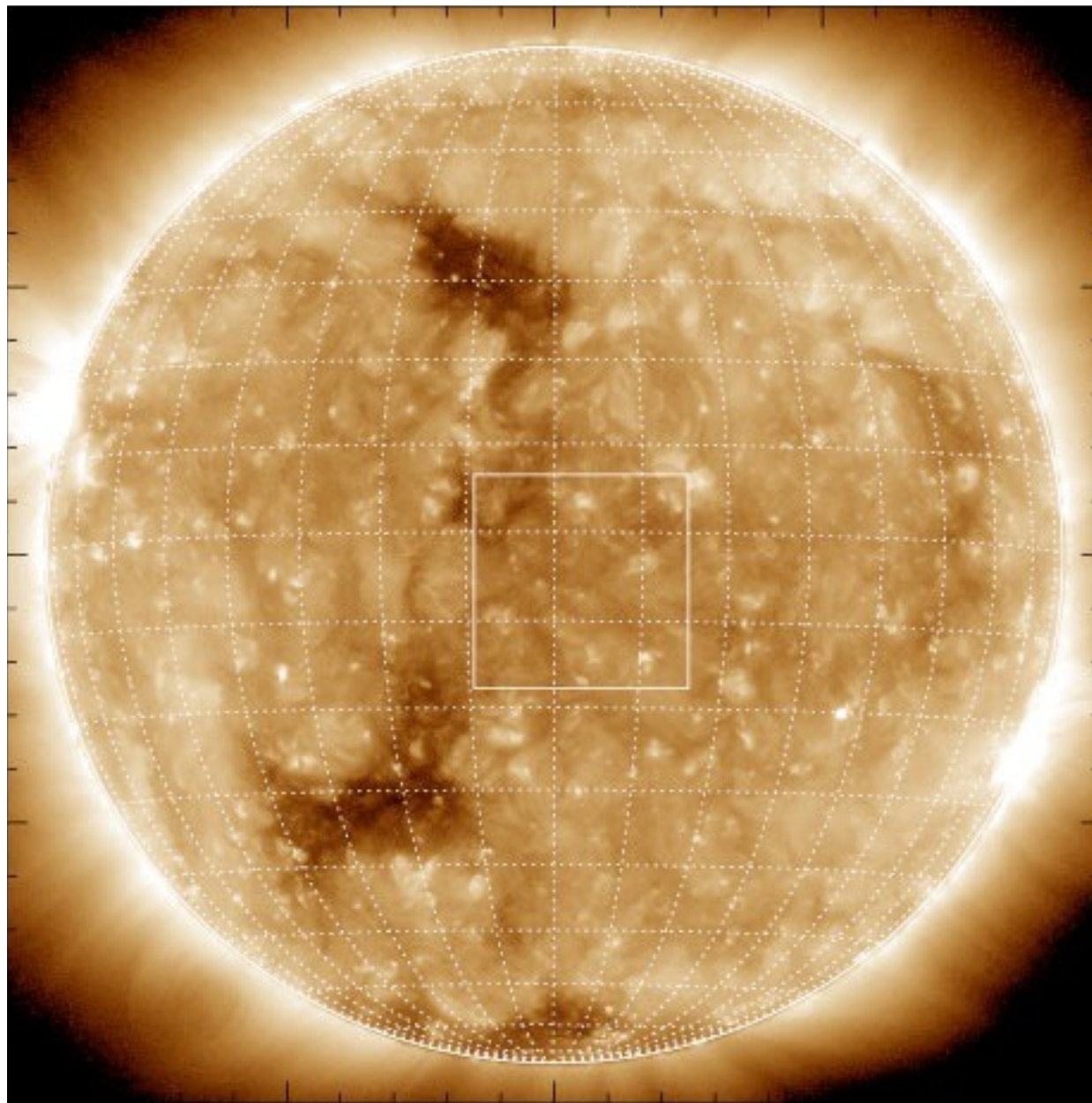
# Rogue Forecast: Testing A Hypothesis In Real Time



**In 2019 we were wondering about the connection of Hale Cycles and Sunspot Cycles to the point where we thought we could forecast what came next. It caused quite a stir.**

**This lecture concerns the origins of that forecast and where it stands **RIGHT NOW!****



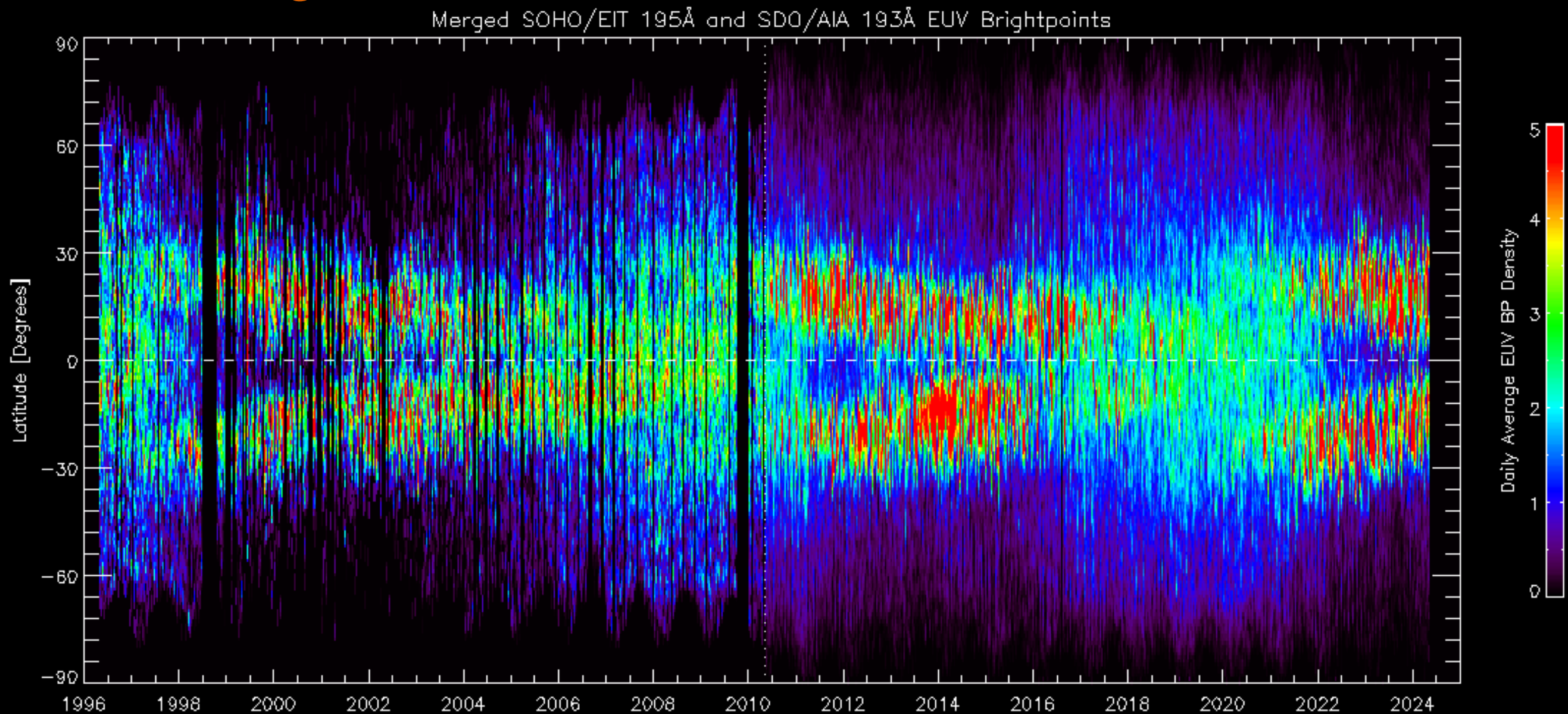


**In addition to sunspots we use space telescopes to identify and track small ubiquitous features in the solar corona called 'EUV Bright Points'**

**“....you might find something interesting” they said.... in 2002.**

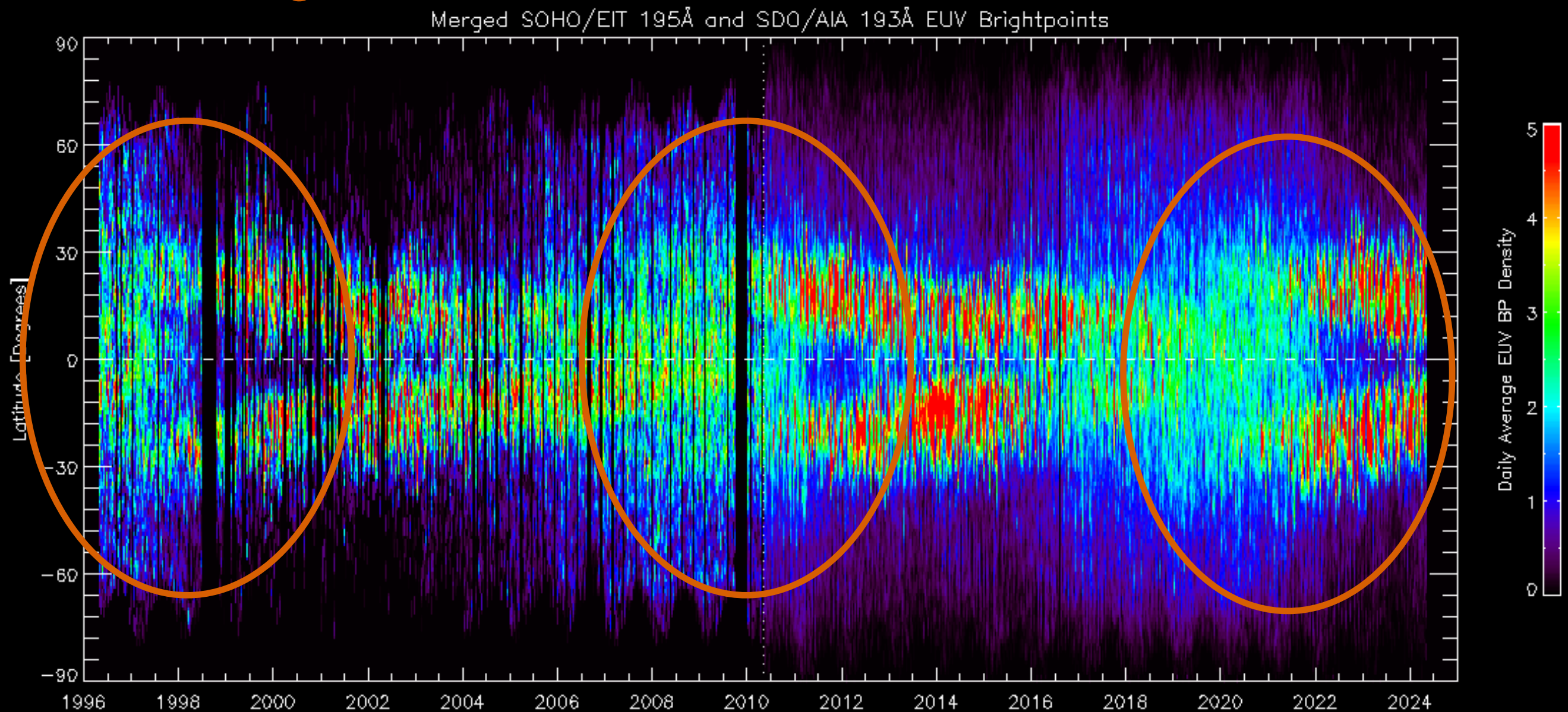


# The EUV BrightPoint Record



In late 2011 - after counting and cataloging 10s of millions of EUV BPs - we noticed a few things upon considering their 'butterfly' diagram:

# The EUV BrightPoint Record

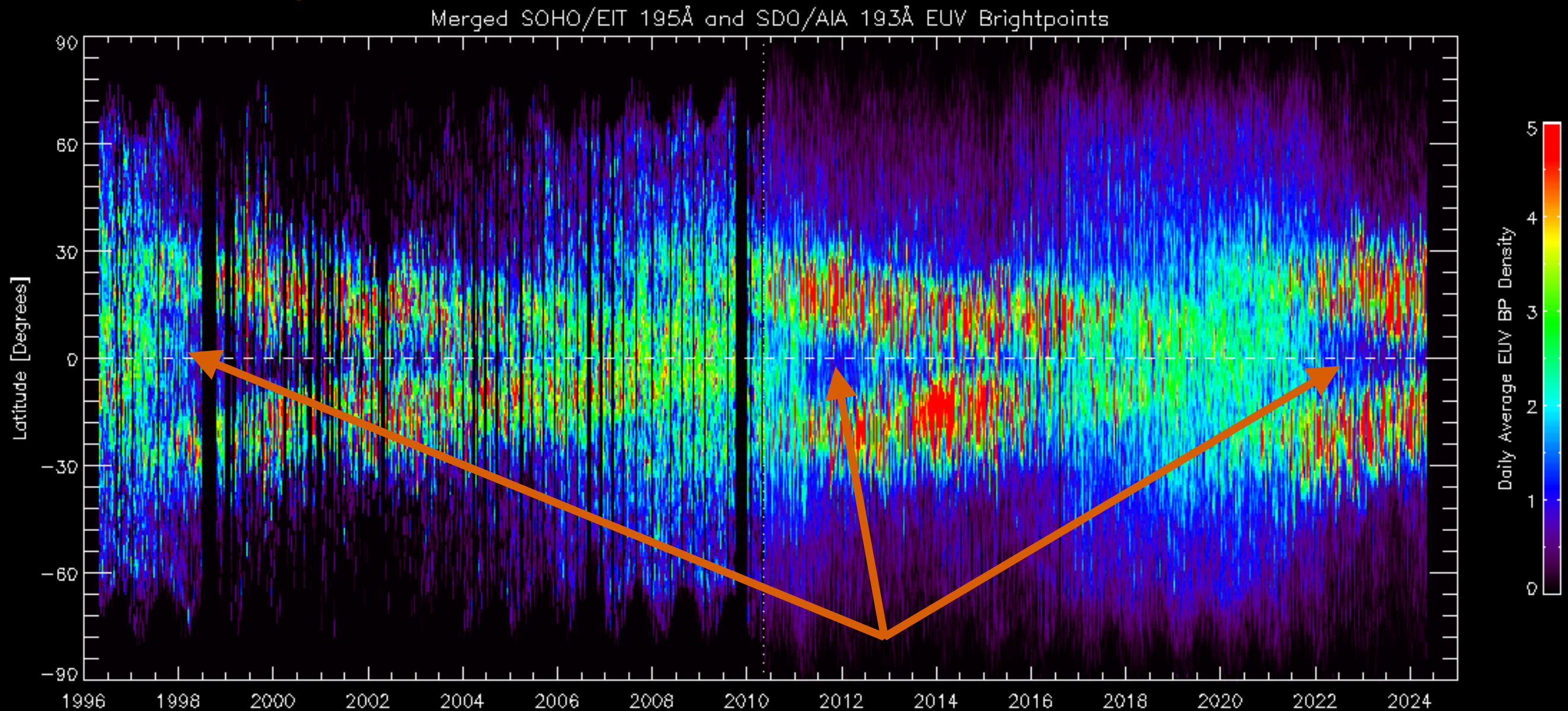


In late 2011 - after counting and cataloging 10s of millions of EUV BPs - we noticed a few things upon considering their 'butterfly' diagram:

- At times there are **CLEARLY FOUR** 'bands' of EUV BPs.



# The EUV BrightPoint Record

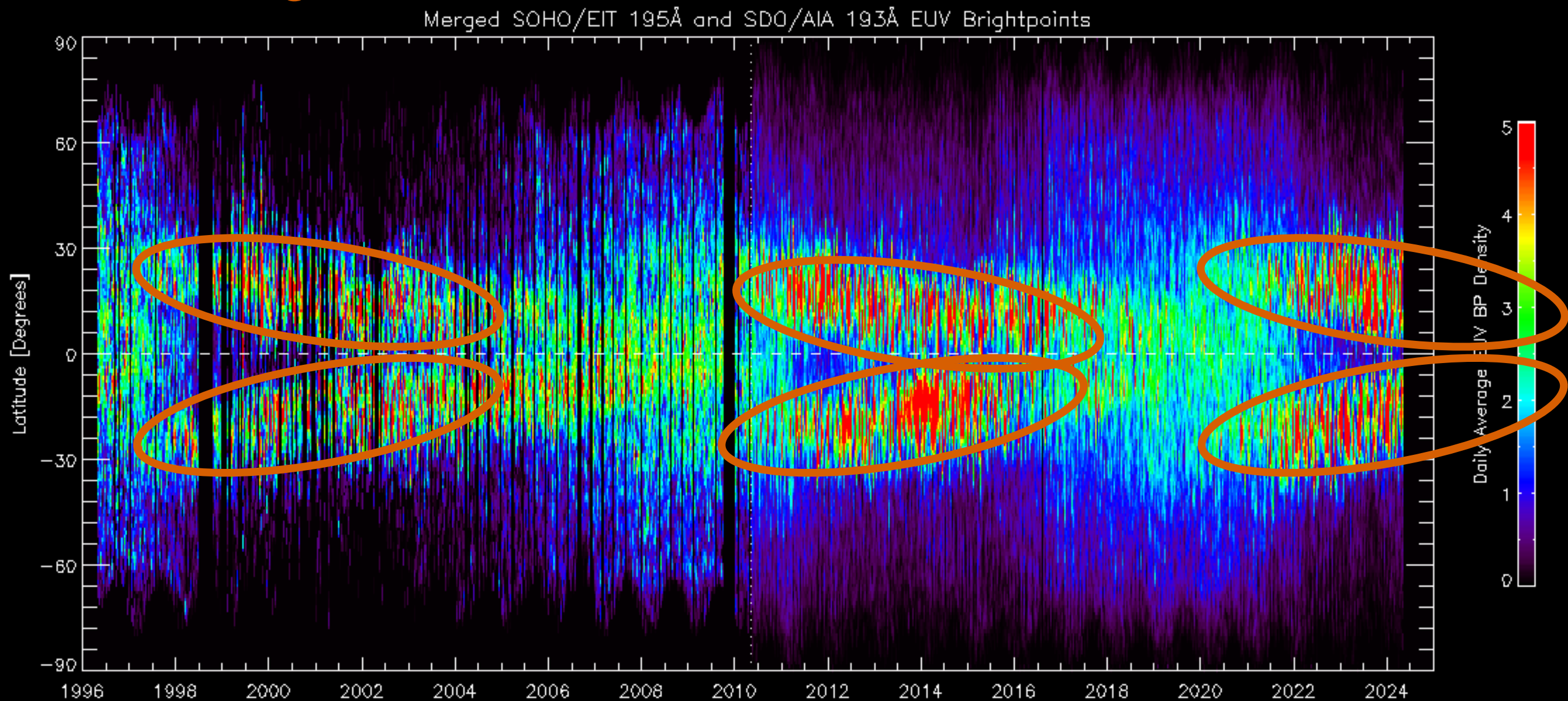


In late 2011 - after counting and cataloging 10s of millions of EUV BPs - we noticed a few things upon considering their 'butterfly' diagram:

- At times there are **CLEARLY FOUR** 'bands' of EUV BPs.
- The lowest latitude bands come to a **VERY** abrupt end at the equator.



# The EUV BrightPoint Record



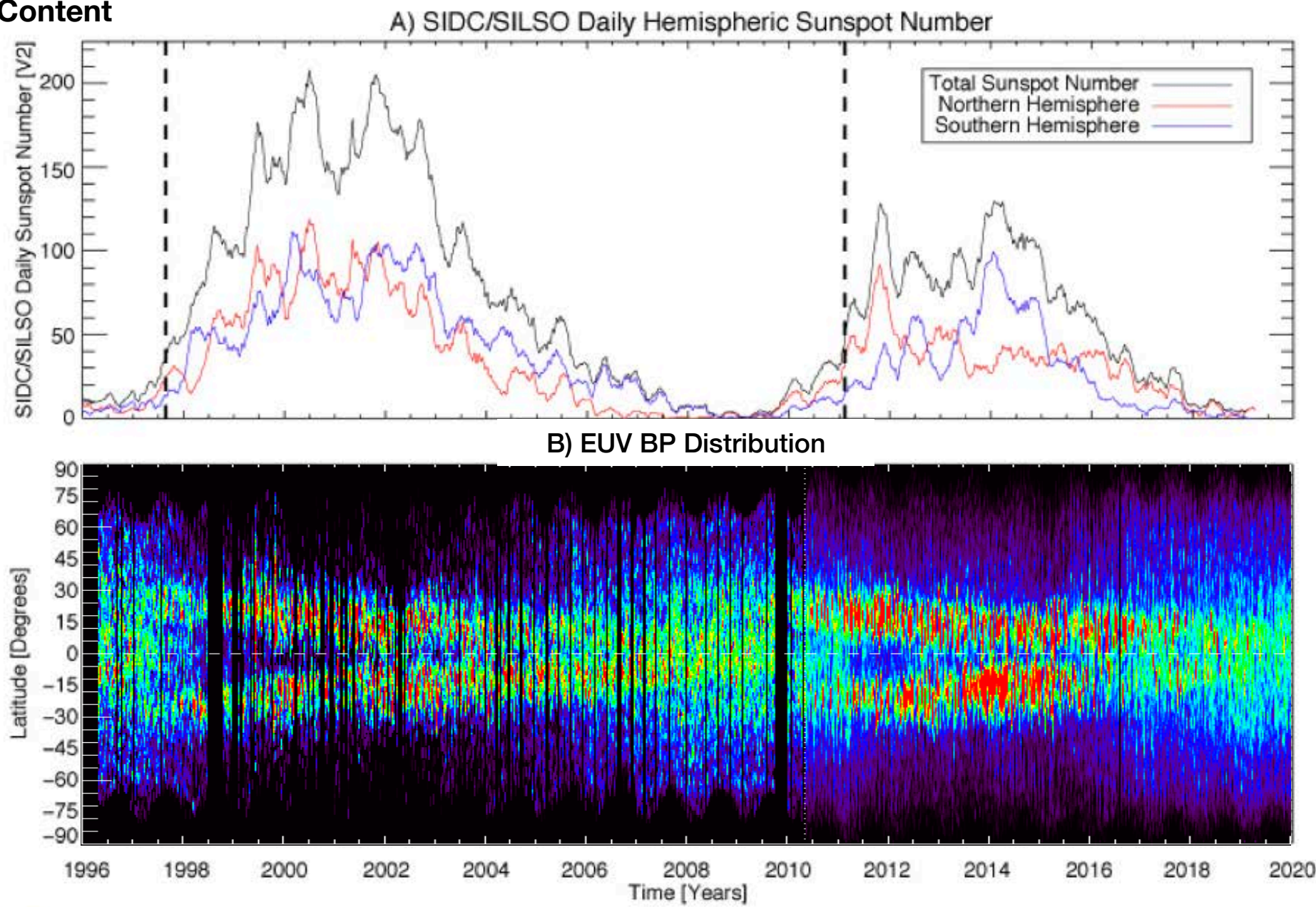
In late 2011 - after counting and cataloging 10s of millions of EUV BPs - we noticed a few things upon considering their 'butterfly' diagram:

- At times there are **CLEARLY FOUR** 'bands' of EUV BPs.
- The lowest latitude bands come to a **VERY** abrupt end at the equator.
- Activity significantly increases on the remaining (mid-latitude) bands.



# EUV BP Record - In Context With The Sunspot Number

2020 Content



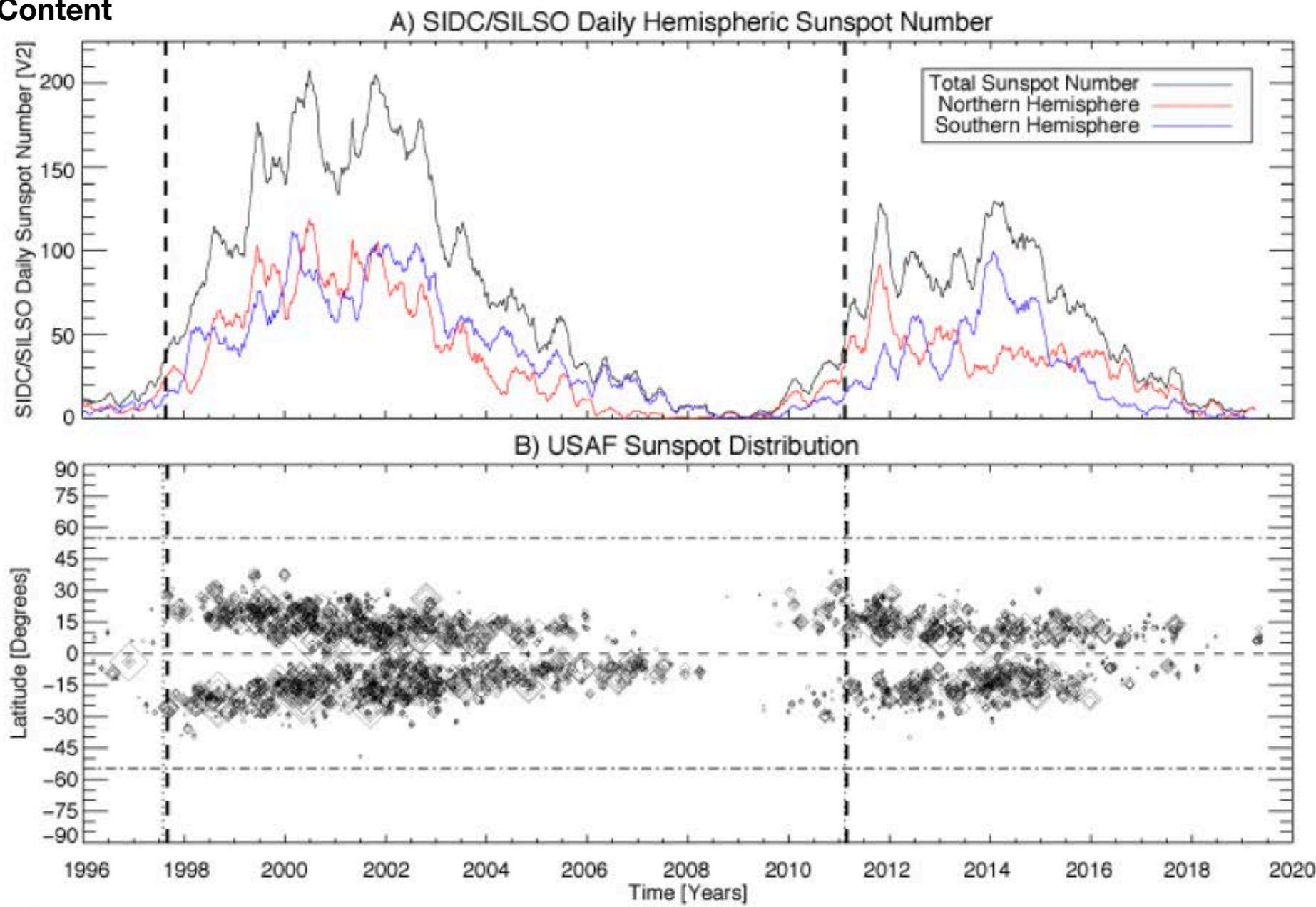
**What IS solar minimum?**  
**Does solar minimum just END?**

msscott@ucar.edu



# EUV BP Record - In Context With The Sunspot Butterfly

2020 Content

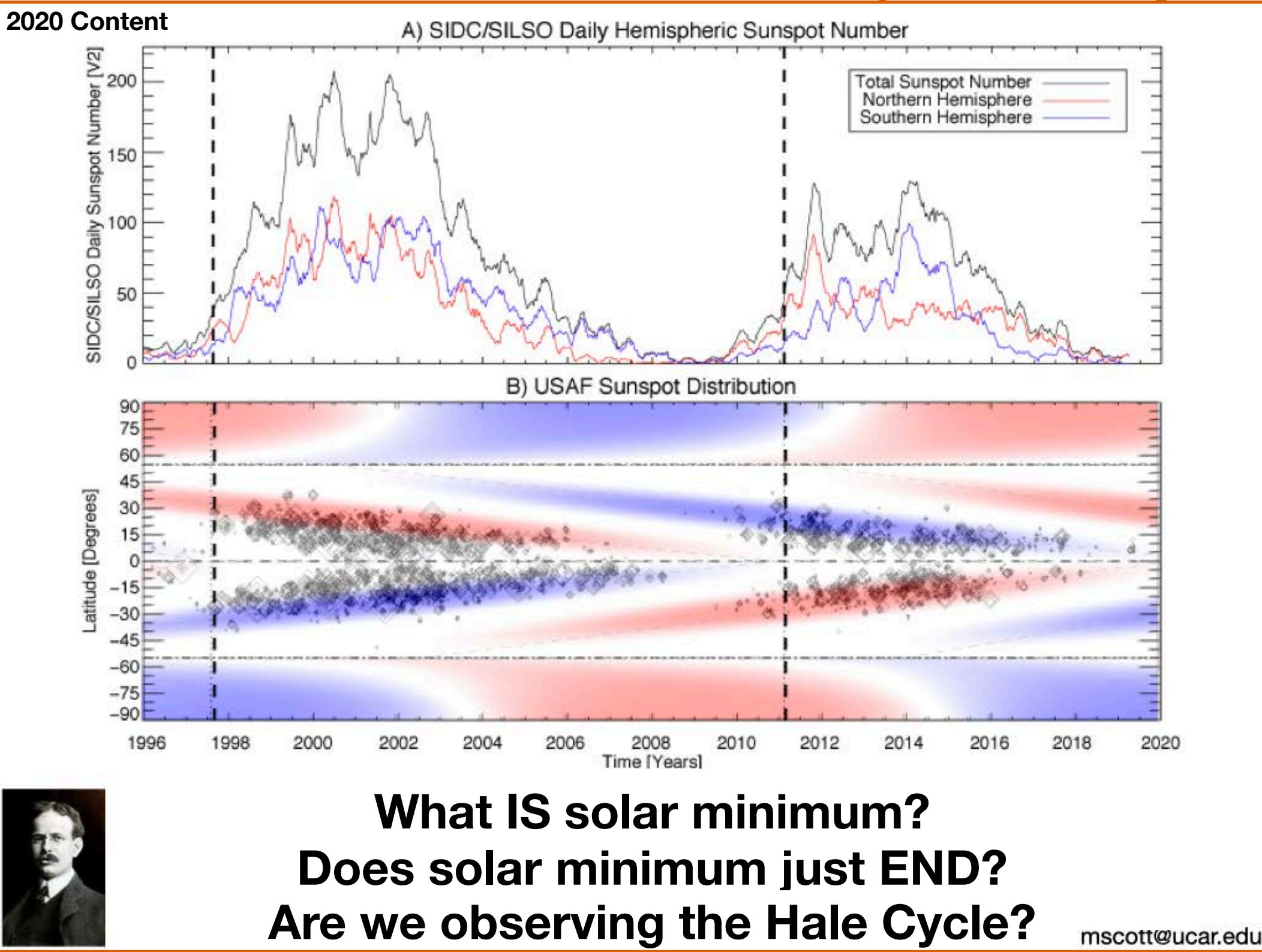


**What IS solar minimum?**  
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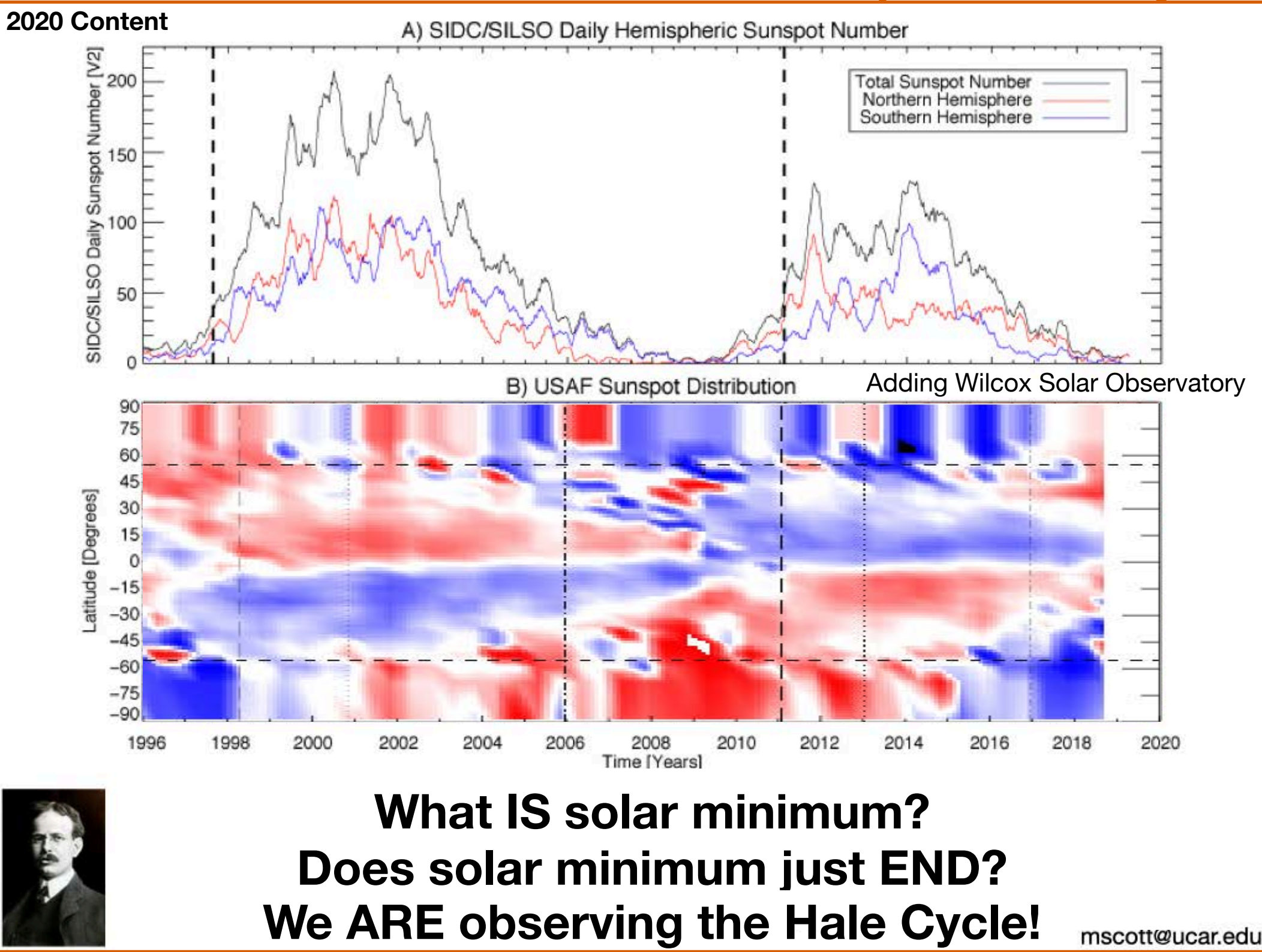


# EUV BP Record - In Context With The Sunspot Butterfly



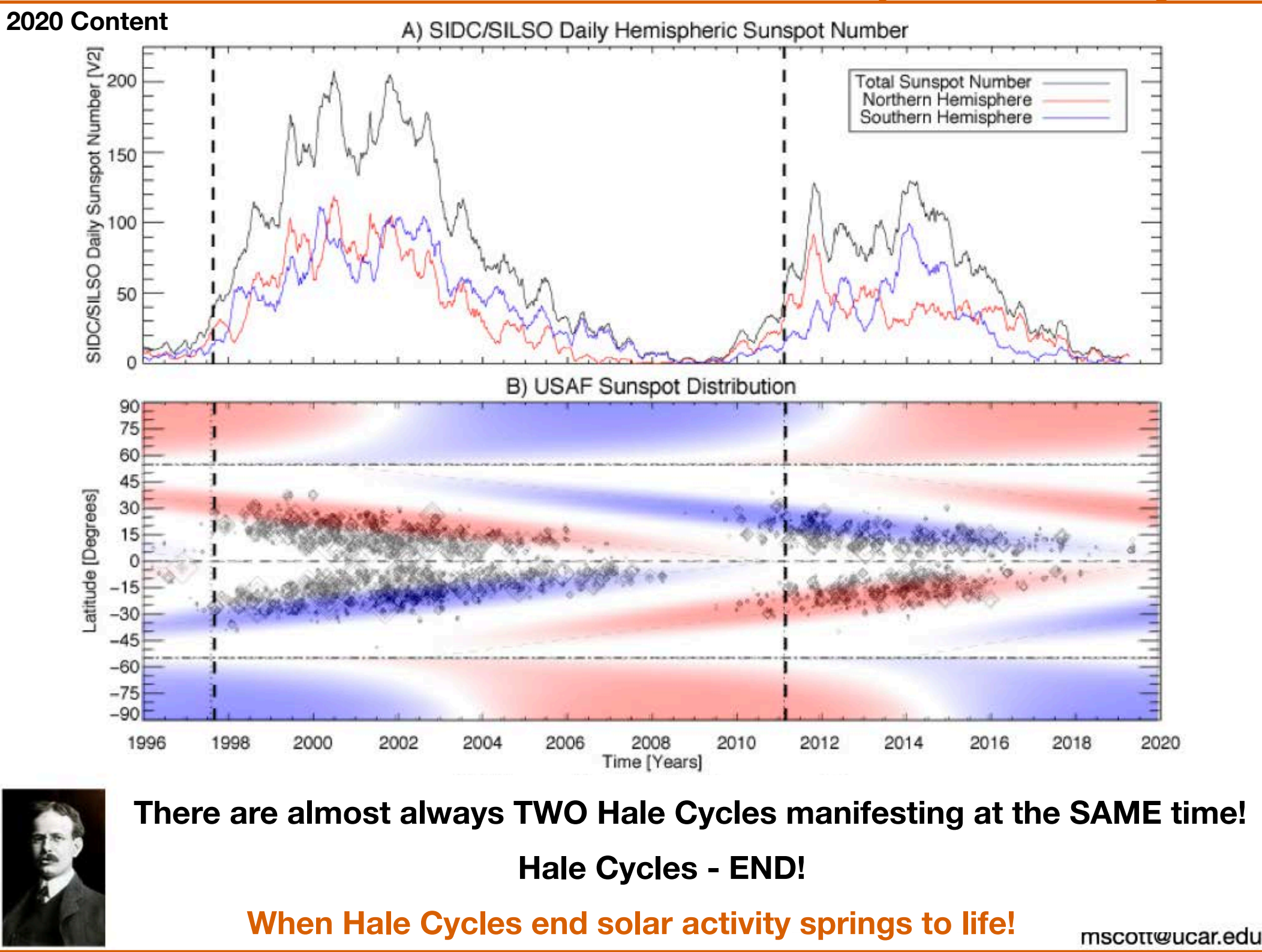


# EUV BP Record - In Context With The Sunspot Butterfly





# EUV BP Record - In Context With The Sunspot Butterfly



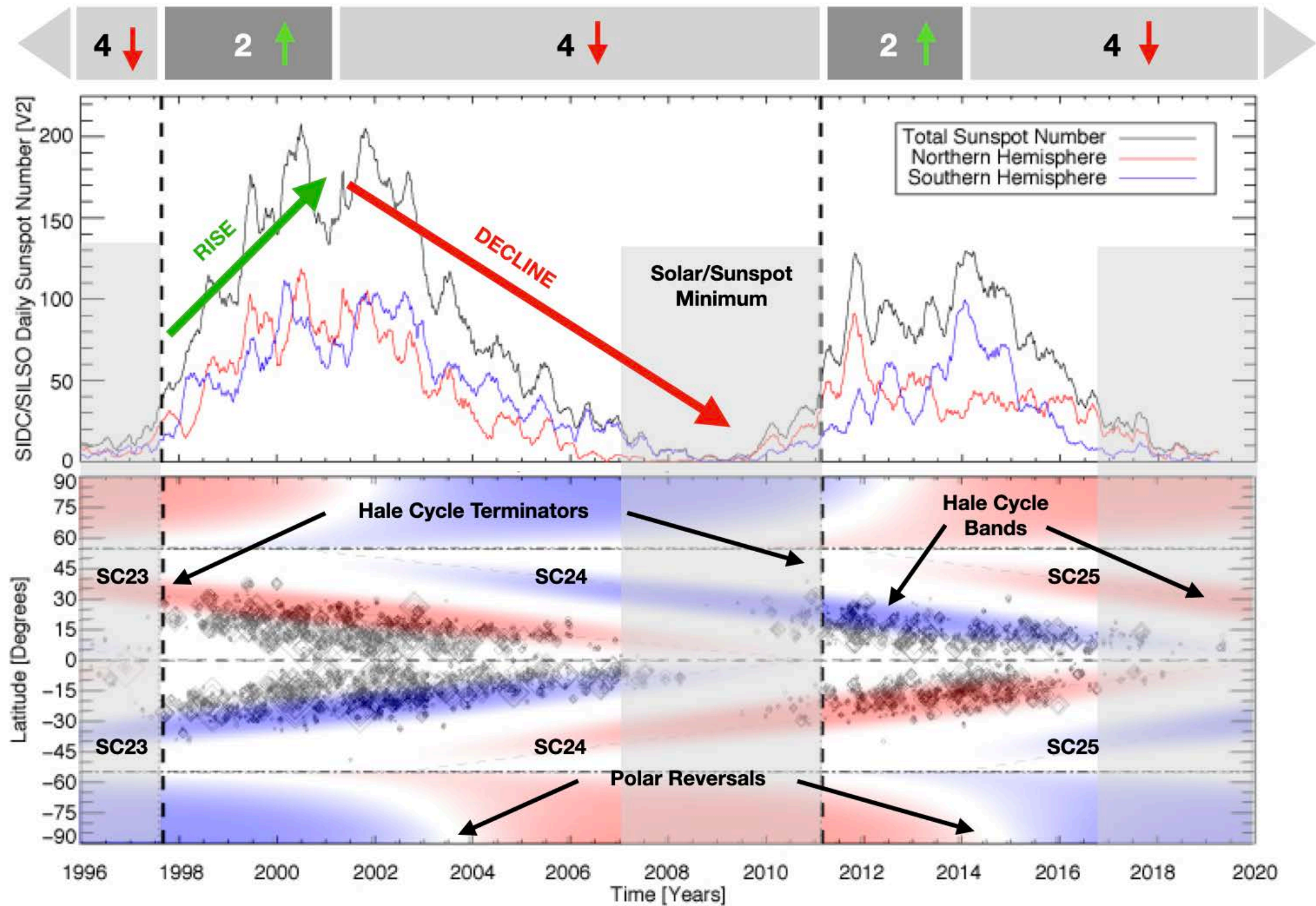
The Sunspot Cycle is derivative of, and dependent on, the Hale Cycle



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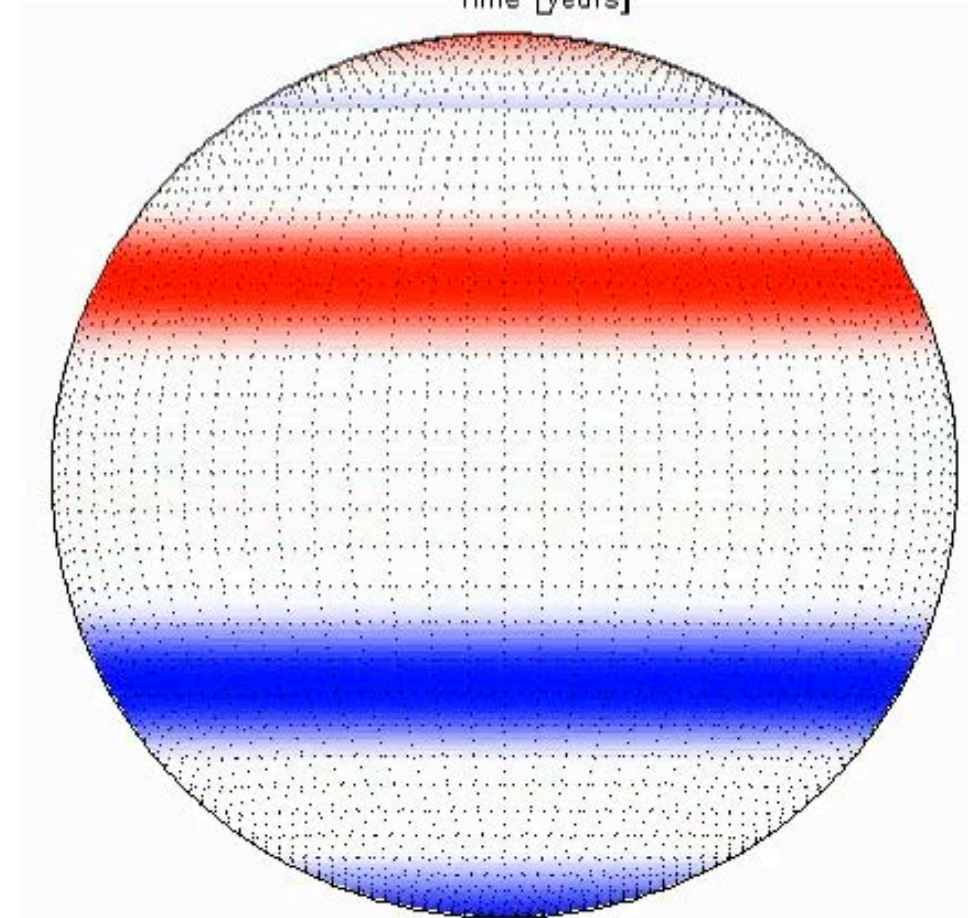
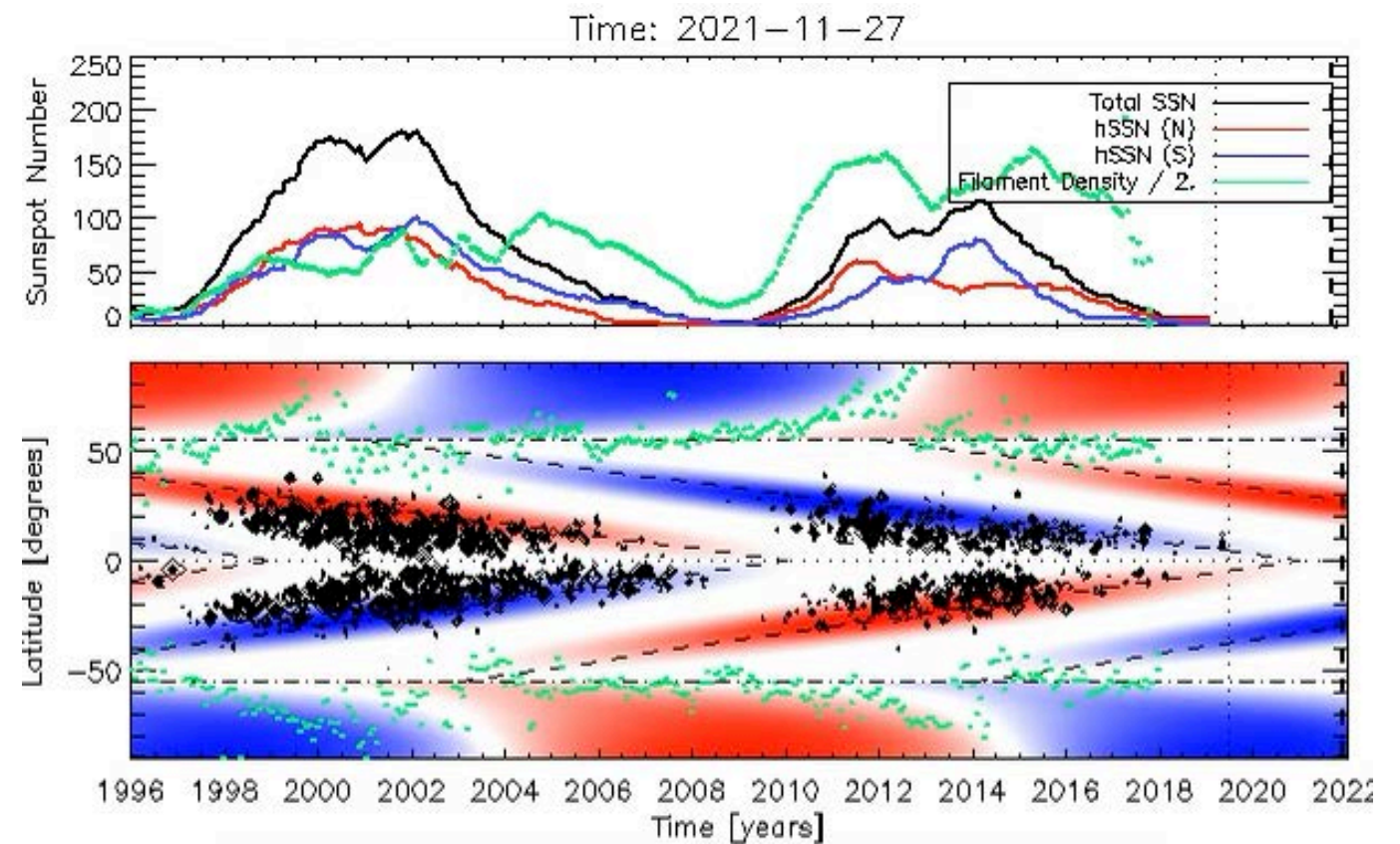
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**Hypothesis: The interaction of Hale Cycles shapes the Sunspot Cycle and sets its amplitude!**



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**The end of the Hale Cycle is so  
important to the process it got its  
own name.....**





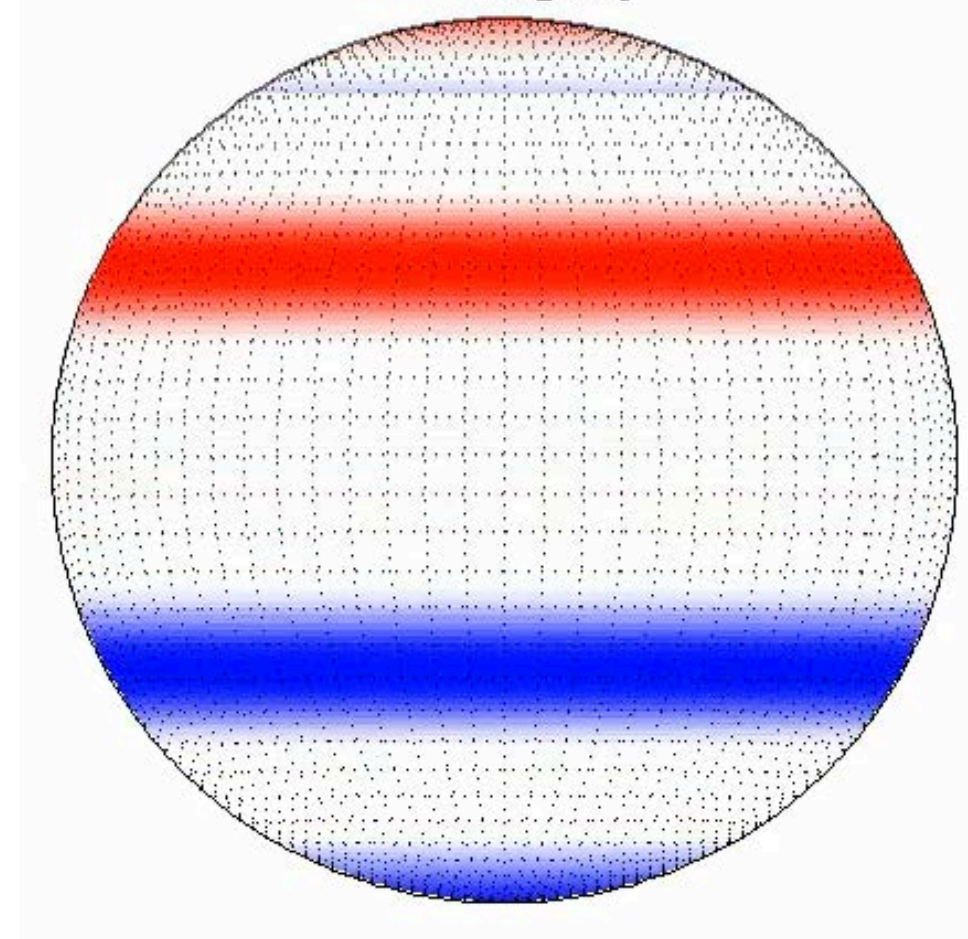
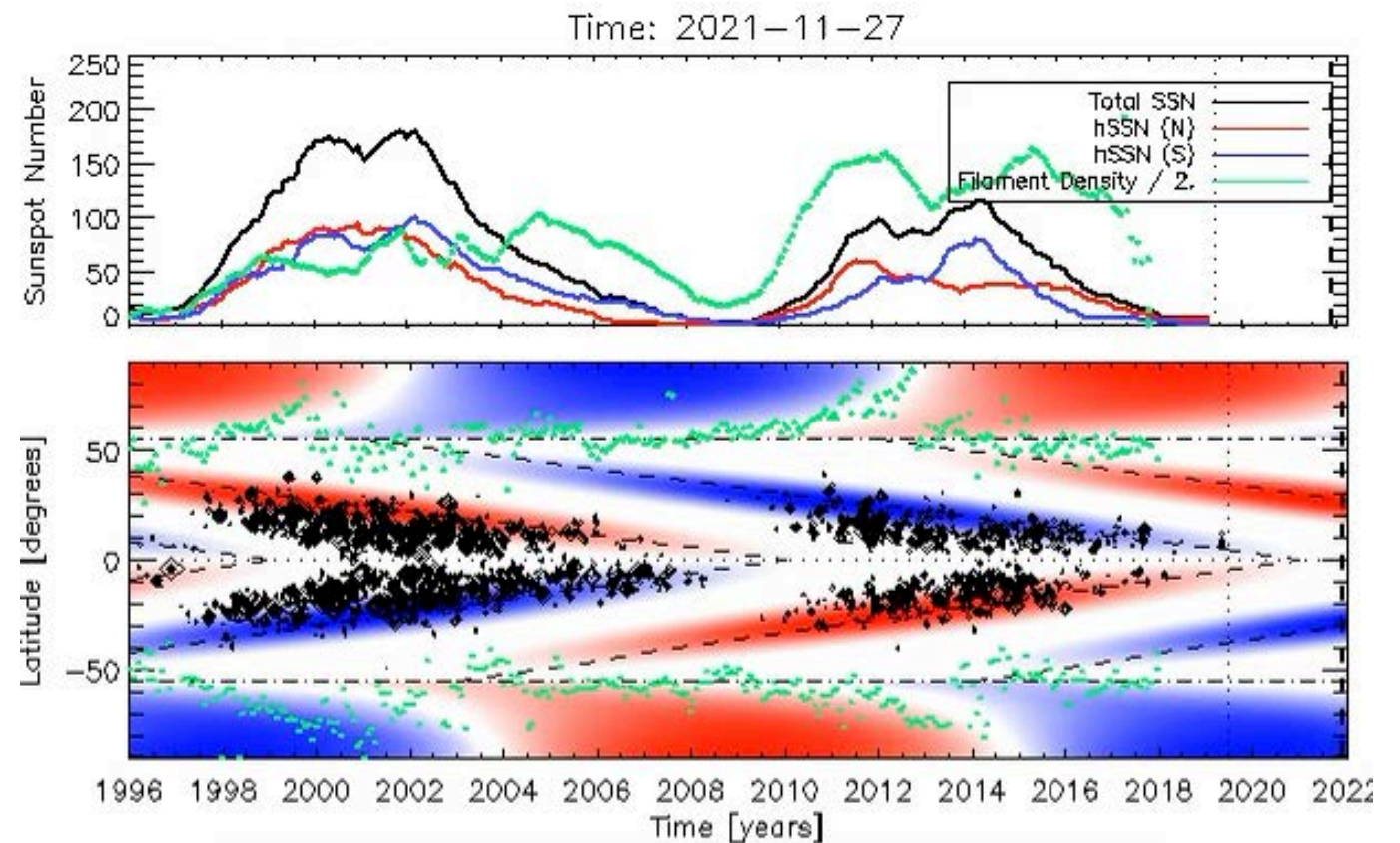
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**“The Terminator”**





The Sunspot Cycle is derivative of,  
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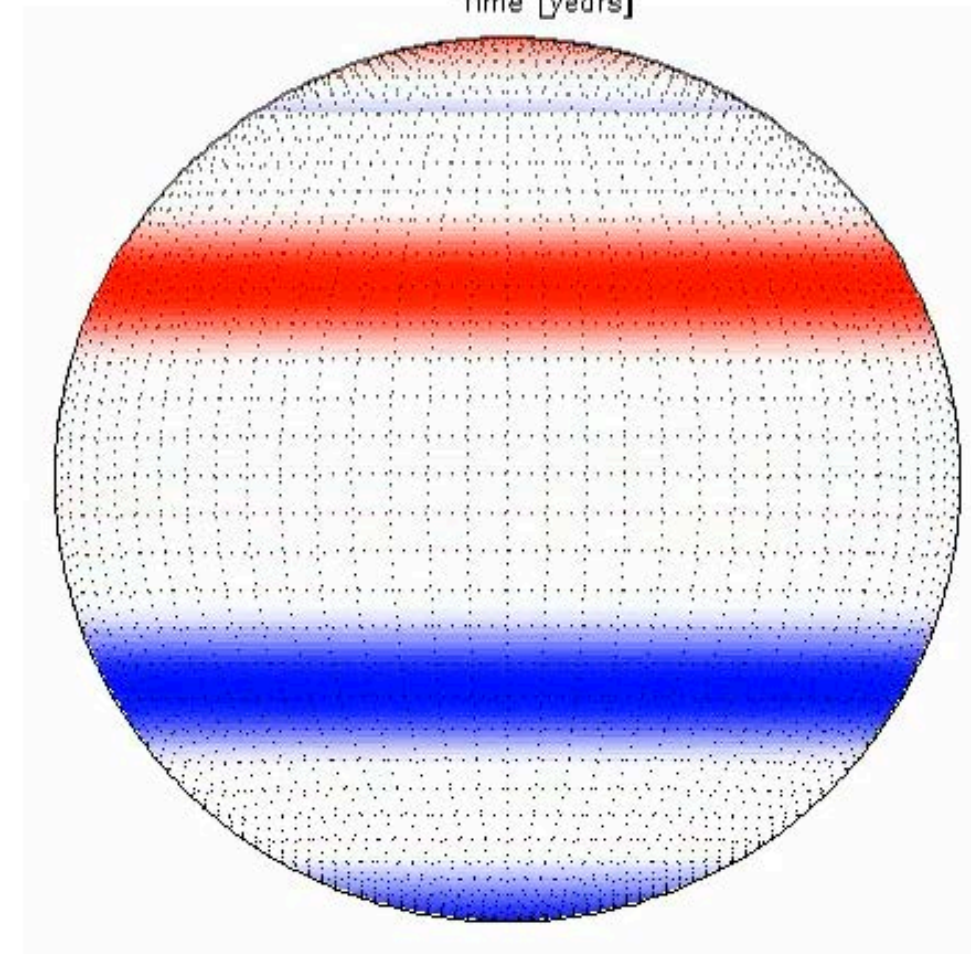
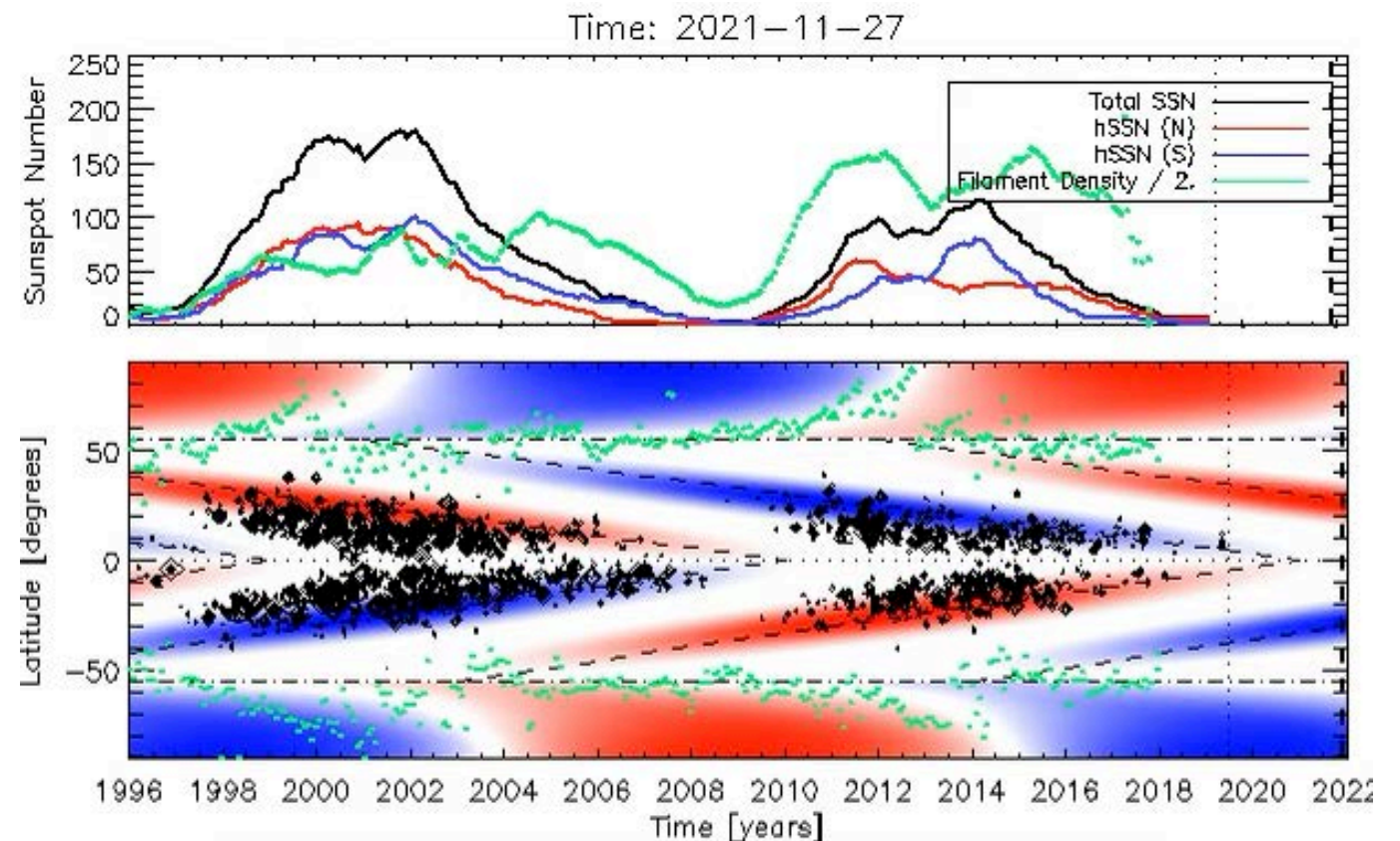
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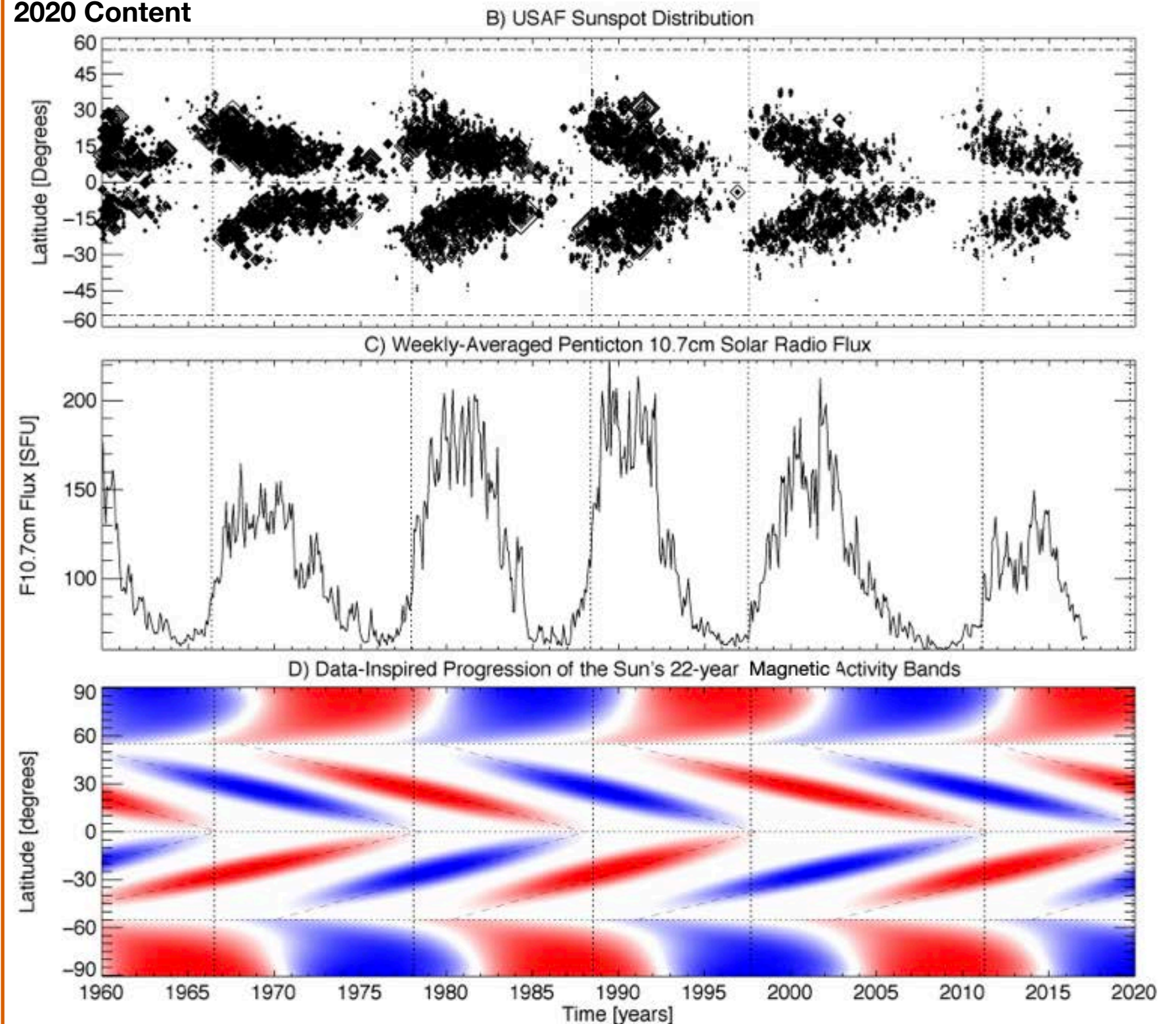


**“The Terminator”**

**Hypothesis: The overlap of Hale  
Cycles sets sunspot cycle amplitude!**

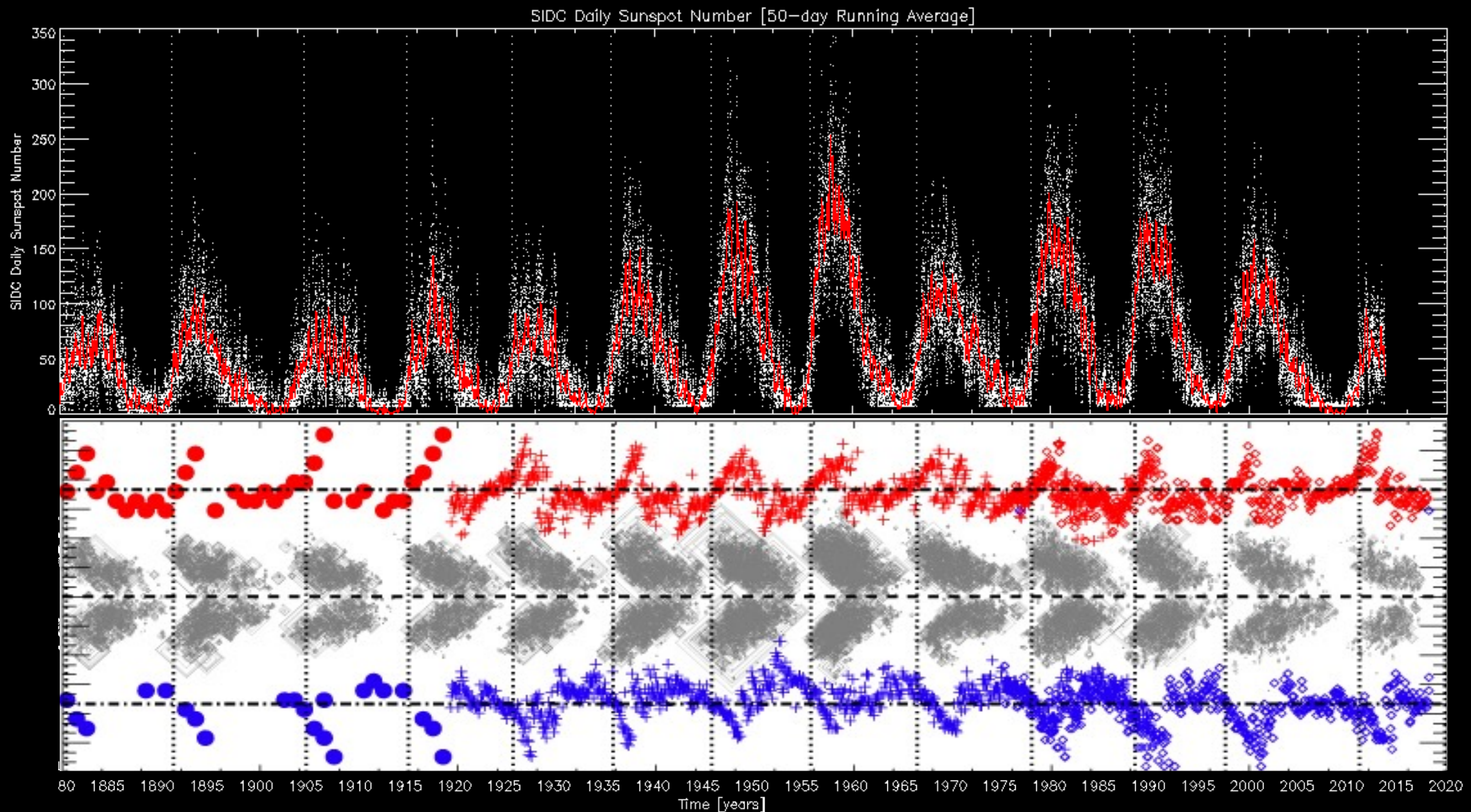






**Looking at historical data. The EUV BP terminators are not isolated. This pattern repeats. We noticed a relationship between the separation of the Terminator events and the amplitude of the upcoming sunspot cycle.**





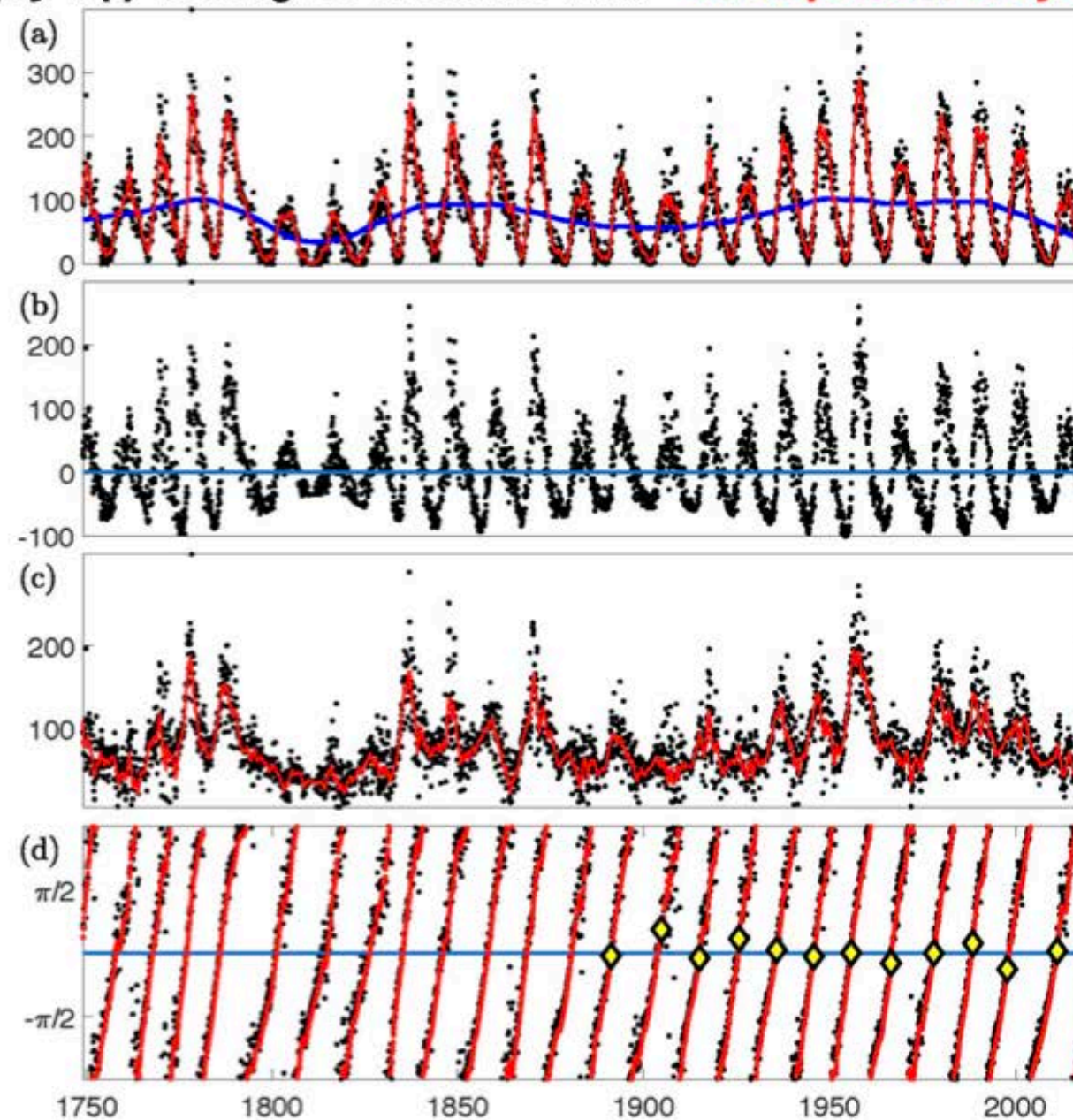
**ASIDE: The end of Hale cycles occurs in (very) close conjunction with the emergence of the sunspot pattern at mid-latitudes AND the start of the polar reversal process ( $\sim 55^\circ$ ).**





# Statistics - Damn Statistics

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

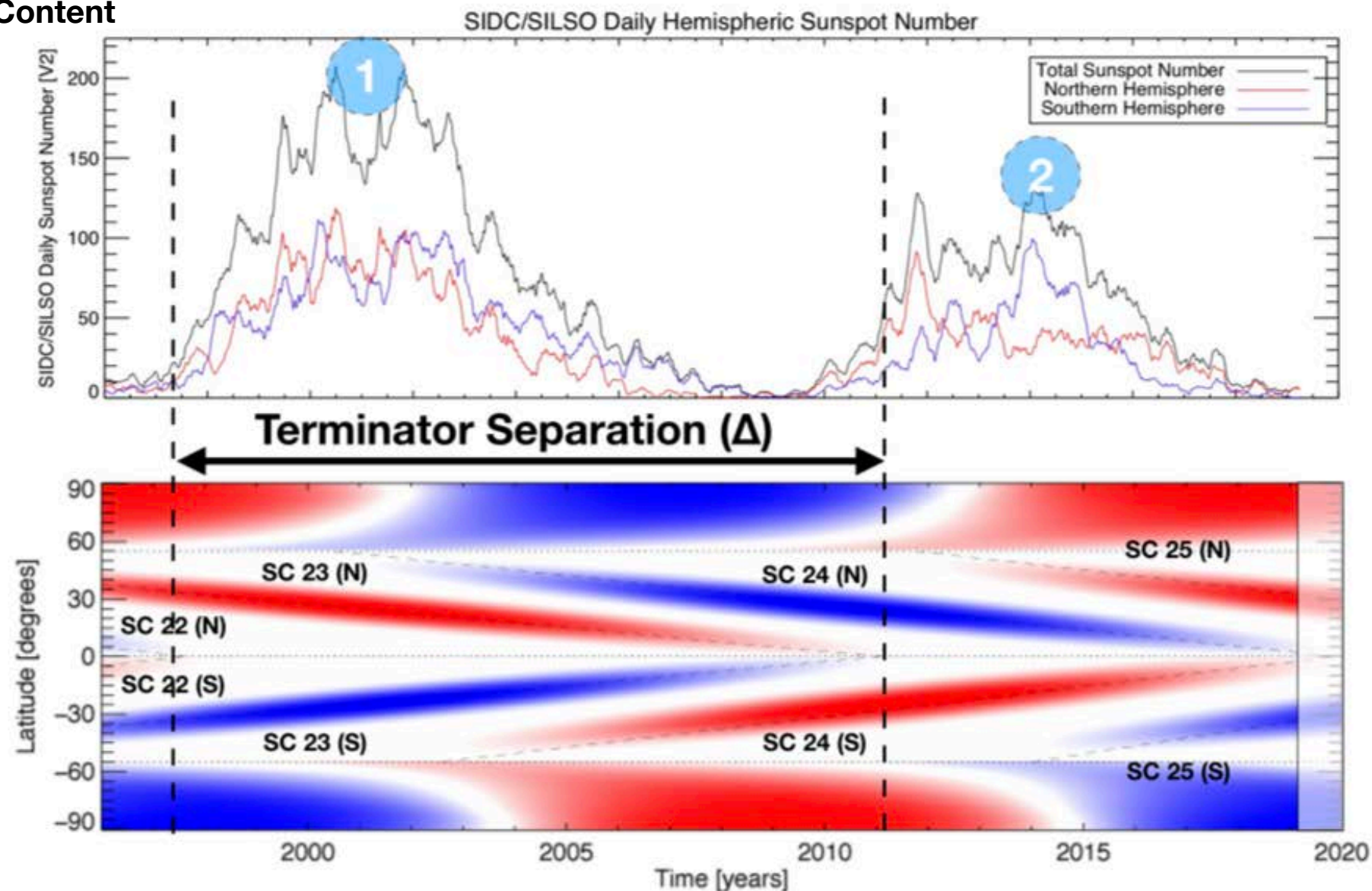


Offsetting phase function by  $\pi$  such that the terminators are now zero-crossings

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**How many Terminators can we identify?**





From the 24 sunspot cycles since 1750 look at relationships:



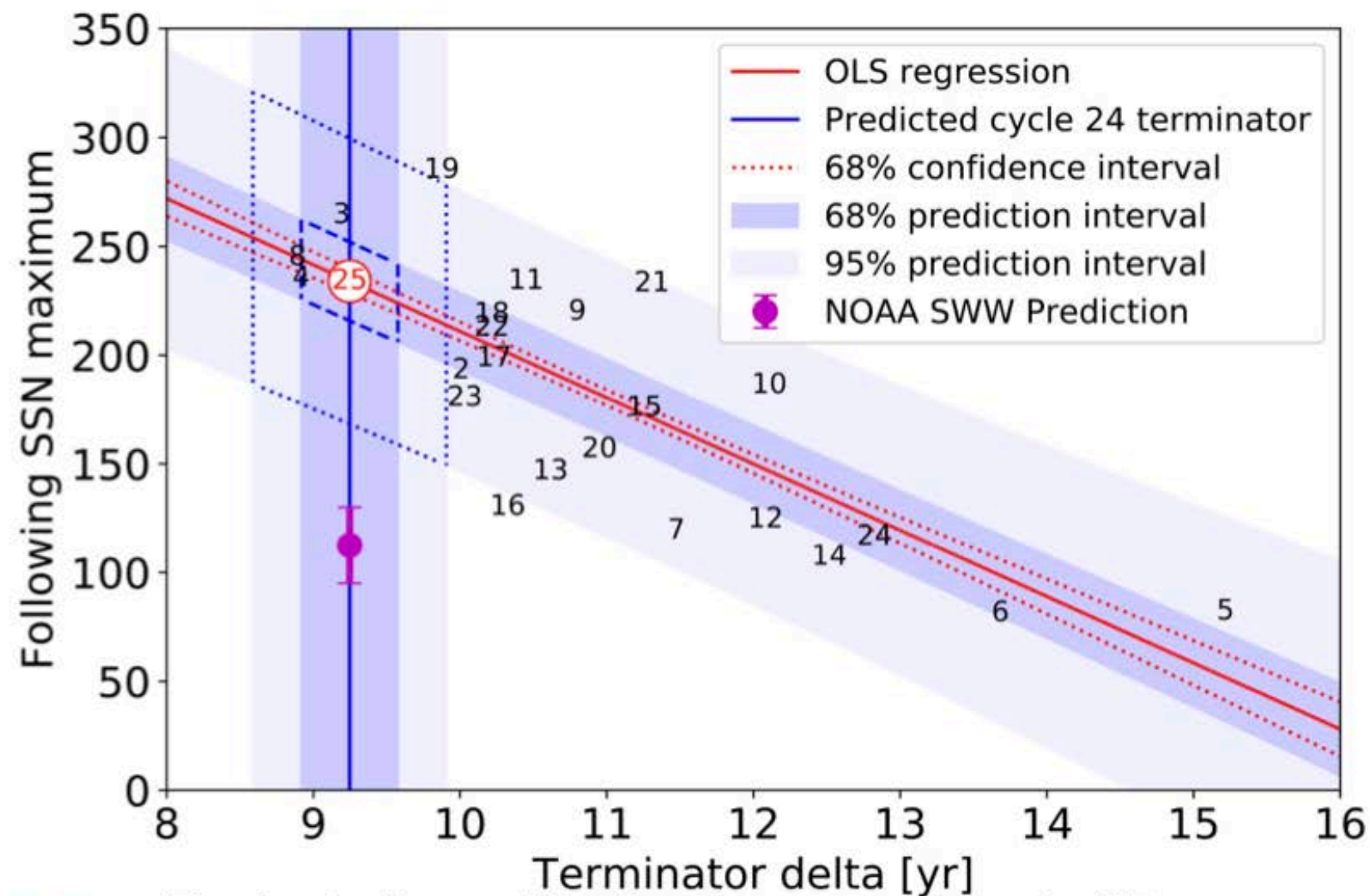
- 1) terminator separation and **INTERMEDIATE** cycle strength
- 2) terminator separation and **UPCOMING** cycle strength

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Next we conduct an experiment.....



# Terminator separation Vs. **UPCOMING** cycle strength



## Projected amplitude of sunspot cycle 25

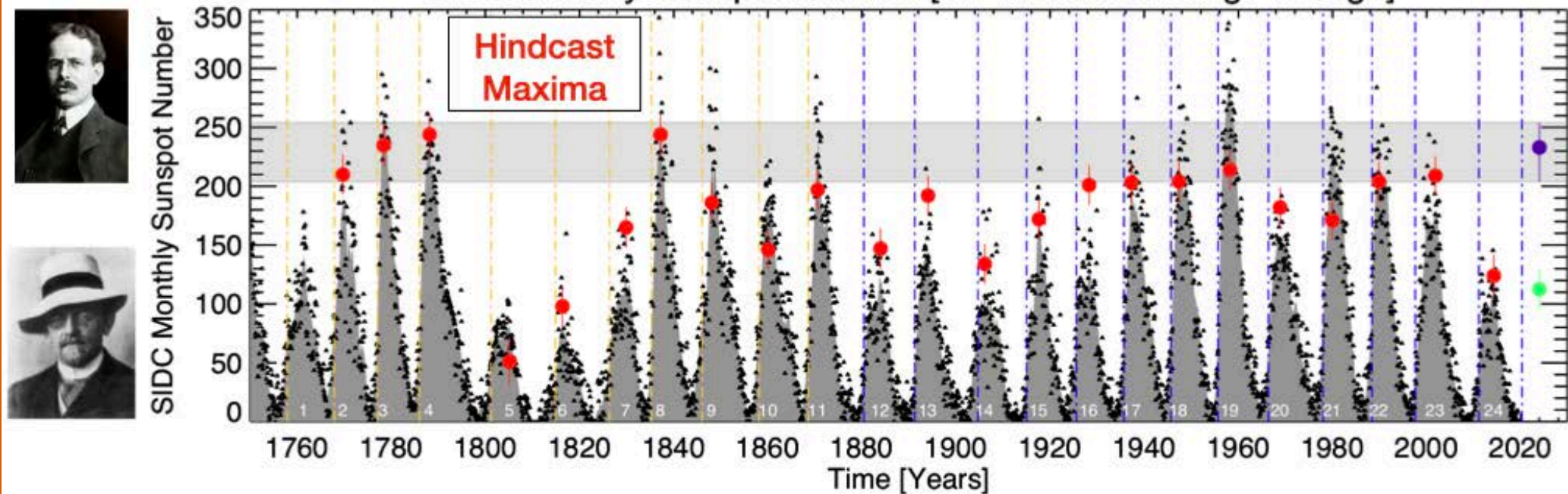
@ 68% confidence: 233 spots (211 - 257)

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

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Looking at historical data we noticed a relationship between the separation of the terminator events and the amplitude of the upcoming sunspot cycle.





**2020 Terminator: Projected amplitude of sunspot cycle 25**  
 @ 68% confidence: 233 spots (211 - 257)  
 @ 95% confidence: 233 spots (159 - 310)

**2021 Terminator: Numbers dropping by 15 - 25**

**Are we ready for a large sunspot cycle?**

**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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**In early 2021 we were still waiting for the Terminator and with every month that passed the forecast sunspot number was dropping.....**

**But we still believed that the relationship was strong.**



# Pause....

2020

2024

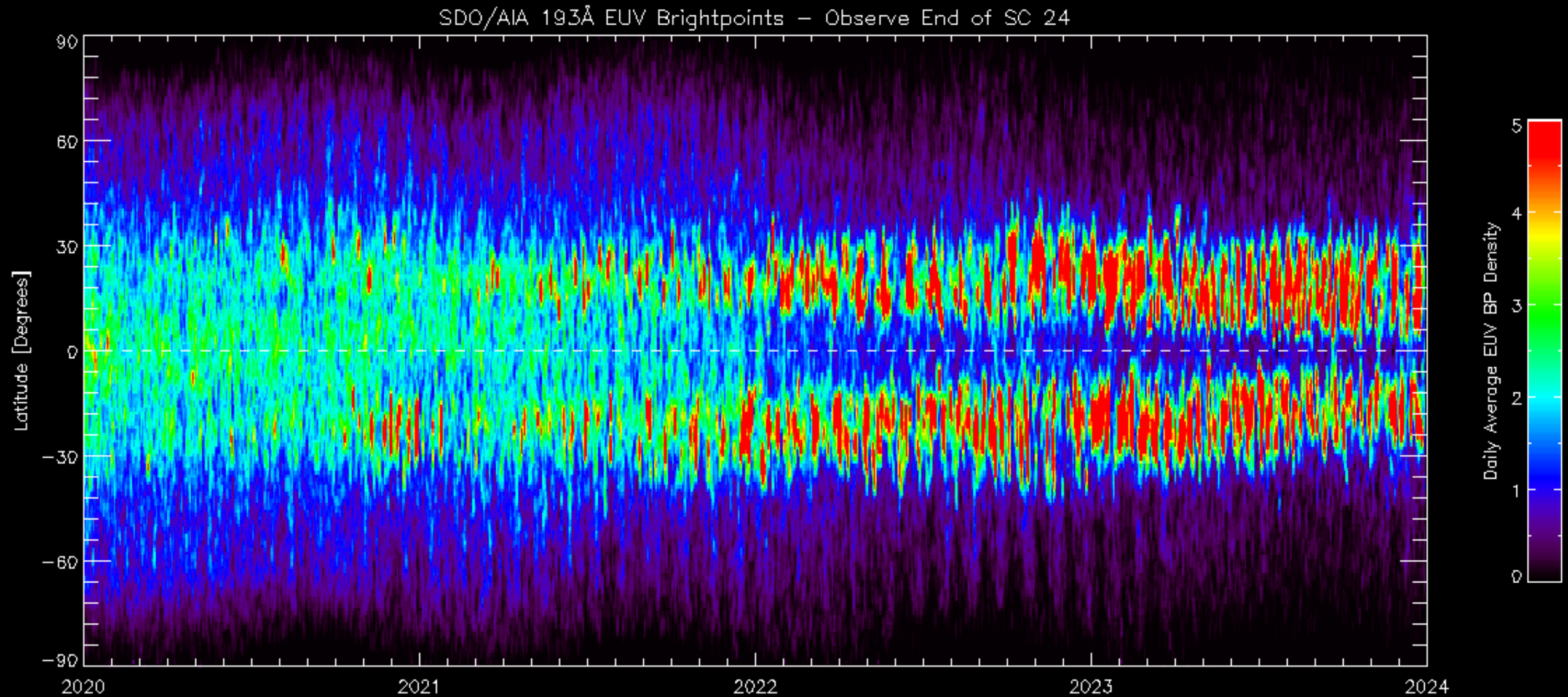


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## Terminator Watch: 2020 - 2024



**The Hale Cycle Terminator FINALLY arrived in December of 2021**

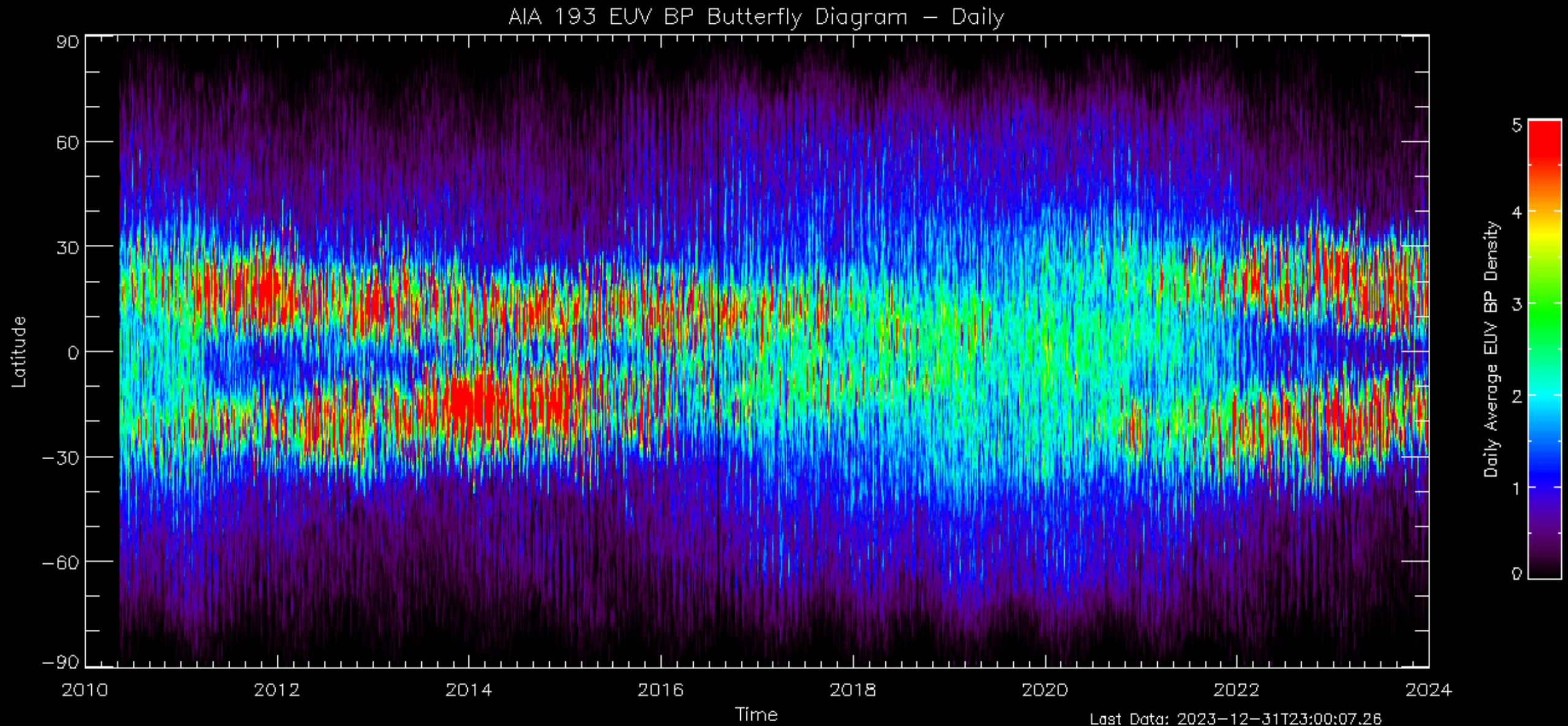


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# Terminator Watch: 2010 - 2024



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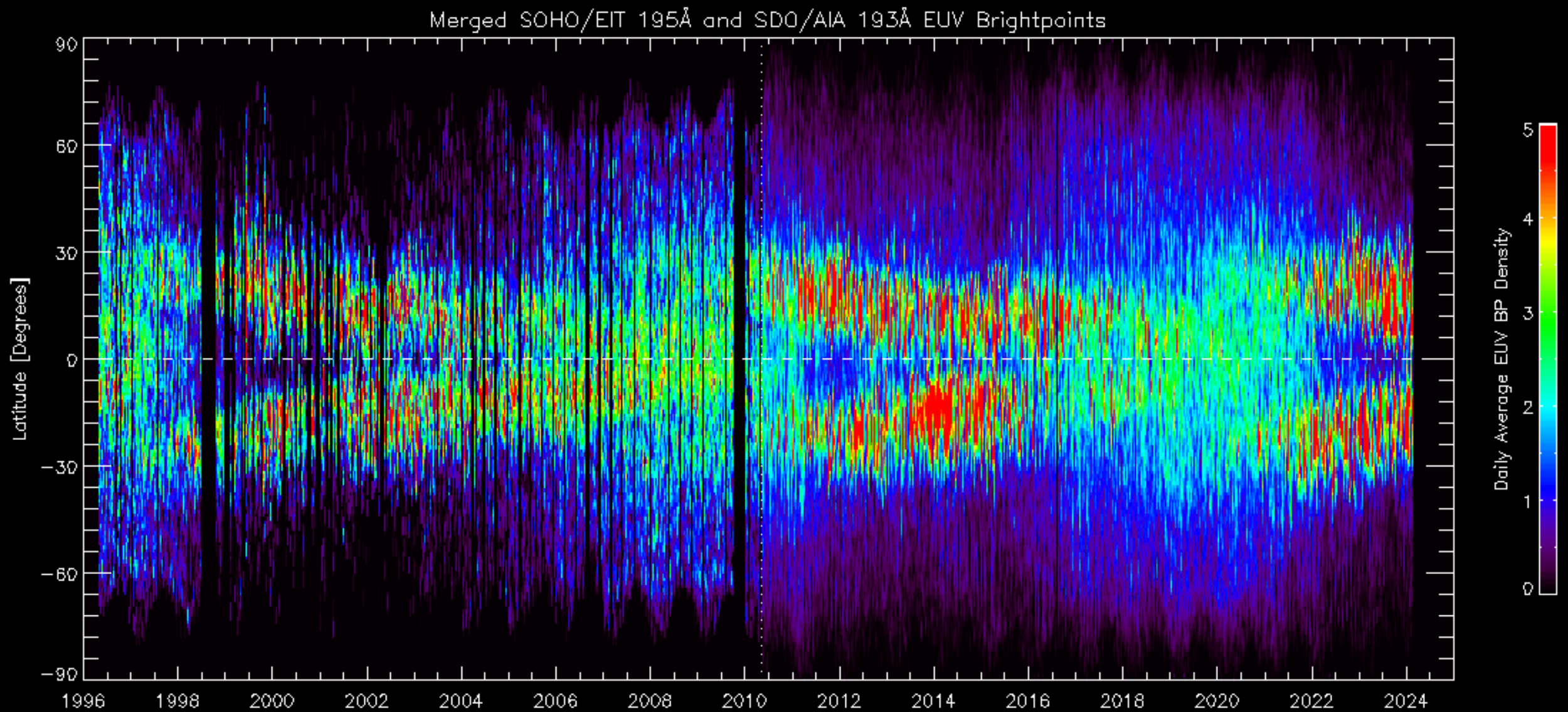


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# Terminator Watch: 1996 - 2024



Last Data: 2024-02-15T23:00:04.84

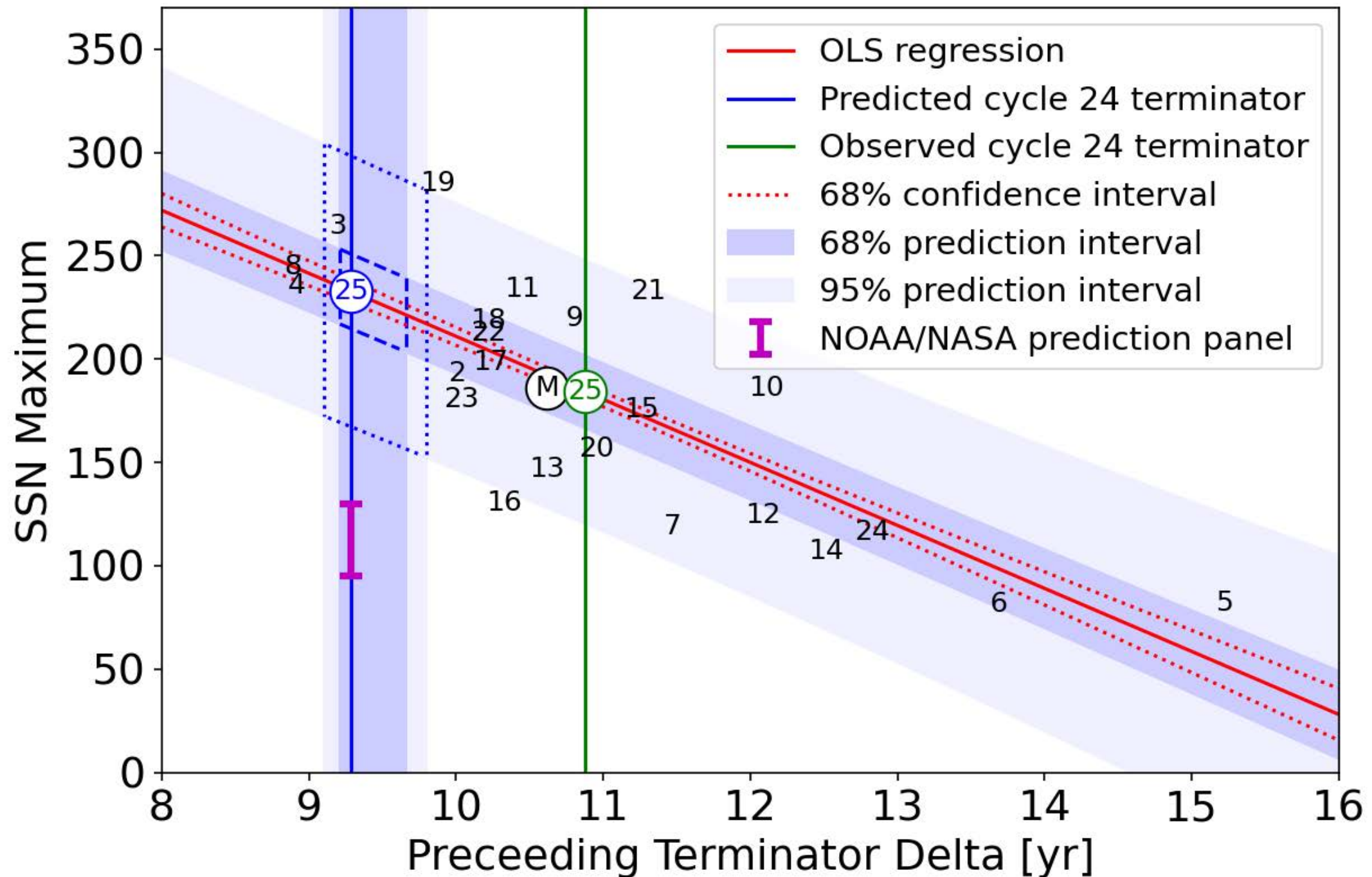
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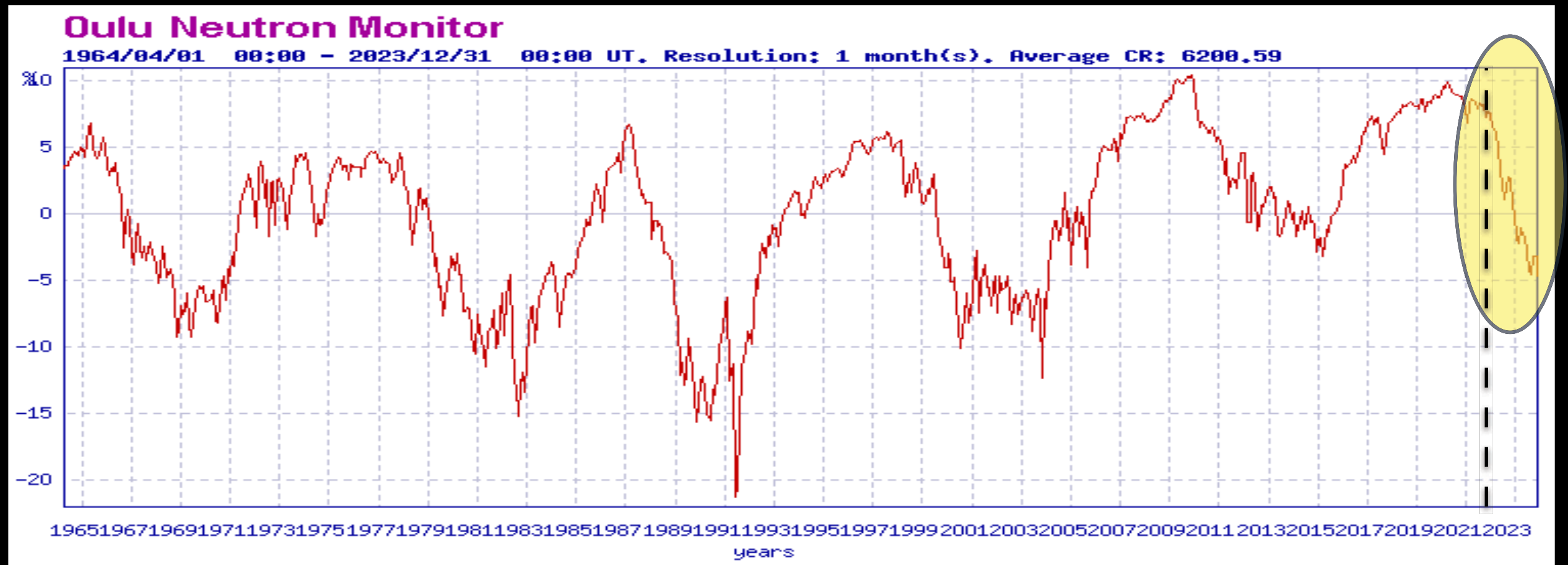


**Revising Our Forecast for a December 2021 Terminator**

**FINAL FORECAST: Sunspot Cycle 25 should be about the historical average!**



When the terminator happens the Sun's magnetism springs to life.....



The energetic particles that bathe our planet drop like a stone....

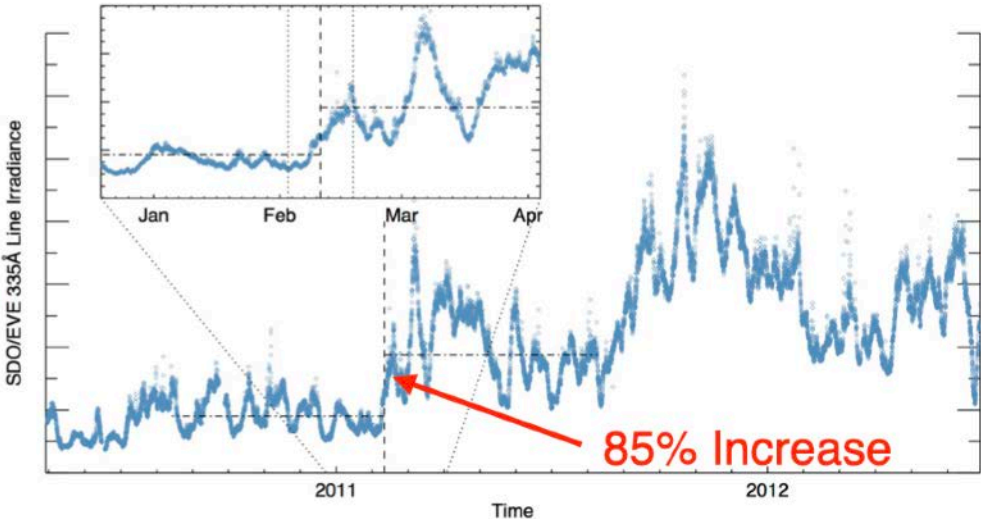


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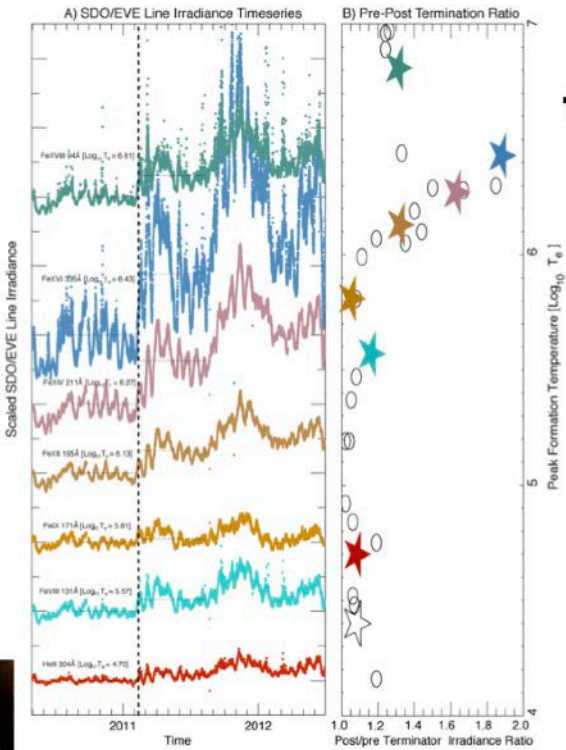


When the terminator happens the Sun's magnetism springs to life.....



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

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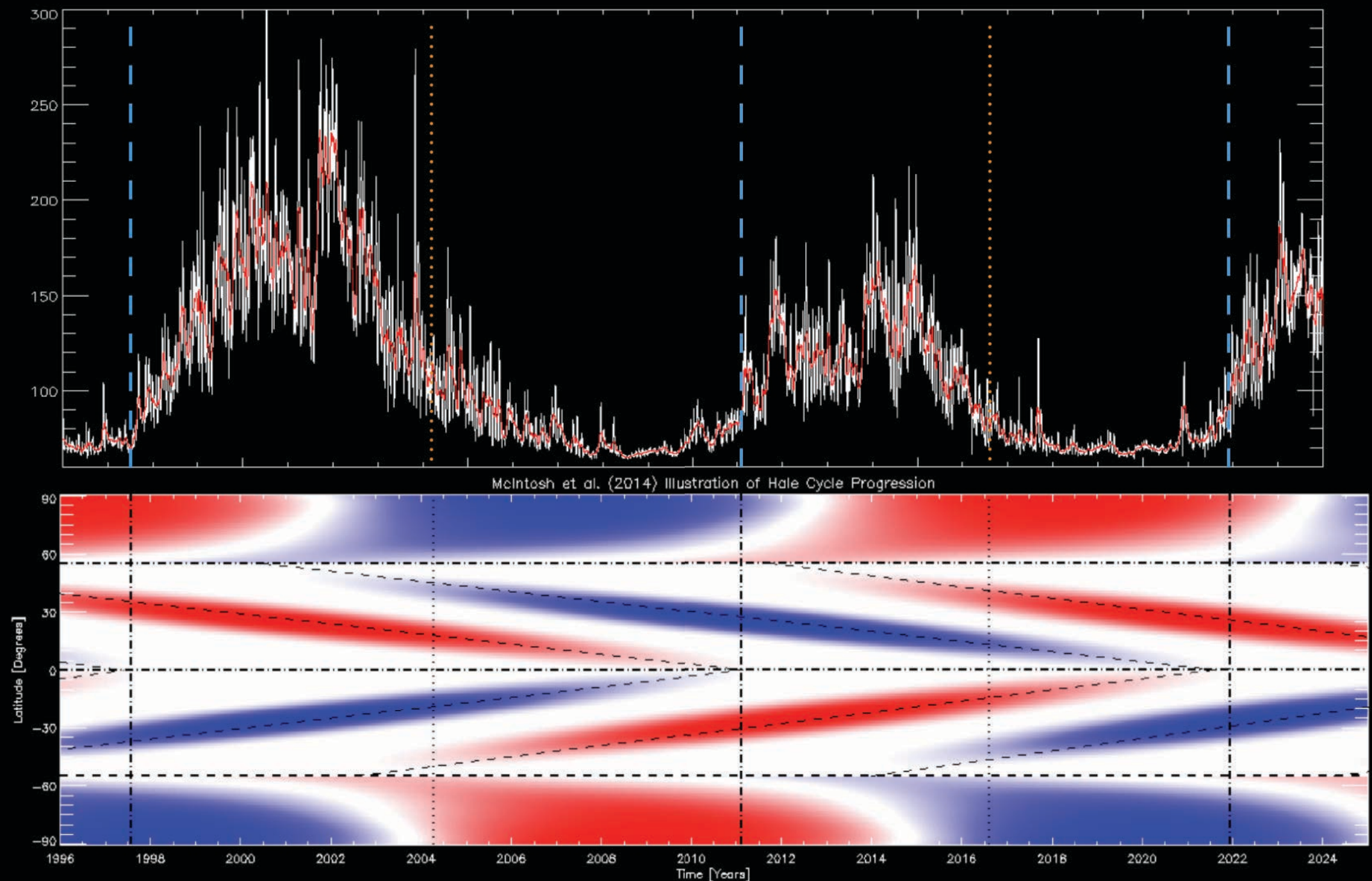
The radiative response to the end of a Hale cycle shows a strong temperature dependence.

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

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**When the terminator happens the Sun's magnetism springs to life.....**



**Solar coronal emission just takes off....  
.... the 10.7cm solar radio flux that bakes the ionosphere!**

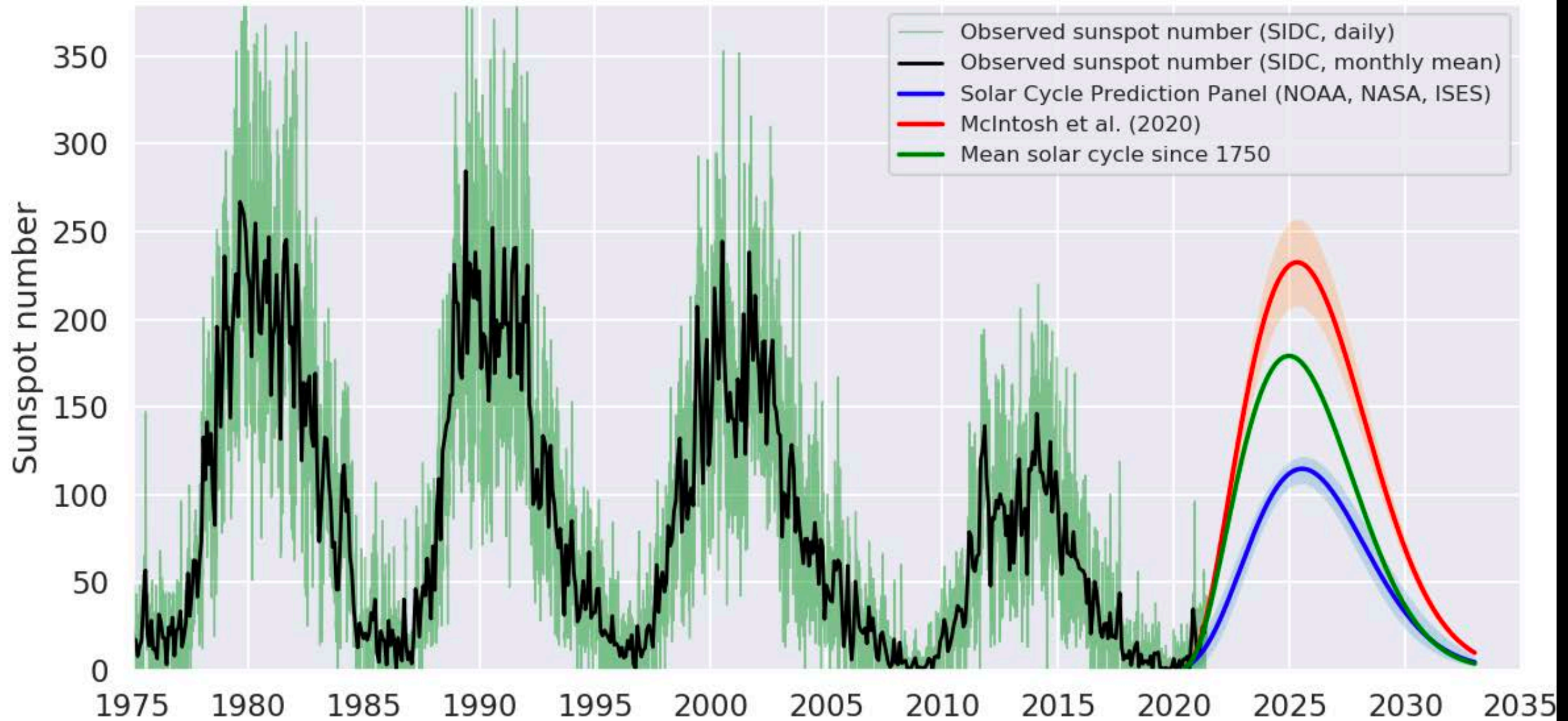


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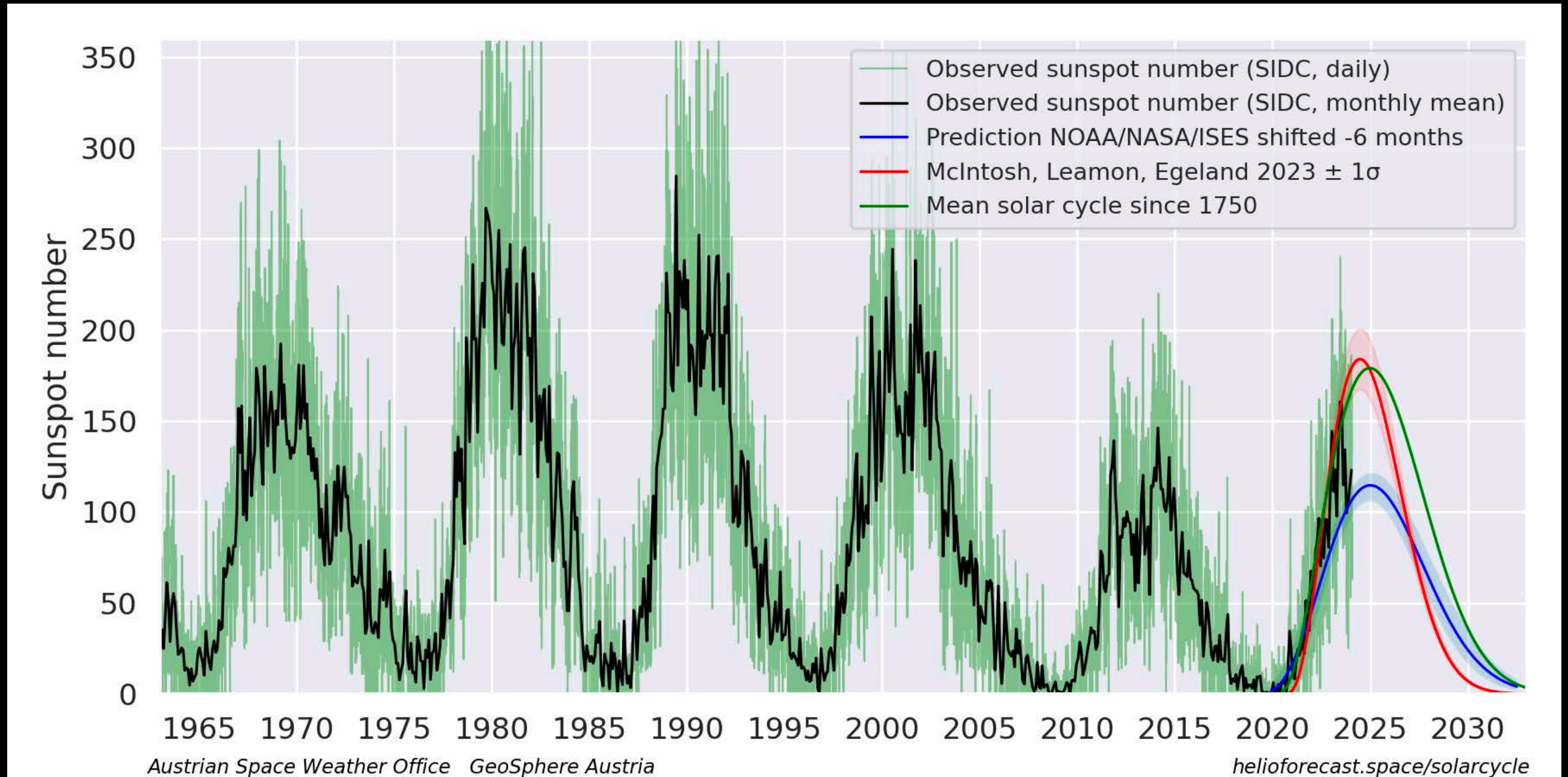


## How It Started....

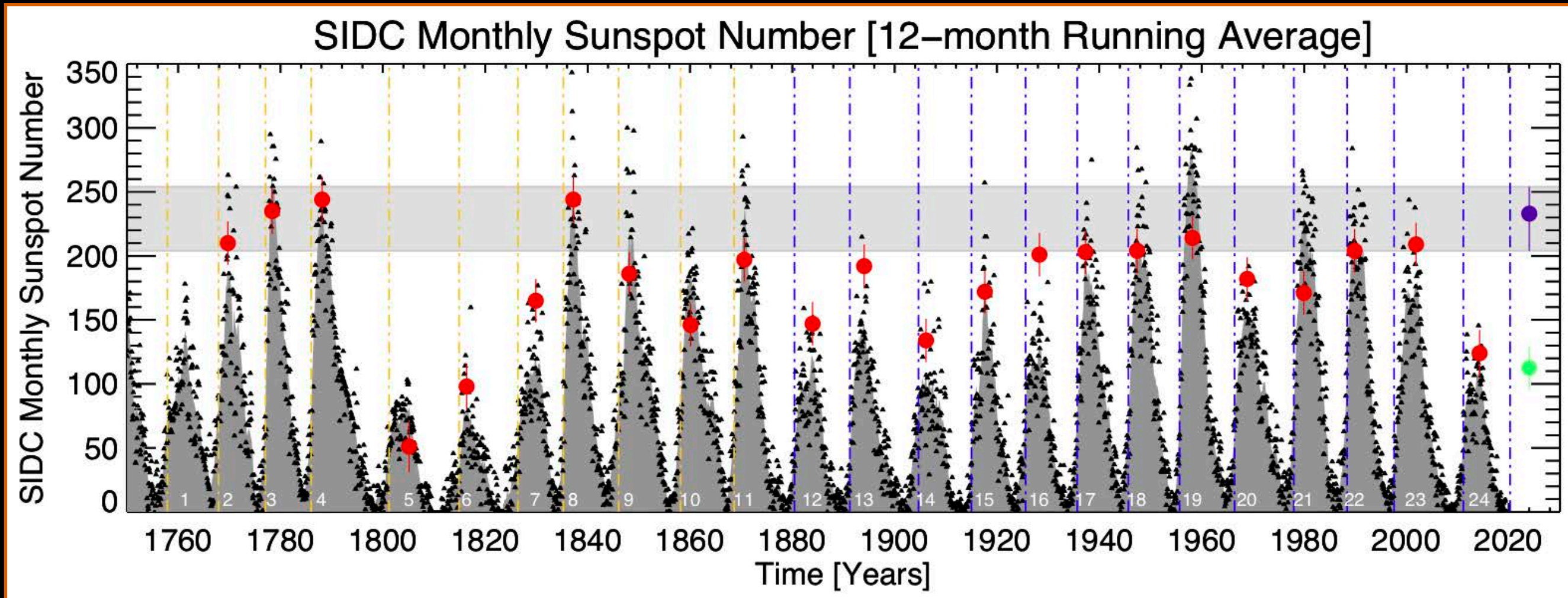




## How It's Going....



## How It Started....



**Revising Our Forecast for a December 2021 Terminator**  
**Sunspot Cycle 25 should be about the historical average**

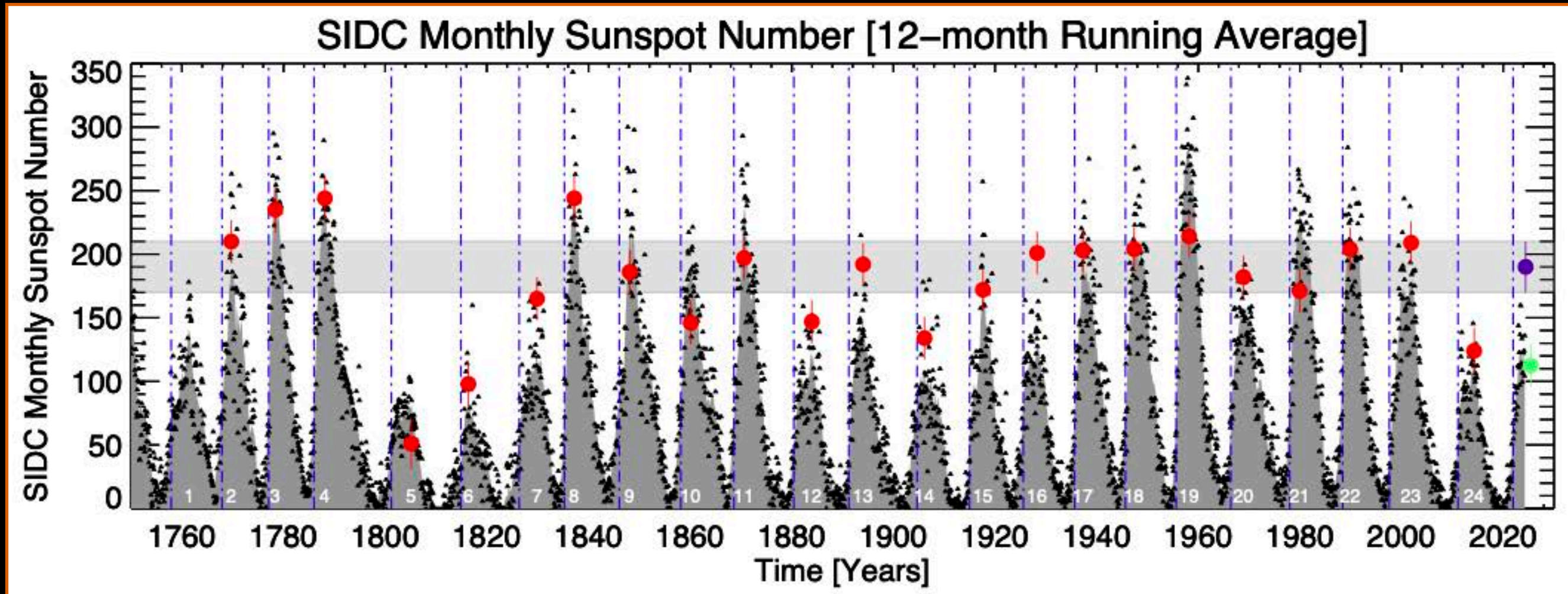


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## How It's Going....



**Revising Our Forecast for a December 2021 Terminator**

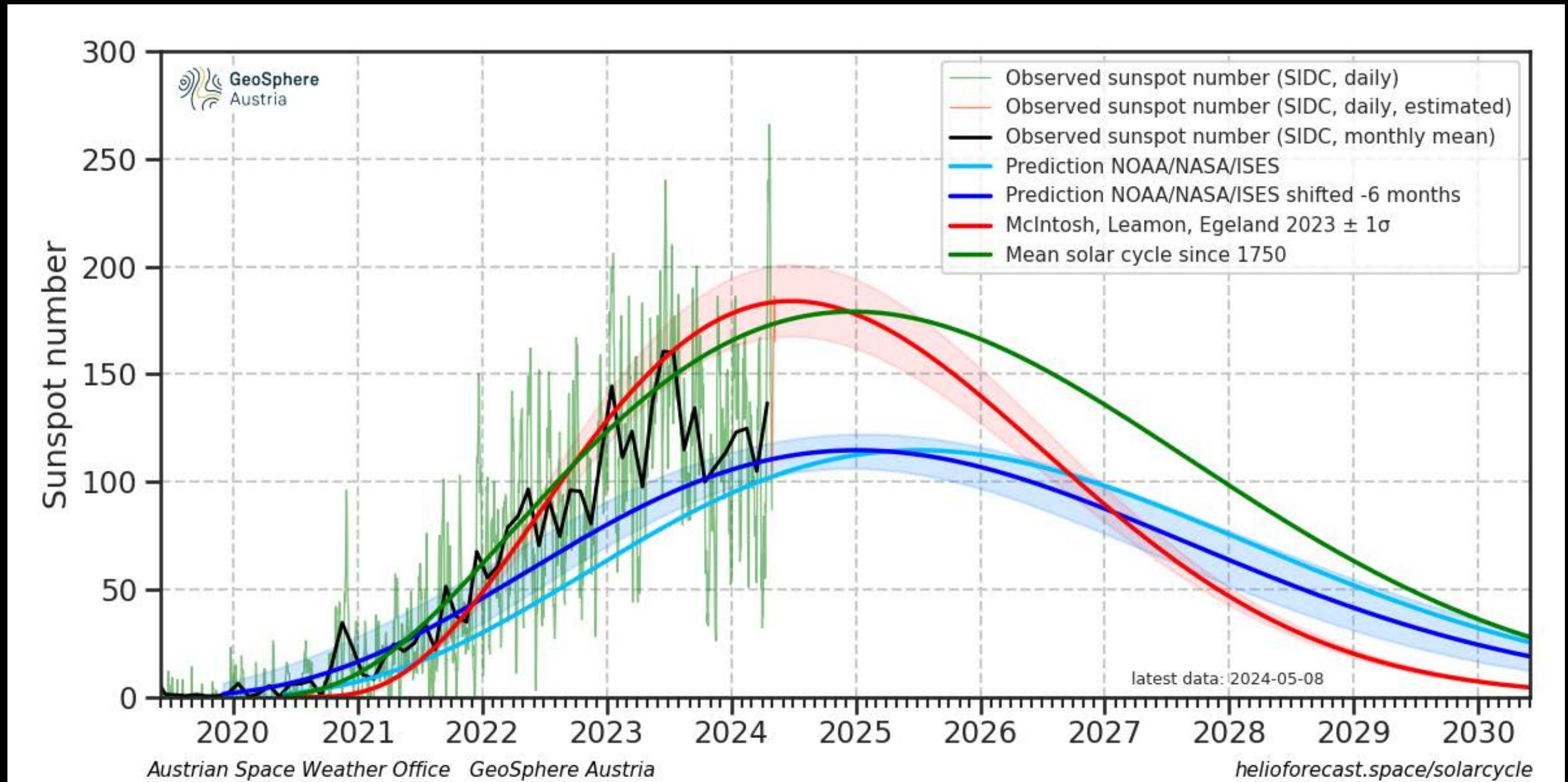
**Sunspot Cycle 25 should be about the historical average**



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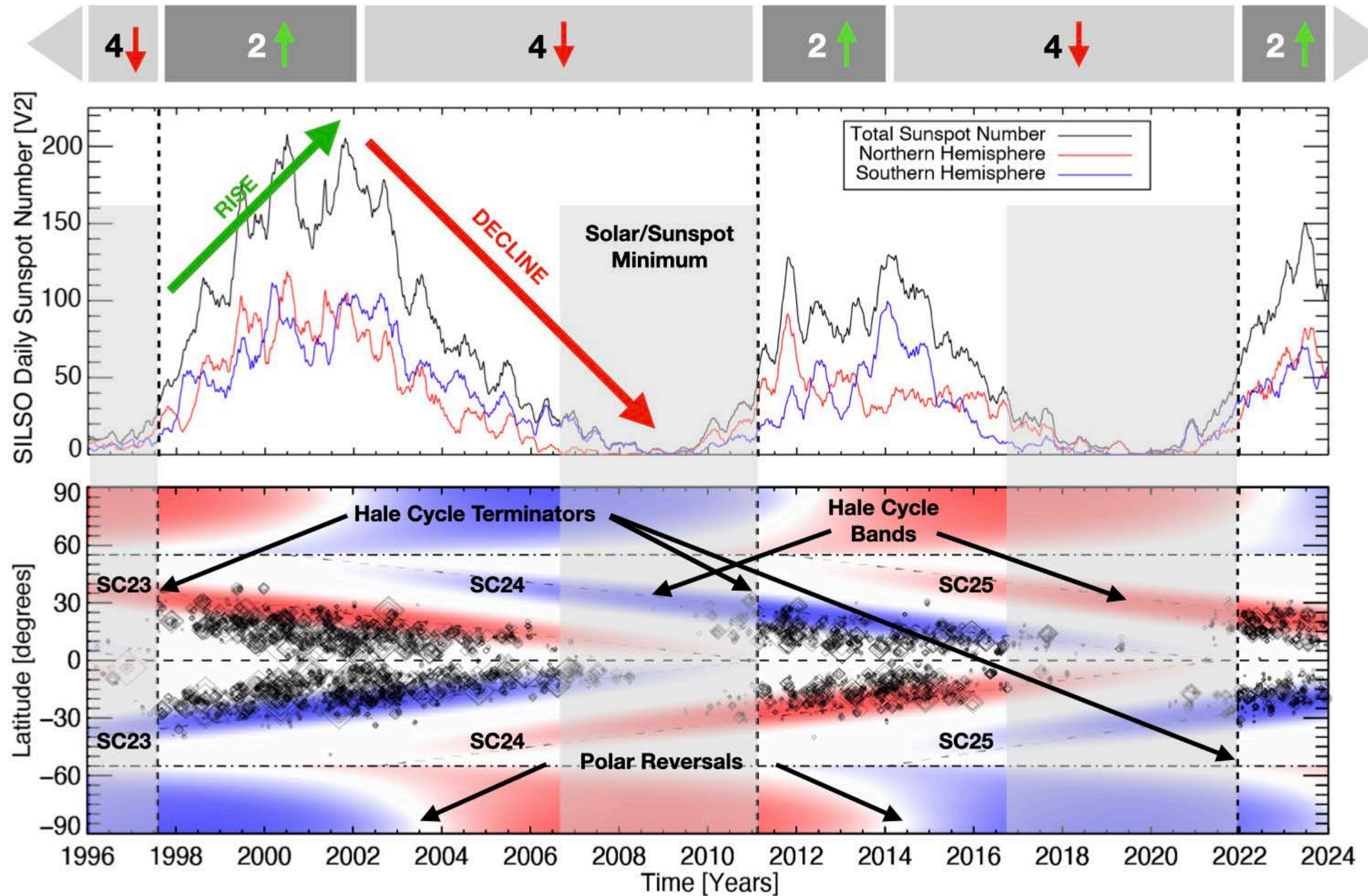
## How It's Going....



**Activity dropped a little since the middle of 2023 but is actively picking up right now!**

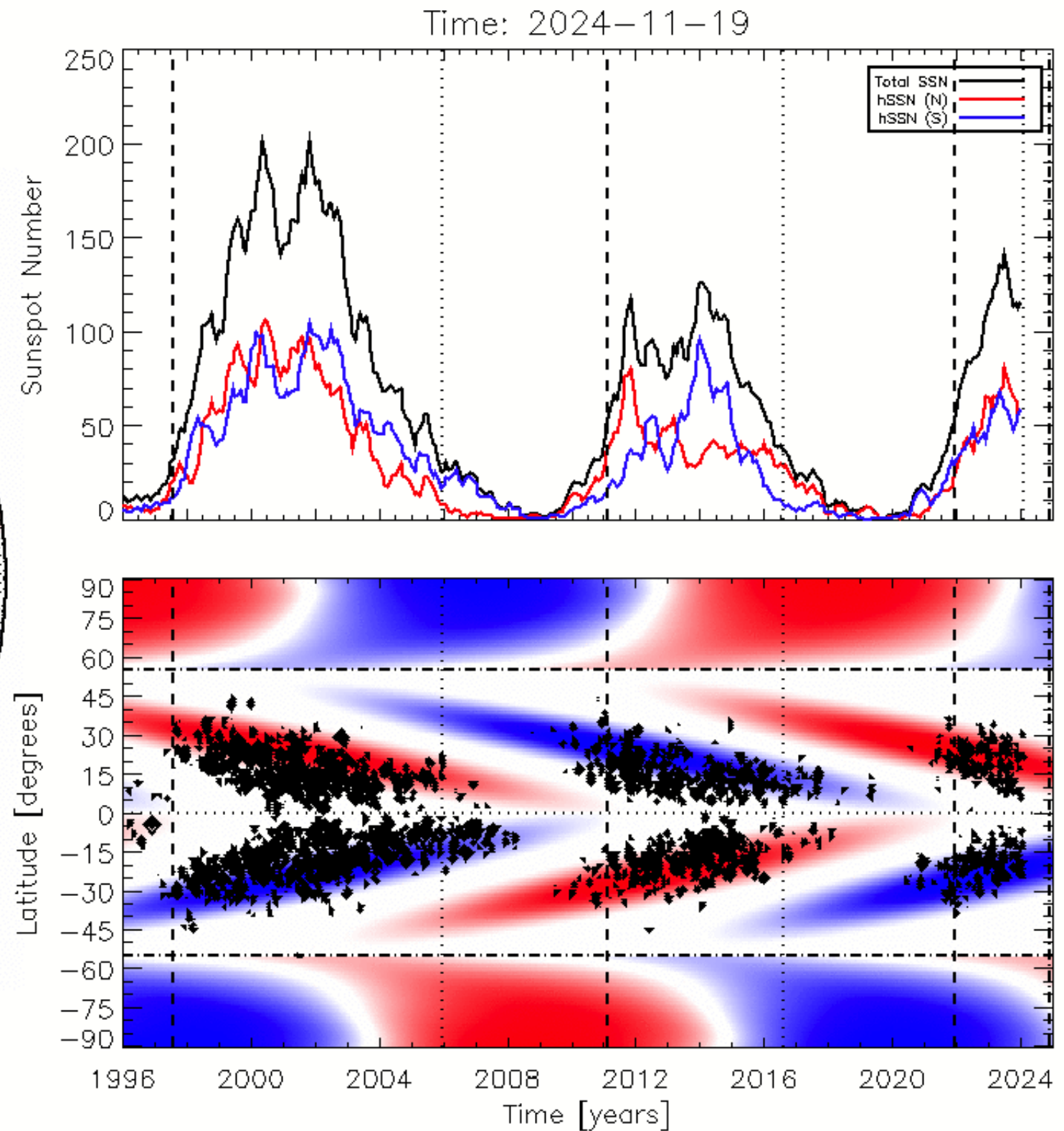
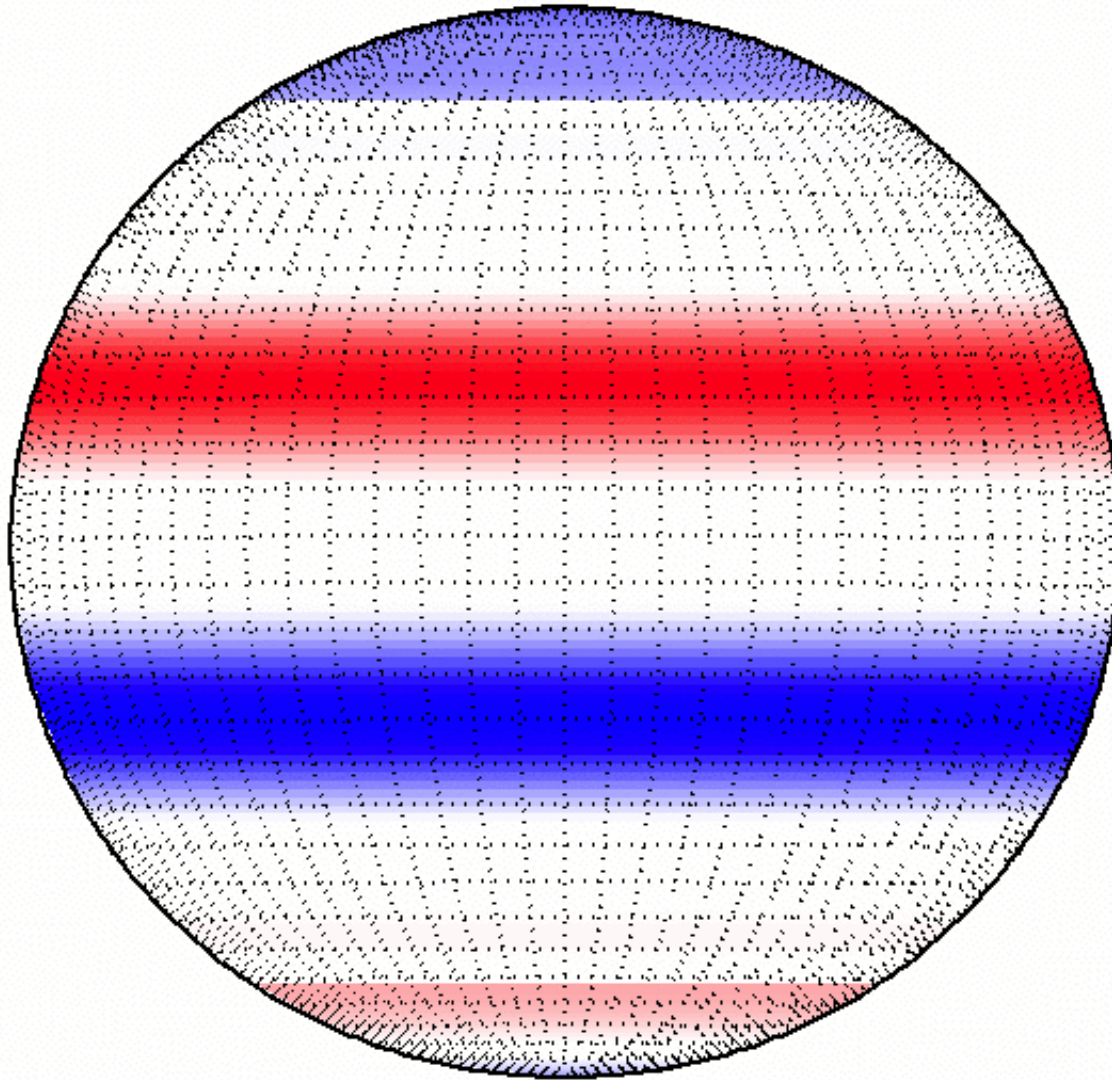


## How It's Going....





## How It's Going....



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 [@swmcintosh](https://twitter.com/swmcintosh)



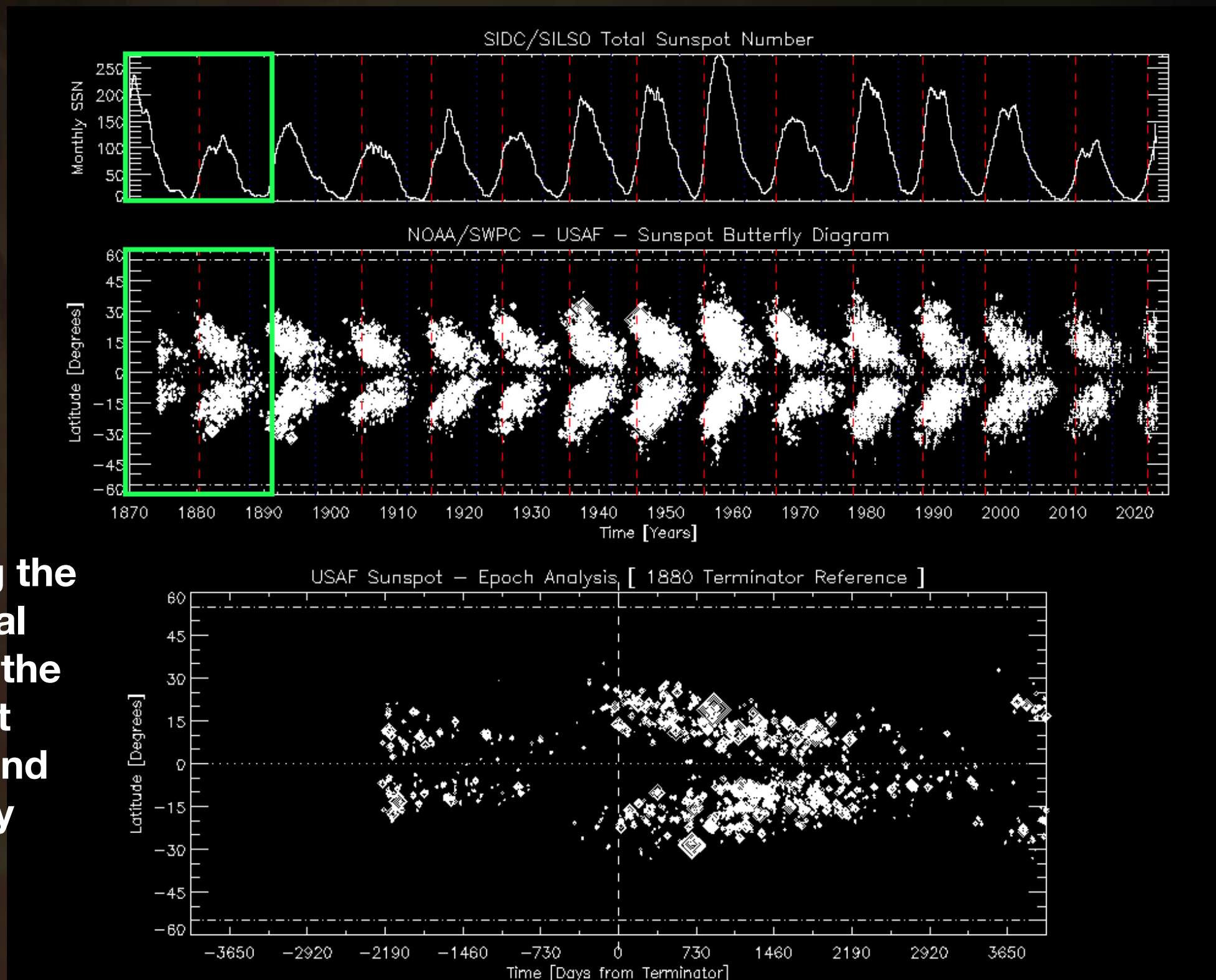
# Pause....



**It's time to consult out crystal ball!!**

# school is in session: Superposed Epoch Analysis

## Forecasting SSN - The Sunspot Number

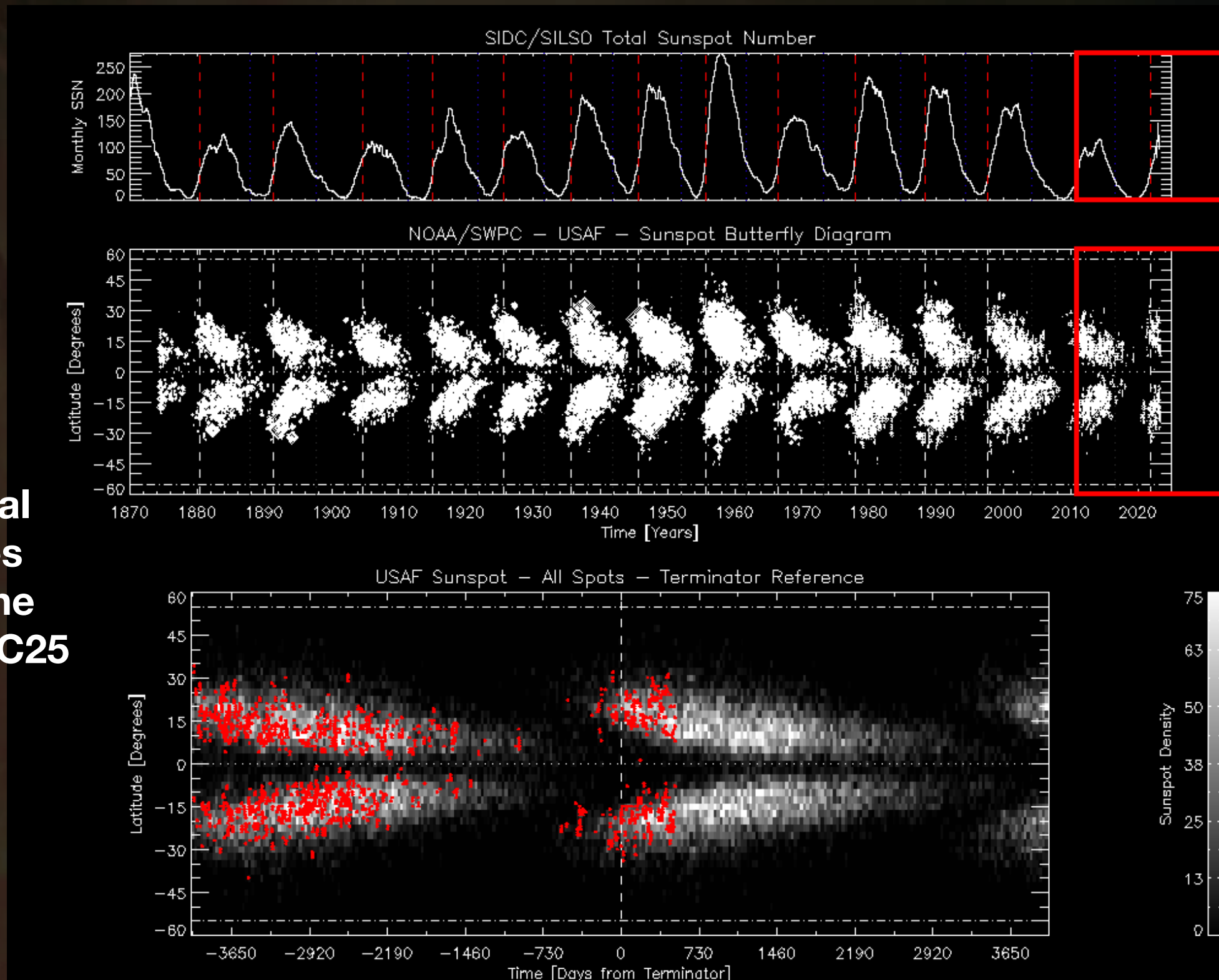


Developing the  
statistical  
model for the  
sunspot  
number and  
butterfly



# school is in session: Superposed Epoch Analysis

## Forecasting SSN - The Sunspot Number



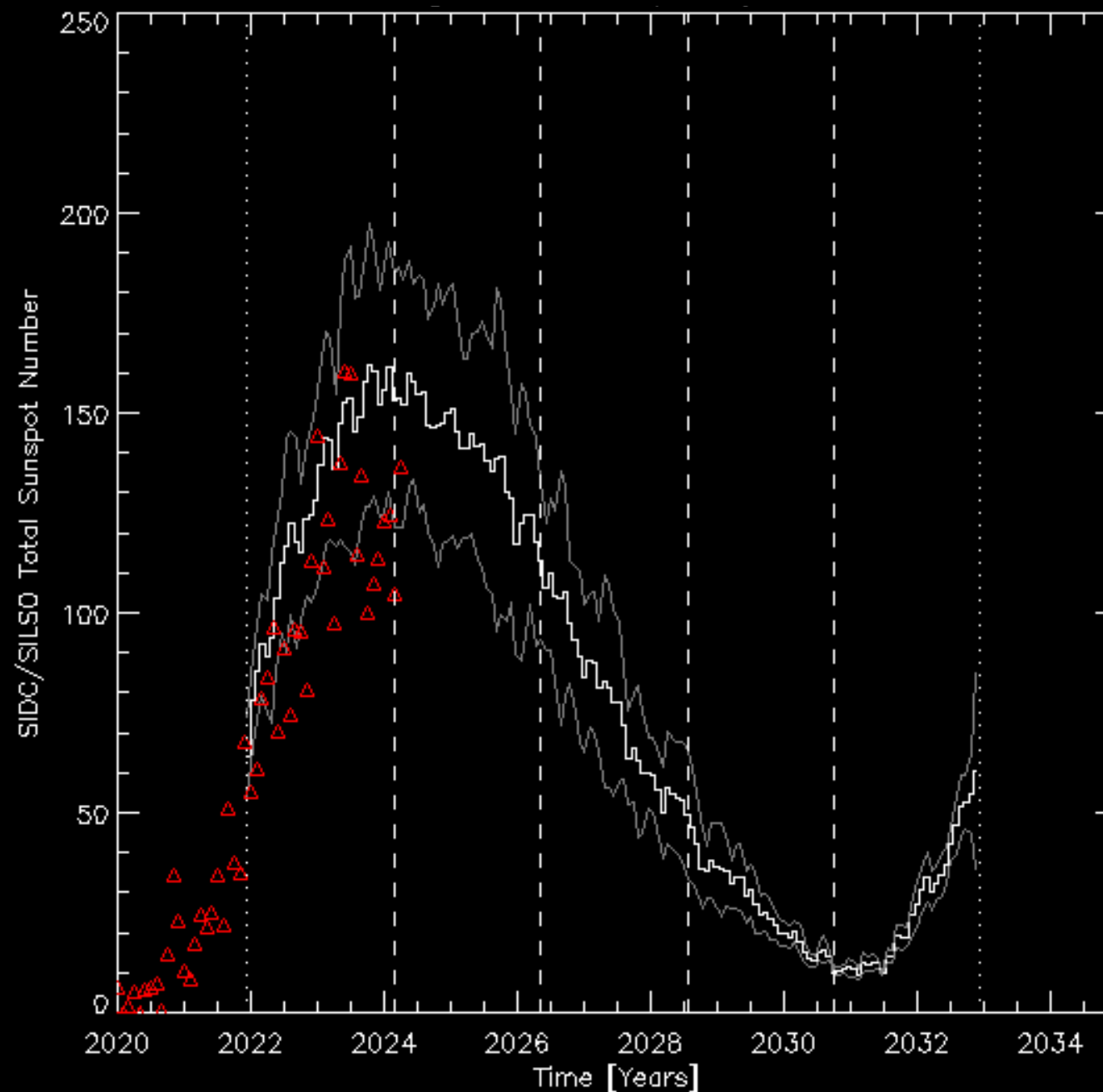
Statistical  
averages  
versus the  
onset of SC25

# school is in session: Superposed Epoch Analysis

## Forecasting SSN - The Sunspot Number

**Statistical  
averages  
versus the  
onset of SC25**

Progress of Sunspot Cycle 25  
[against the #Terminator separation mSEA mean]

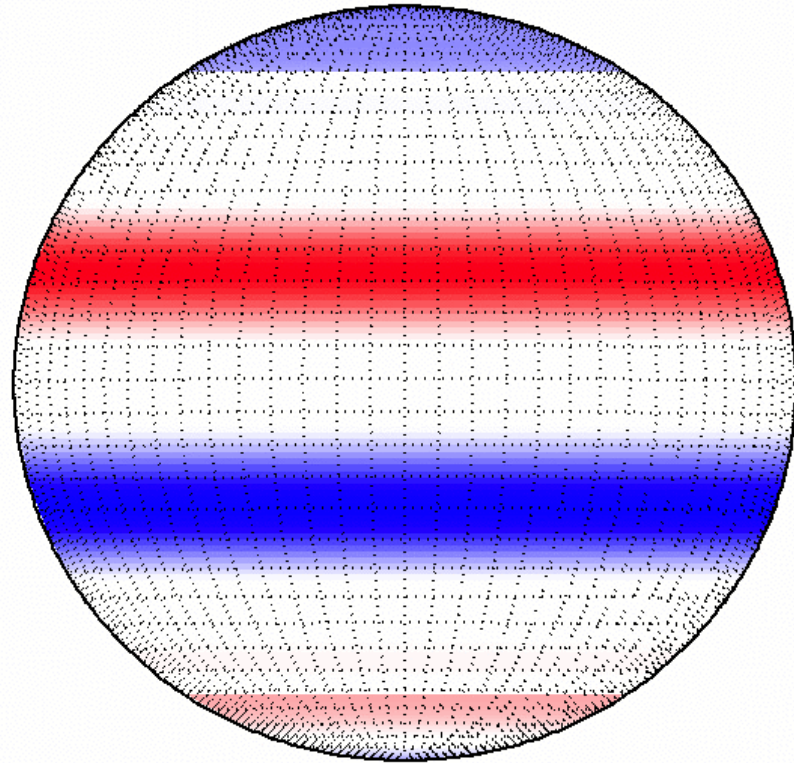


Co-author Bob Leamon  
(NASA) riding a loop-course  
time trial.

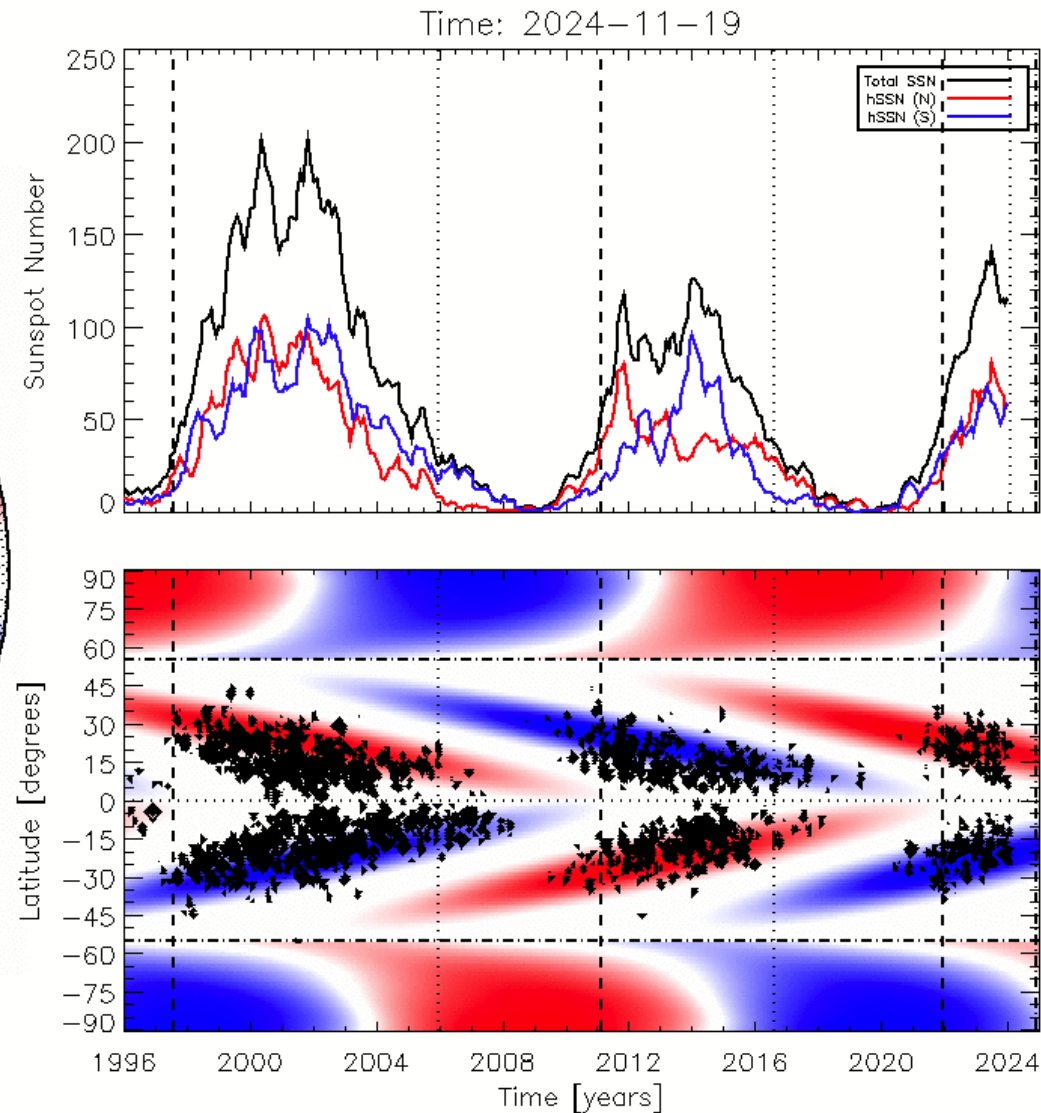
Key insight during the race:  
it's not the time around the  
course that's constant - it's  
the milestones on the  
course that are constant!



# Conclusions: What Have We Learned?



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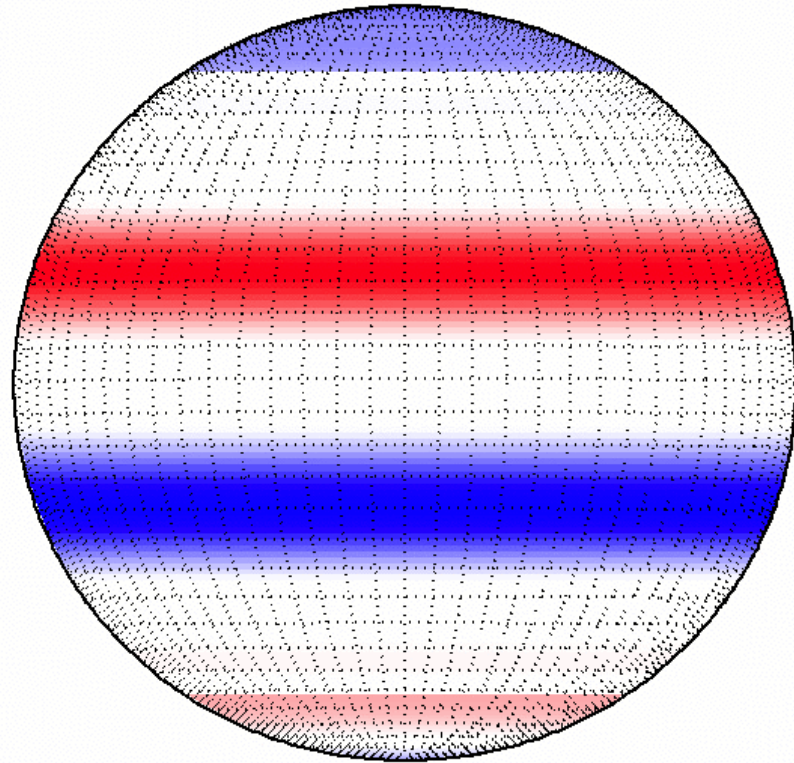


**The “22-year” Hale (magnetic polarity) Cycle of the Sun is recurrent and robust.**

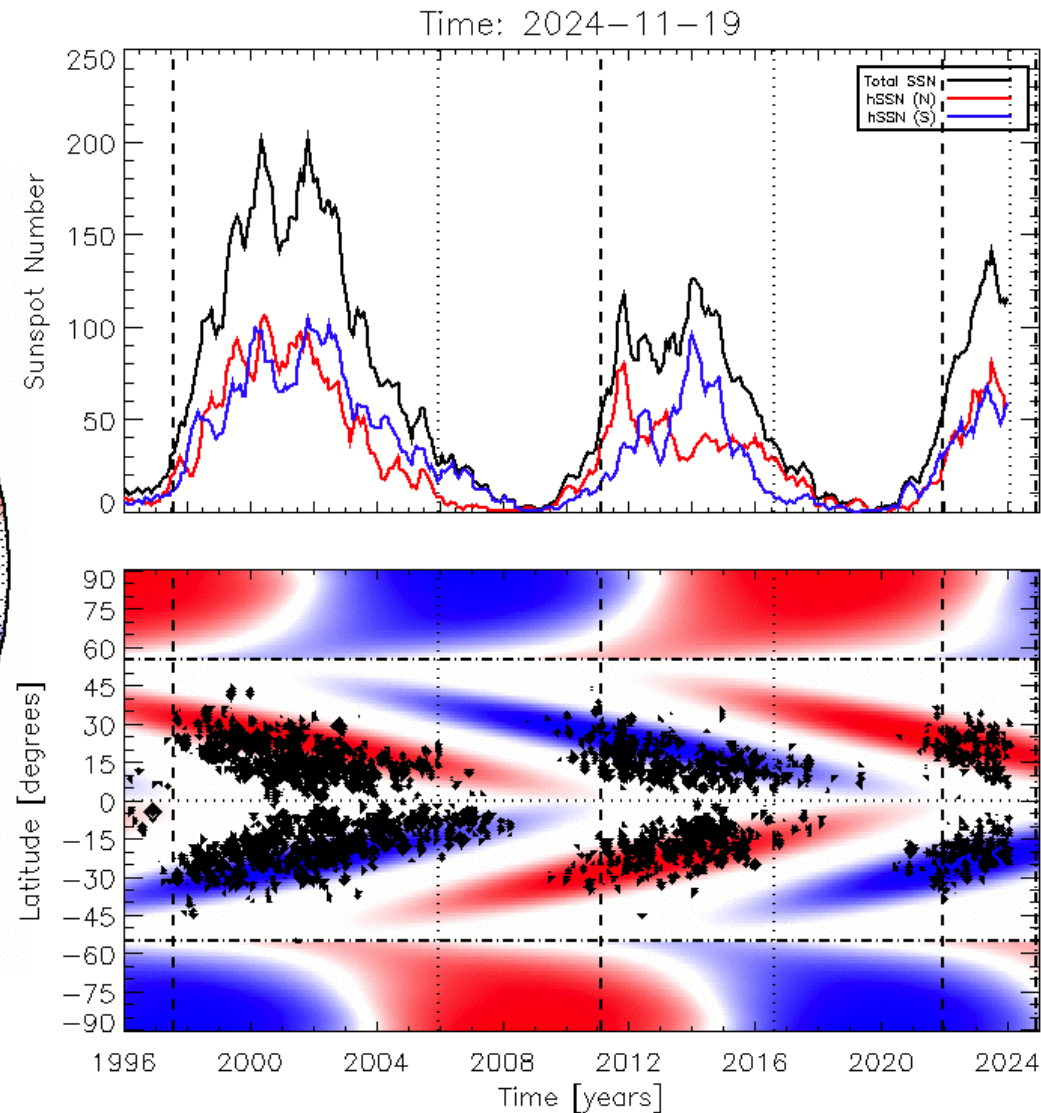
**The bands of the Hale Cycle have a definitive end, the “terminator”, at the equator.**

**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.**

# Conclusions: What Have We Learned?



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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.**

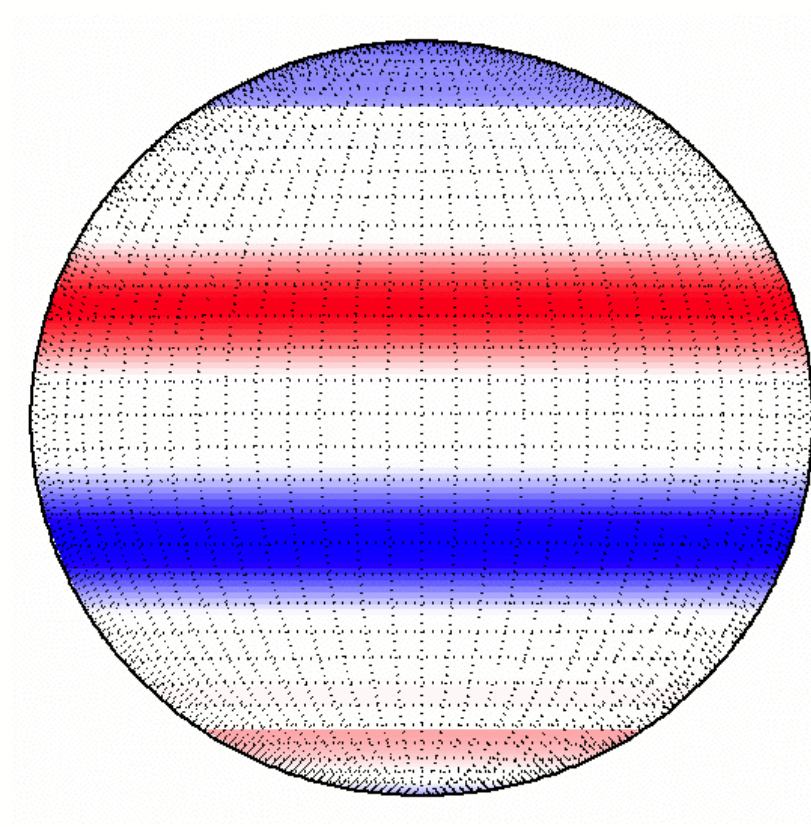


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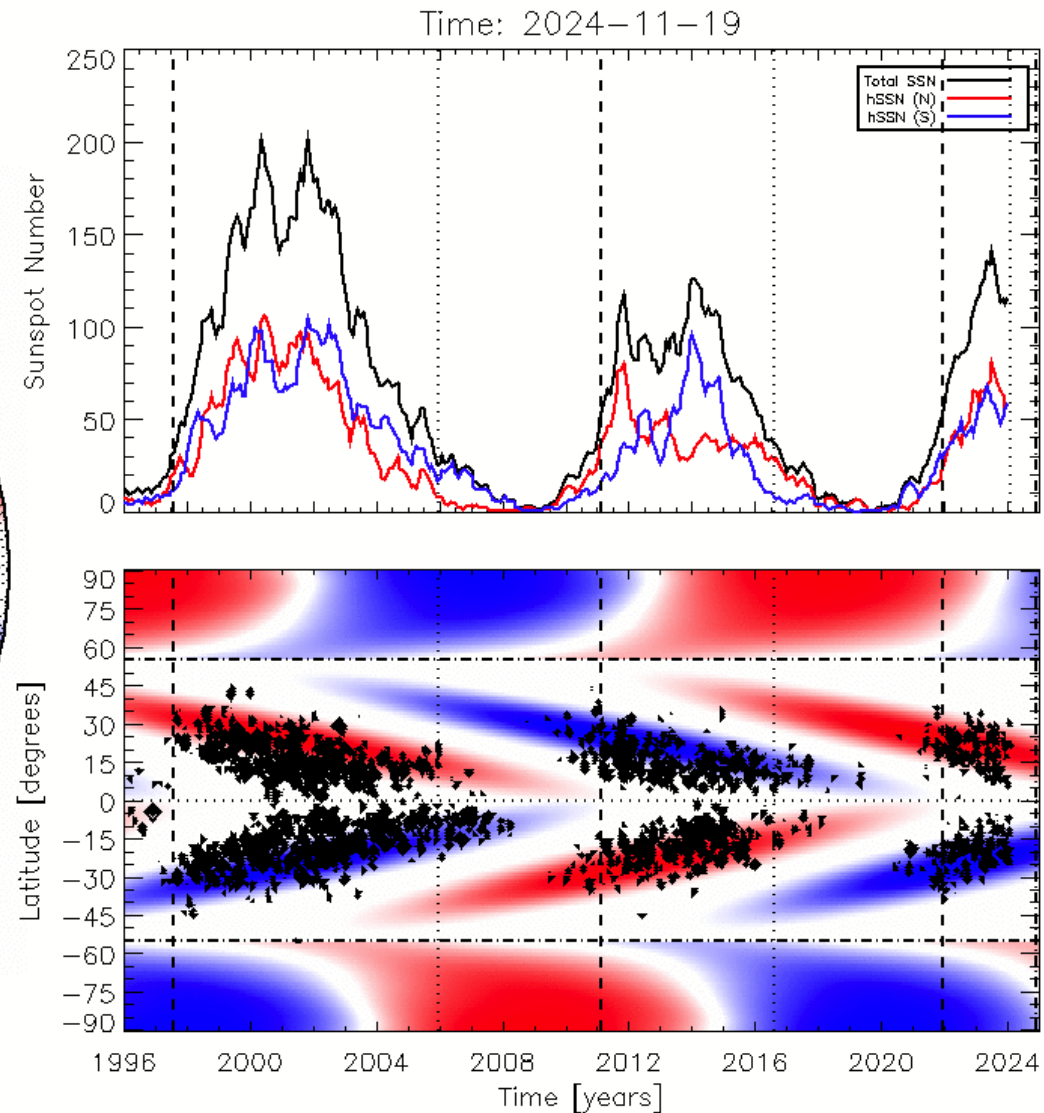
 @swmcintosh



# Conclusions: What Have We Learned?



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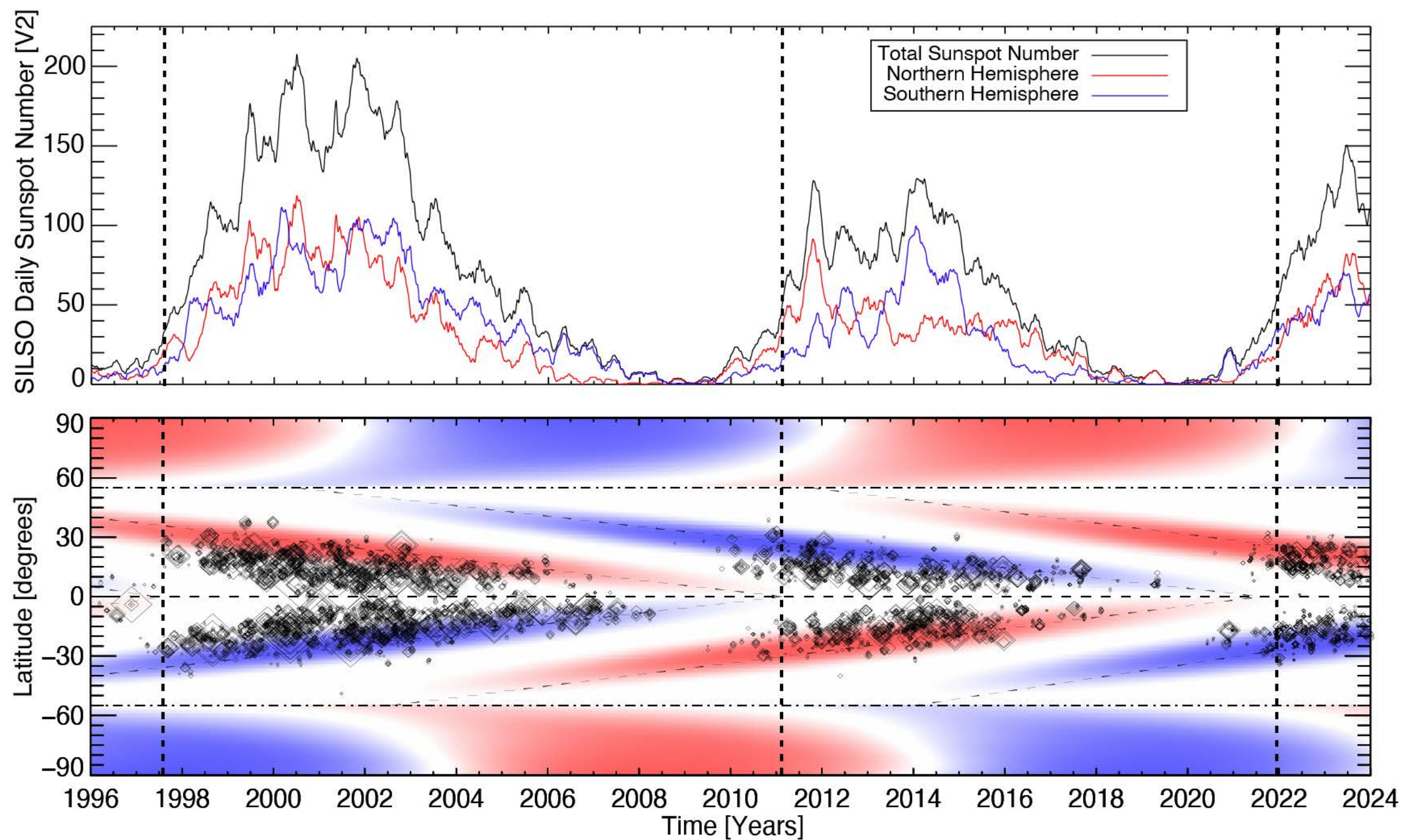


**Long terminator separations yield small upcoming cycles and vice versa.**

**Our forecast is on target!**

**Solar maximum is here!**

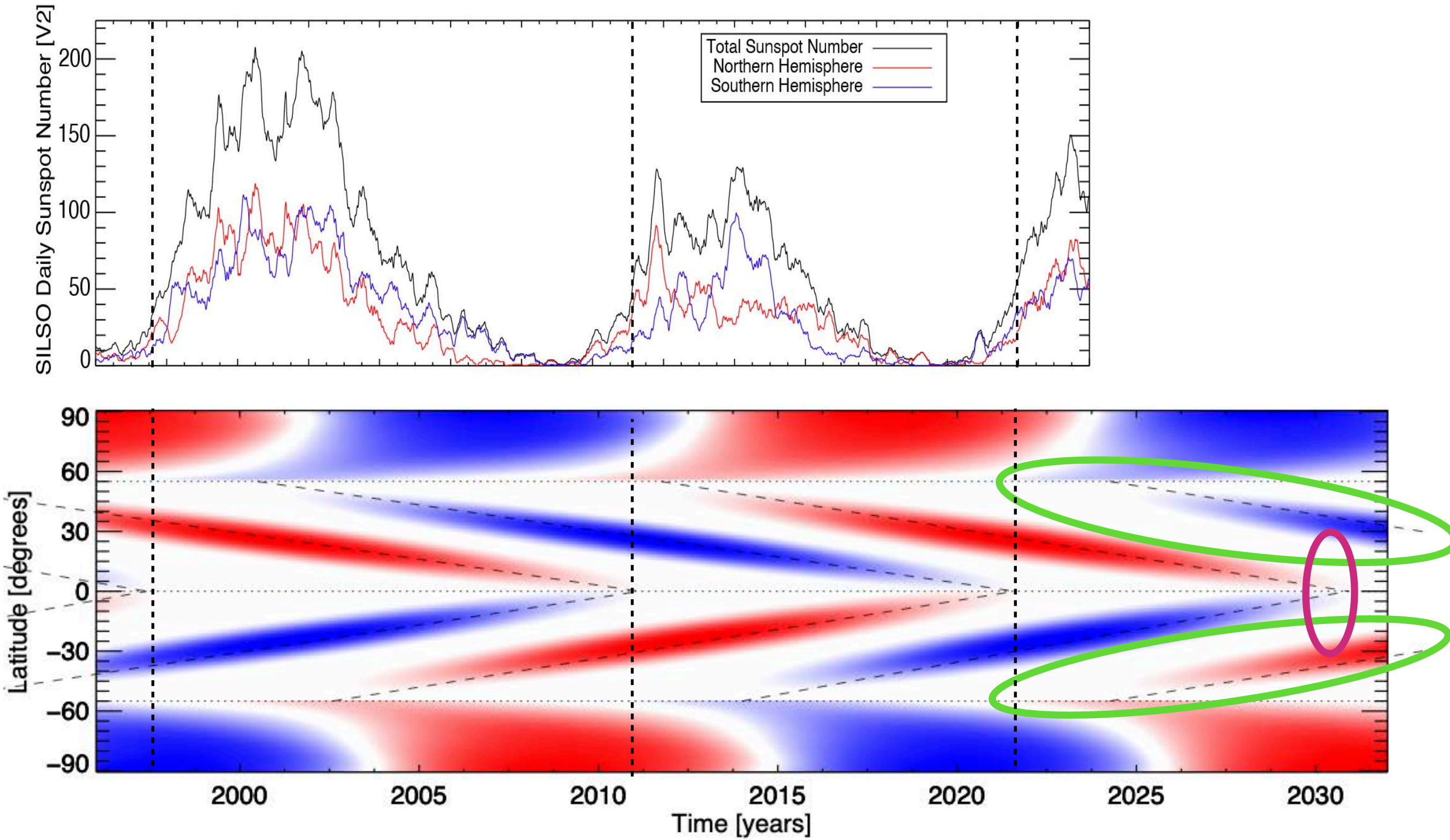
**Watch Out! Solar Activity picks up in the year following solar maximum...**



**What comes next?**



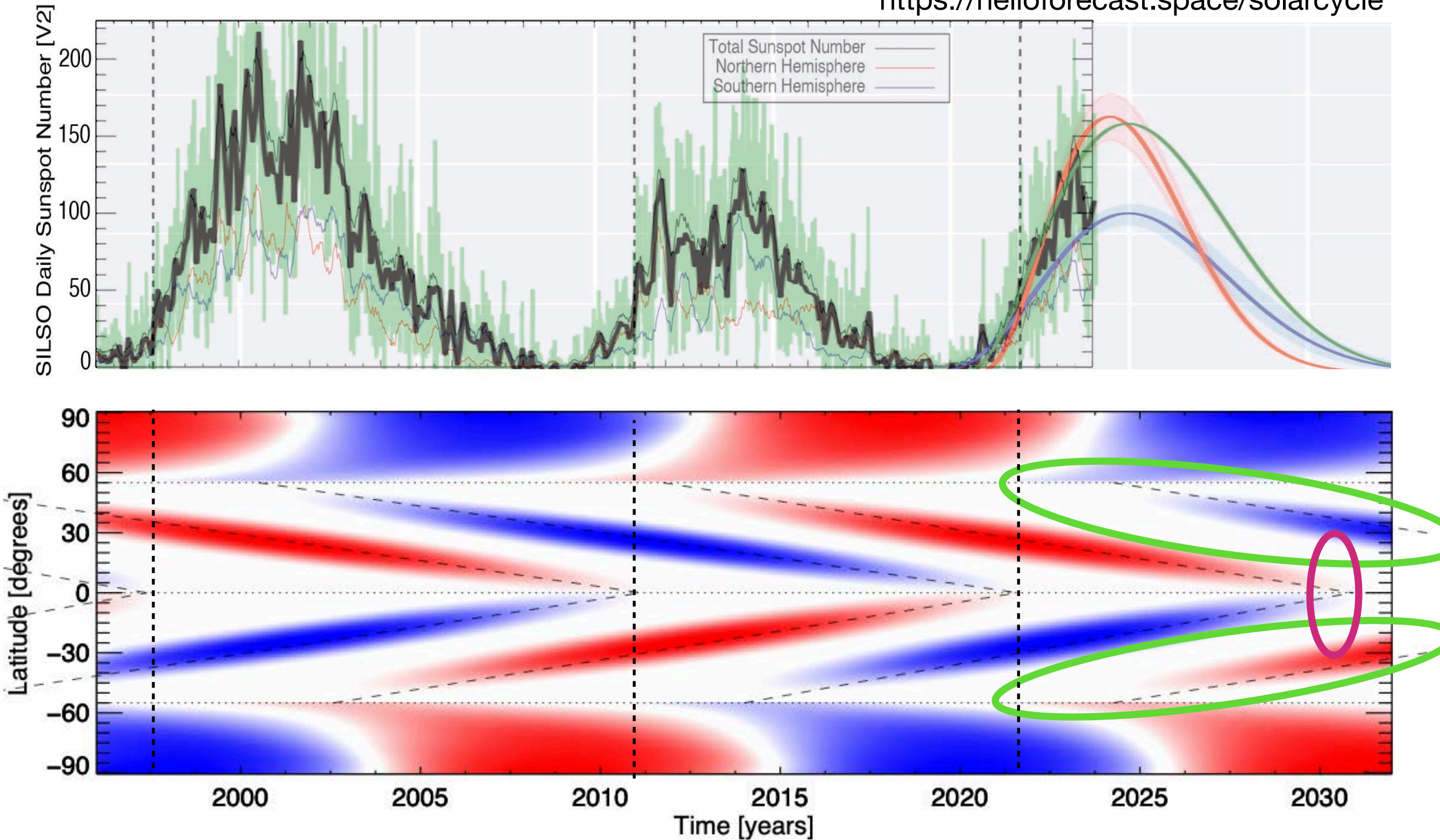
What comes next?





What comes next?

Follow Along.....  
<https://helioforecast.space/solarcycle>



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 @swmcintosh



# RECALL: Are there [real world] risks associated with adopting this model for Sunspot Cycle 25?

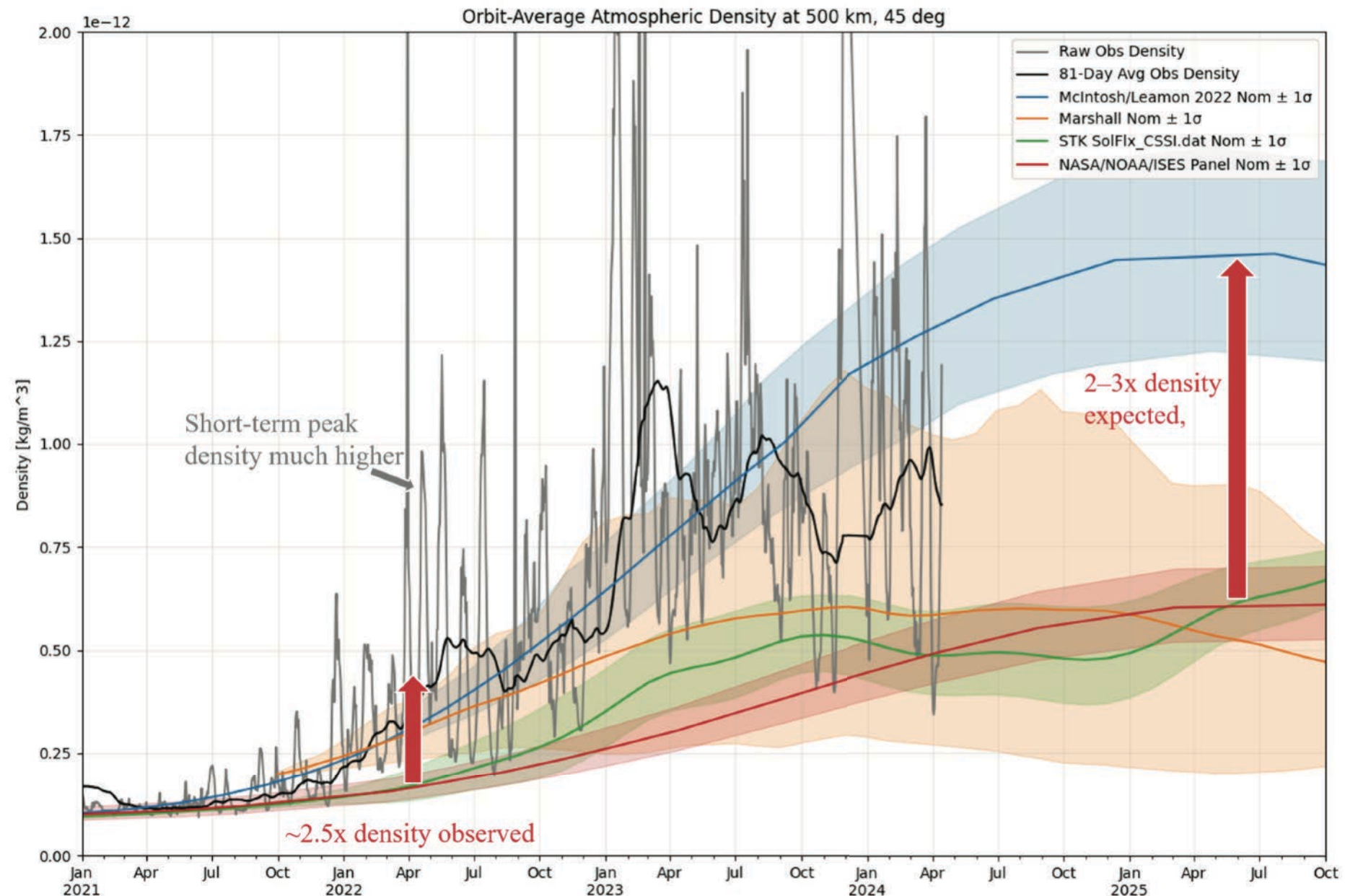


Figure 7: Density estimates for Solar Cycle 25 for a 500 km circular orbit at  $i = 45^\circ$  inclination, with predictions from Table 1 sources circa April 2022. Where applicable, confidence intervals were converted to  $1\sigma$  values using a normality assumption.

Shambaugh et al. (2024)

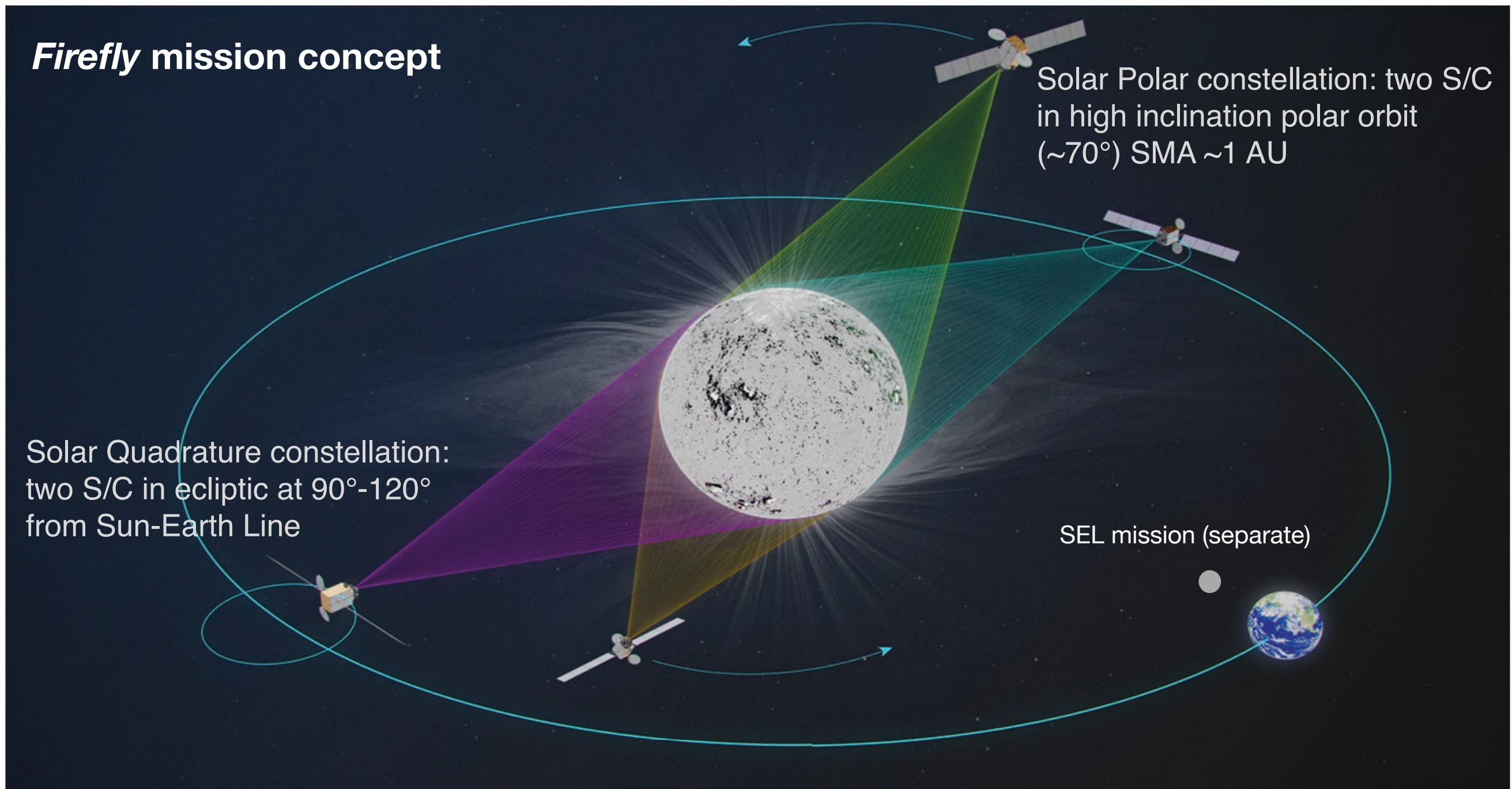
**The answer is very definitely yes!!!**

# We need to observe the *entire* Sun to make progress!

***Observing from the Sun-Earth line alone is not enough.***

Even adding L4 and L5 leaves out the majority of the far-side hemisphere.

## ***Firefly mission concept***







**Questions?**

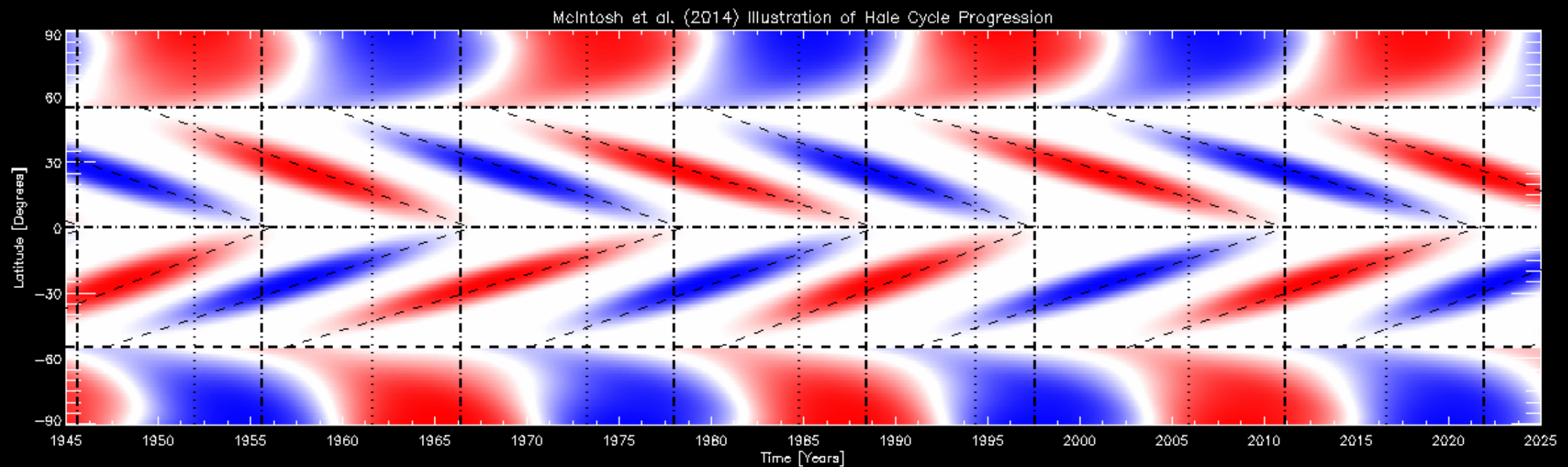
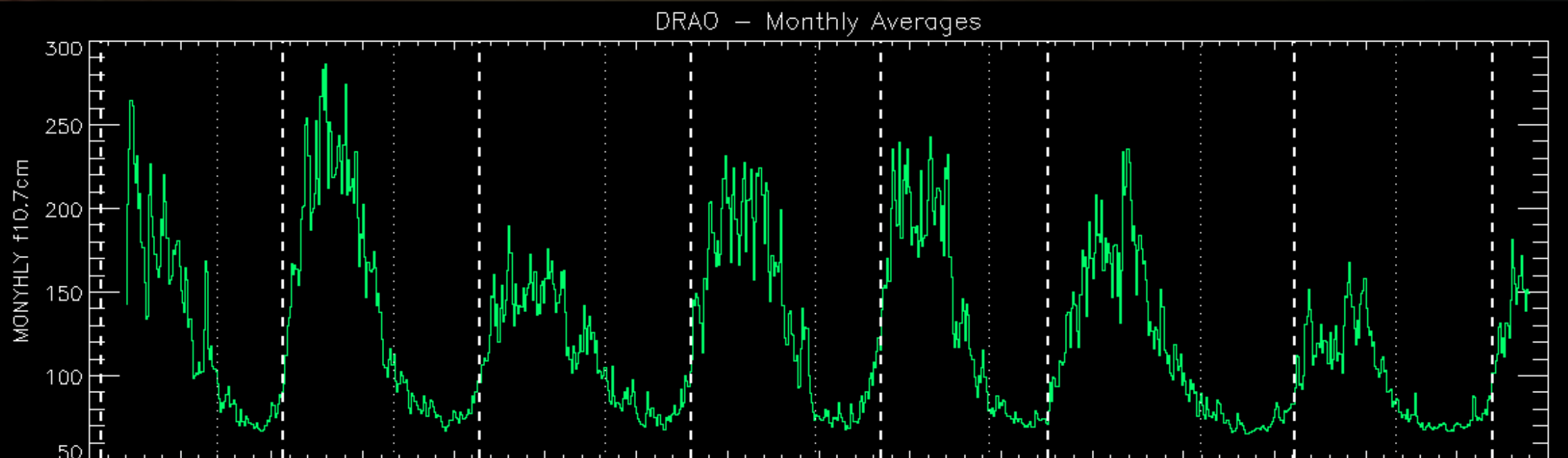


Backup Material



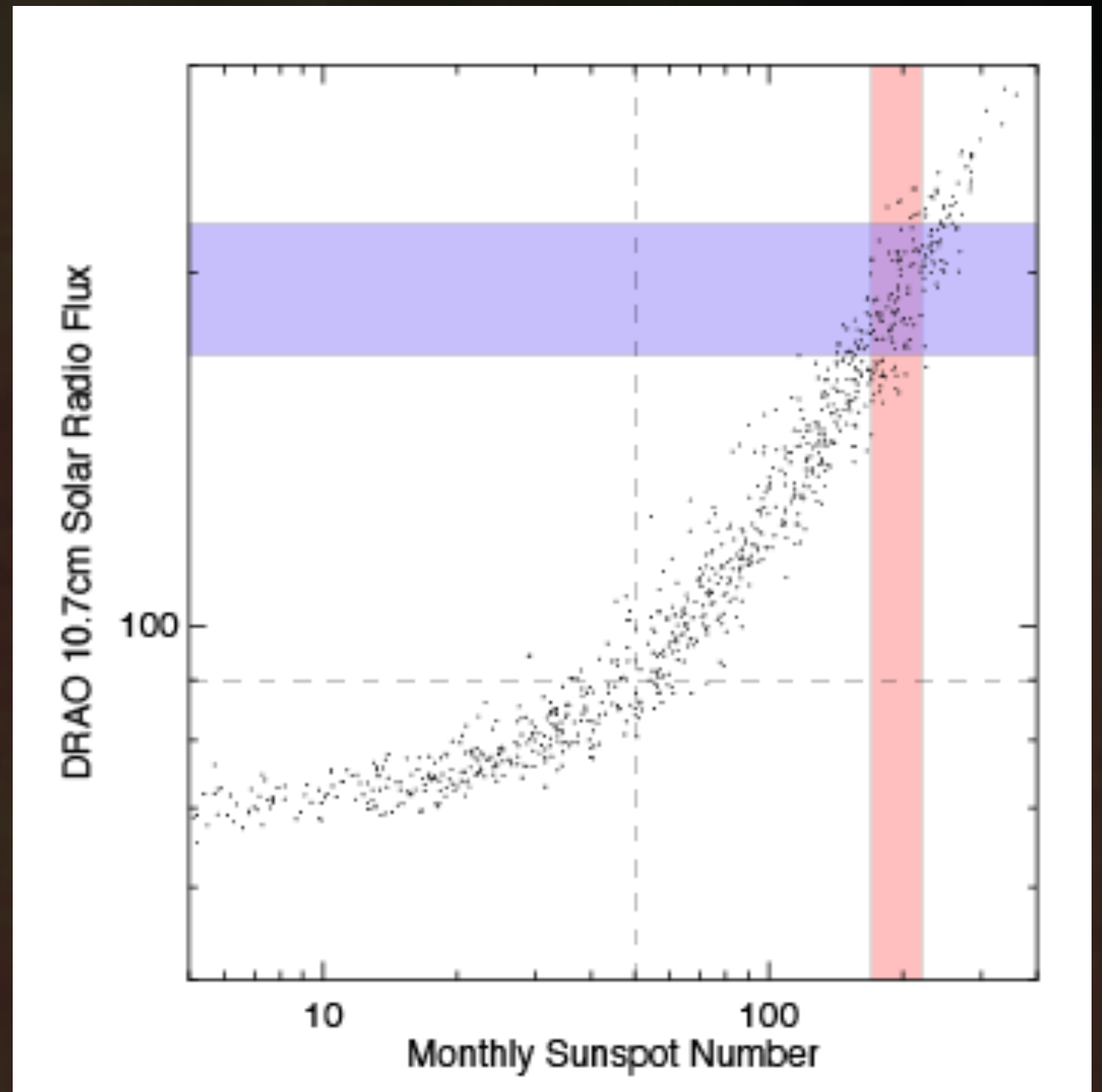
# school is in session: Superposed Epoch Analysis

## Forecasting f10.7cm - The Solar Radio Flux



## school is in session: Superposed Epoch Analysis Forecasting f10.7cm - The Solar Radio Flux

- Develop a statistical average 'unit cycle' f10.7cm model
- Use the SSN terminator separation amplitude relationship
- Use the relationship between SSN and f10.7cm for the SC25 Amplitude to project an scaled f10.7cm model for #SunspotCycle25

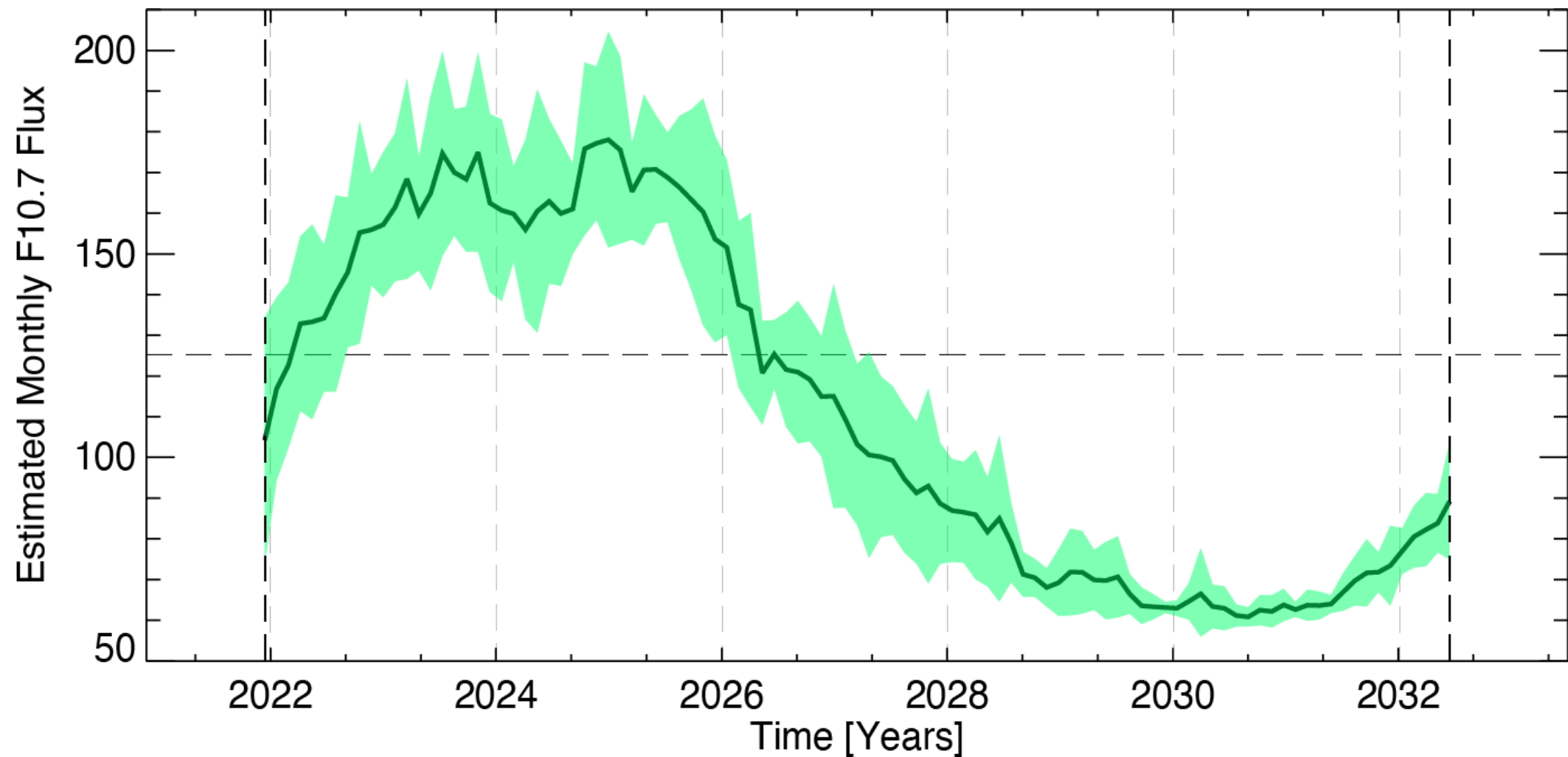




# School is in session: Superposed Epoch Analysis

## Forecasting f10.7cm - The Solar Radio Flux

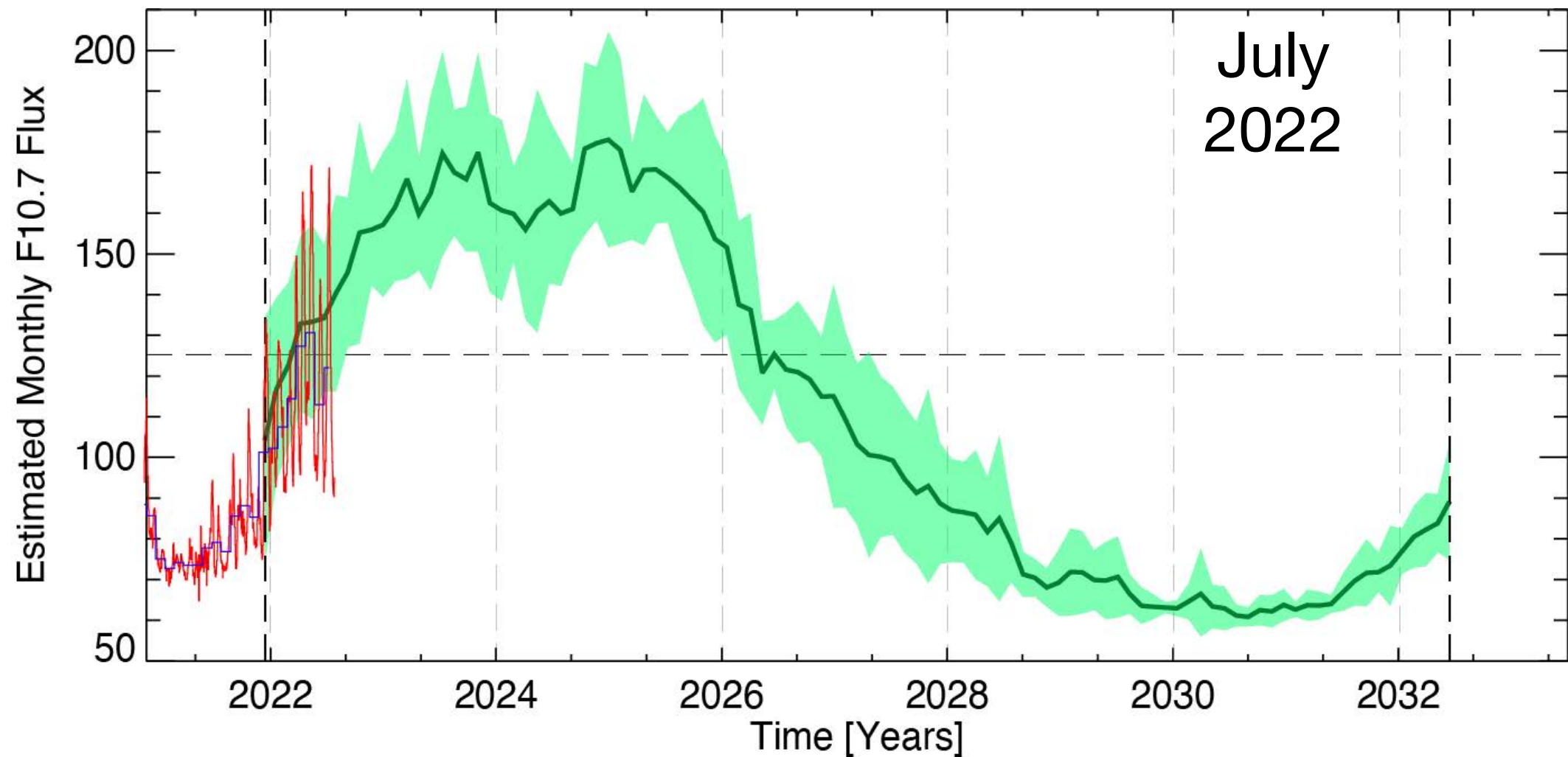
### Scaled f10.7cm mSEA model for #SunspotCycle25



# School is in session: Superposed Epoch Analysis

## Forecasting f10.7cm - The Solar Radio Flux

### Scaled f10.7cm mSEA model for #SunspotCycle25

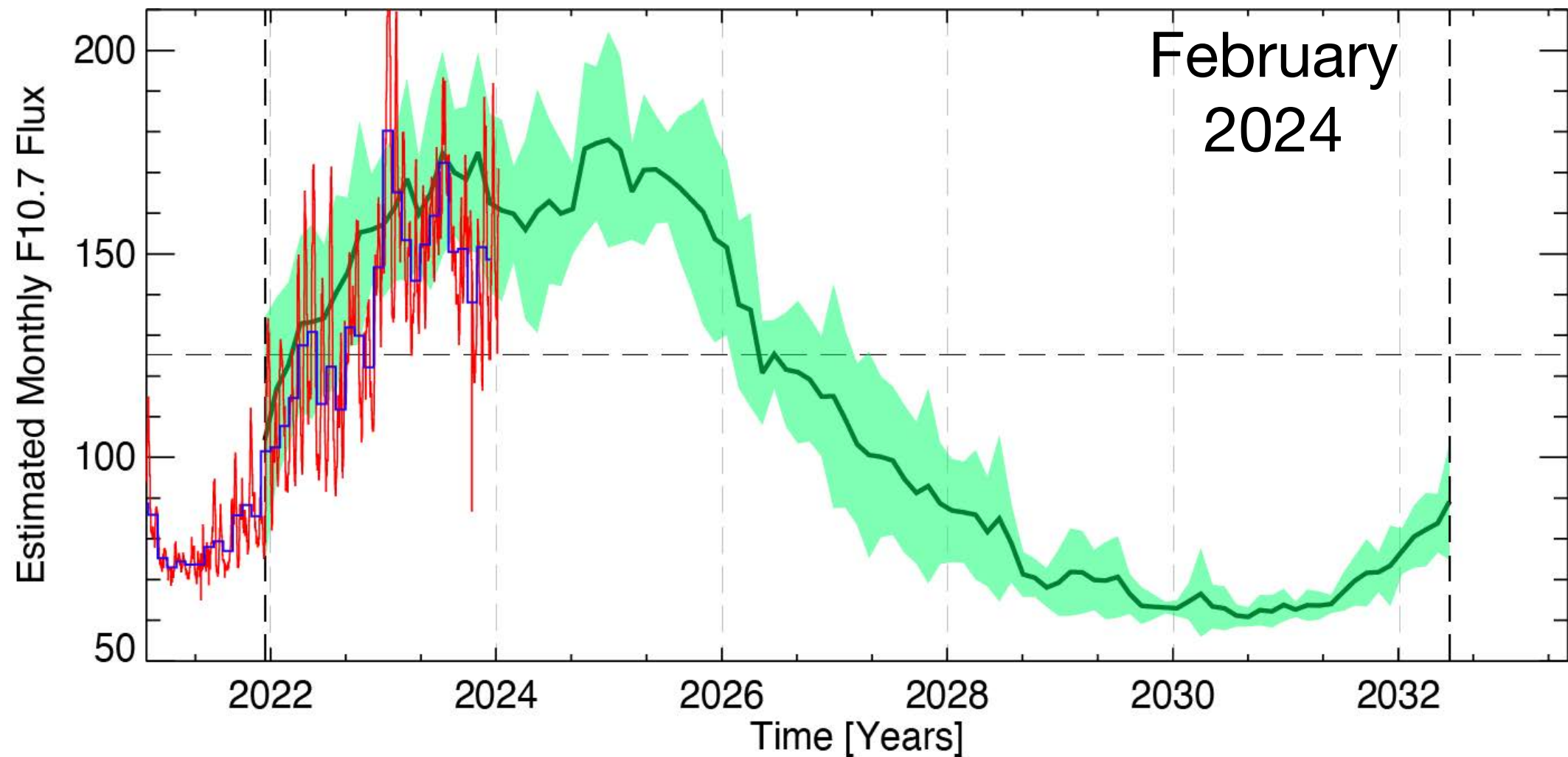




# School is in session: Superposed Epoch Analysis

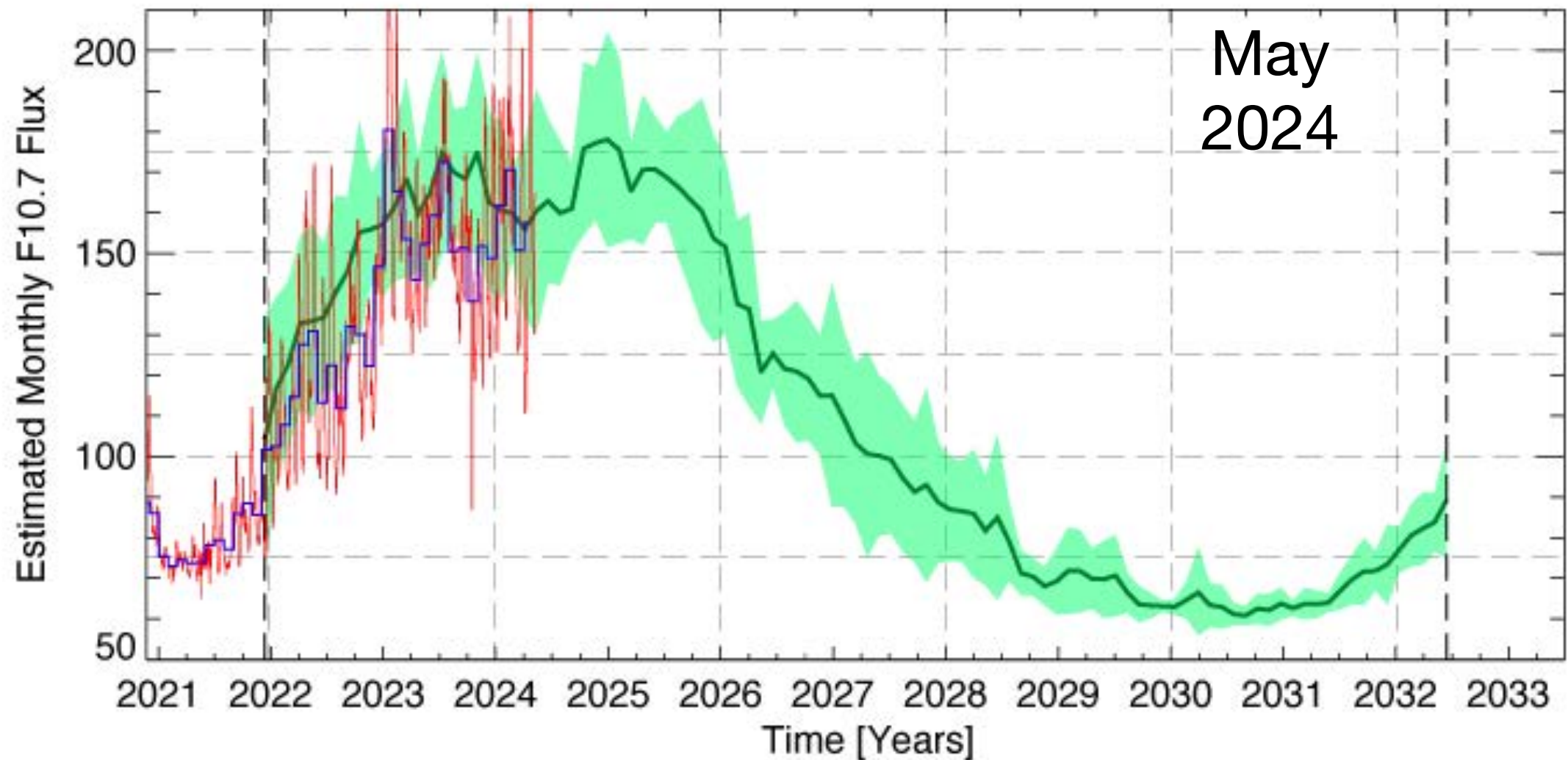
## Forecasting f10.7cm - The Solar Radio Flux

### Scaled f10.7cm mSEA model for #SunspotCycle25



# School is in session: Superposed Epoch Analysis Forecasting f10.7cm - The Solar Radio Flux

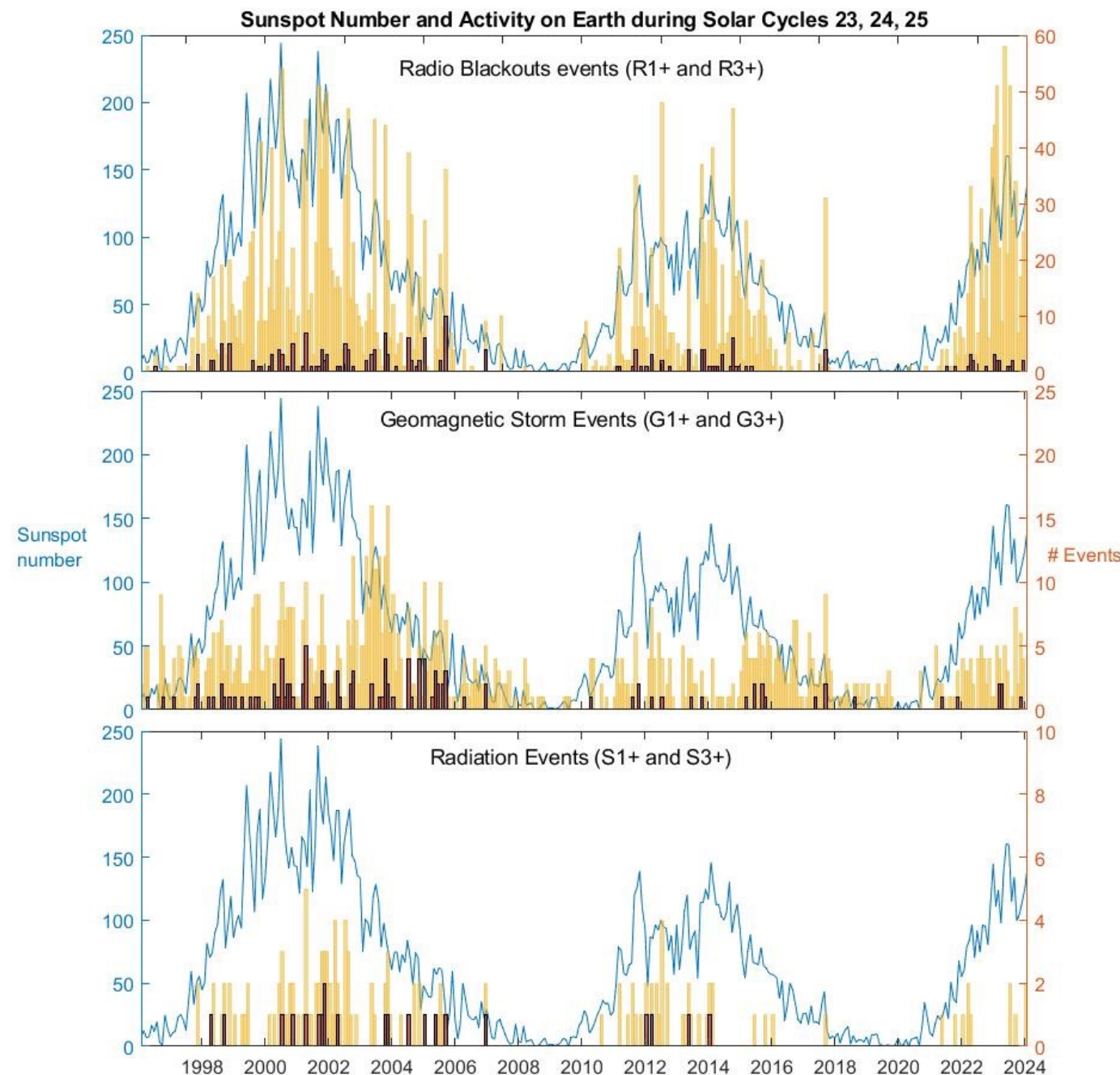
## Scaled f10.7cm mSEA model for #SunspotCycle25





# Are sunspots the right things to count?

Until the recent explosion of activity from AR 13664, the number of sunspots on the Sun did not seem to correlate to past levels of eruptive activity:



SC25:

M1+ (R1) flare numbers comparable to SC 23 but X-flare numbers lagging SC24...

Number of G3 geomagnetic storms lagging SC 24...

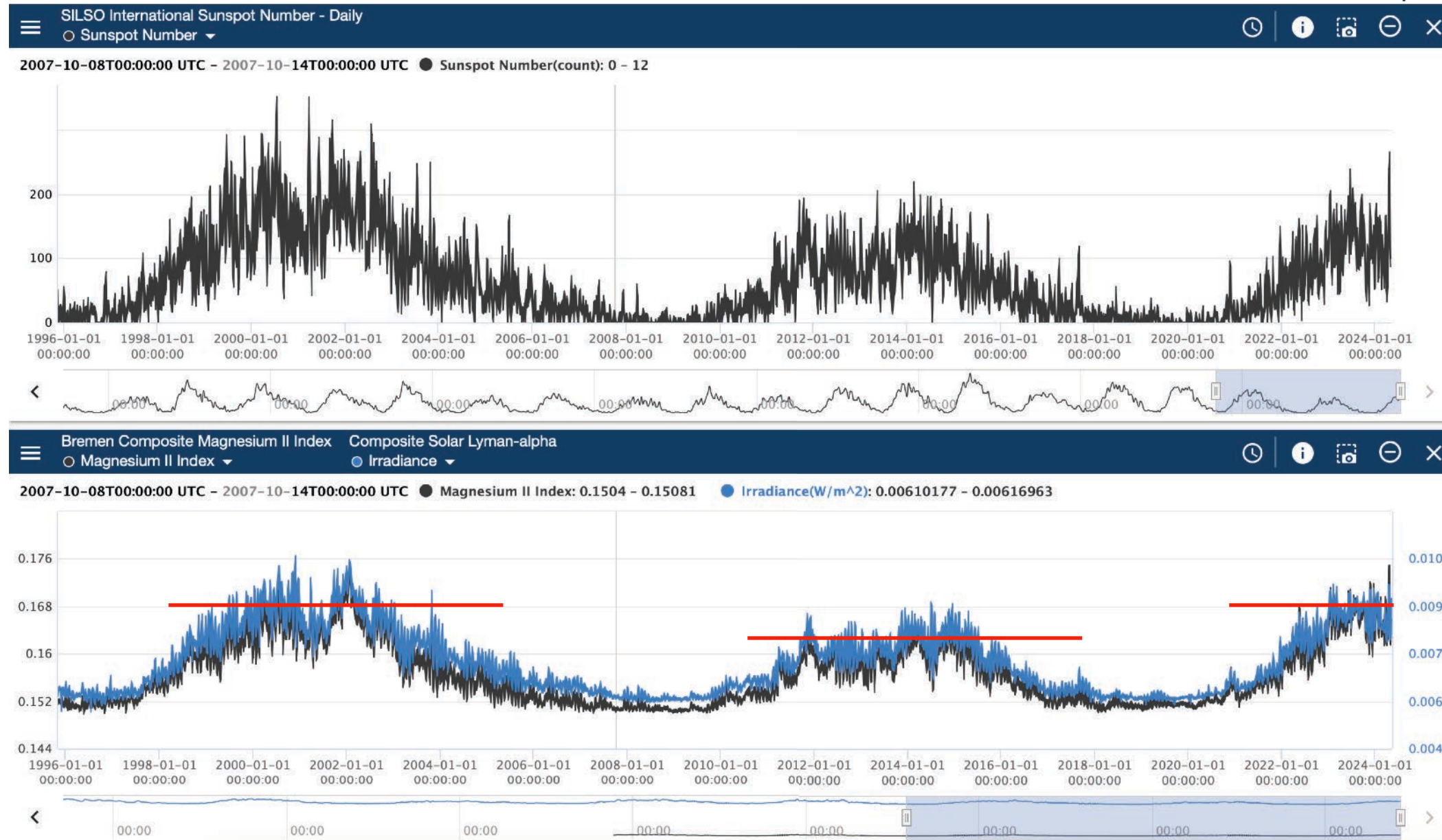
Number of radiation storms is **MUCH** lower than either SC 23 or Sc 24.

***Question: is the level of eruptive activity really low or is it just that the eruptions are taking place off the Sun-Earth line?***

# Is the solar dynamo doing something strange?

Fact: the level of solar irradiance, particularly in Mg II lines is as high as Solar Cycle 23 and significantly higher than SC24 for the same level of sunspots.

<https://lasp.colorado.edu/lisird/>



Mg II and Lyman- $\alpha$  brightness are correlated with “plage” magnetic fields, i.e, small-scale magnetic structure.

***Question: is the solar dynamo producing lots of smaller, simpler, spot groups such that the sunspot count is high but energy is not able to build up for eruptions?***