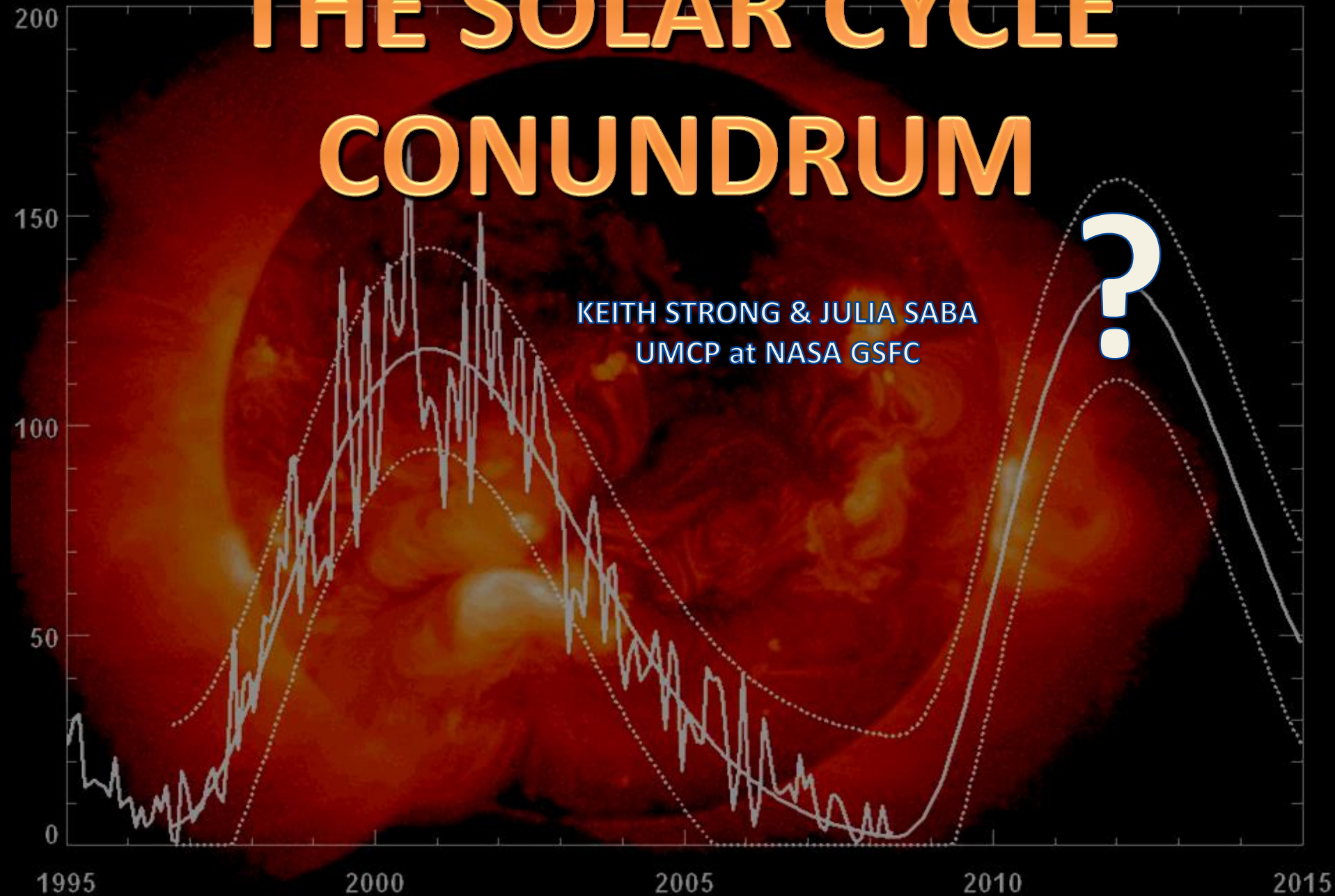


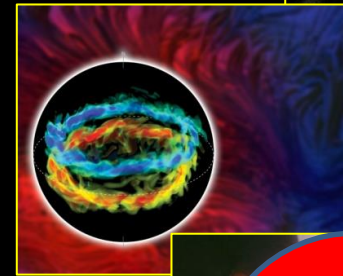
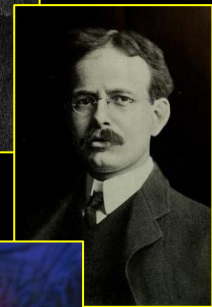
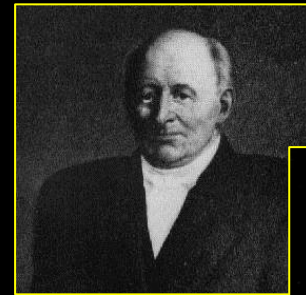
THE SOLAR CYCLE CONUNDRUM

KEITH STRONG & JULIA SABA
UMCP at NASA GSFC



A CONUNDRUM?

- SCHWABE (1843): SUNSPOTS VARY ON AN 11-YEAR PERIOD
- HALE (1908): SUNSPOTS ARE MAGNETIC
- A DYNAMO DEEP INSIDE THE SUN MODULATED BY CYCLIC PROCESSES
- PREDICTION OF TIMING AND AMPLITUDE OF UPCOMING CYCLE



THREE POSSIBILITIES ...

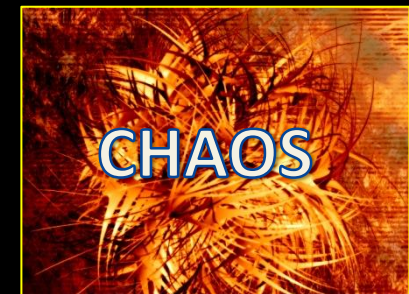
- CONCEPT IS COMPLETELY WRONG



- THE BASIC CONCEPT IS CORRECT, BUT THERE IS SOMETHING MISSING

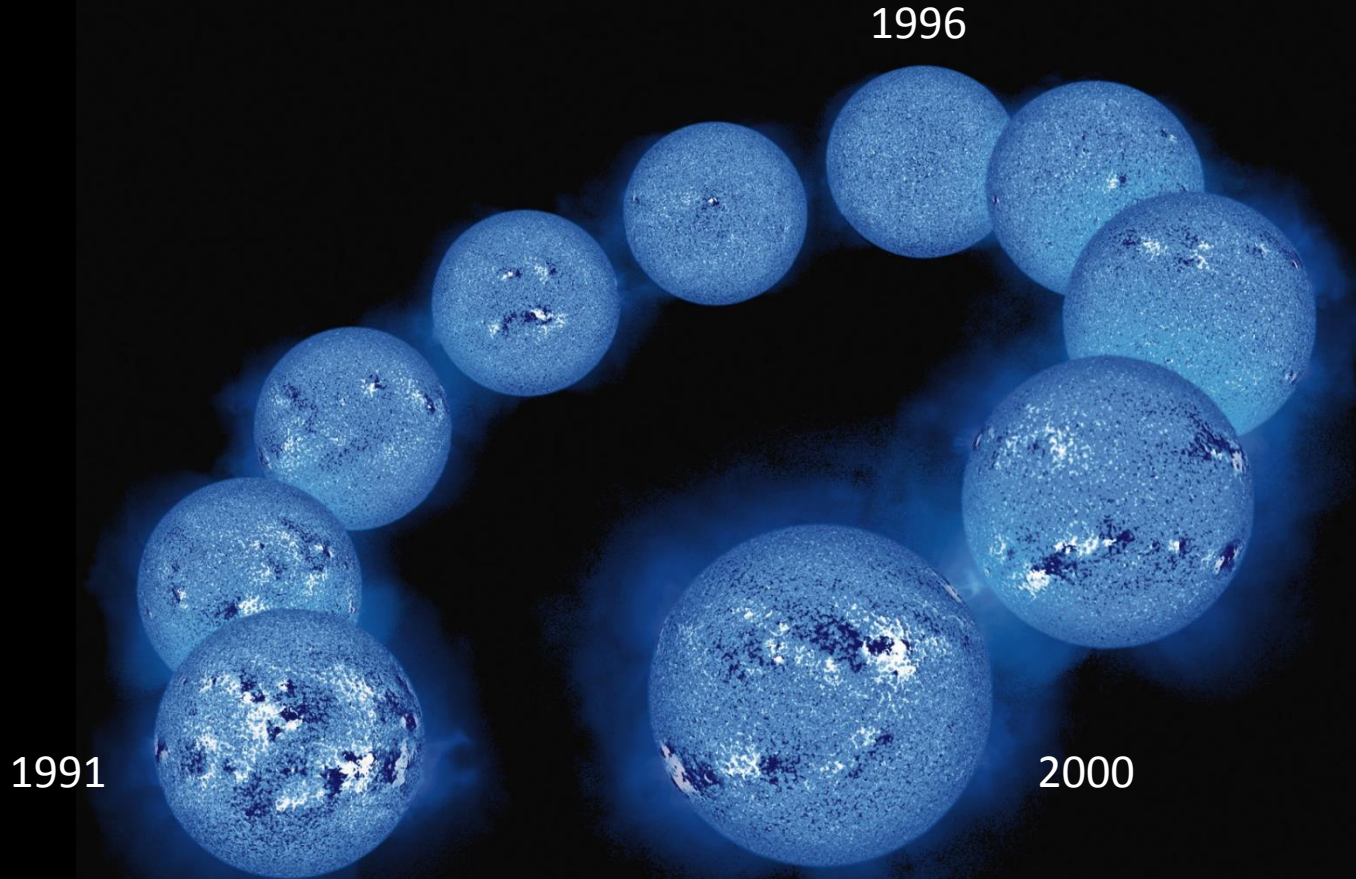


- THE SOLAR CYCLE CAN NEVER BE PREDICTED



TALK OUTLINE

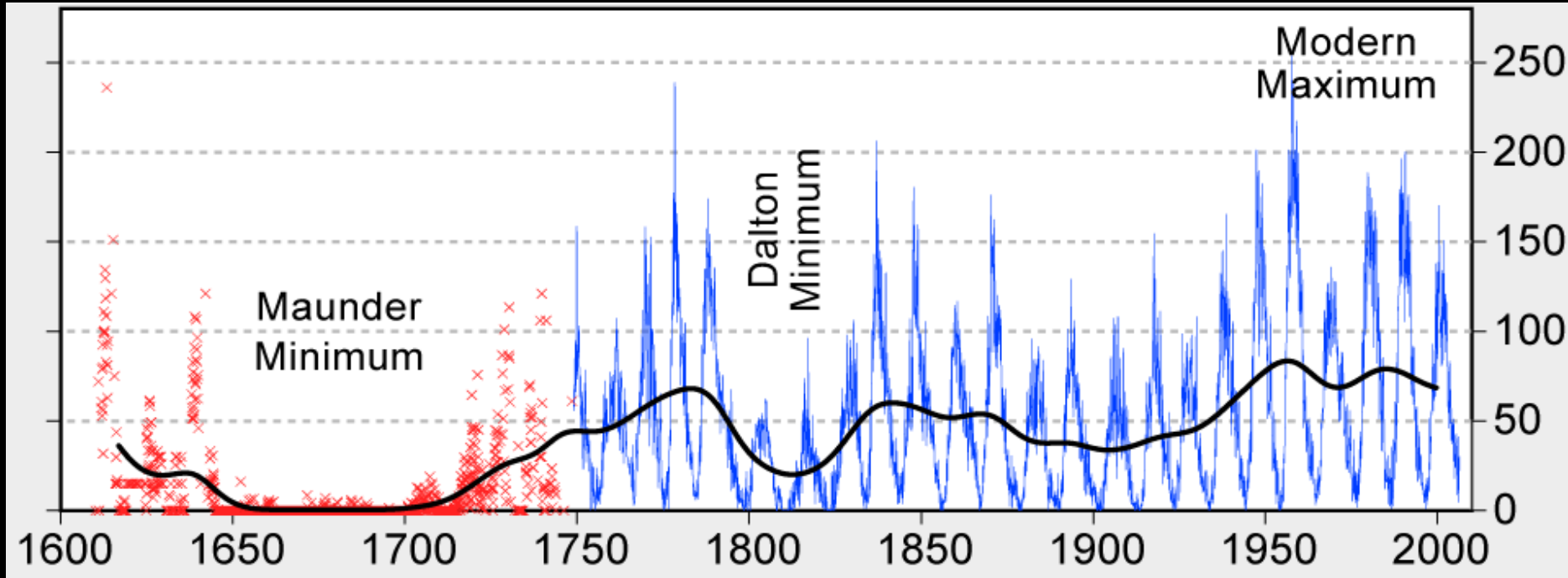
- 
- THE SUN AS A MAGNETIC VARIABLE STAR
 - SOLAR CYCLE MODELS
& THEIR ABILITY TO FORECAST
 - A DIFFERENT APPROACH NEEDED?
 - REQUIREMENTS FOR PROGRESS



PART 1:

THE SUN AS A MAGNETIC VARIABLE STAR

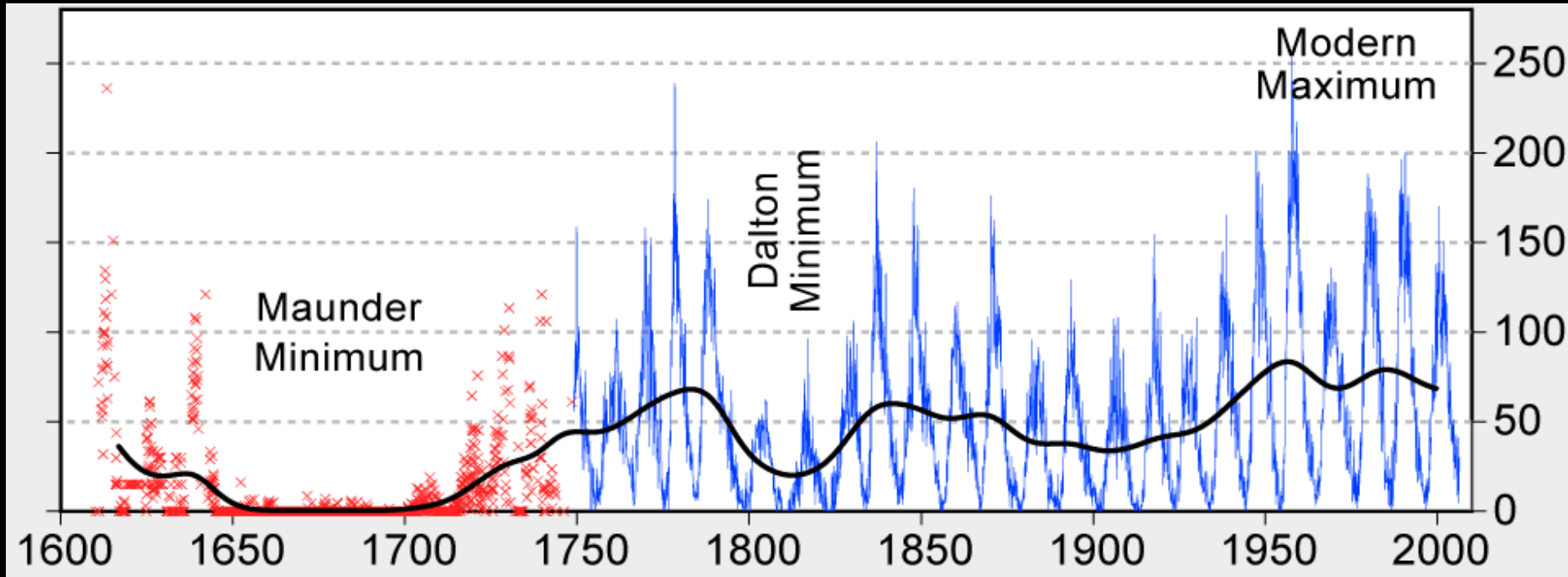
400 YEARS OF SUNSPOT DATA



X DATA INTERMITTENT AND LOWER QUALITY

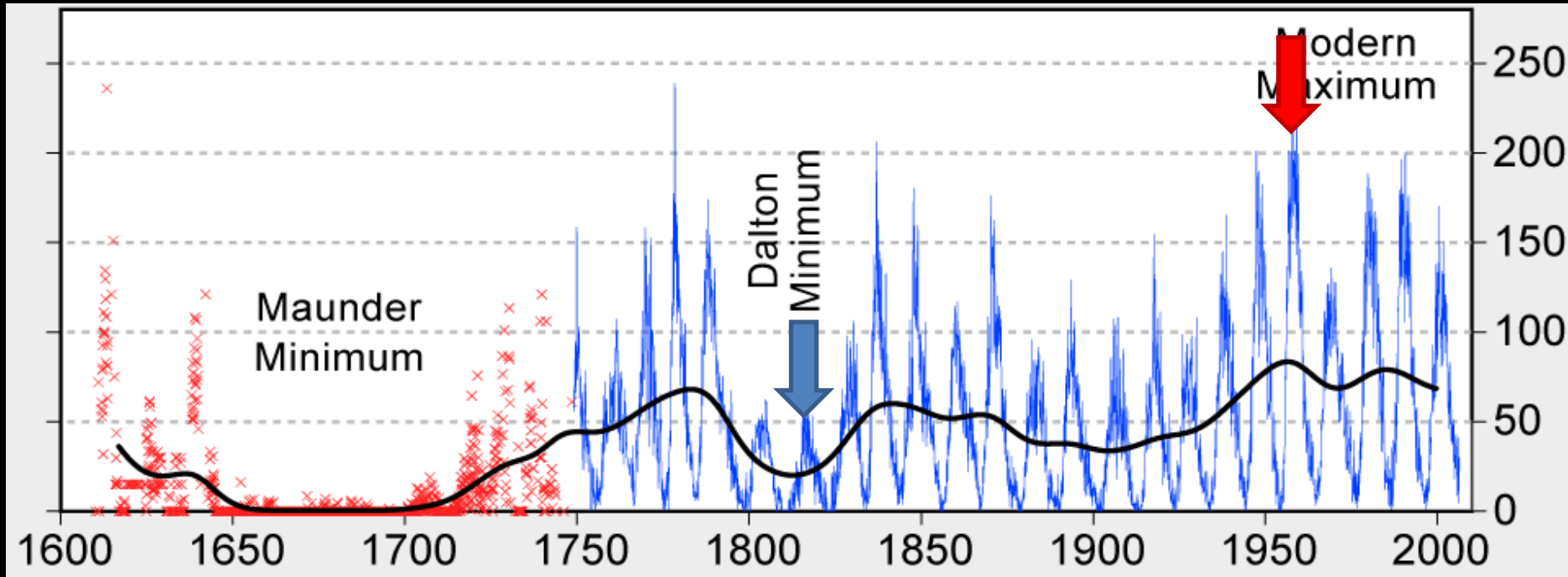
| DATA MORE COMPLETE AND RELIABLE

11-YEAR MODULATION OF SUNSPOTS NUMBERS



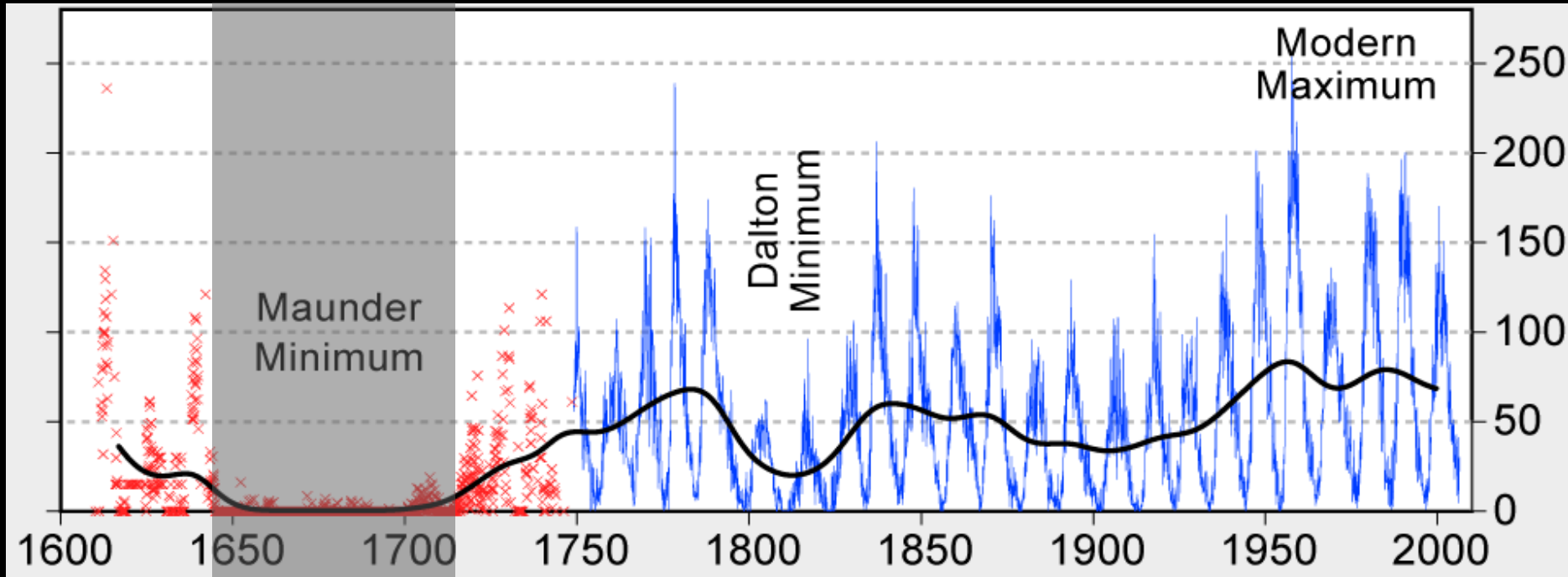
**... BUT THE PERIOD IS NOT EXACTLY 11 YEARS
RANGING FROM 8 TO 14 YEARS**

THE AMPLITUDE OF THE CYCLES VARIES



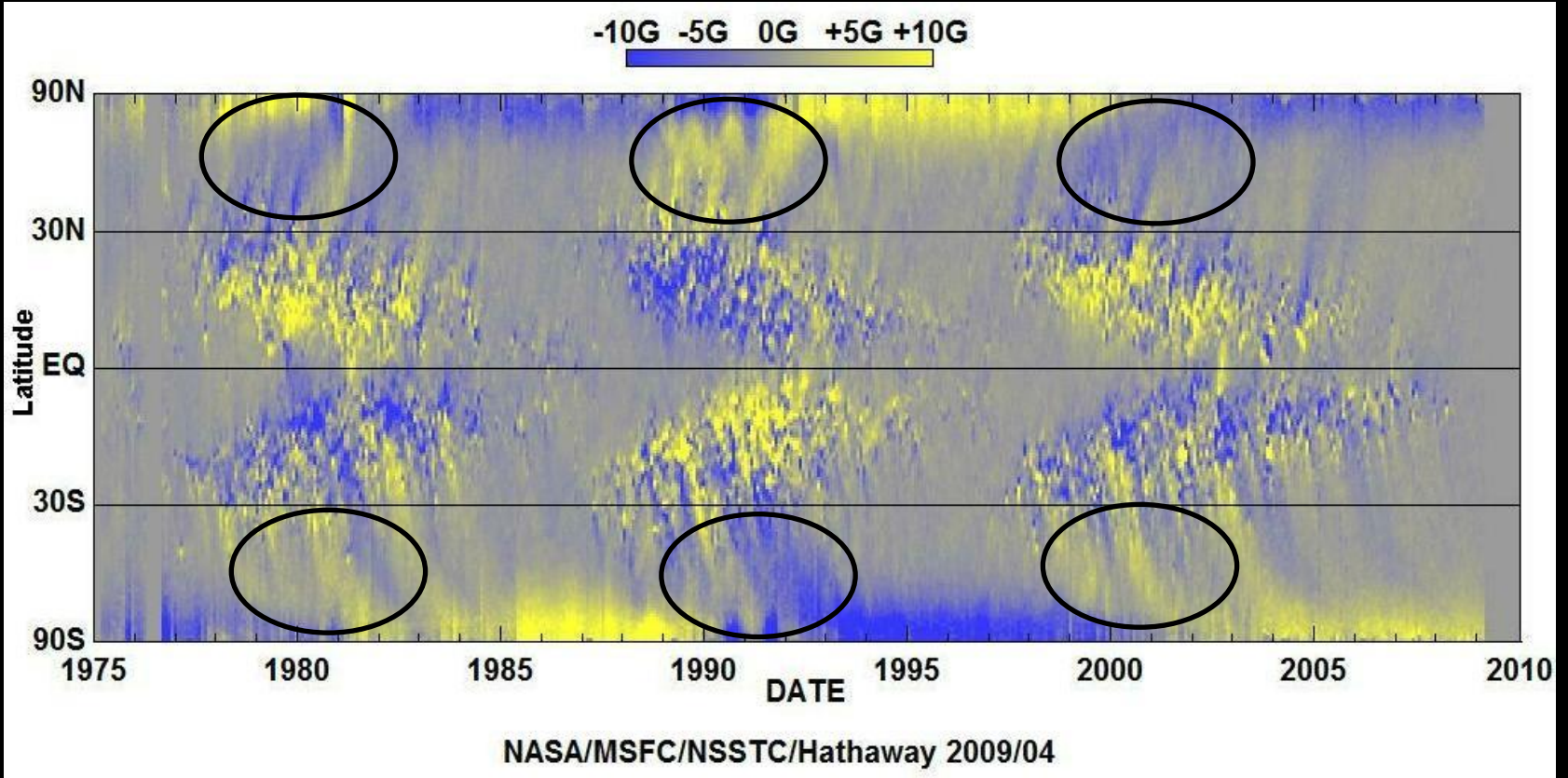
... RANGING FROM <50 TO >200

A LONG PERIOD WITHOUT MANY SPOTS APPEARING



**A HARD TEST FOR ANY SOLAR CYCLE MODEL
HOW TO START A EXTENDED MINIMUM
HOW TO GET OUT OF IT**

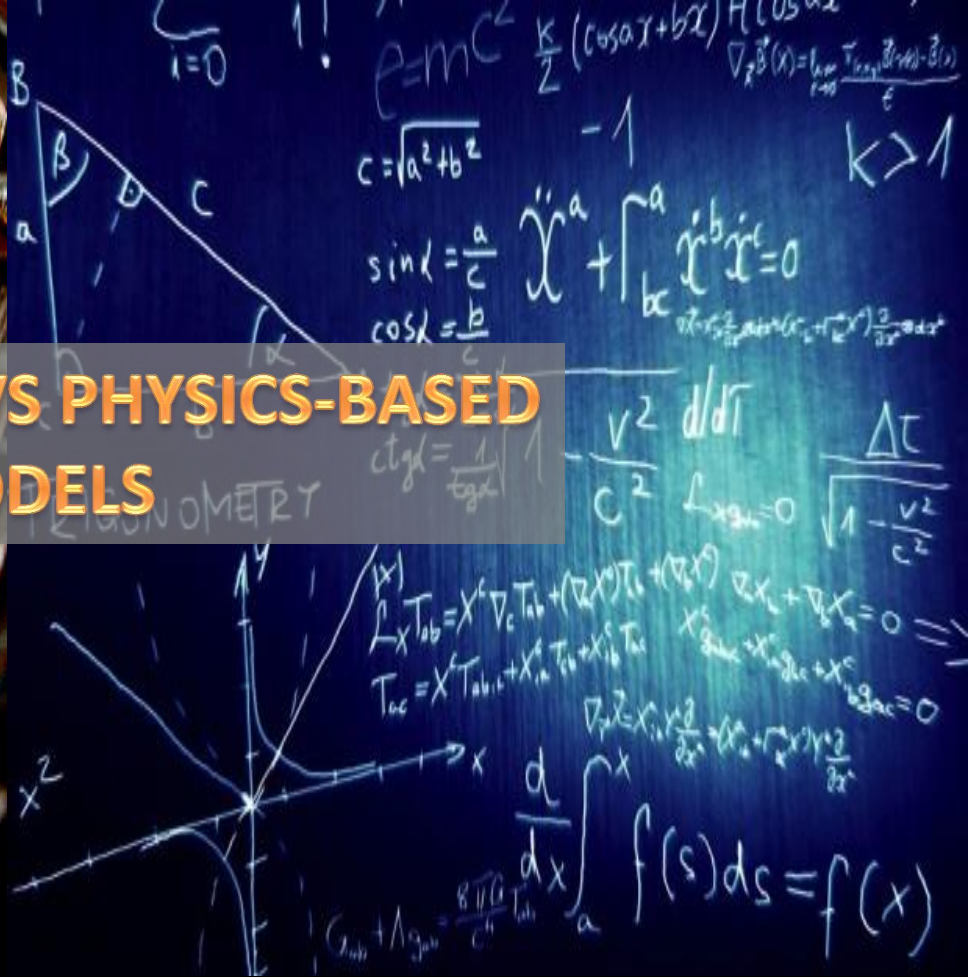
THE MAGNETIC CYCLE IS 22 YEARS



1. NORTHERN & SOUTHERN REGIONS HAVE OPPOSITE POLARITY
2. MAGNETIC POLARITY REVERSES FROM SOLAR CYCLE TO CYCLE
3. POLAR MAGNETIC FIELD REVERSAL IN MIDDLE OF SOLAR CYCLE



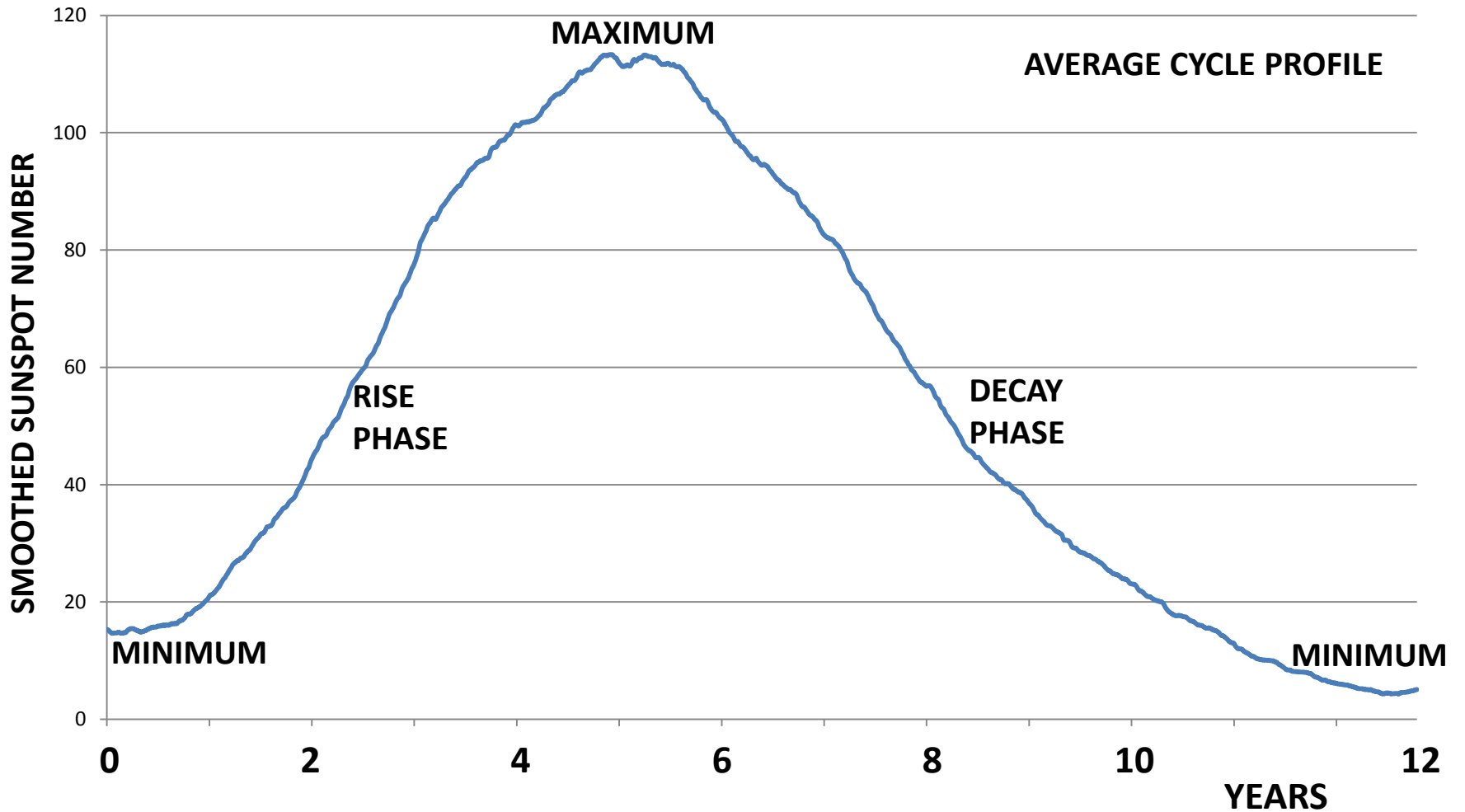
EMPIRICAL VS PHYSICS-BASED MODELS



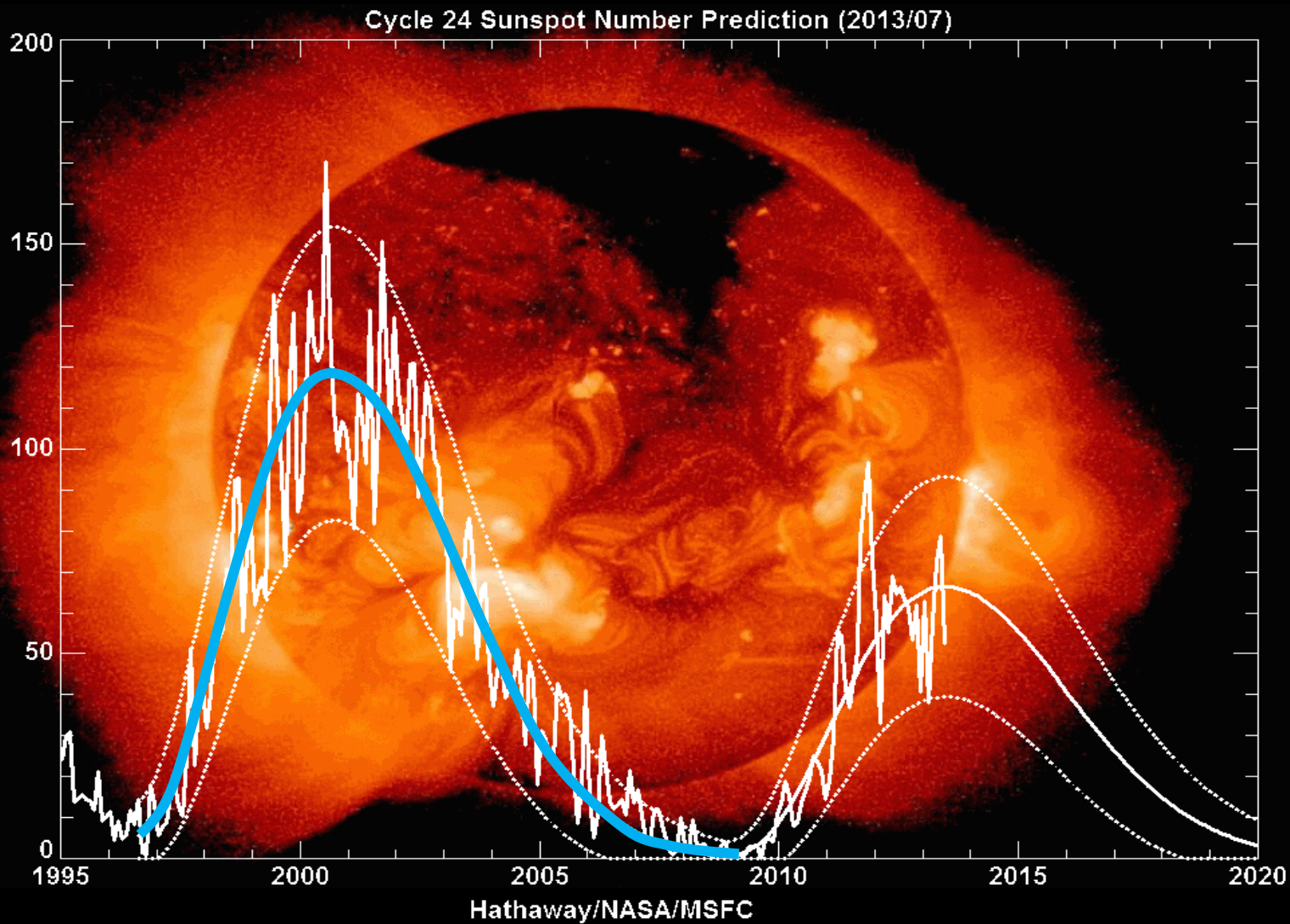
PART 2:

SOLAR CYCLE MODELS & THEIR ABILITY TO FORECAST

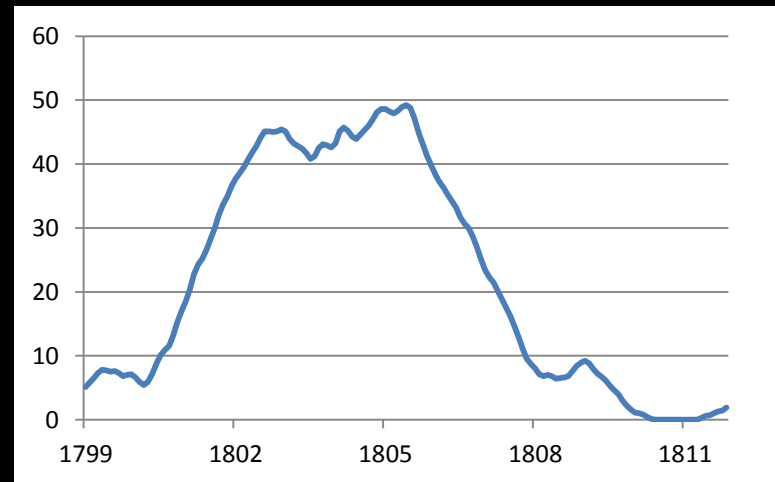
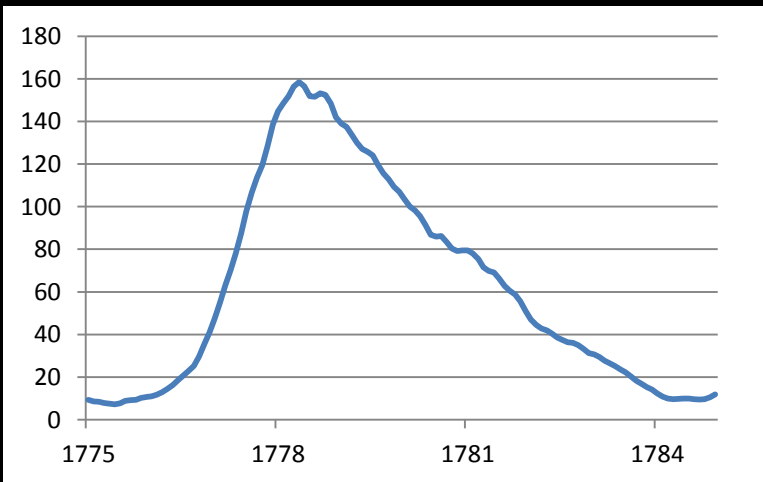
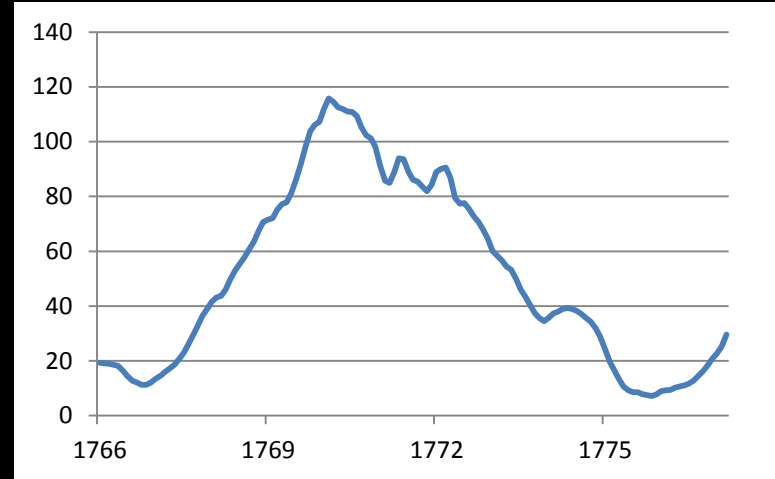
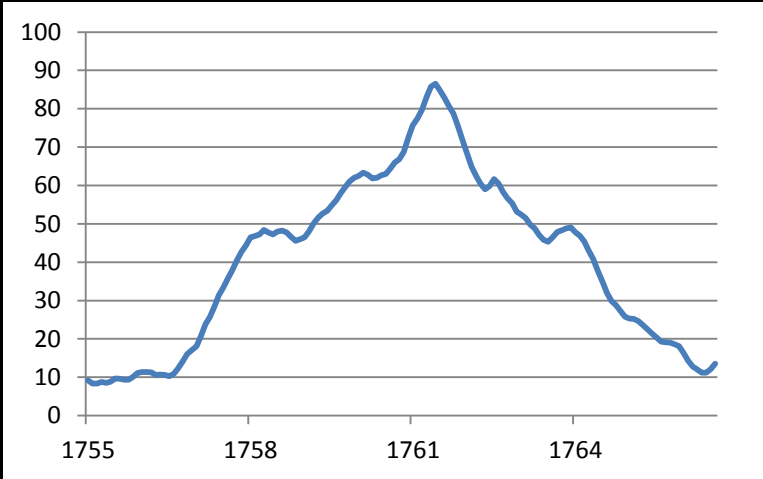
AN EMPIRICAL MODEL

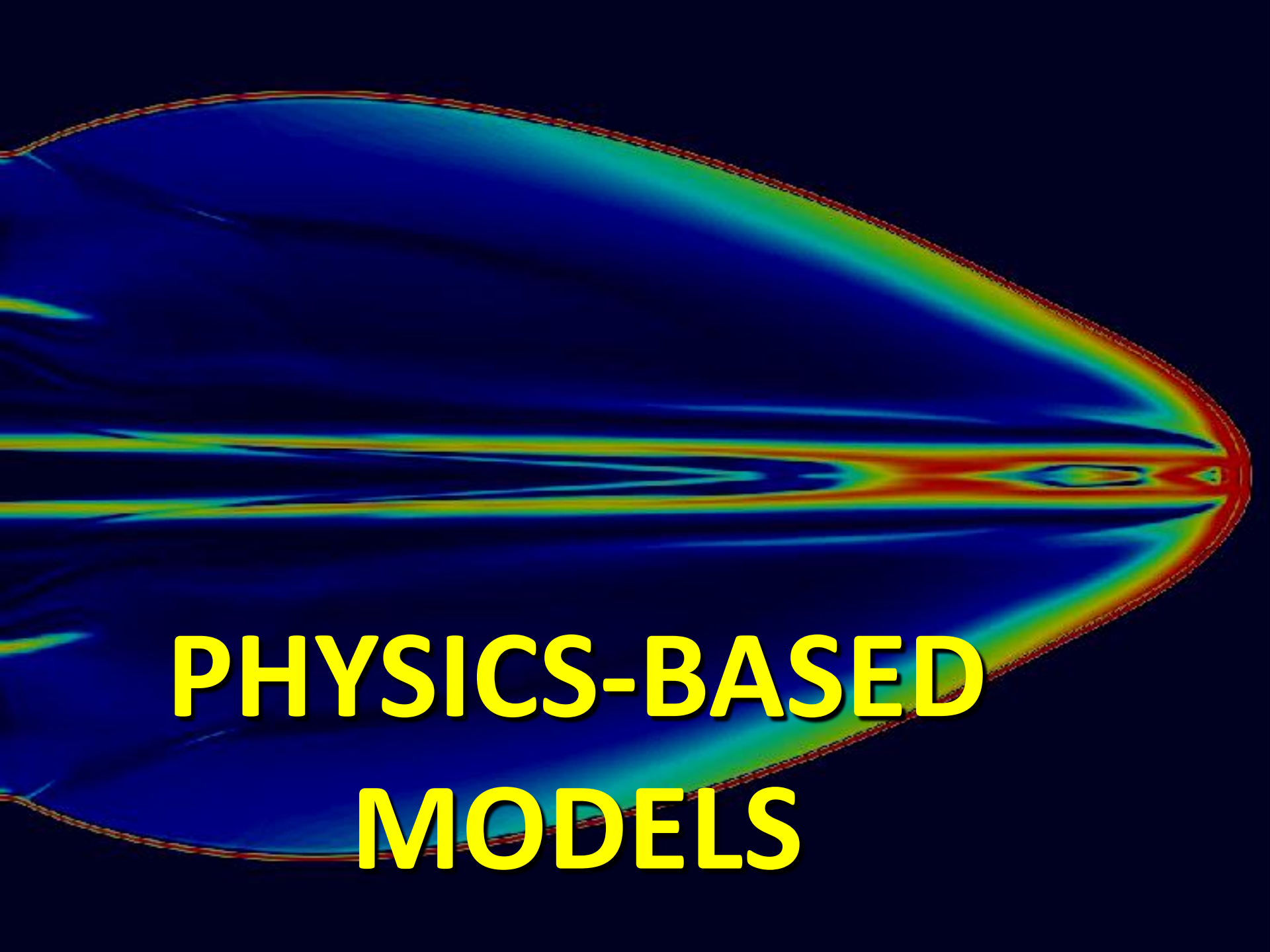


SHAPE FITTING ...



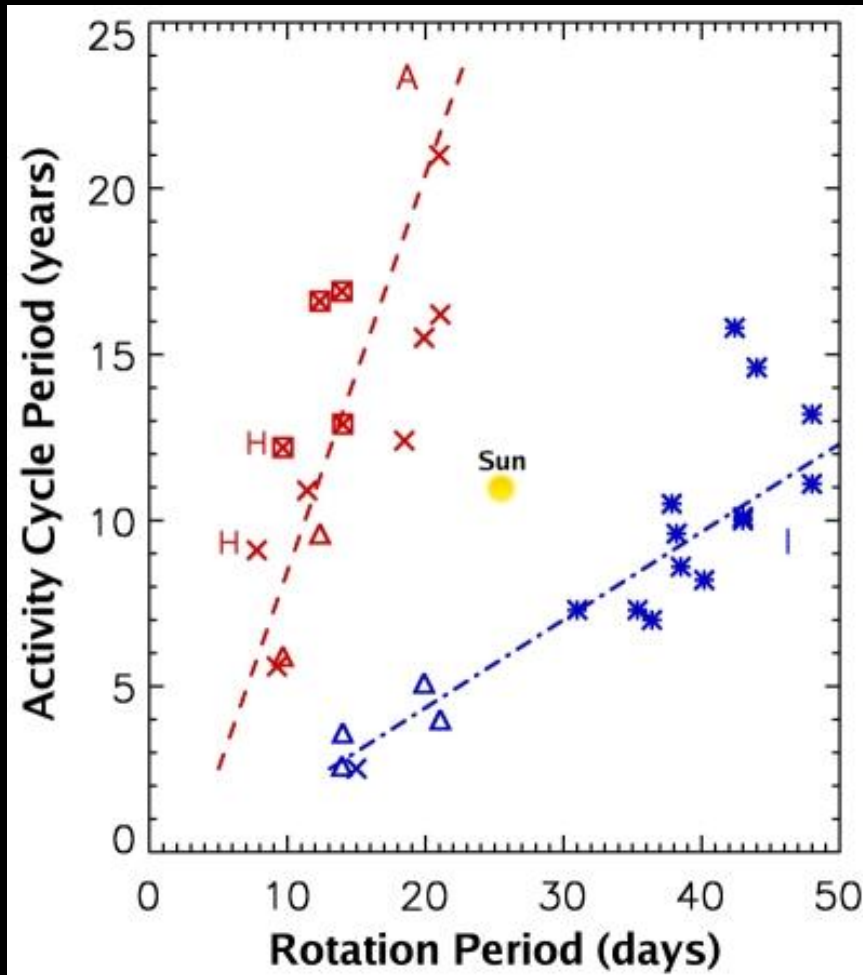
... BUT GIVES LOTS OF FALSE RESULTS



The image features a horizontal, elongated shape with a color gradient from dark blue on the left to bright red on the right. The shape is wider on the left and tapers to a point on the right. The color gradient is not uniform; it shows complex patterns of light and dark bands, suggesting a simulation of a physical process like fluid flow or heat transfer. The text "PHYSICS-BASED MODELS" is overlaid in the lower half of the image.

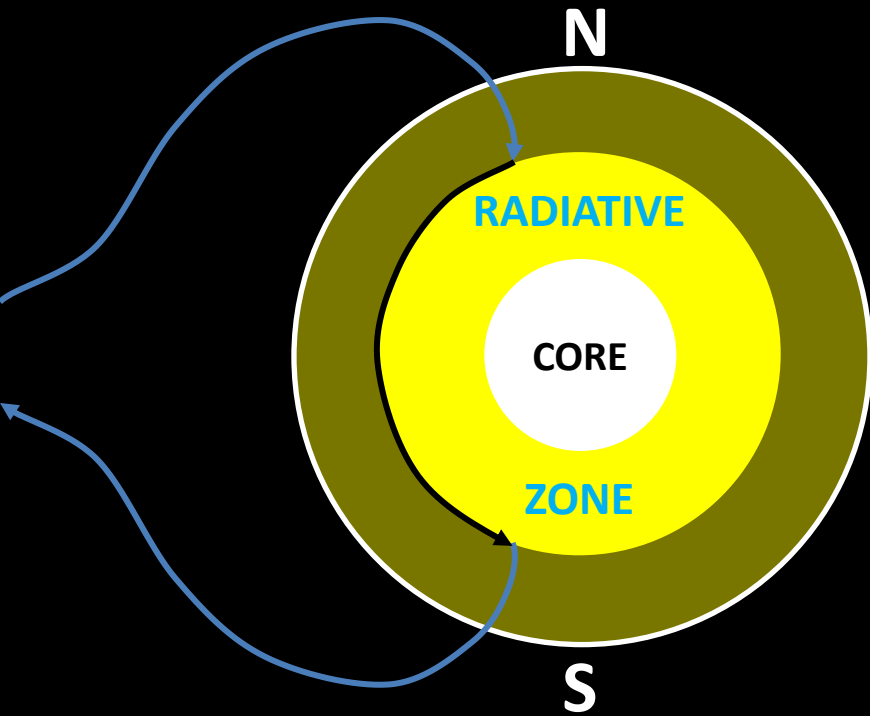
**PHYSICS-BASED
MODELS**

ROTATION IS A CLUE TO THE NATURE OF THE SOLAR DYNAMO



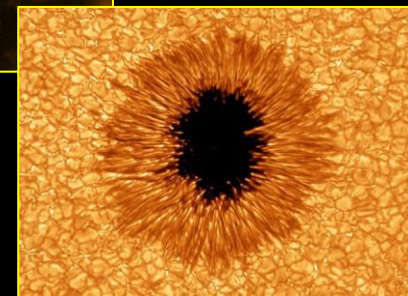
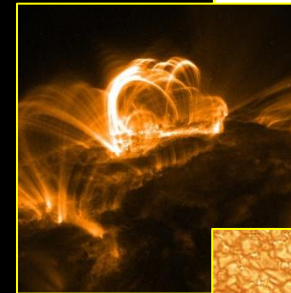
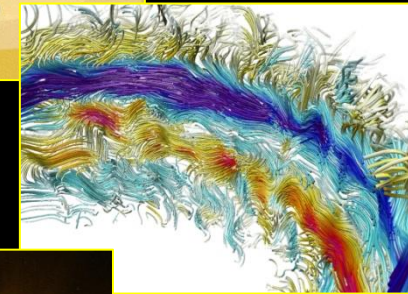
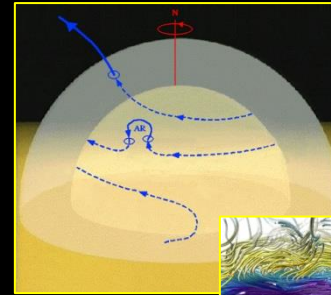
BOHM-VITENSE (2007)

WINDING UP



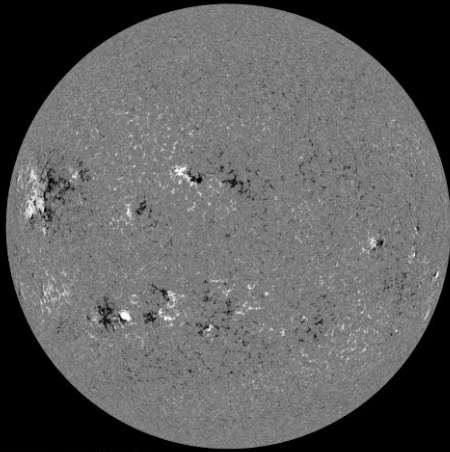
INSTABILITY SETS IN

- WINDING UP CREATES STRONGER MAGNETIC FIELDS
- MAGNETIC PRESSURE EXCEEDS GAS PRESSURE
- MAGNETIC FLUX ROPES EXPAND AND BECOME BUOYANT
- RISE TO THE SURFACE TO APPEAR AS SUNSPOTS

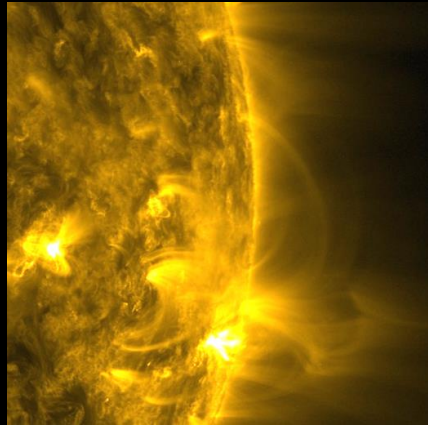


AND THEN IT GETS COMPLICATED

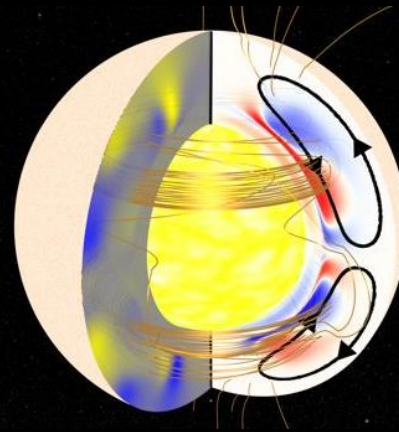
STARTING POINT



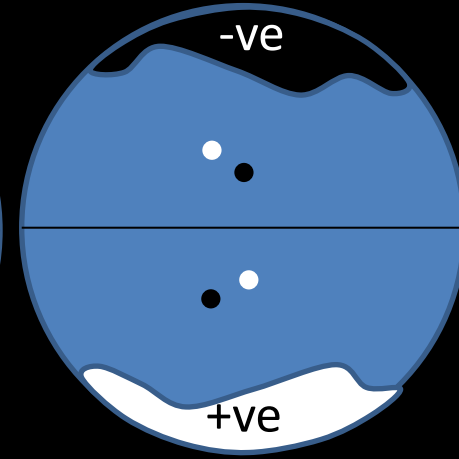
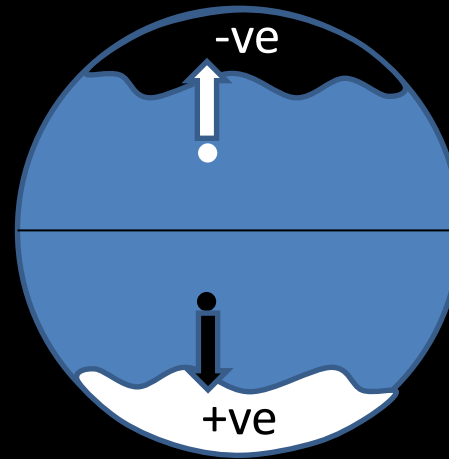
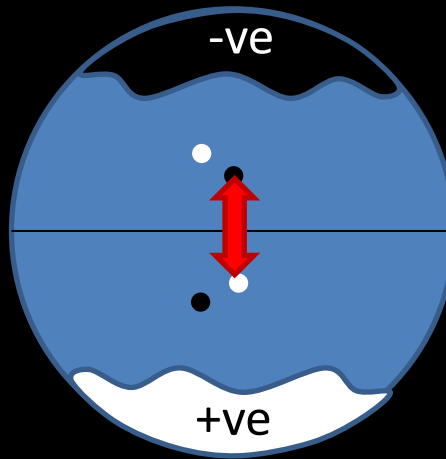
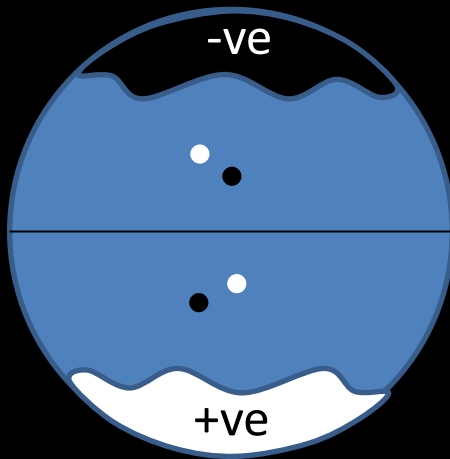
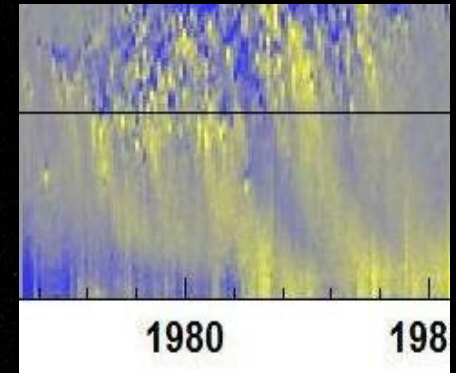
CANCELLATION



TRANSPORT

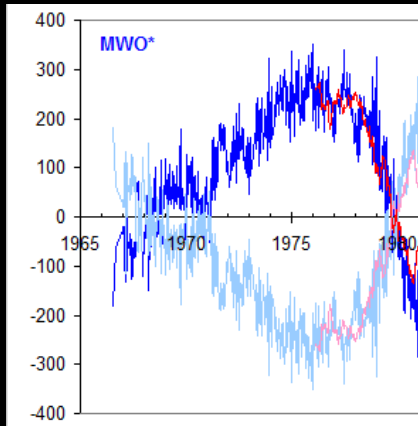


EROSION

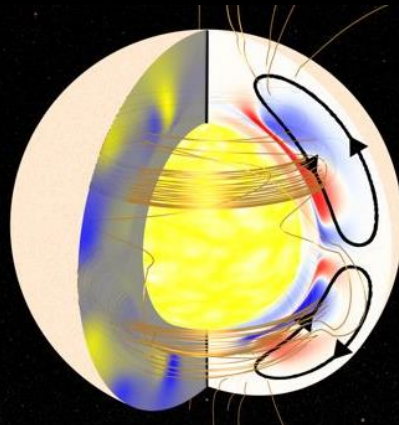


AND THEN IT GETS COMPLICATED

ZERO POLES



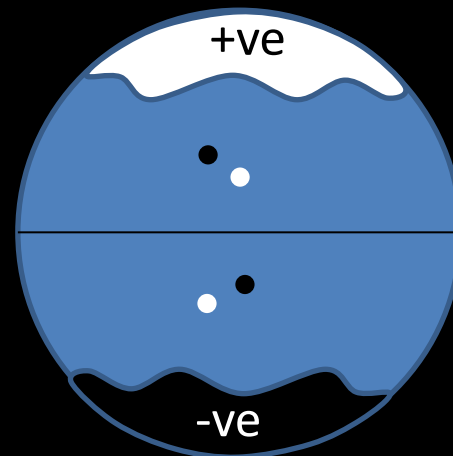
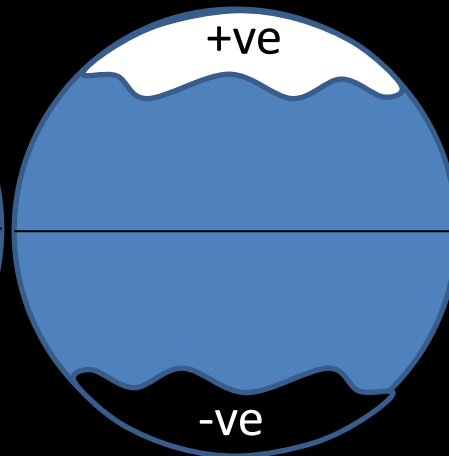
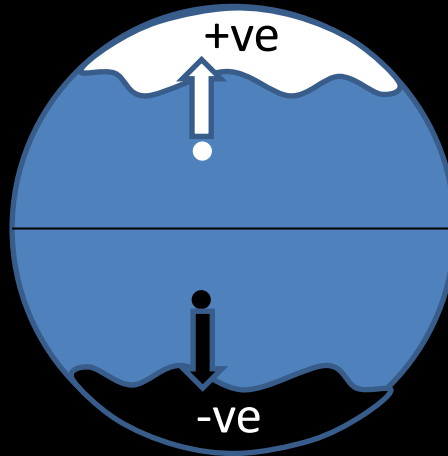
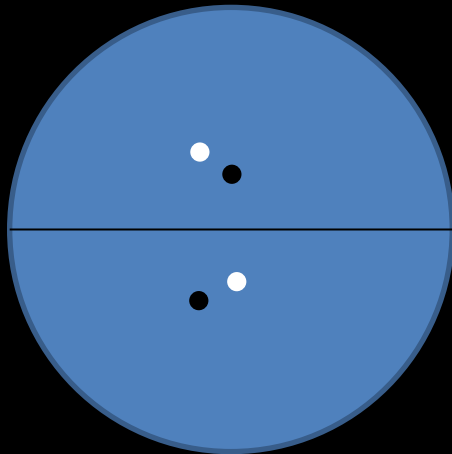
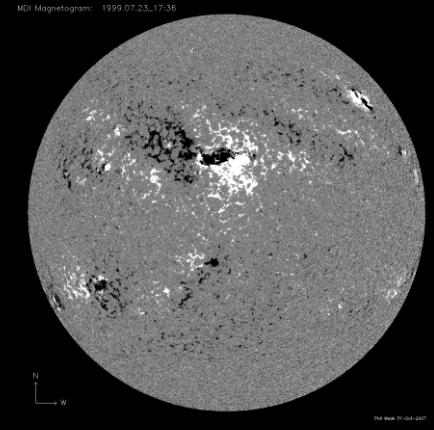
REVERSAL



MINIMUM

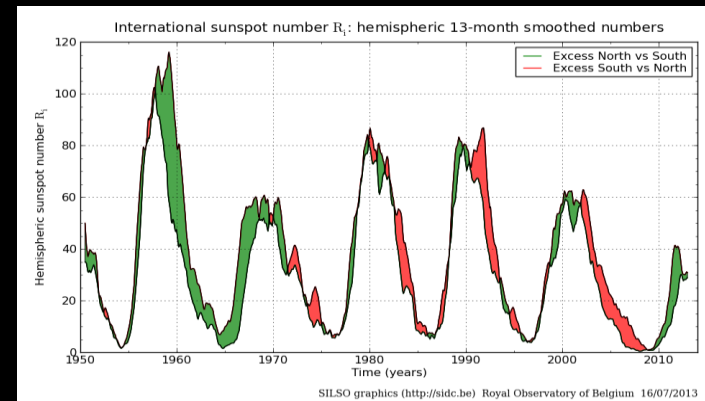


NEW CYCLE

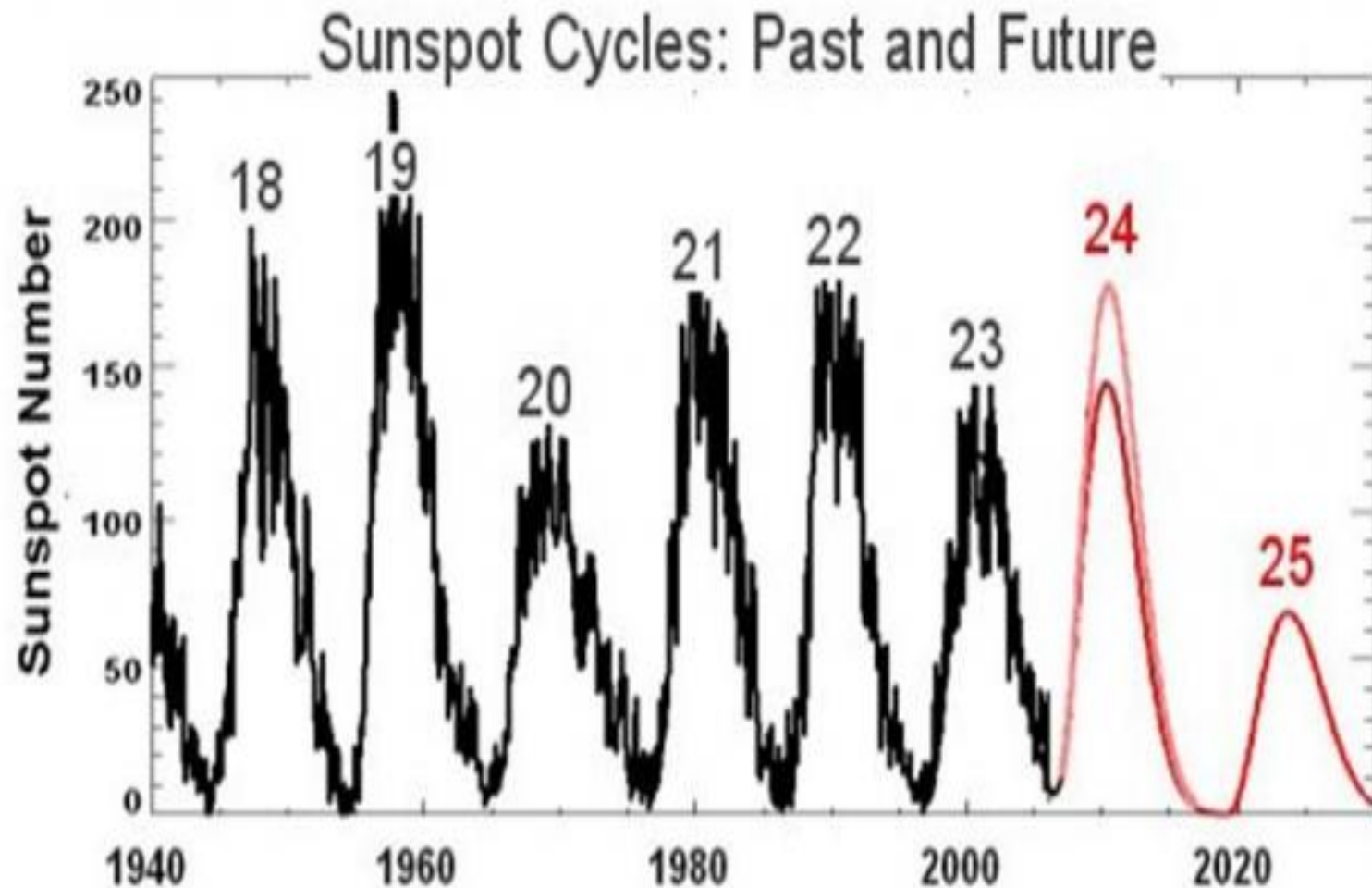


BUT ALL WAS NOT WELL ...

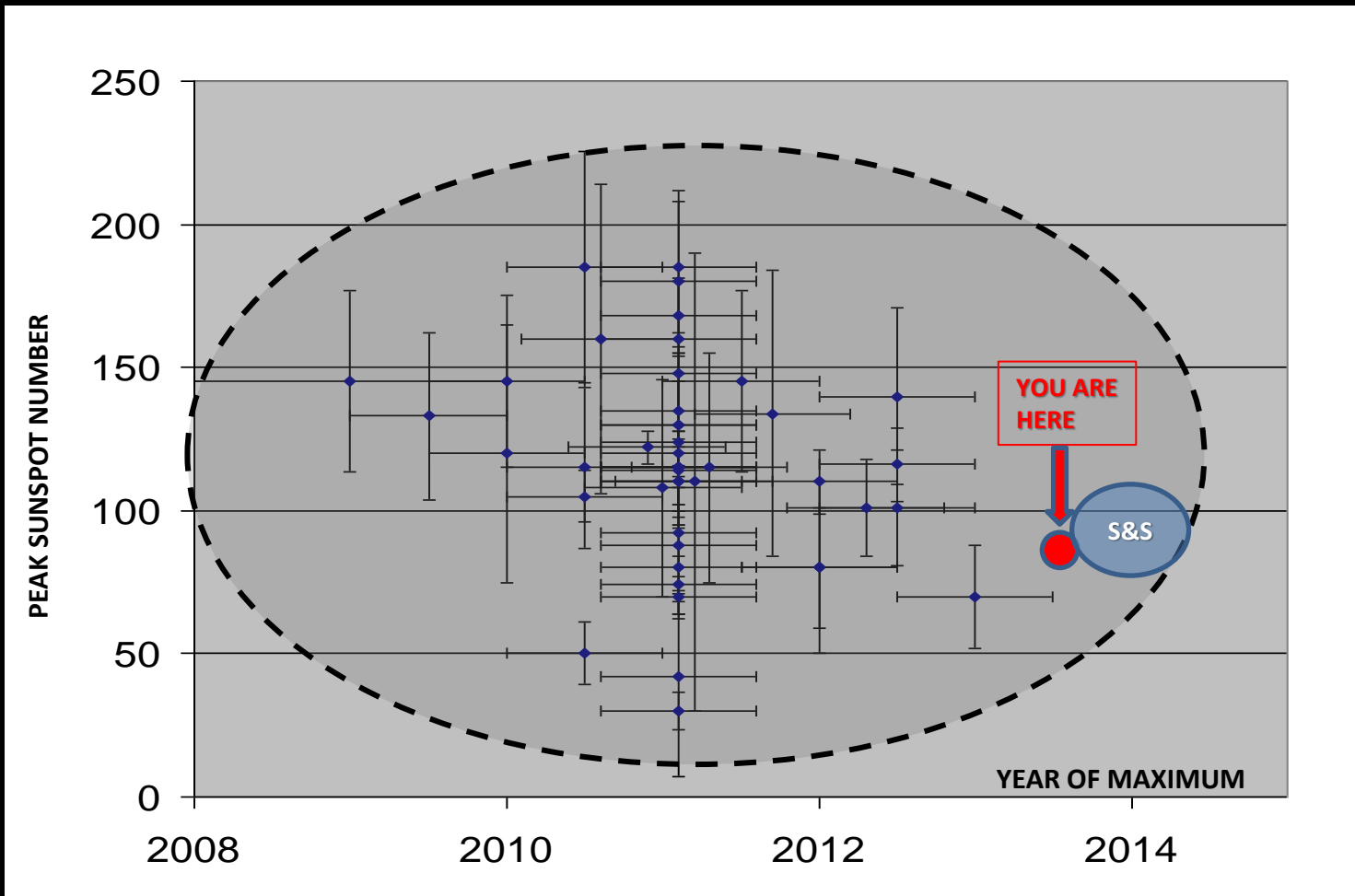
- THE EARLY MODELS REQUIRED SHEAR THROUGHOUT THE CONVECTIVE ZONE
 - HELIOSEISMOLOGY SHOWS SHEAR AT THE BASE OF THE CONVECTION ZONE AND NEAR THE SURFACE
- PREDICTED CYCLES TOO SHORT (ONLY 2 YEARS!)
- MOST MODELS ASSUME N-S MAGNETIC SYMMETRY
- A DEEP MERIDIONAL FLOW?



THE DIKPATI MODEL

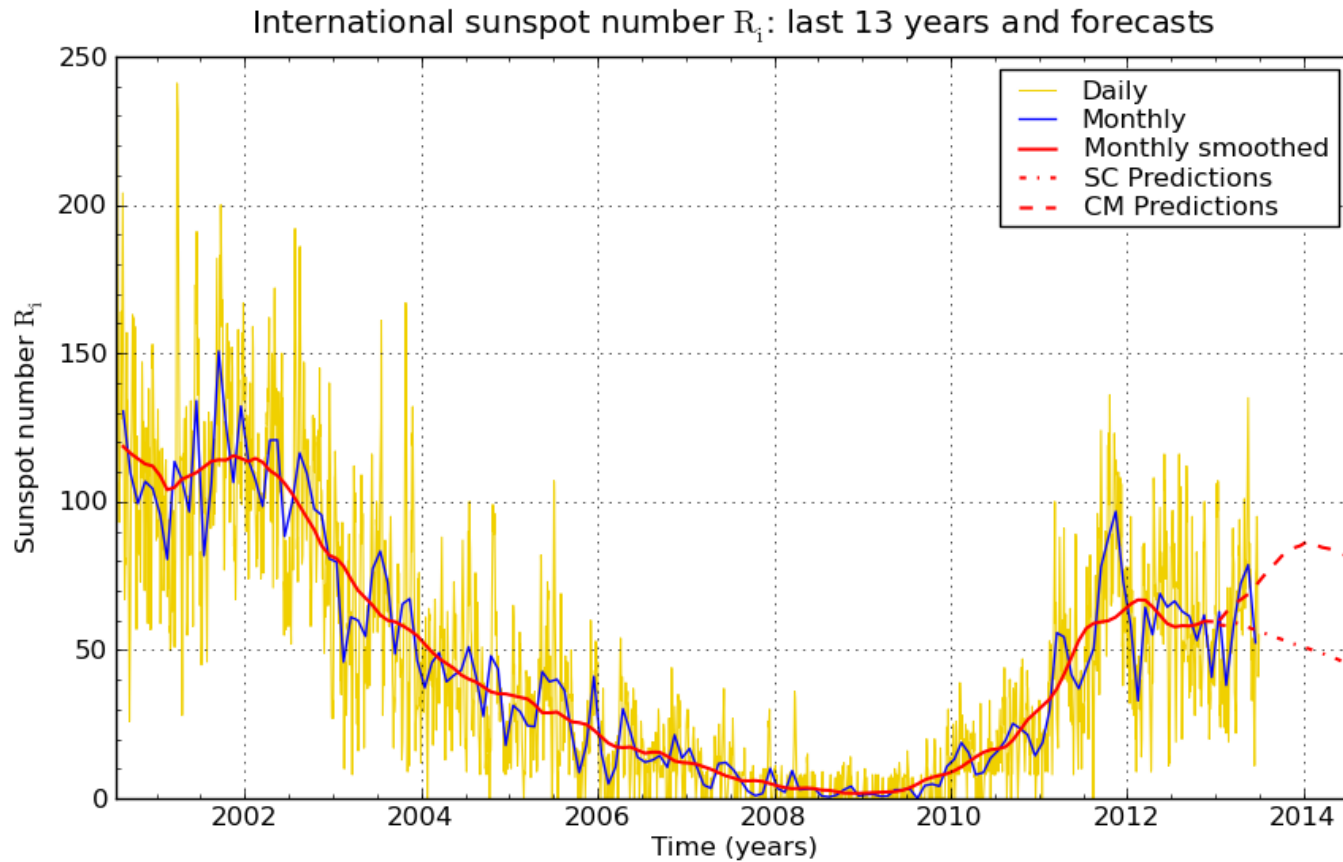


HOW WELL DID WE DO?



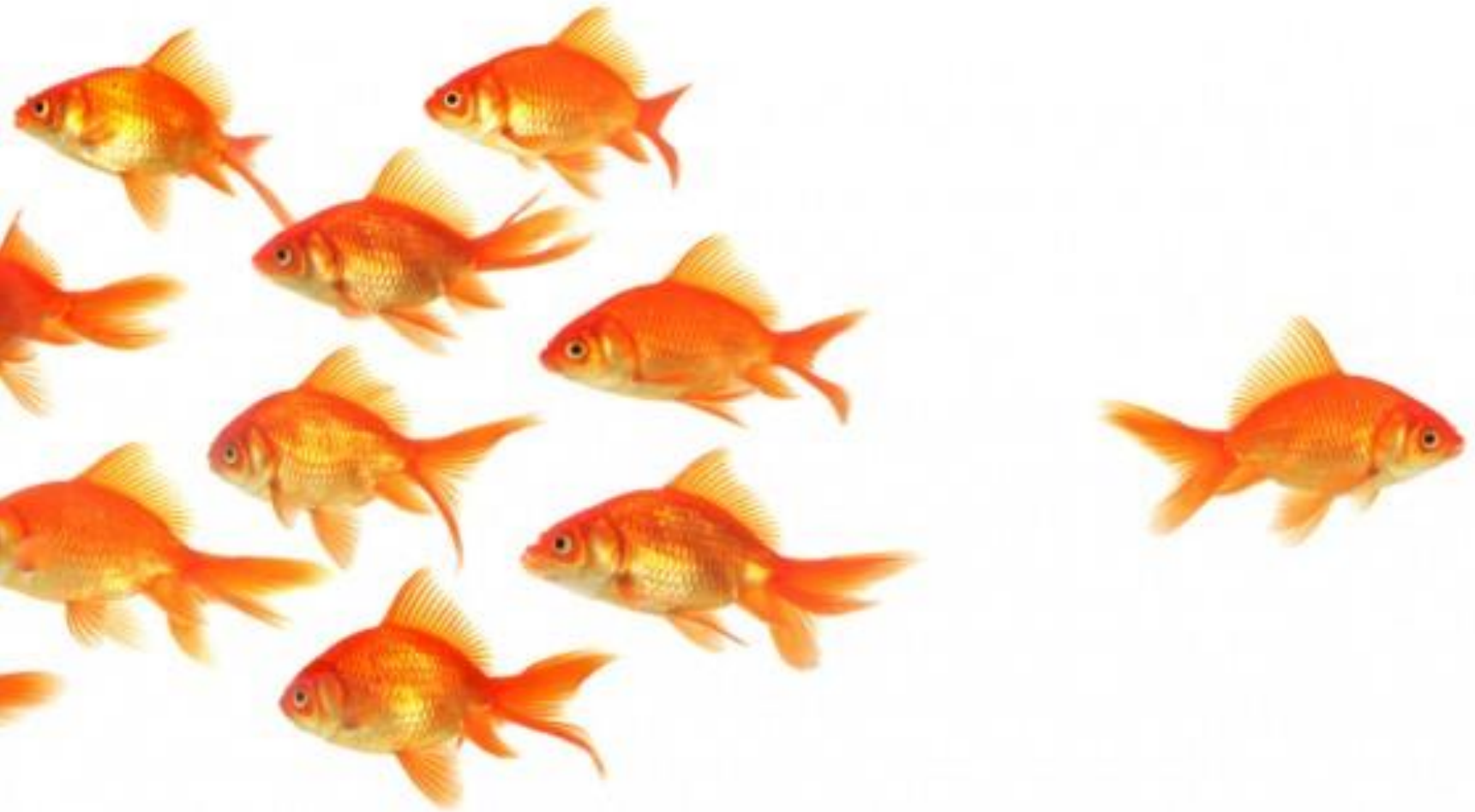
Data Tabulated by D. Pesnell (GSFC)

THE EXPERTS ARE FALLING IN LINE?



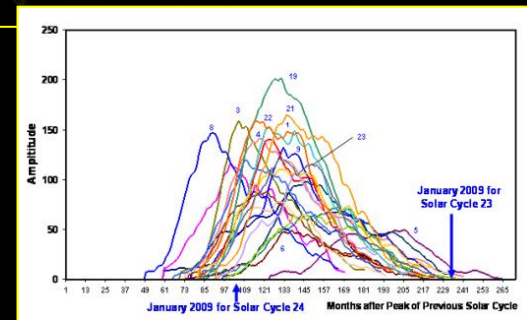
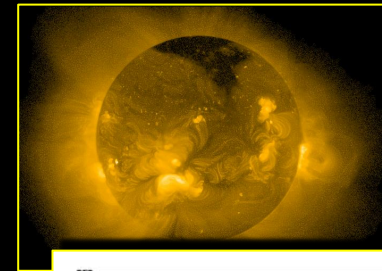
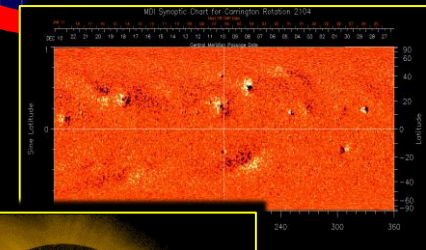
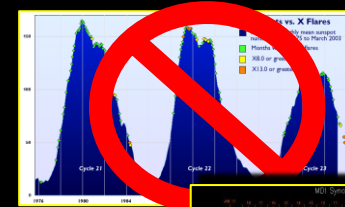
PART 3:

A DIFFERENT APPROACH ...



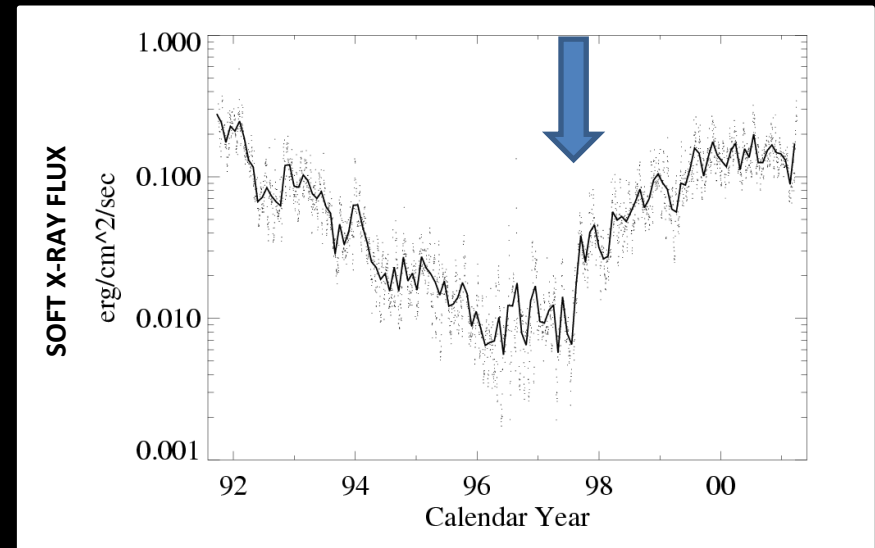
OUR NEW APPROACH

- **DITCH SUNSPOT NUMBER**
 - AT SOLAR MINIMUM B FIELD PRESENT BUT FEW OR NO SPOTS
- **USE NEW DATA SOURCES**
 - DIRECT MEASUREMENTS OF SOLAR MAGNETIC FIELDS
 - CORONAL X-RAY EMISSIONS
- **FIND WHAT THE SUN WILL ALLOW US TO FORECAST (IF ANYTHING)**

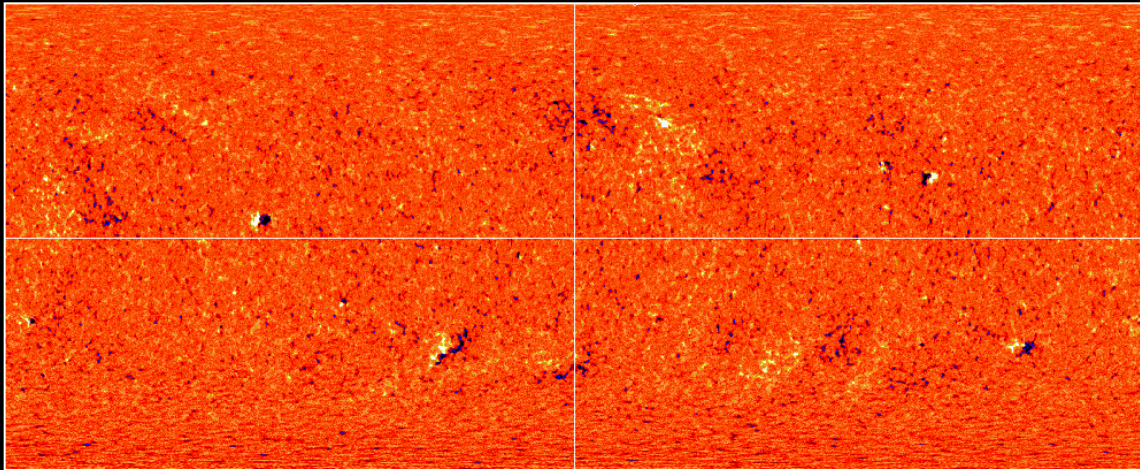


TIMING IS KEY

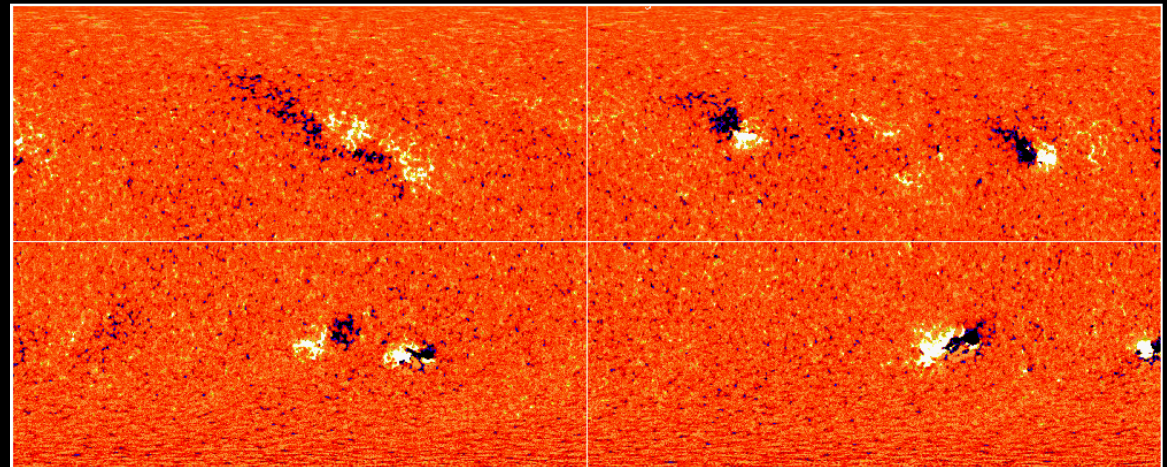
- SOLAR CYCLES MEASURED WRT SOLAR MAX OR SOLAR MINIMUM DATES
 - 13-MONTH SMOOTHED SUNSPOT NUMBER
 - UNCERTAIN
 - DON'T KNOW UNTIL A YEAR HAS PASSED
- DEFINED A NEW TIMING REFERENCE: THE "ONSET"



The Onset is a Global Burst of Activity

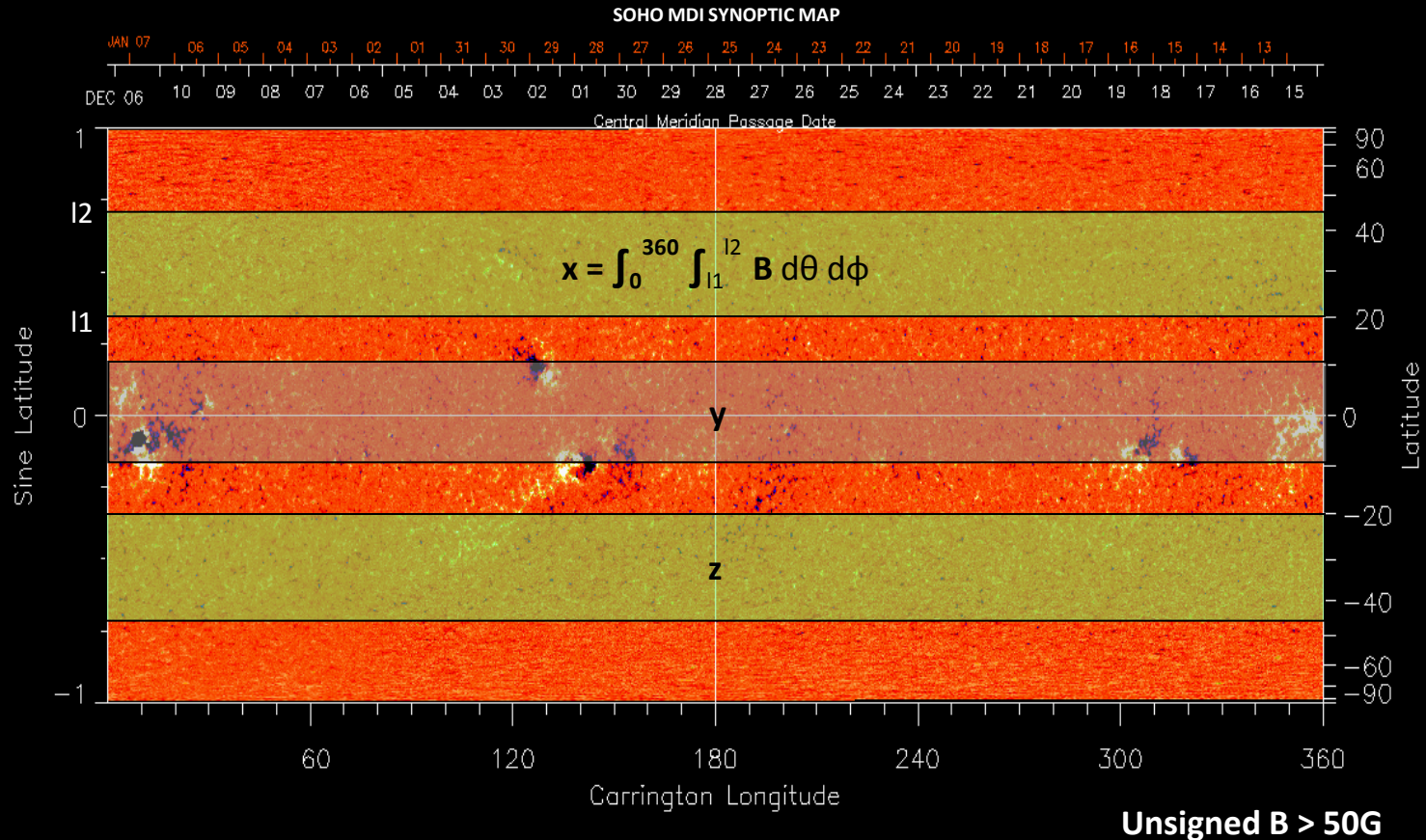


BEFORE
Carrington Rotation 1924



AFTER
Carrington Rotation 1927

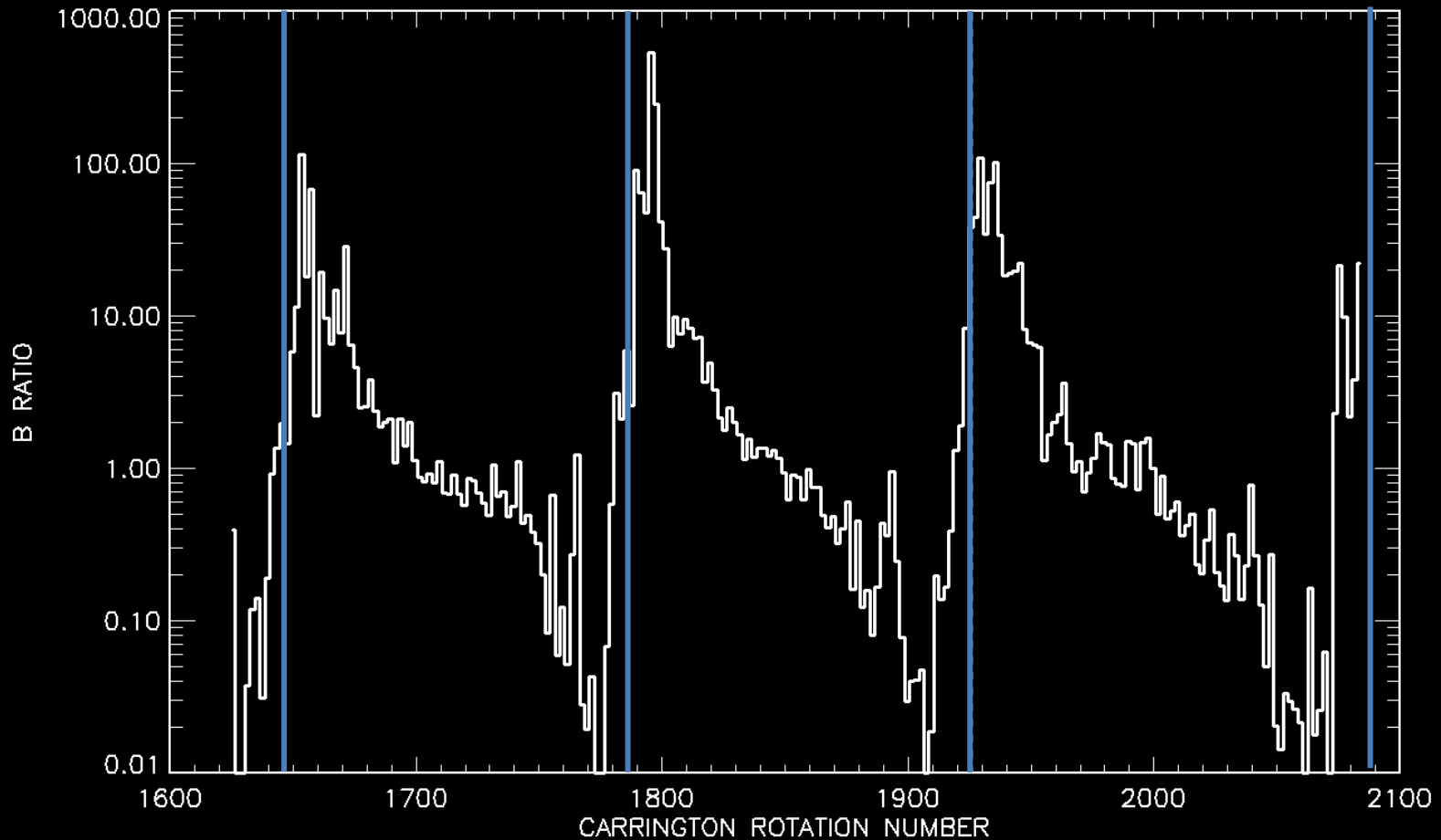
The B Ratio: A PERFECT FIDUCIAL



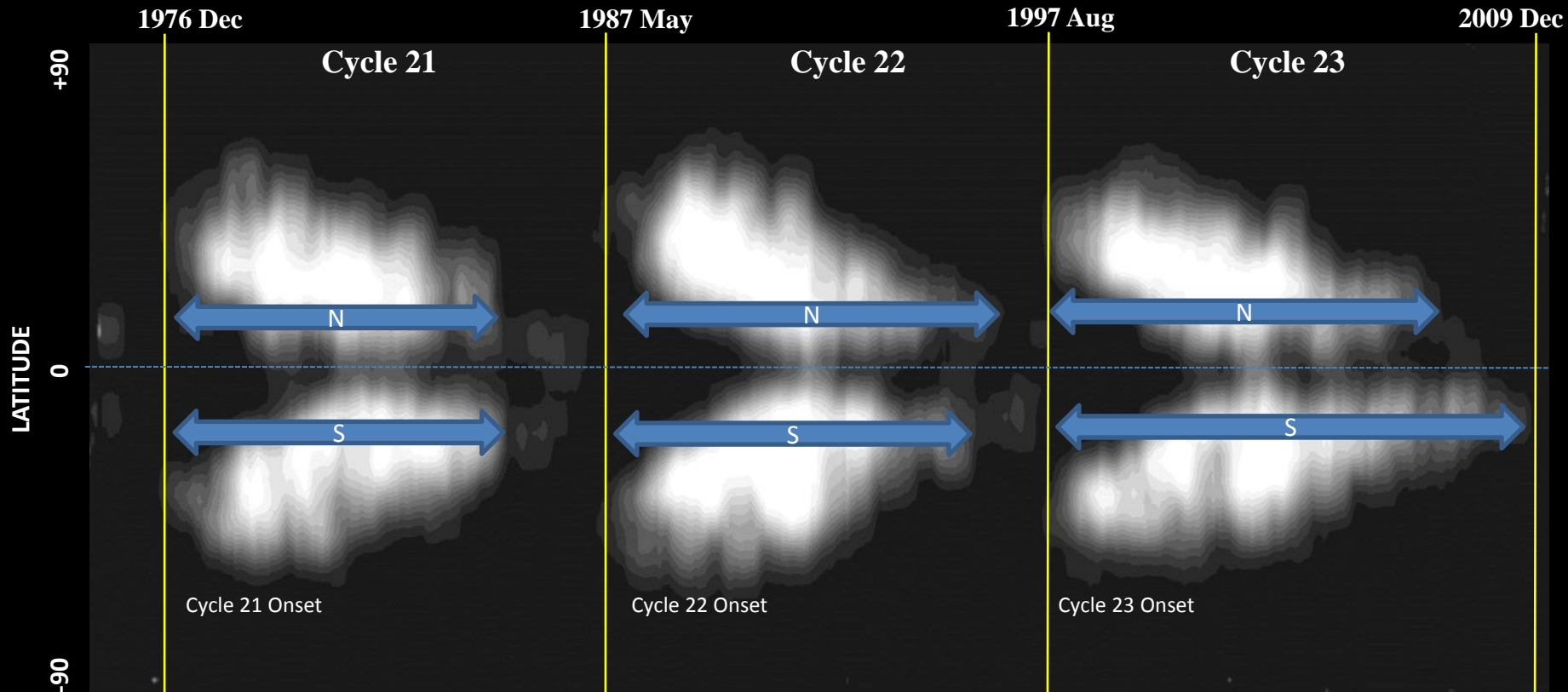
$$\text{B-RATIO} = (x + z) / y$$

Tune x, y, and z boundaries and B threshold to show different aspects of a solar cycle

THE B RATIO CAN BE USED TO PREDICT THE ONSET

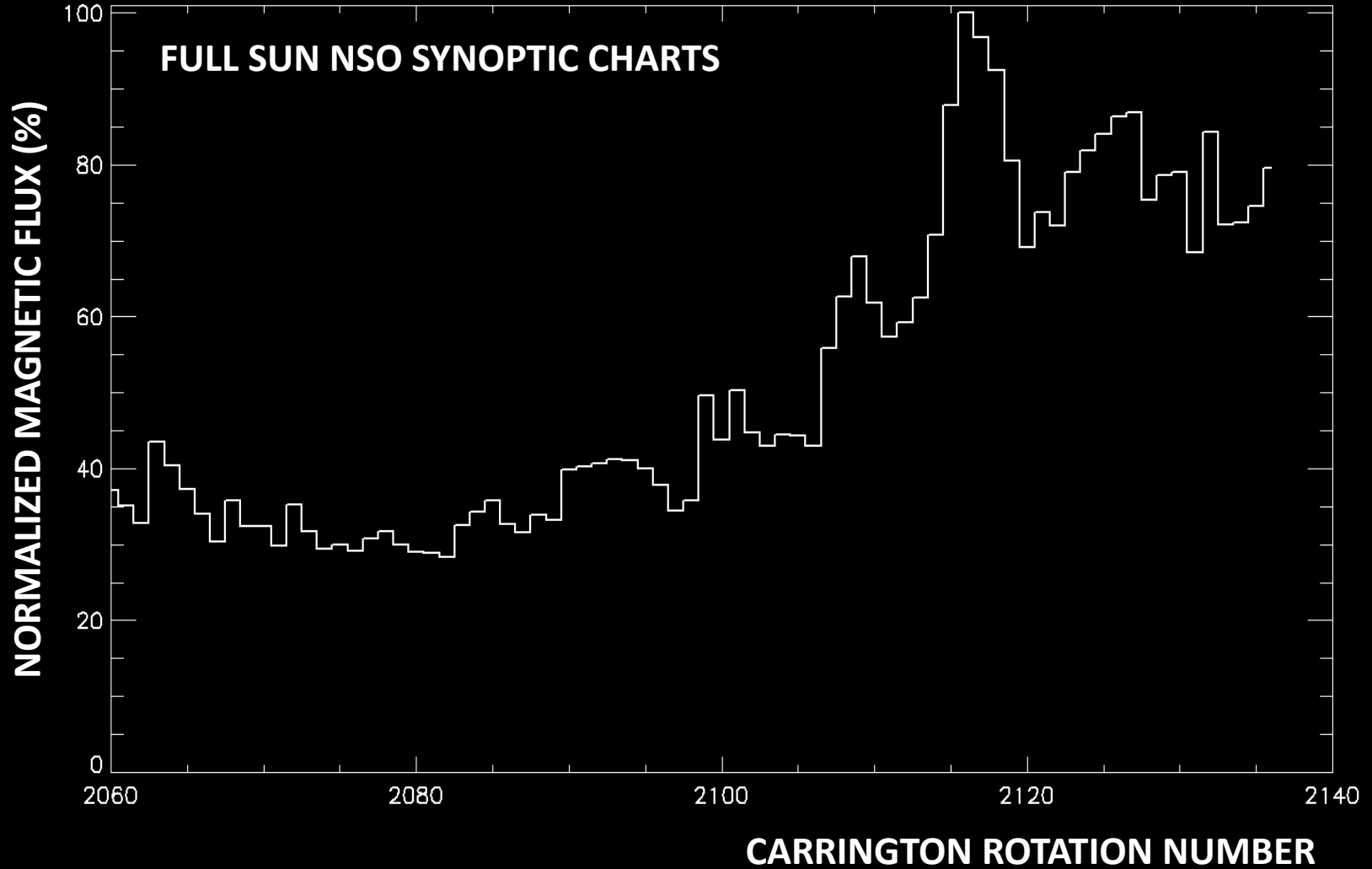


THE ONSET MARKS THE DEATH OF THE OLD CYCLE AND THE BLOSSOMING OF THE NEW



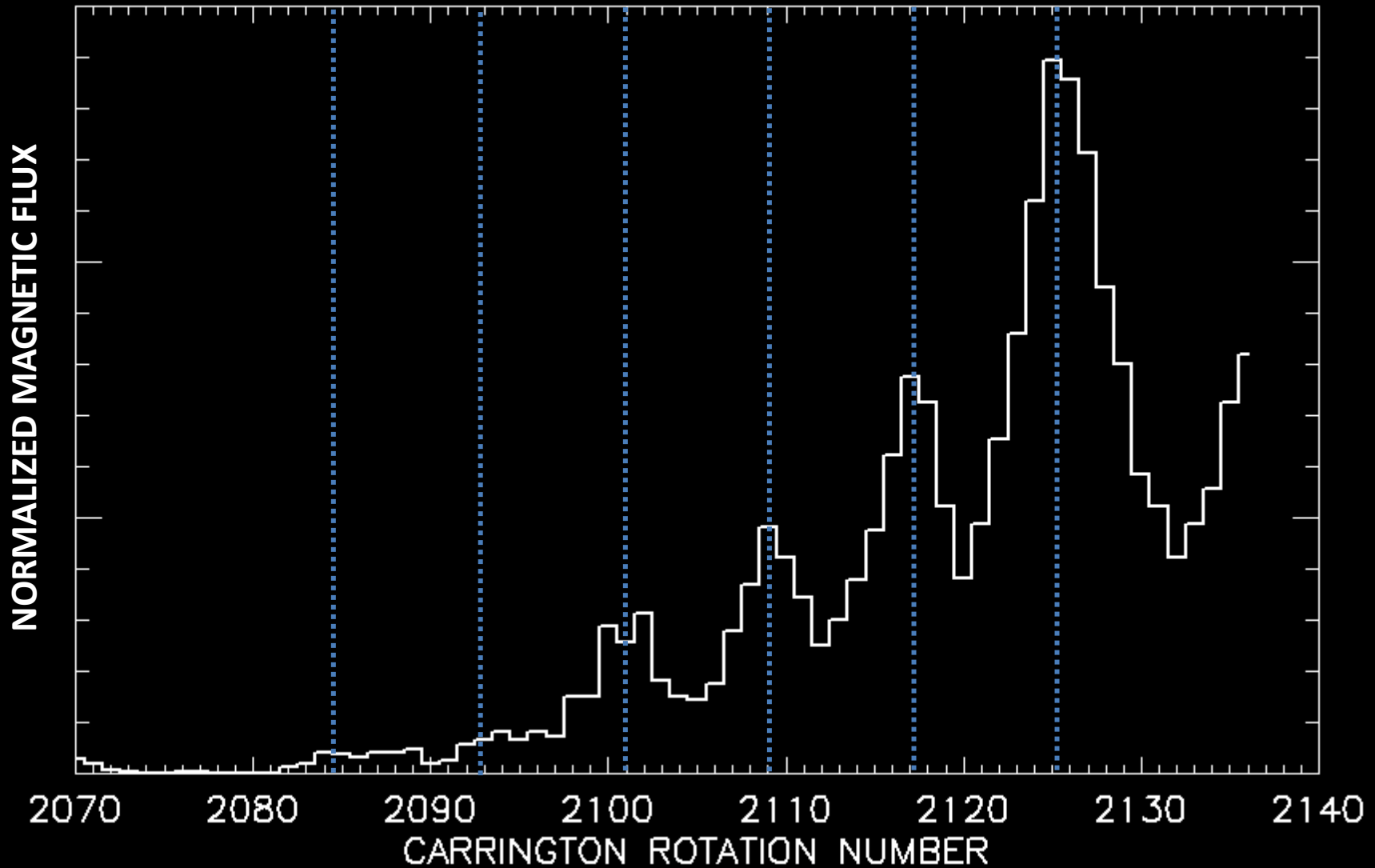
THE BEGINNING OF CYCLE 24

A SERIES OF BURSTS



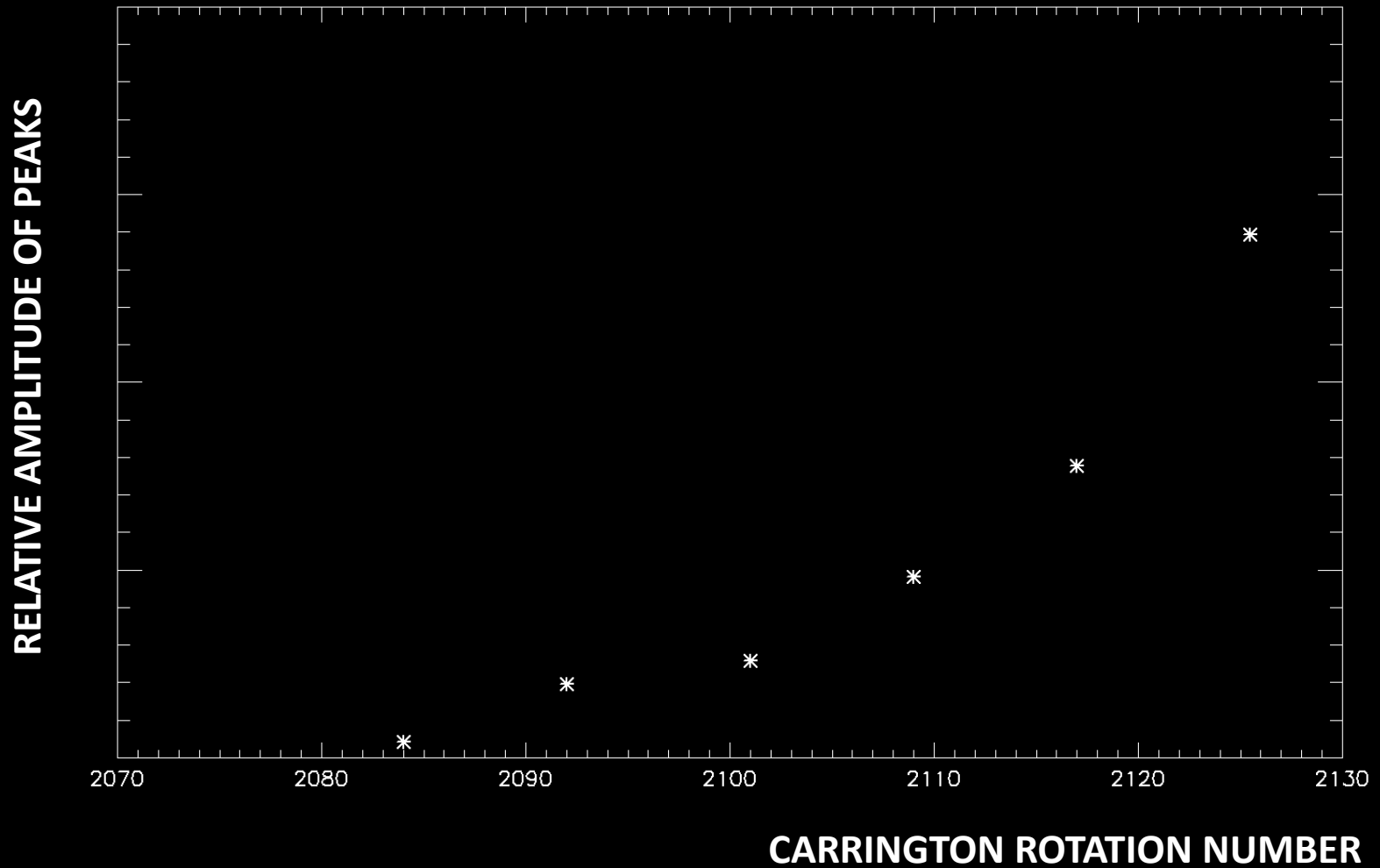
THE SOUTHERN HEMISPHERE

(10S – 60S; $B > 50G$)

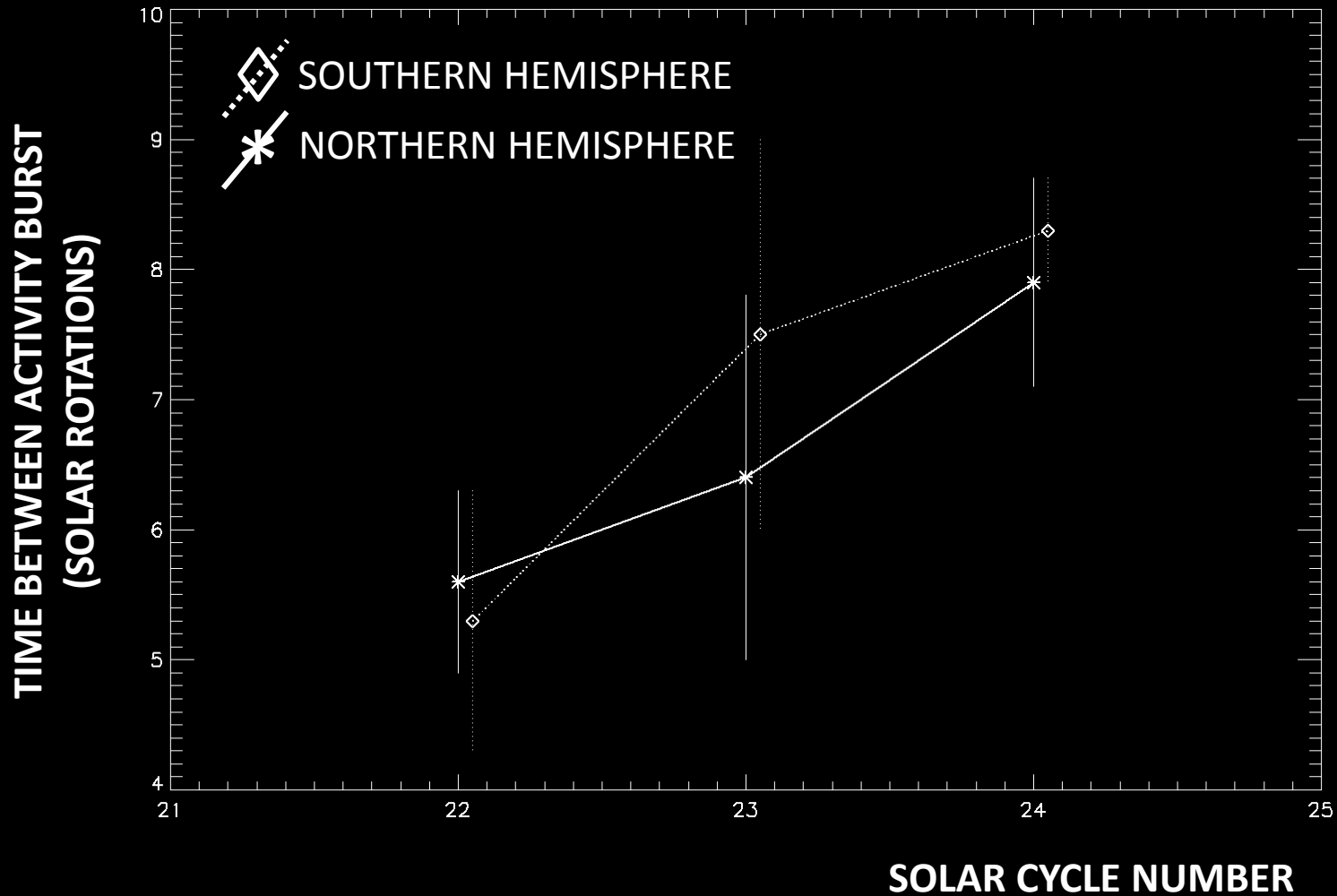


ONSET OF SC24

SOUTH; B>50; dt = 8.3 (.4) solar rotations



AVERAGE LENGTH OF BURST THROUGH ONSET PHASE OF CYCLES 22-24

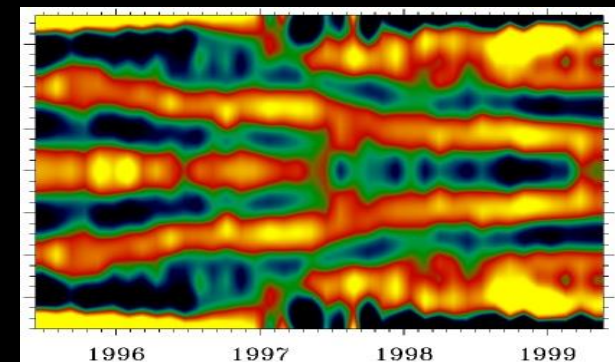
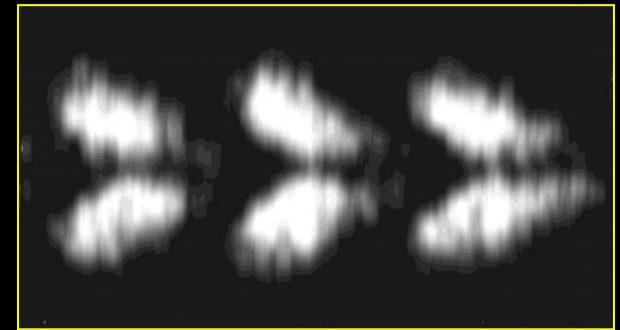
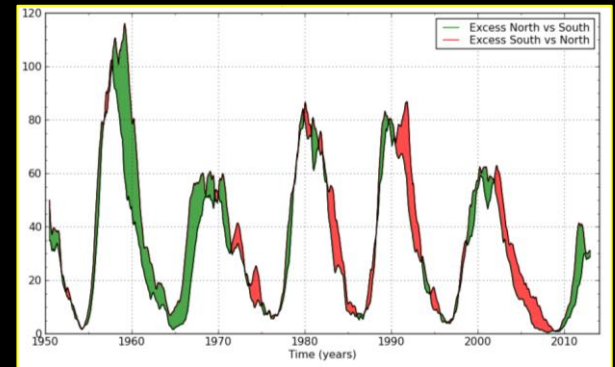


SOMETHING HAS CHANGED

- LOWEST SOLAR CYCLE IN 100 YEARS (SO FAR)
- SOLAR CYCLES GETTING LONGER?
 - SC21: 10.3 YEARS
 - SC22: 10.6 YEARS
 - SC23: 12.6 YEARS
 - SC24: ????? YEARS
- PROBLEM: HOW CAN THIS HAPPEN?

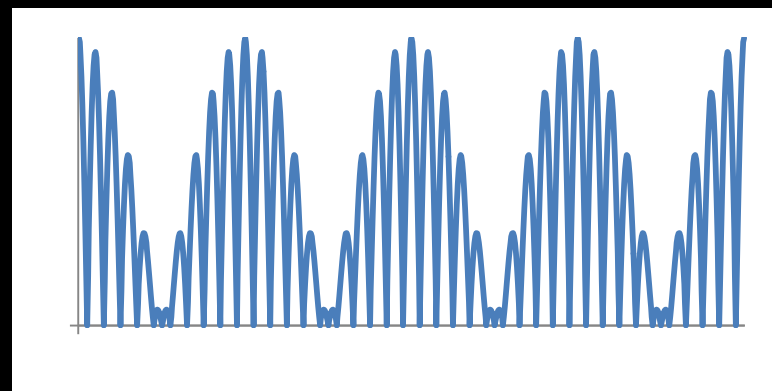
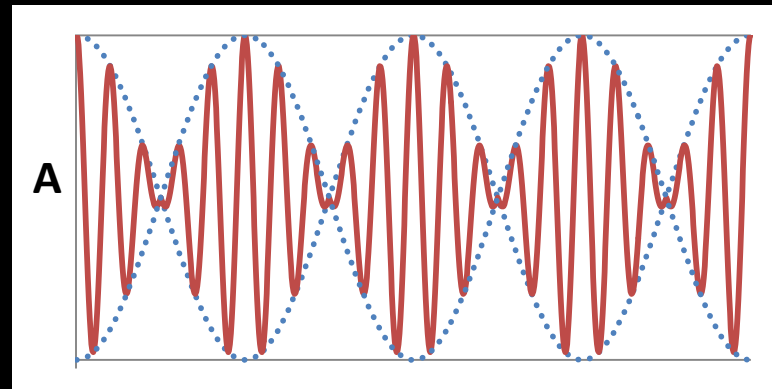
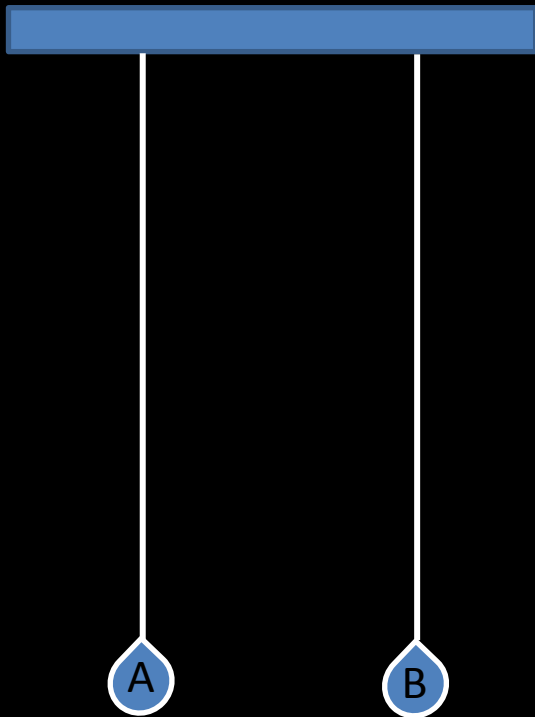
HINTS

- NORTHERN & SOUTHERN HEMISPHERES INTERACTING
- CYCLE TO CYCLE INTERACTIONS
- MULTIPLE CYCLES PRESENT SIMULTANEOUSLY

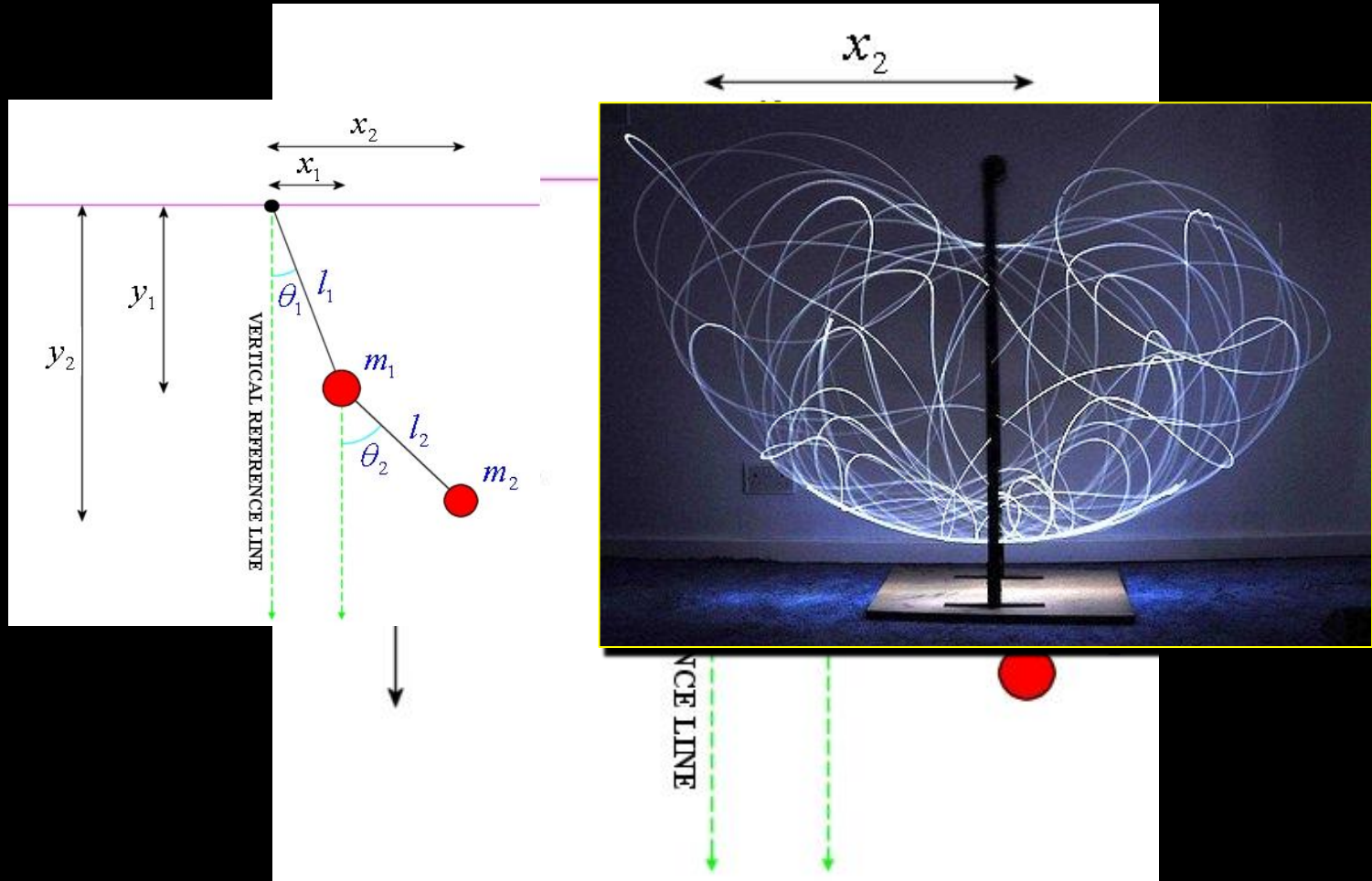


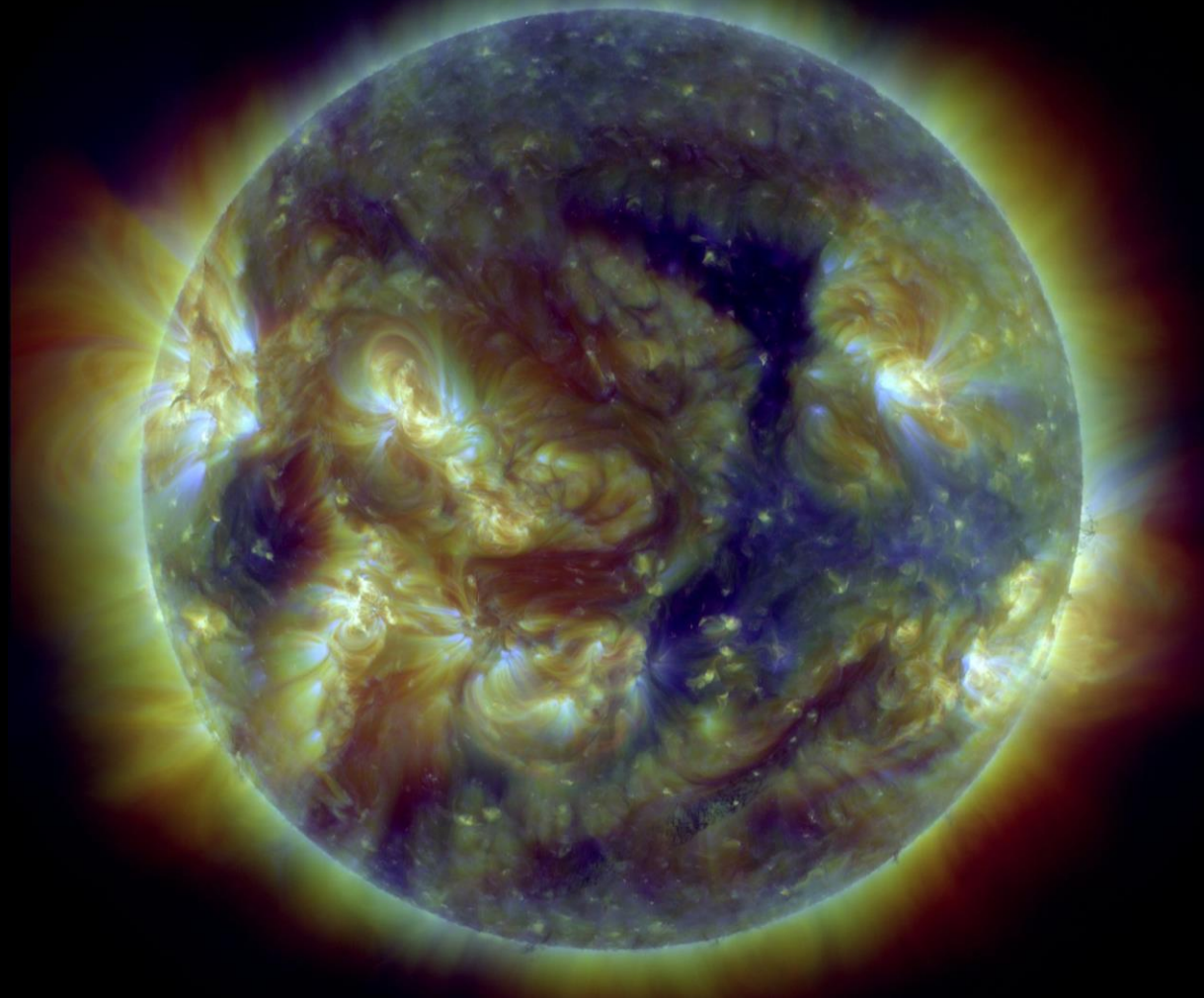
A NEW MODEL

- RESONANCE OSCILLATORS



OR A COMPOUND OSCILLATOR?





PART 4:

WHAT NEEDS TO BE DONE?

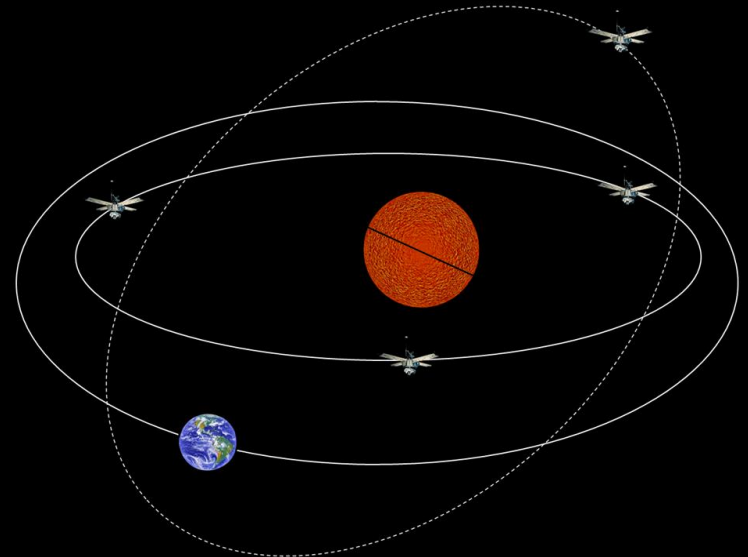
THE BASIC PROBLEM

- WE SEE LESS THAN 35% OF THE SOLAR SURFACE MAGNETIC FIELD FROM EARTH
- NEVER GET A CLEAR VIEW OF THE POLAR REGIONS

**NEED TO BUILD ON THE
SUCCESS OF STEREO**

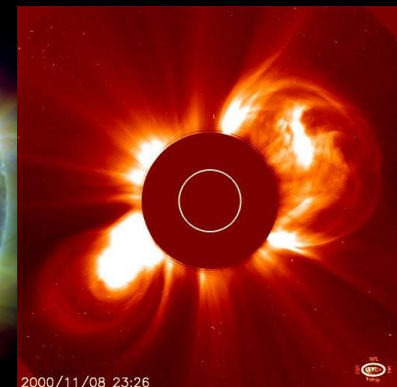
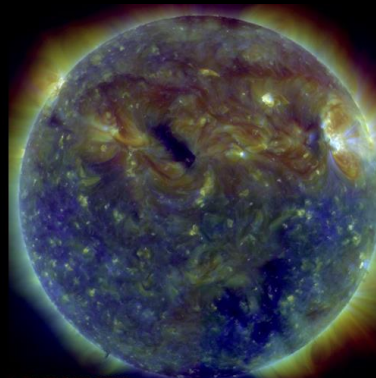
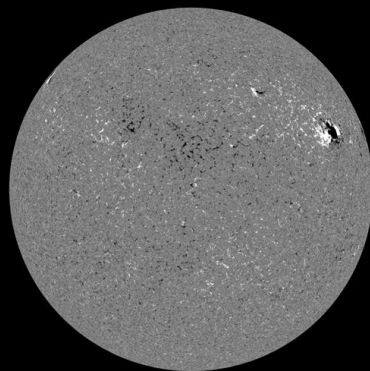
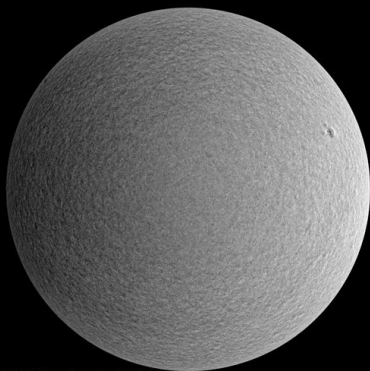
THE 4π CONCEPT

- MULTIPLE SPACECRAFT ORBITING THE SUN IN THE ECLIPTIC PLANE AND OVER THE POLES
- INSTRUMENTS
 - MAGNETOGRAPH/HELIOSEISMOMETER
 - CORONAL IMAGER
 - CORONAGRAPH
 - PARTICLES AND FIELDS MONITORS



4 π SCIENCE

- CONTINUOUS OBSERVATIONS OF THE SOLAR GLOBAL MAGNETIC FIELD AND SOLAR WIND
- MEASUREMENTS OF GLOBAL OSCILLATIONS TO PROBE DEEPER AND MORE BROADLY THE INTERNAL DYNAMIC OF THE SUN
- FOLLOW THE EVOLUTION IN 3D OF ALL SUNSPOT REGIONS, FLARES AND CMES
- DETERMINE THE ROLE OF LARGESCALE CORONAL FIELDS IN THE EVOLUTION OF THE SOLAR CYCLE



CONCLUSIONS

- **CURRENT SOLAR CYCLE MODELS ARE INADEQUATE FOR PREDICTION OF THE SOLAR CYCLE**
- **SC24 WILL LIKELY BE THE LOWEST CYCLE IN 100 YEARS**
 - LENGTHENING OF THE CYCLE
 - LOW % OF LARGE (M & X) FLARES
 - EXTENDED SOLAR MINIMUM
- **SOMETHING HAS SLOWED?**
- **SUGGESTED IMPROVEMENTS TO THE MODELS**
 - USE THE MAGNETIC FIELD, NOT THE SMOOTHED SUNSPOT NUMBER
 - NEED BETTER TIME FIDUCIAL
 - INCLUDE ASYMMETRY IN N-S HEMISPHERES
 - CYCLE NOT SMOOTH BUT A SERIES OF BURST OF MAGNETIC ACTIVITY
- **A WAY FORWARD: THE 4π CONCEPT**

THANKS



YOUTUBE: drkstrong

WHY IS FORECASTING THE SOLAR CYCLE IMPORTANT?

- OUR EXISTENCE DEPENDS ON THE SUN'S VARIABILITY BEING BENIGN
- A TEST OF HOW WELL WE UNDERSTAND STARS
- SOCIETAL IMPACTS
- SOLAR SYSTEM EXPLORATION

