

What Causes Total Solar Irradiance Changes During a Deep Solar Minimum ?

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The total solar irradiance (TSI) variability is known to be governed ***primarily*** by two competing factors (used as proxies in the TSI modeling):

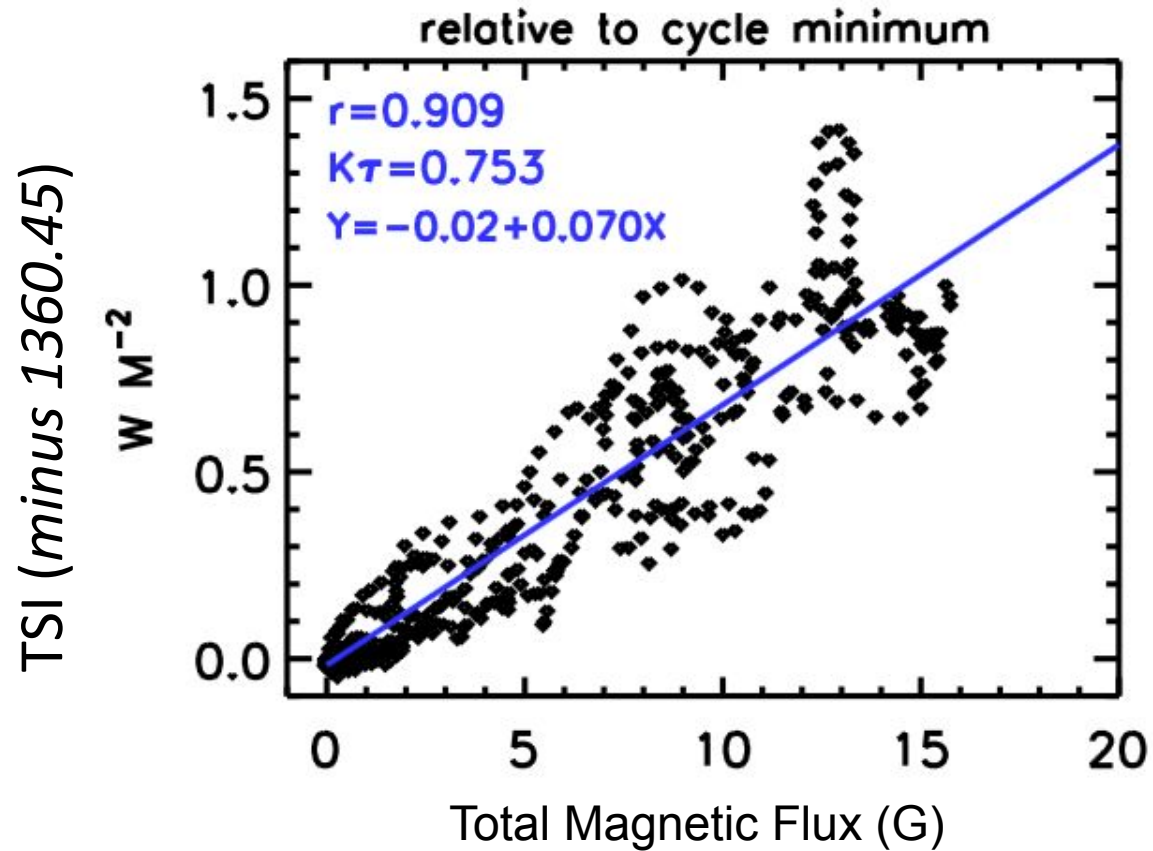
- the dark (mostly sunspots) and
- bright (facular fields, networks, plages, etc.) surface features.



These two sources may explain
 $\geq 85\%$ of ΔTSI

Is there any additional factor to be

Δ TSI and photospheric magnetic fields



Rempel (2020): Quiet Sun + weak network environment

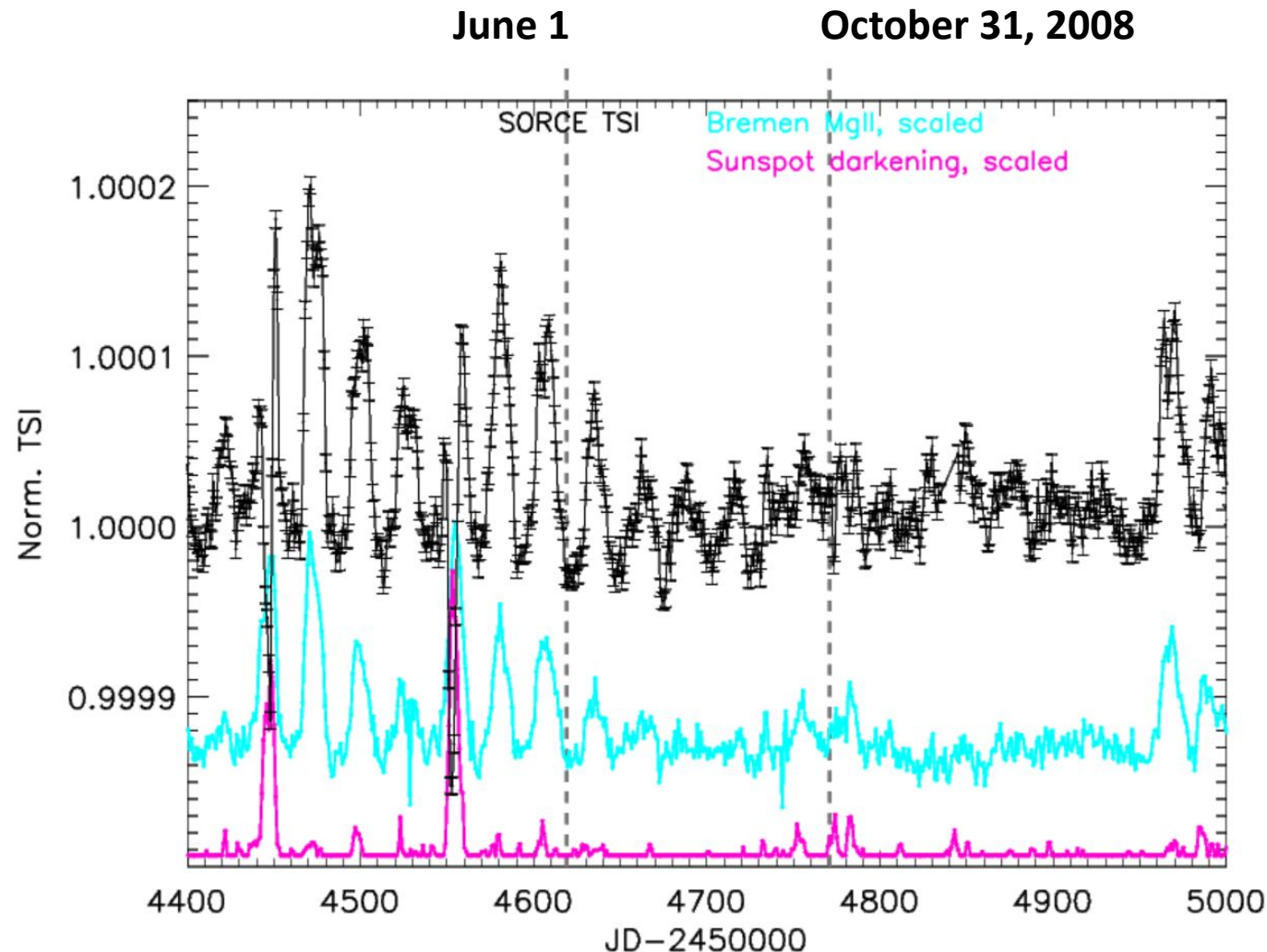
$$\Delta \log(\text{TSI}) / \Delta B \text{ (G}^{-1}\text{)} = \begin{cases} 1.42 \times 10^{-4} \\ 1.73 \times 10^{-4} \end{cases}$$

from the flux transport simulations (*Wang & Lean, ApJ, 2021*)

What happens to ΔTSI if one to

‘remove’ the darkening factor and
‘diminish’ the influence of the brightening factor?

The fabulous 2008-2009 solar minimum: ‘the best space-era proxy for the Maunder minimum’

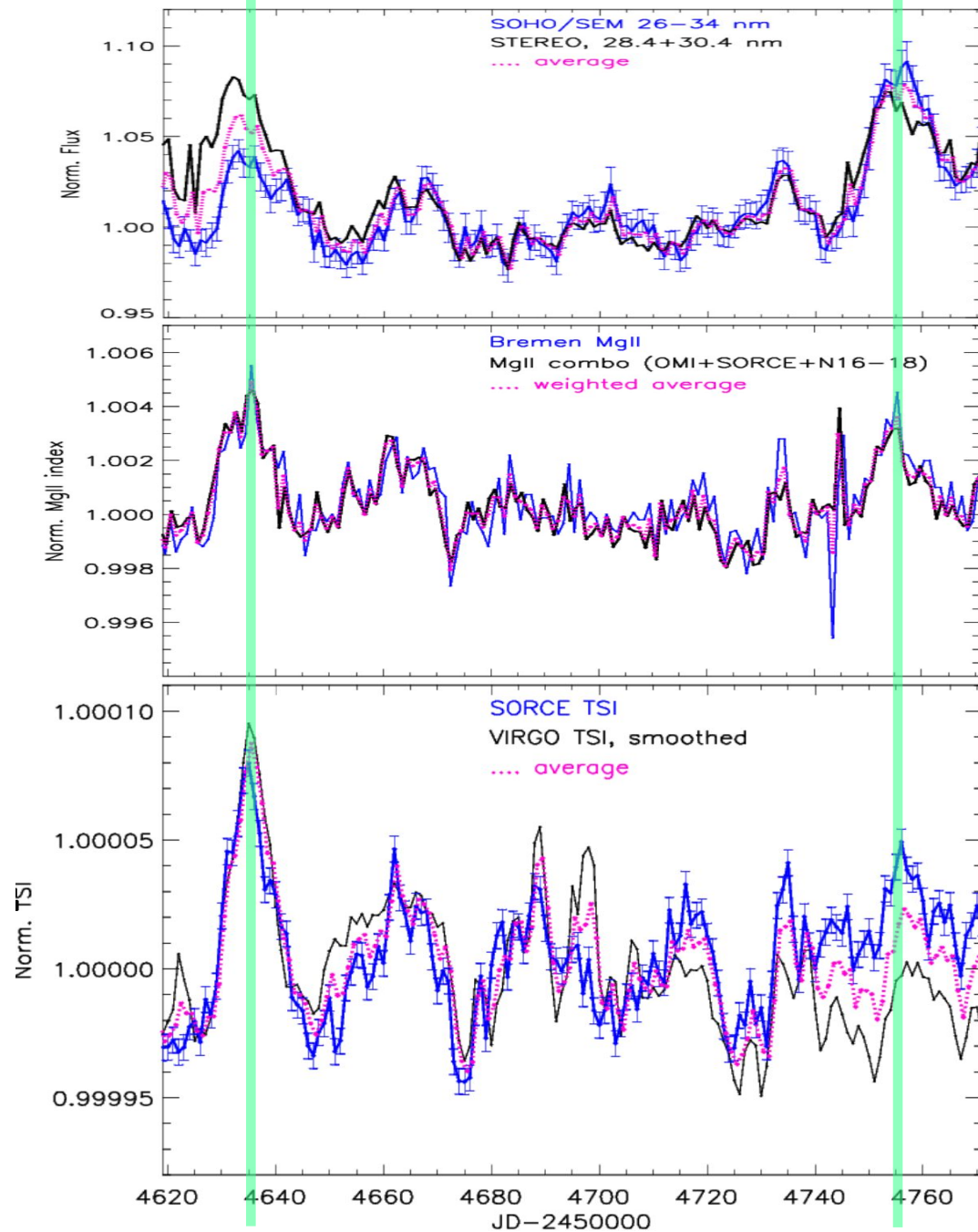


June 1 – October 31, 2008:

- in the beginning, a single, rapidly decaying, small-scale active region; another small-scale AR at the end
- practically spotless environment
- clear (though low-amplitude) TSI modulation
- a wealth of data to choose from

June 1

October 31, 2008



10%

EUV: SoHO/SEM & STEREO (A&B) →
~uniform surface coverage

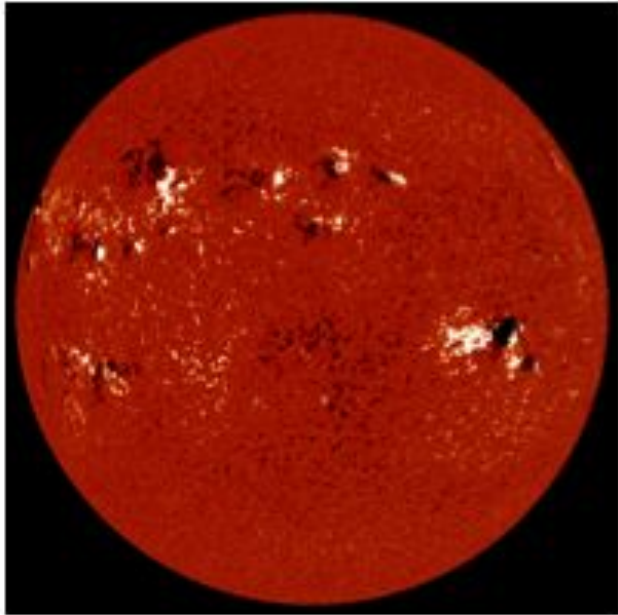
0.5%

Mg II indices: cf. >6% solar-cycle changes

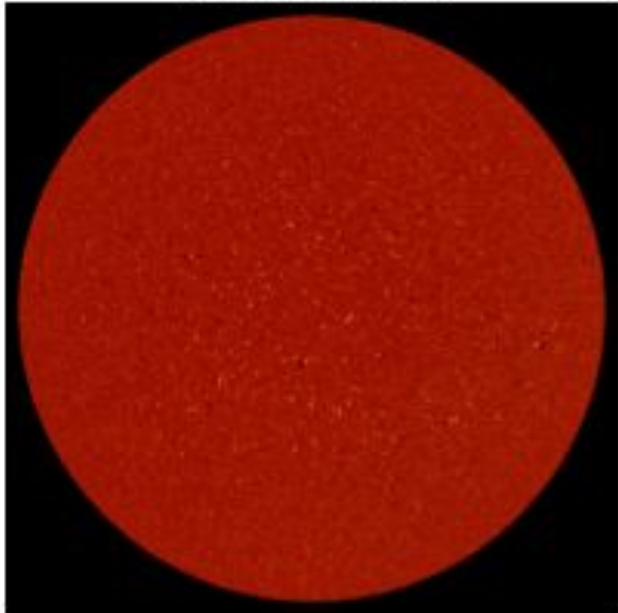
100ppm

TSI: cf. >1000 ppm solar-cycle changes

MDI: 2001 1 4

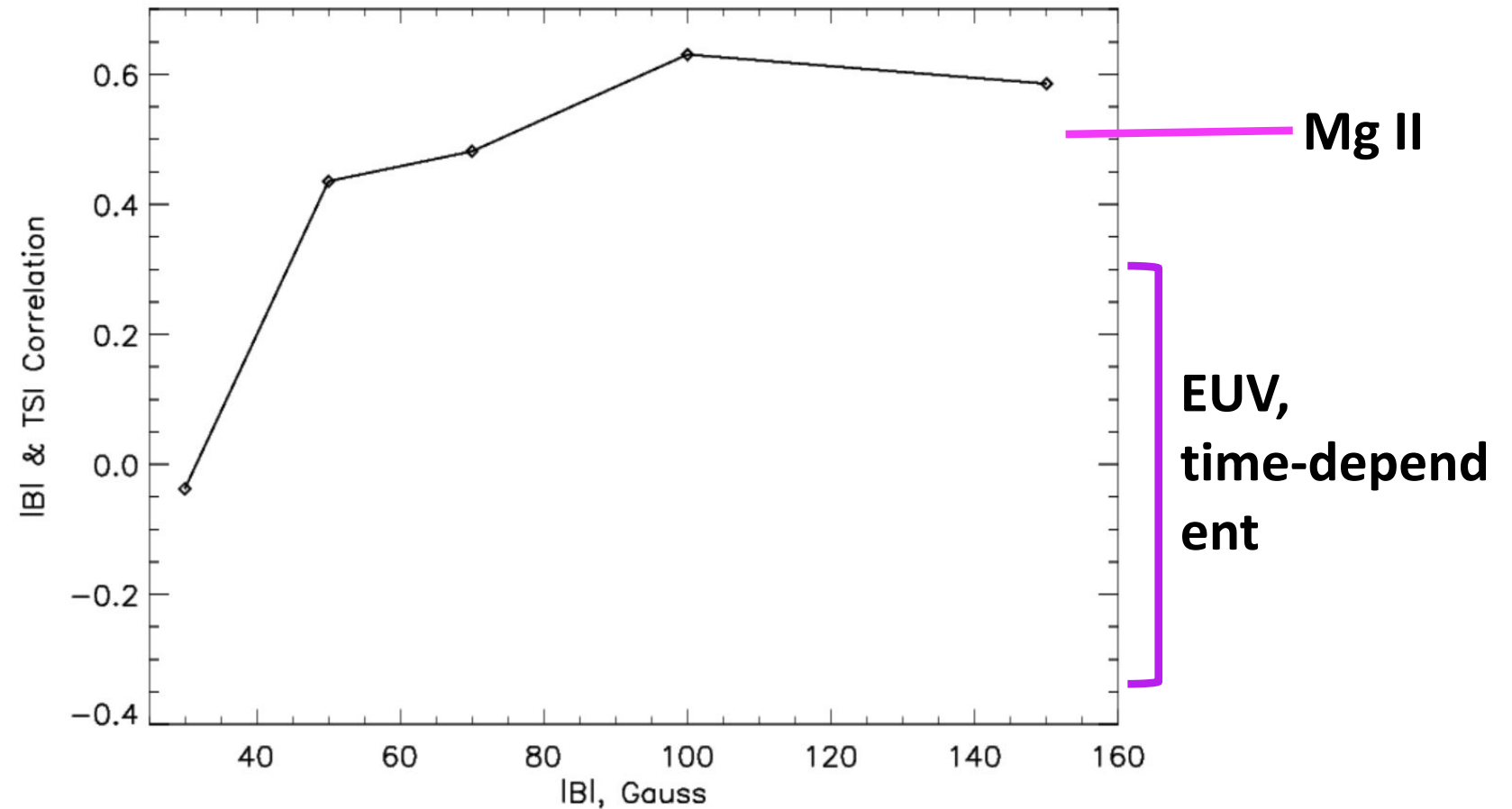


MDI: 2008 3 8

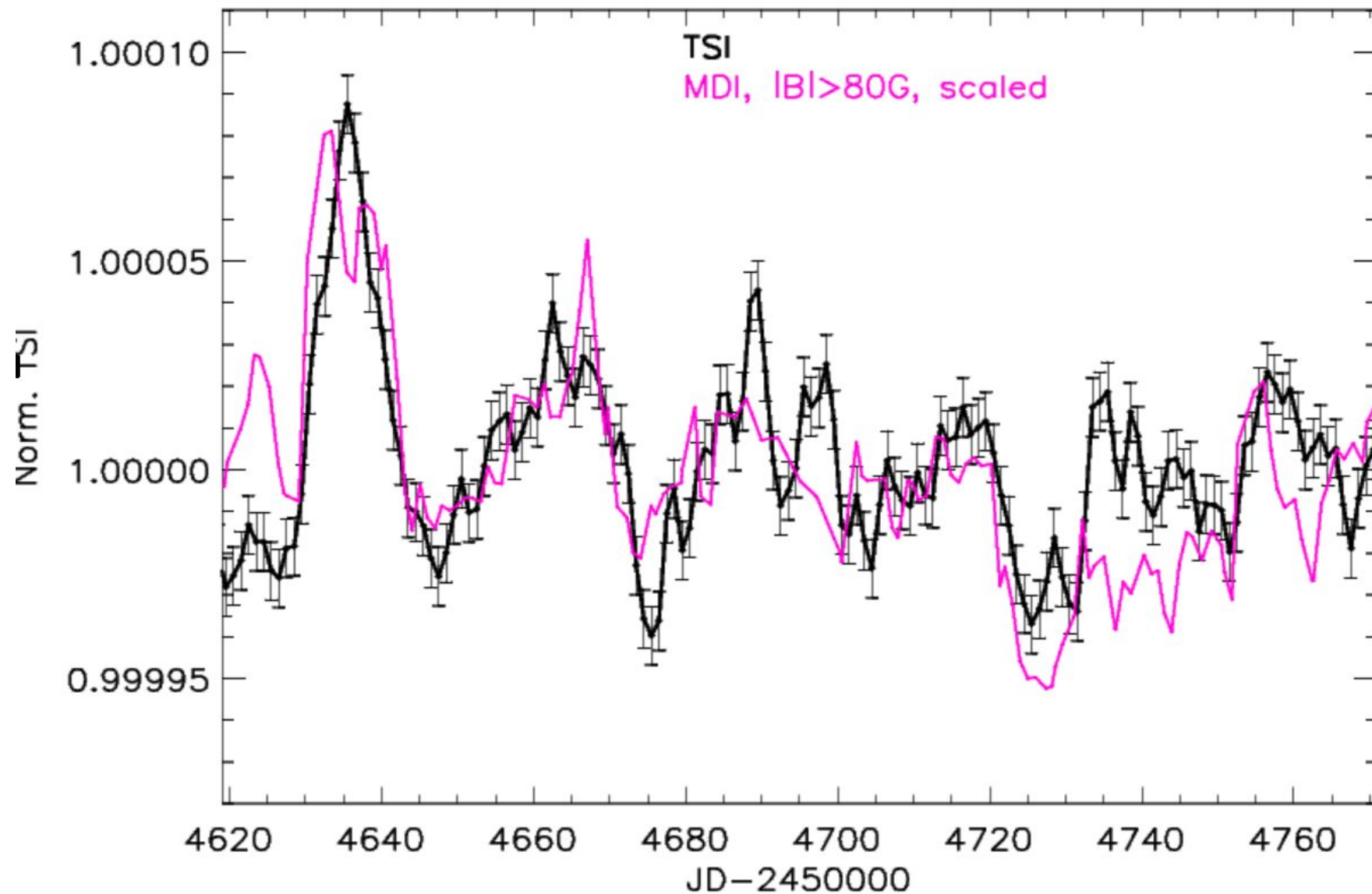


SoHO Michelson Doppler Imager (MDI)

MDI magnetograms: full-disk, $\text{los } |B|$, de-noised, μ -constrained and assembled into 20-min sequences



The MDI magnetic $|B| > 80 \text{ G}$ sources (source area fractions) are the best ΔTSI proxies for June-October 2008.

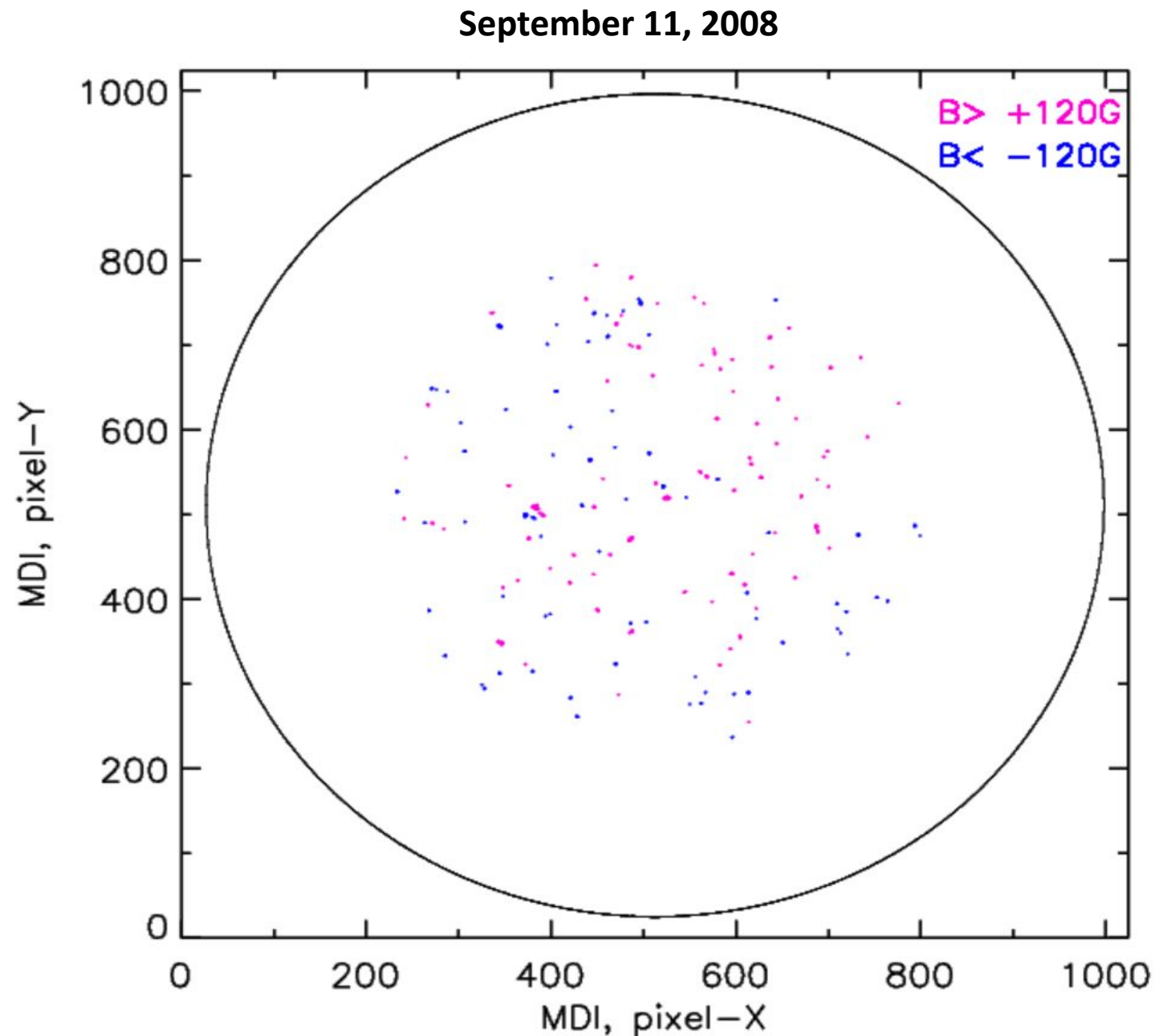


These $|B| > 80$ G sources are:

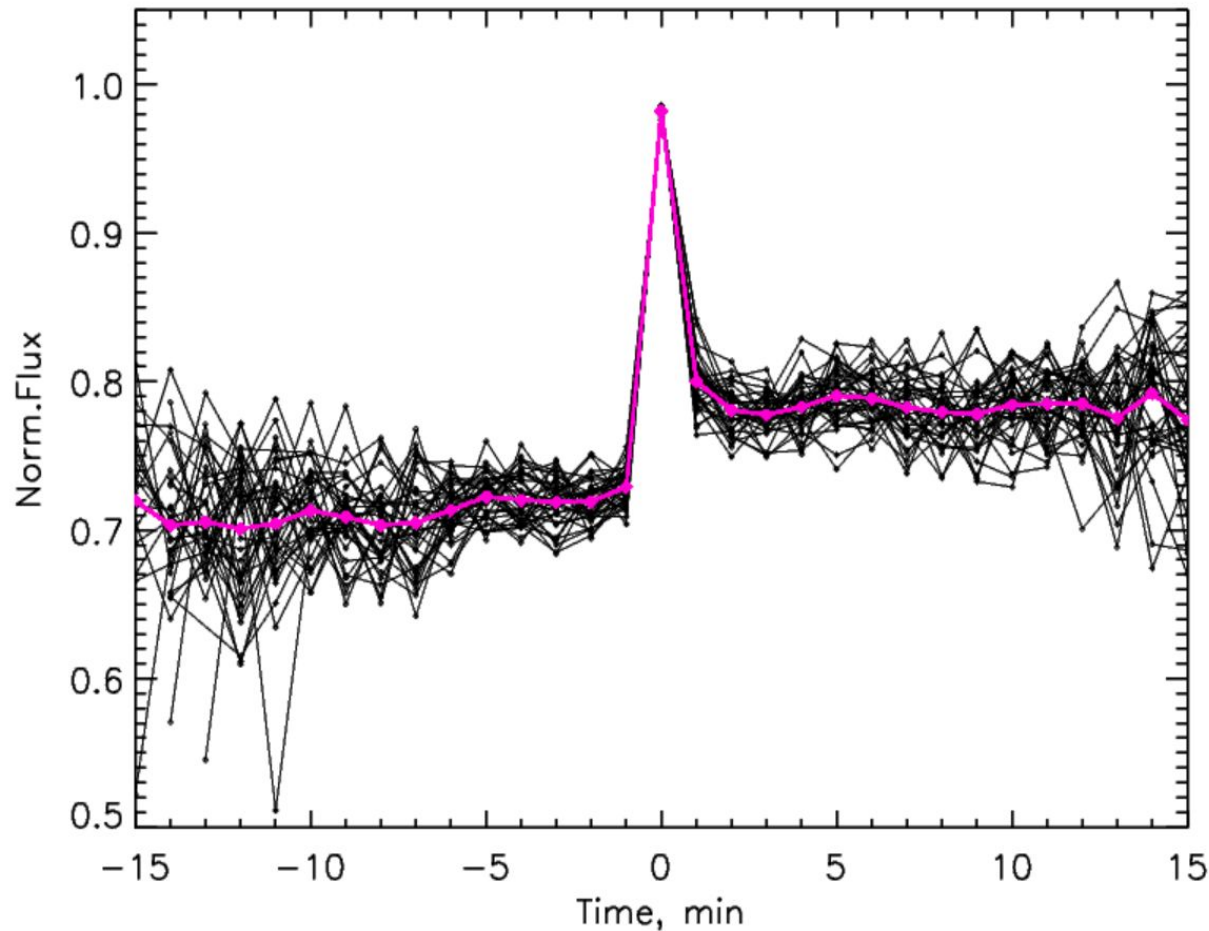
- small-scale ($\sim 50\%$ @ 1 MDI $2''$ pixel)
- short-living - a mix of
 - magnetic bright points (**$\sim 25\%$; $T < 20$ min lifetimes**) and
 - ephemeral regions (**$\sim 75\%$; $T \sim 2-4$ h**)

ERs are:


- clustering on **$D \sim 200-230$ Mm** scales
- most active in the equatorial, $|l| < 20^\circ$, zone



Normalized magnetic flux of the short-living ($T \leq 15$ min) sources from July 03, 2008.

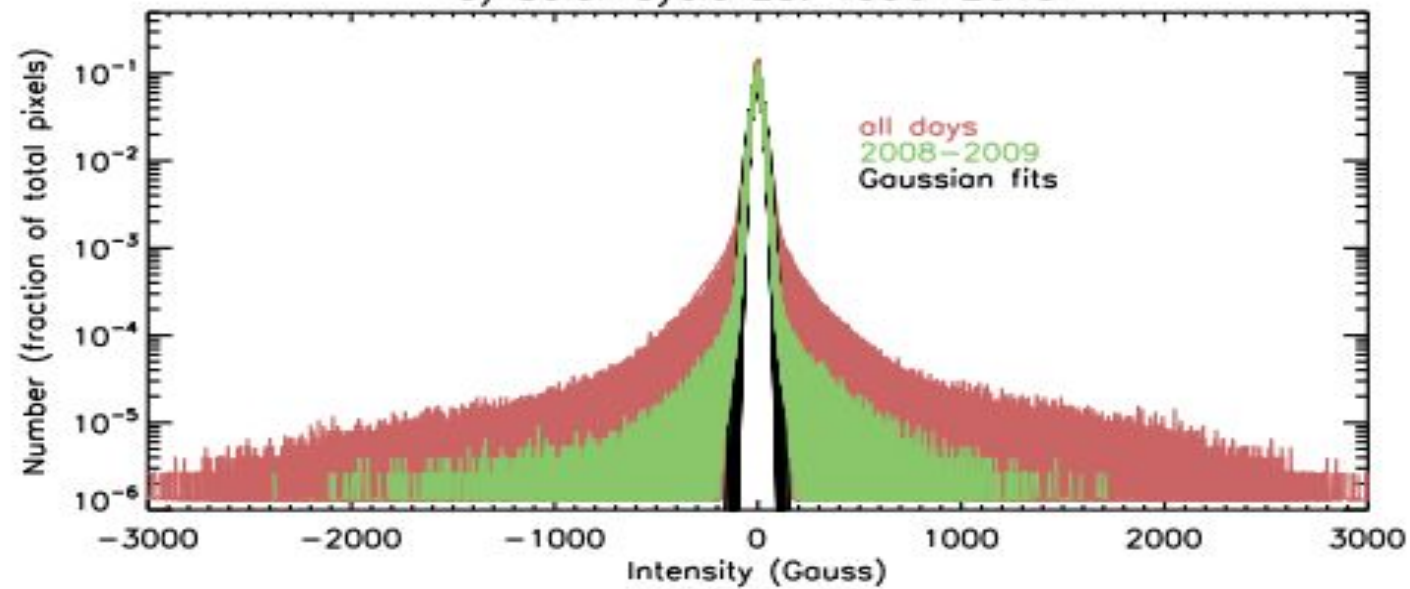


Most likely, these are **magnetic bright points** (e.g., Berrios Saavedra et al. 2022):

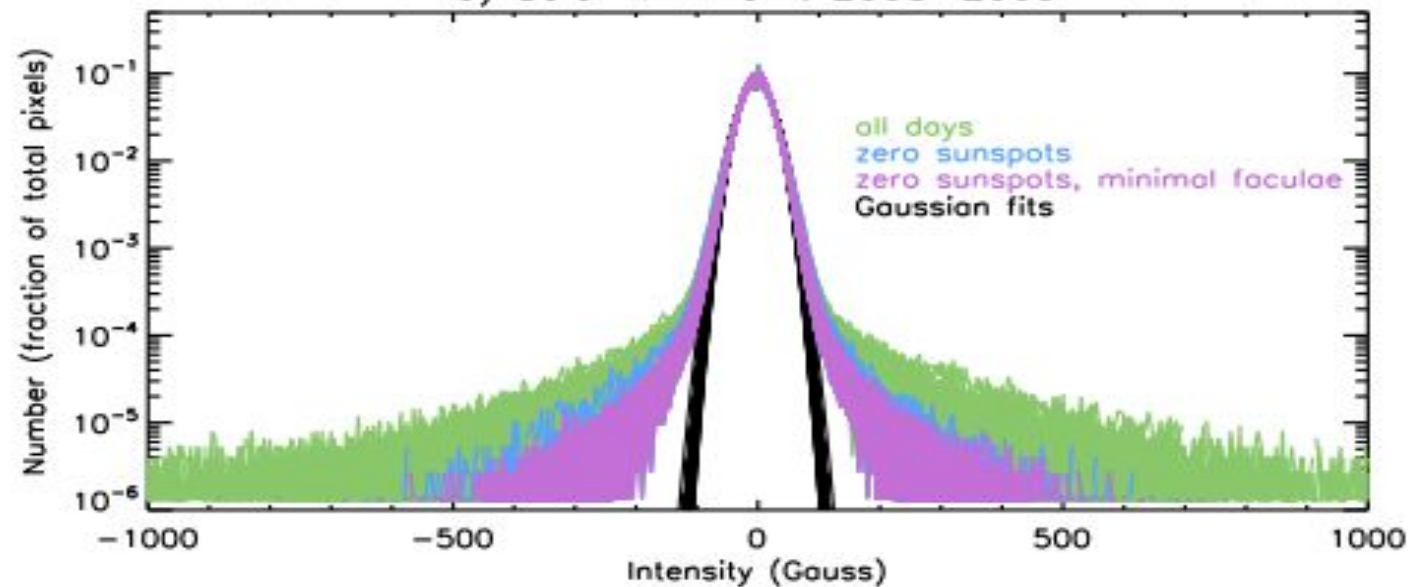
small ($d \ll 500$ km) magnetic flux tubes experiencing rapid convective collapse  magnetic field and temperature/brightness spike[s].

HISTOGRAMS OF MDI MAGNETOGRAMS

a) Solar Cycle 23: 1996–2010



b) Solar Minimum: 2008–2009



The MDI data show that even during the deep 2008-2009 minimum the level of total magnetic flux remained slightly elevated relative to an "invariant" baseline (presumably the Maunder minimum):

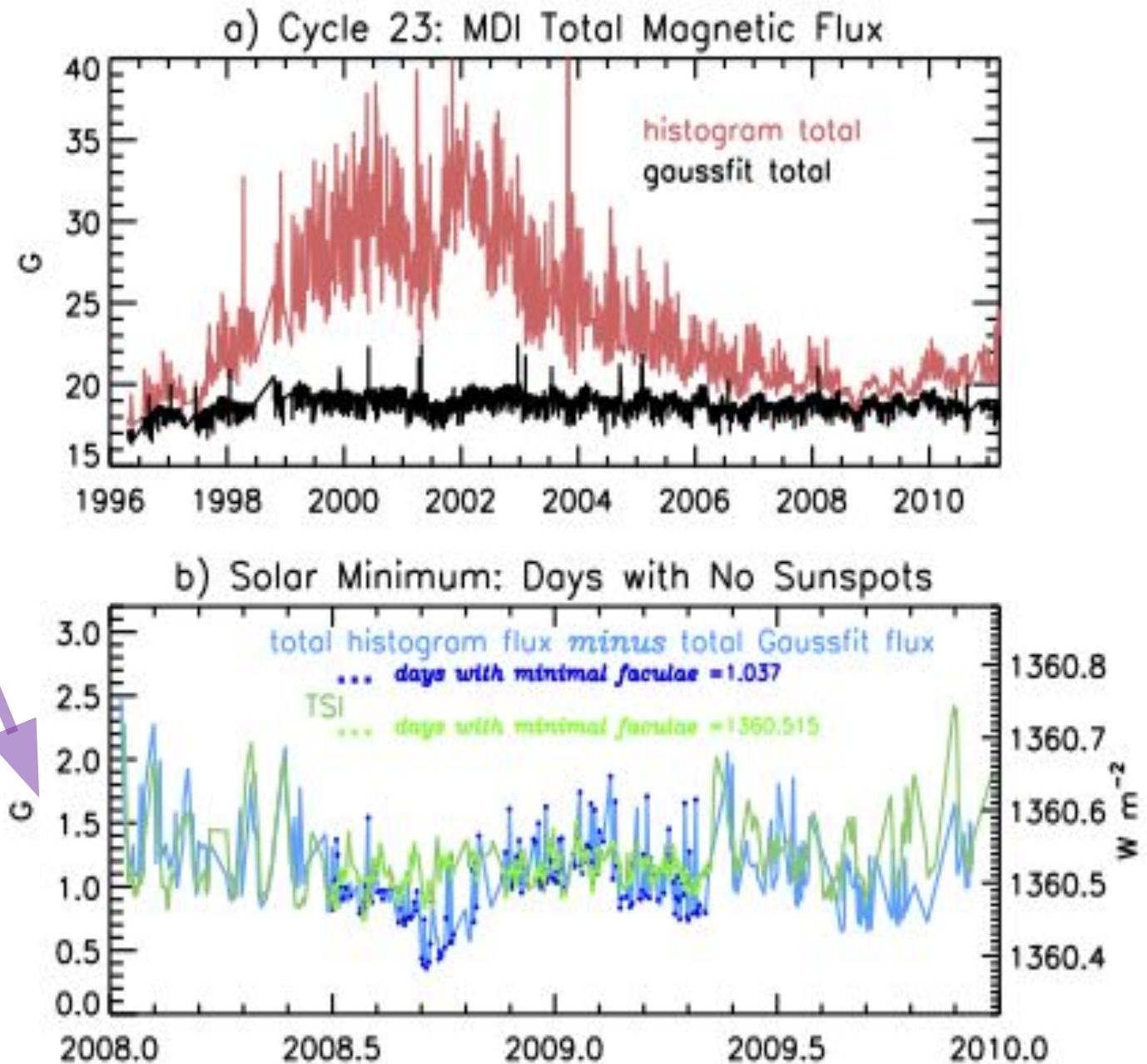
1 G = the average of total MDI histograms minus gaussfits during "quiet" conditions in 2008-2009

1 G leads to:

~**0.07 W/m² TSI change** using flux transport simulations of |B| from Wang & Lean (2021)

or

~**0.19 W/m² TSI change** using the linear |B| - TSI relationship from Rempel (2020)



Conclusions

During the deep, practically spotless 2008 minimum

- variations in TSI closely follow changes in total magnetic flux of the sources with $|B| > 80 \text{ G}$;
- these sources comprise the populations of
 - short-living ($< 20 \text{ min}$), small-scale, \sim evenly distributed magnetic bright points,
 - more extended (a few MDI pixels), longer-living (140-260 min median lifetimes) ephemeral regions that cluster on $\sim 200\text{-}230 \text{ Mm}$ scales.

Analysis of the histogram distributions of magnetic flux regions in 2008 indicates that TSI during more extended, deep minima, such as the Maunder Minimum, may be lower by **~ 0.07 to 0.19 W/m^2**
... assuming invariant Quiet Sun conditions