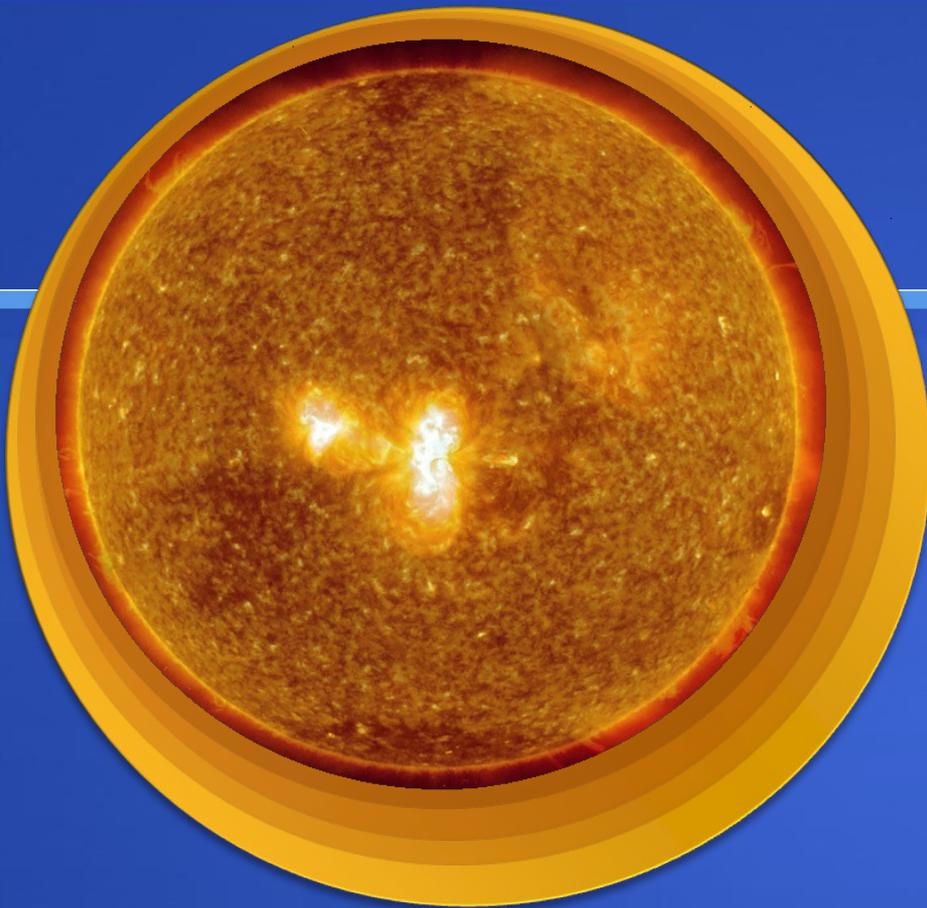


# How Low is Low?

Latest News on this  
Current Solar Cycle Minimum



**Tom Woods**

**LASP / University of  
Colorado**

**[tom.woods@lasp.colorado.edu](mailto:tom.woods@lasp.colorado.edu)**

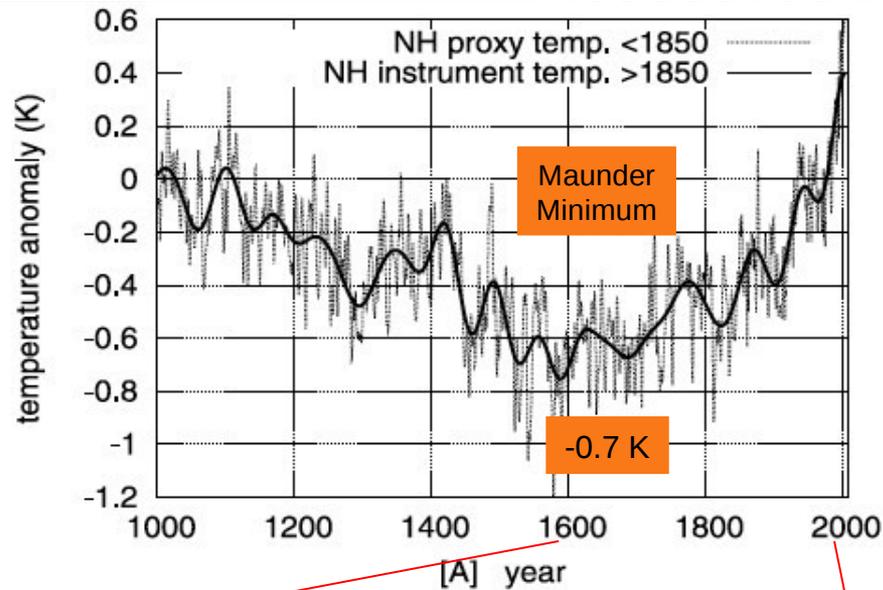
Many Contributions: Philip Barabga, Sid Das, Debra Cole, Paul  
Didkovsky, Frank Eparvier, Juan Fontenla, Claus Fröhlich, Sarah Gibson,  
Jerry Harder, David Hathaway, Rachel Hock, Andrew Jones, Judith Lean,  
Bill McClintock, Mark Rast, Erik Richard, Leif Svalgaard, Neil Sheeley,  
Marty Snow, Dave Webb



**Why do we care what the solar cycle minimum level is?**

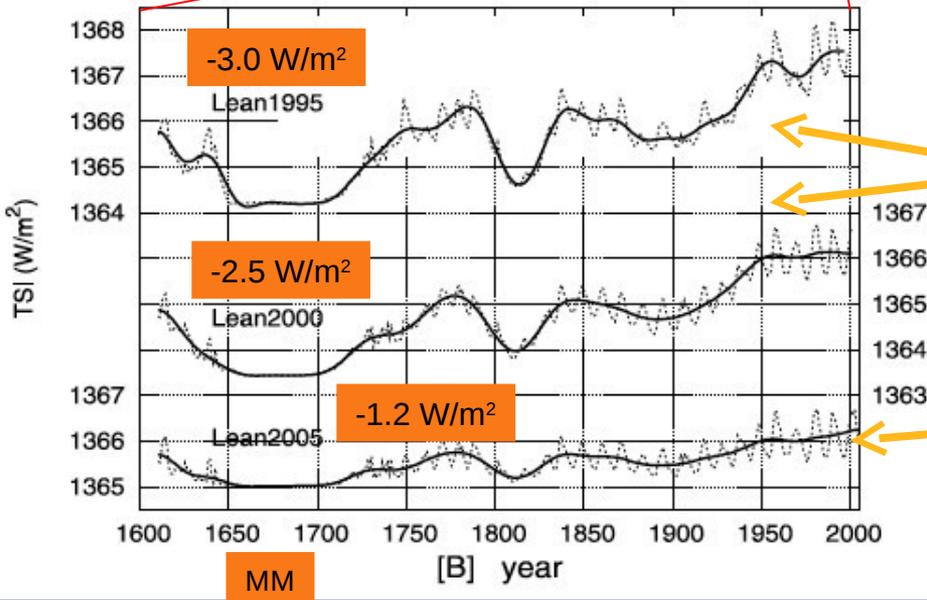


# Solar Forcing on Long-term Climate Change



Global temperature change at Maunder Minimum is about -0.4 K. Shown is Northern Hemisphere.

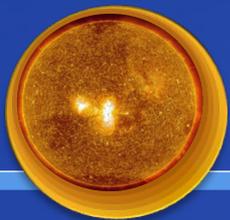
Secular (long-term) changes of solar irradiance can be estimated by trending results at the cycle minima.



1970-2000 estimates for MM total solar irradiance (TSI) are mostly based on sun-like stars and are considered too high now.

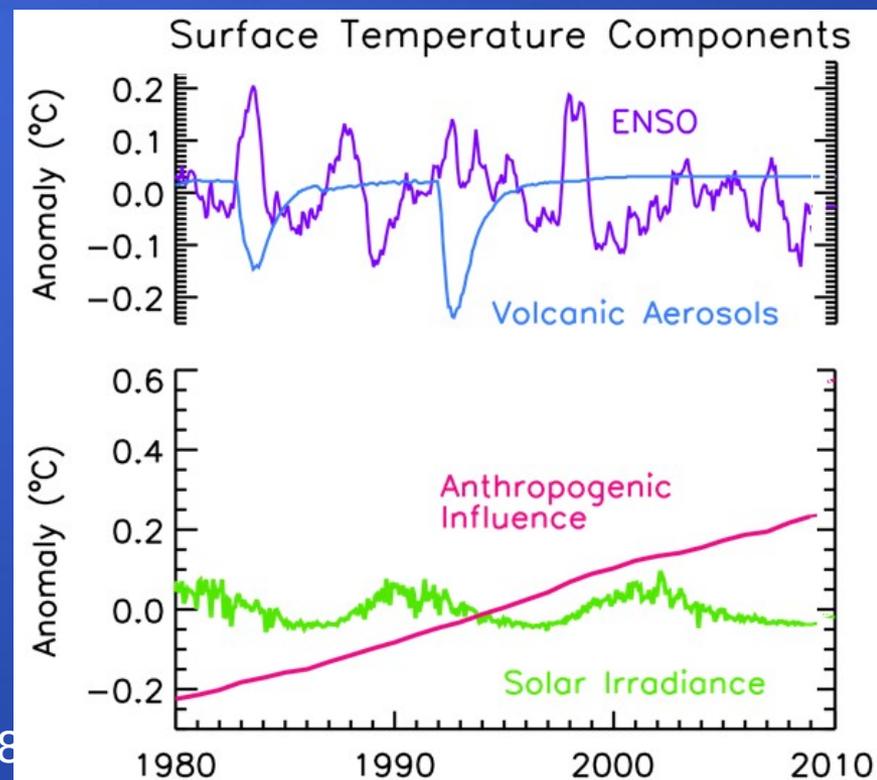
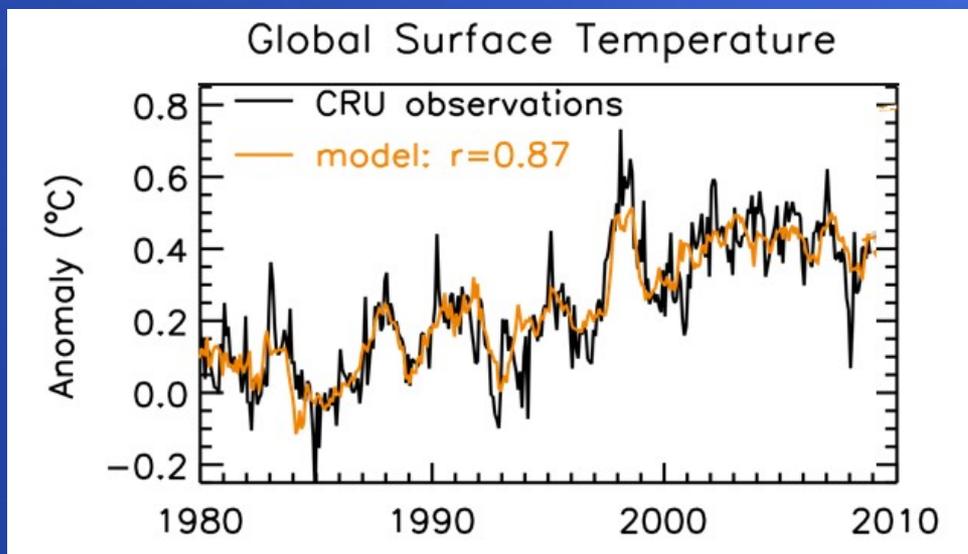
Recent MM TSI estimates are based on magnetic field changes and are about 1-2  $W/m^2$  (0.15-0.3 K).

[figures from Scafetta and West, *GRL*, 2006]

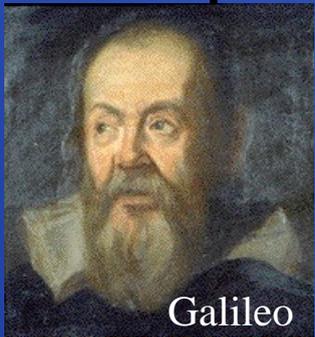
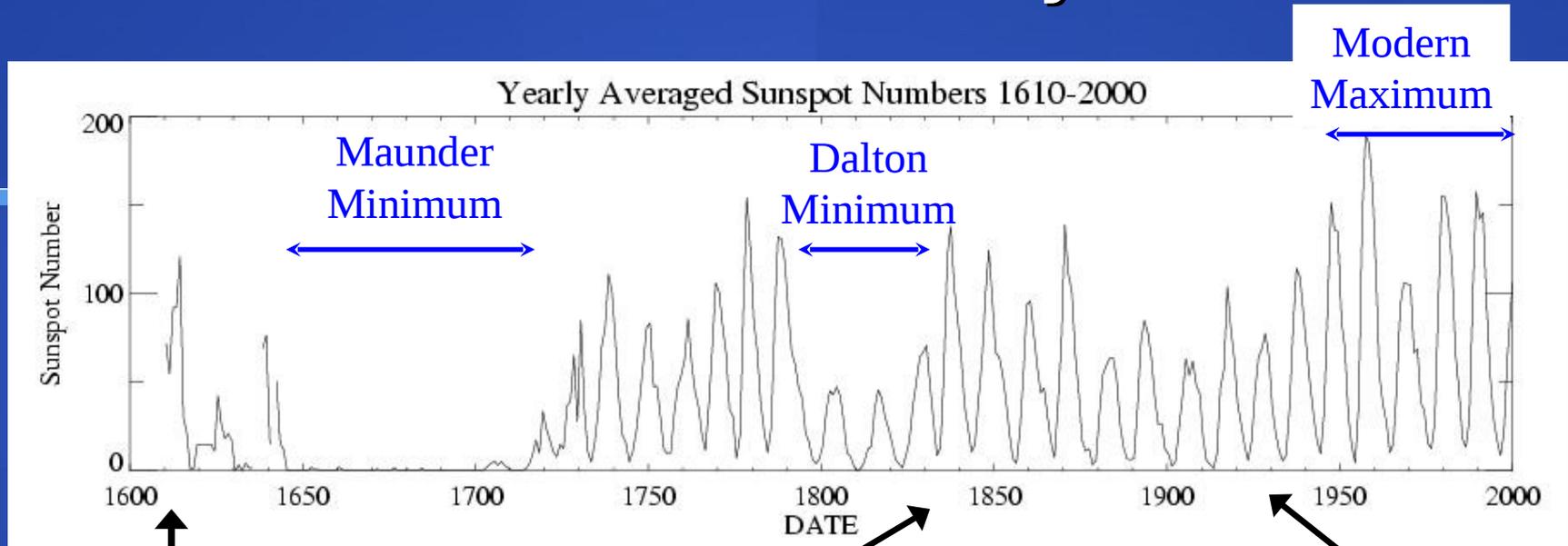


# Recent “Cooling” Trend

- The total solar irradiance (TSI) is known to vary about 0.07% over the 11-year solar cycle
- Part of 2002-2009 trend can be explained by solar variations
  - Expect Earth’s global temperature to change by 0.1 K over solar cycle
  - This includes positive feedbacks with factor of ~2
    - Empirical analysis, e.g. Lean & Rind, *GRL*, 2008
    - GCM models, e.g. NCAR and GISS, Shindell *et al.*, *J. Climate*, 2003



# What is a solar cycle?



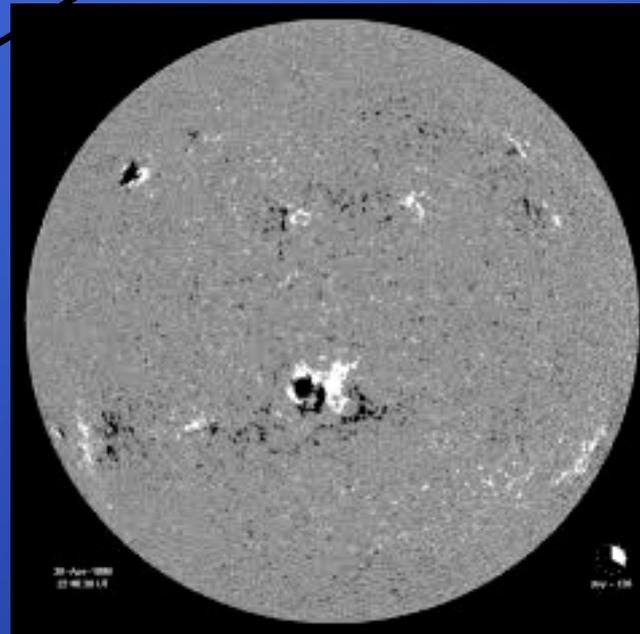
Galileo

Telescope Observations

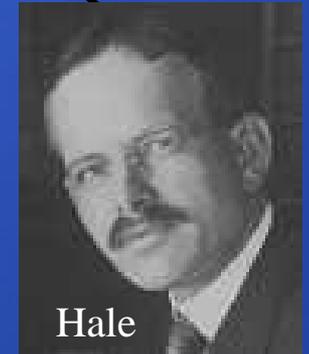


Schwab

11-year Intensity Cycle



movie from SOHO web site

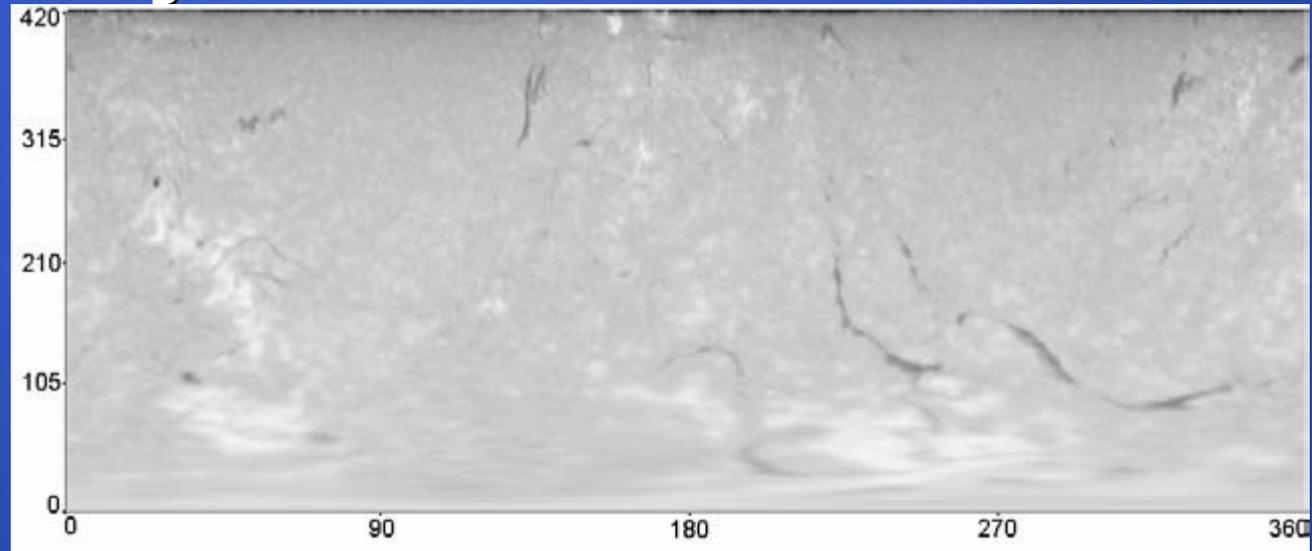
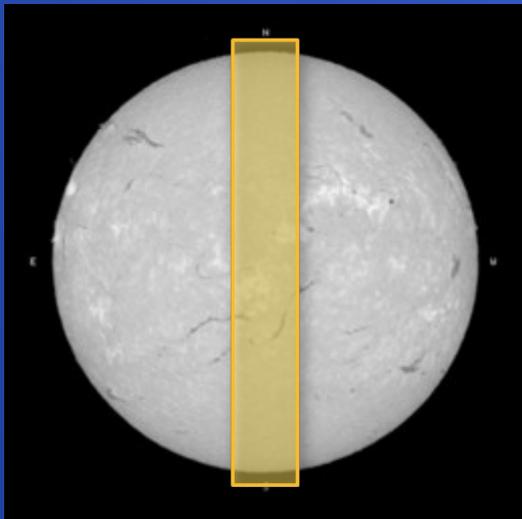


Hale

22-year Magnetic Cycle

# Full-Disk Image versus Synoptic Image

- Full-disk Image – the way the Sun looks from Earth
- Synoptic Image – unwrapping the Sun including the back side
  - Made by taking stripe from the full-disk image each day
  - Time goes from right to left



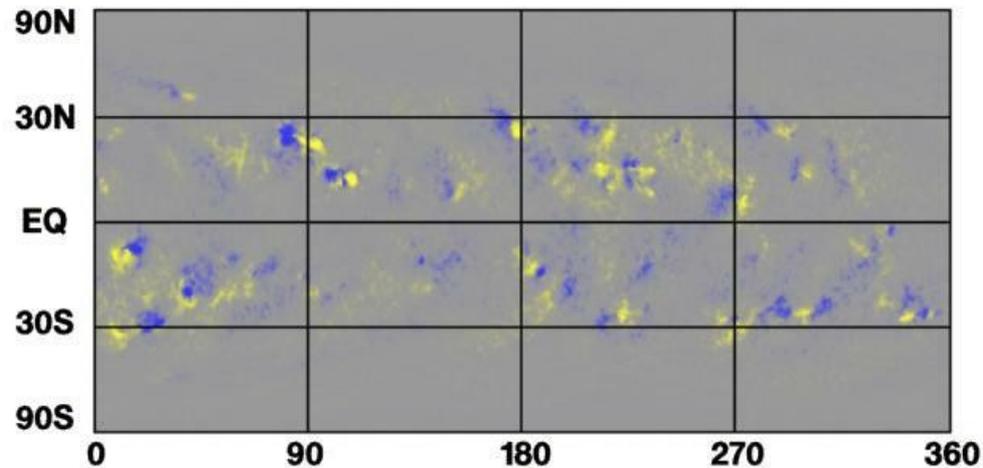
Example from V.V. Zharkova

time

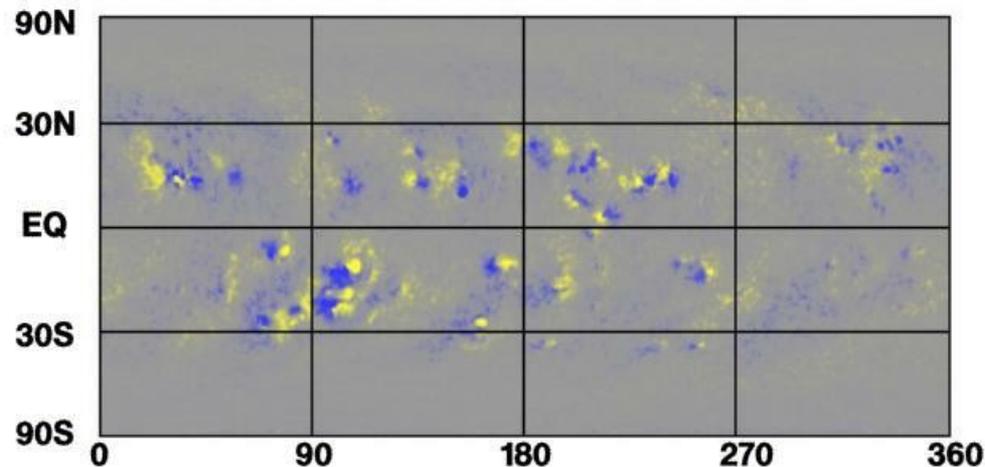
# Hale's Polarity Law:

The polarity of the leading spots in one hemisphere is opposite that of the leading spots in the other hemisphere and the polarities reverse from one cycle to the next.

**Cycle 21**



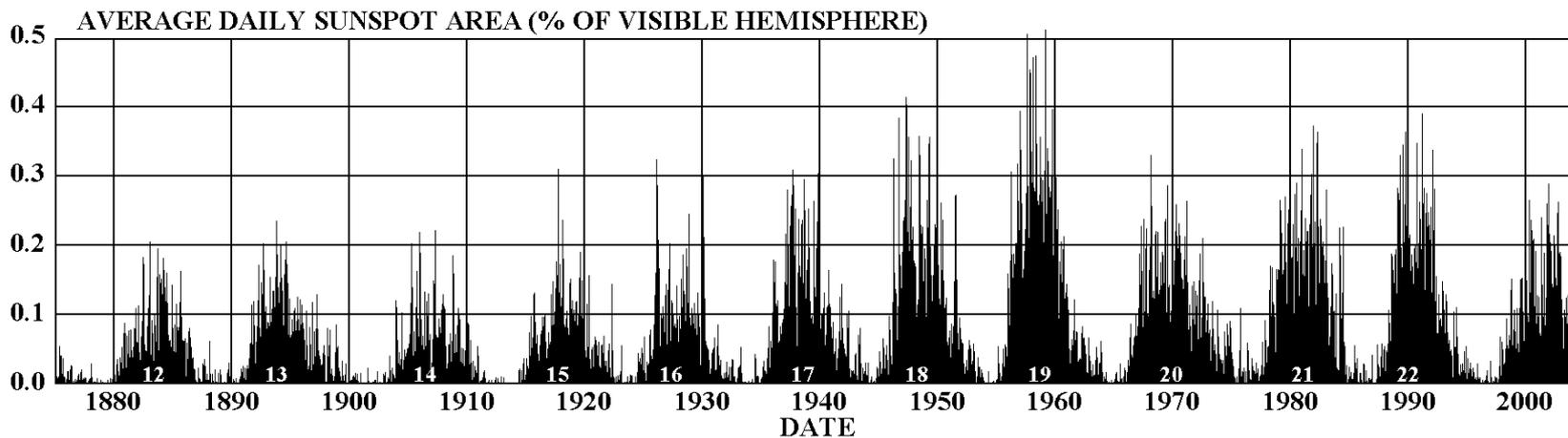
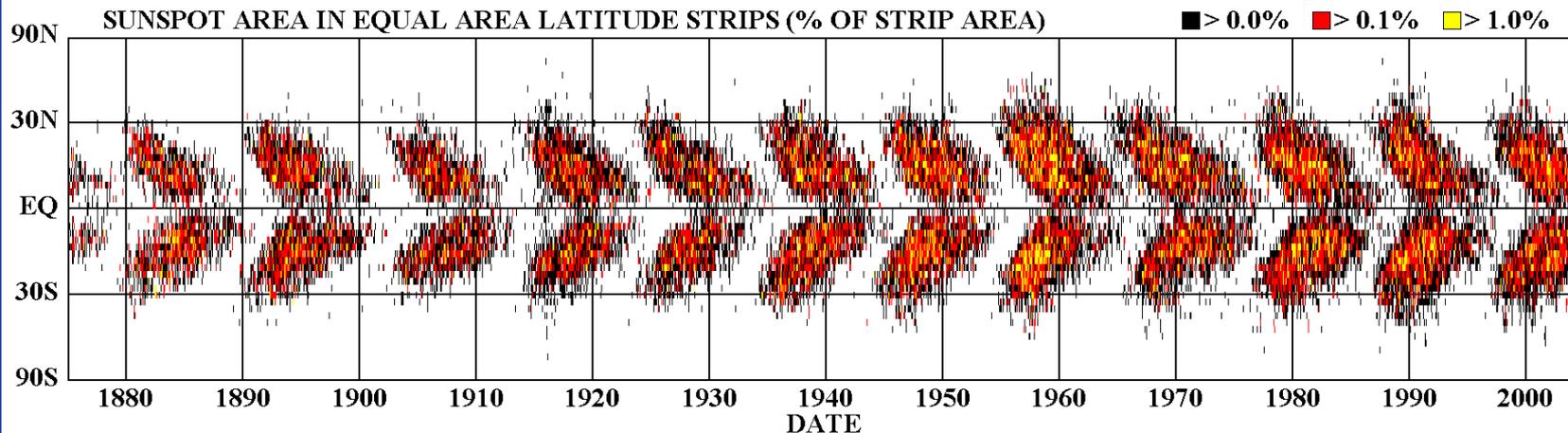
**Cycle 22**



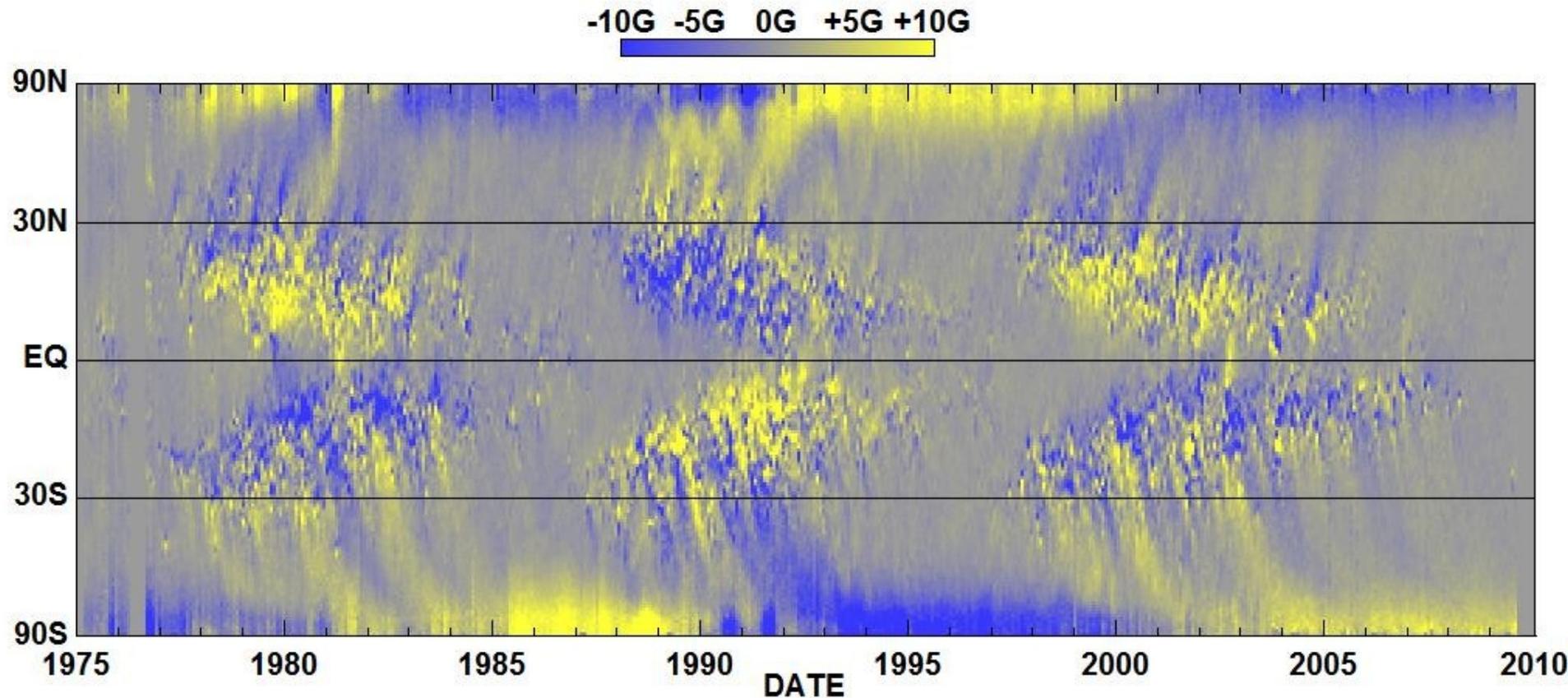
# Butterfly Diagram: Compress Synoptic Images

## 11-year Sunspot (Intensity) Cycle

### DAILY SUNSPOT AREA AVERAGED OVER INDIVIDUAL SOLAR ROTATIONS



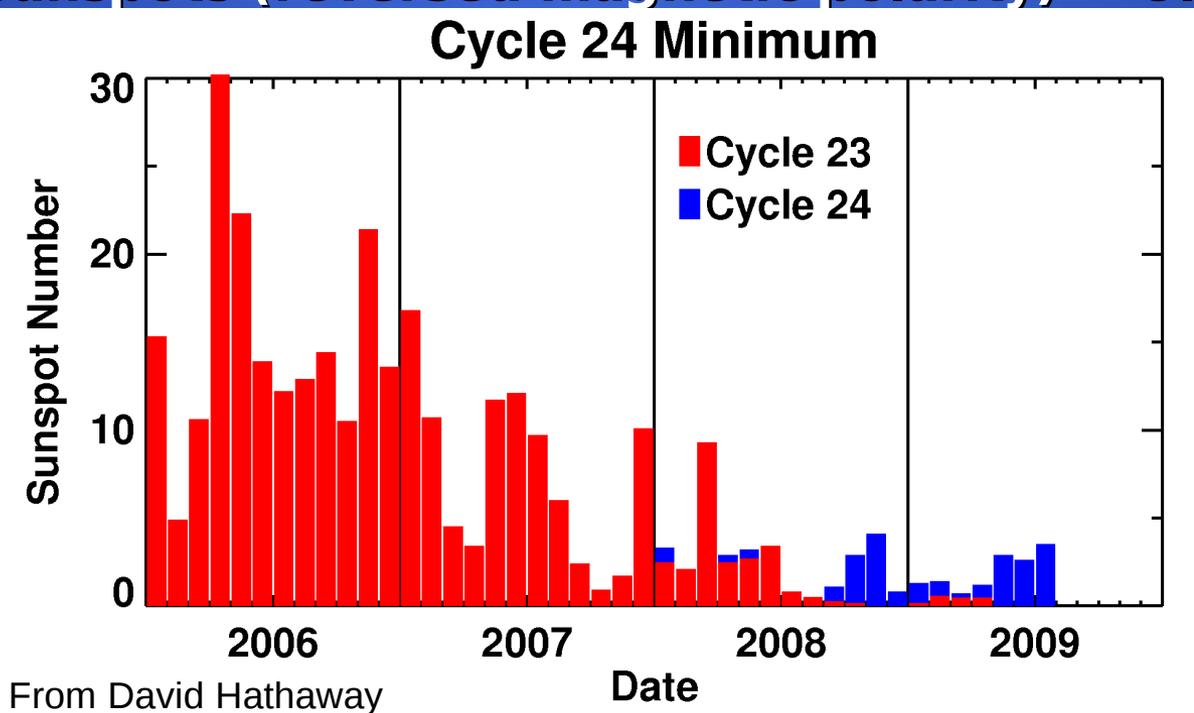
# Butterfly Diagram for 22-year Magnetic Cycle



Hathaway/NASA/MSFC 2009/09

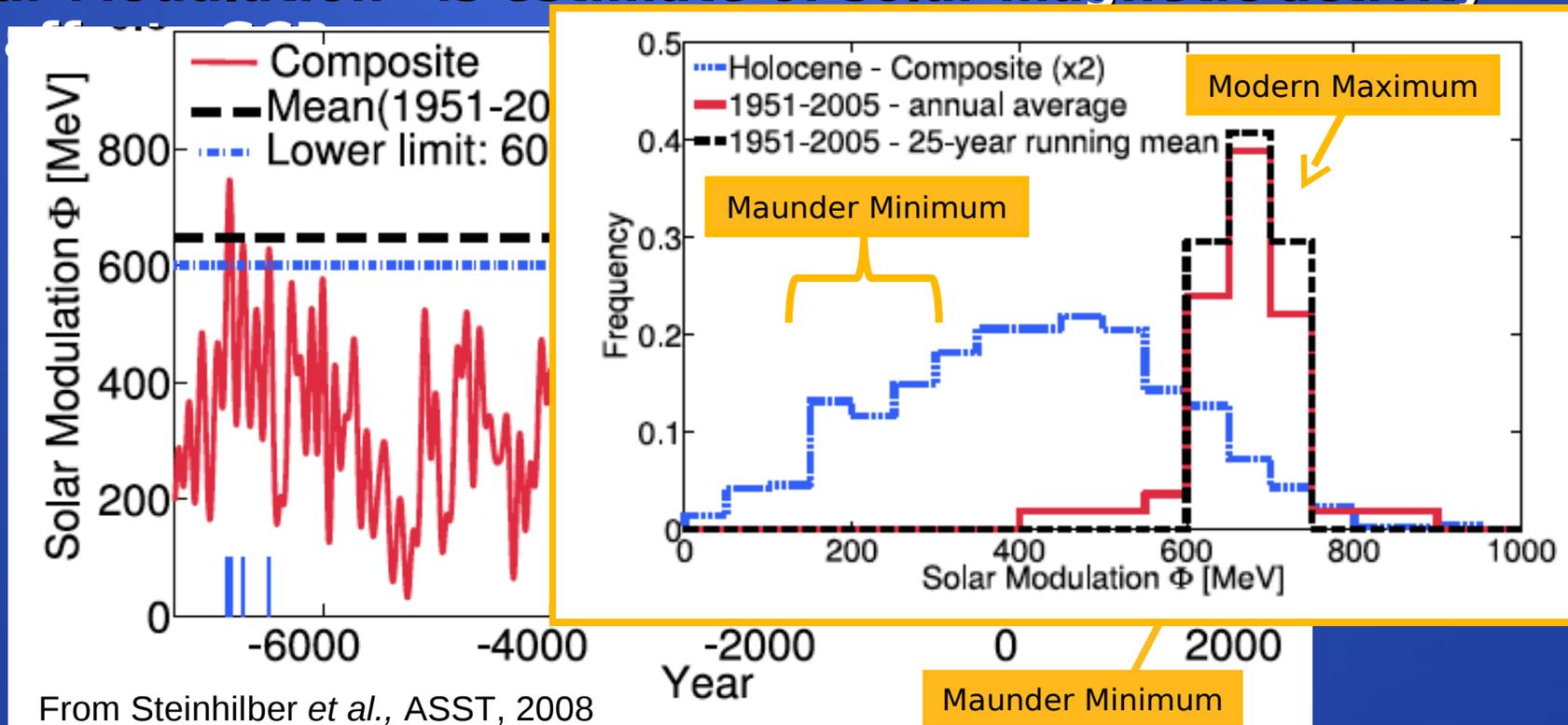
# What is Solar Minimum?

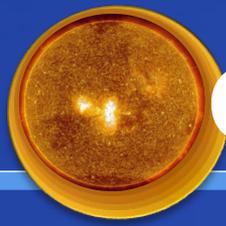
- Minimum of what?
- What time period / smoothing for minimum?
- Smoothed sunspot number minimum = Nov/Dec 2008
- Smoothed spotless days maximum = Nov/Dec 2008
- Irradiance minimum = Aug 2008
- New cycle sunspots (reversed magnetic polarity) > Old cycle sunspots =



# What does secular (long-term) trend indicate for extreme minimum?

- Tree-rings  $^{14}\text{C}$  and ice-cores  $^{10}\text{Be}$  provide indication of solar magnetic fields affecting galactic cosmic rays (GCRs)
  - NOTE: There are more GCRs at Earth during solar minimum
- “Solar Modulation” is estimate of solar magnetic activity that



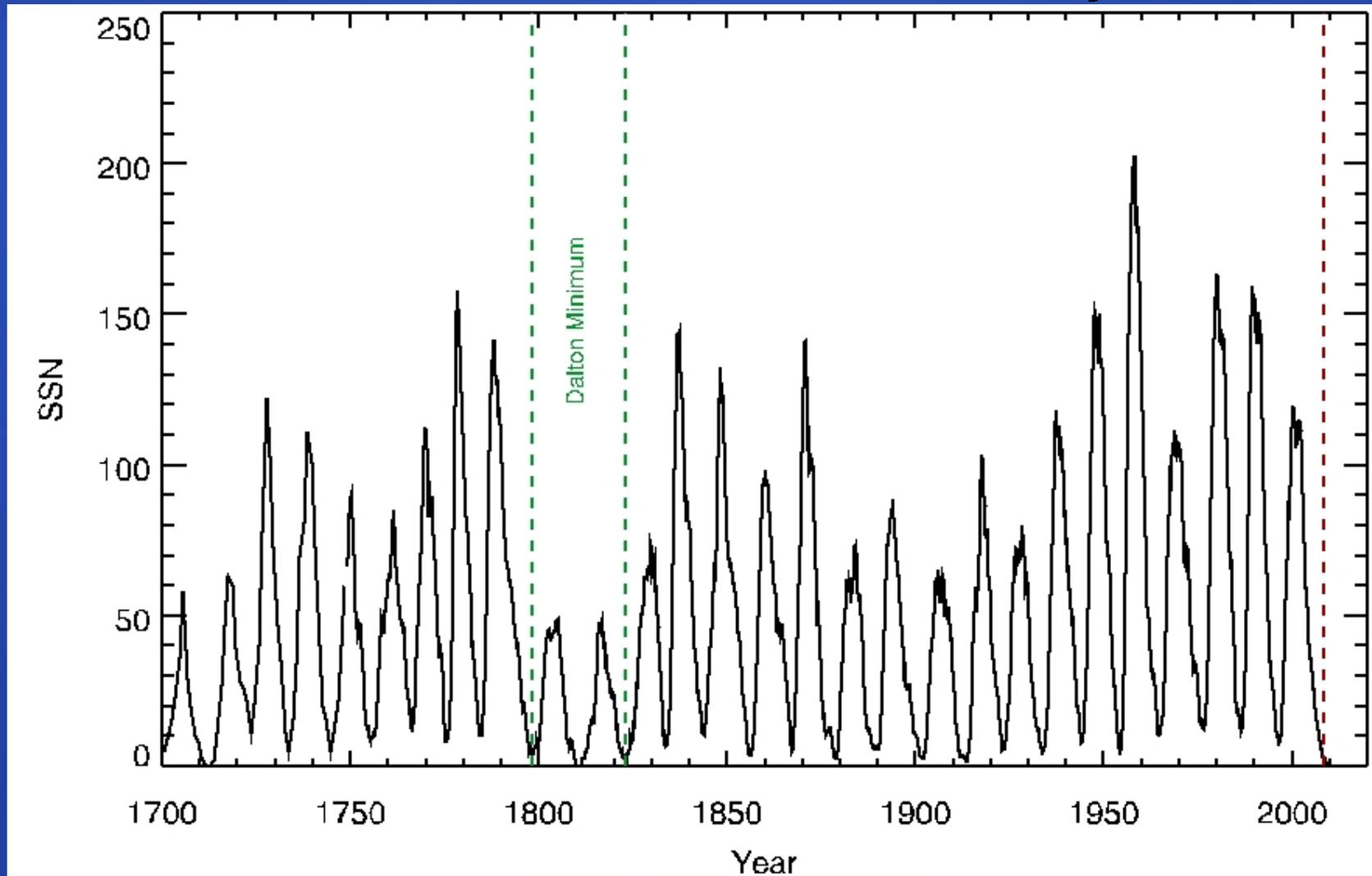


# Cycle Minimum Highlights

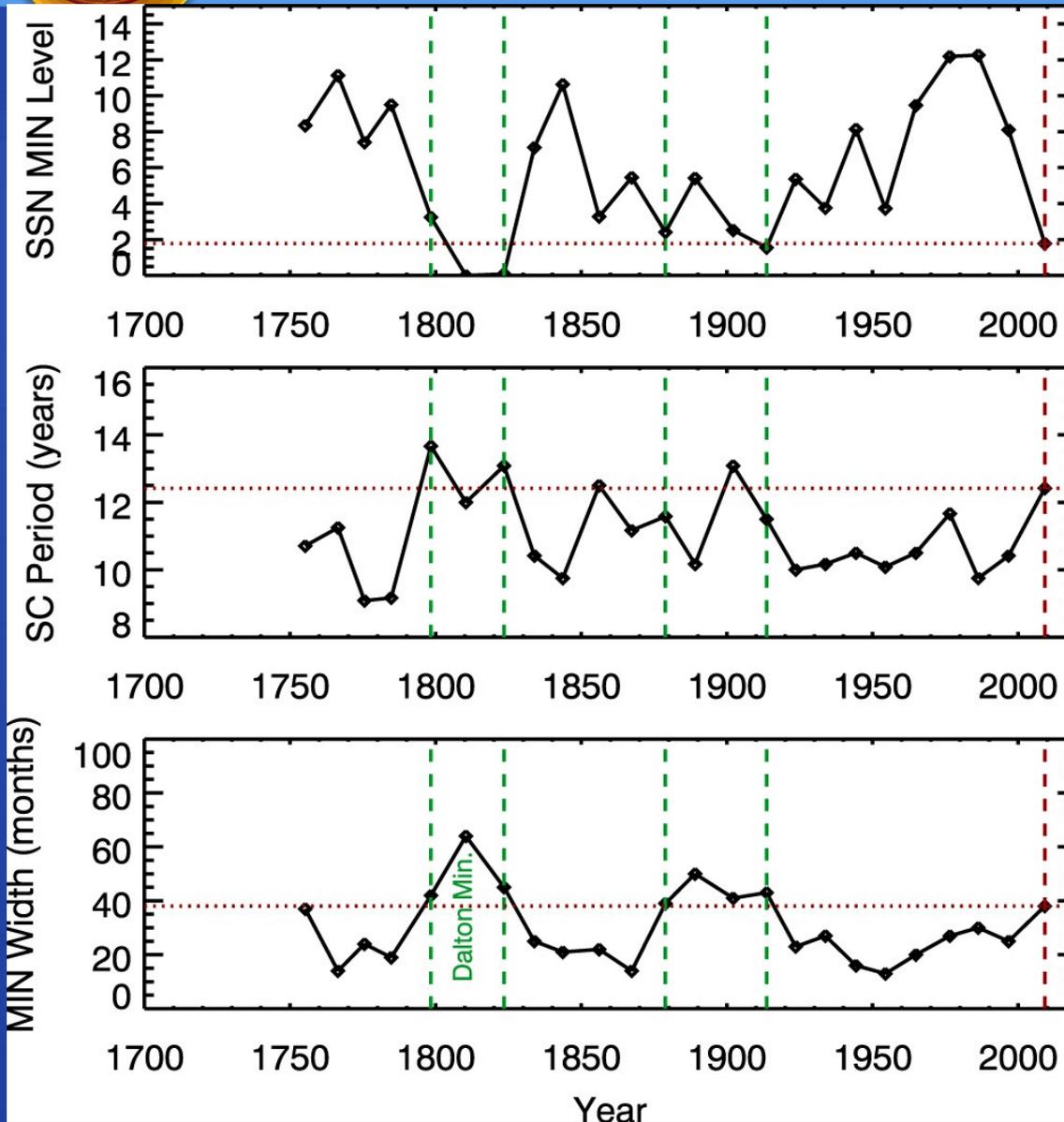
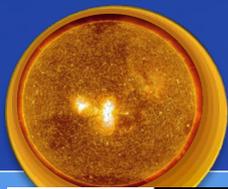
- PECULIAR as compared to recent cycles, but NORMAL as compared to ~1900 & Dalton Minimum
- Weaker polar field and smaller polar cap area
- More low-latitude coronal holes
- Faster meridional (poleward) flow

# What does the **sunspot** record tell us?

- Sunspot Number (SSN) provides the longest, direct measurement of solar activity since the

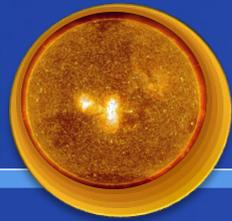


# What does the sunspot record tell us?



- **SSN Minimum Level**
  - **Lowest since 1920s**
  - **(3 of 24 are lower)**
- **SC Period Length**
  - **Longest since 1900**
  - **(4 of 24 are longer)**
- **Minimum Duration**
  - **Widest since 1920s**
  - **(7 of 24 are wider)**
- **NOTE: This MIN is not completed yet, so expect width to go up !**

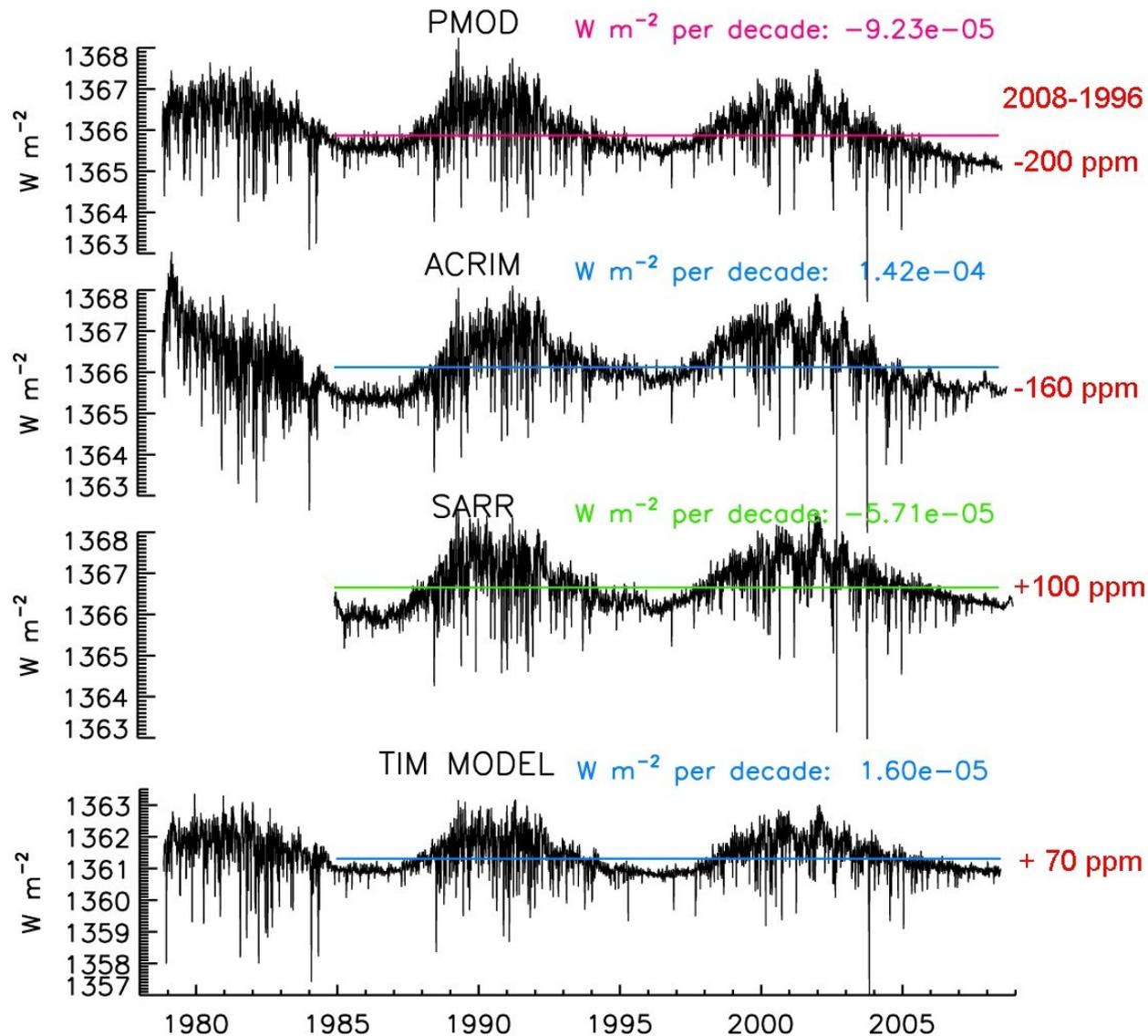
# 4 TSI Composites: Conflicting Results



- SOHO VIRGO PMOD (Fröhlich) and ACRIM (Willson) composites indicate 2008 TSI is lower than 1996 level

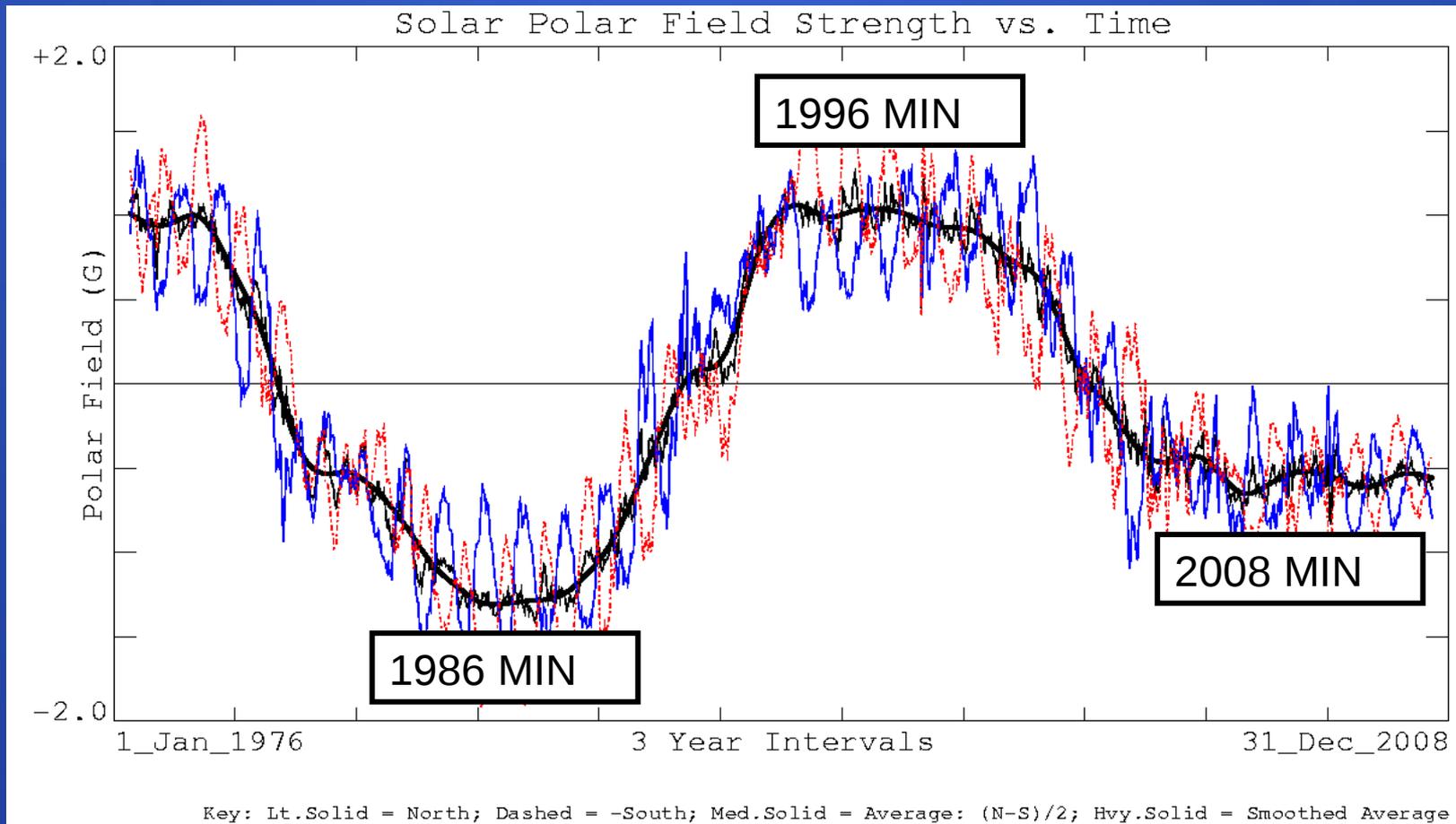
- SOHO VIRGO DIARAD (DeWitte) and SORCE TIM / Model (Lean) composites indicate 2008 TSI is higher

- Uncertainty for 2008-1996 trend is about 100 ppm

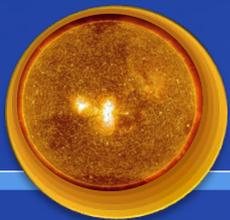


# Weaker Polar Magnetic Field

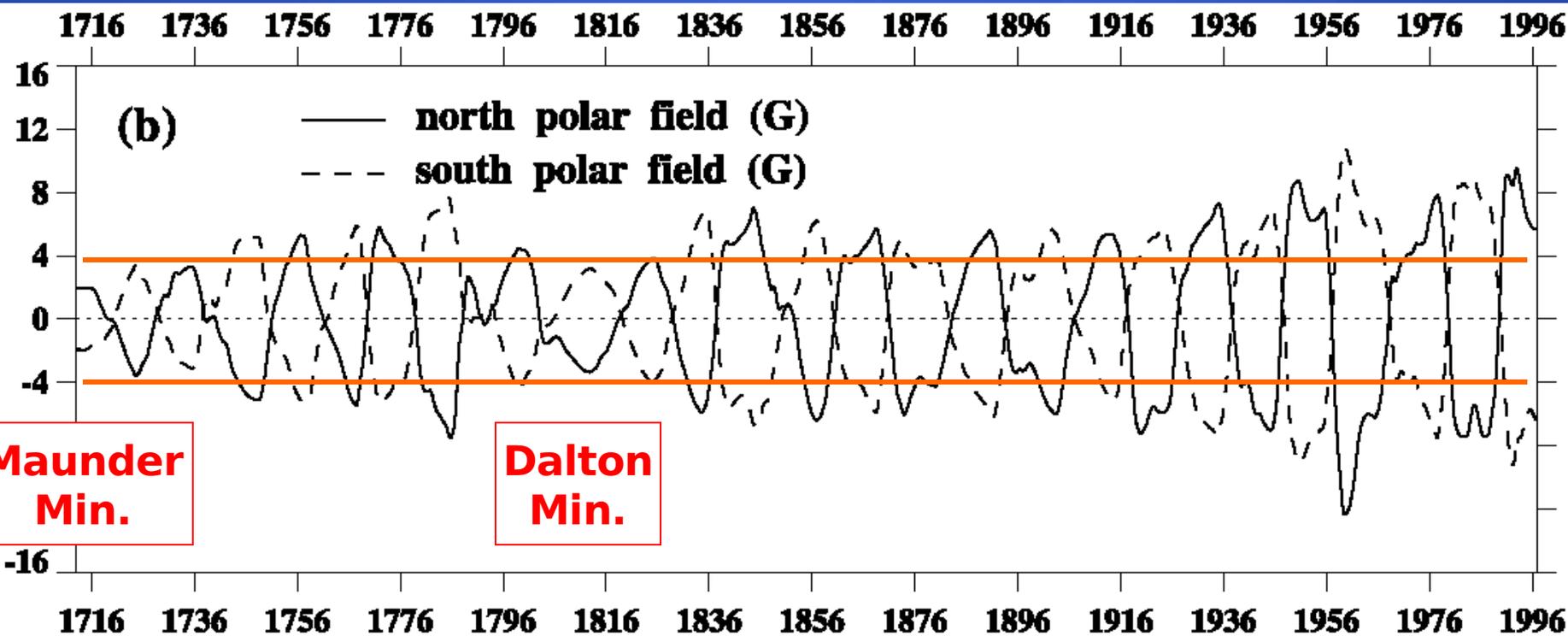
- Solar polar magnetic field (PMF) during this minimum is 40% lower than the last few solar cycles



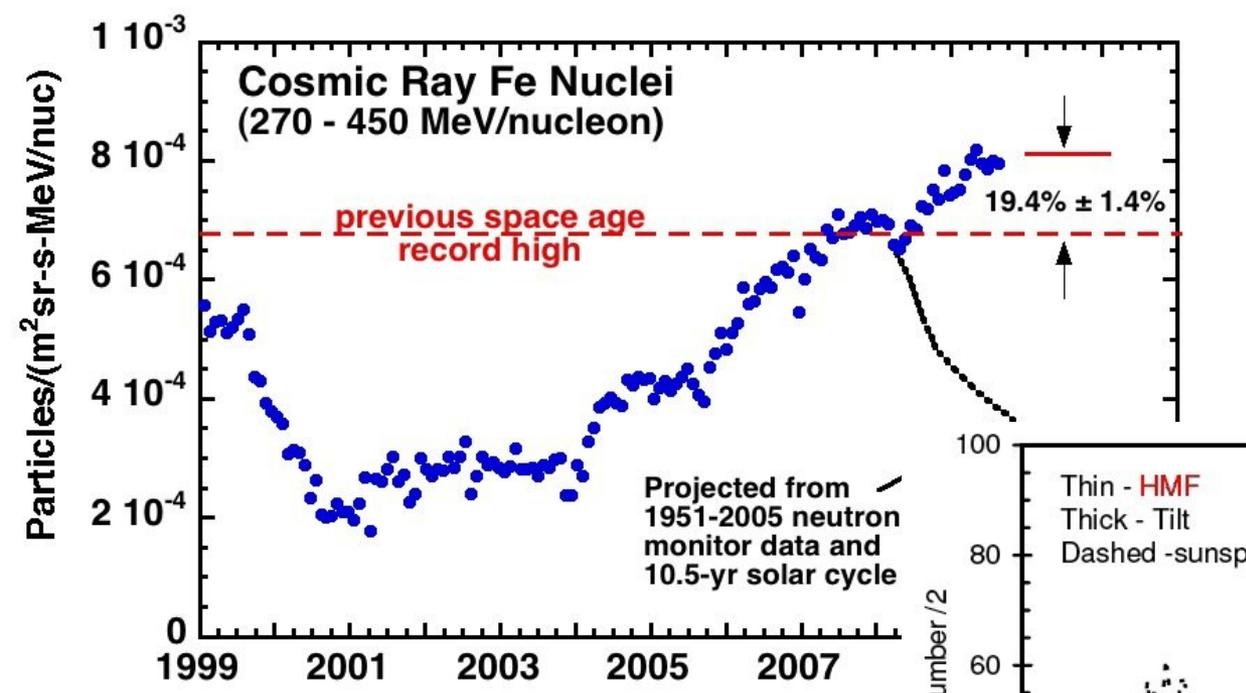
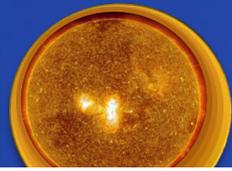
# Reconstructed Polar Magnetic Field



- Current Minimum level is similar to that before 1920
- Maunder Minimum and Dalton Minimum levels are lower
  - Polar magnetic field is reconstructed by Wang, Lean, and Sheeley [*Ap. J.*, 2005]
- Polar magnetic field is used in some predictions of the next solar cycle maximum, so those predictions are expecting next maximum to be small

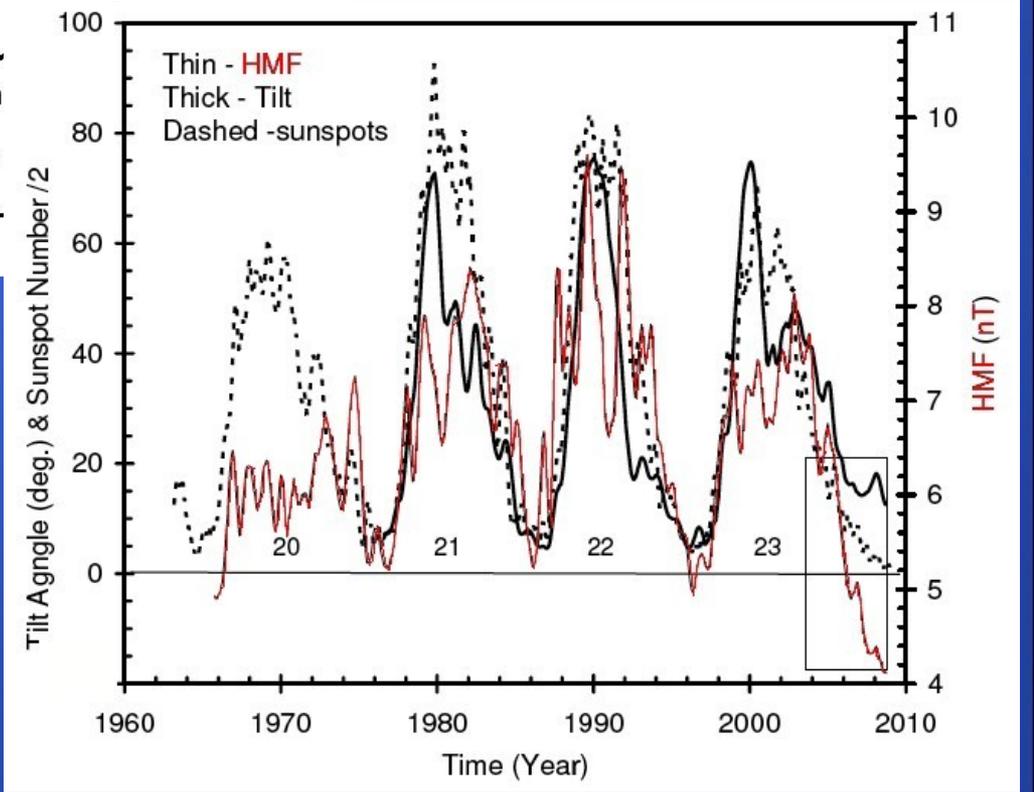


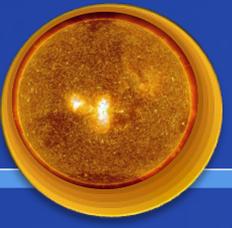
# Record Low Heliospheric Magnetic Field (HMF) → Record High Cosmic Rays



- Dick Mewaldt: highest level of cosmic rays in the 54 year record

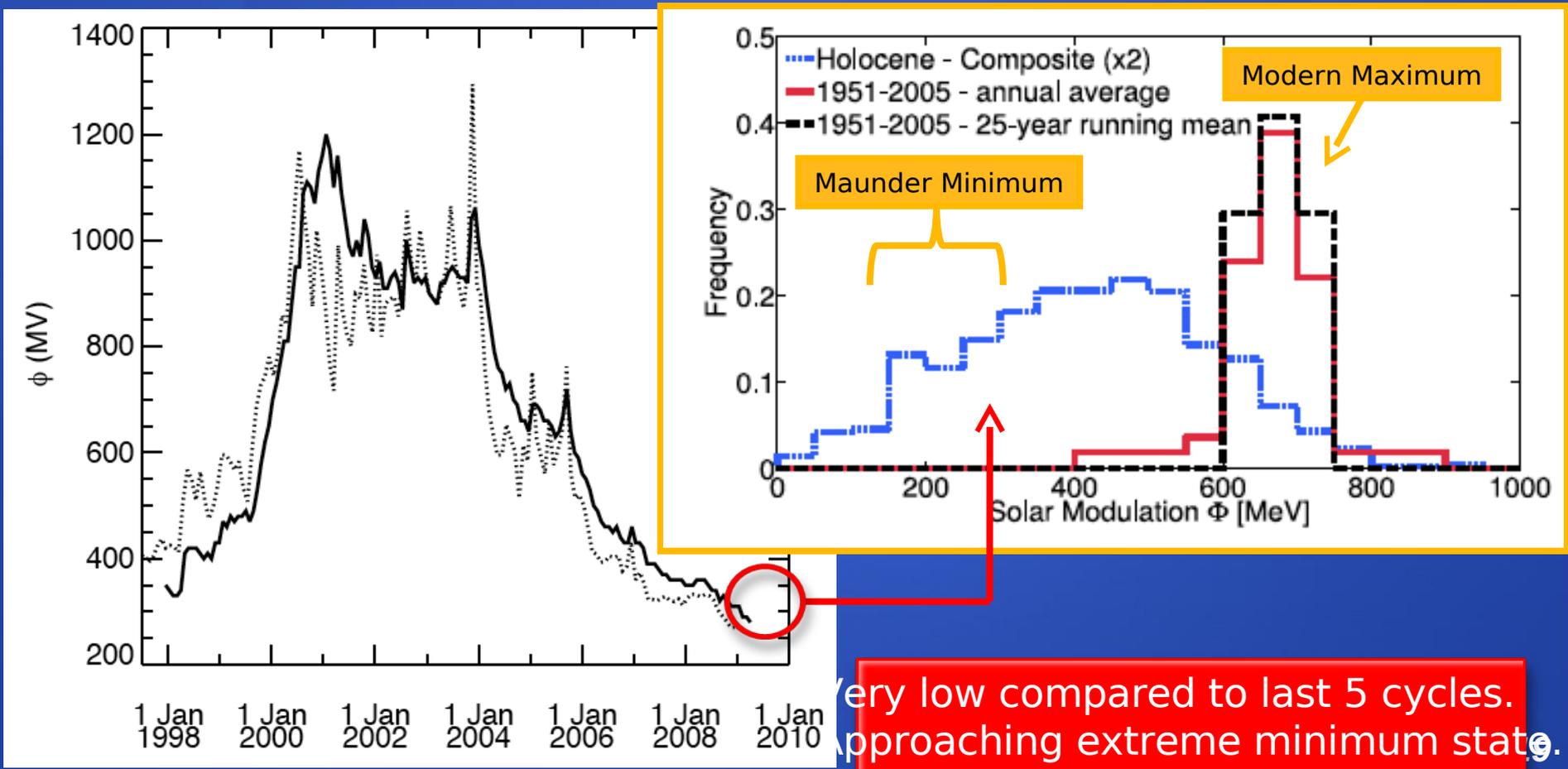
- Moraal *et al.* (2009) report that record high Galactic Cosmic Rays is consistent with standard modulation theory for GCRs
- That is, high GCRs are consistent with low HMF





# High GCRs → Low Solar Modulation

- Solar Modulation is  $< 300$  MeV and still declining
- Figure from Wiedenbeck *et al.* (2009): dashed line is neutron monitor GCRs

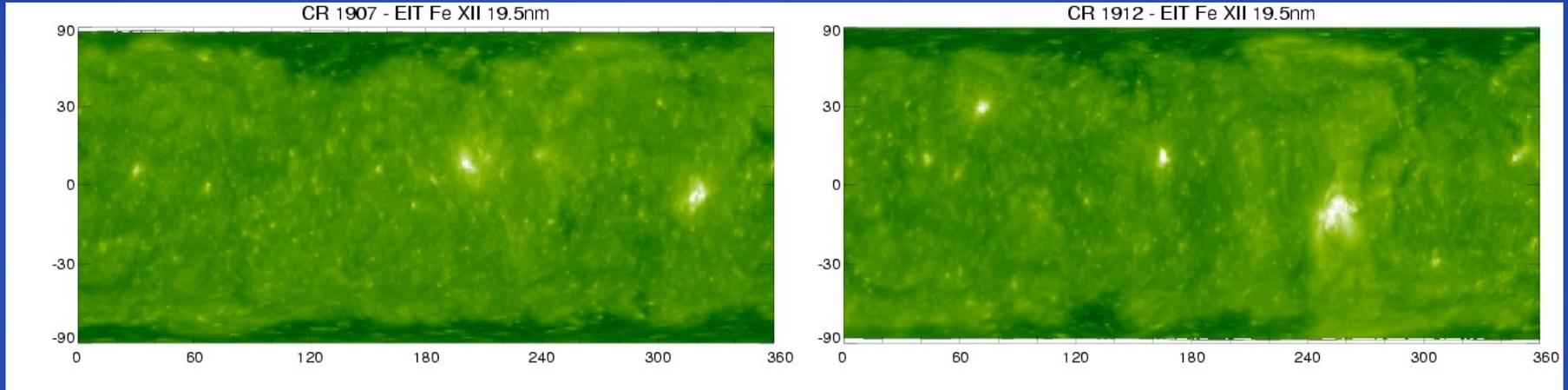


Very low compared to last 5 cycles. Approaching extreme minimum state.

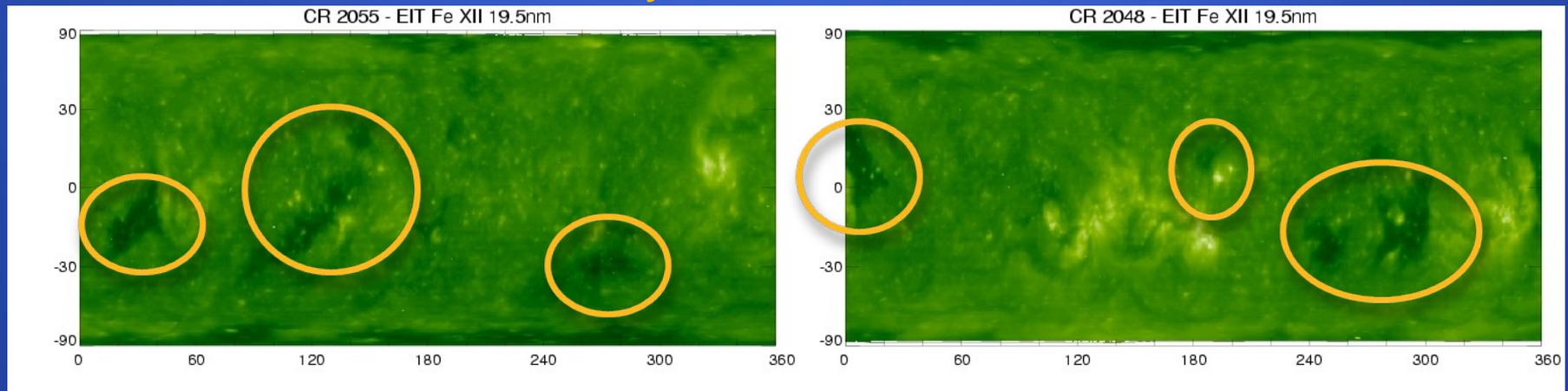
# Comparison of Coronal Holes

from Giuliana de Toma – SOHO EIT Images

Cycle 22 minimum

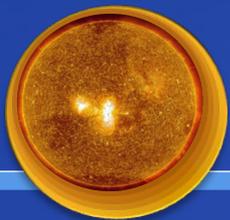


Cycle 23 minimum



● polar coronal holes are smaller (by ~40-50%) than in 1996

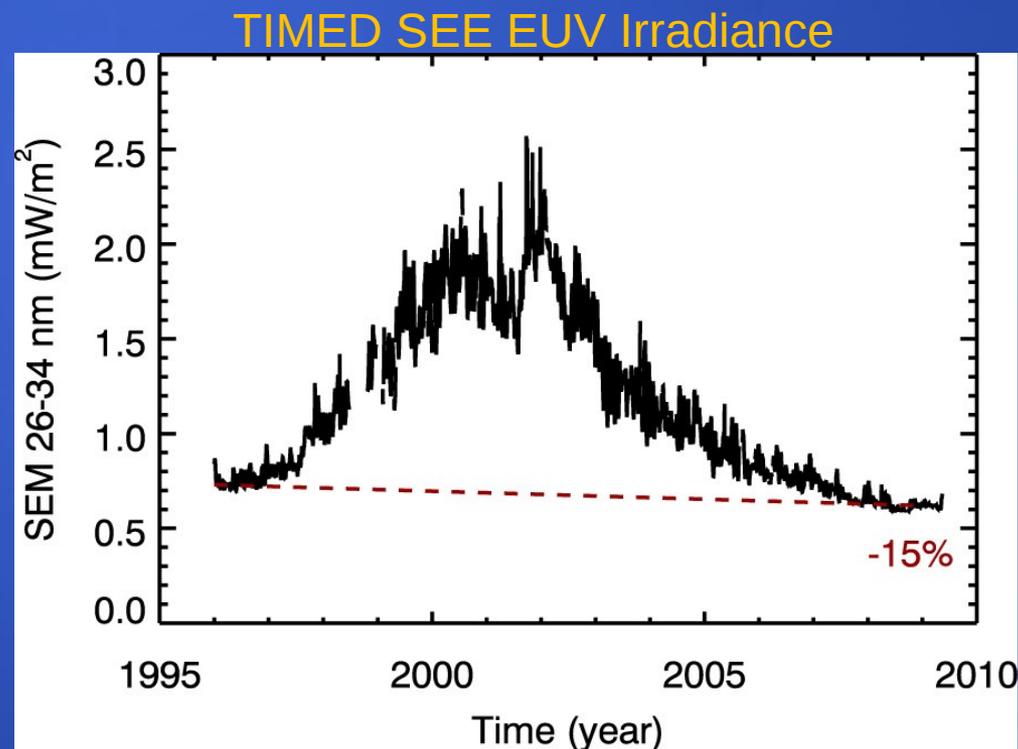
● large, mid- and low-latitude coronal holes persisted for most of the minimum phase



# Coronal Holes Affect EUV Radiation

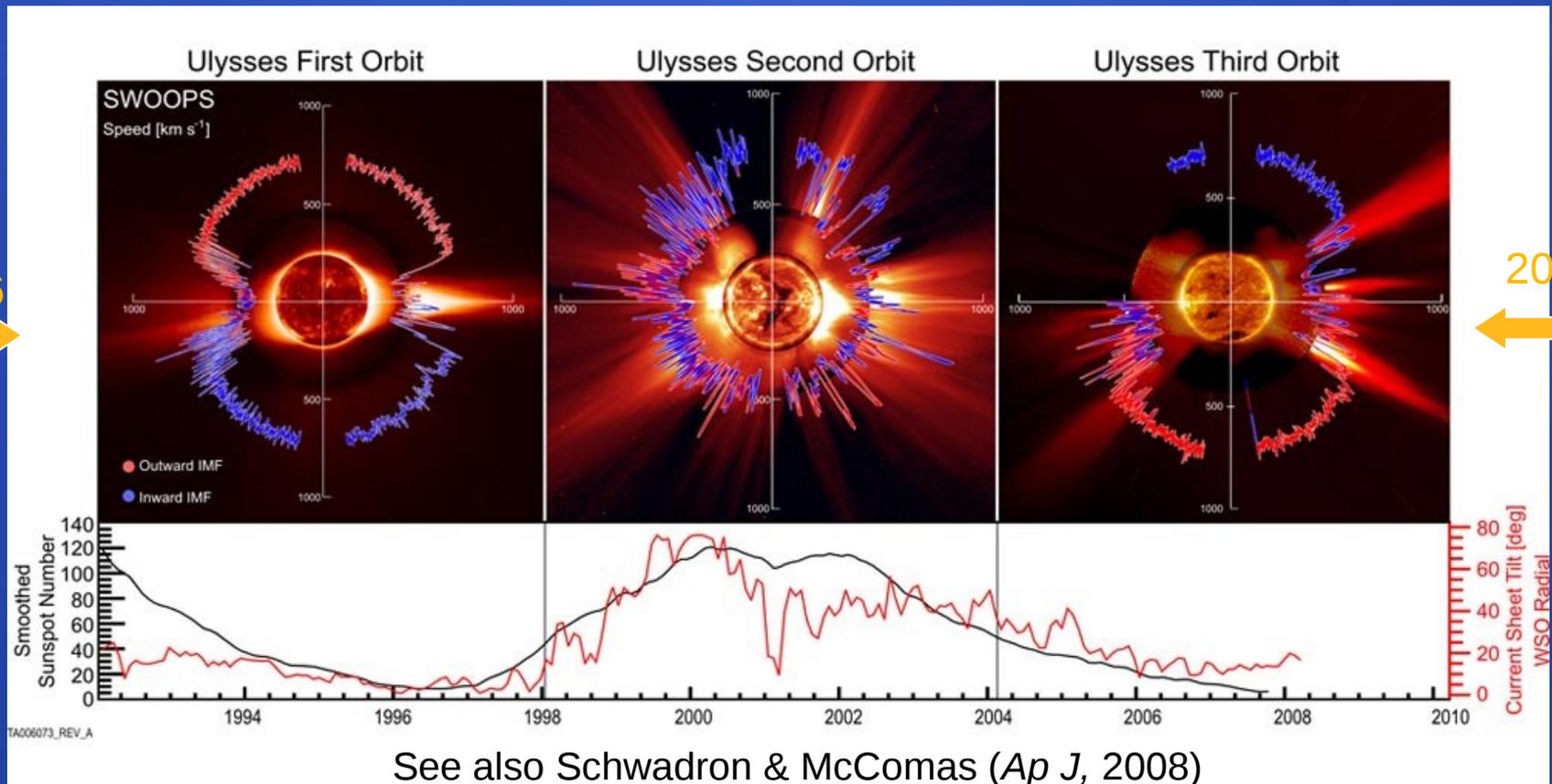
- This minimum has more low-latitude coronal holes than in 1996
  - Low-latitude coronal holes start to go away in 2009 (deToma, SOHO-23)
- Is minimum in solar EUV irradiance in August 2008 related to the larger low-latitude coronal hole area or just minimum in active region area?

- SOHO SEM 26-34 nm is about 15% less in 2008 than in 1996 (Leonid Didkovsky, '09 SPD 18.07)
  - Uncertainty is ~6% →



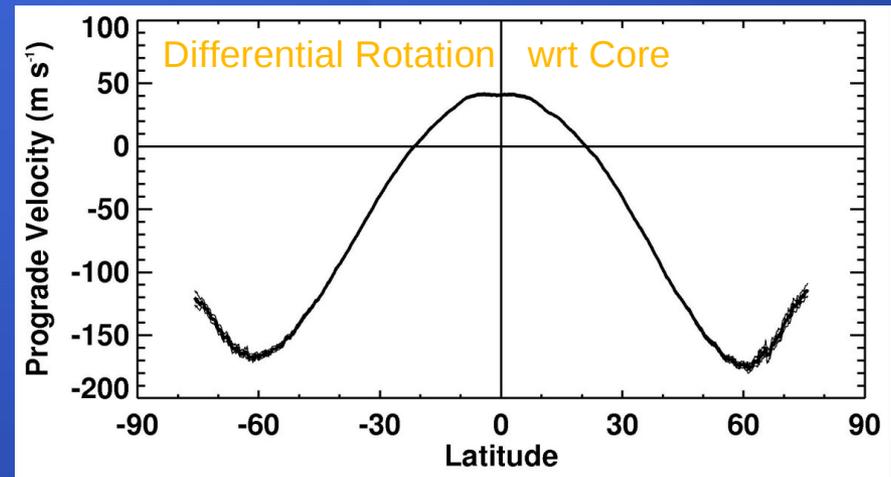
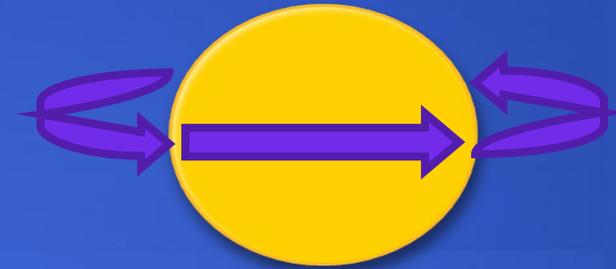
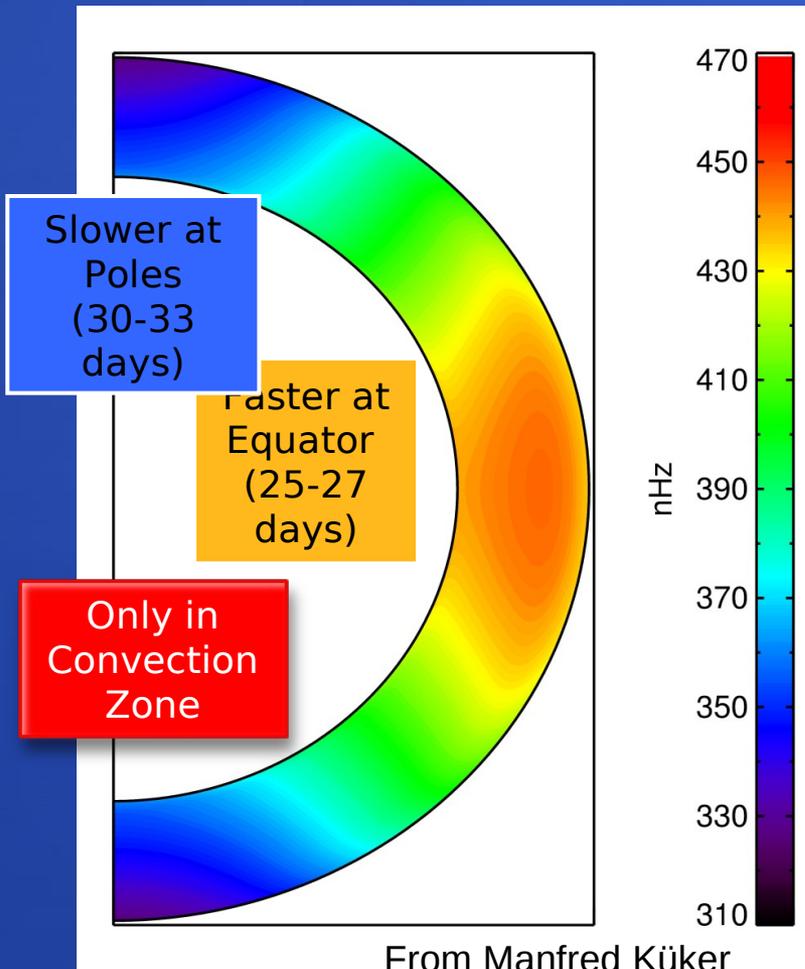
# Coronal Holes Also Affect Solar Wind

- Solar wind density (near ecliptic) is 45% lower
- But solar wind speed is 13% higher and number of fast solar wind periods is more [Gibson *et al.*, *JGR*, 2009]



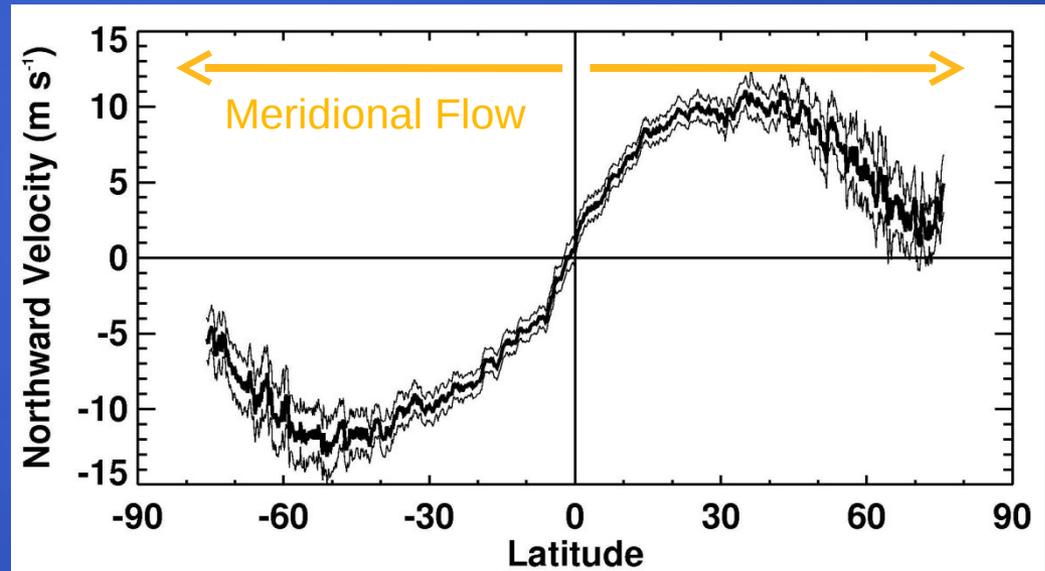
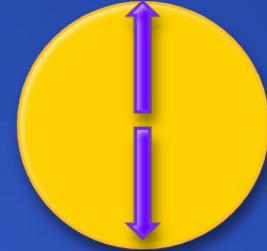
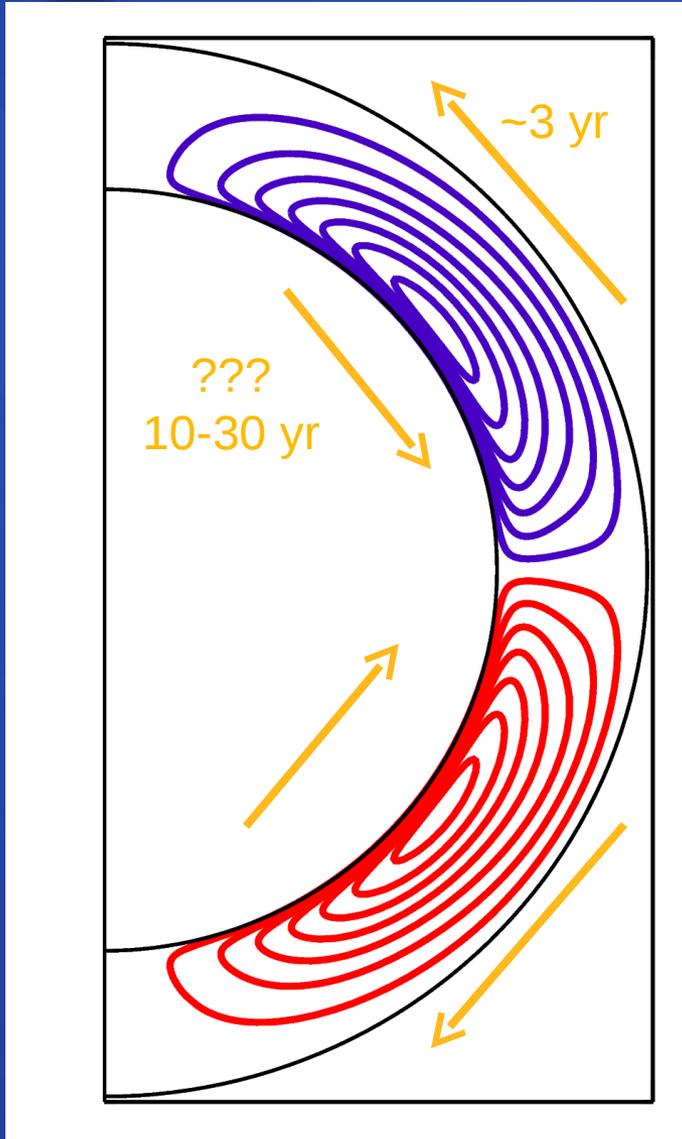
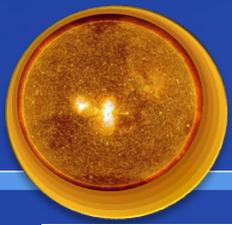
# Zonal Flow Varies with Latitude

from David Hathaway



# Meridional (Poleward) Flow Varies with Latitude

from David Hathaway



The **Meridional Flow** is from equator to the poles – peak velocity in the north is 10  $\text{m/s}$  at  $30^\circ$  while peak velocity in the south is 12  $\text{m/s}$  at  $50^\circ$

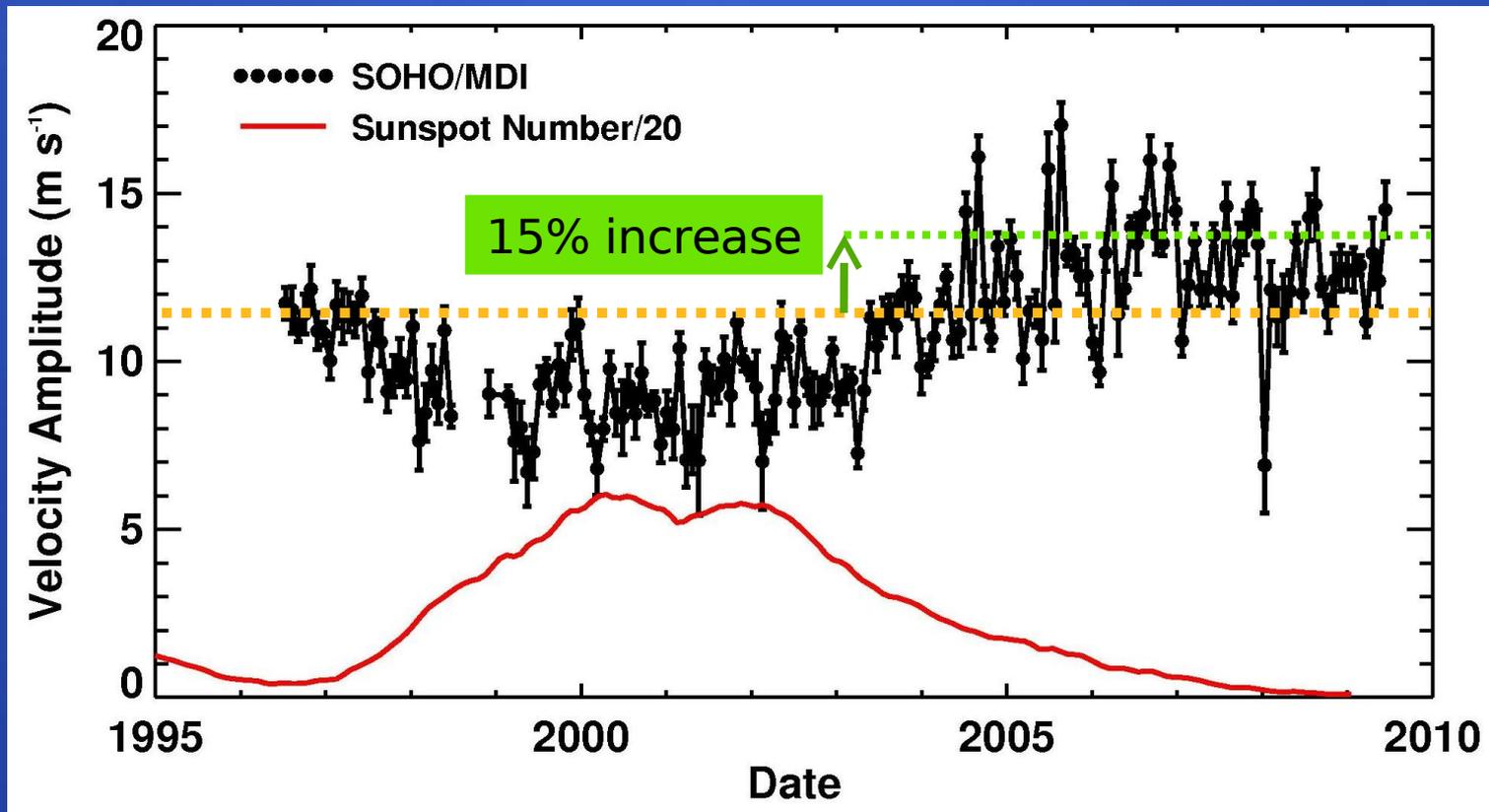


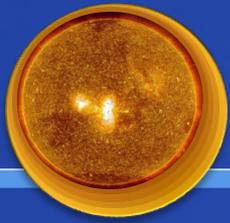
# Meridional Flow is Now Faster

from David Hathaway

The Meridional Flow slowed from 11.5 m/s in 1996 to 8.5 m/s in 2001 (cf. Basu & Antia, 2003) – this is a solar cycle effect in having more sunspots on the disk at cycle maximum (Komm, Howard, & Harvey, 1993).

Then rapidly increased in speed to 13.0 m/s by 2004. This is unexpected result, but this can explain why there is lower polar magnetic field now.





# What's Next?

- When is this Minimum going to end?
- Are we entering into a Dalton Minimum state?
- How does faster polar transport (dynamo) impact this next cycle?
- Is the WHI April 2008 campaign representative of this minimum?
  - WHI Workshop Nov 10-13, 2009 in Boulder
  - <http://ihy2007.org/WHI/>
- How is this minimum affecting climate change?
  - SORCE Workshop May 19-21, 2010 in Keystone
  - <http://lasp.colorado.edu/sorce/>