The Sun & Solar Activity

…Lecture 1

Scott W McIntosh

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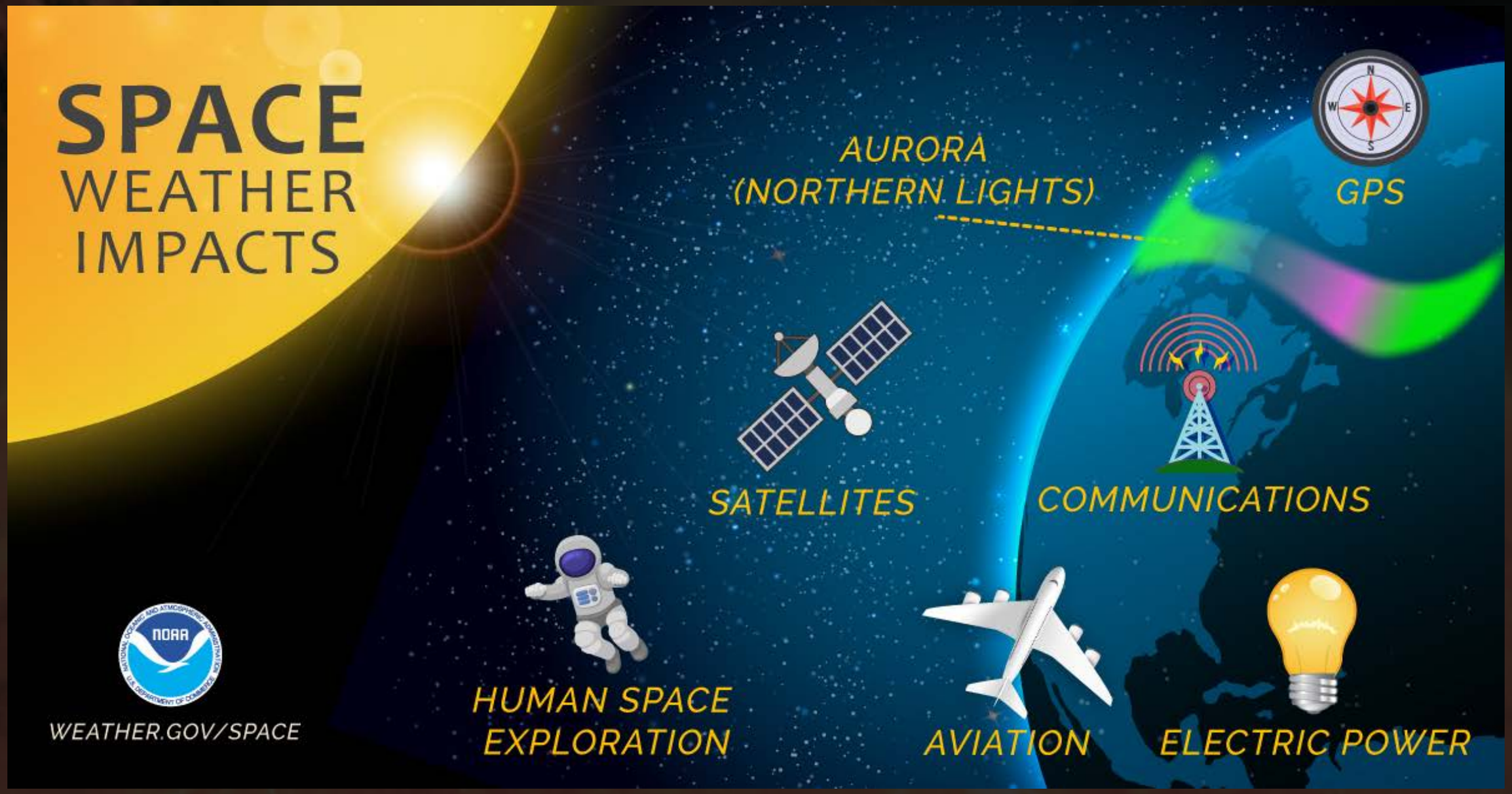
Presented by Tom Berger

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?



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.

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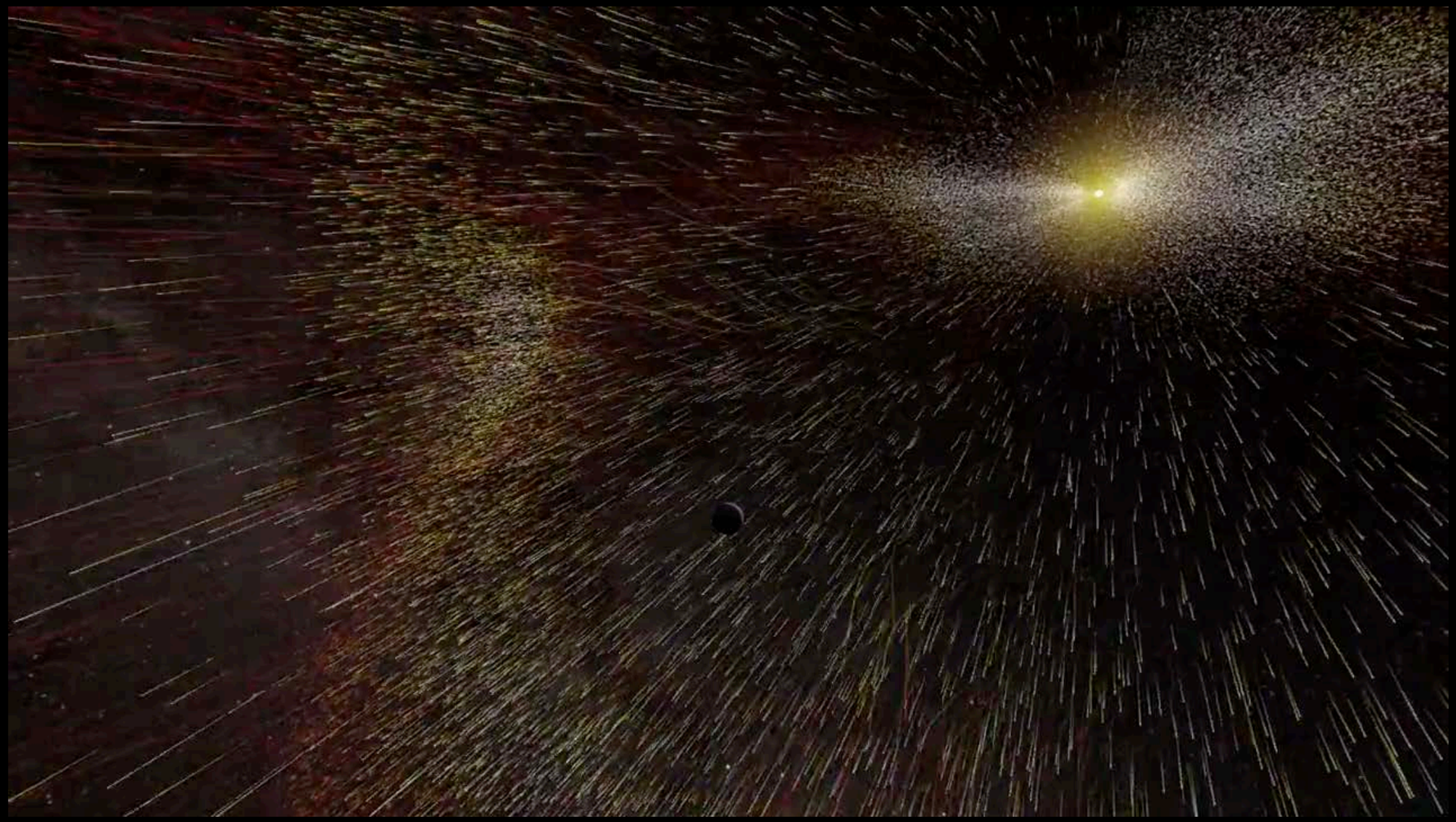
Because, we live in the atmosphere of our Star!



We are dependent on it for almost everything…

we are also increasingly vulnerable to it…

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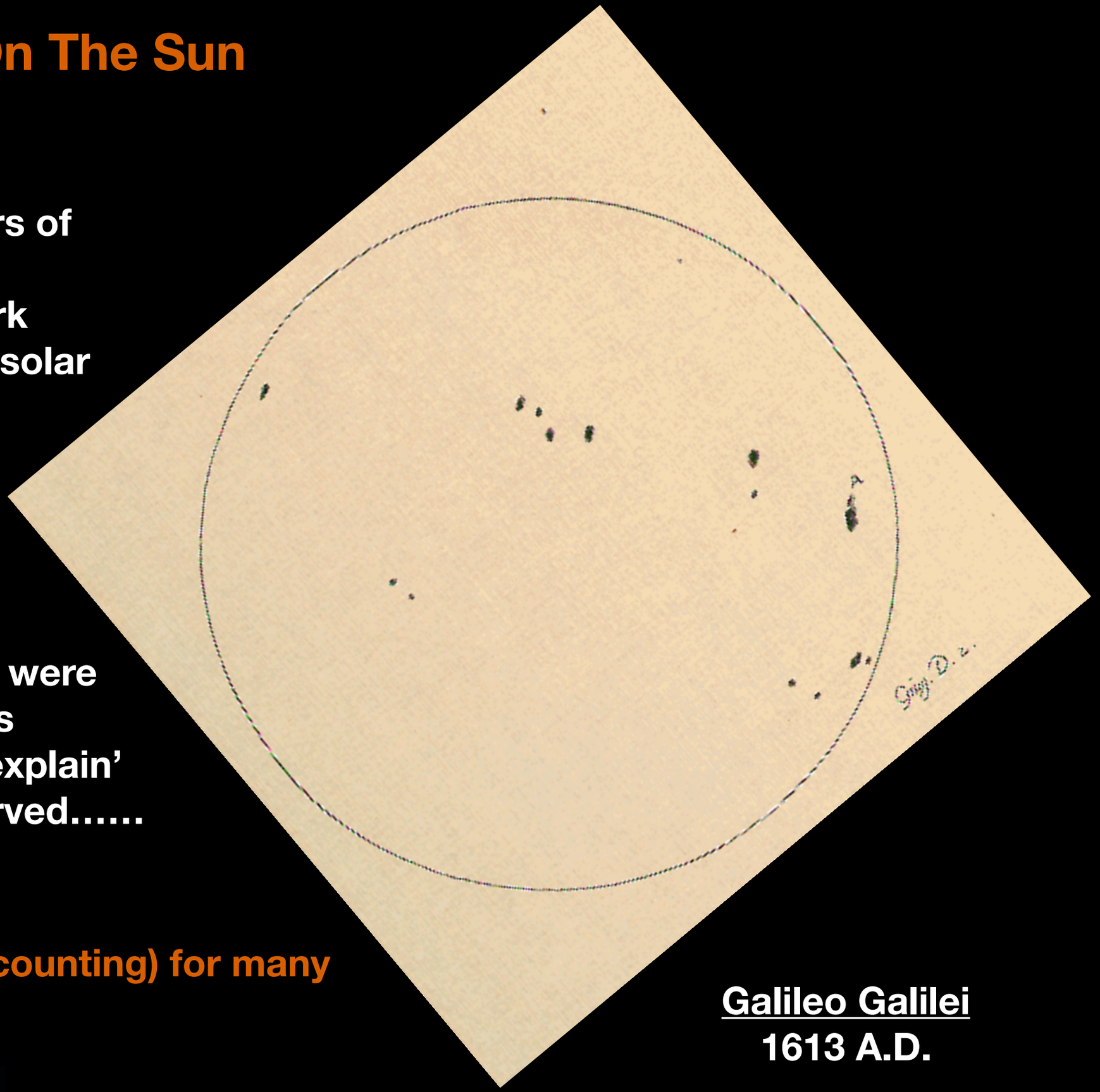
Rewind: Spots On The Sun

In the (very) early years of telescopic astronomy observers tracked dark features crossing the solar disk……

Needless to say there were some pretty wild ideas pushed out there to ‘explain’ what was being observed……

Keep observing (and counting) for many decades….



Galileo Galilei
1613 A.D.

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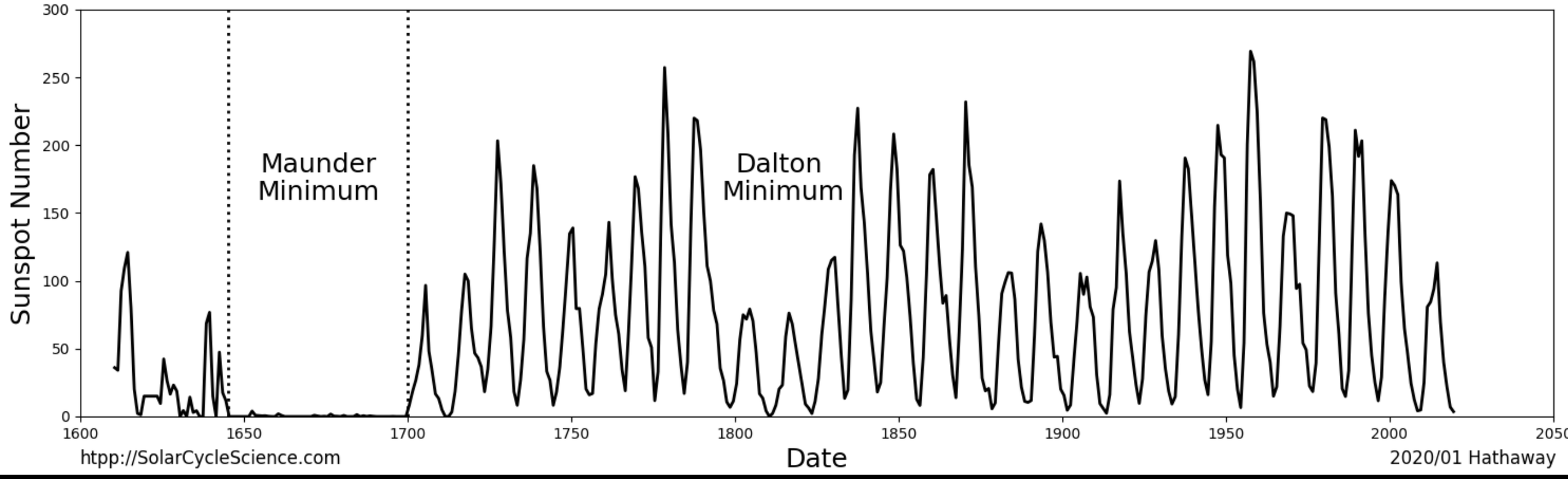
Rewind: Spots On The Sun



“Cyclic” Sunspot Evolution : Average period of about 11-Years

Except when there are NONE.

[ASIDE: Jack Eddy - The Sun continued to cycle even though there were no spots!]

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

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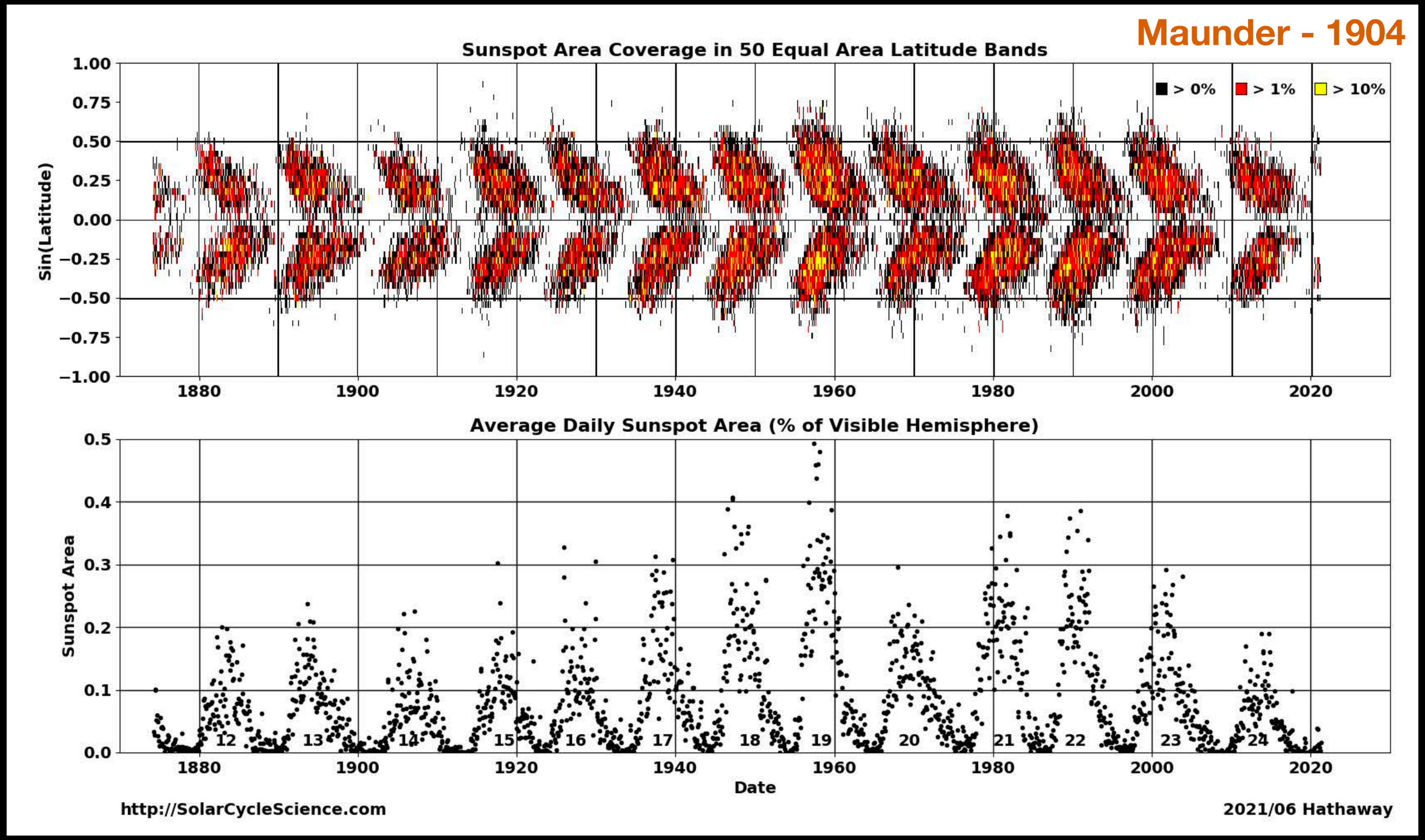
Rewind: Spots On The Sun



Breakthrough: “Butterfly”

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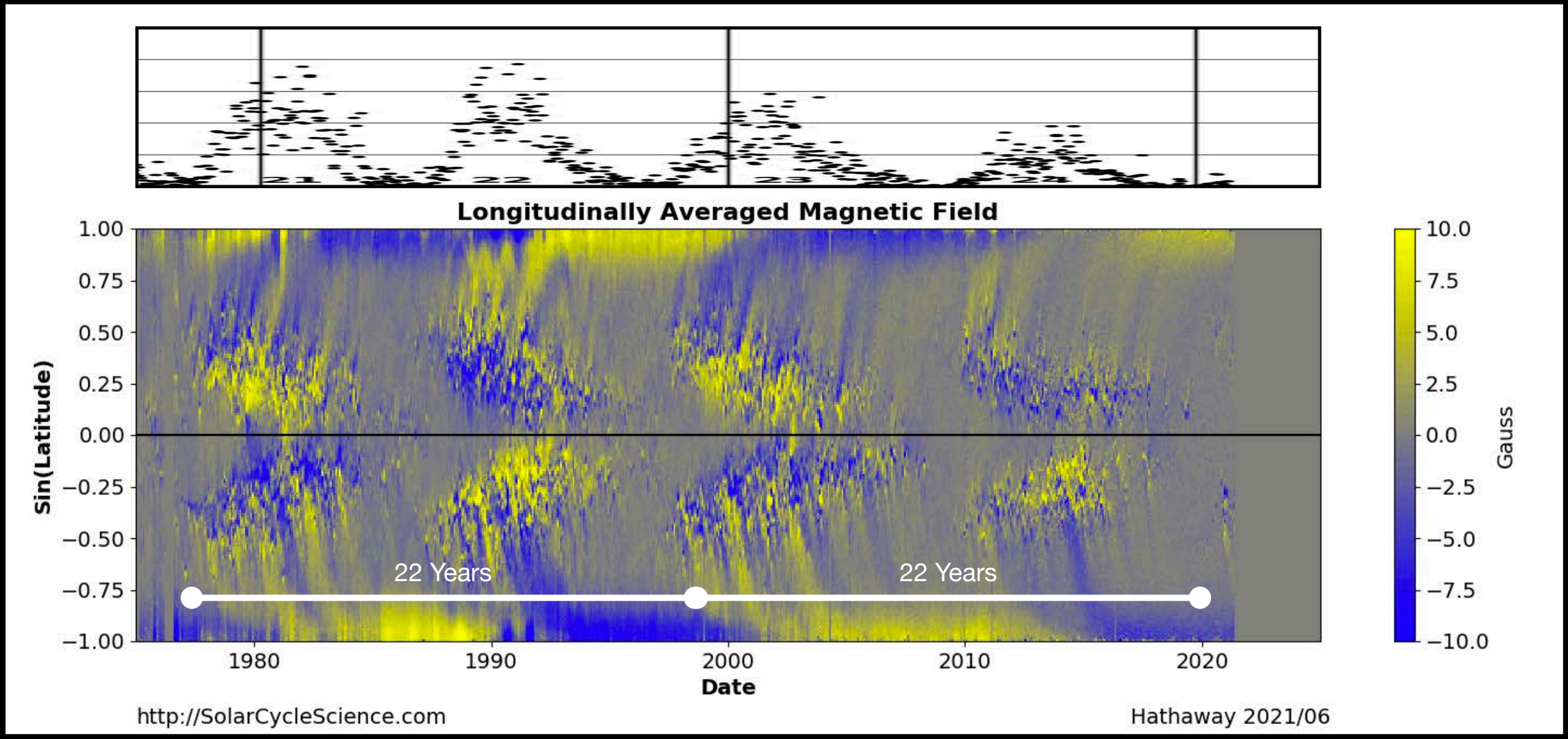
Rewind: Spots On The Sun

Hale - 1913-1919: Sunspots are magnetic objects

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



Breakthrough: “Magnetic Butterfly”

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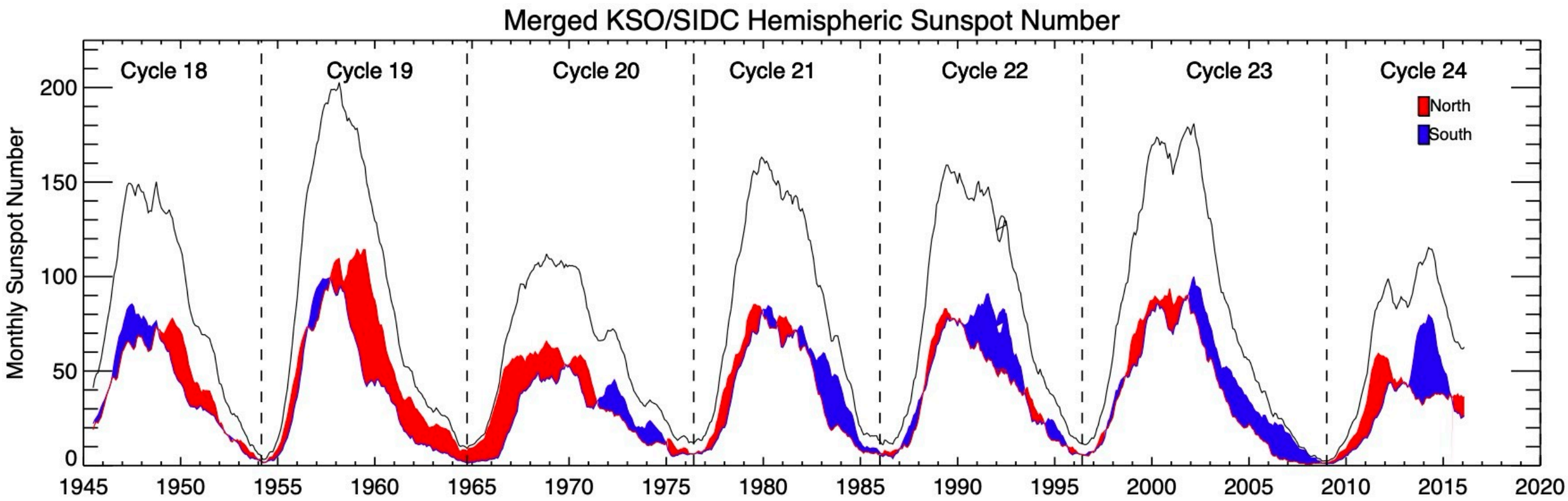
Fast-Forward: Spots On The Sun



SUNSPOT CYCLES ARE NOT SINUSOIDAL

CYLES MORE OFTEN THAN NOT DOUBLE PEAKED

HEMISPHERIC ACTIVITY NOT SYMMETRIC

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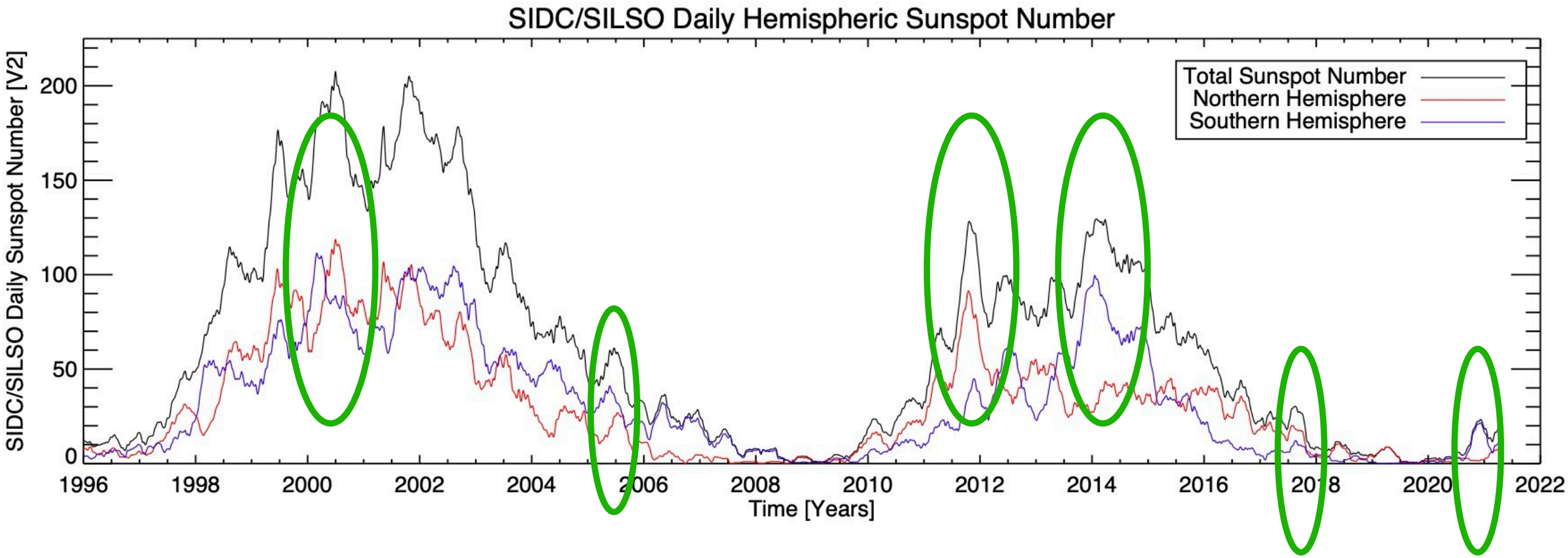
Fast-Forward: Spots On The Sun



The Sun also has periods of enhanced spot formation on shorter timescales [although maybe not enough time in these talks to discuss in detail :-( ]

The strongest space weather events occur during these “surges” of sunspot production.

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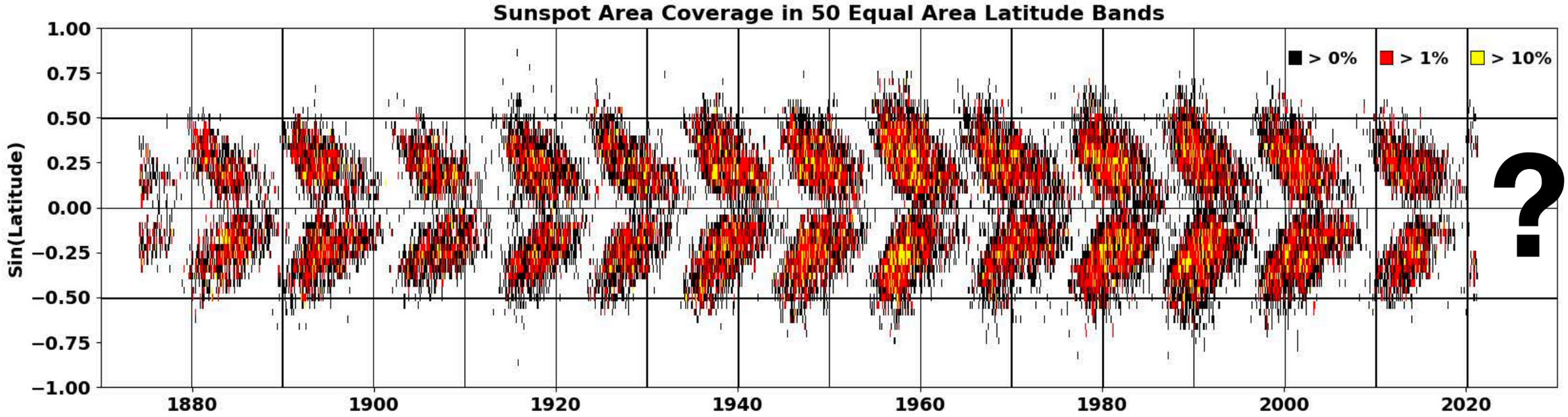

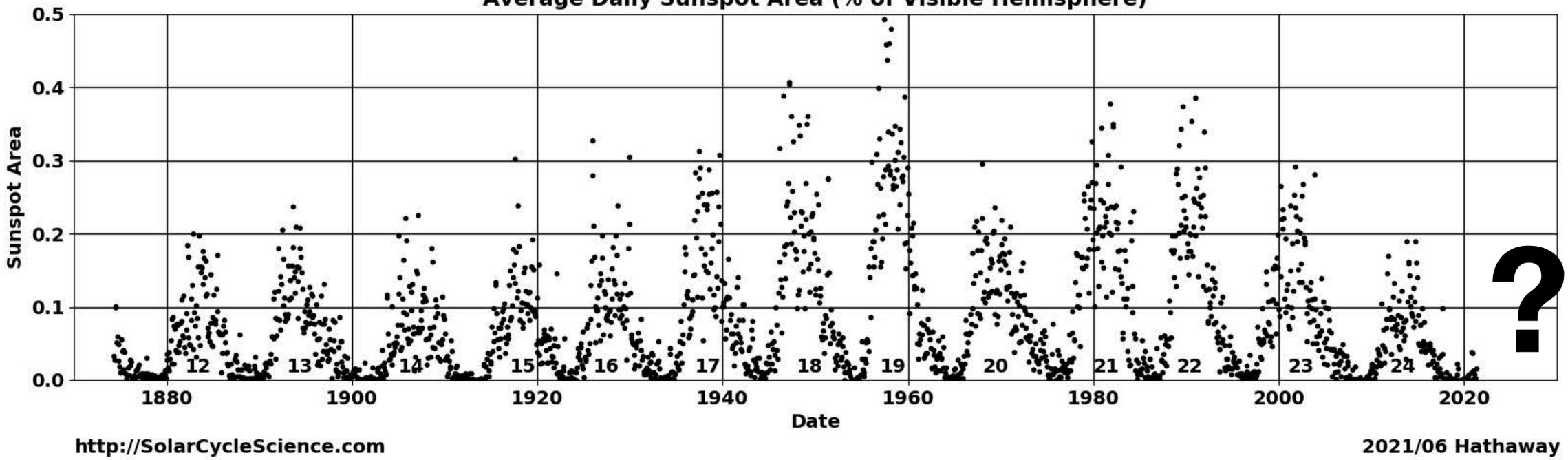

400+ years of measured sunspot number?

100+ years of the measured magnetic data

∞ potential solutions to the puzzle

250+ ‘predictions’ of sunspot cycle 25….. what is the Sun doing?

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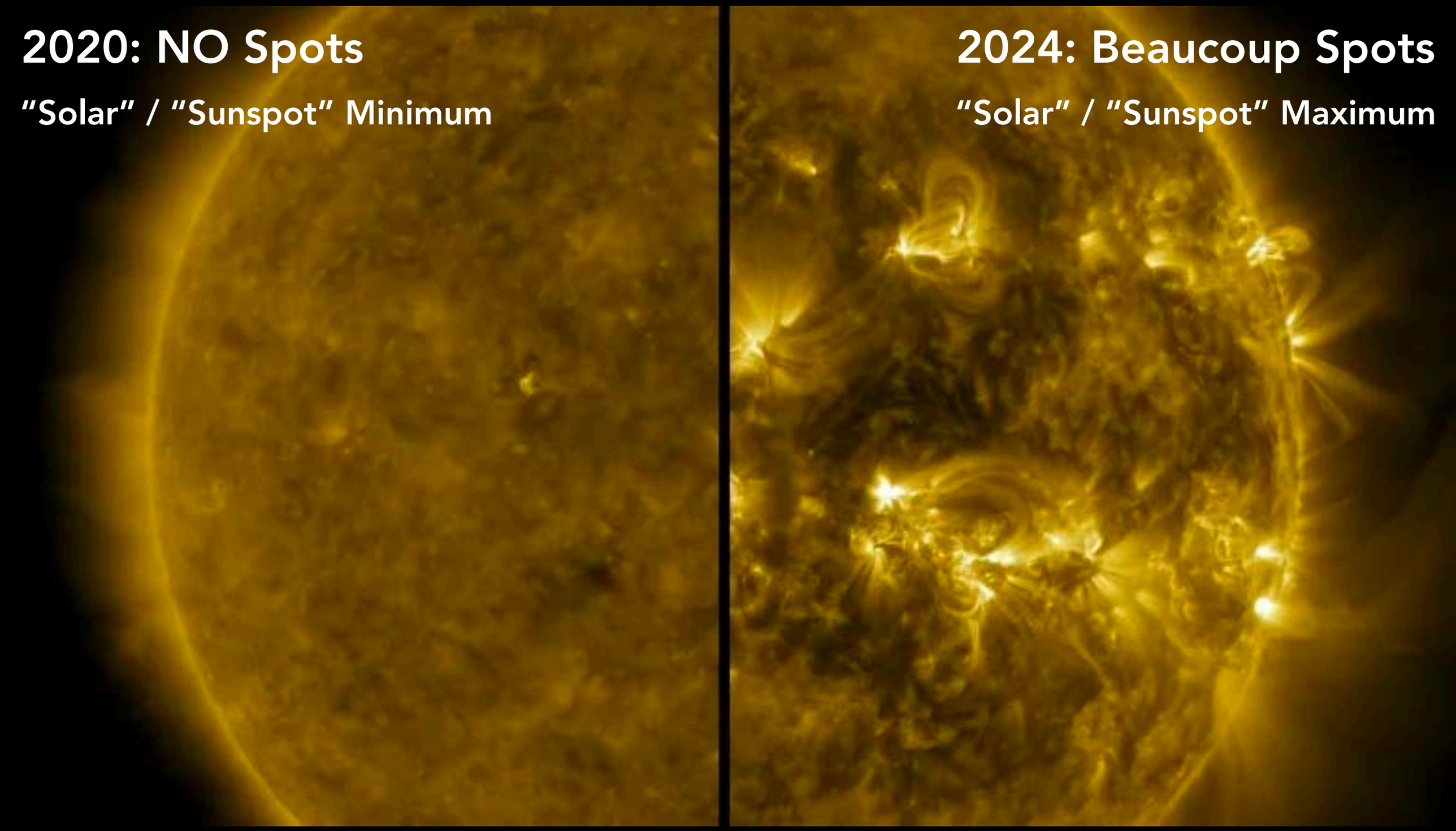
Jump Forward…..Stark Contrasts in Activity Levels

2020: NO Spots

"Solar" / "Sunspot" Minimum

2024: Beaucoup Spots

"Solar" / "Sunspot" Maximum



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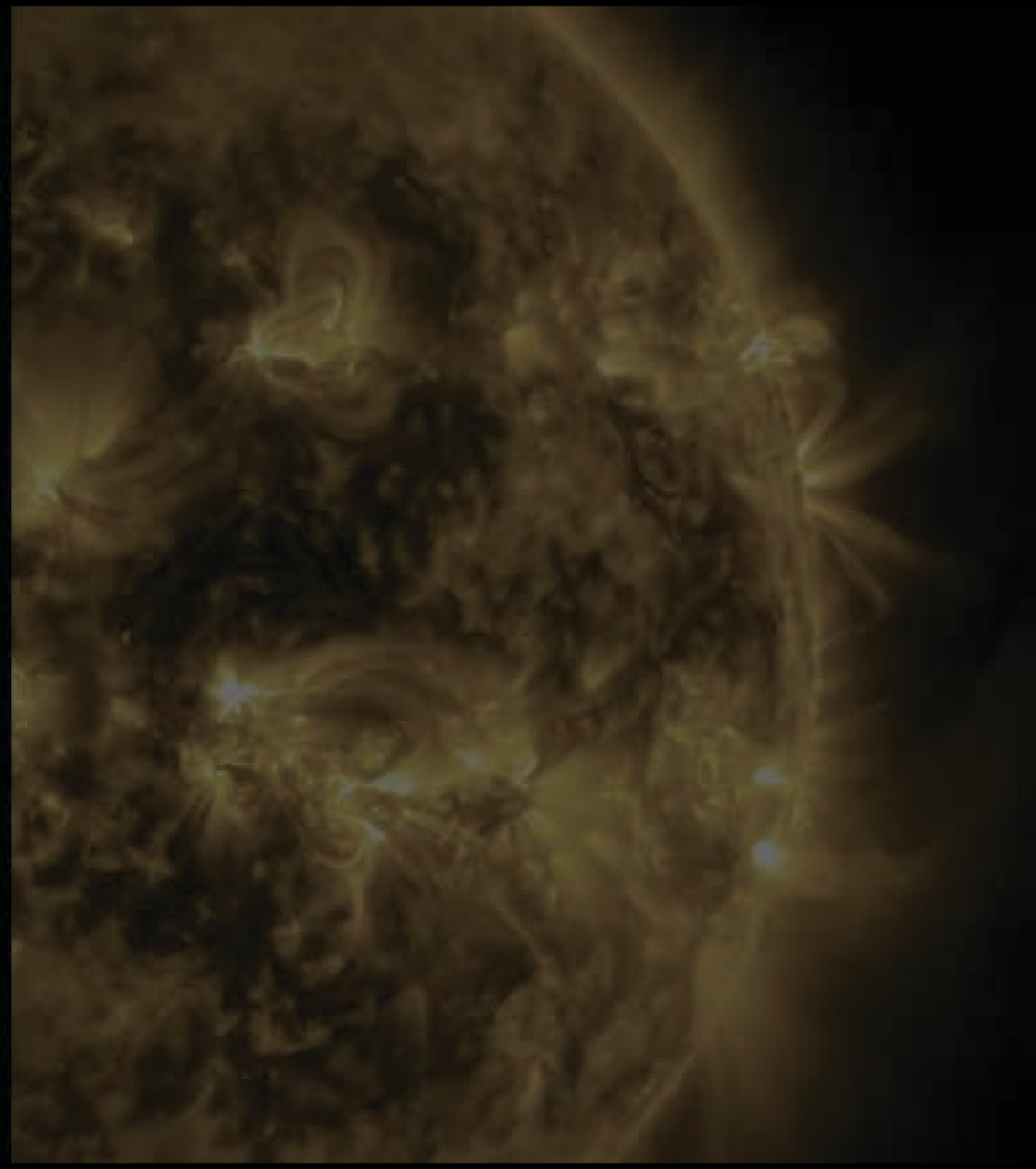
Jump Forward…..Stark Contrasts in Activity Levels

- The Sun has an 11(-ish) year sunspot cycle.
  - Sunspots appear first at mid-solar latitudes and migrate to the equator - never crossing.
  - This forms a butterfly pattern.
- The Sun has a 22(-ish) year magnetic polarity cycle.
  - The wings of the sunspot butterfly alternate in dominant polarity.
  - For reference the Earth's magnetic poles reverse every 200,000 years…
- The Sun experiences extended periods where the number of spots can be very large and times when there are almost no spots!
- *It is our job to explain all of these features self-consistently……. [and then predict the future….]*



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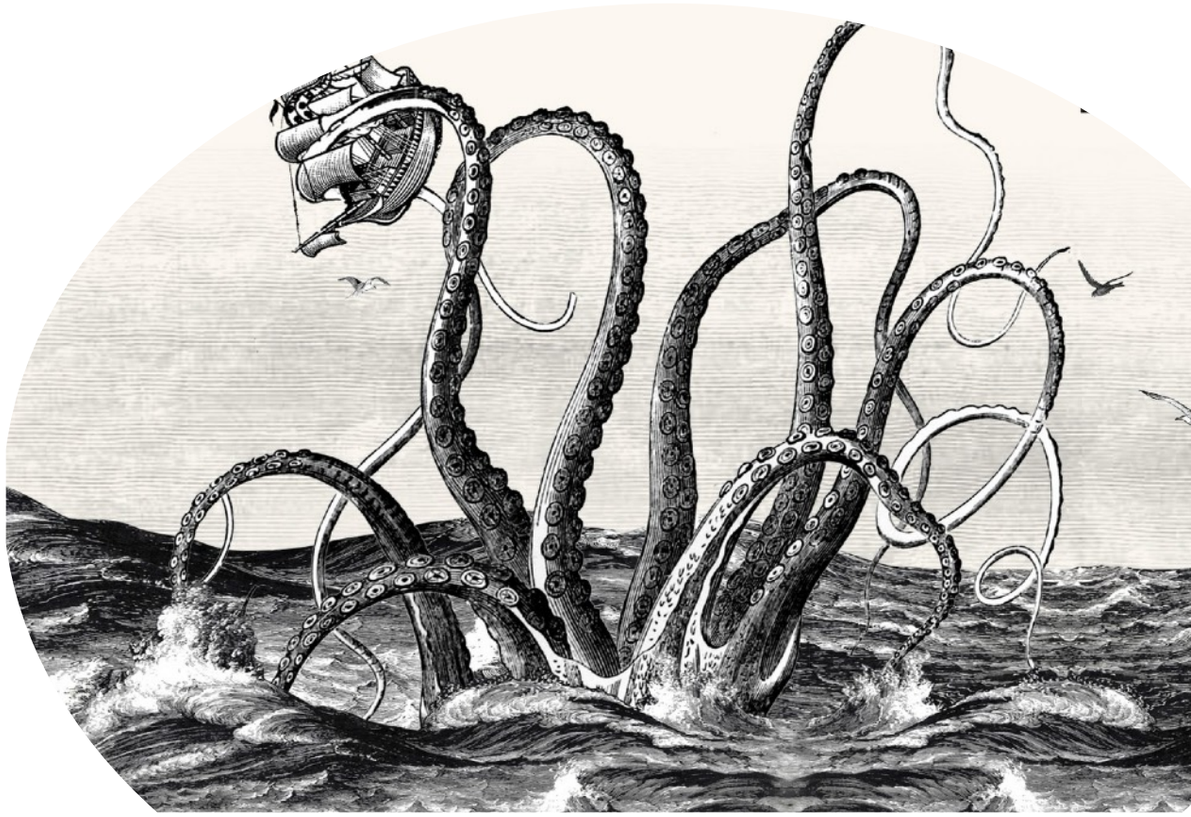
Driving Questions

How does the Sun's internal magnetic machine produce the variability observed?



Can the magnetic machine be observed?

Do models permit a reliable "forecast" of activity over hours, days, weeks, months, years, decades (and centuries)?

What are the impacts of varying solar activity in deep space and the near-Earth environment (and in the troposphere)?

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How does the Sun's magnetic machine work?

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How do we think that the Sun's magnetic machine works?

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A magnetic kraken lurks beneath the surface!
We imply what It looks like through observation of its tentacles.

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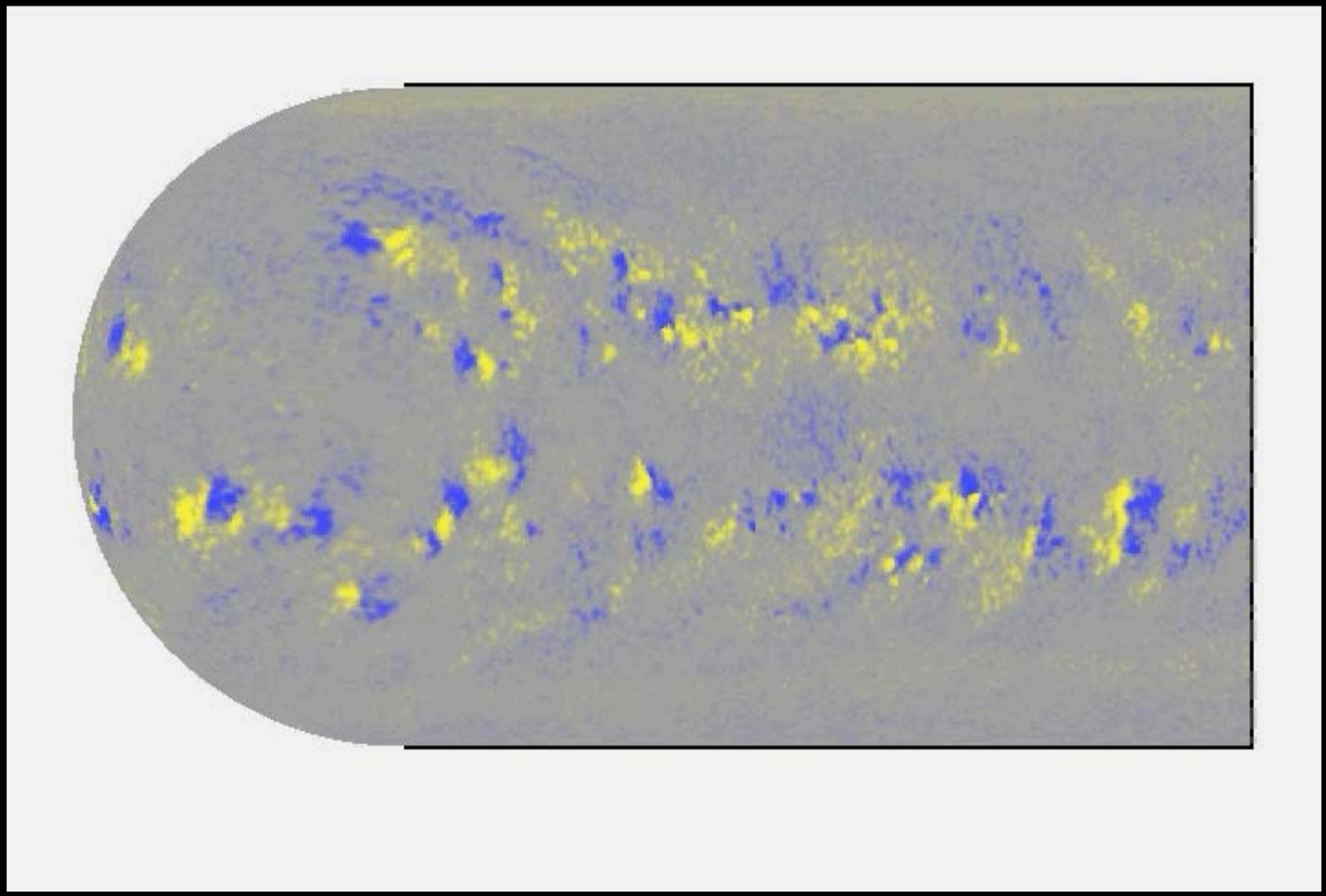
Tentacles…..



The Sun’s massive internal magnetic field dictates the time & location of magnetic field eruption and hence sunspot production.

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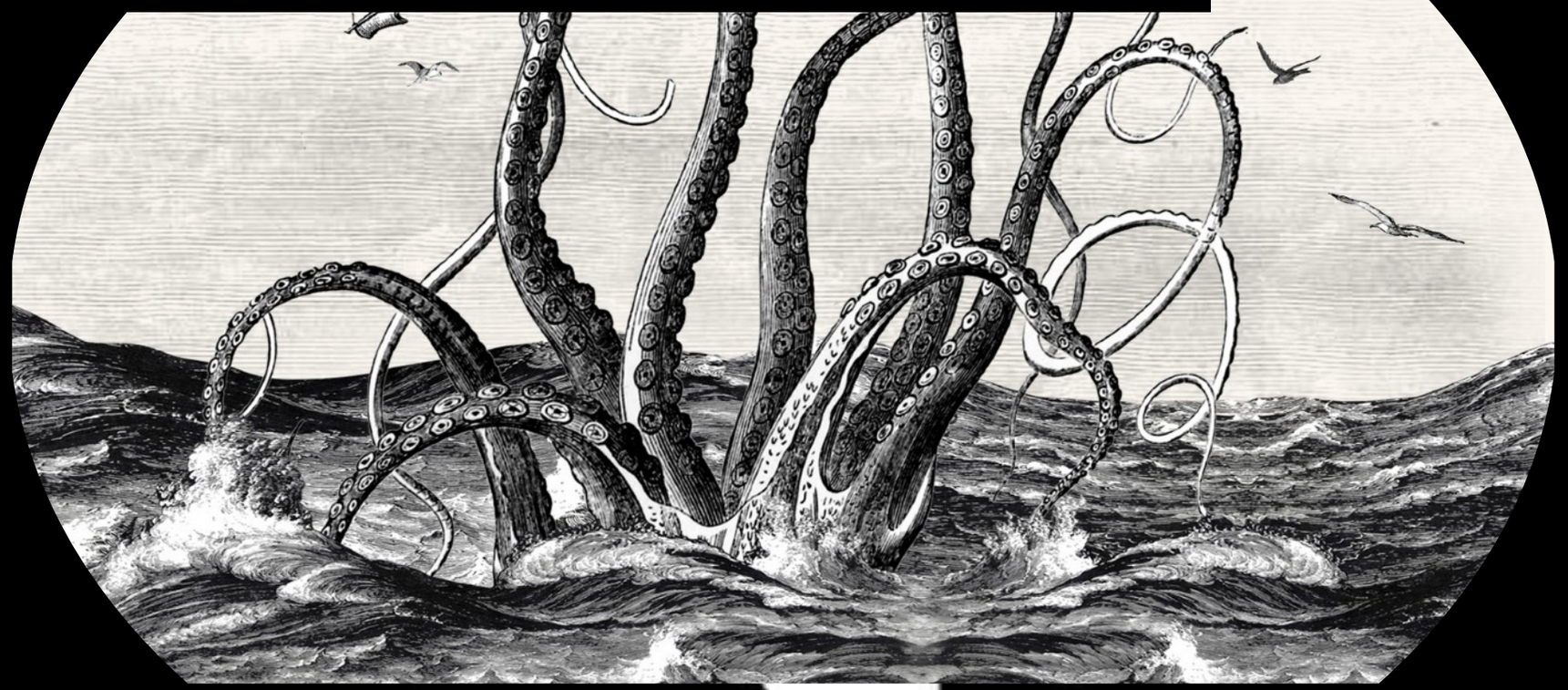
How do we think that the Sun's magnetic machine works?



A magnetic … the surface!
We imply what It … observation of its

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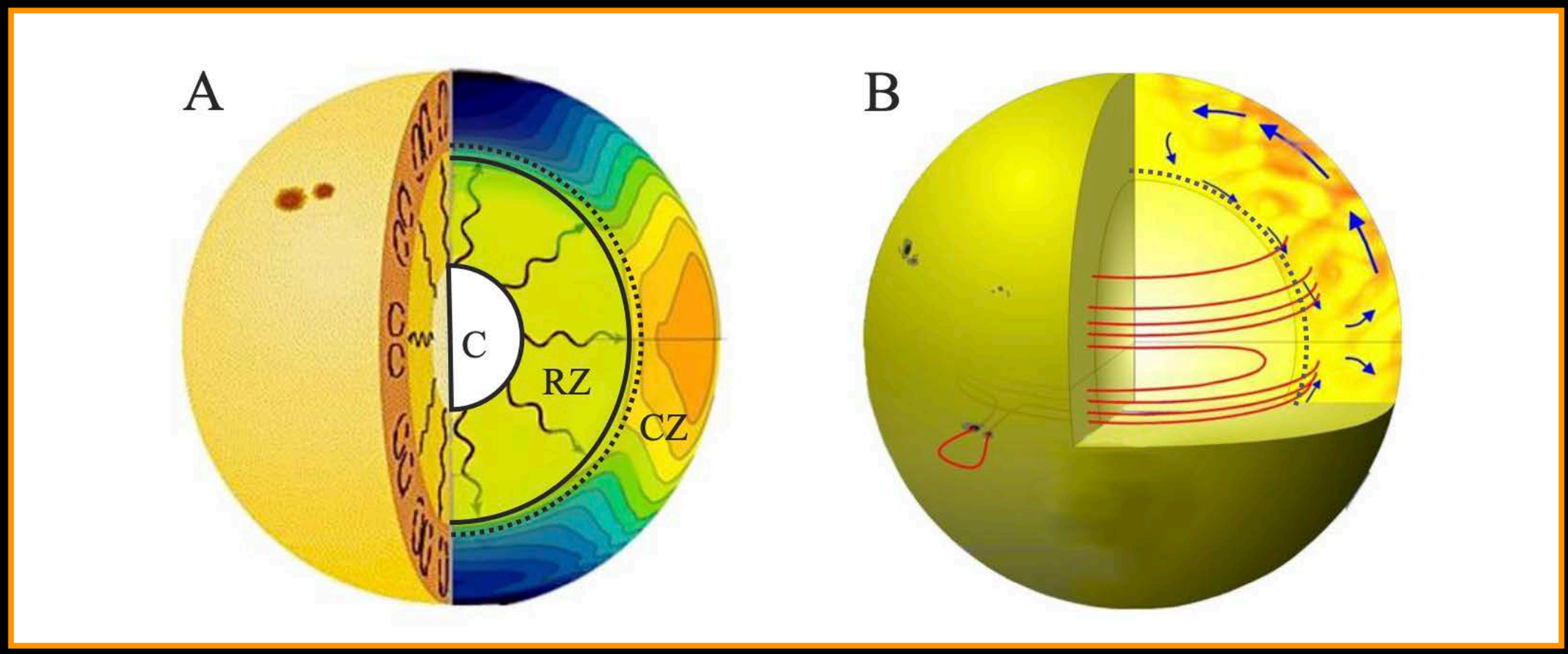

A) Heat derived from nuclear fusion in the core heats the surrounding hydrogen 'ocean'. The outer portions of the hydrogen ocean convects.

B) The Sun rotates. The rotational forces create circulation and impact the convection. The hydrogen ocean experiences 'weather'

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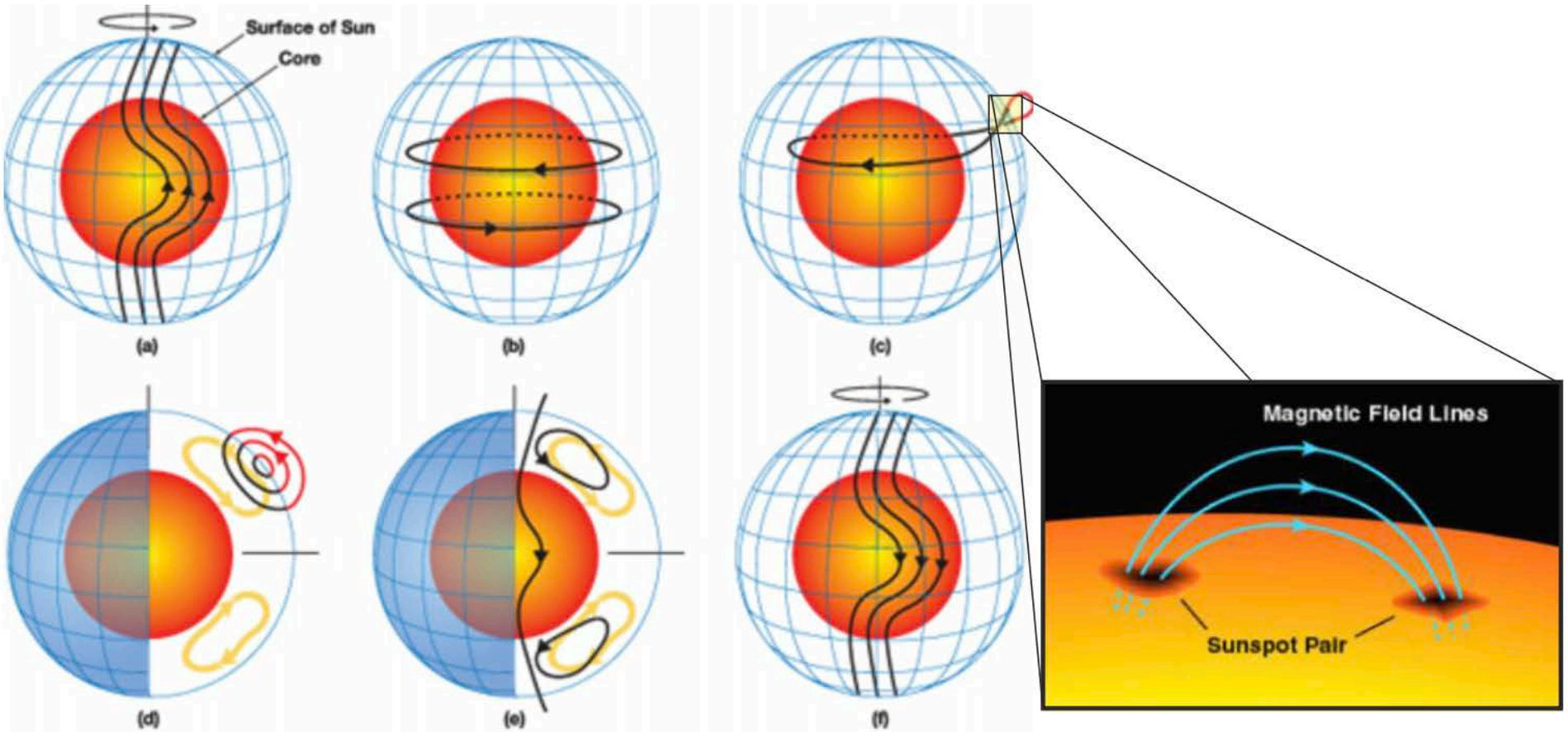
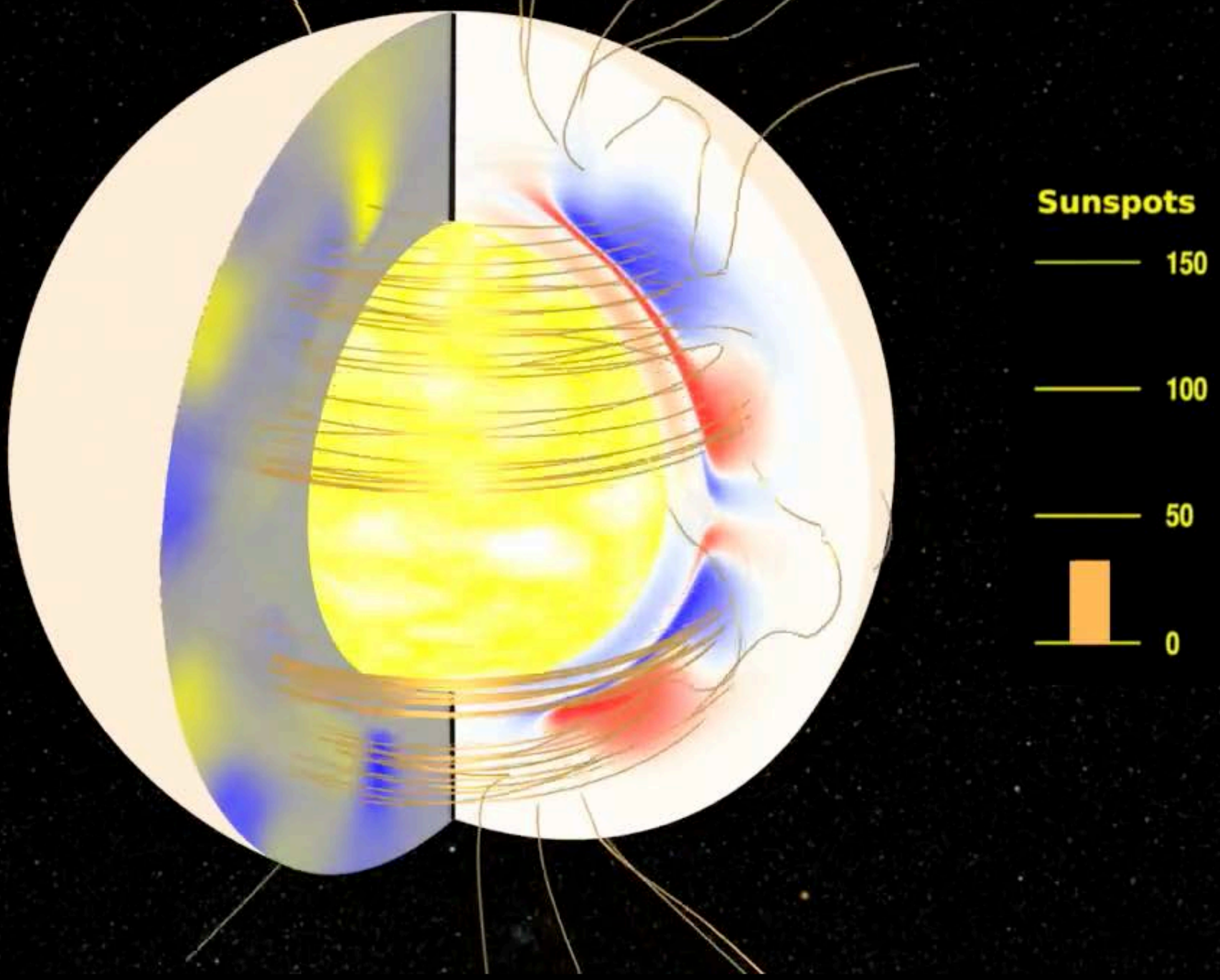
How do we think that the Sun's magnetic machine works?



…..the convection, circulation and rotation intact to generate magnetic fields. The magnetic fields strengthen and become buoyant, piercing the Sun's surface… appearing as sunspots and active regions (bipolar pairs of spots)

How do we think that the Sun's magnetic machine works?



A beautiful animation
[but is it correct?]

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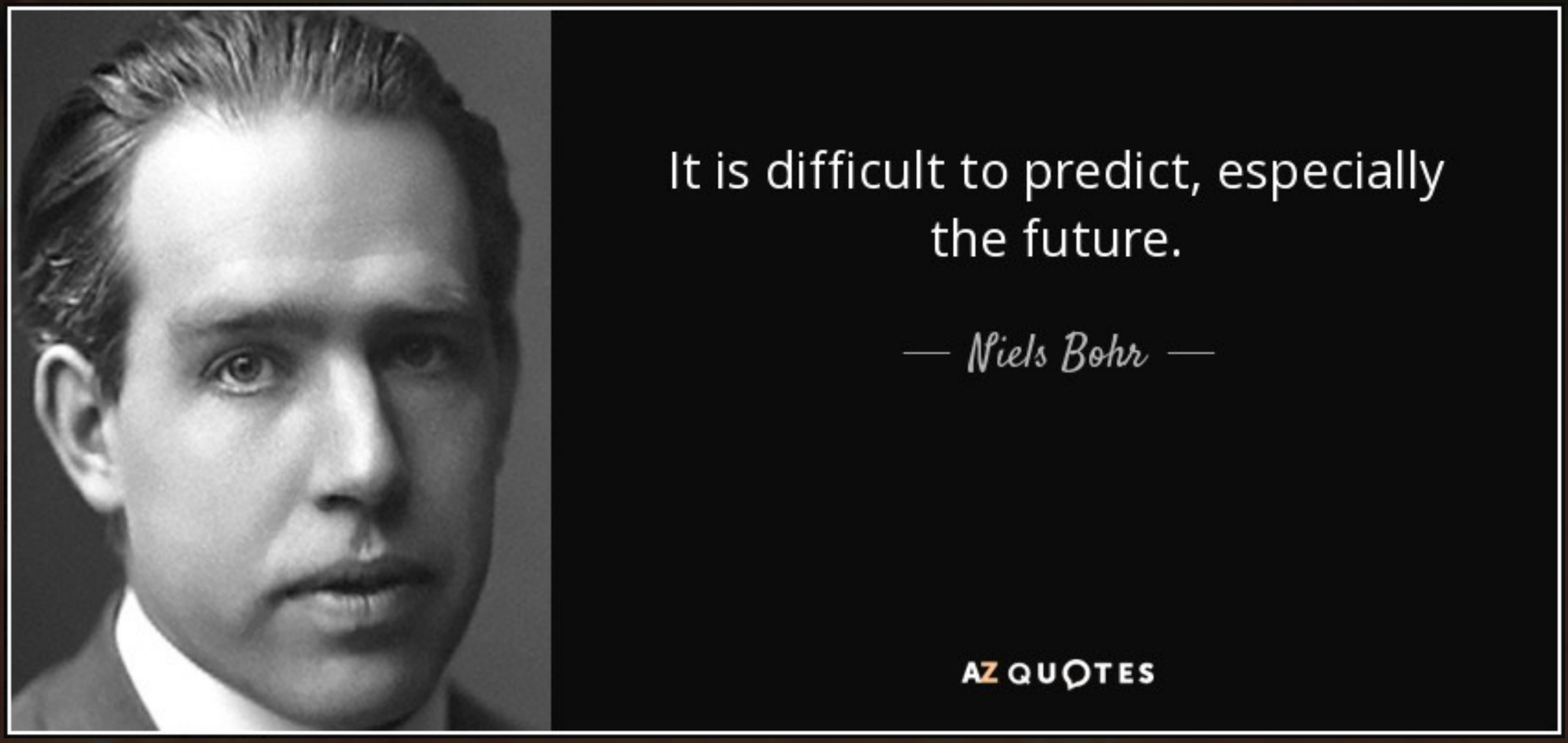
A Warning.....



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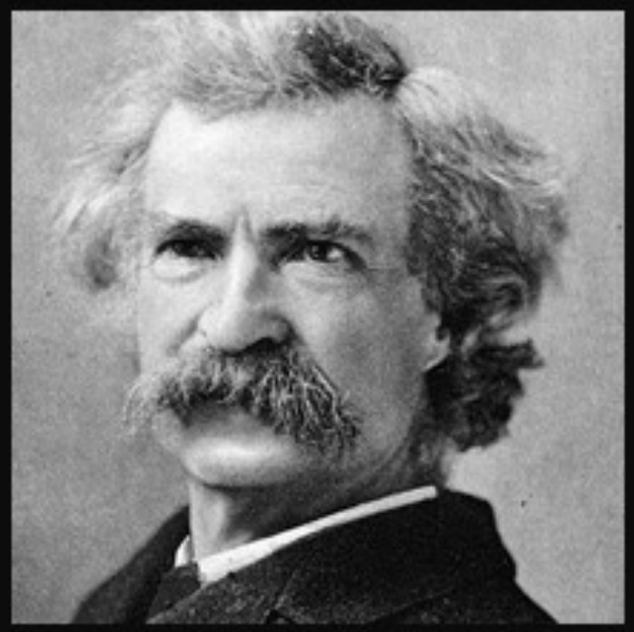
A Warning.....



Prediction is difficult-
particularly when it involves the
future.

~ Mark Twain

AZ QUOTES

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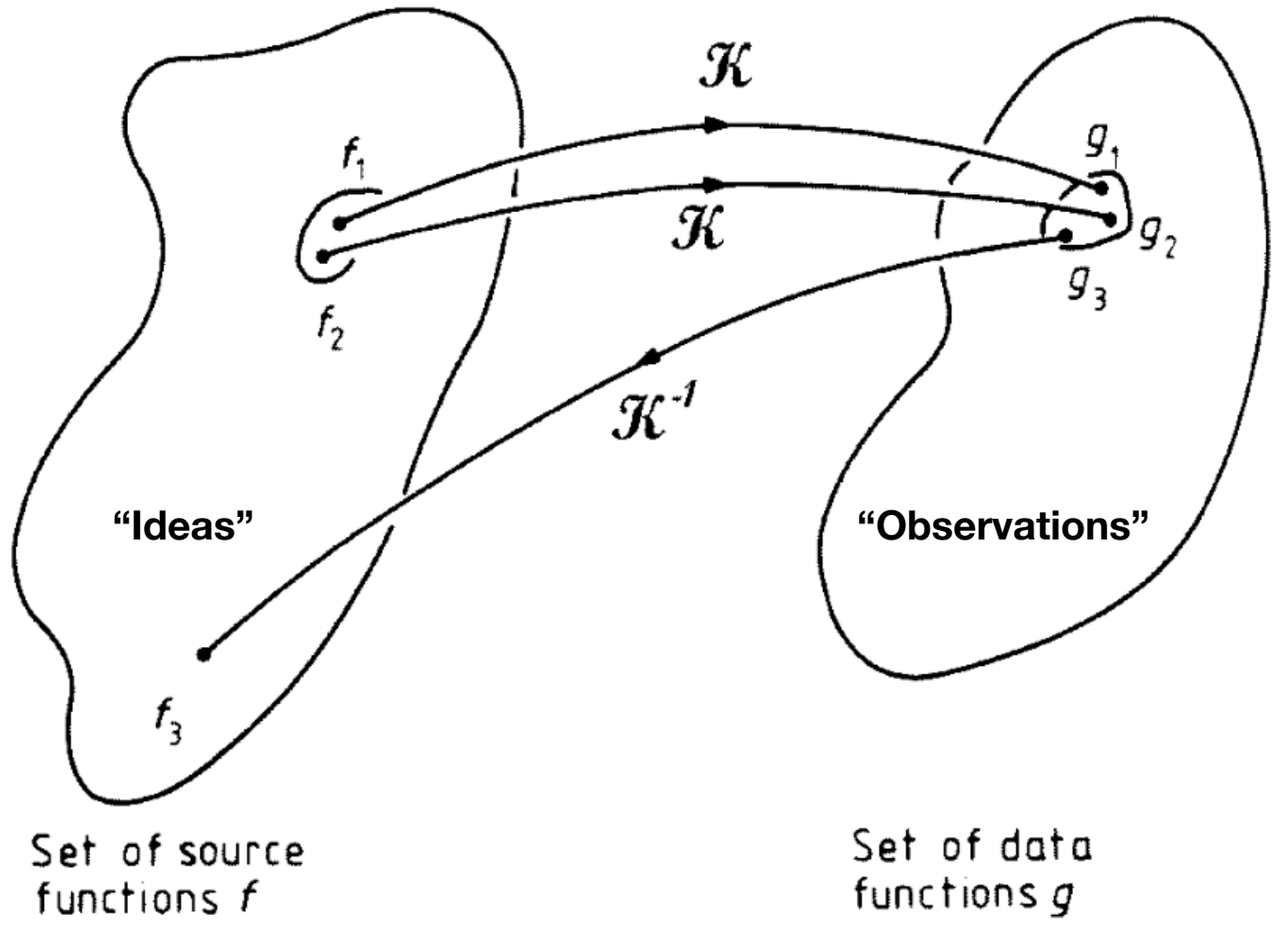
Another Warning

Forecasting Goal: Understand the underlying physics well enough to project what the system will do in the future……



Observe Spots ⇒ Infer Physics

[many "ideas" can produce the same "observations"]

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Over the last three decades our community has engaged in the ultimate pursuit - to predict what comes next!

With every iteration since our understanding has improved and the range of viable mechanisms have reduced……

It has become the World Cup of solar (and space weather) science.

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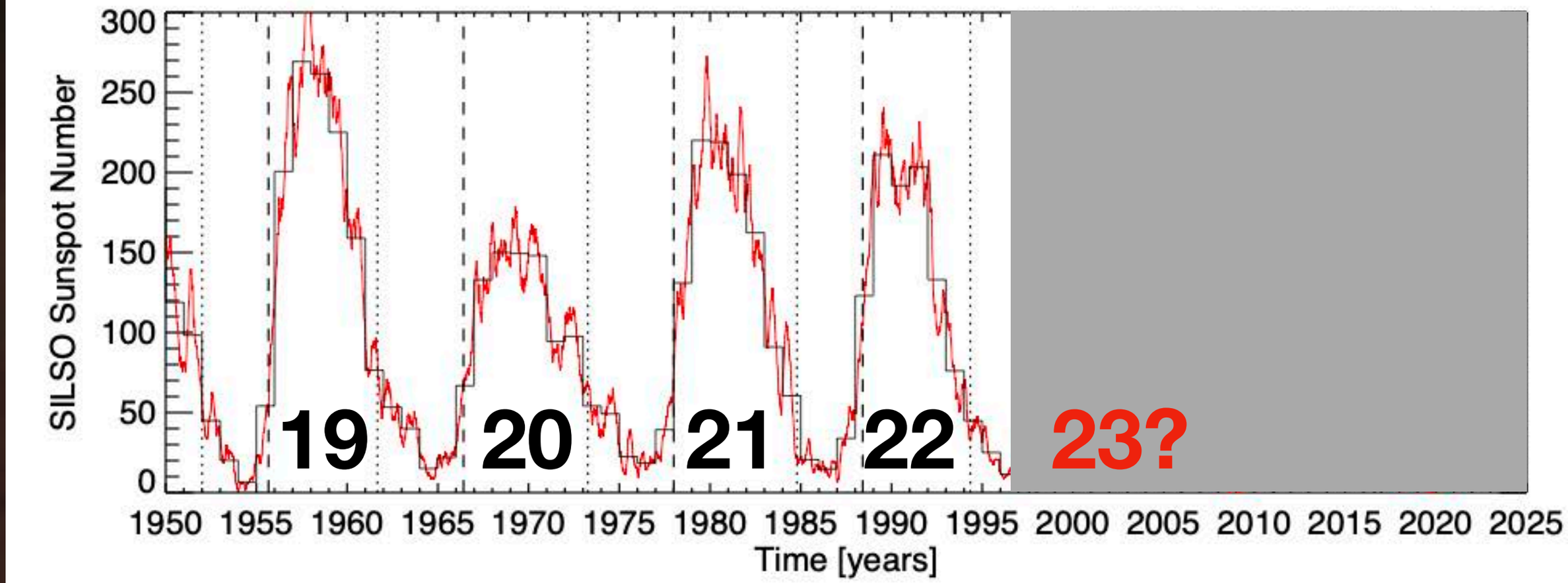
Forecasting Sunspot Cycle 23



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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

28 Forecasts Submitted

Predictive Methods Employed:

- “Precursor” Methods
- Empirical
- Climatology
- “Recent Climatology”
- Neural Networks
- “Spectral” Methods

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

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The Precursor Method

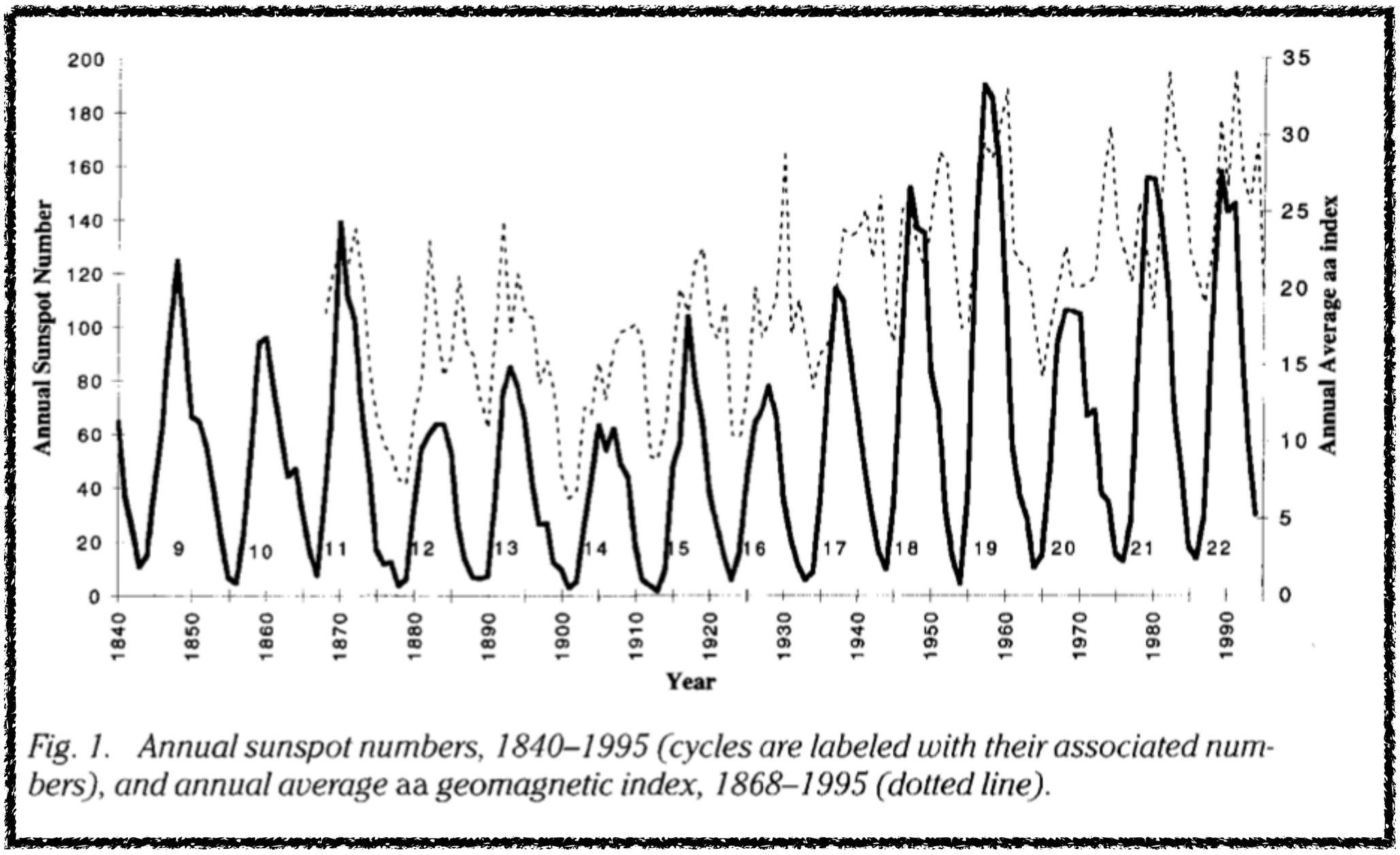

Fig. 1. Annual sunspot numbers, 1840–1995 (cycles are labeled with their associated numbers), and annual average aa *geomagnetic index, 1868–1995 (dotted line).*

Joan Feynman [name sound familiar?] and others in the 1980s noticed a relationship between the geomagnetic index at Earth at solar minimum and the magnitude of the UPCOMING sunspot cycle at maximum.

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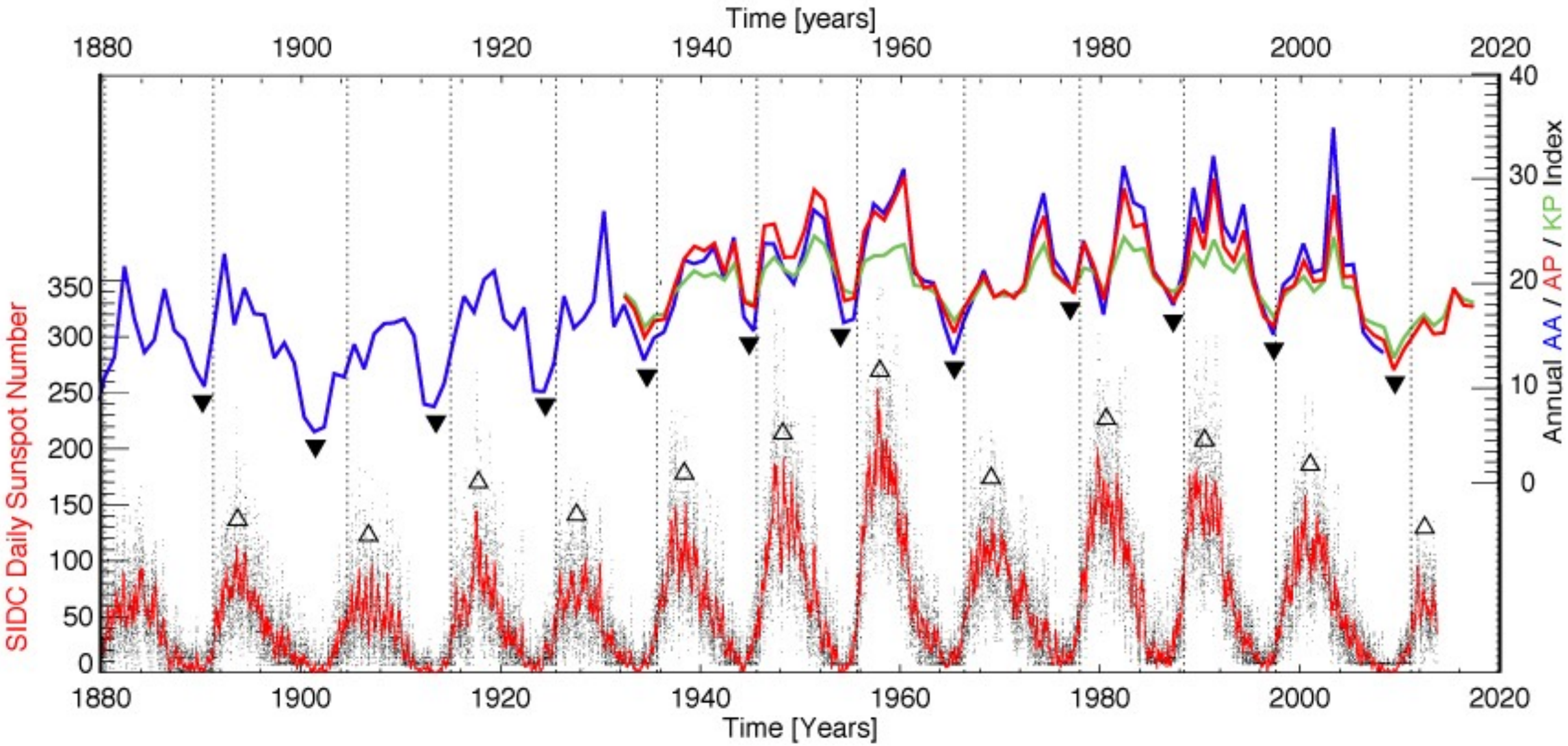
The Precursor Method



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The SC23 “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

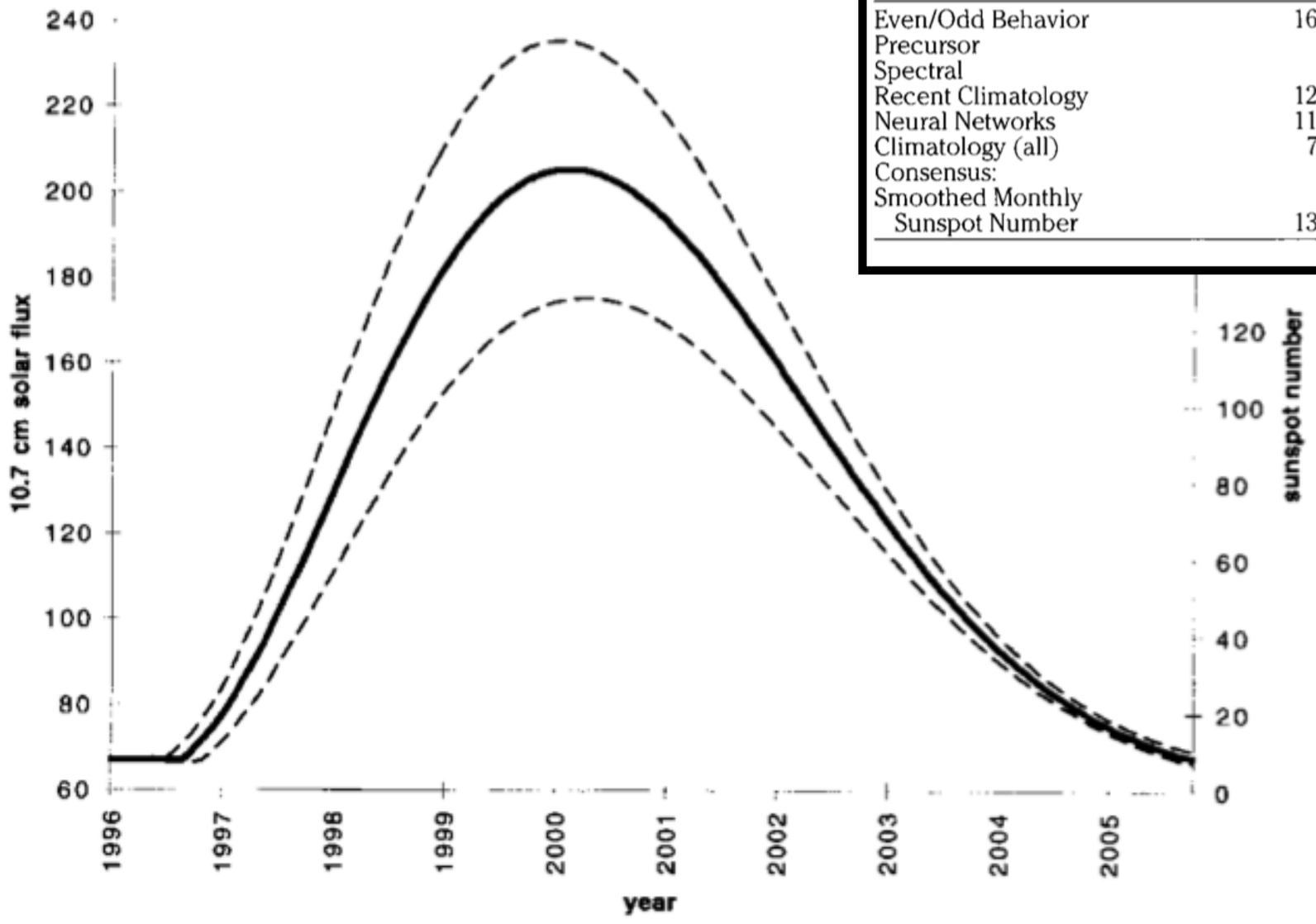

Fig. 2. The estimated profile for Cycle 23 of sunspot number and 10.7-cm solar flux.

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The SC23 “Consensus” Forecast: Joselyn

Amplitude: Not Bad
Timing: Off
Shape: Off

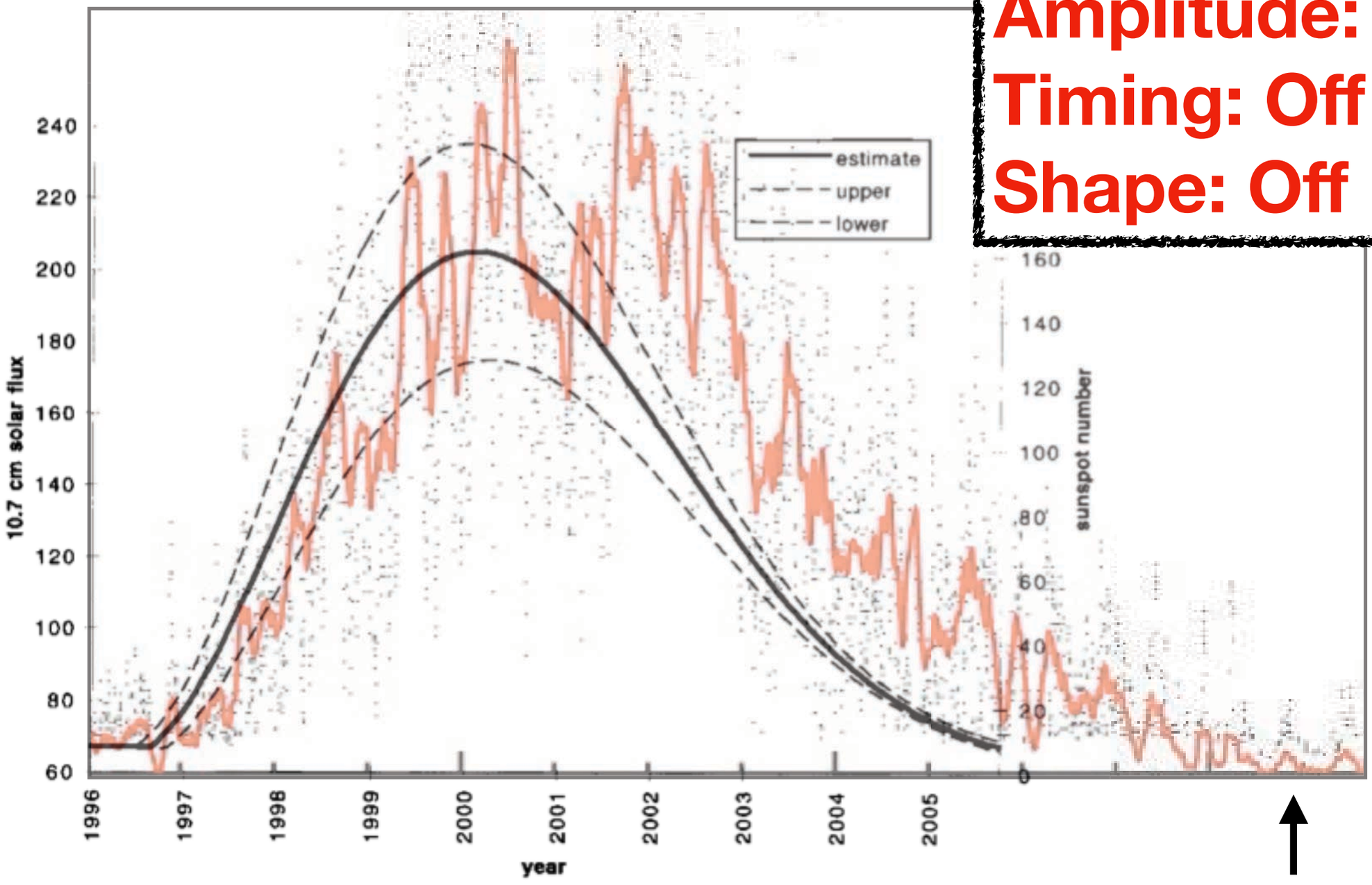

Fig. 2. The estimated profile for Cycle 23 of sunspot number and 10.7-cm solar flux.

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Key Recommendation: Joselyn

cores, tree rings, etc.), should be continued.
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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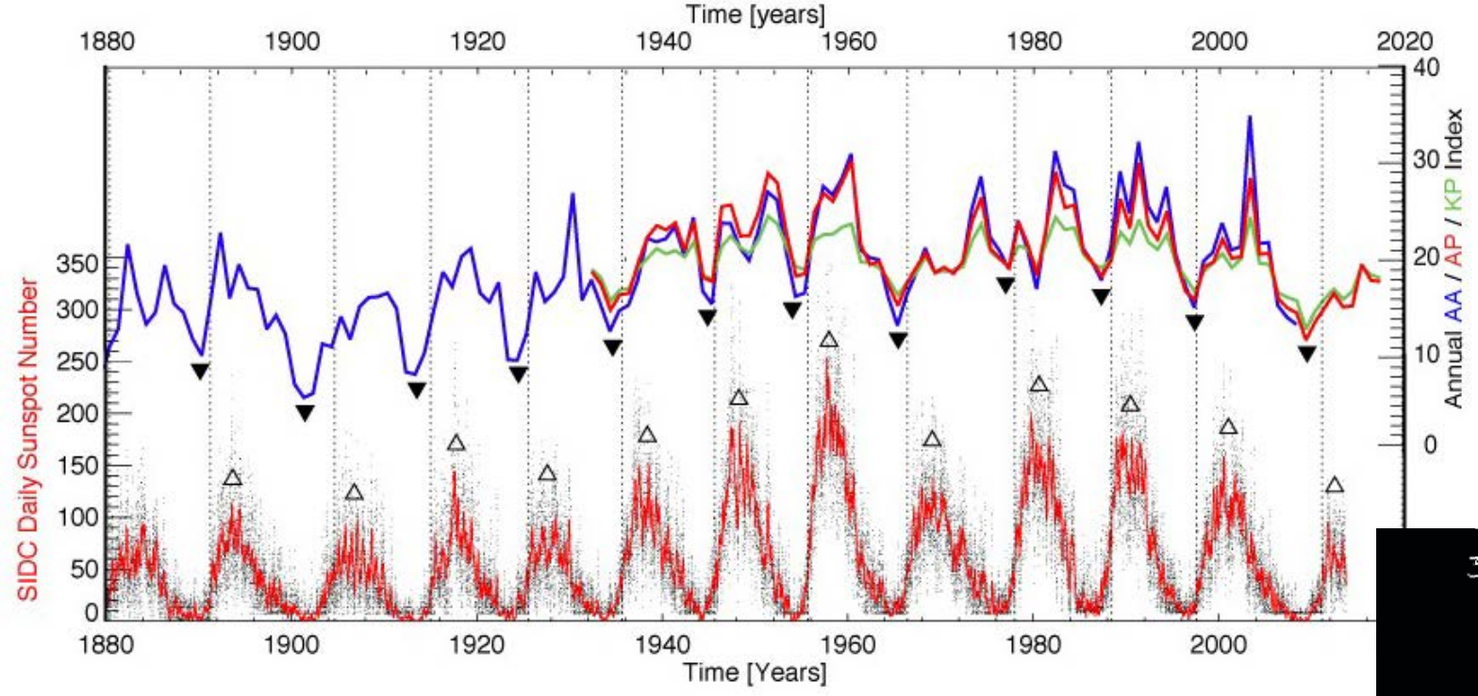

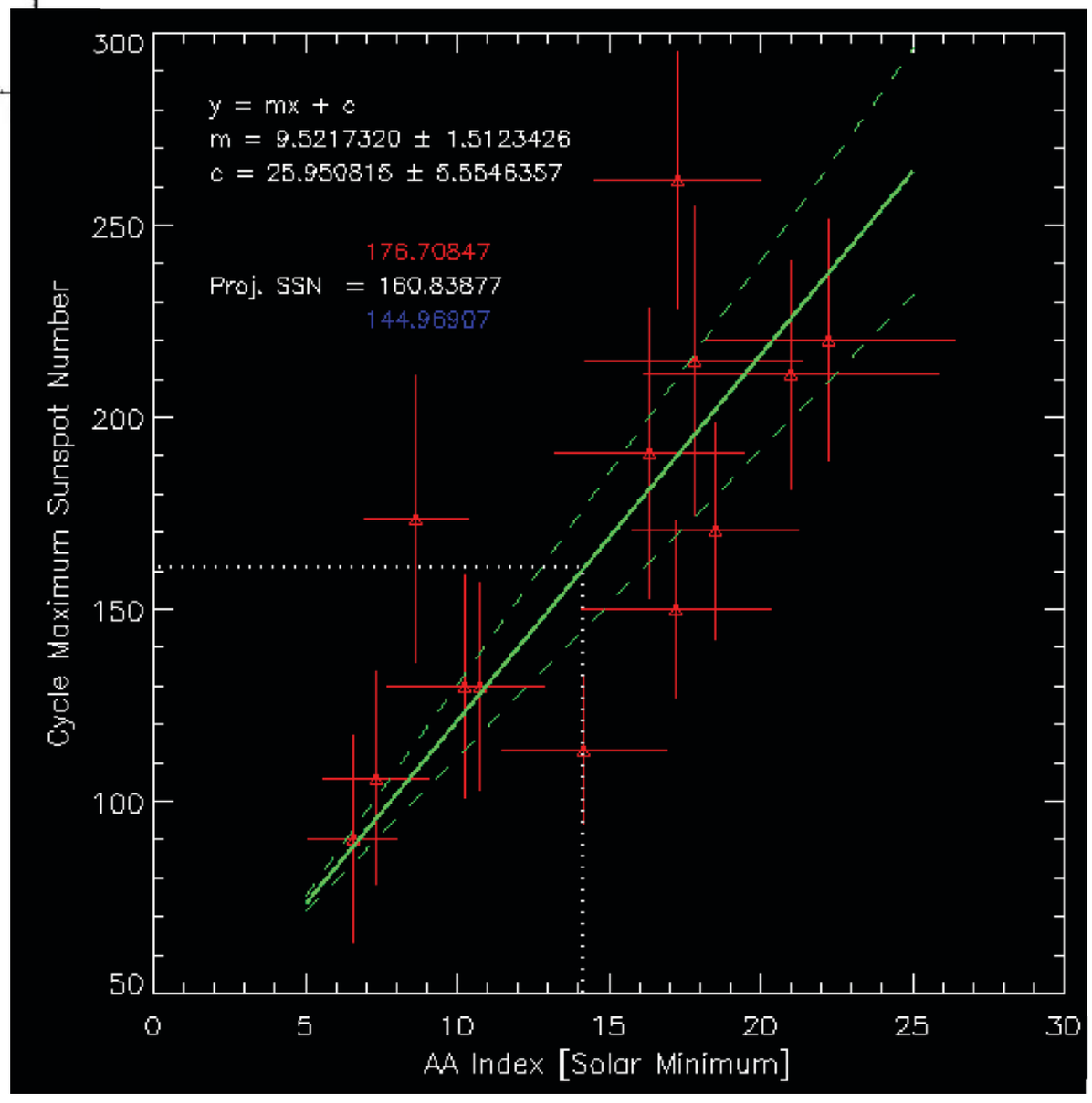

There's something to the precursor method…. store this for later. Is it more than just chance?

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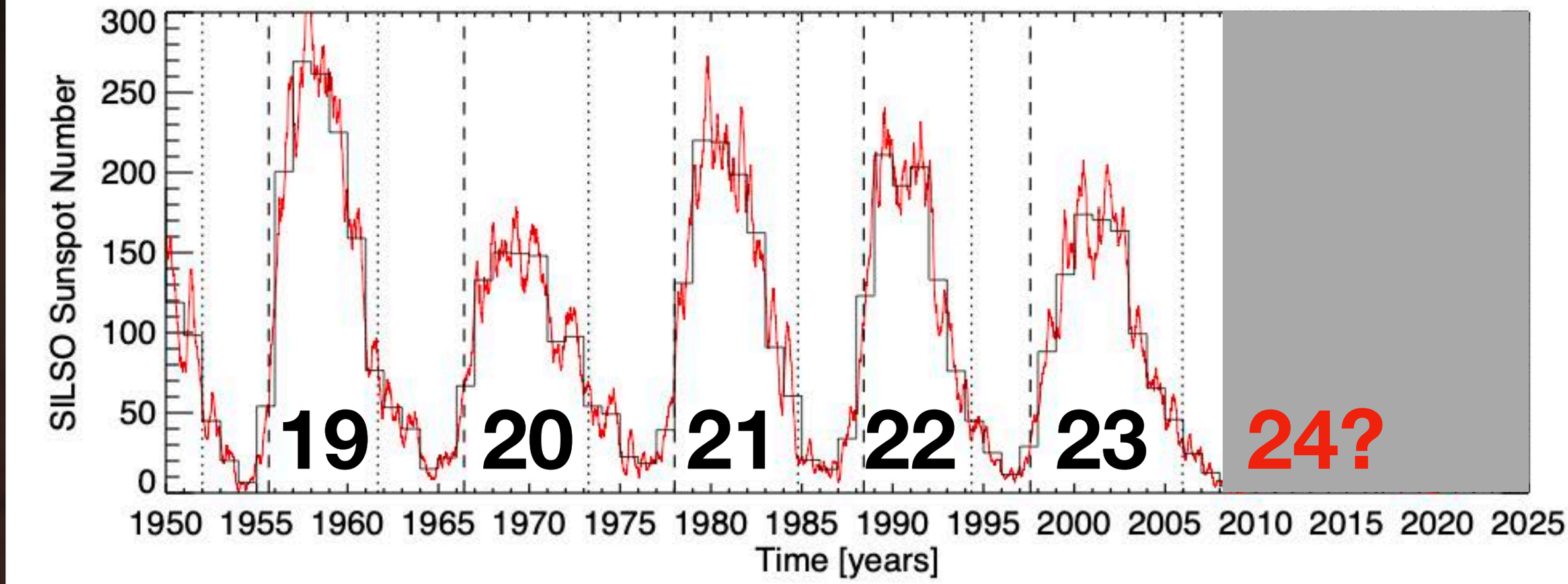
Forecasting Sunspot Cycle 24



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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

50+ Forecasts

Methods

- “Precursor” Methods
- Empirical
- Climatology
- “Recent Climatology”
- Neural Networks
- “Spectral” Methods
- Dynamo Models

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Predictions of Solar Cycle 24

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50+ Forecasts

Methods

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- Dynamo Models

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

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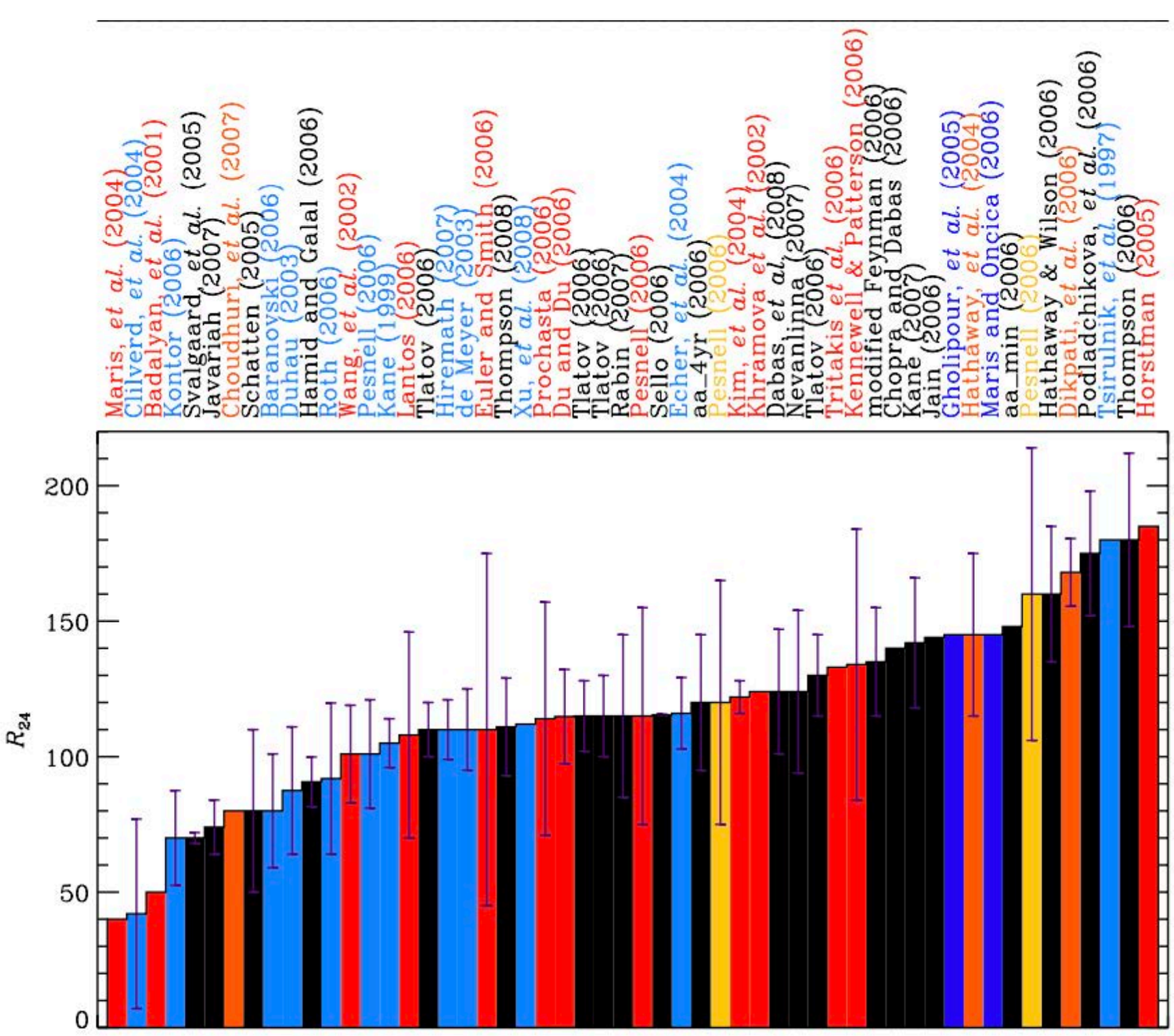
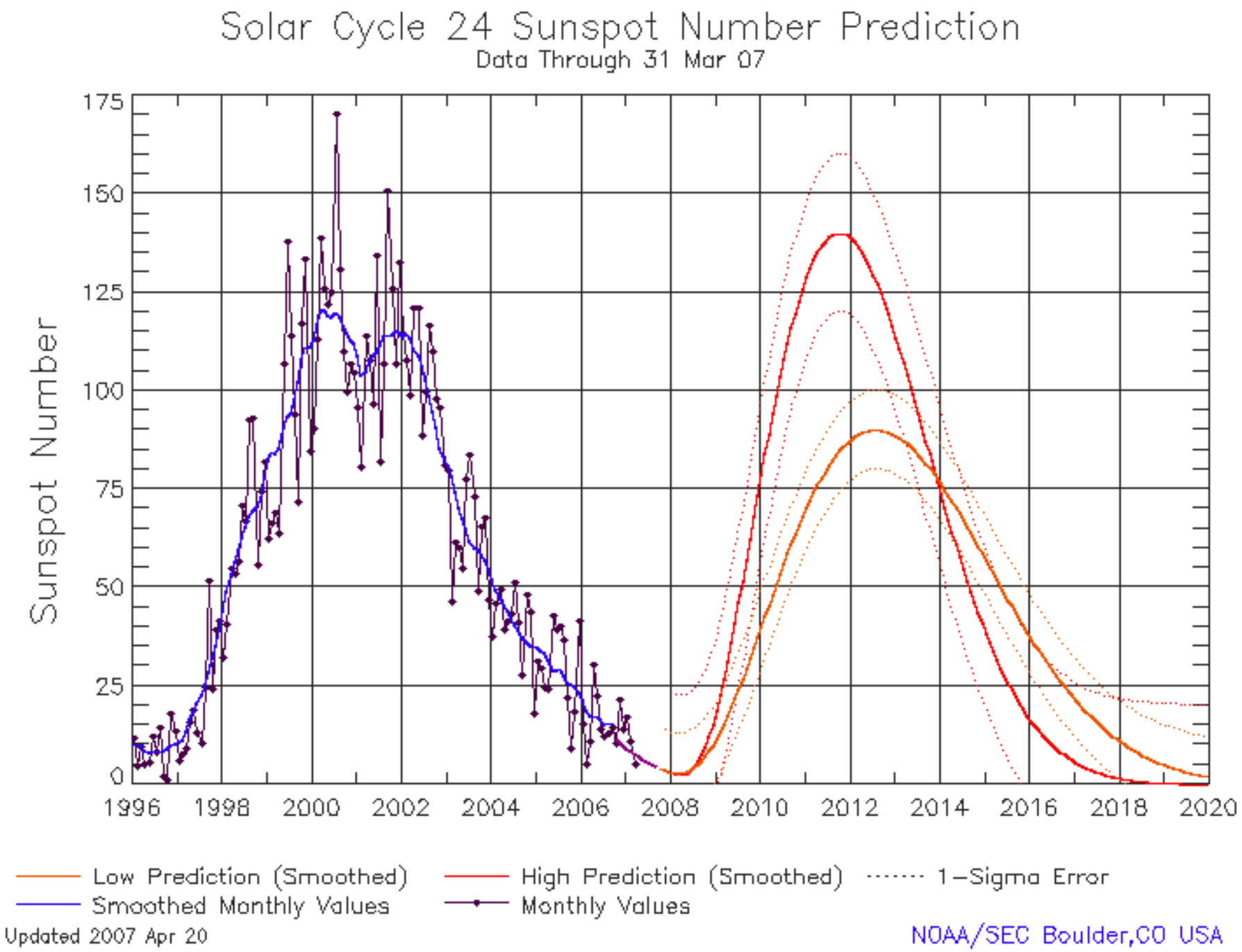


Figure 1 The predictions from Table 1, plotted in order of increasing predicted maximum for Cycle 24. The prediction categories are color coded as in the top panel. The upper plot is the significance of the difference from the climatological average of 115 ± 40 for those predictions that included an 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.

The SC24 “Consensus” Forecast: Pesnell

Note! In 2015 SILSO produced a ‘revised sunspot number’ that significantly Increased the monthly numbers. This plot is the **OLD** sunspot number series.

Clette, F. et al. (2015) ‘Revision of the Sunspot Number(s)’, Space Weather, 13(9), pp. 529–530. https://doi.org/10.1002/2015SW001264.



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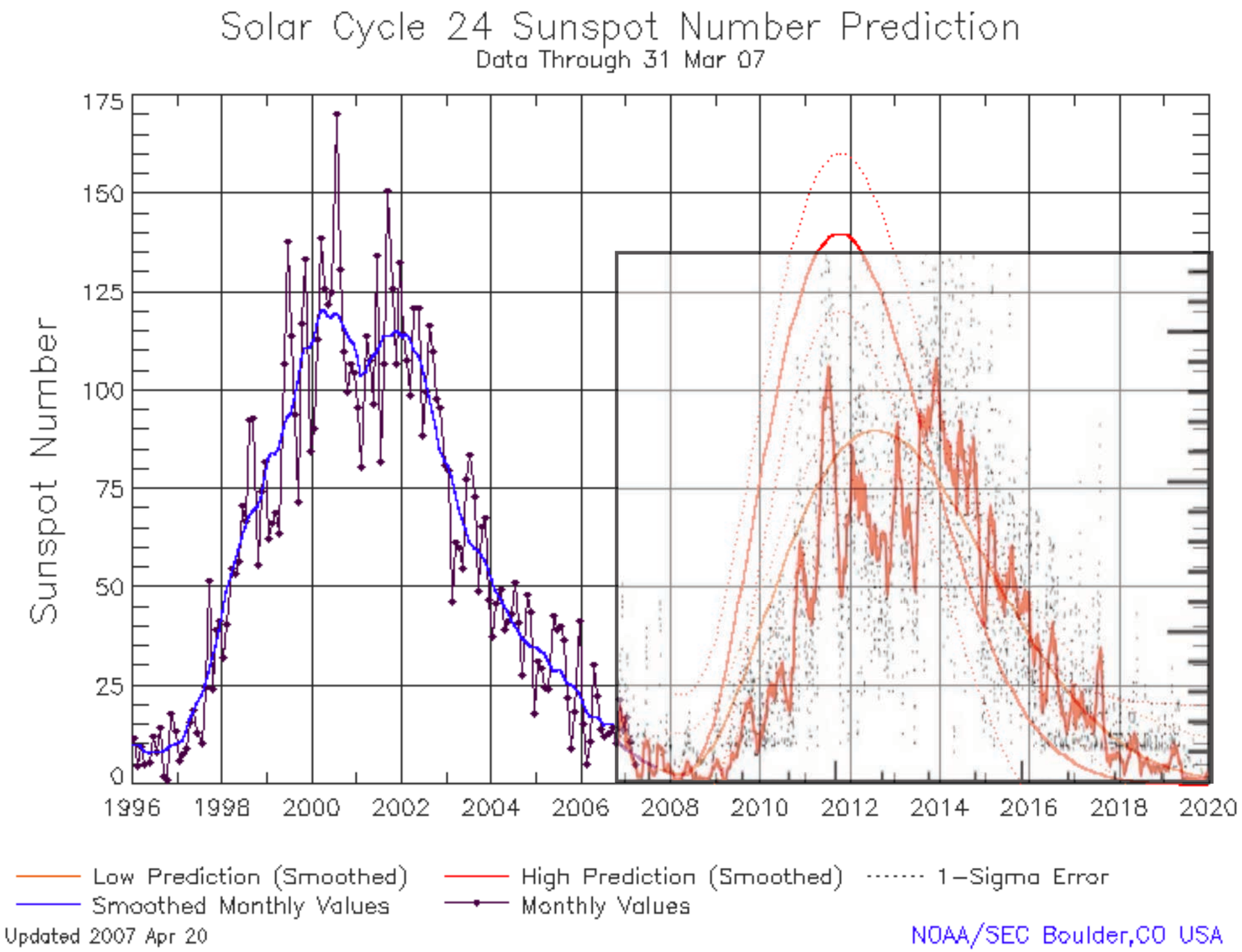

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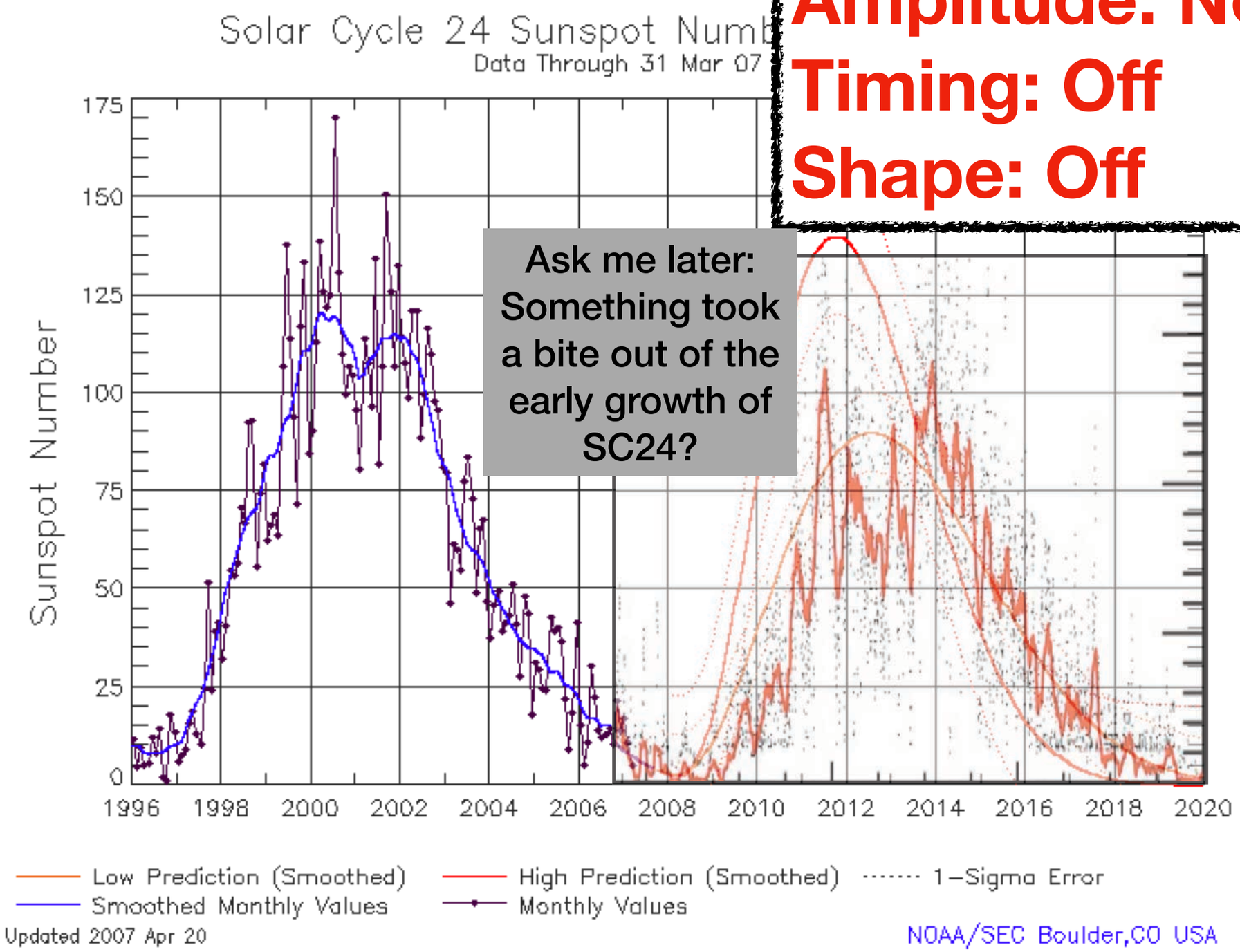

Ask me later: Something took a bite out of the early growth of SC24?

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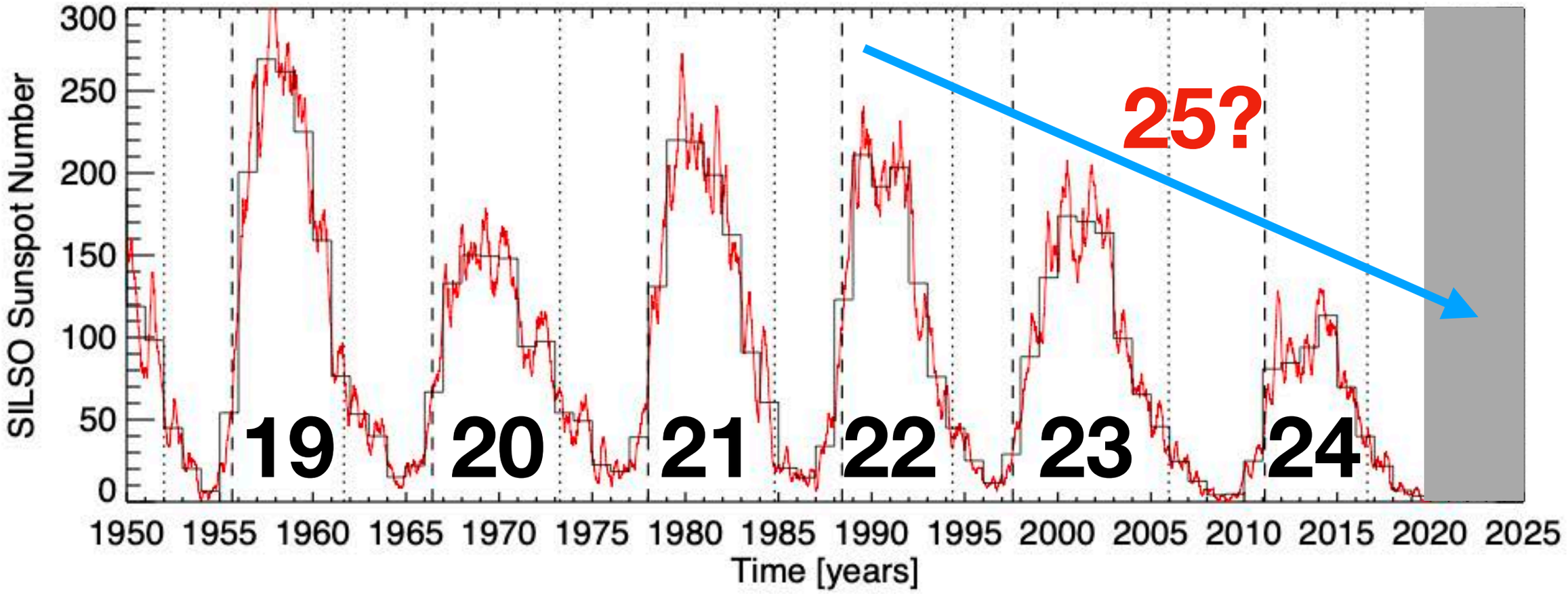
Forecasting Sunspot Cycle 25



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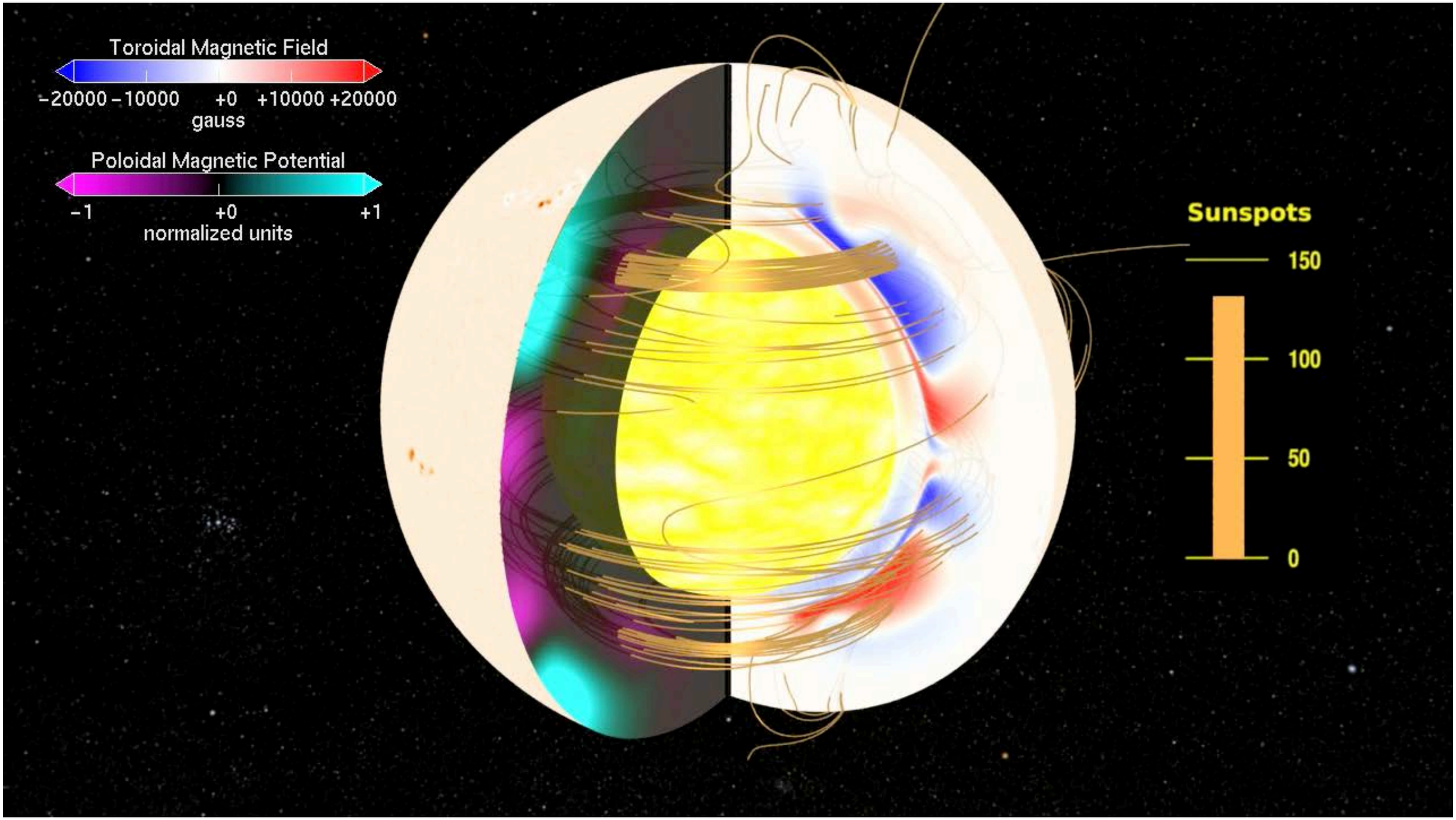
The Rise of the Physical Model

Incorporating the polar magnetic field variation and lessons learned for the SC25 World Cup, new improved 'physical' numerical simulations are ready to show their predictive skill…..



…. and beautiful animation.

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

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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 'Physical' Models

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

80+ Forecasts

Methods

- Dynamo 'Physical' Models

In Three Classes:

- Assimilative: Incorporating Polar Field
- Surface Flux Transport
- Full MagnetoHydroDynamics (MHD)

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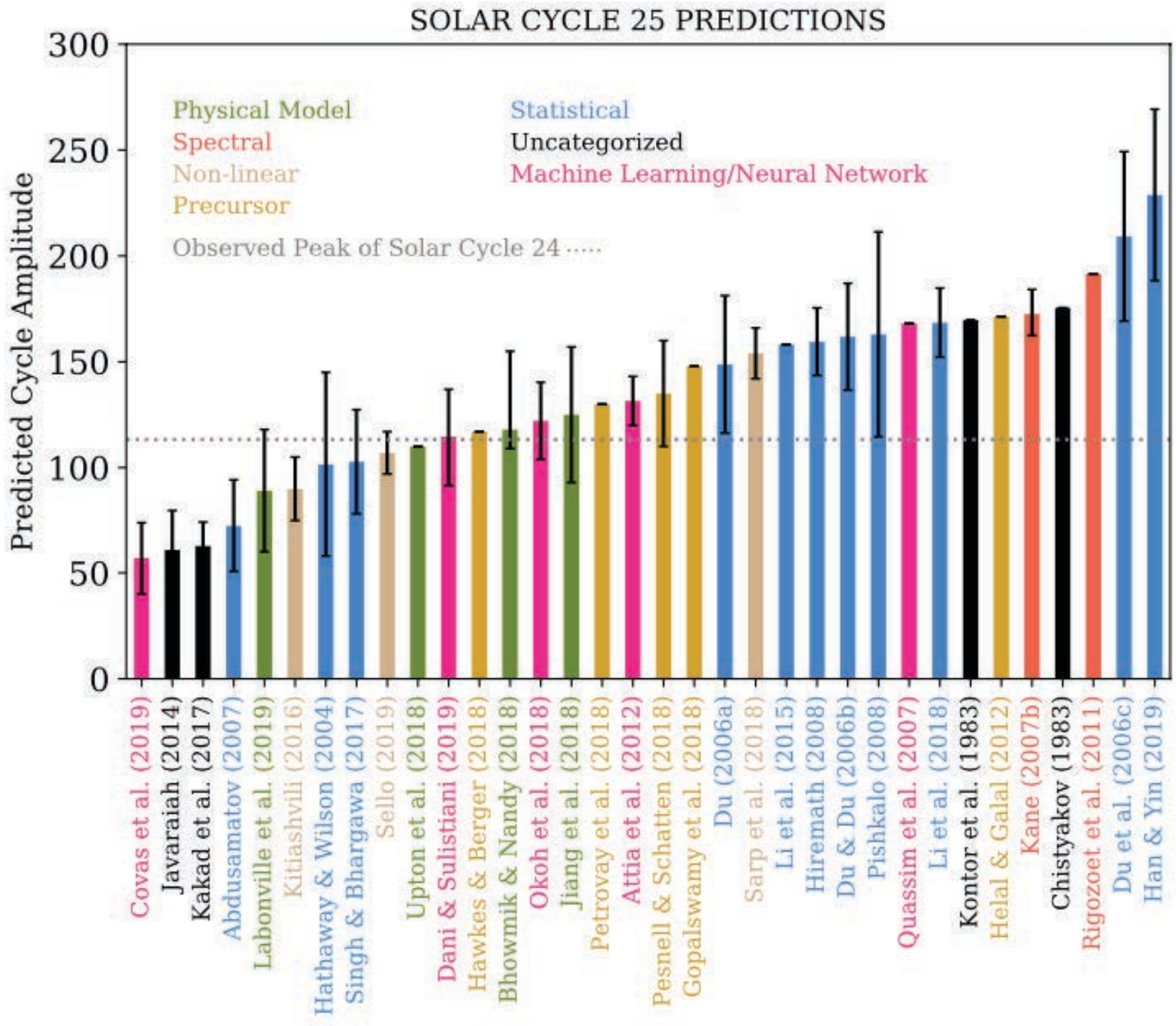


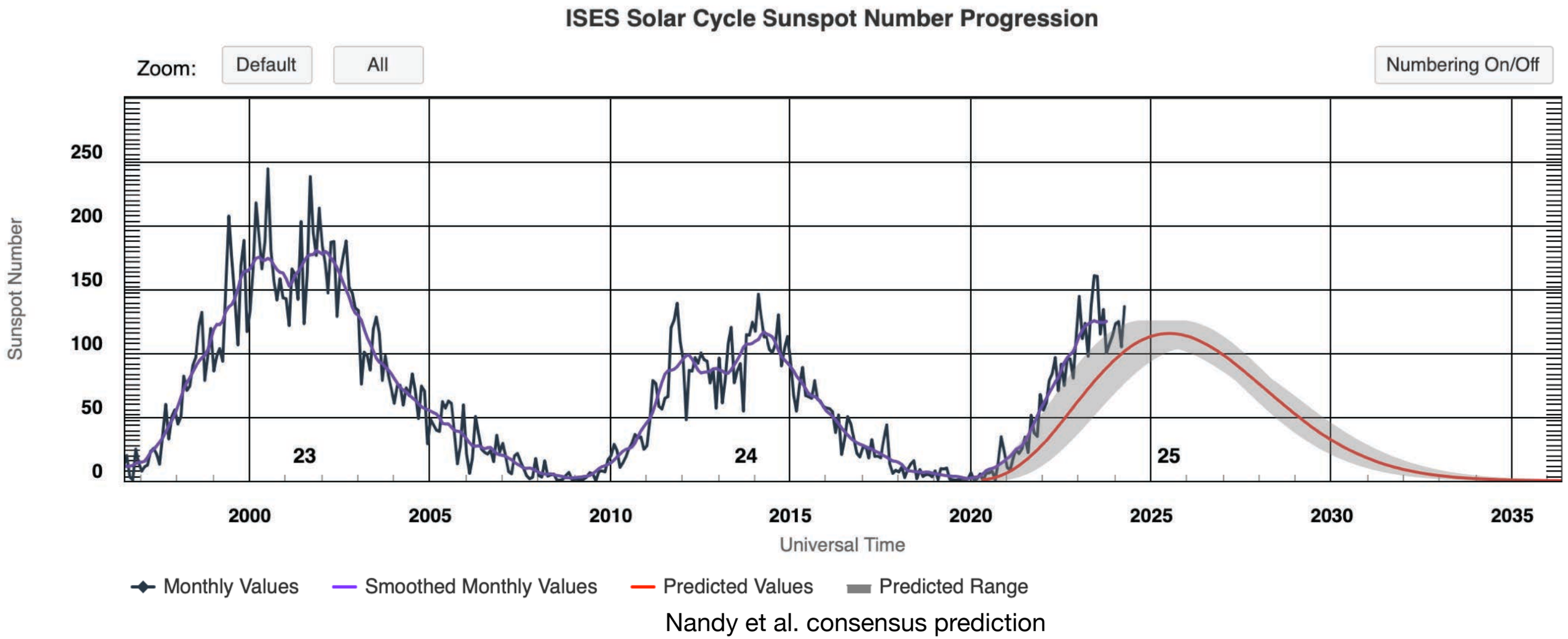
Historical Avg Max
175

Consensus
115

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 indicate 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.

The SC25 “Consensus” Forecast (2020)

https://www.swpc.noaa.gov/products/solar-cycle-progression



Nandy et al. consensus prediction

- 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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Lecture 1 Recap

- The Sun has an 11(-ish) year sunspot cycle.
  - Sunspots appear first at mid-solar latitudes and migrate to the equator - never crossing.
  - This forms a butterfly pattern.
- The Sun has a 22(-ish) year magnetic polarity cycle.
  - The wings of the sunspot butterfly alternate in dominant polarity.
  - For reference the Earth's magnetic poles reverse every 200,000 years…
- The Sun experiences extended periods where the number of spots can be very large and times when there are almost no spots!
- Surges of sunspot production give rise to the strongest space weather events.

- Predicting the sunspot cycle amplitude, timing and shape is not easy.
- Those predictions drive a host of other operational forecasts so this really is not an academic game.
- Precursor methods seem to be more robust than 'physical' models in predicting sunspot cycles 23 and 24 amplitude.
  - Reproducing the shape and timing of the sunspot cycles are not great!
- "Sunspot Cycle 25 will have the same (or smaller) magnitude as Sunspot Cycle 24 and reach maximum in July of 2025."
- Now for some coffee….

~~1988: 1996: 2009:~~ **2019:**

Do we (think we) know enough to forecast what the Sun is going to do?

FEATURES

THE CALM BEFORE THE STORMS

A spotless sun, as seen in May by NASA's Solar Dynamics Observatory. The sun is nearing solar minimum.

Scientists studying the 11-year solar cycle are trying to predict when a quiet sun will next turn violent

By **Sarah Scoles**, *in Boulder, Colorado*

For all of February the sun is nearly spotless, a smooth circle filled in with a goldenrod crayon. It has been more than a decade since it was so lacking in sunspots—dark magnetic knots as big as Earth that are a barometer of the sun's temperament. Below the surface, however, a radical transition is afoot. In 5 years or so, the sun will be awash in sunspots and more prone to violent bursts of magnetic activity. Then, about 11 years from now, the solar cycle will conclude: Sunspots will fade away and the sun will again grow quiet.

In early March, a dozen scientists descend on the National Center for Atmospheric Research (NCAR) here to predict when the sun will reach its peak, and how unruly it will become. As light reflects off snow caught in the trees and streams through the tall windows of a conference room, the Solar Cycle 25 Prediction Panel comes to order. NASA and the National Oceanic and Atmospheric Administration (NOAA) have sponsored these panels since 1989, aiming to understand what drives the sun's 11-year cycles and assess methods for predicting them. But the exercise is not just academic: The military, satellite operators, and electric utilities all want to know what the sun has in store, because the flares and bursts of charged particles that mark solar maximum can damage their technologies.

Sunspots can be seen with the naked eye, but it wasn't until the mid-1800s that astronomers realized they come and go on a rough schedule. They first appear at midlatitudes and then proliferate, migrating toward the equator over about 11 years. In 1848, Swiss astronomer Johann Rudolf Wolf published an account of the sunspot record, identifying 1755–66 as "Cycle 1," the first period when counts were reliable. He then created a formula for counting the number of daily sunspots—a somewhat subjective technique that has evolved into a counting method used today to marry data sets across the centuries.

The cycles are capricious, however. Sometimes, the sun goes quiet for decades,

Published by AAAS

Apr 13, 2019

mber [12−month Running Average]

SIDC Daily Sunspot Number

0 50 100 150 200 250 300 350

1760 1780 1800 1820 1840 1860 1880 1900 1920 1940 1960 1980 2000 2020

Time [Years]

?

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