# Report on ‘Extreme Space Weather Events’ workshop that I co-organized in Boulder in June 2014

Leif Svalgaard
Stanford University

**Stanford Solar Group Science Meetings**

July 2, 1024

# Extreme Space Weather Events II

# Program

**Monday, June 09 (chair: Noe Lugaz)**

09:00 NASA Presentation on LWS Program

09:15 Invited talk: The Maunder and other Grand Minima (Owens)

Session 3: Limits to the maximum flare energy of stars from formation to solar age (Soderblom/Osten)

Session 4: Conditions Leading to Extreme SEP Events (Cohen/Mewaldt/Li)

Session 9: Understanding the Maunder Minimum (Svalgaard/Riley)

**Tuesday, June 10 (chair: Dave Soderblom)**

Session 9: Understanding the Maunder Minimum (Svalgaard/Riley)

Session 7: Extreme Space Weather: Campaign Events (Dayeh/Lugaz)

Session 1: Interpretation of Ice Core Records as Proxies of ESWEs (Smart/Dibb/Randall)

Session 5: Extreme CMEs: Origins and Evolution (Manchester/Torok)

**Wednesday, June 11 (chair: Leif Svalgaard)**

Session 2: 775 event and Aurora during ancient times (Shea)

Session 6: Extreme Events: What constitutes them and what are their effects? (Townsend)

Session 8: Propagation of extreme events through the atmosphere (Randall/Solomon)

http://www.predsci.com/eswe-workshop/presentations-unsorted/

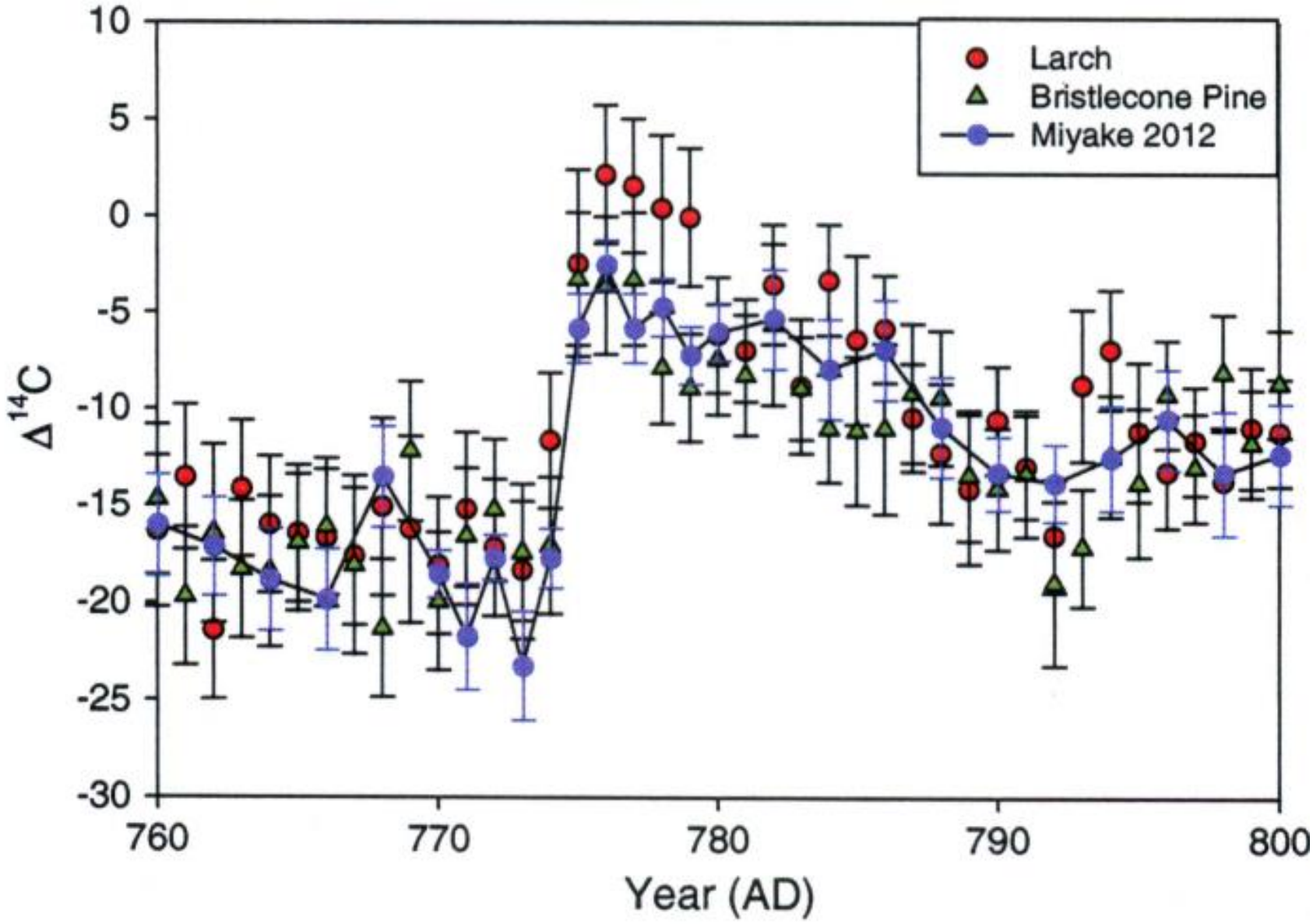
# $^{14}C$ increase 775 and 993 AD:

## Aurora observations in ancient times.

**M. A. Shea**

Session 2

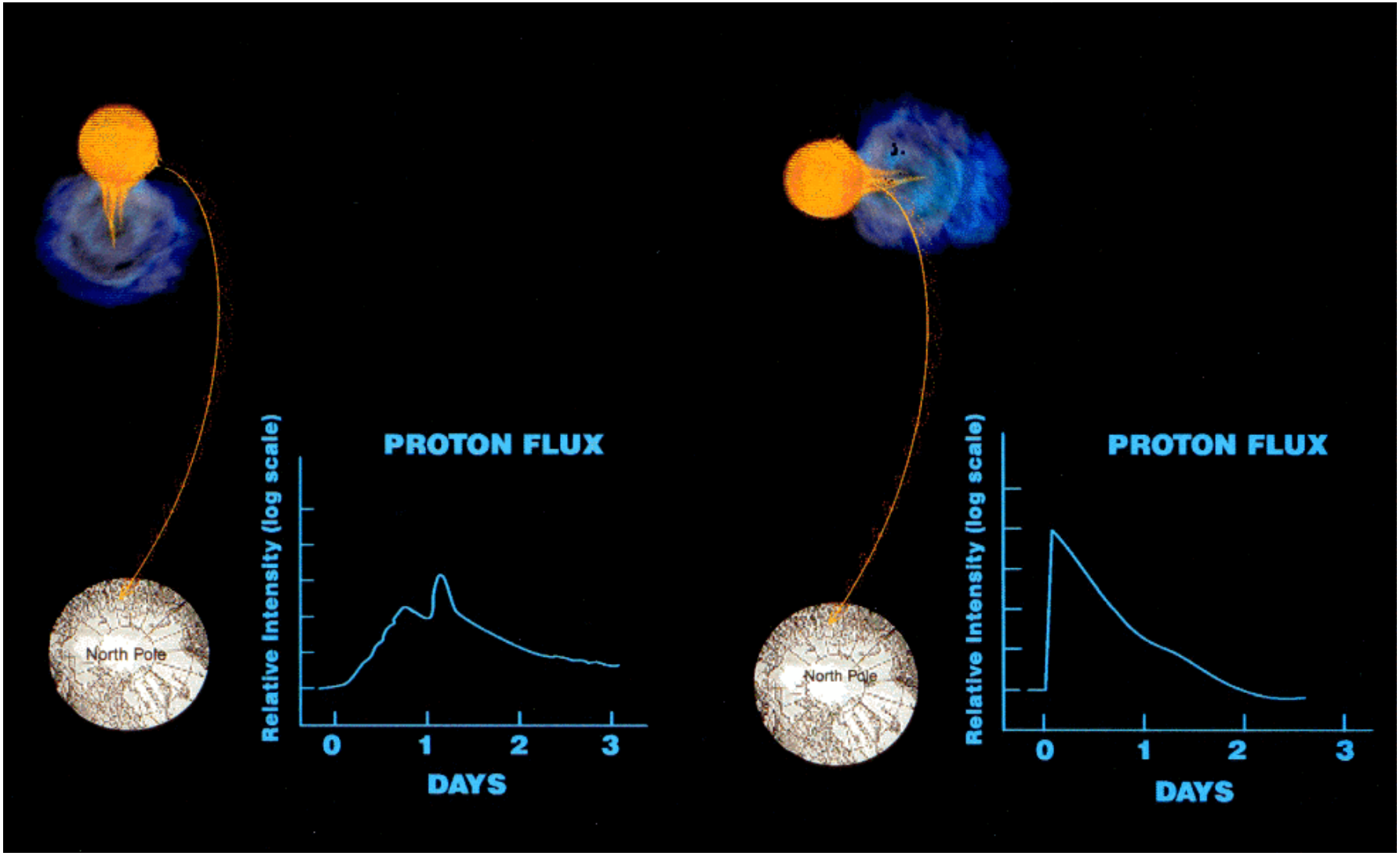
Jull et al., 2014



## Possible explanations:

**Extreme Solar Proton Event**
**Comet Collision - January 773**
**Gamma-ray Burst – Super Nova**

**HOW CAN OUR MODERN KNOWLEDGE HELP IN THE UNDERSTANDING OF HISTORICAL PHENOMENA?**




Sharp rise may indicate a near West-limb flare. If so, the CME may not have hit Earth

# THINGS WE HAVE LEARNED:

**MAJOR SPEs FROM CENTRAL MERIDIAN ACTIVITY GENERALLY HAVE SOFTER SPECTRA THAN EVENTS FROM THE WEST LIMB.**

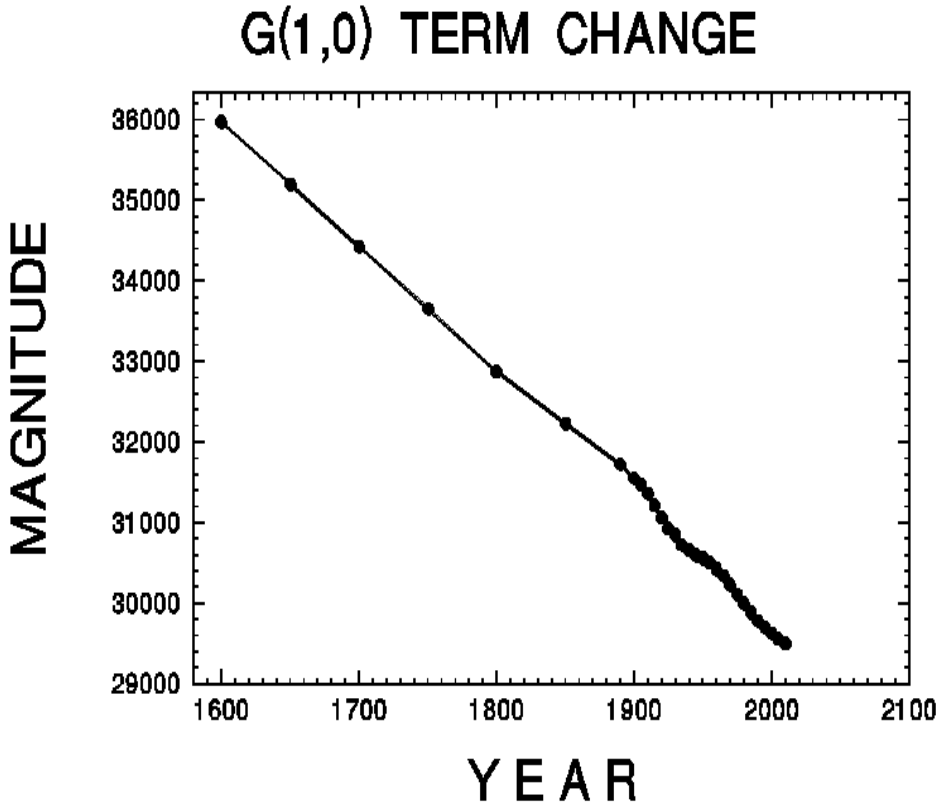
**MAJOR HIGH ENERGY ( 4 GeV) SPEs FROM CENTRAL MERIDIAN ACTIVITY ARE RARE.**

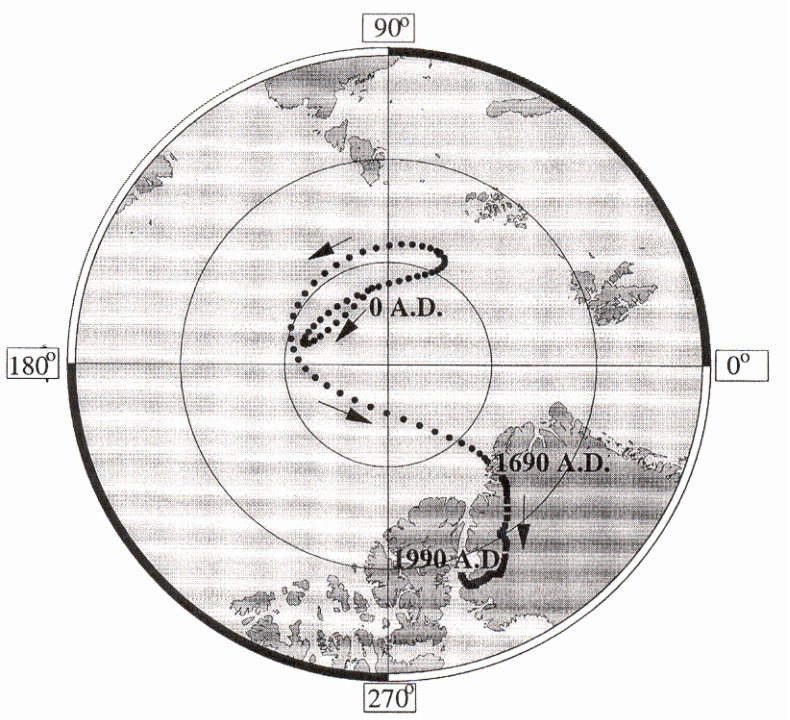
**MAJOR HIGH ENERGY SPEs ARE NOT ALWAYS ASSOCIATED WITH A SUBSEQUENT GEOMAGNETIC STORM.**

**MAJOR GEOMAGNETIC STORMS CAN OCCUR WITHOUT A LARGE SPE.**

# CAN IDENTIFICATION OF LOW LATITUDE AURORA HELP TO RESOLVE UNUSUAL GEOPHYSICAL RECORDS SUCH AS $^{14}C$ INCREASES IN TREE RINGS?

# CHANGE IN MAGNITUDE OF THE G(1,0) TERM OF THE EARTH'S MAGNETIC FIELD, 1600-2010 (18% decrease in 400 years)



# EXAMPLES OF GEOMAGNETIC LATITUDE CHANGES

| LOCATION | 1000 | 2000 | CHANGE |
|---|---|---|---|
| S. SPAIN | 35° N | 40° N | 5° N |
| SAN DIEGO | 25° N | 40° N | 15° N |
| CHICAGO | 36° N | 51° N | 15° N |
| EGYPT | 34° N | 28° N | 6° S |
| TASMANIA | 38° S | 50° S | 12° S |

**(VALUES ARE APPROXIMATE)**

So far, no known aurorae in ~775 AD

# HISTORIC MID AND LOW LATITUDE AURORA

- Oct 817 Iraq
- 816/817 Yemen
- Oct 879 Morocco
- 939-940 Syria
- May 941 Spain
- Aug 977 Egypt
- Sept 979 Morocco
- 991-992 Egypt*
- Apr 1050 Egypt*
- 1059-1060 Egypt
- 1176 Syria*
- May 1179 Syria
- Nov 1203 Yemen
- 1223 Syria*
- 1264 Syria*
- 1321/1322 Yemen
- Nov 1370 Syria
- 1422-23 Egypt
- Aug 1449 Yemen
- 1570-71 Spain

- * Suspected aurora

Ref: Basurah, Sol. Phys, 225,2005; JASTP, 68, 2006

# We have the Needle, where is the haystack?

# Hypothetical 775 AD Free Space Doses

- Organ doses behind 5 g cm$^{-2}$ Al shielding (2 cm)
  - skin: 9 Gy-Eq (1.5) (NASA limits)
  - eye lens: 7 Gy-Eq (1.0)
  - BFO: 4.1 Gy-Eq (0.25)
  - CNS: 4.3 Gy-Eq (0.5)
  - Heart: 3.4 Gy-Eq (0.25)
  - Eff. Dose: 4.1 Sv (≤ 1.2) (4π)
- These doses are likely lethal

1 Gy-Eq (gray) is an absorbed dose of 1 J/kg

Larry Townsend

# Feb 1956 Free Space Doses

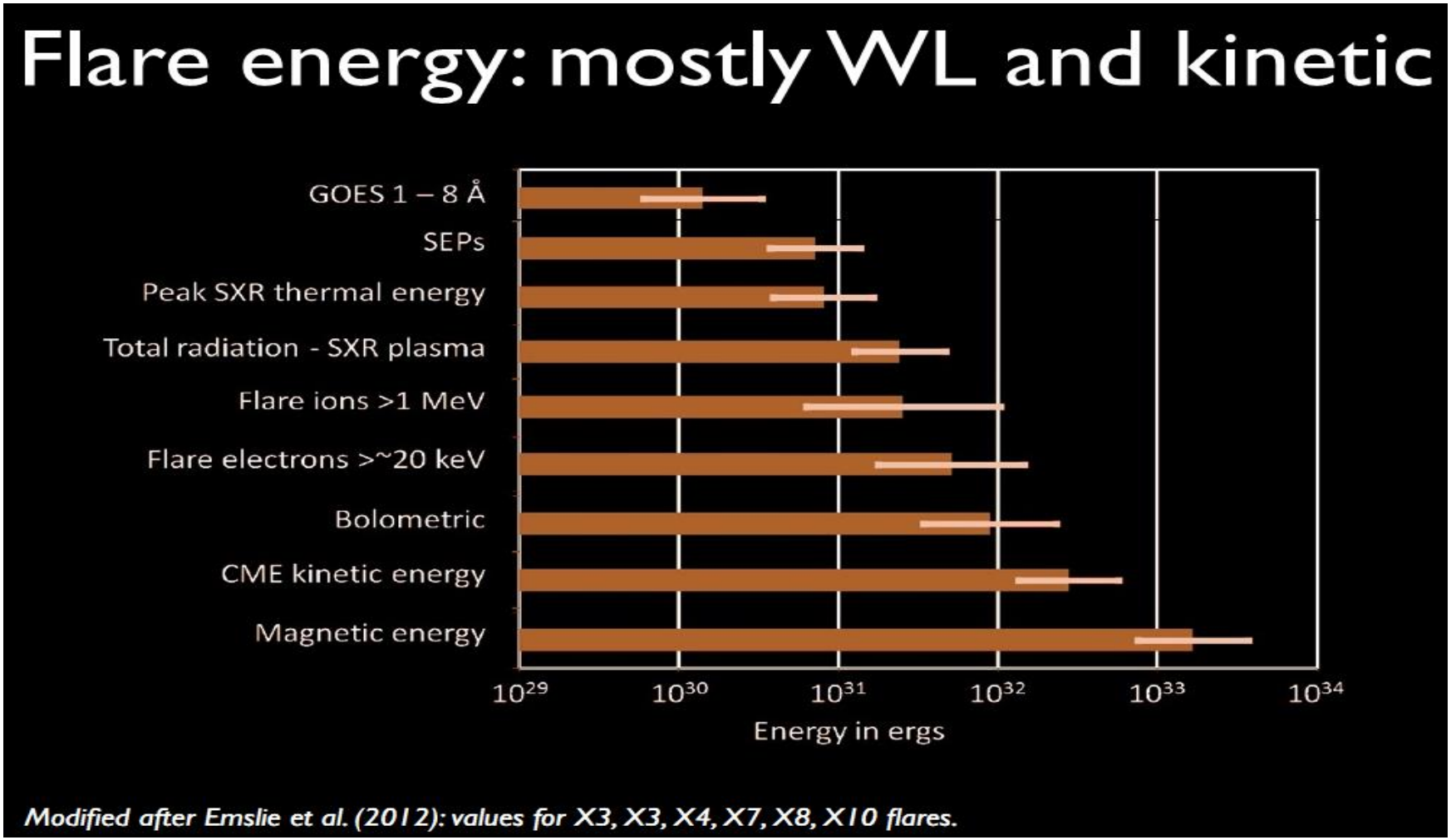
- Organ doses behind 5 g $cm^{-2}$ Al shielding
  - skin: 0.42 Gy-Eq (1.5)
  - eye lens: 0.33 Gy-Eq (1.0)
  - BFO: 0.19 Gy-Eq (0.25)
  - CNS: 0.20 Gy-Eq (0.5)
  - Heart: 0.16 Gy-Eq (0.25)
  - Eff. Dose: 0.19 Sv (≤ 0.6) (2π)
- These doses are below applicable NASA limits

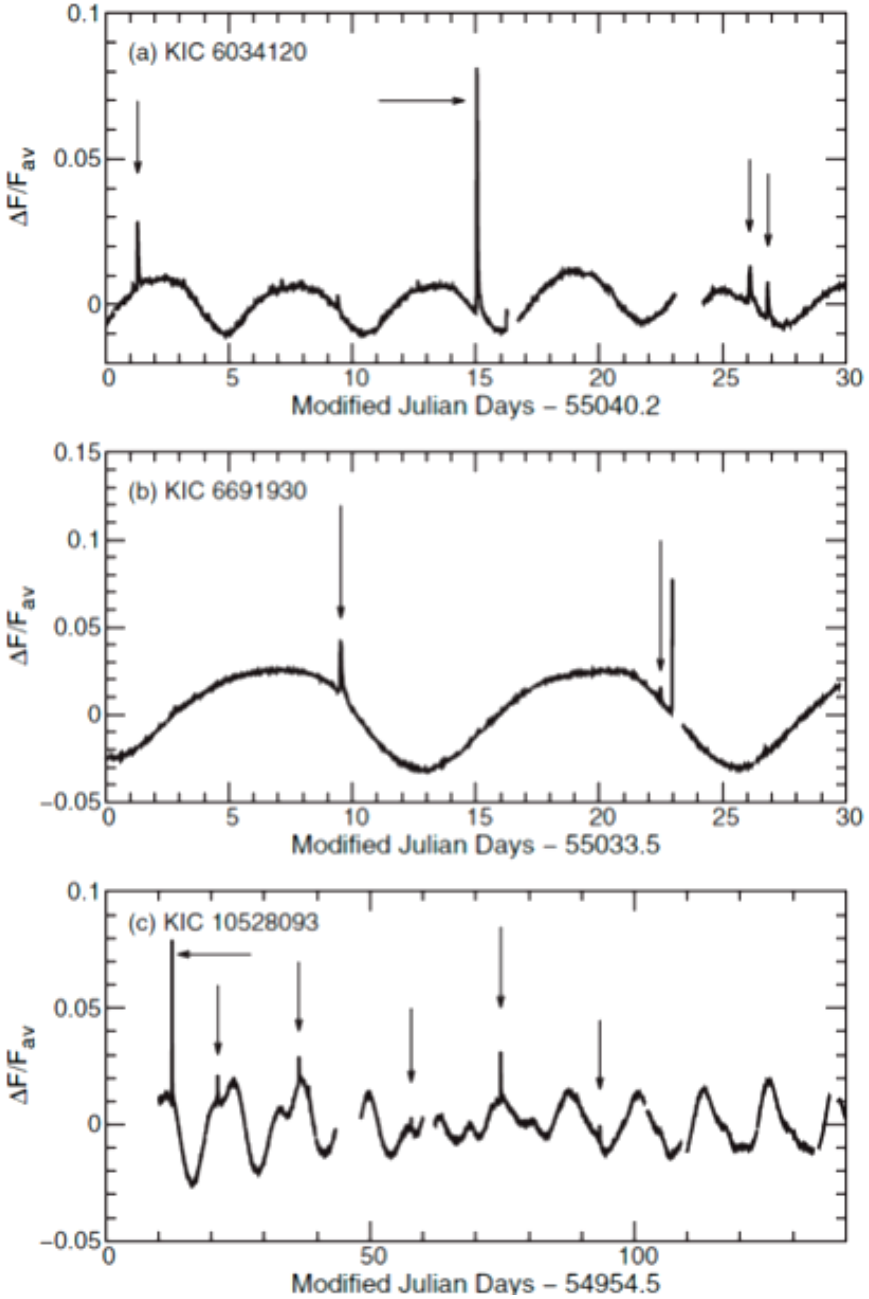
# Hypothetical 775 AD Free Space Doses

15 cm

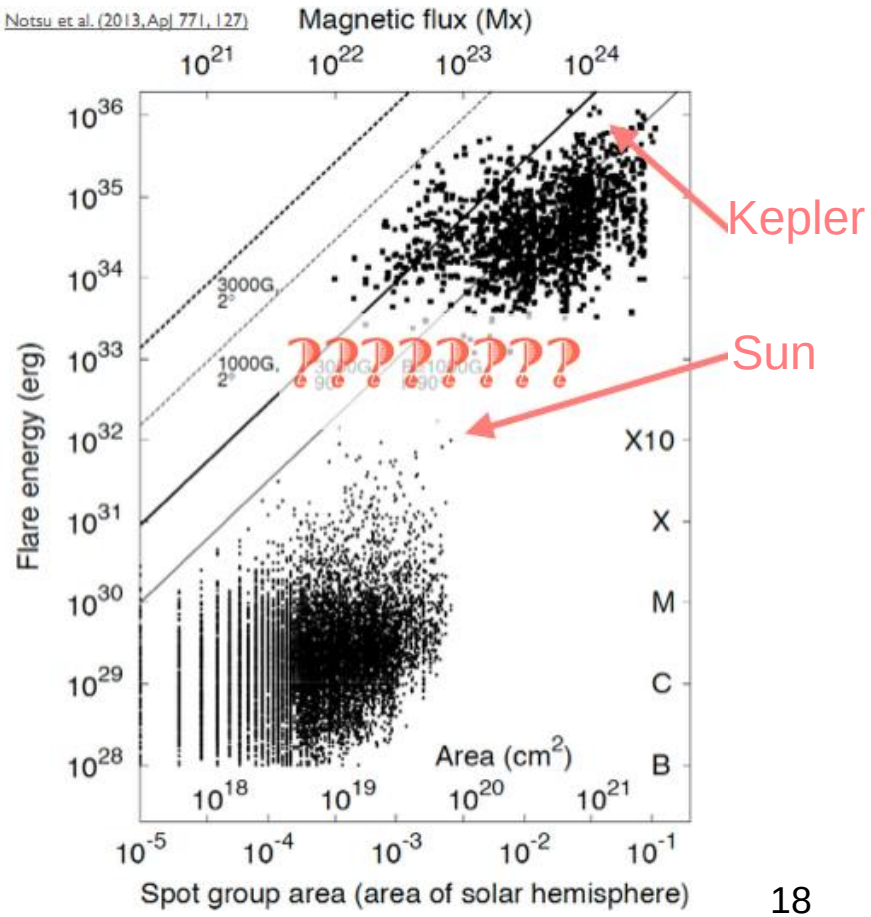
- Organ doses behind 40 g $cm^{-2}$ Al shielding
  - skin: 1.5 Gy-Eq (1.5)
  - eye lens: 1.5 Gy-Eq (1.0)
  - BFO: 1.2 Gy-Eq (0.25)
  - CNS: 1.3 Gy-Eq (0.5)
  - Heart: 1.4 Gy-Eq (0.25)
  - Eff. Dose: 1.4 Sv (≤ 1.2)
- Possibly lethal but certainly acute radiation syndrome effects (“radiation sickness”).

# Solar Flare Energetics

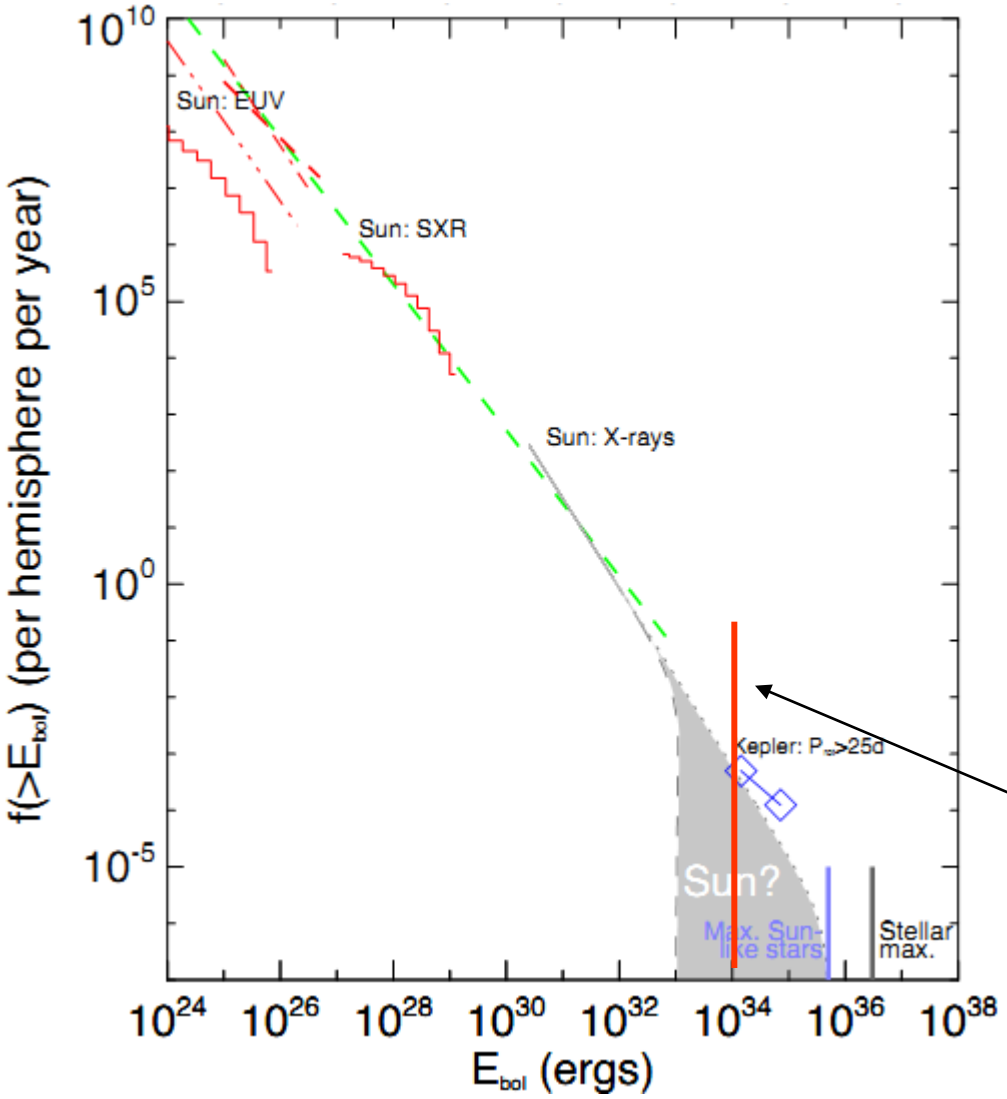





# White-Light Flaring on Stars, Kepler



# Extreme Solar Flares. Where are they?

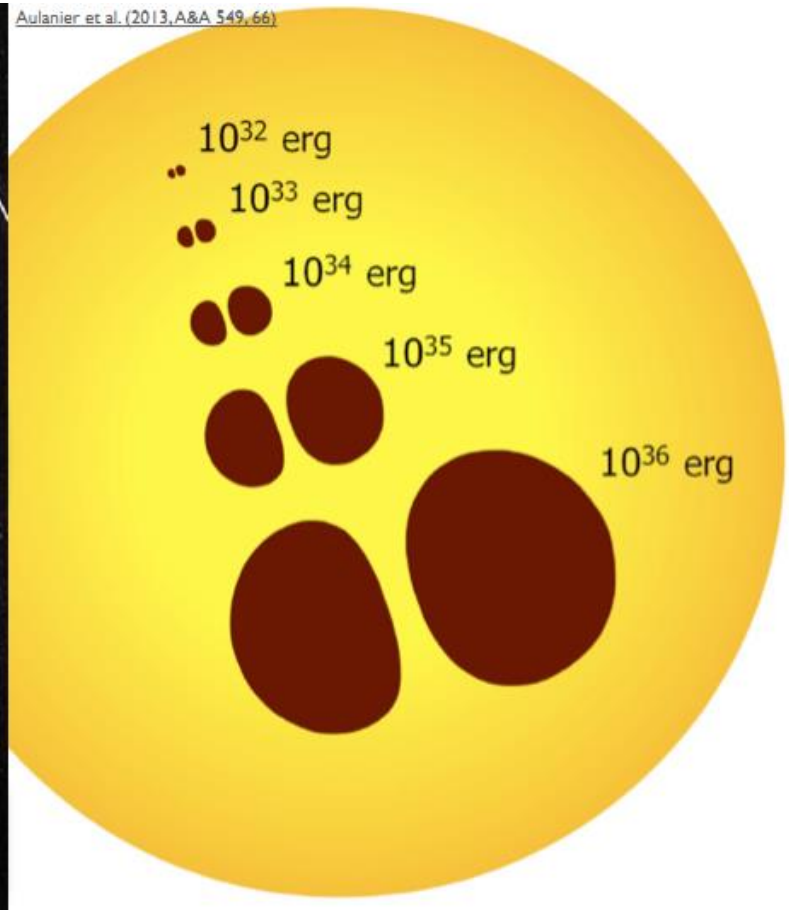



Maximum for cool stars in general: ~3 $10^{36}$ erg

Kepler observations of Sun-like stars suggest continuation up to at least ~5 $10^{35}$ erg

Estimated fluence needed to create the 775AD $^{14}C$ spike

# Sizes of Spots as a Function of Flare Energy

# The Worst Space Weather

Stellar data reveal that some space weather can be much more severe than what we have recently experienced:

• Solar flares may reach energies up to 100-300 times above those observed in the past four decades.

• Effects on Earth *may* (luckily) saturate at values several times Space-Age maxima

• All these potential extremes exceed the levels to which modern technologies, connected in a network of growing complexity, have been exposed.

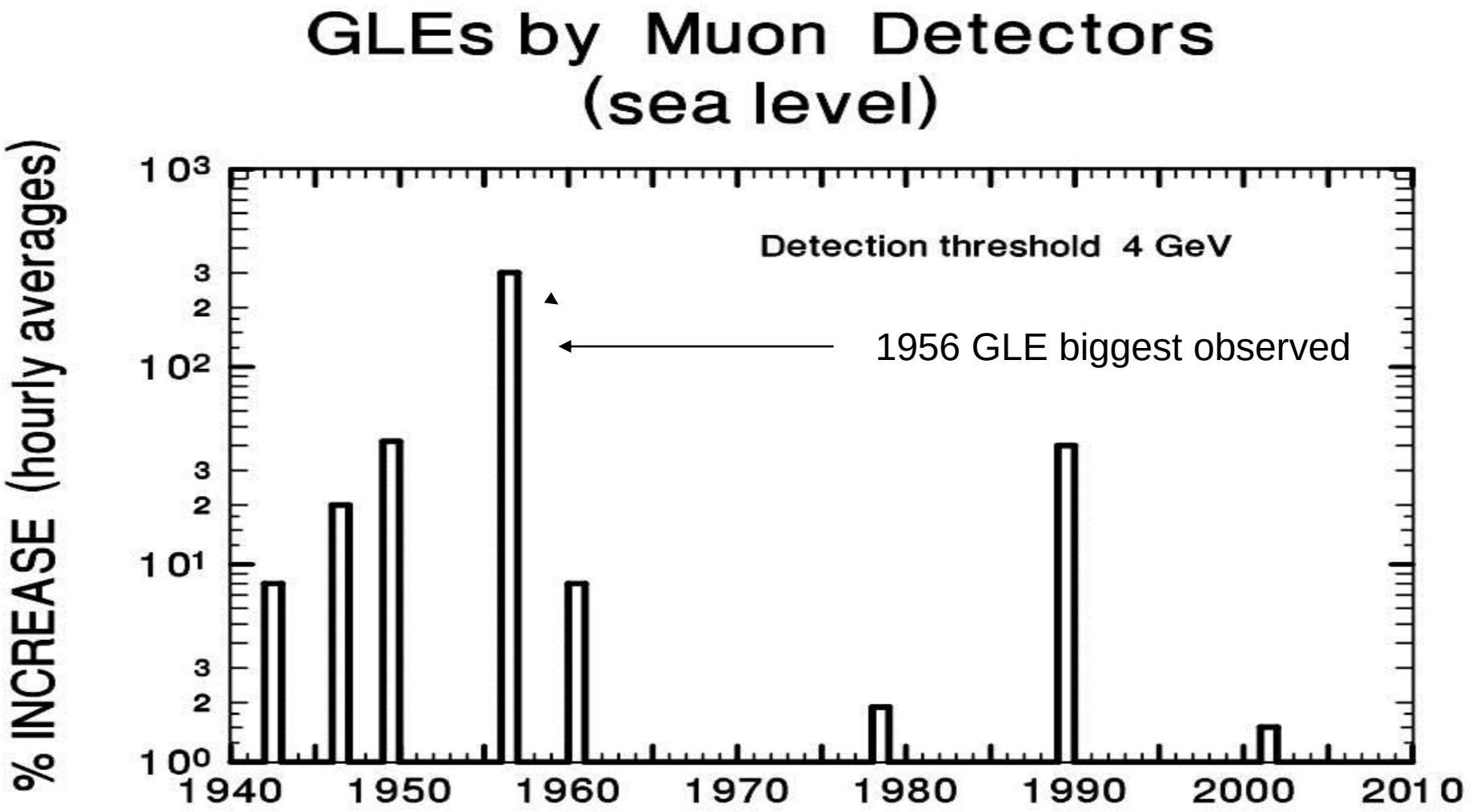
# INTRODUCTION AND OVERVIEW OF ICE CORE RECORDS AND EXTREME SOLAR PROTON EVENTS

Don Smart

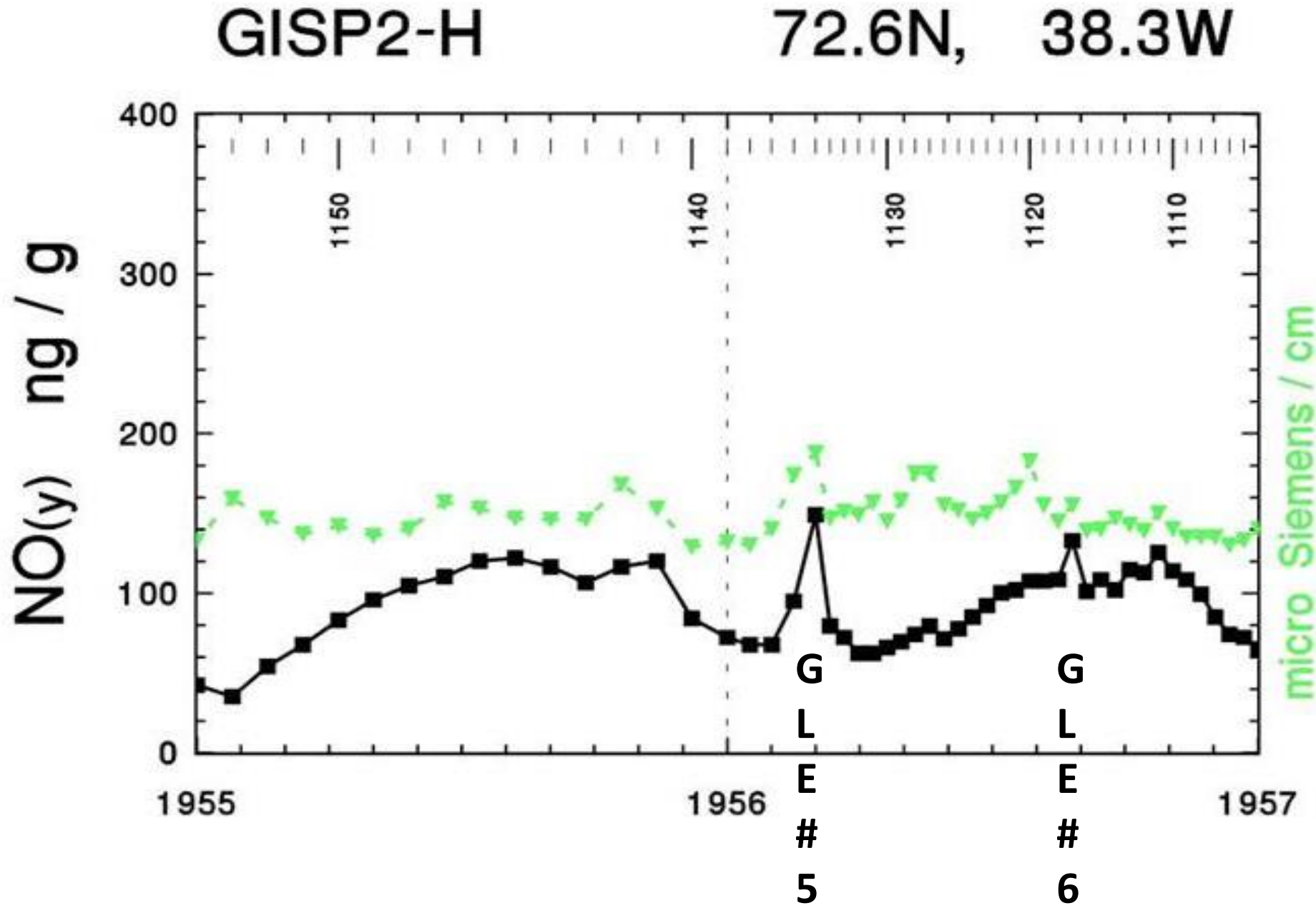
sssrc@msn.com

The Current Nitrate Spike Controversy

# VERY LARGE HIGH ENERGY SOLAR COSMIC RAY EVENTS DURING THE COSMIC RAY MEASUREMENT ERA




GLE = Ground Level Event of Solar Cosmic Rays. Only ~72 are known



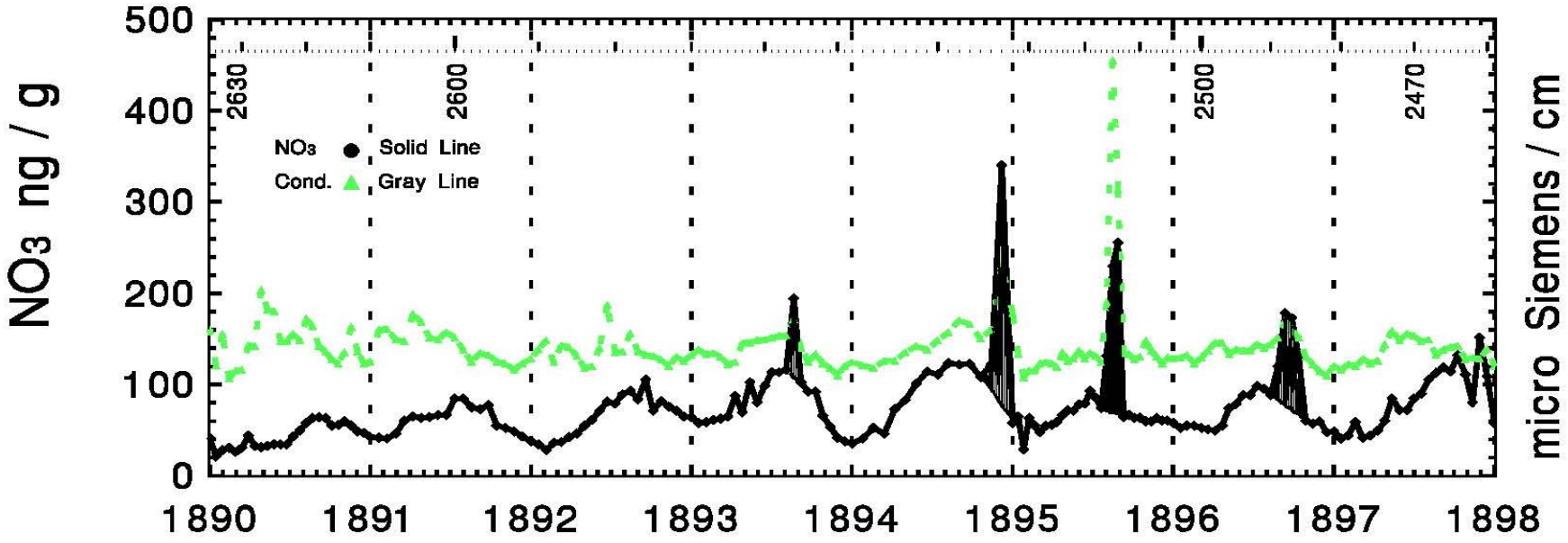

**N**itrate (▬) and conductivity (▼) data from the GISP2-H ice core for 1955-1957.

# Historic NO(y) events

McCracken et al. documented 70 potential impulsive NO(y) increases in the interval 1562 to 1950, all equivalent to or larger than the February 1956 event.

**These have been essentially ignored, except for a few.**

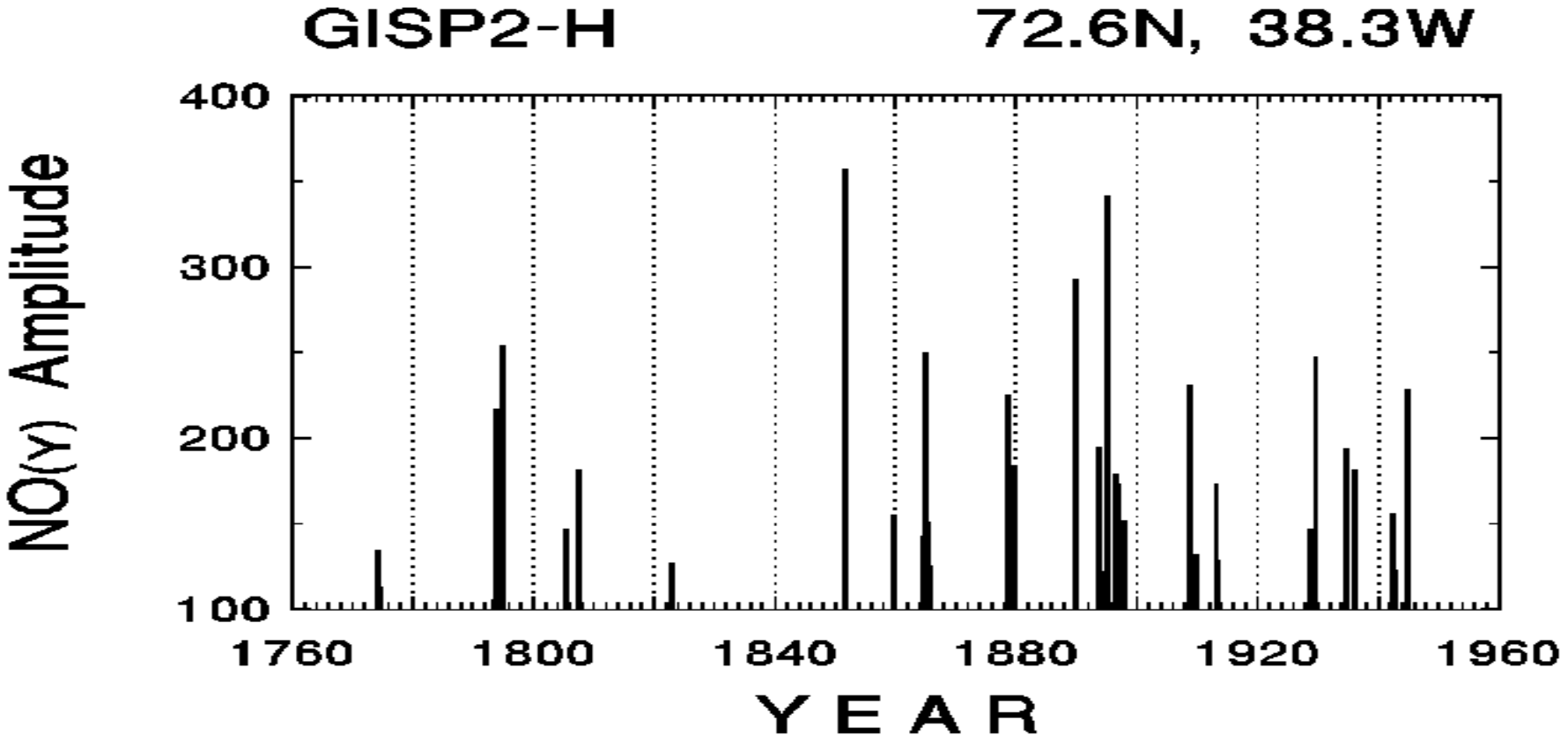
Jack Dibb noted a probable biomass event in 1895



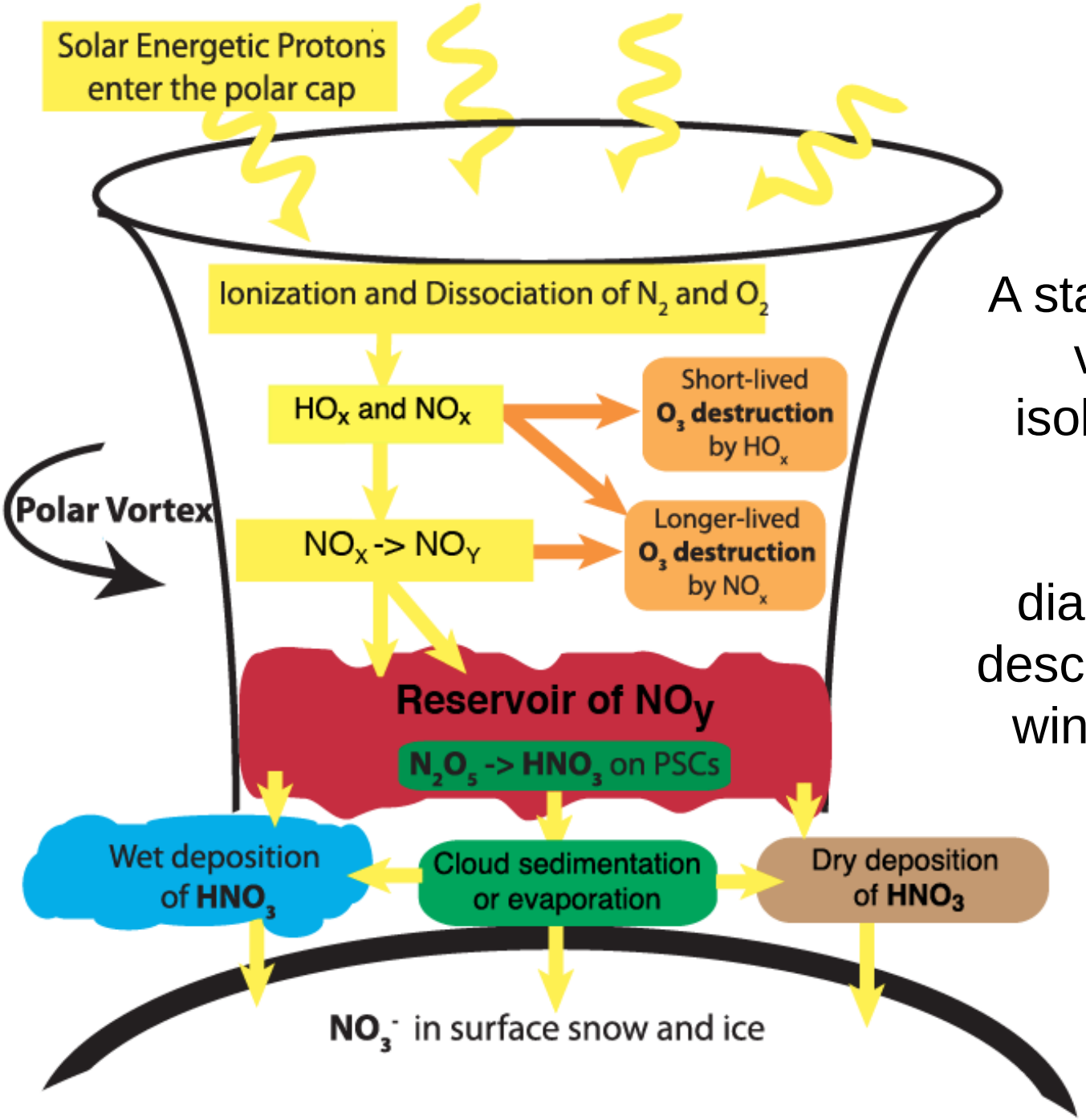

**Note that there are impulsive NO(y) increases where there are not large increases in conductivity.**

There are at least 40 impulsive nitrate events in the last 300 years, each as large as the February 1956 high energy solar cosmic ray event that should be detectable in high time resolution polar ice cores.

None of these correspond to dated biomass burning events in the Zoe or D4 ice cores.



# Polar Night




A stable polar vortex isolates air.

$NO_x$ diabatically descends over winter pole.

# Conclusions

- *SPEs significantly increase reactive nitrogen and decrease ozone* in the stratosphere following November 2000 events.
- *No convincing evidence that SPEs are related to impulsive nitrate spikes*.
- Tropospheric sources provide an alternative explanation for nitrate spikes at Summit during the winter of 2000-2001.

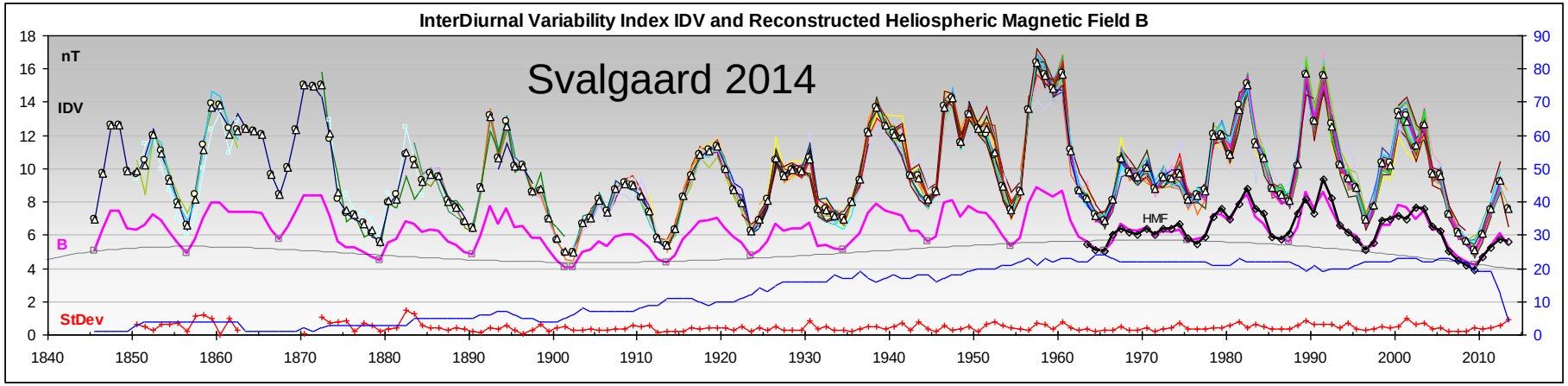
## Remaining Questions

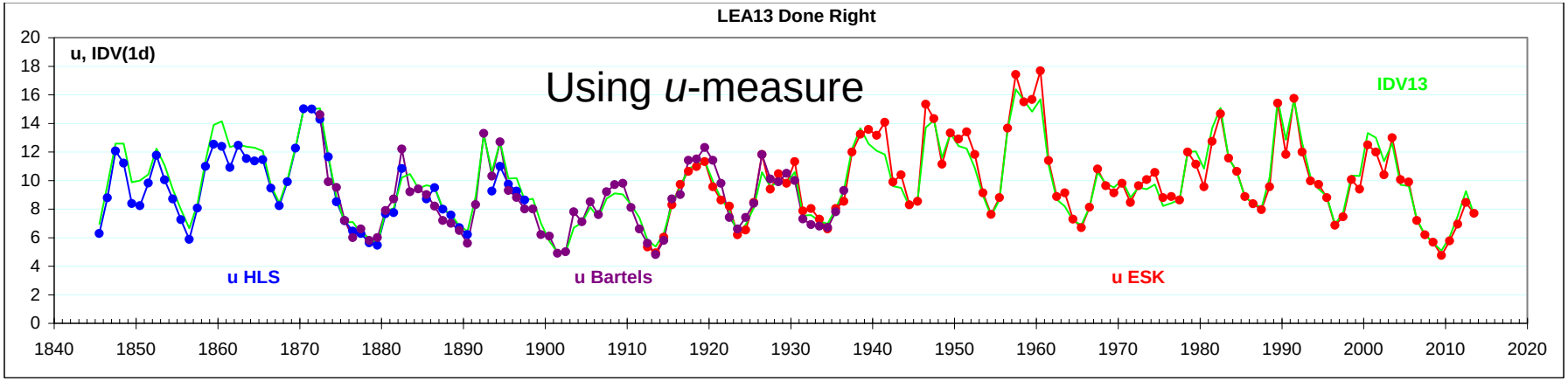
- *How large would an SPE have to be* to produce discernable nitrate spikes at the surface, given the limits of solar flare energy?
- *Longer-term variations* in nitrate related to solar activity continue to be of interest (Gleissberg cycles, millennial variations, etc.).
- *Are there alternative proxies* for SPEs? On what timescale can cosmogenic radionuclides (e.g., $^{14}C$ and $^{10}Be$) or other isotopes be used to study solar variability? The controversy continues…

# To predict Extreme Events we need to understand Ordinary Events and Ordinary ‘Background’ in the historical setting

Svalgaard, Boulder 2014

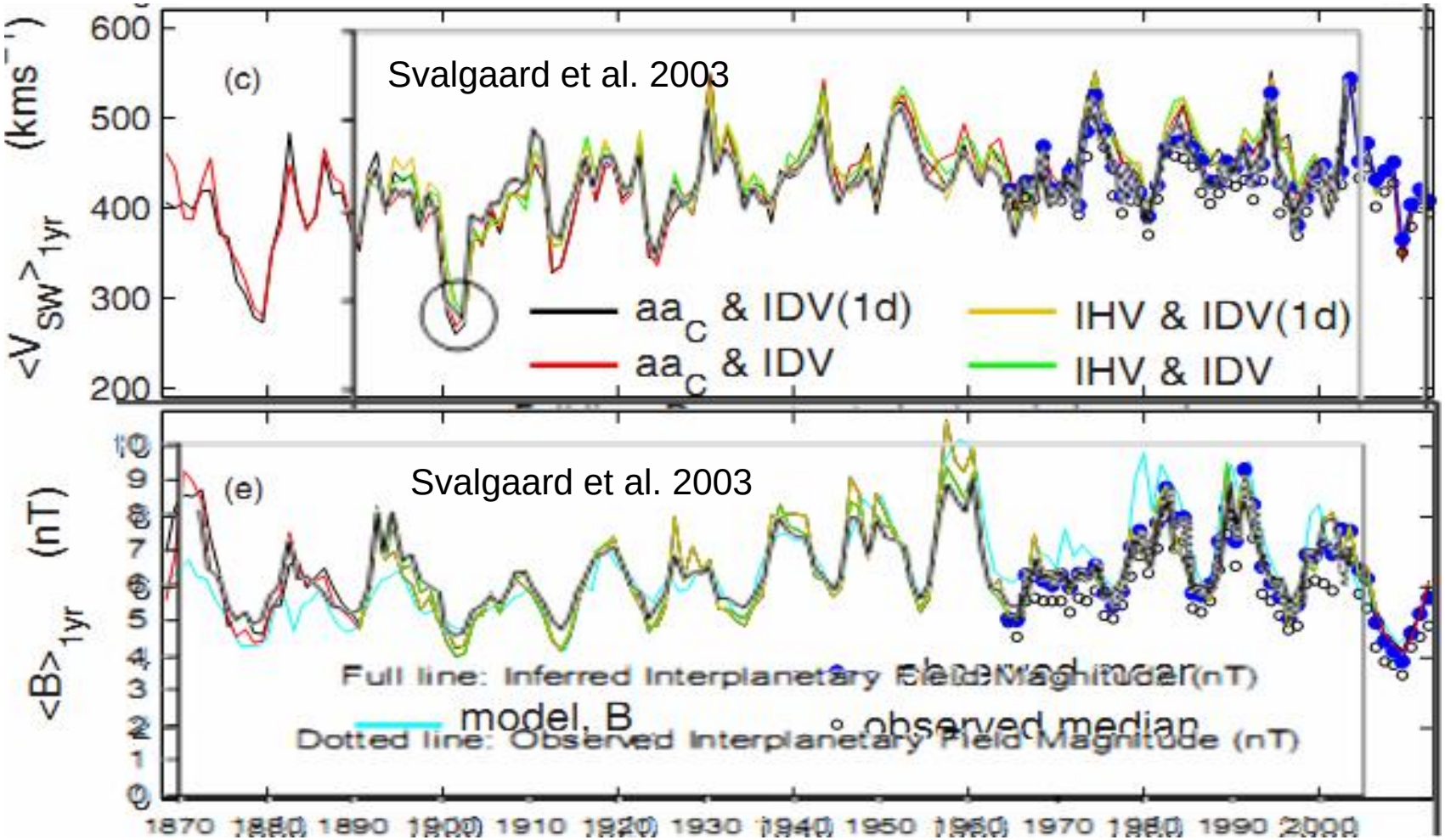
# Progress in Reconstructing Solar Wind Magnetic Field back to 1840s



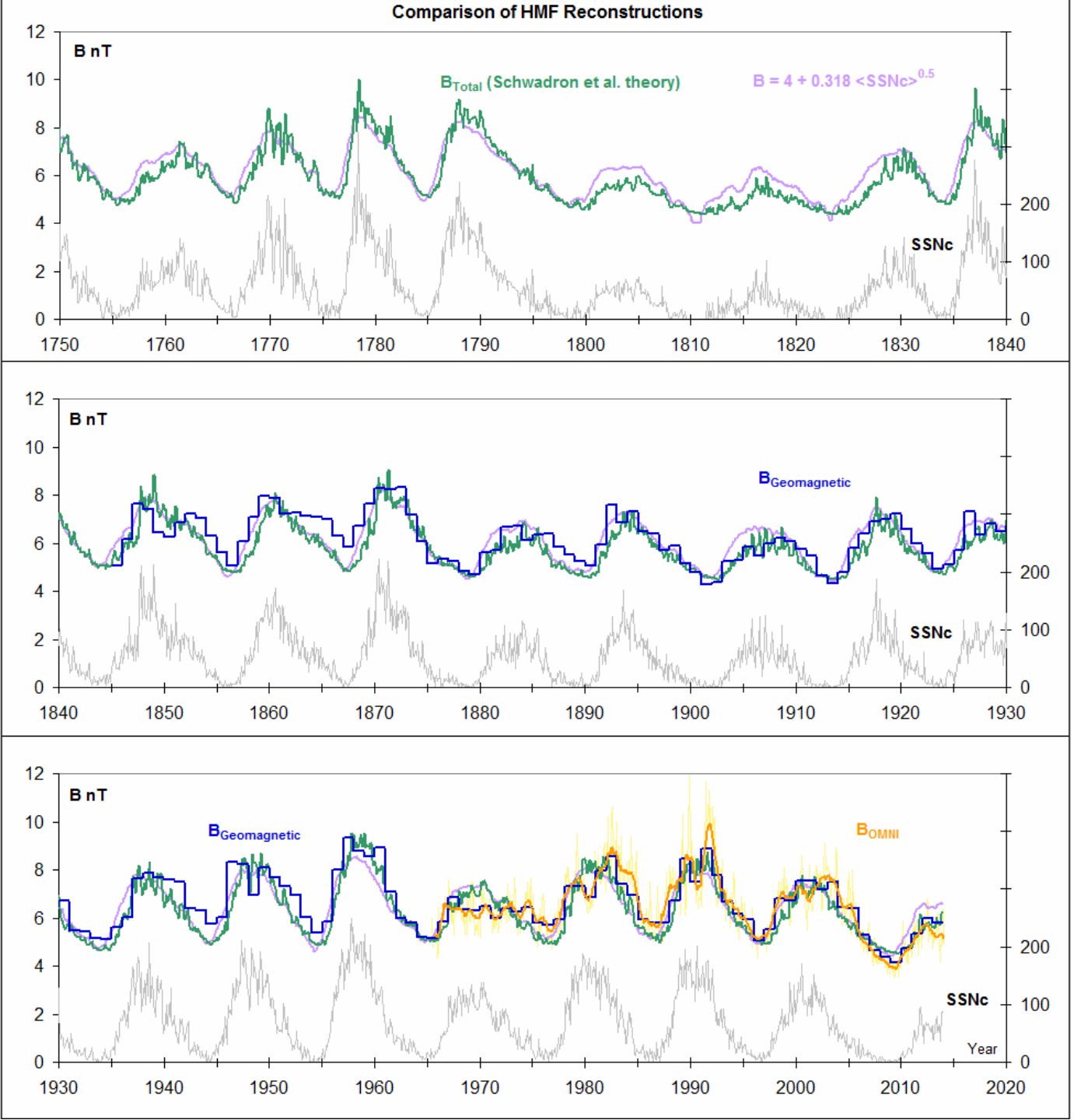




Even using only ONE station, the 'IDV' signature is strong enough to show the effect

# After a Decade of Struggle, Lockwood et al. (2014) are Fast Approaching the Svalgaard et al. Reconstructions of 2003




This is a healthy development and LEA should be congratulated for their achievement, although their **model**, based on a flawed Sunspot Number series, is not doing too well



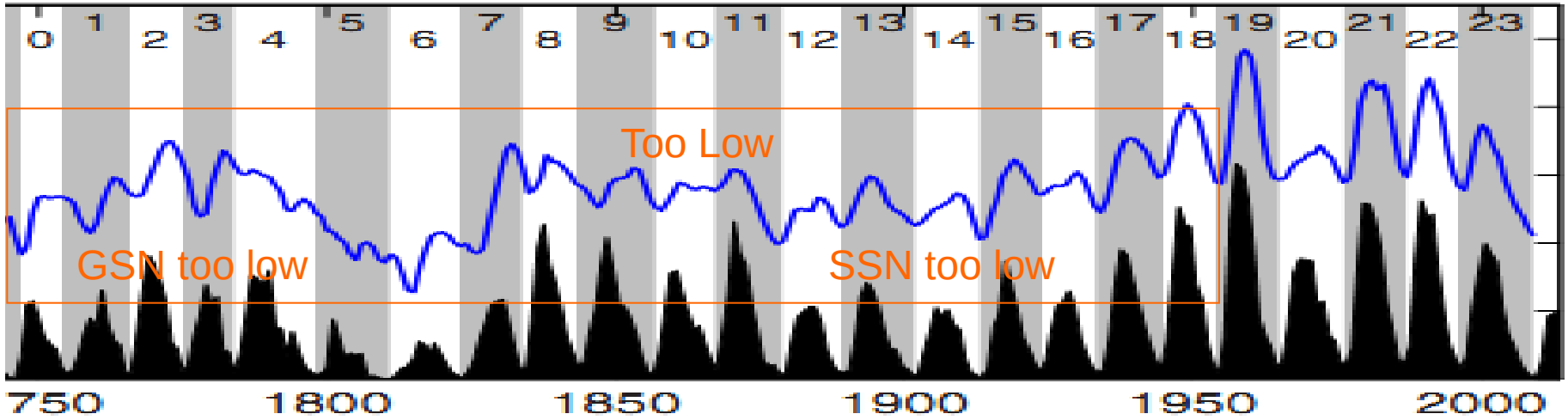

# Schwadron et al. (2010) HMF B Model, with my set of parameters

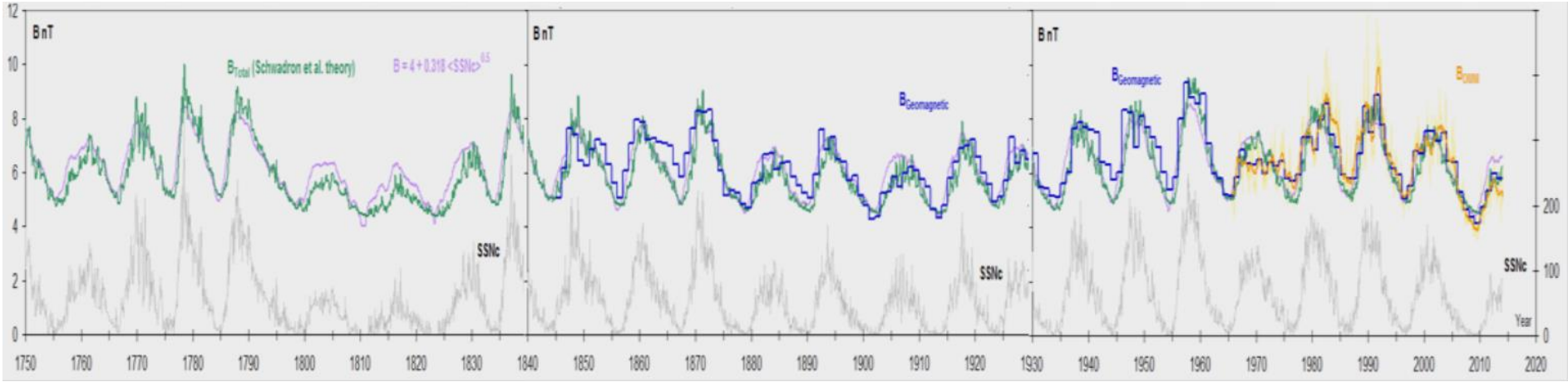
von Neumann: “with four parameters I can fit an elephant, and with five I can make him wiggle his trunk”

This model has about eight parameters…

“It is not clear if the version of the code obtained from the original authors is incomplete or in some other way inaccurate”

# The Tale of Two Models…



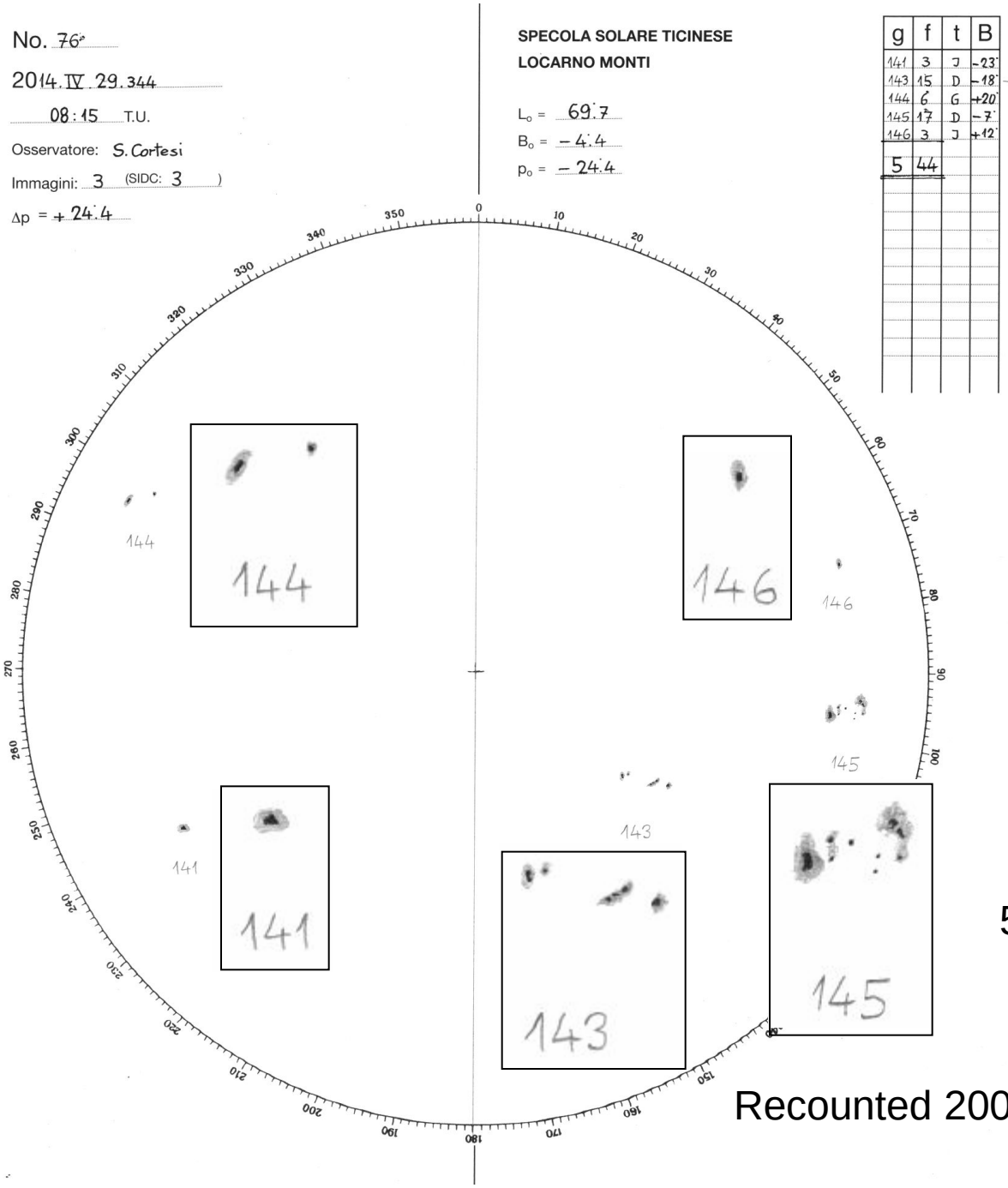




The models operate with the ‘open [radial] flux’, so it is important to get that right

# As the Sunspot Number is used as Model input it is important to get that right

- Four recent Sunspot Number Workshops (2011-2014) have critically examined the historical sunspot number record(s)
- There is now broad consensus among the participants that we have identified the major problems with the SSN series:
- A) Error (65%) in Wolf-Wolfer calibration for the GSN before ~1882
- B) Weighting of sunspot counts (20%) for the Int. SSN starting in 1940s

# Counting with no Weighting



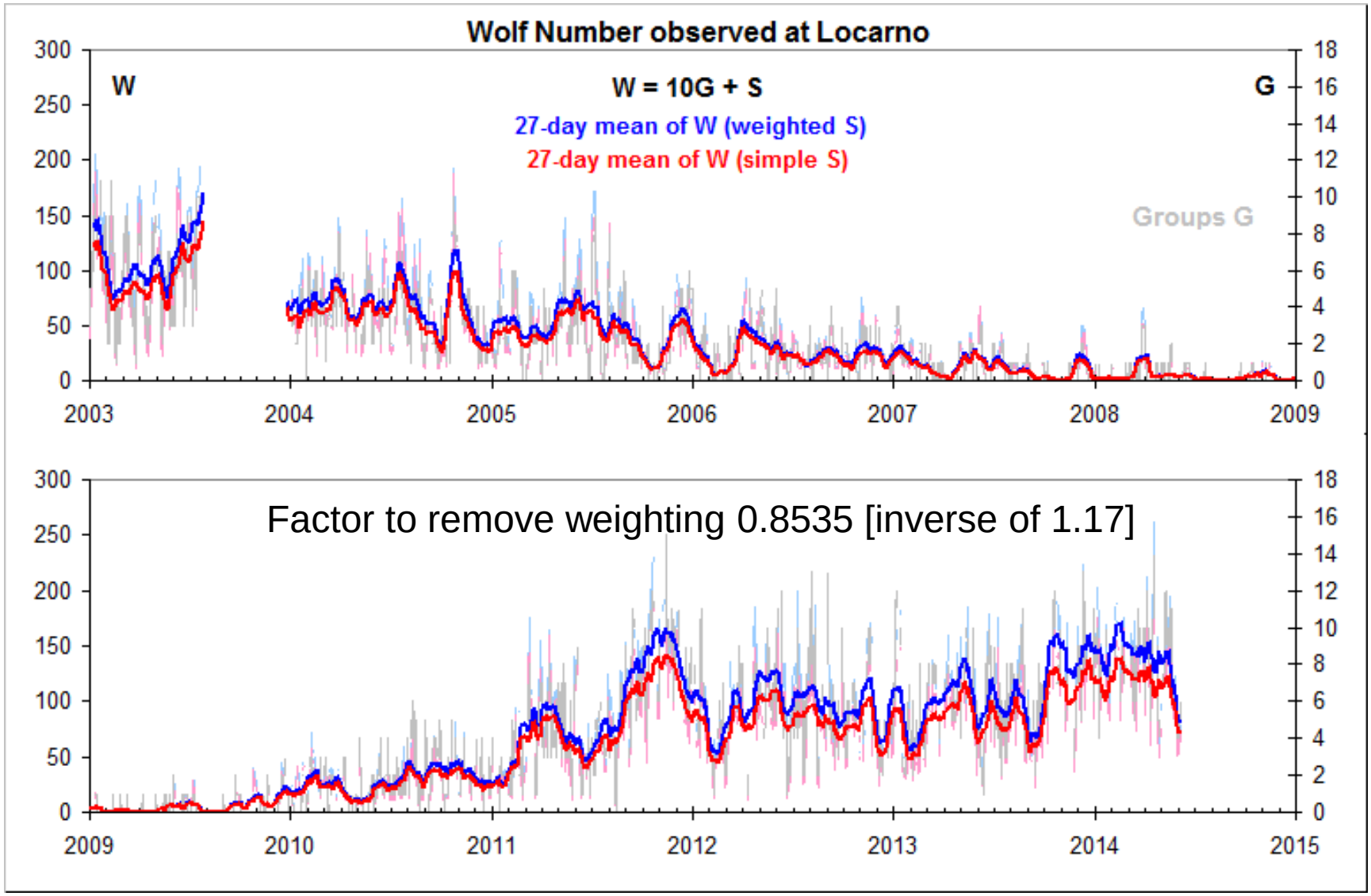

| g | f | |
|---|---|---|
| 141 | 3 | 1 |
| 143 | 15 | 6 |
| 144 | 6 | 2 |
| 145 | 17 | 9 |
| 146 | 3 | 1 |
| 5 | 44 | 19 |

5x10+44=94 5x10+19=69

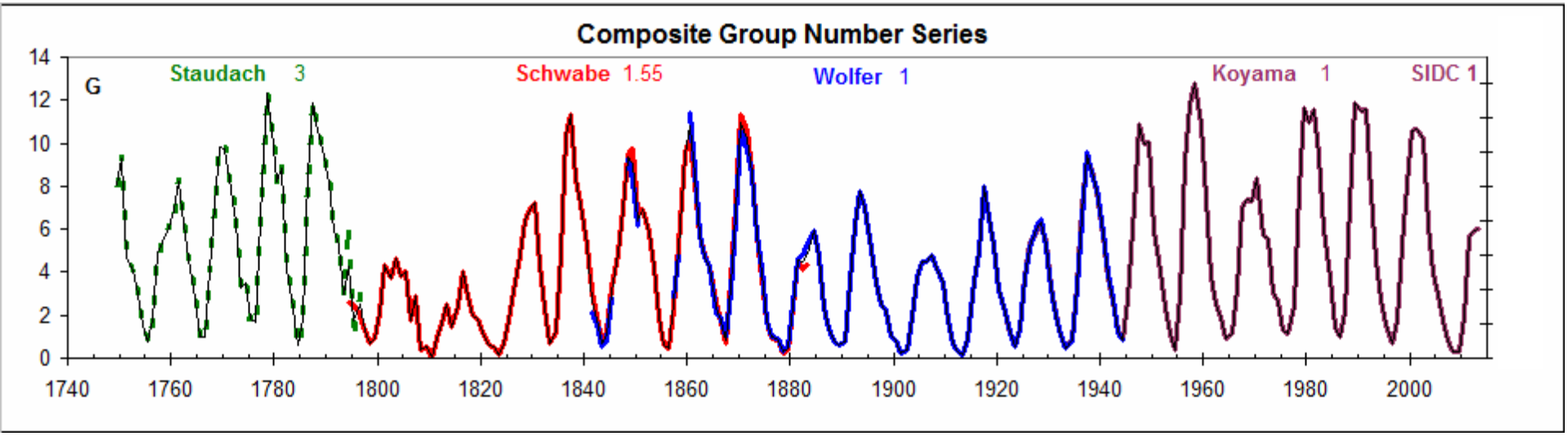
94/69 = 1.36

Recounted 2003-2014: ~55,000 spots

# Effect on the Wolf Number



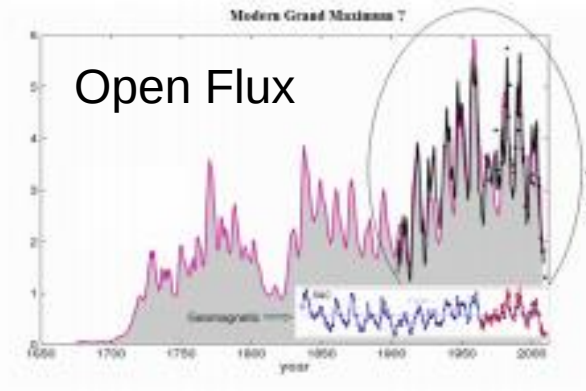
# SSN4: No Modern **Grand** Maximum

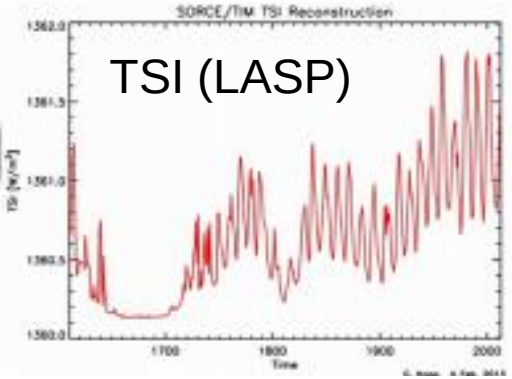


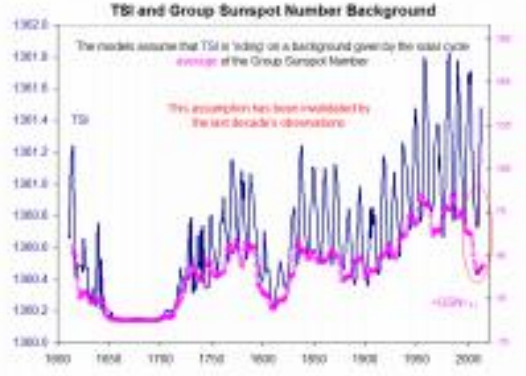

The preliminary new sunspot record expressed in terms of the number of sunspot groups. Of note is that there is a maximum in every century, none of them particularly ‘Grand’.

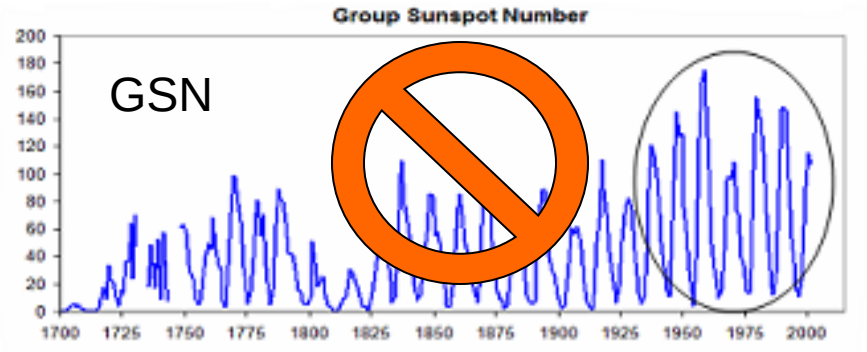
The new Wolf Number should be used as model input and we should understand the behavior and the fit of the model to the new perspective and to HMF B before we can extrapolate with any degree of confidence to the Maunder Minimum.

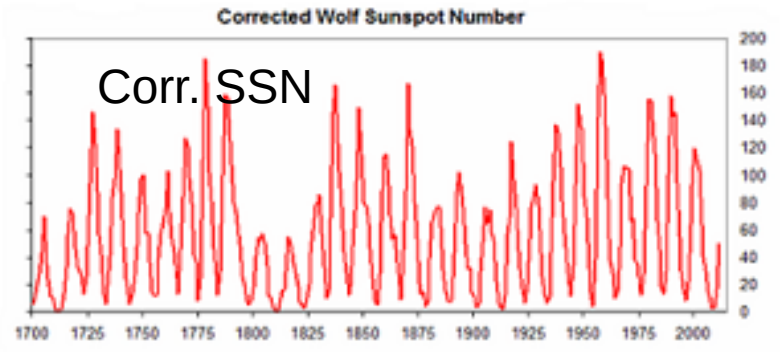
# No Rising Background ‘Base Level’

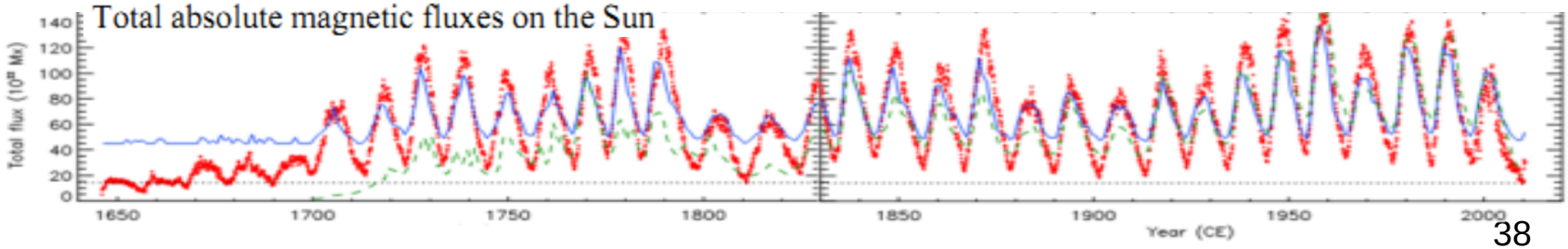


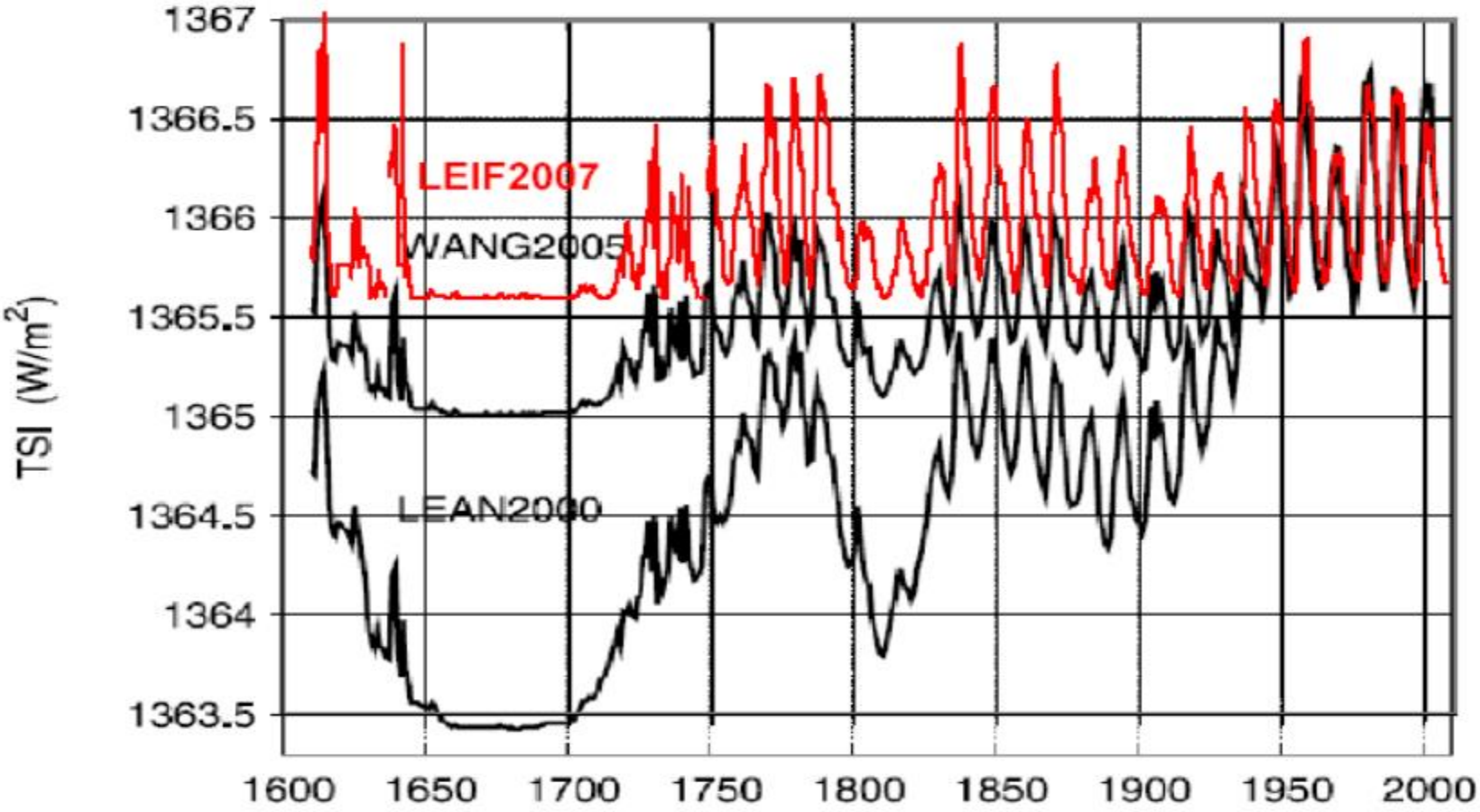



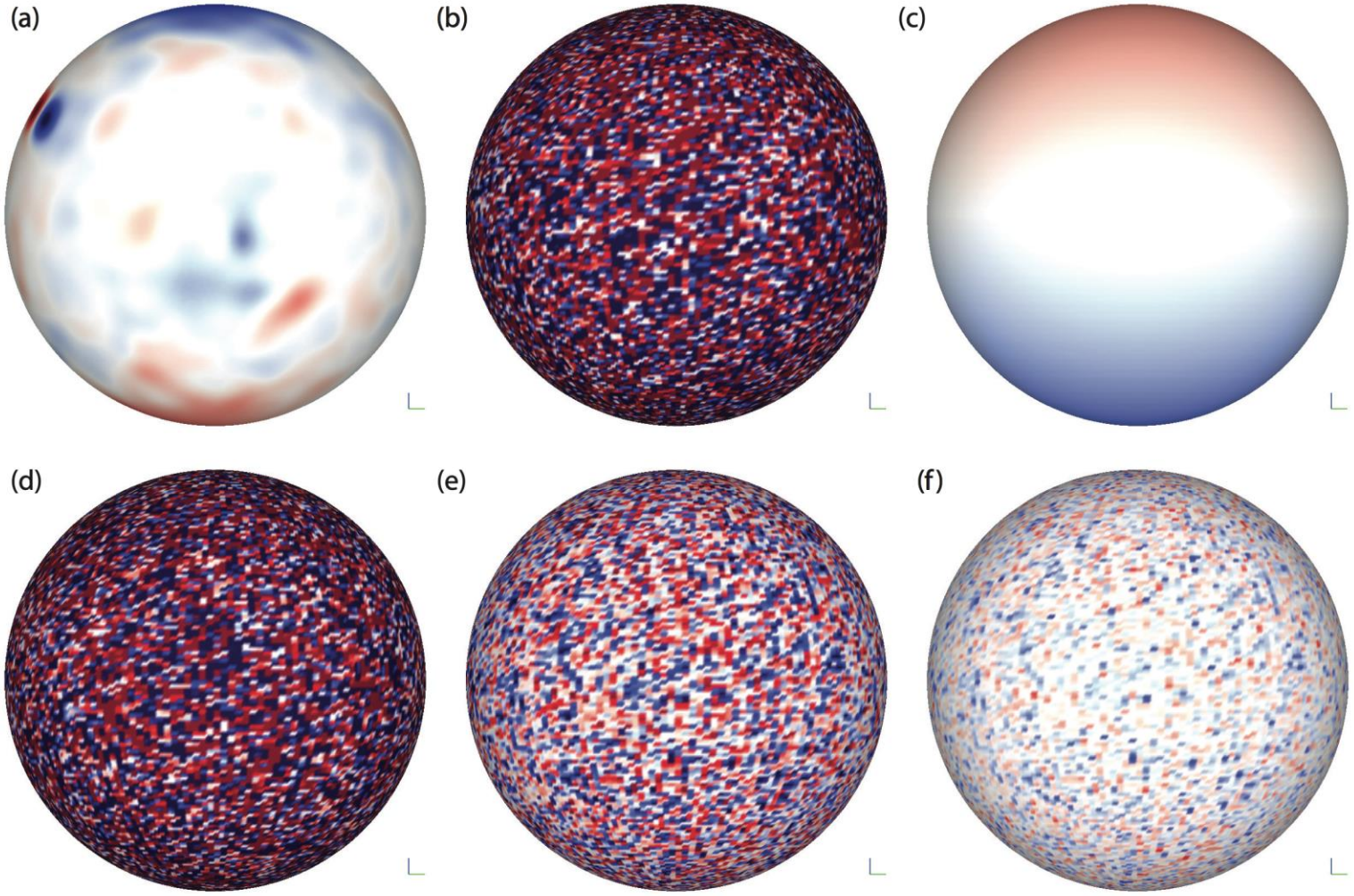



# Perhaps the Maunder Minimum was Less Extreme than we Thought




The emergence of ‘ephemeral regions’ does not show any solar cycle dependence [e.g. Hagenaar, 2008], thus no ever-increasing background

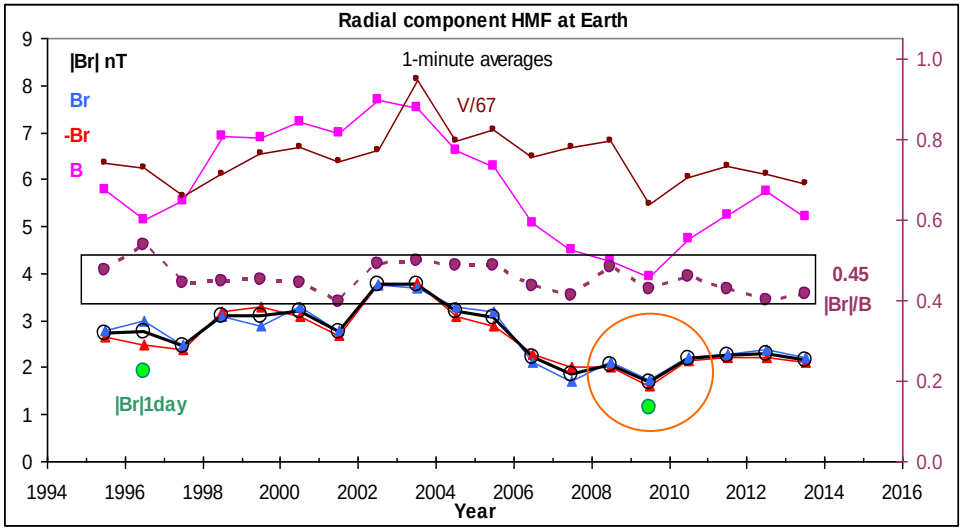
# MHD Modeling [Riley et al.]

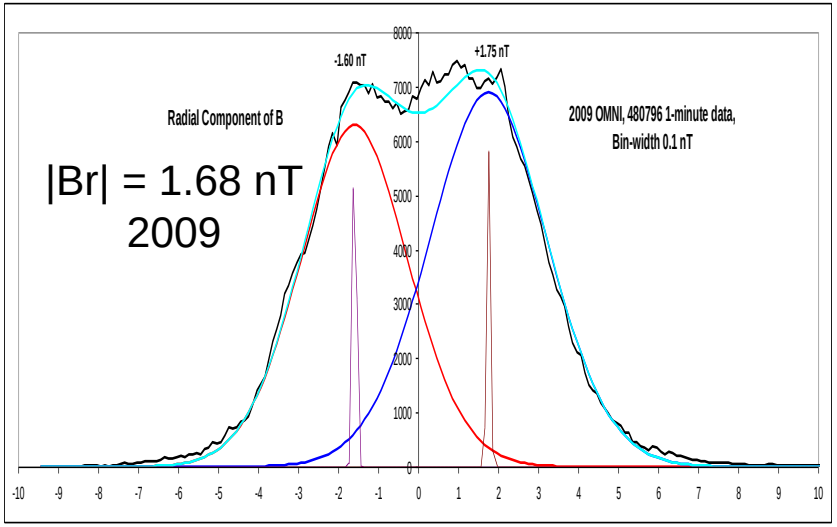


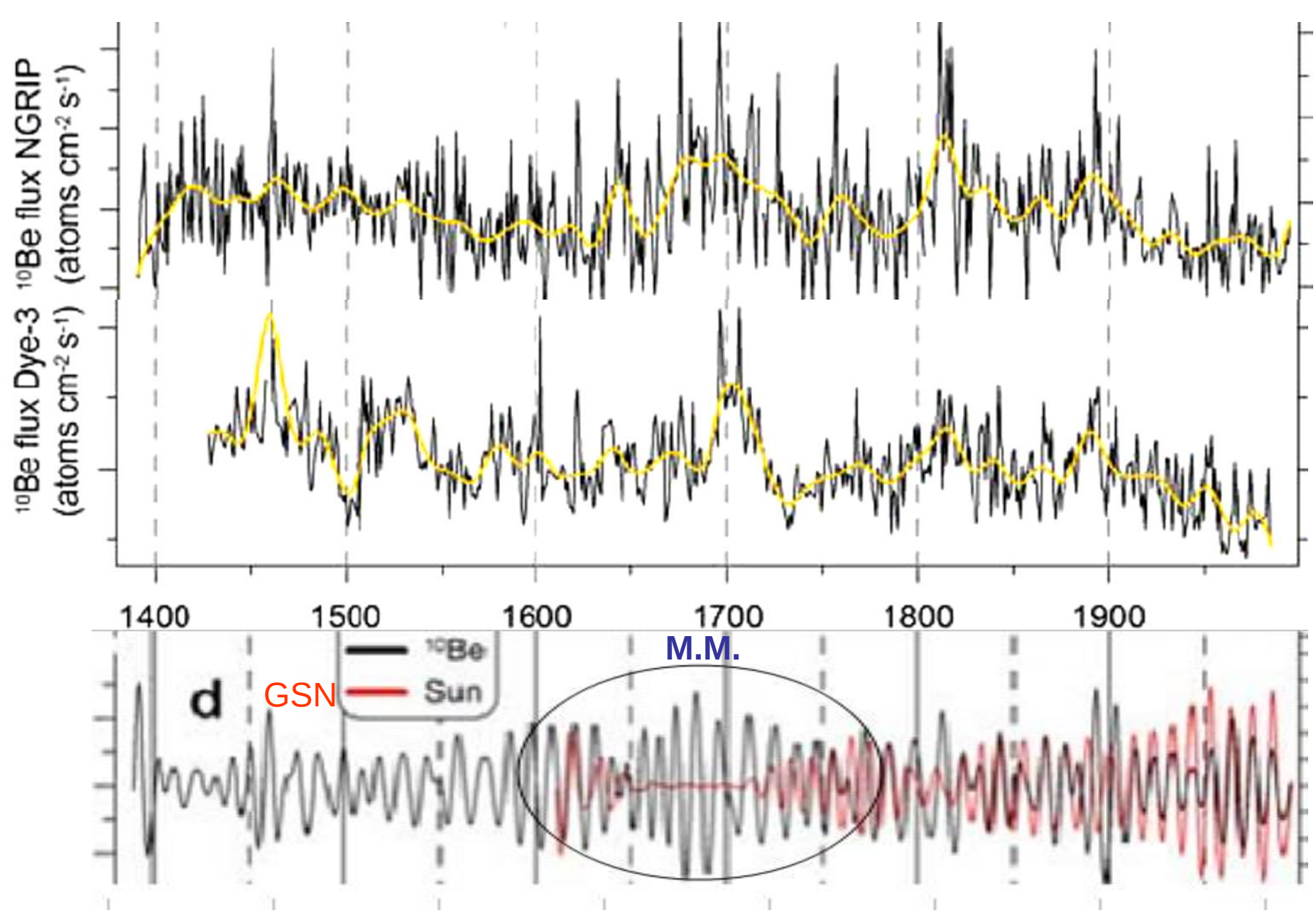
# Computed Radial HMF at 1 AU

| Model | Description | Open Flux |
|---|---|---|
| (a) | CR 2085 (06/26/09-07/23/09) | 1.0 nT |
| (b) | Parasitic polarity (±10 G) + Large-scale dipole (3.3G) | 2.4 nT |
| (c) | Large-scale dipole only (3.3G) | 2.2 nT |
| (d) | Parasitic polarity (±10 G) + Large-scale dipole (1G) | 1.2 nT |
| (e) | Parasitic polarity only (±10 G) | 0.29 nT |
| (f) | Parasitic polarity only (±3.3 G) | 0.08 nT |

Polar Fields needed

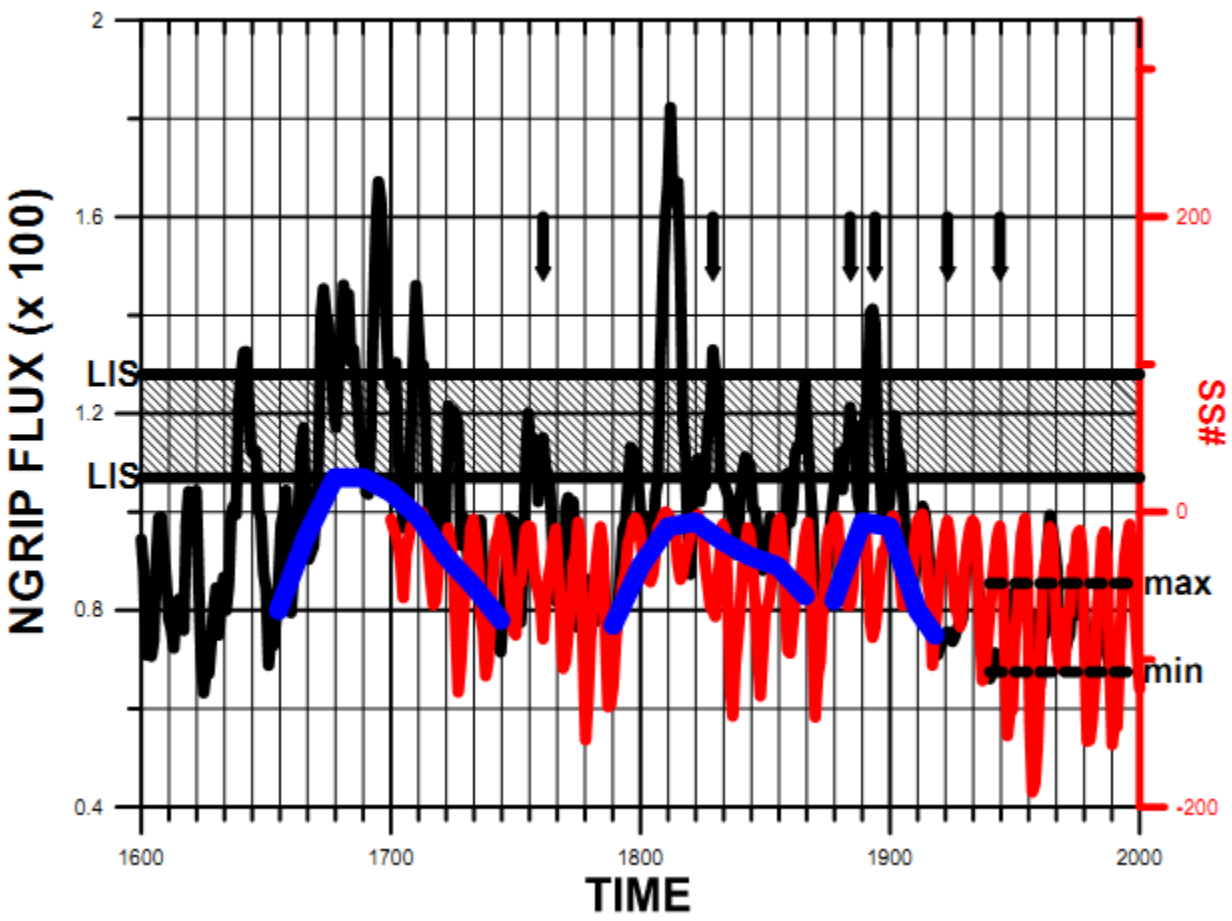





# Cosmic Ray Proxy [Berggren et al., 2009]

# We do not understand the 10Be modulation




"we have an upper limit to the absolute maximum 10Be flux which is only ~1.25 times the recent average maximum intensity of 10Be measured. This value corresponds to the lowest bound of the shaded region in Figure 5. This lower bound includes many other earlier time periods with 10Be flux values that exceed those possible from 10Be production alone from the full LIS spectrum. Indeed this implies that **more than 50% the 10Be flux increase around, e.g., 1700 A.D., 1810 A.D. and 1895 A.D. is due to non-production related increases!** "

"Other influences on the ice core measurements, as large as or larger than the production changes themselves, are occurring. These influences could be climatic or instrumentally based. We suggest new ice core measurements that might help in defining more clearly what these influences are and-if possible-to correct for them. " **Webber et al. arXiv:1004.2675 (2010)**

# ‘Burning Prairie’ => Magnetism

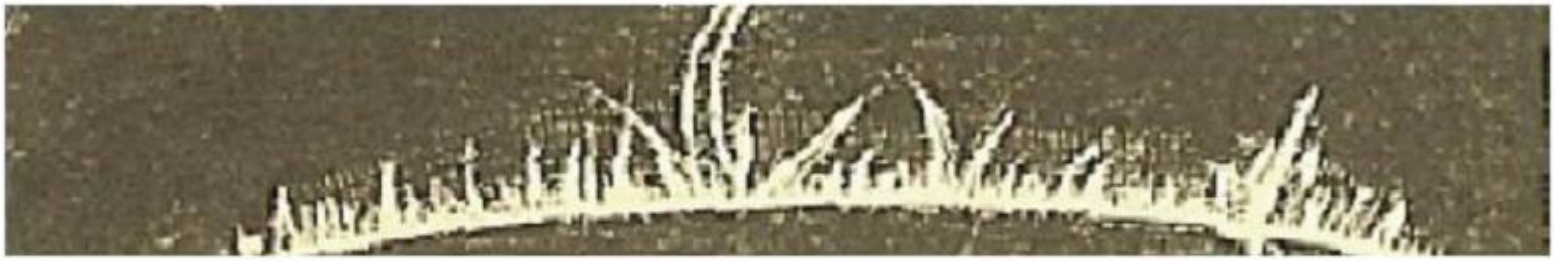


**Figure 1** An early drawing of the “burning prairie” appearance of the Sun’s limb made by C.A. Young, on 25 July 1872. All but the few longest individual radial structures are spicules.

It is now well known (see, *e.g.,* the overview in Foukal, 2004) that the spicule jets move upward along magnetic field lines rooted in the photosphere outside of sunspots. Thus the observation of the red flash produced by the spicules requires the presence of widespread solar magnetic fields. Historical records of solar eclipse observations provide the first known report of the red flash, observed by Stannyan at Bern, Switzerland, during the eclipse of 1706 (Young, 1883). The second observation, at the 1715 eclipse in England, was made by, among others, Edmund Halley – the Astronomer Royal. These first observations of the red flash imply that a significant level of solar magnetism must have existed even when very few spots were observed, during the latter part of the Maunder Minimum.

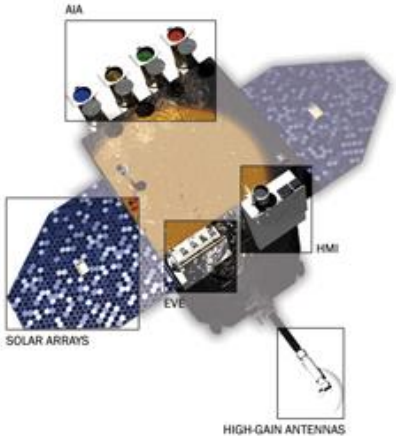
Foukal & Eddy, Solar Phys. 2007, *245*, 247-249

# Birth of an Active Region


NOAA 11158, February, 2011

Solar Dynamics Observatory (SDO)

“All the Sun, All the Time”




Visible Light

Sunspots grow by the accumulation of smaller spots and pores.

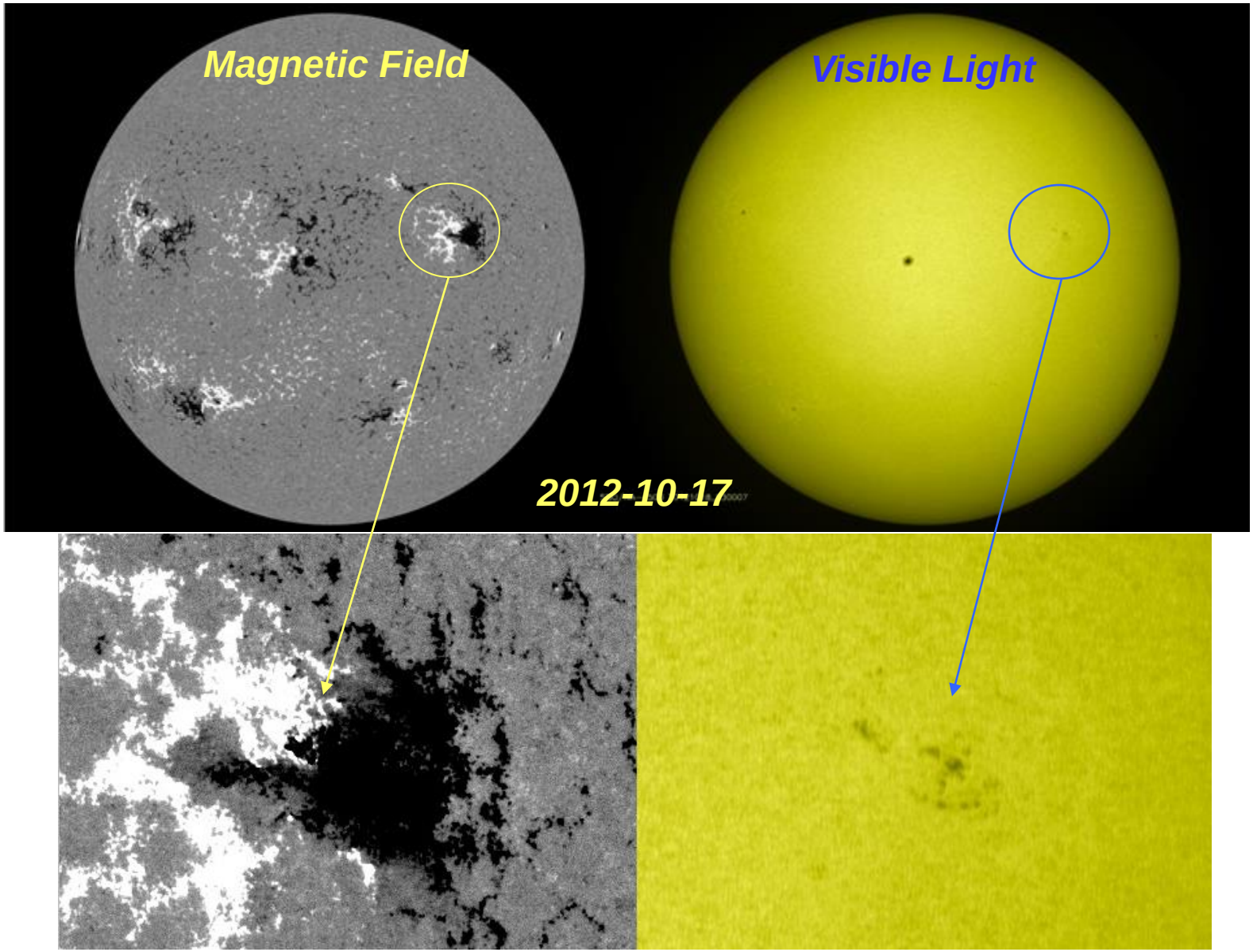
You may have to click on the area to play the movie.

It may not play on a Mac.

# My Personal Working Hypothesis

- The Maunder Minimum was not a serious deficit of magnetic flux, but
- A lessening of the efficiency of the process that compacts magnetic fields into visible spots
- This may now be happening again soon
- If so, there is new solar physics to be learned

# Perhaps like this:



# The Maunder Minimum is as Mysterious as Ever

(but so was the notion a decade ago that we would ever successfully reconstruct the solar wind properties for the past 170 years…)