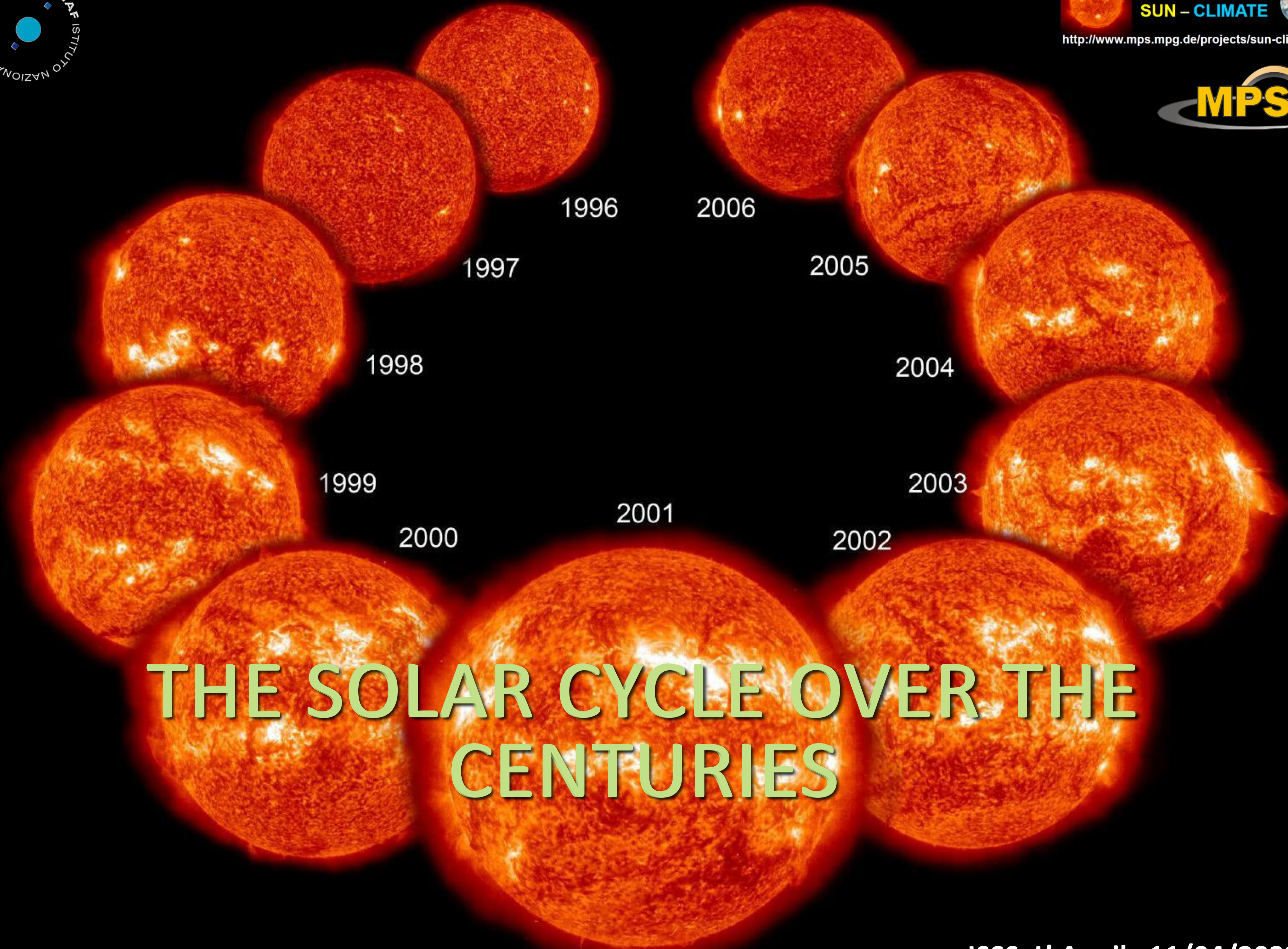
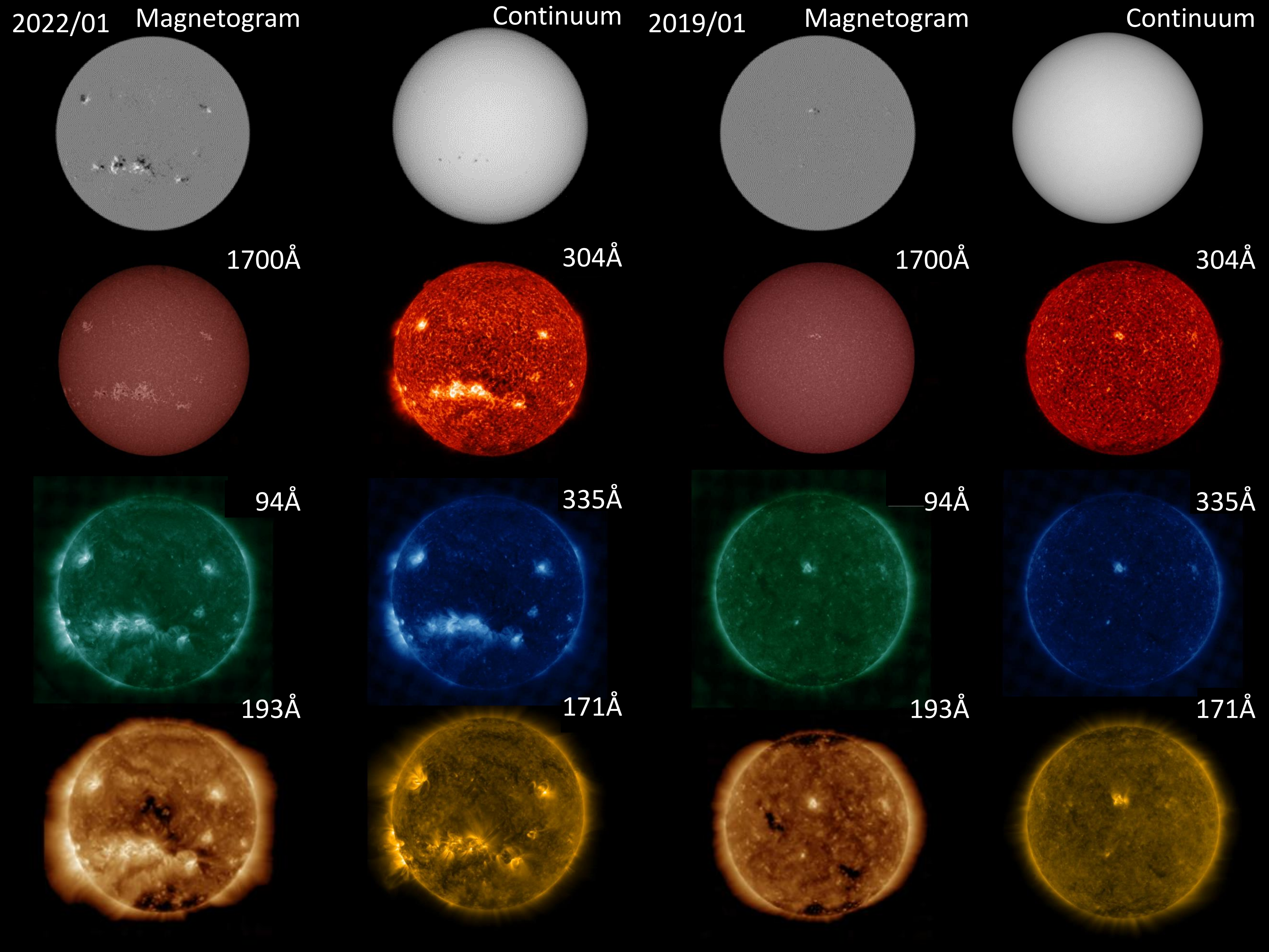
INAF ISTITUTO NAZIONALE DI ASTROFISICA

SUN – CLIMATE
http://www.mps.mpg.de/projects/sun-climate/
MPS



THE SOLAR CYCLE OVER THE CENTURIES

ISSS, L' Aquila 11/04/2022


2022/01
Magnetogram
Continuum
2019/01
Magnetogram
Continuum
1700Å
304Å
1700Å
304Å
94Å
335Å
94Å
335Å
193Å
171Å
193Å
171Å

Outline

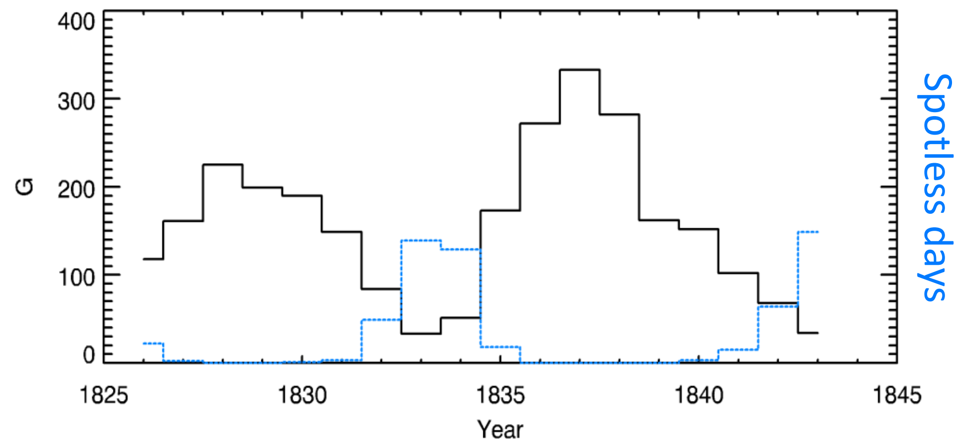
Part A

1. Sunspot (group) number/areas

Part B

1. ~~Filaments/Prominences~~
2. Plage areas
3. Solar irradiance

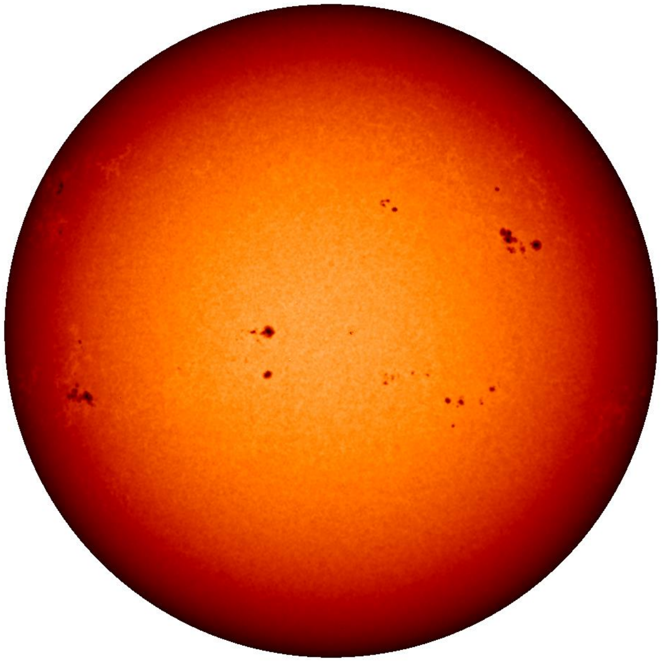
Sunspot number series

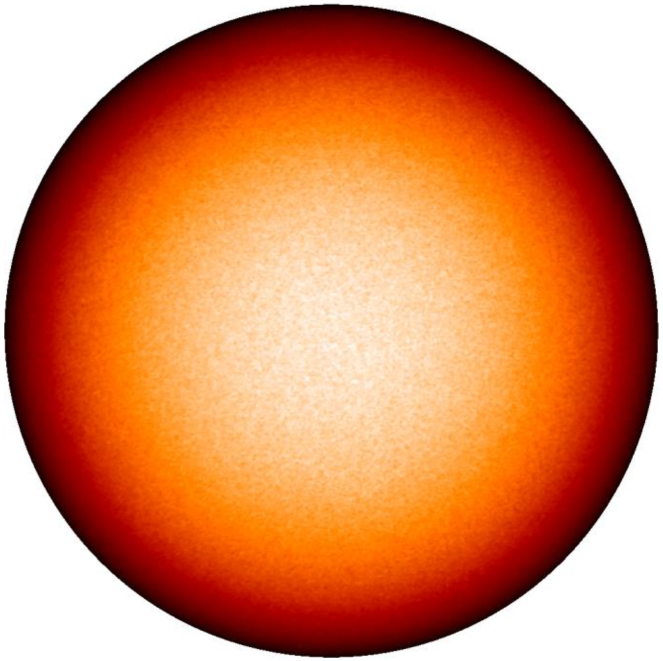


Schwabe 1844

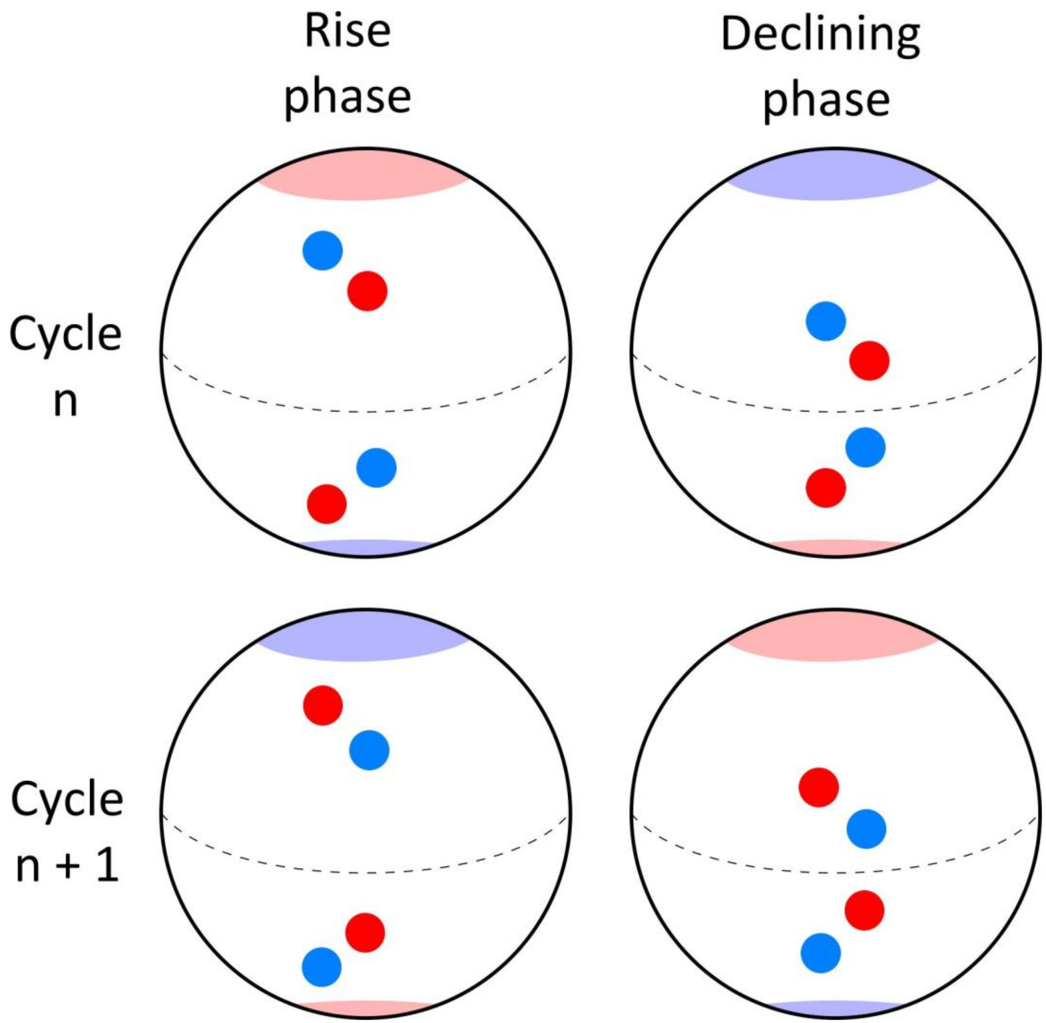
Solar Maximum

Solar Minimum

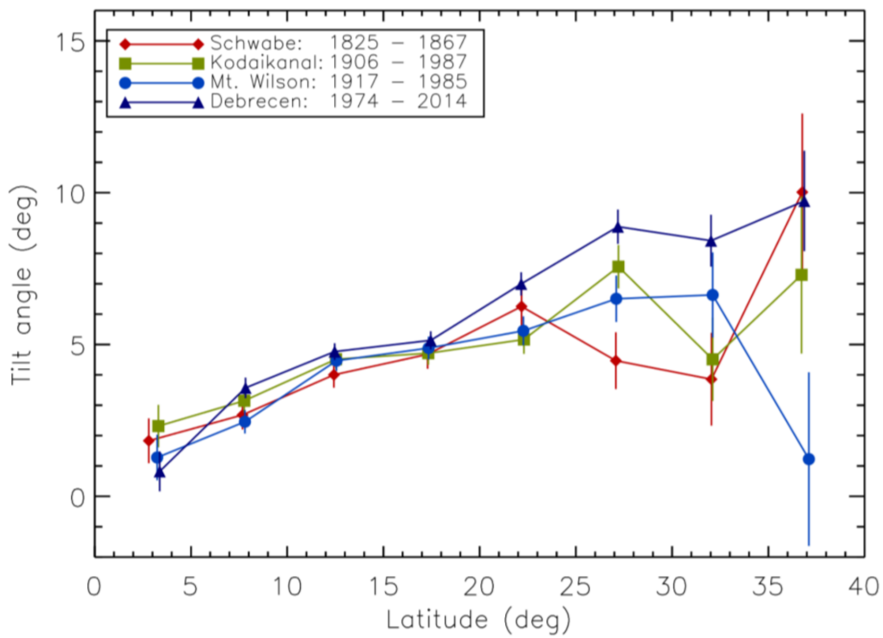




- **Hale's Law:** the polarity of the leading spot is the same as the one of the polar fields at the start of the solar cycle.
- **Spoerer's Law:** sunspots appear at progressively lower latitudes as the cycle evolves
- **Joy's Law:** the following-polarity spot is at higher latitude than the leading-polarity one.
- Tilt between following and leading polarity spots increases with latitude



van Driel-Gesztelyi & Owens 2020



Senthamizh Pavai et al. 2015

Monastery at Worcester, 08/12/1128

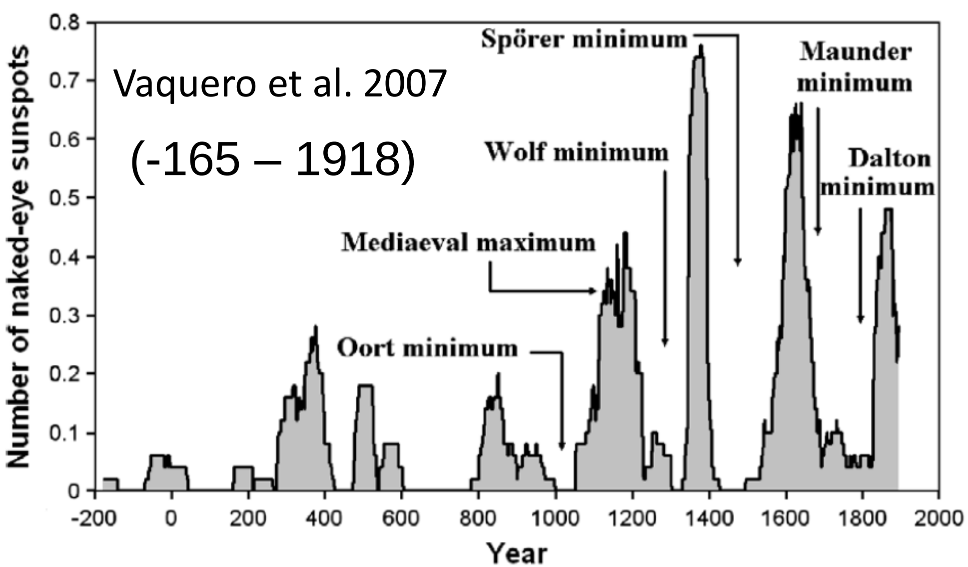
79. 1151 Mar 21, Mar 31 and Apr 1 (visible on 3 separate days)
[KOREA] King Uijong, 5th year, 3rd month, day *kuei-yu* (10) - Mar 21. "On the Sun there was a black spot as large as a hen's egg. On day *kuei-wei* (20) - Mar 31 - and day *chia-shen* (21) - Apr 1 - it was the same." (*Koryo-sa*, 47) (CS75, K74, CD89, CD90, WX)

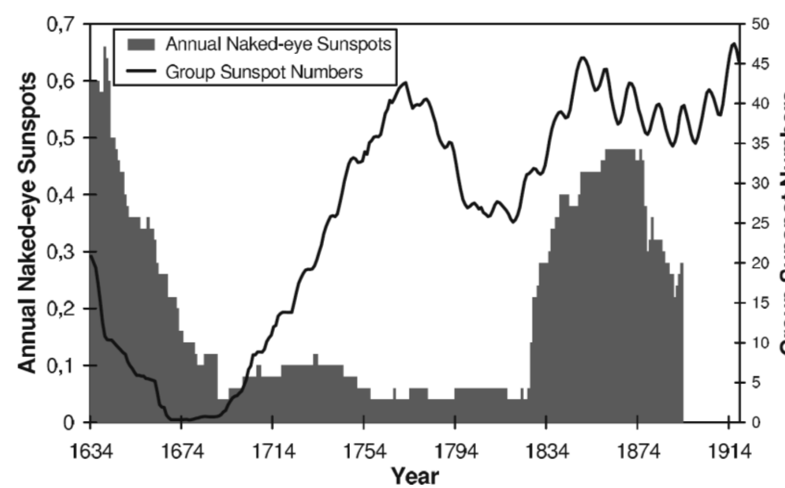
7. 187 Mar/Apr? (scribal error in date)
[CHINA] Chung-p'ing reign-period, 4th year, 3rd month, day *ping-shen* (33), (no *ping-shen* in 3rd month, cannot suggest a viable alternative). "A black vapour as large as a melon was within the Sun." (*Hou-han-shu*, 18) (CS3, K3, CD7, WX)

8. 188 Feb 15 - Mar 15 (only month given)
[CHINA] Chung-p'ing reign-period, 5th year, 1st month. "The Sun was orange (reddish-yellow) in colour. Within it there was a black vapour like a flying magpie. After several months it dispersed." (*Hou-han-shu*, 18) (CS4, K4, CD8, WX)

9. ** 240 (only year given)
[CHINA] Ch'ih-wu reign-period, 3rd year. "Within the Sun, a three-legged crow was seen." (*K'ai-yuan Chan-ching, Jih-chan*, 2) (CD9, WX)

10. 299 Feb 17 - Mar 18 (only month given)
[CHINA] Yuan-k'ang reign-period, 9th year, 1st month. "Within the Sun there was the form of a flying swallow. After several days/months it dispersed." (*Chin-shu*, 12 and *Sung-shu*, 34) (CS6, K5, CD11, WX)
[N.B. *Chin-shu*, 12 records a duration of several days; *Sung-shu*, 34 states several months]





Since ~1609

February 21. No. 14: a train of large spots, with two large leader spots. No. 15: a very fine, large group, still having the nuclei connected by a narrow dark line.

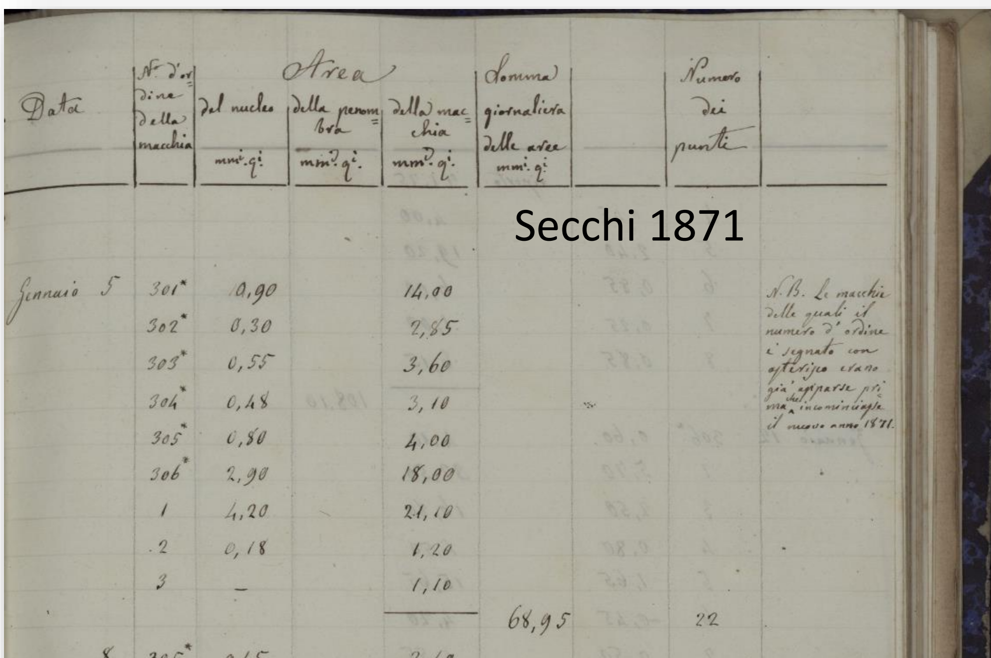
February 23. No. 14: this group is a superb object; it is fully one-tenth of the apparent diameter of the Sun in length, and consists of three fine large spots. Each of the first two spots contains double nuclei, and a "bridge" was noticed crossing a portion of the umbra of the second spot. No. 15 is also a very interesting and superb group; the large leader spot has triangular umbra in nearly round penumbra; this is followed by a larger, somewhat rectangular penumbra containing a series of small spots; many small spots and penumbral matter are also in vicinity. A group of four fine prominences was observed on west limb; one large banyan-tree-like form was quite interesting.

Hadden 1896

A few days later (July 12/22), G. Schultz wrote to G. Kirch about his observation on July 5–7 using Gregorian dates (no. 277, Herbst 2006):

> Da Ich sie denn noch gutt genug befunden habe, und zugleich, nach wuntsch eine Maculam in quadrante occidentali partis inferioris Disci Solaris, ohngefehr 3 zoll vom centro gefunden, welche Ich auch folgenden 6 und 7 Julij, so lange das Wetter gutt gewesen, mit fernerer annäherung zum margine occidentali, darinnen gesehen.
>
> Since I approved them [lenses] I, as I wished, found a sunspot in the lower, western quadrant of the Sun's disc, around 3 inches from the centre. As long as the weather was good, I could see it also 6 and 7 July, approaching the western edge.

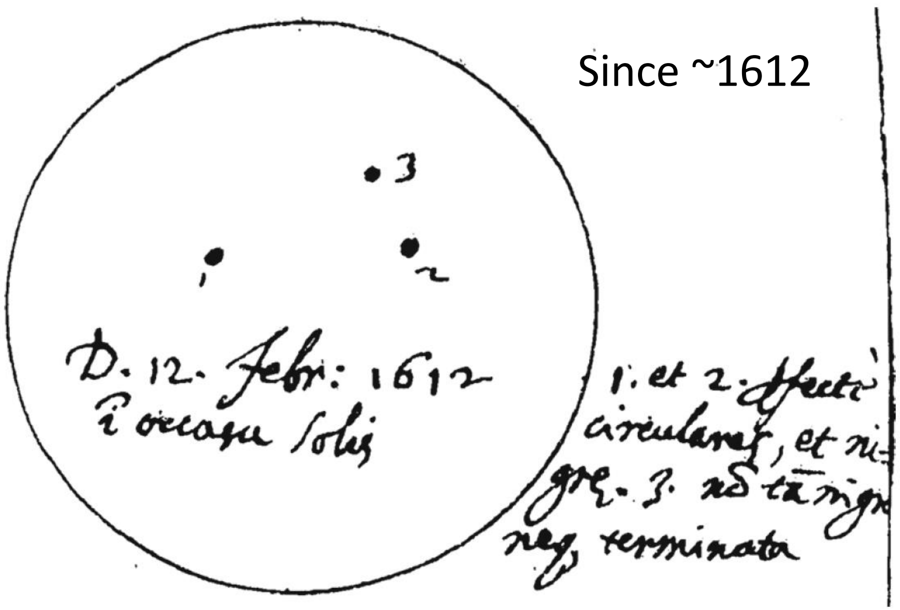
Kirch 1684
(from Neuhäuser et al. 2018)



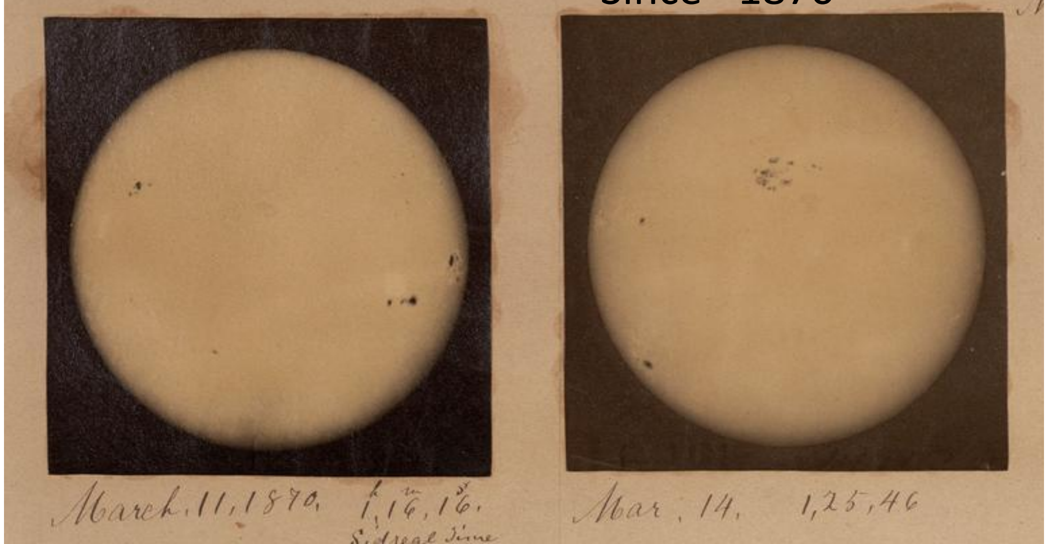
Data	N. d'ordine della macchia	Area del nucleo mm.q.	della penombra mm.q.	della macchia mm.q.	Somma giornaliera delle aree mm.q.		Numero dei punti	
Gennaio 5	301*	0,90		14,00				N.B. Le macchie delle quali il numero d'ordine è segnato con asterisco erano già apparse prima che incominciasse il nuovo anno 1871.
	302*	0,30		2,85				
	303*	0,55		3,60				
	304*	0,48		3,10				
	305*	0,80		4,00				
	306*	2,90		18,00				
	1	4,20		21,10				
	2	0,18		1,20				
	3	–		1,10				
					68,95		22	
" 8	305*	0,45		2,40				

Secchi 1871

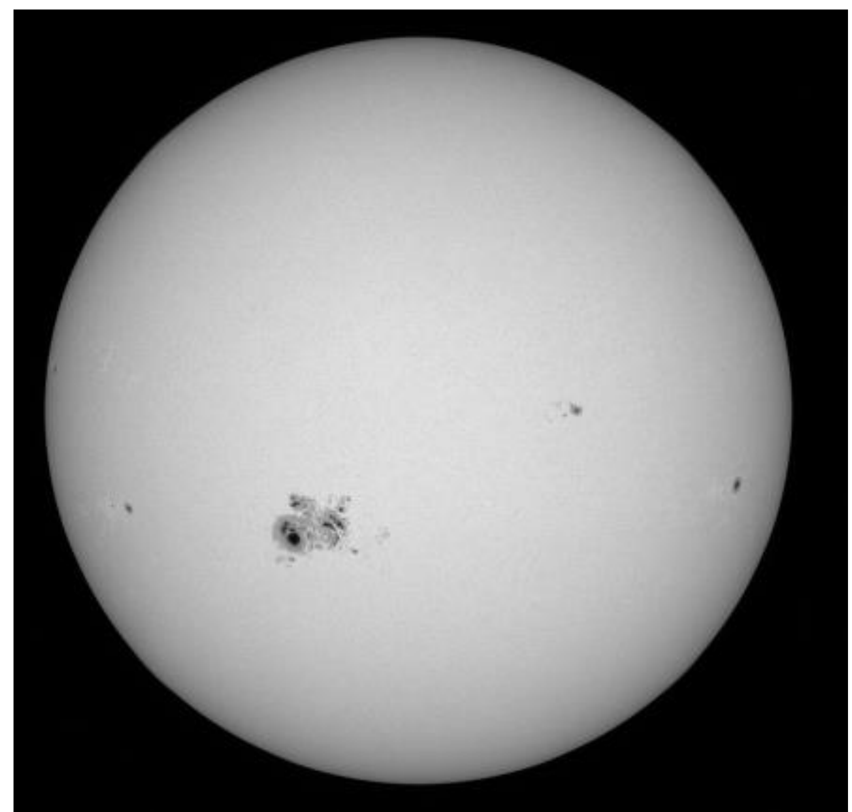
Since ~1612



Since ~1870



Since ~1980



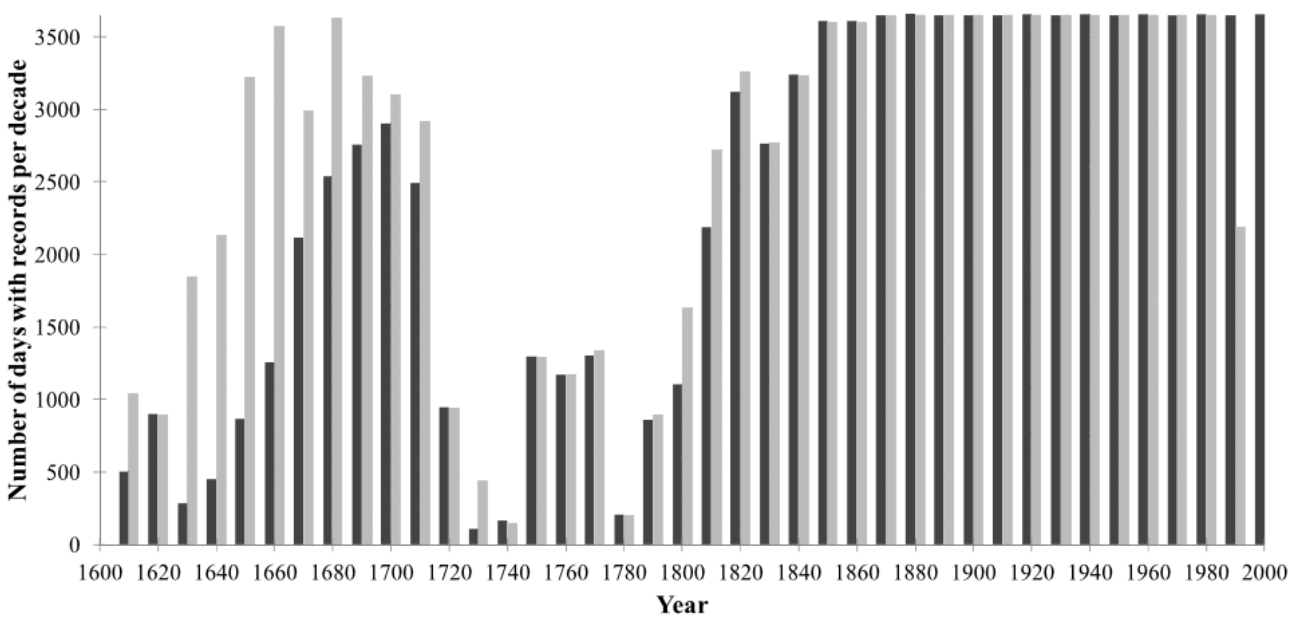
Wolf (1840)

Hoyt & Schatten (1998)

- Extended dataset back to 1610
- Filled-in 0s for many missing values

Vaquero et al. (2016)

- Corrected erroneous values
- Removed ambiguous values
- Added new observers



Vaquero et al. 2016

Individual observer series

$S(t)$: Number of individual spots

$G(t)$: Number of groups of spots

$a(t)$: fractional area of sunspots

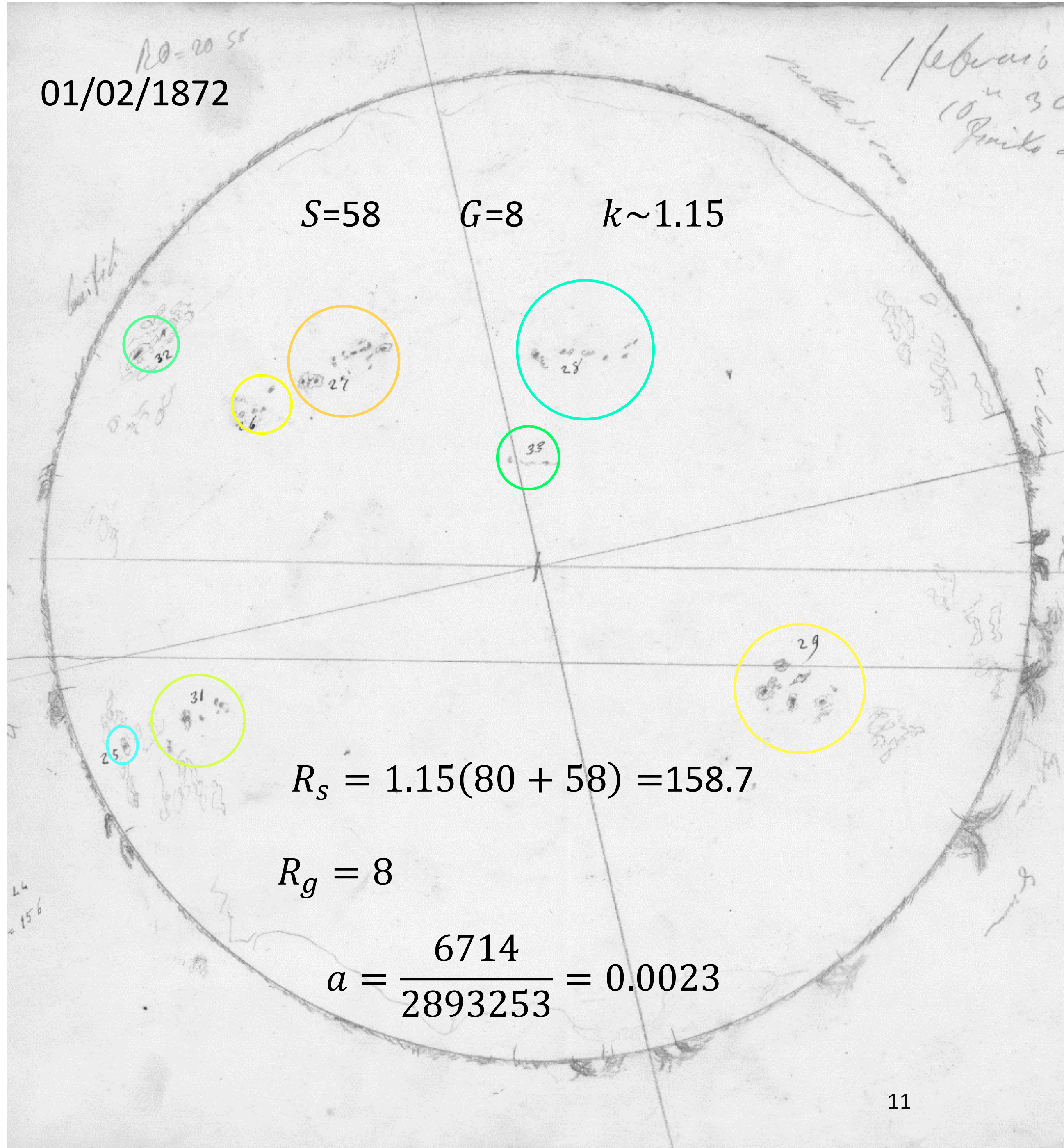
Composite series

$R_s(t) = k(10G(t) + S(t))$

k: scaling parameter

$R_g(t) = G^*(t)$

$R_\alpha(t) = a^*(t)$



01/02/1872

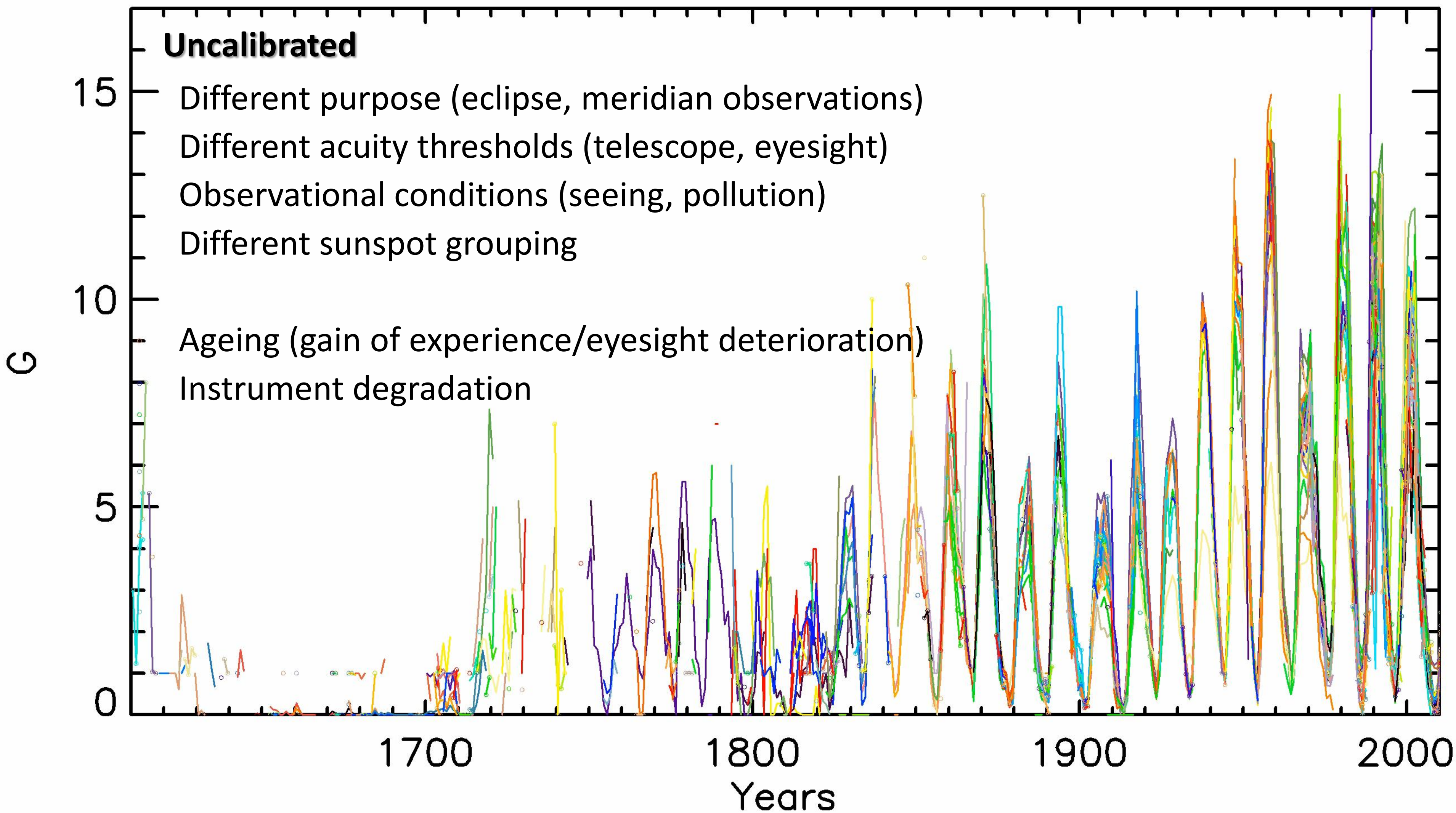
S=58 G=8 k~1.15

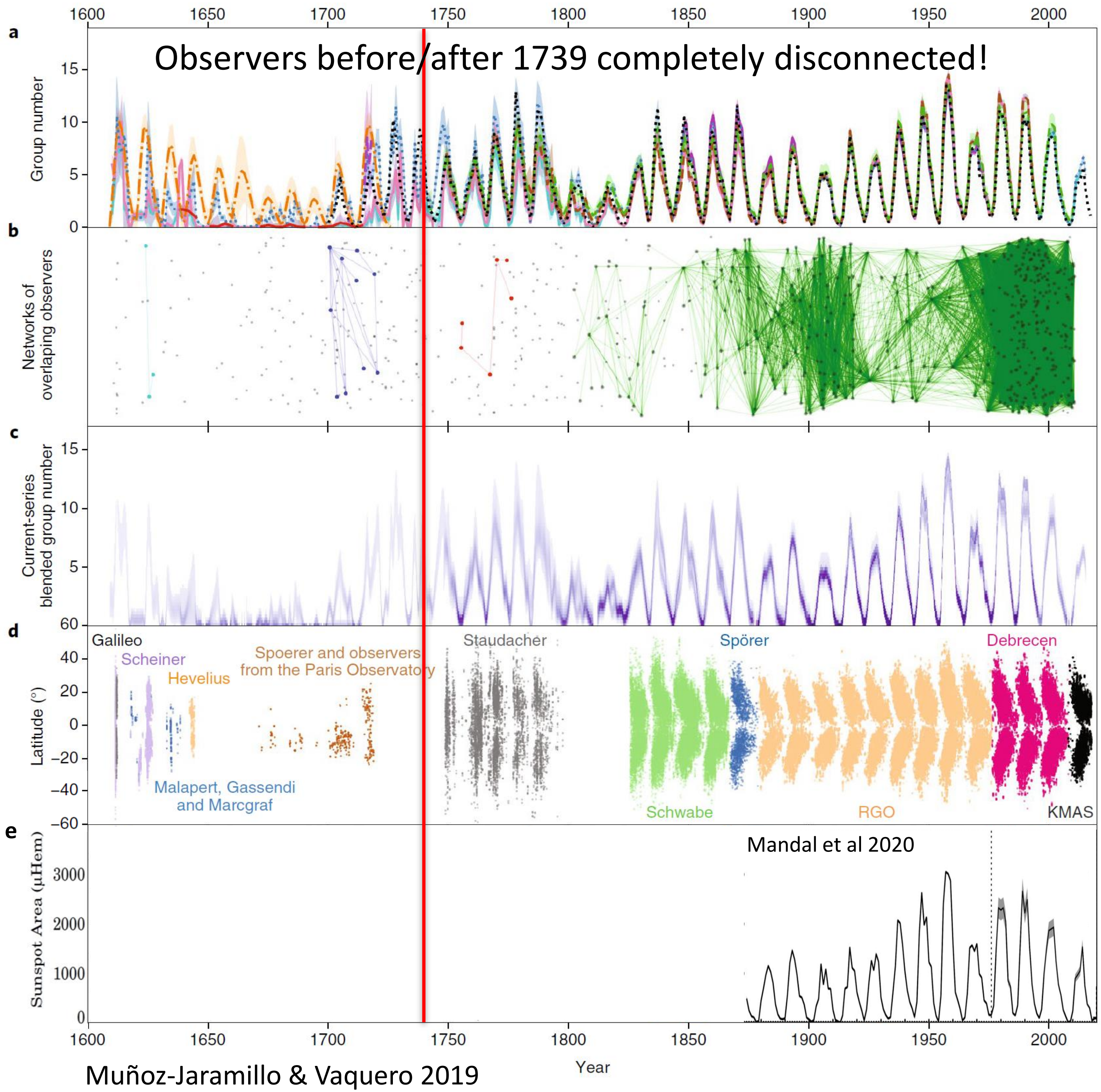
$R_s = 1.15(80 + 58)$ =158.7

$R_g = 8$

$a = \frac{6714}{2893253} = 0.0023$

1. Sunspots
   2. Instrumental
      2. Datasets of raw data
         2. Raw data in Vaquero et al. (2016)





Sunspot Number series (R_s)

Wolf sunspot number/20
Clette and Lefèvre (2016)

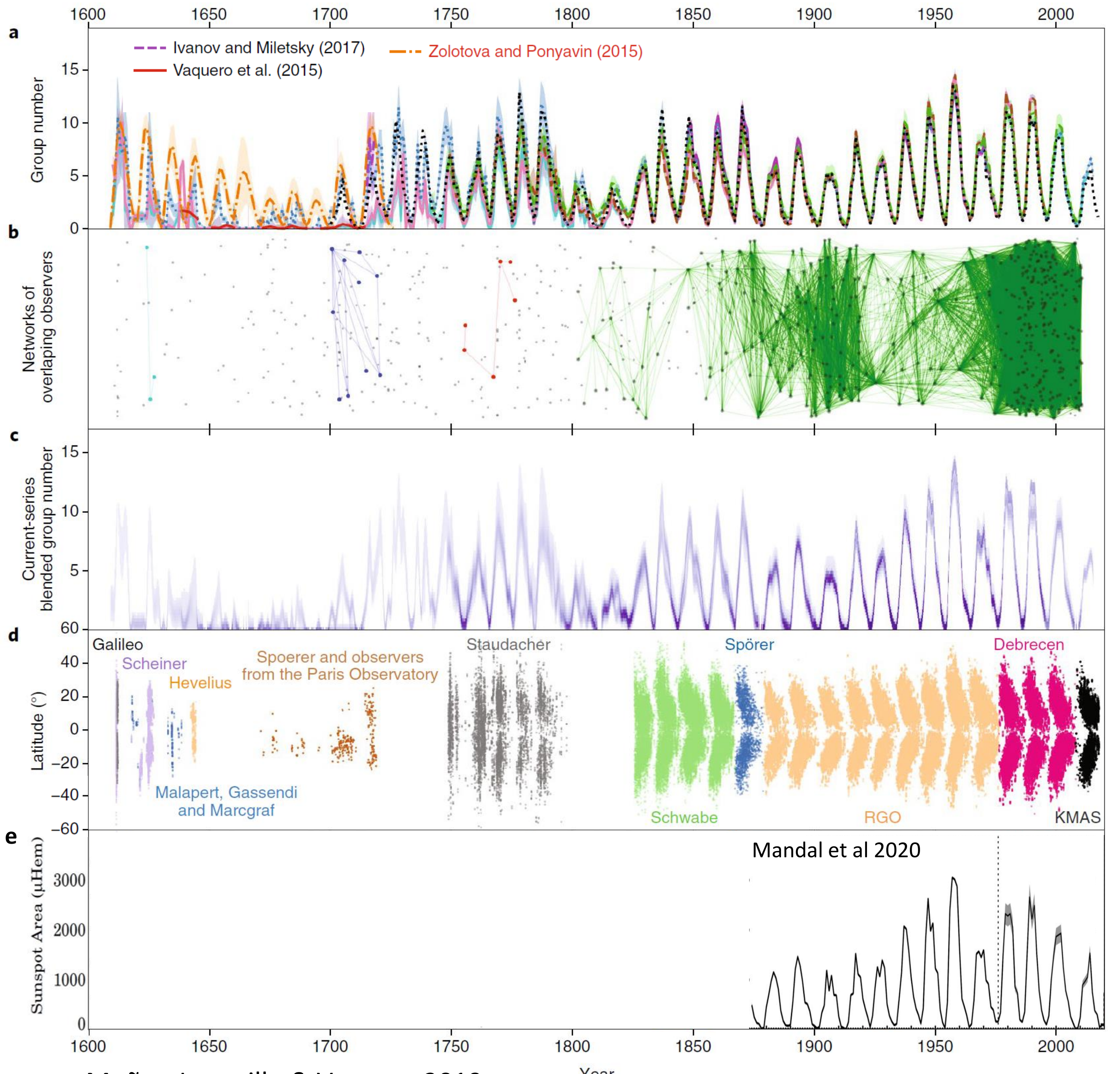
Group Sunspot Number series (R_G)

Hoyt and Schatten (1998)
Lockwood et al. (2014)
Cliver and Ling (2016)
Svalgaard and Schatten (2016)
Chatzistergos et al. (2017)
Willamo et al. (2017)
Usoskin et al. (2016, 2021)
Ivanov and Miletsky (2017)
Vaquero et al. (2015)
Zolotova and Ponyavin (2015)

Sunspot area series (R_a)

Balmaceda et al. (2009)
Mandal et al. (2020)

Muñoz-Jaramillo & Vaquero 2019



Muñoz-Jaramillo & Vaquero 2019

Linear scaling/daisy chaining

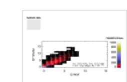
Hoyt and Schatten (1998)
Lockwood et al. (2014)
Cliver and Ling (2016)
Wolf sunspot number/20
Clette and Lefèvre (2016)

Linear scaling/backbones

Svalgaard and Schatten (2016)

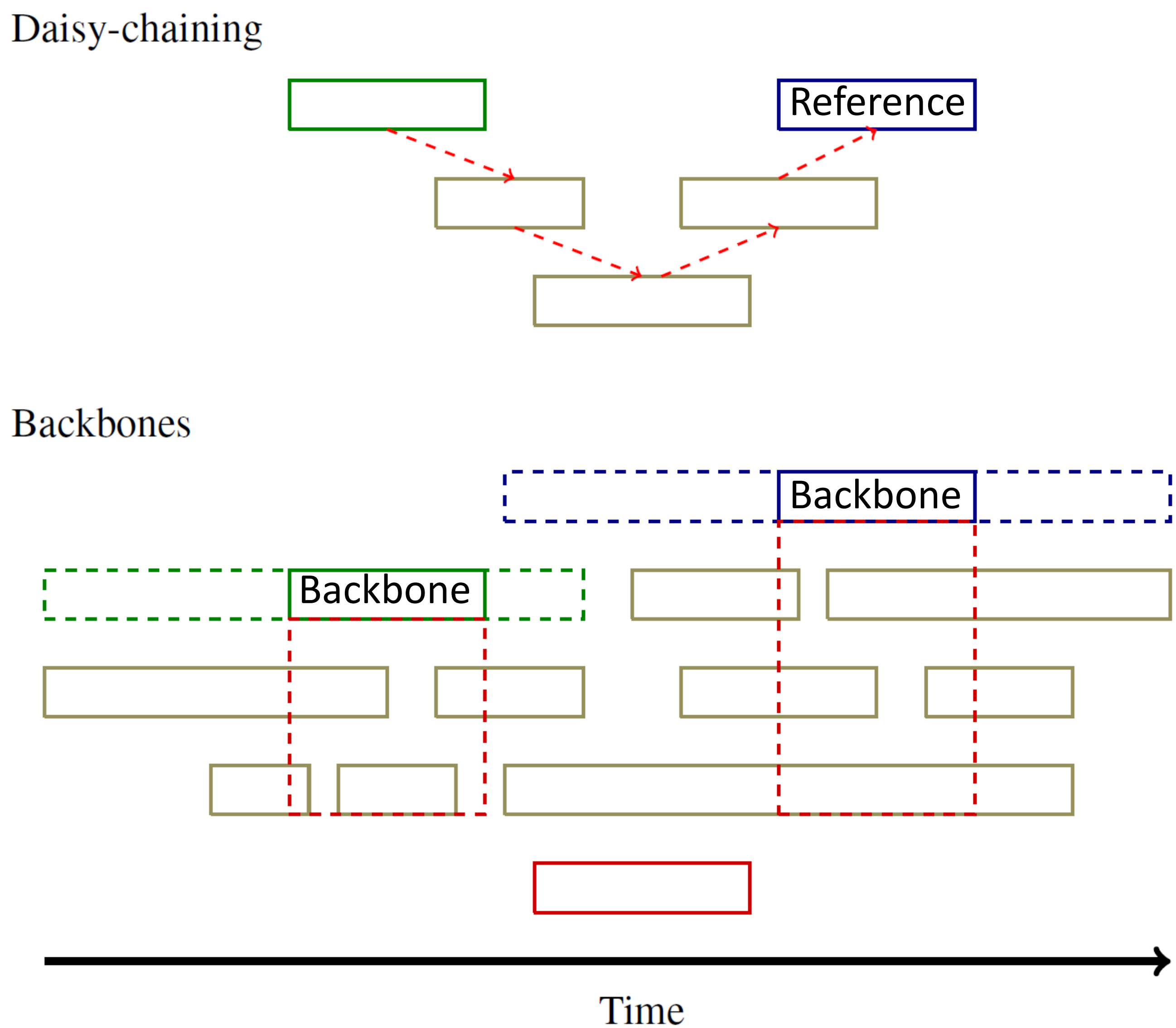
PDF matrices/backbones

Chatzistergos et al. (2017)

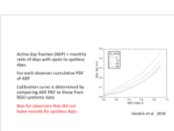


PDF matrices/Active-day fraction

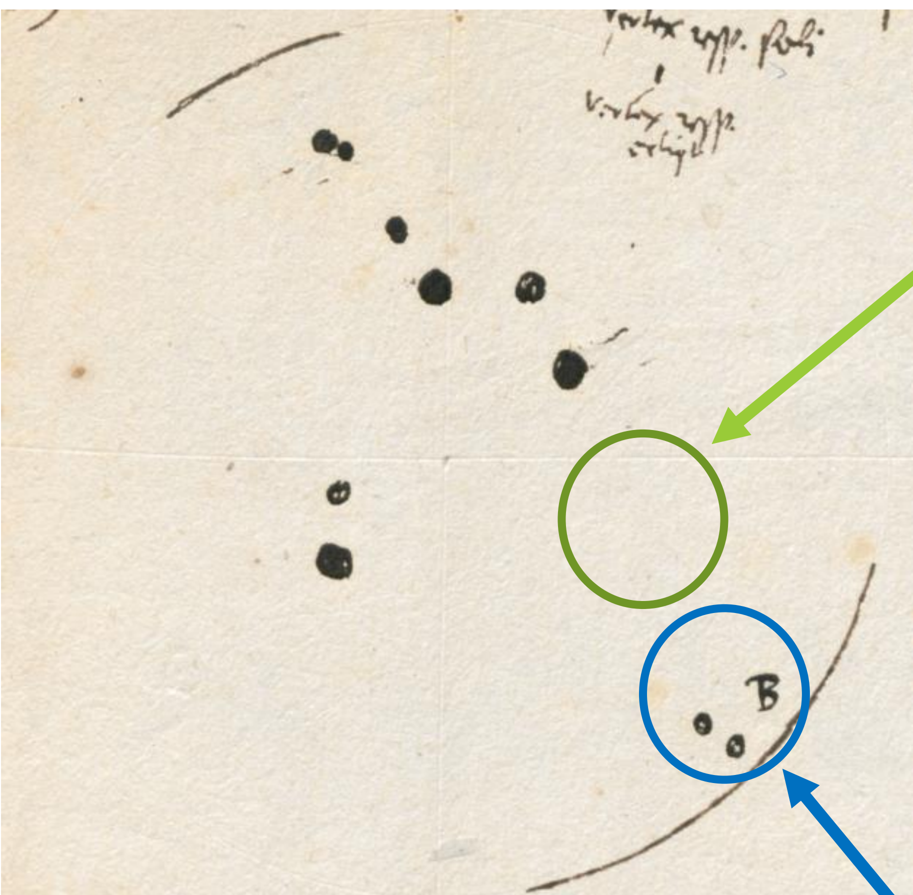
Willamo et al. (2017)
Usoskin et al. (2016, 2021)



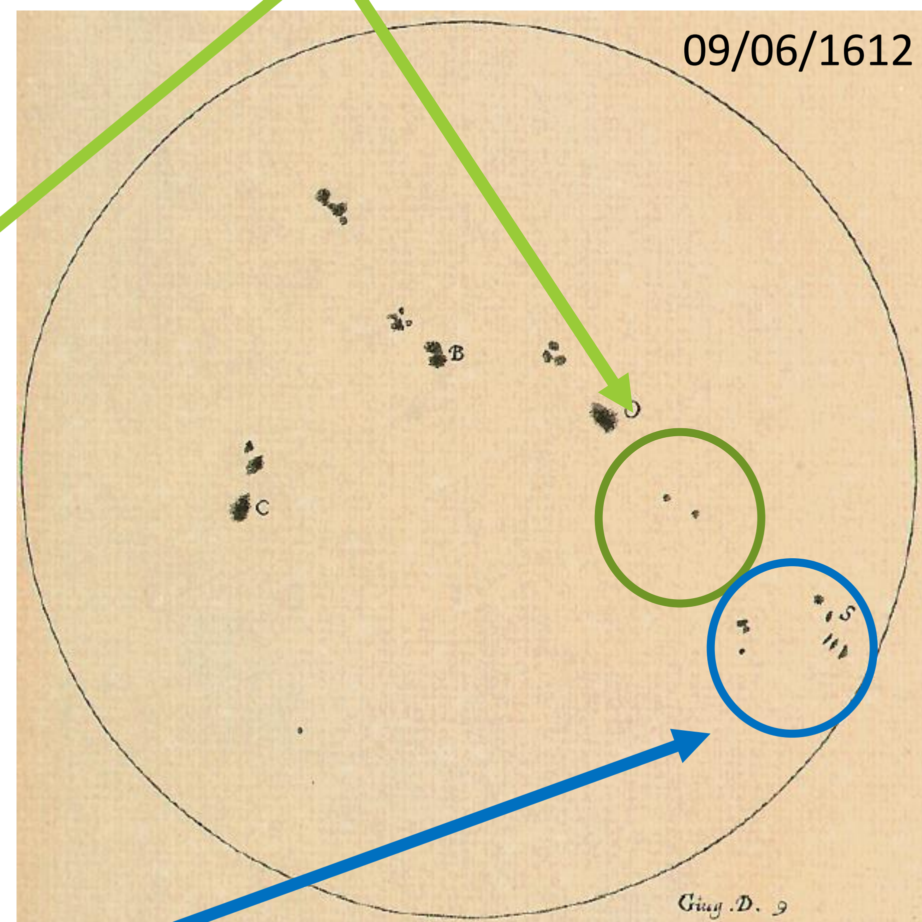
Chatzistergos 2017



Missing groups

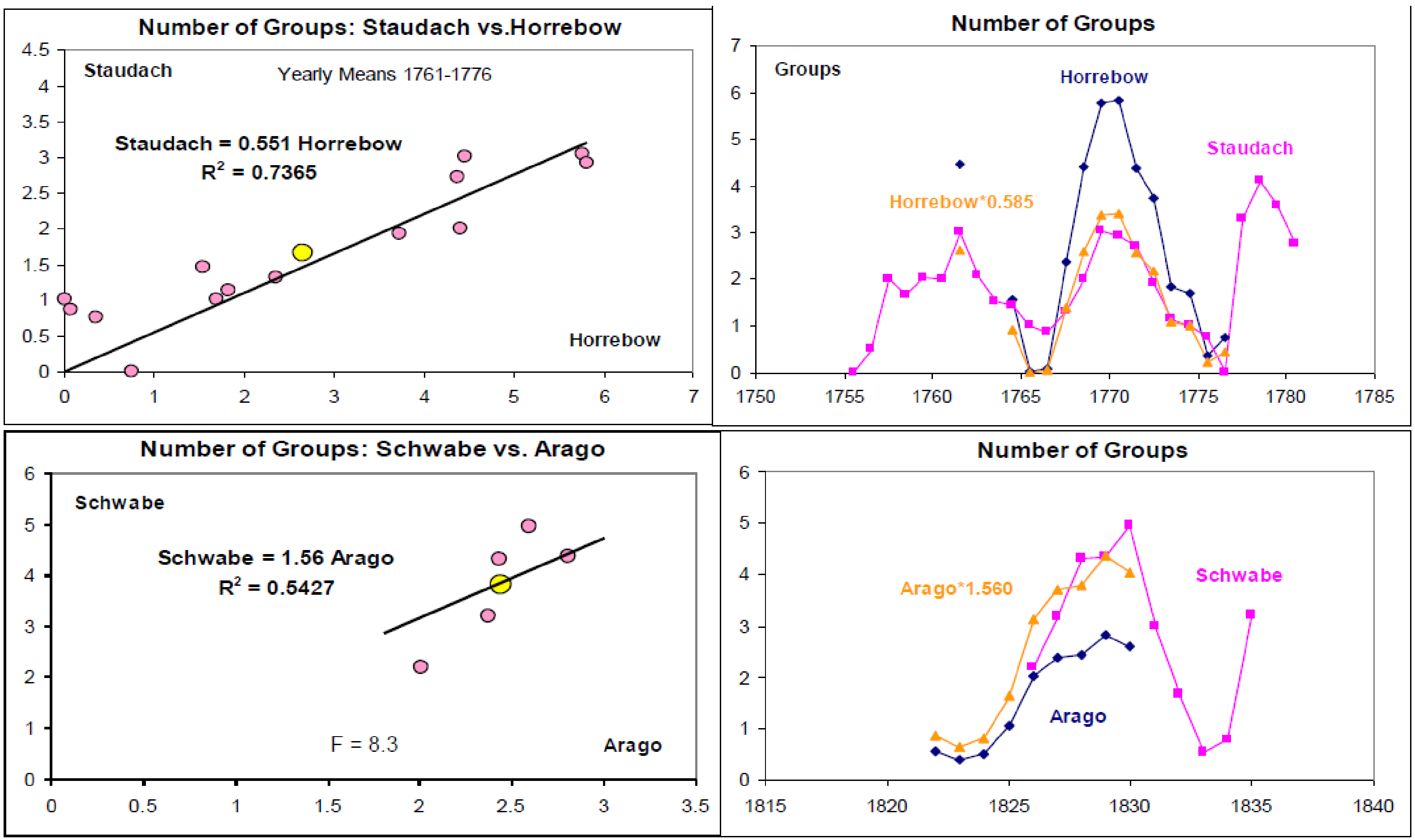


Jungius

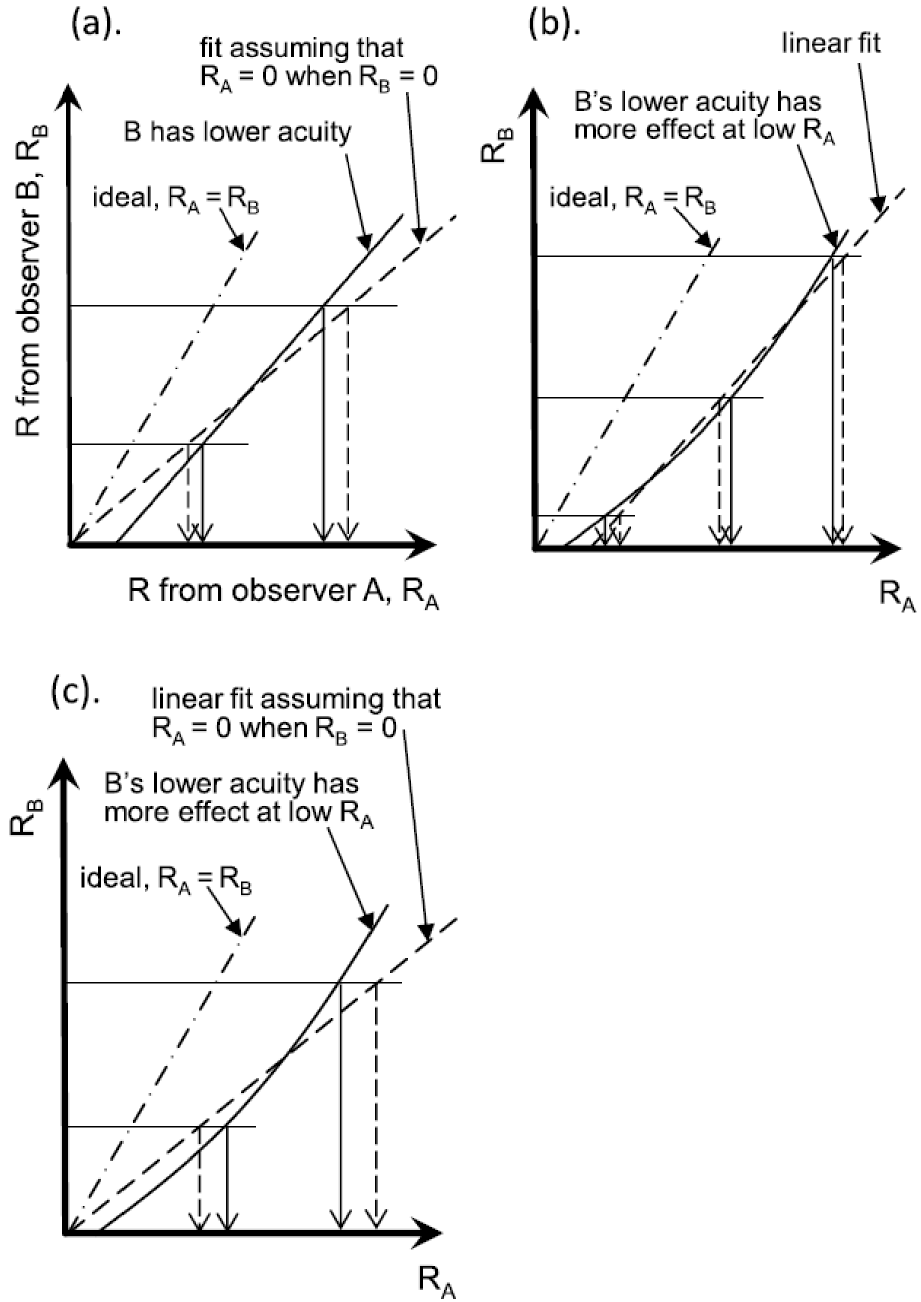


Galileo

Missing sunspots

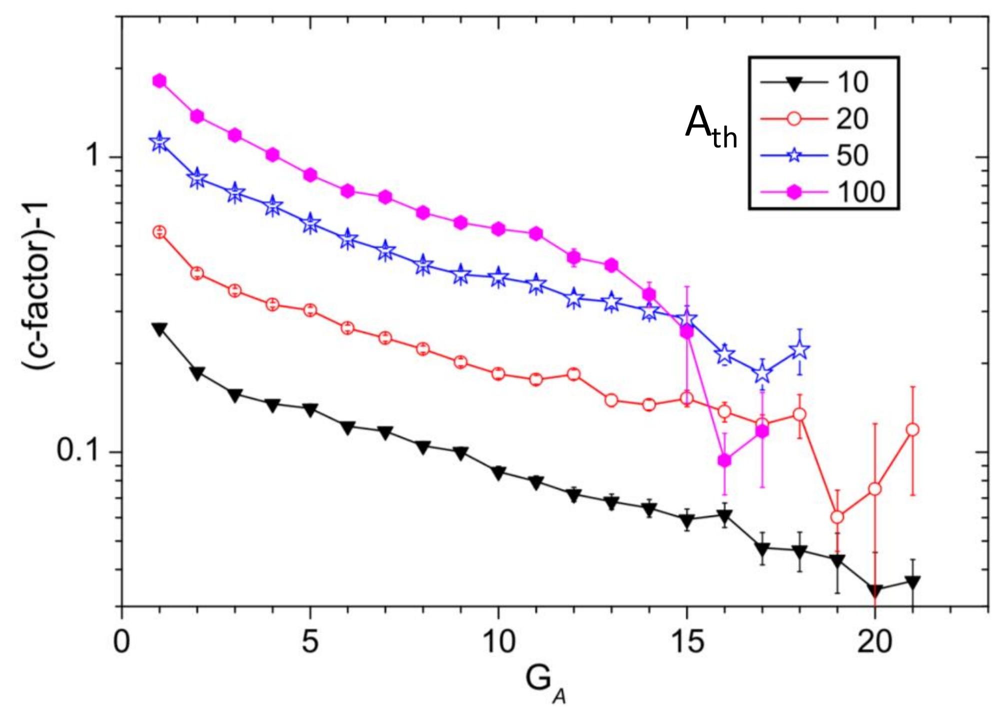


Svalgaard 2013

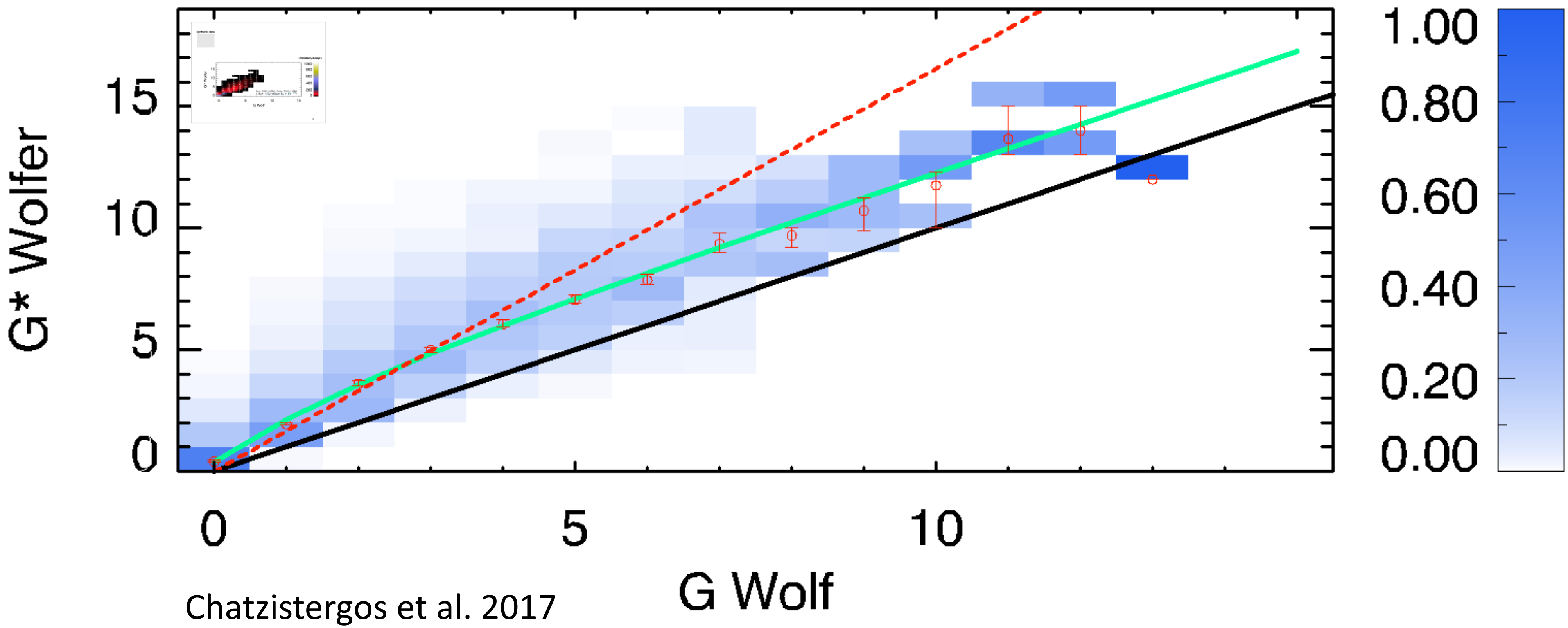


Lockwood et al. 2016

C-factor = ratio of spots smaller than A_{th} to spots larger than A_{th}

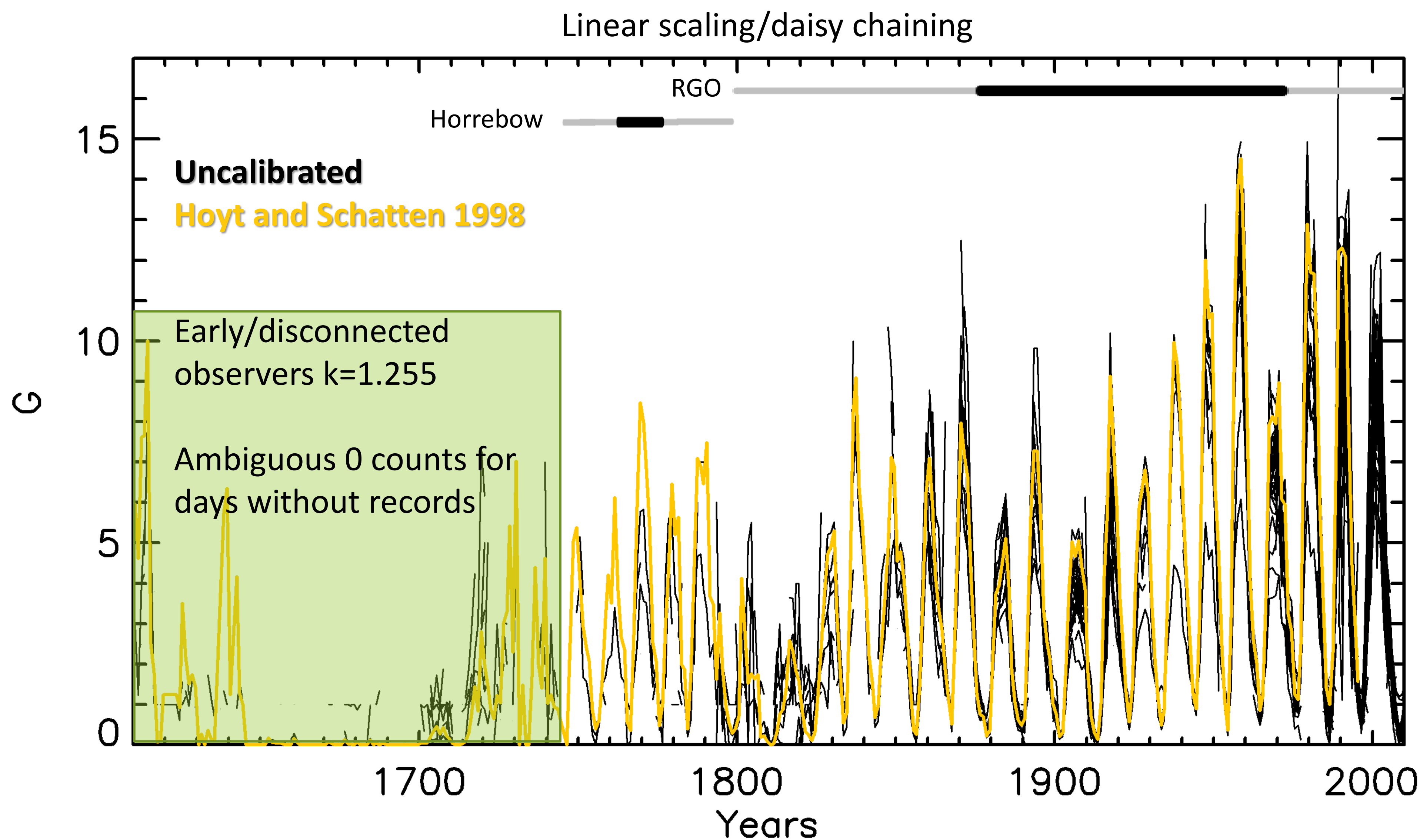


Usoskin et al. 2016

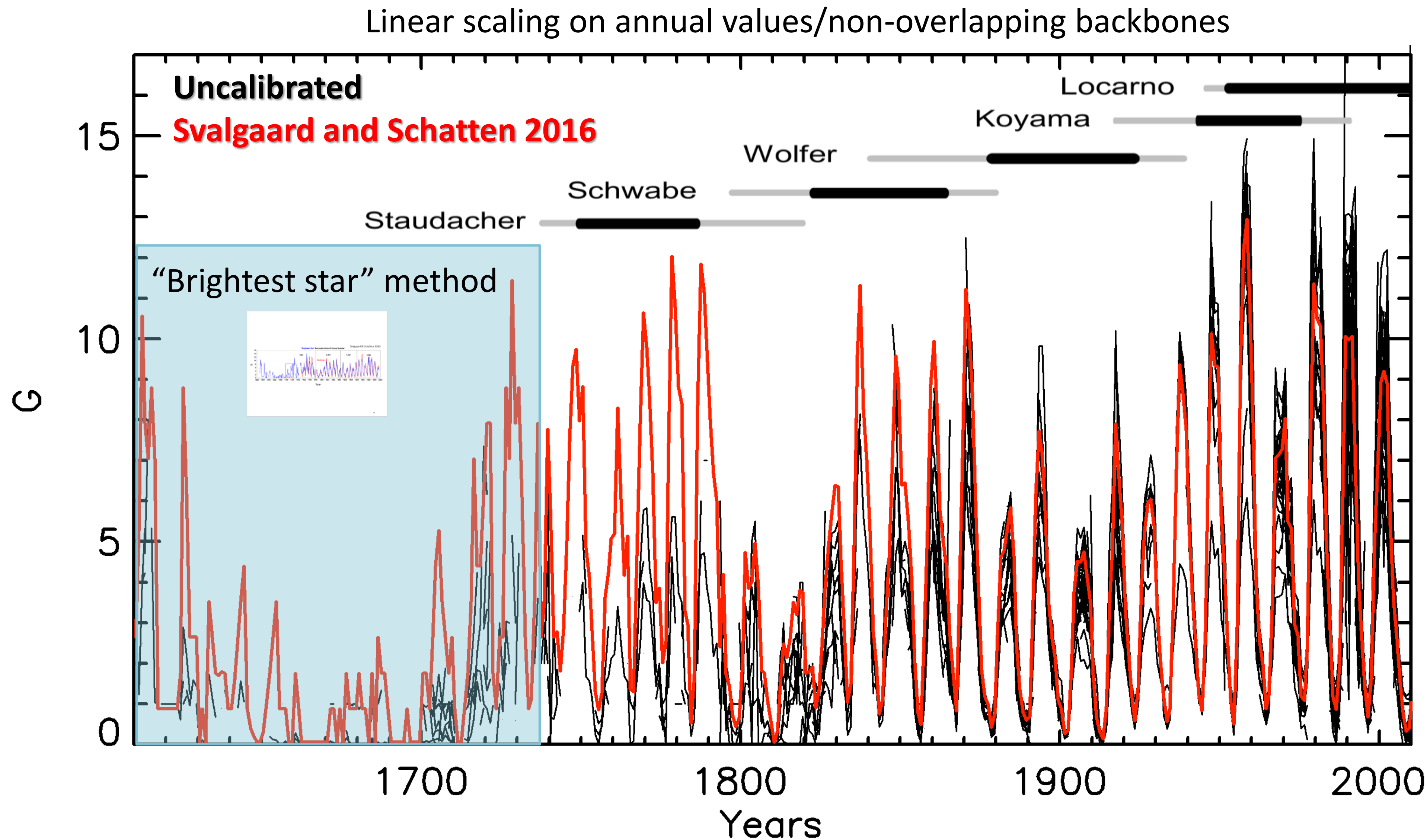


Chatzistergos et al. 2017

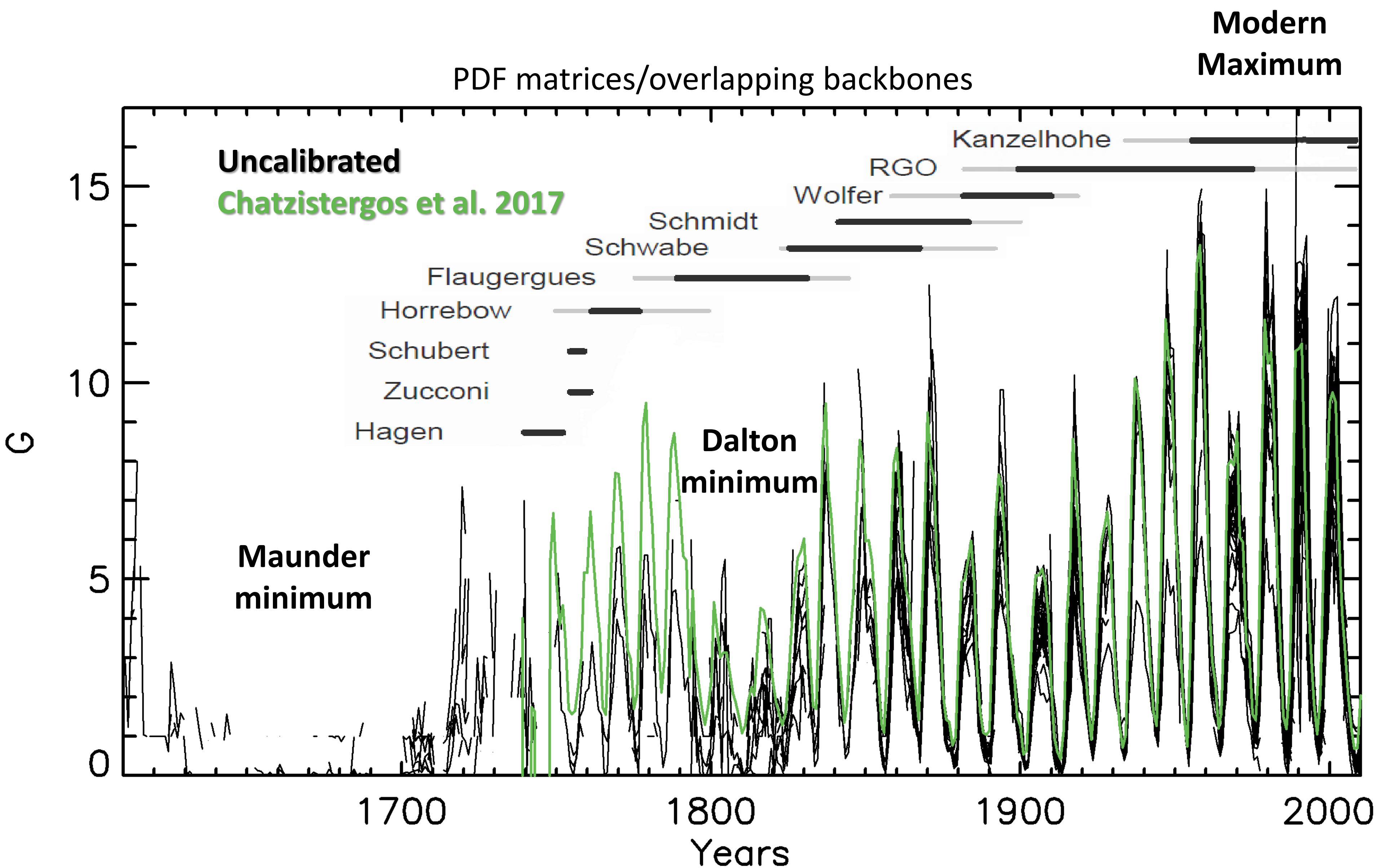
Hoyt & Schatten 1998

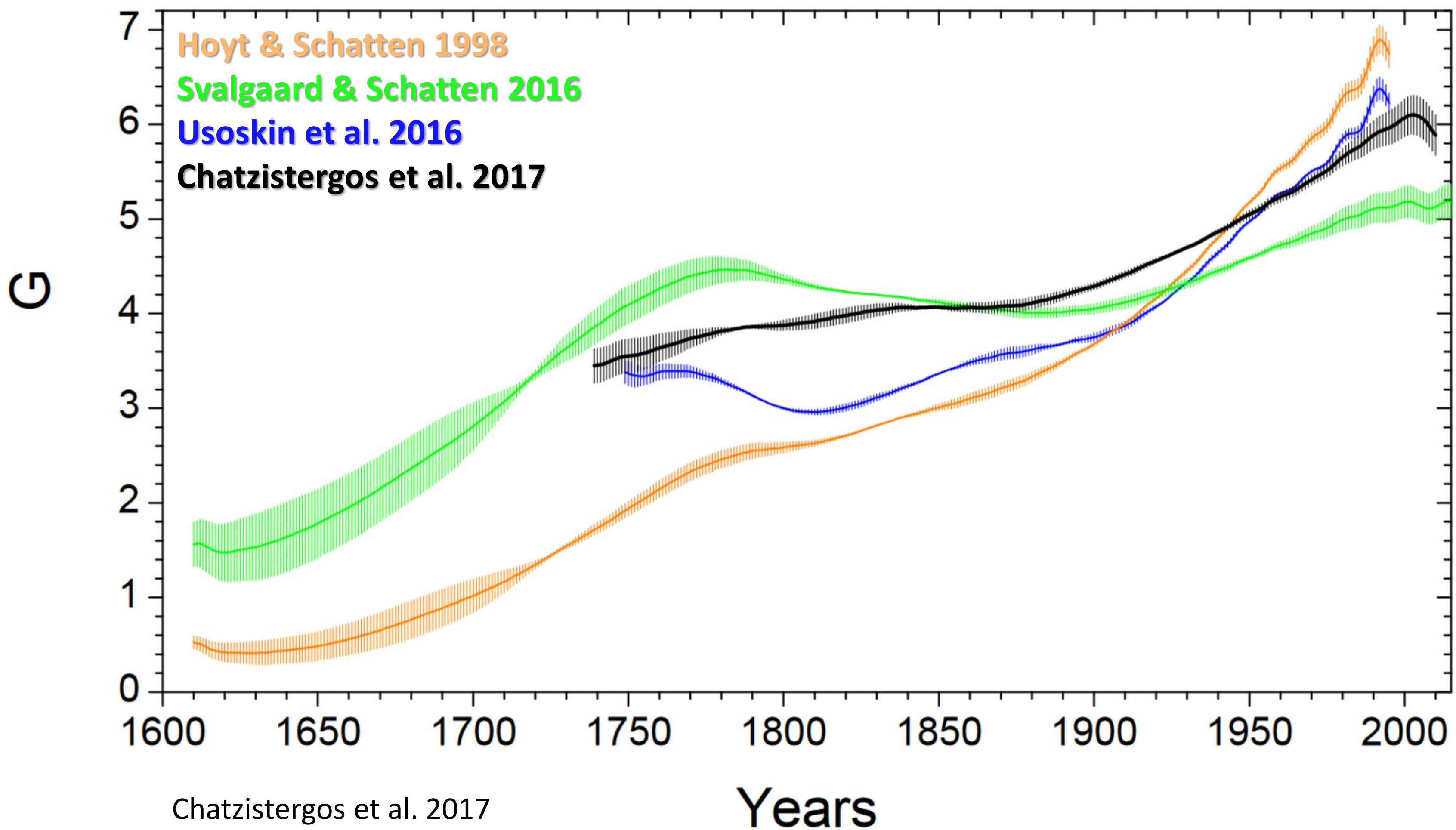


Svalgaard & Schatten 2016



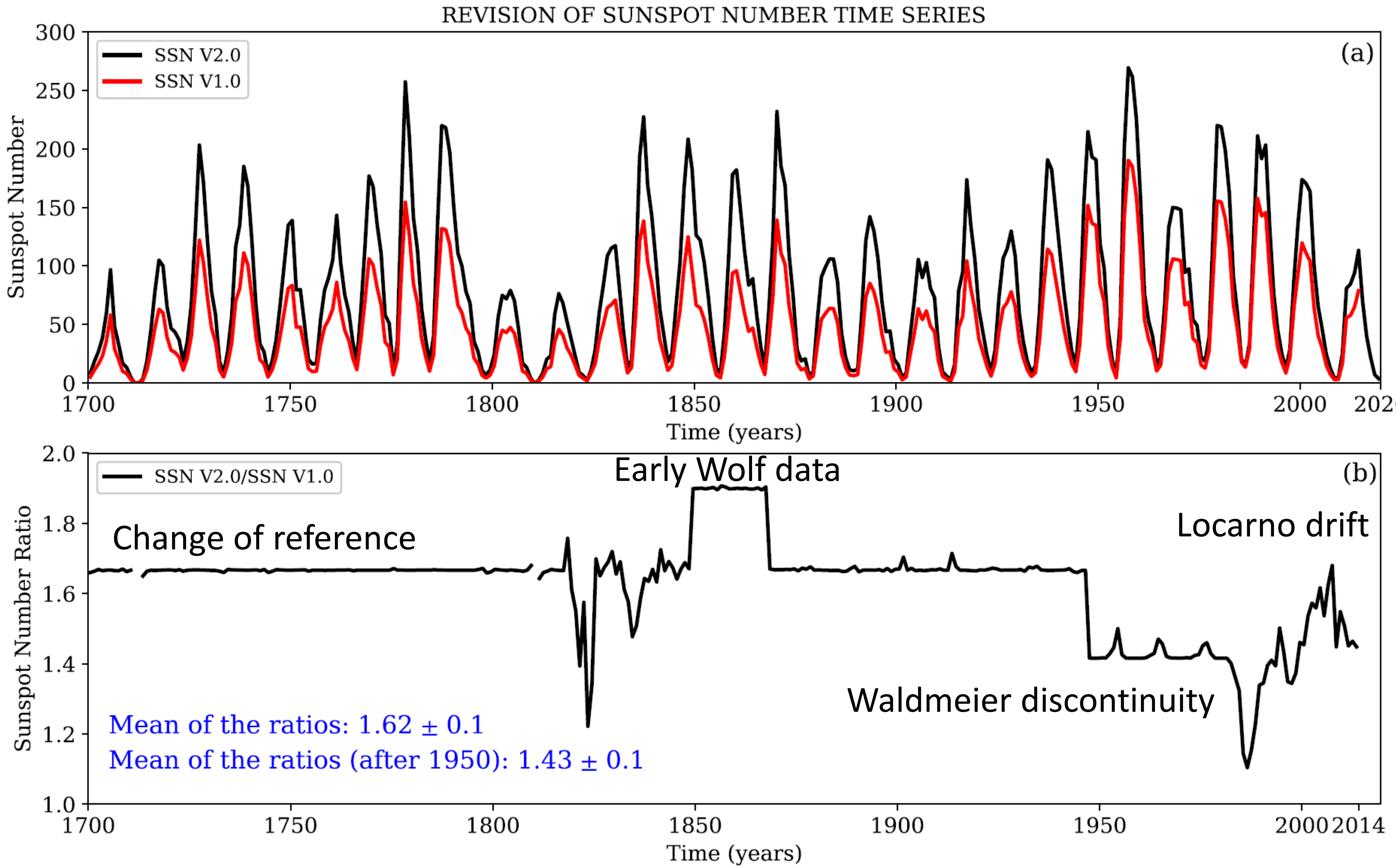
Chatzistergos et al. 2017



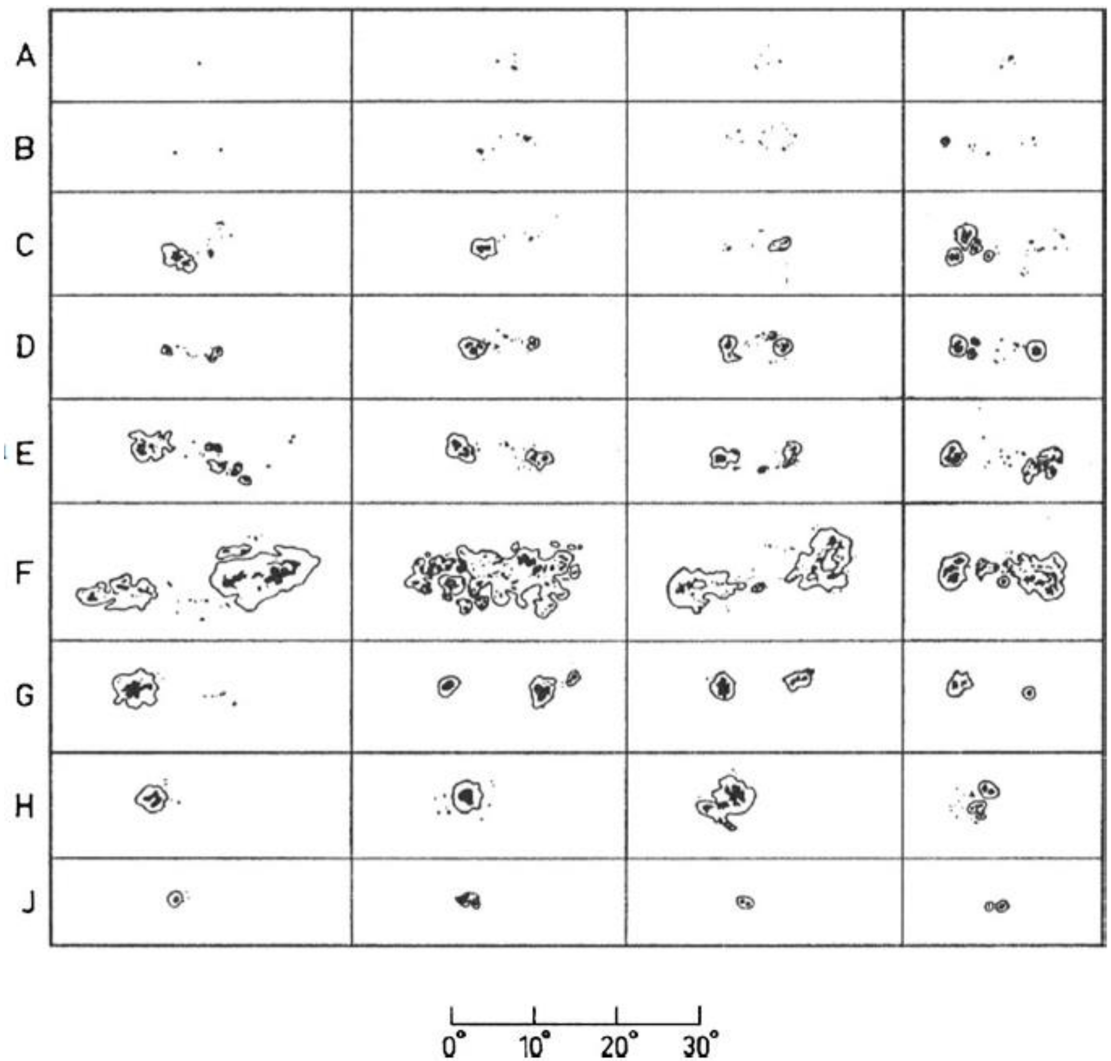


Chatzistergos et al. 2017

1700/1749/1818 for annual/monthly/daily



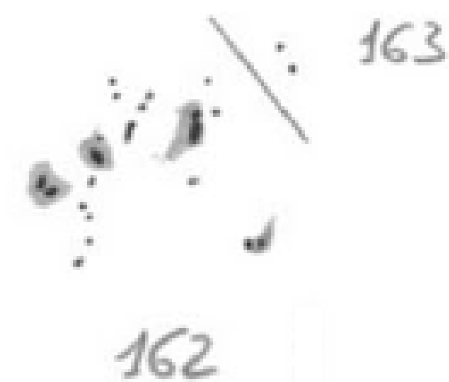
Nandy 2021

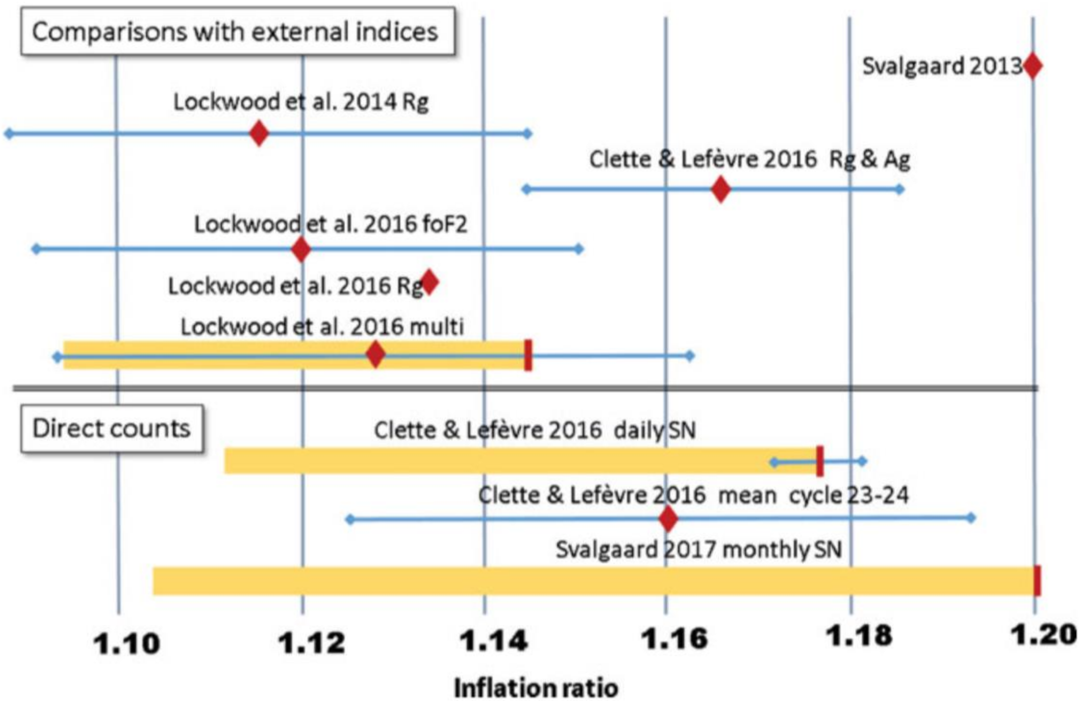


Waldmeier 1955

Separating groups due to evolution track

Sunspot weighting based on size



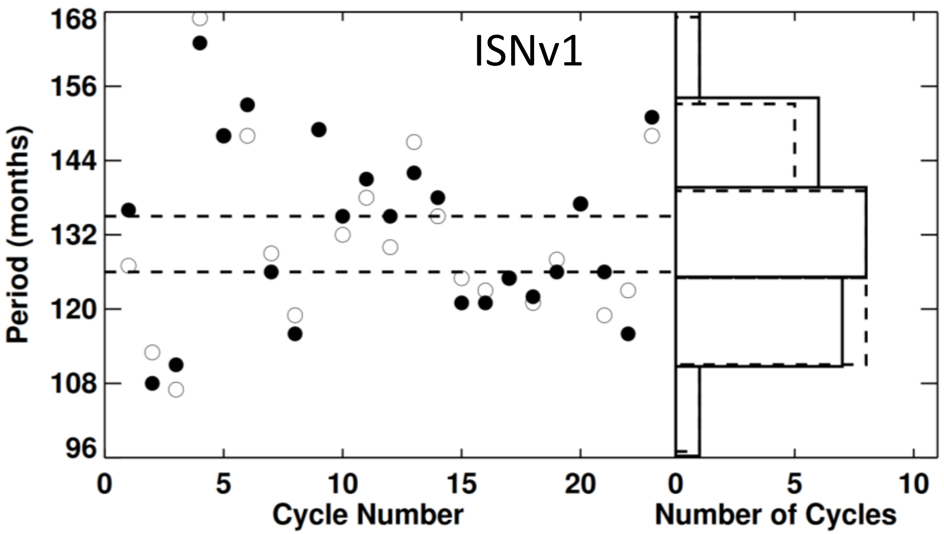


Clette & Lefevre 2018

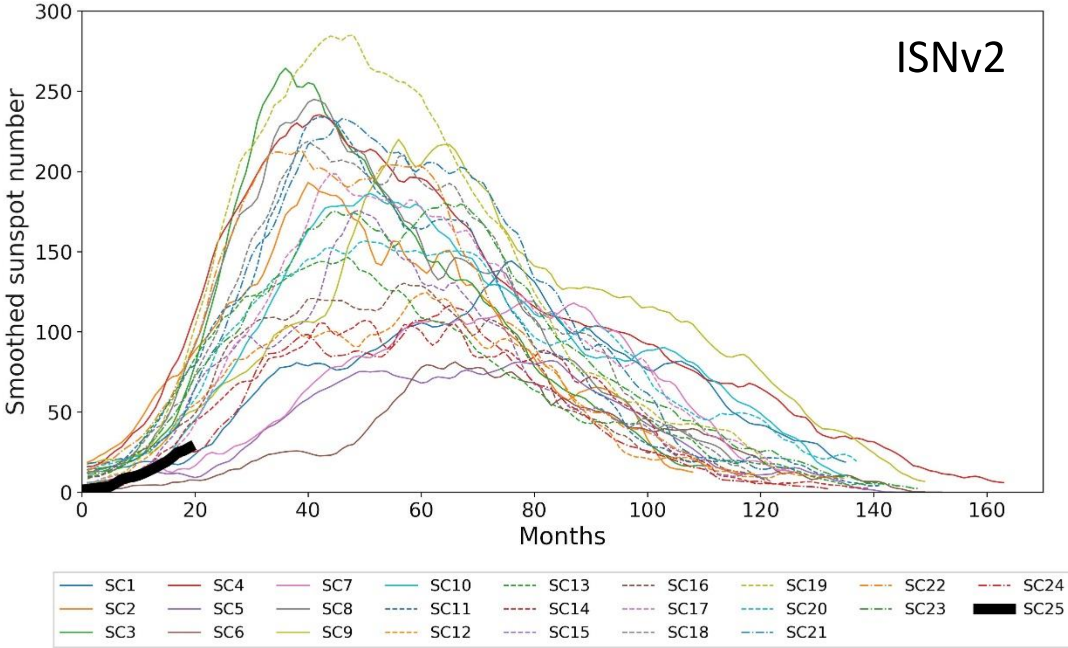
Not all observers adopted it
Unknown starting period

Not clear correction

- GSN
  - ~ 7% (Svalgaard 2016)
  - Not needed (Lockwood et al. 2016)
- ISN
  - ~20% (Svalgaard 2011)
  - ~ 10% (Lockwood et al. 2016)

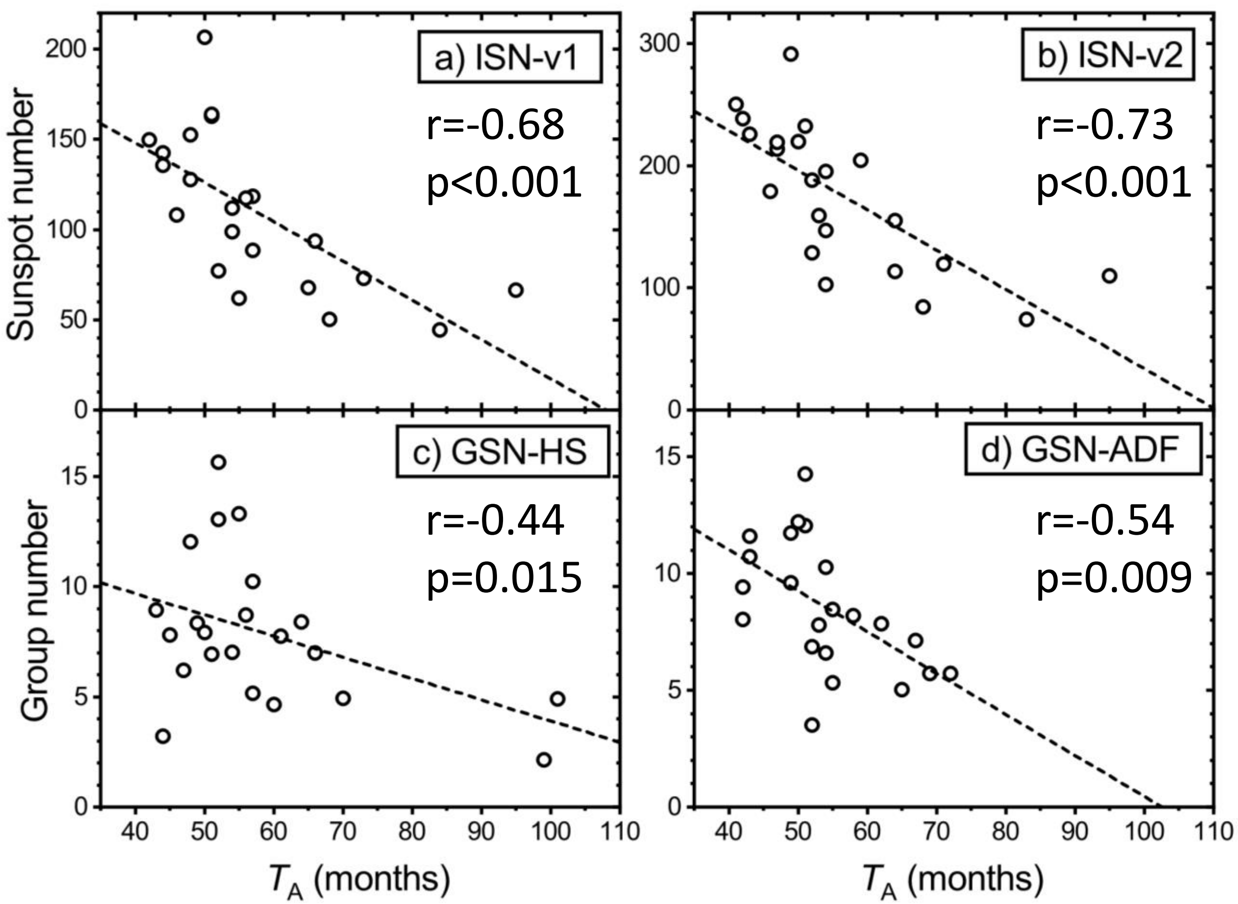


Hathaway 2015

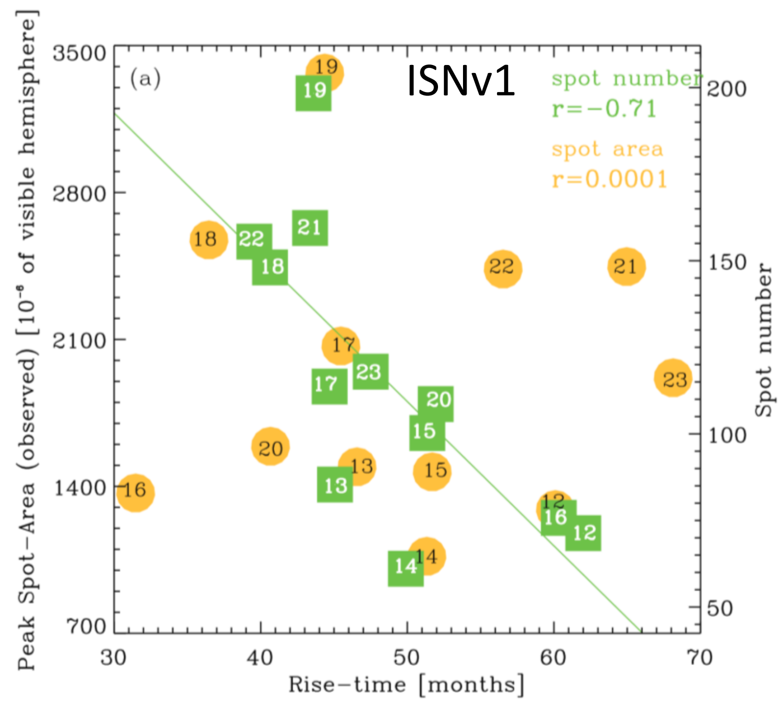


Carrasco & Vaquero 2021

Waldmeier rule: cycle's magnitude anti-correlated to rise time (minimum to maximum)

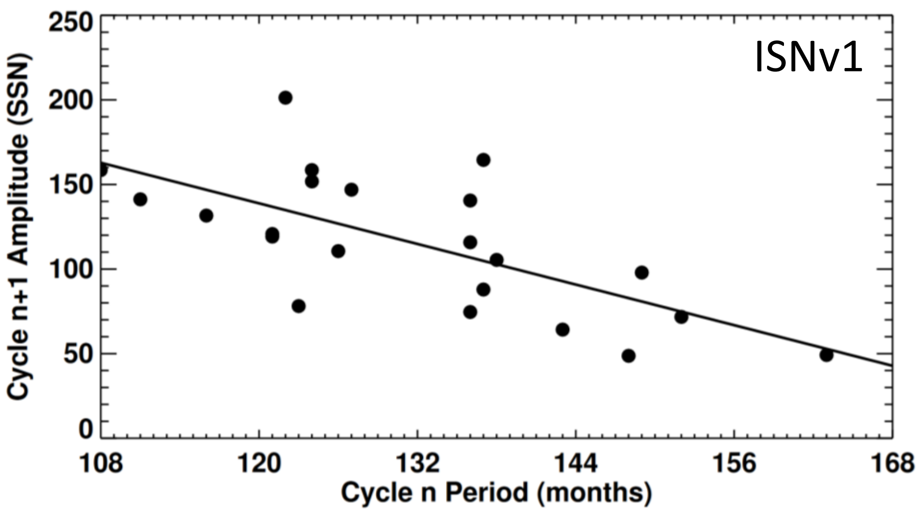


Usoskin et al. 2021



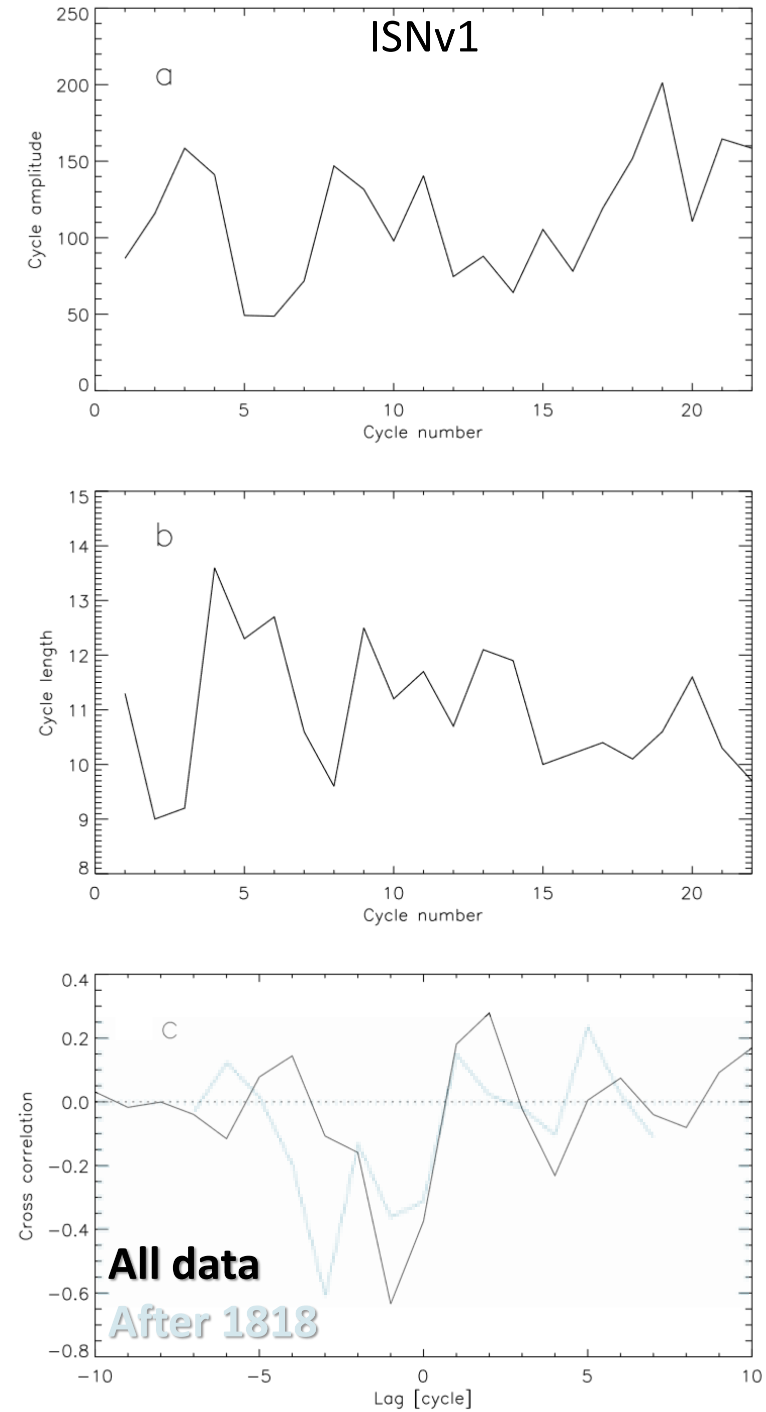
Dikpati et al. 2008

Cycle amplitude relationship or simplified/(n+1) Waldmeier rule



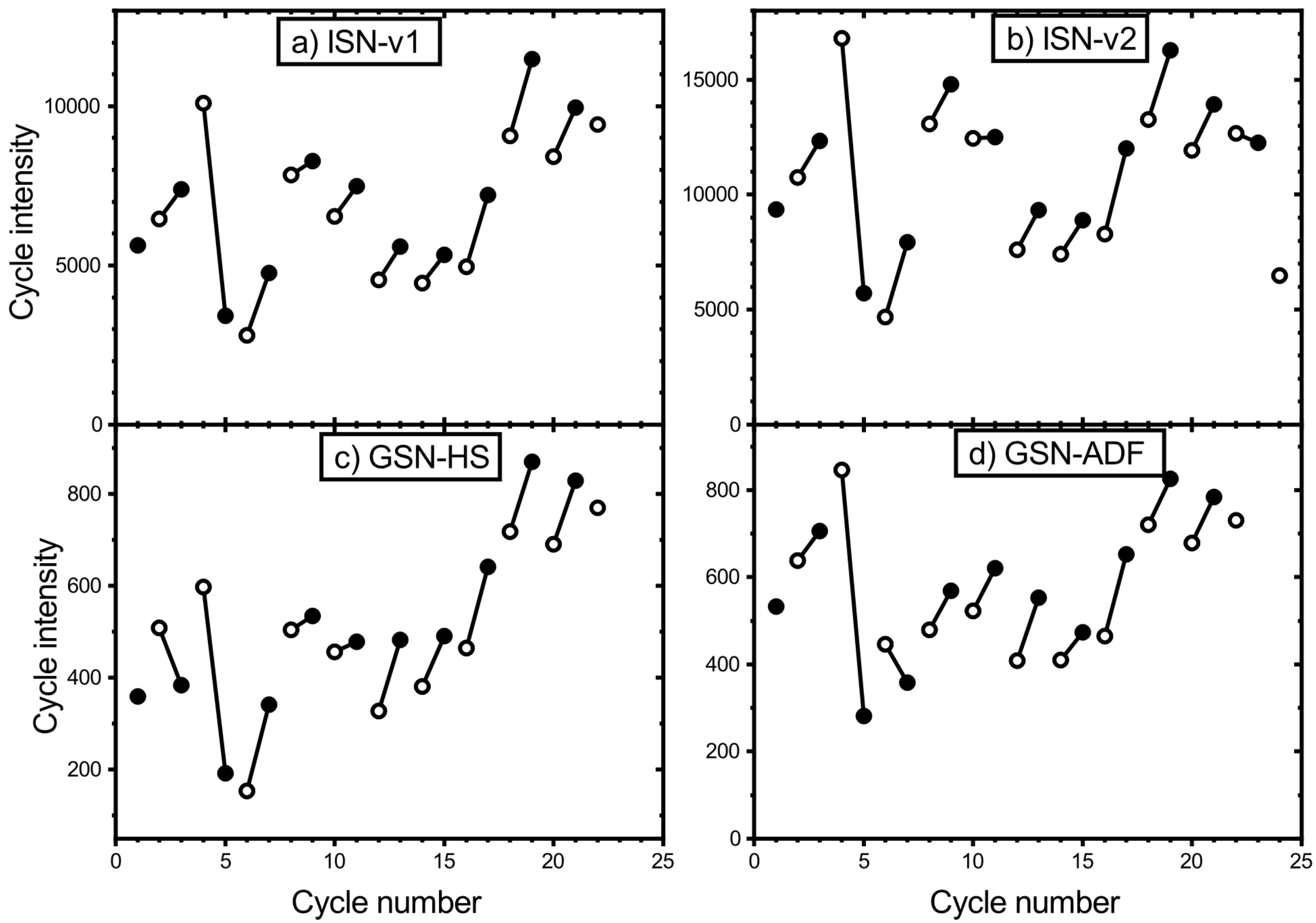
Hathaway 2015

Waldmeier rule		ISN-v1	ISN-v2	GSN-HS	GSN-ADF
Classical	r	$-0.68^{+0.14}_{-0.11}$	$-0.73^{+0.13}_{-0.09}$	$-0.44^{+0.20}_{-0.16}$	$-0.54^{+0.18}_{-0.14}$
	p	< 0.001	< 0.001	0.015	0.009
Simplified	r	$-0.35^{+0.22}_{-0.18}$	$-0.29^{+0.24}_{-0.20}$	$-0.32^{+0.22}_{-0.18}$	$-0.27^{+0.25}_{-0.20}$
	p	0.07	0.12	0.10	0.14
$(n+1)$	r	$-0.66^{+0.16}_{-0.12}$	$-0.71^{+0.13}_{-0.09}$	$-0.42^{+0.21}_{-0.17}$	$-0.59^{+0.18}_{-0.12}$
	p	< 0.001	< 0.001	0.015	< 0.001



Solanki et al. 2002

Gnevyshev–Ohl Rule: When solar cycles are arranged in pairs with an even-numbered cycle and the following odd-numbered cycle then the sum of the sunspot numbers in the odd cycle is higher than in the even cycle.

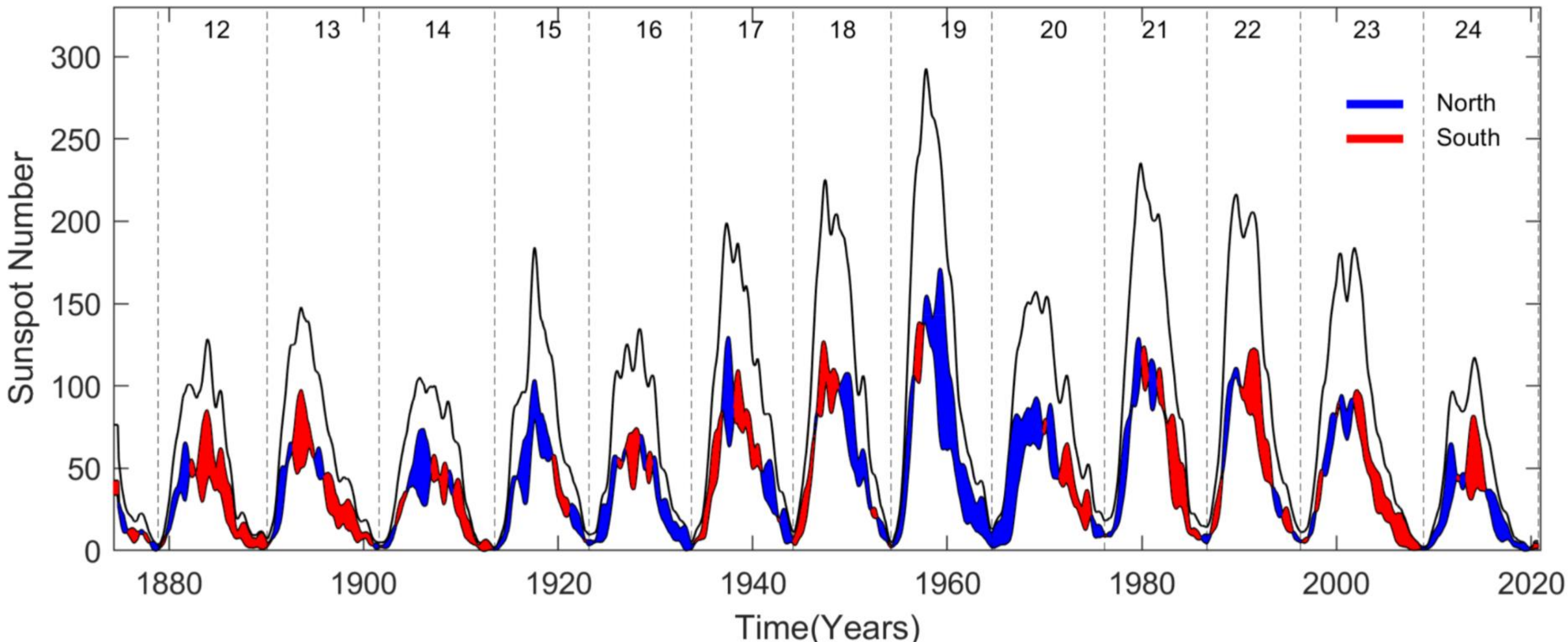


Usoskin et al. 2021

Lost cycle

Hemispheric asymmetry

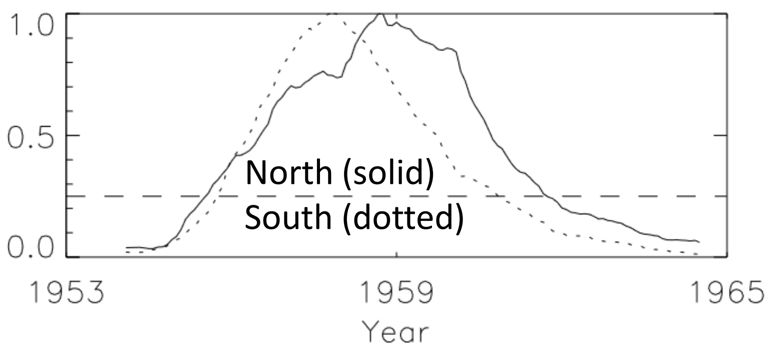
No clear pattern in N-S predominance
Strongest asymmetry for cycle 19 (42%N)
N reaches cycle maximum before S most of the times



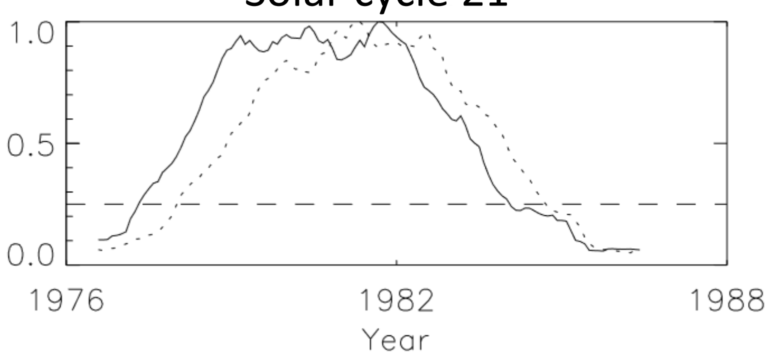
Veronig et al. 2021

Gnevyshev gap

Solar cycle 19



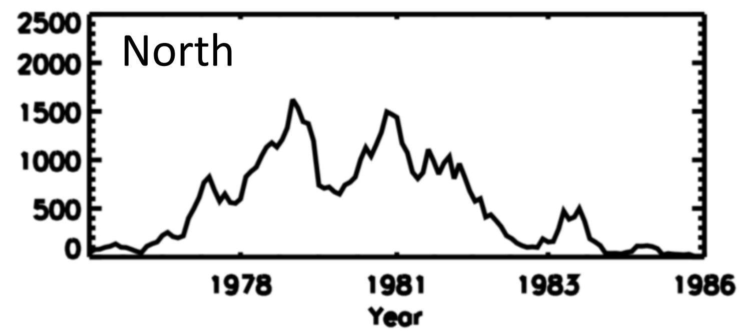
Solar cycle 21

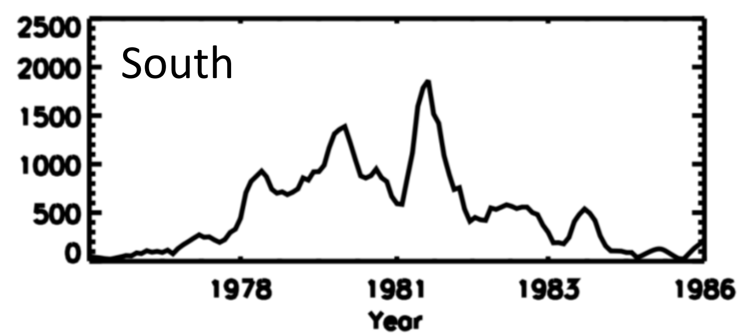


RGO sunspot areas

Norton & Gallagher 2009

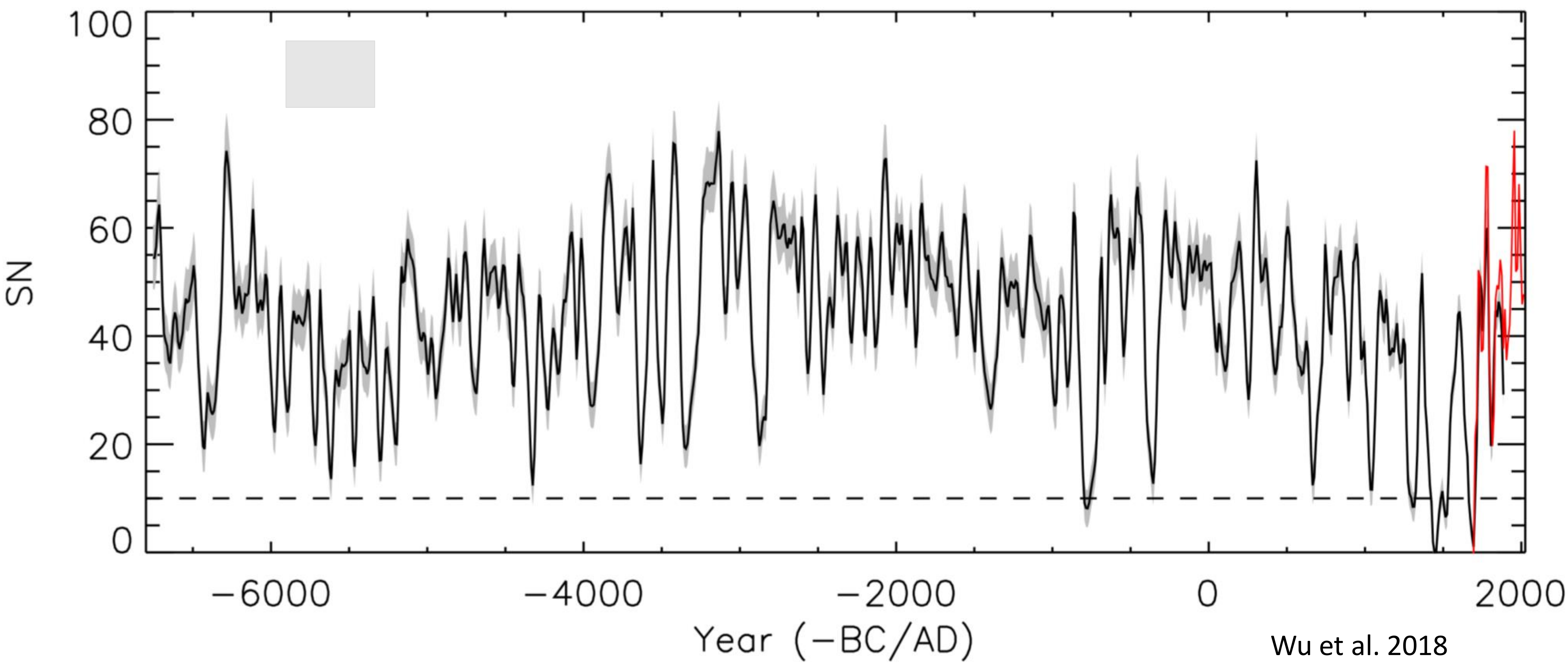
Solar cycle 21





Kodaikanal sunspot areas

Ravindra et al. 2021



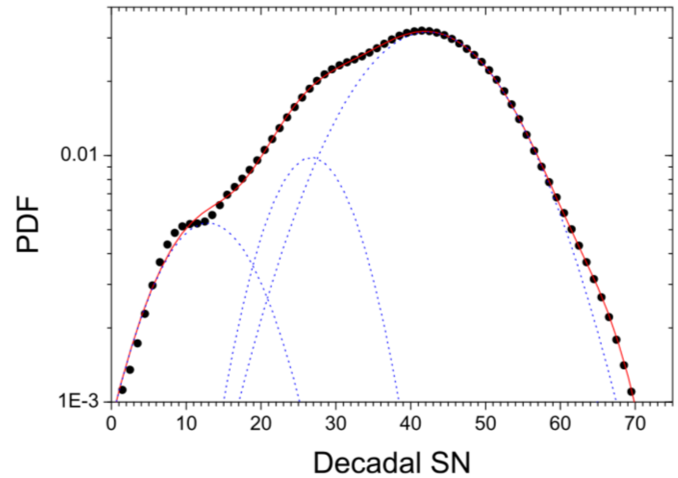
Wu et al. 2018

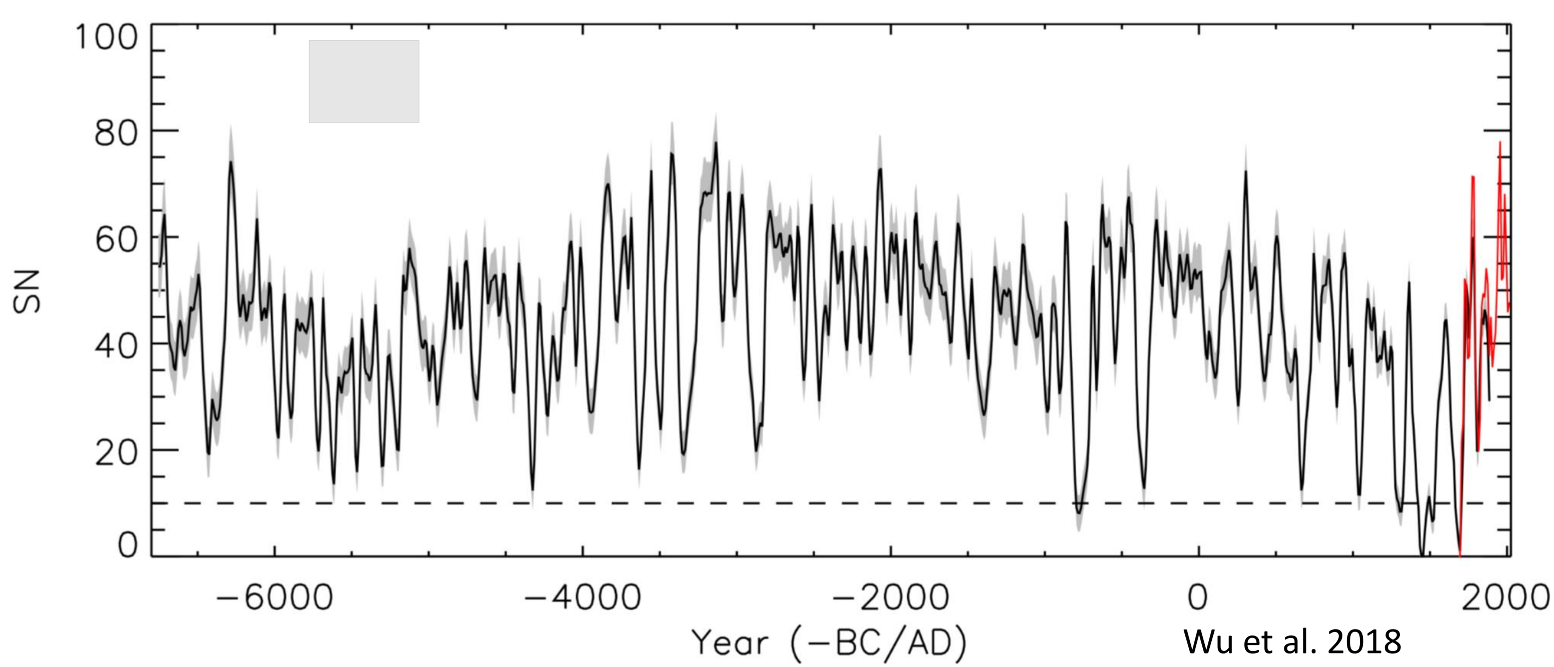
~75% moderate activity levels
~15% grand minimum
~10% grand maximum

Grand minima

Center (−BC/AD)	Duration (years)	Comment	Center (−BC/AD)	Duration (years)	Comment
1680	80	Maunder[a]	−3620	50	1–3
1470	160	Spörer	−4220	30	1–3
1310	80	Wolf	−4315	50	1–3
1030	80	Oort	−5195	50	2, 3
690	80	1–3	−5300	50	1–3
−360	80	1–3	−5460	40	1–3
−750	120	1–3	−5610	40	1–3
−1385	70	1–3	−6385	130	1–3
−2450	40	2, 3	−7035	50	1
−2855	90	1–3	−7305	30	1
−3325	90	1–3	−7515	150	1
−3495	50	1–3	−8215	110	1
−3620	50	1–3	−9165	150	1

Usoskin 2017



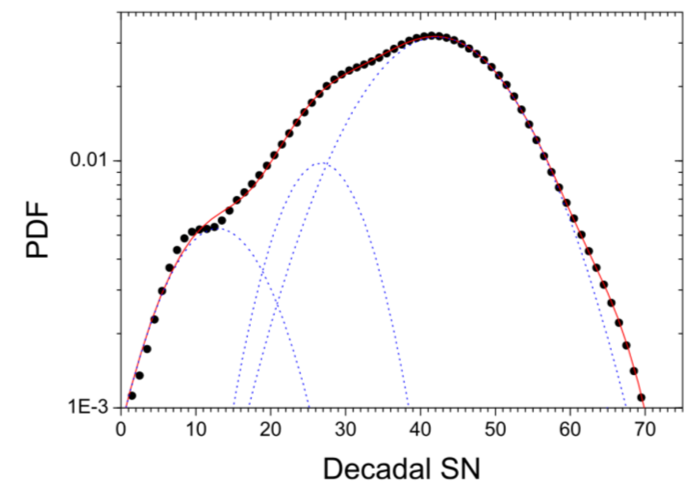


Wu et al. 2018

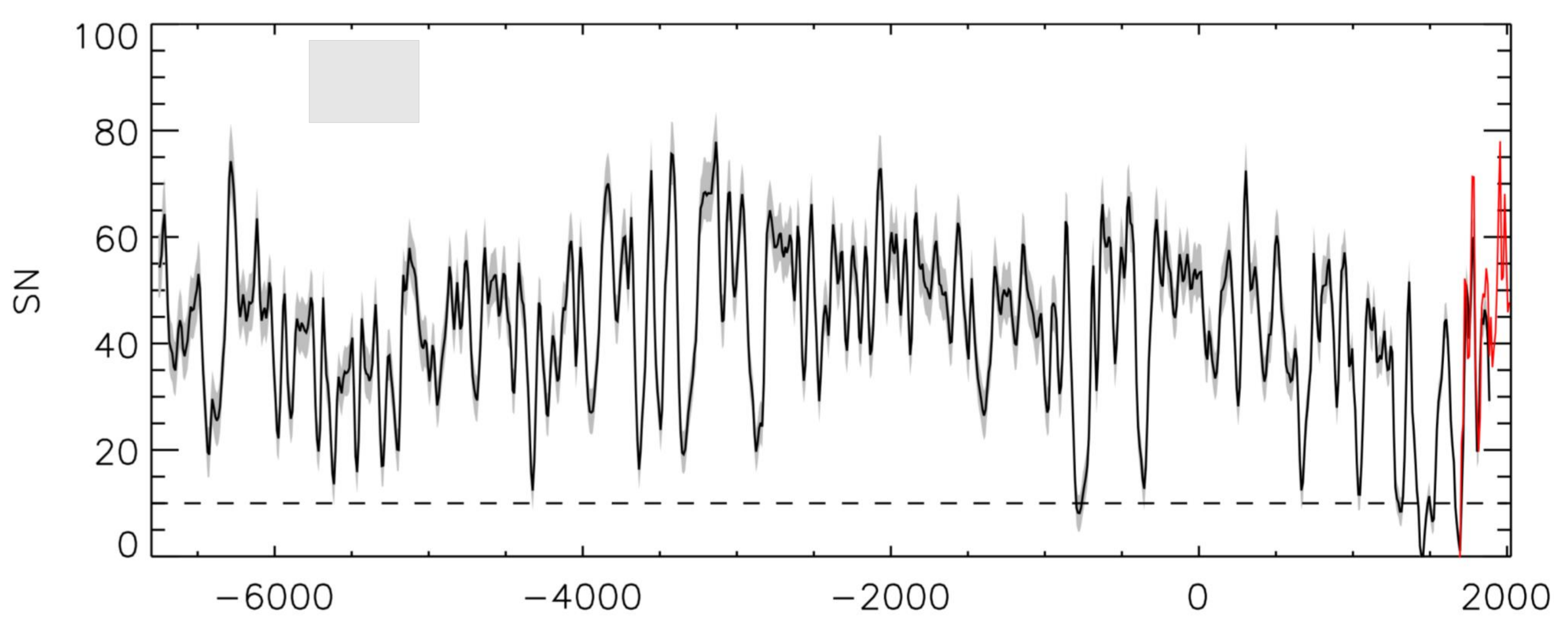
~75% moderate activity levels
~15% grand minimum
~10% grand maximum

Grand maxima

Center (−BC/AD)	Duration (years)	Comment	Center (−BC/AD)	Duration (years)	Comment
1970	80	Modern	−6515	70	1
505	50	2, 3	−6710	40	1
305	30	2, 3	−6865	50	1
−245	70	2, 3	−7215	30	1
−435	50	1–3	−7660	80	1
−2065	50	1–3	−7780	20	1
−2955	30	2, 3	−7850	20	1
−3170	100	1–3	−8030	50	1
−3405	50	2, 3	−8350	70	1
−3860	50	1–3	−8915	190	1
−6120	40	1–3	−9375	130	1
−6280	40	2, 3			

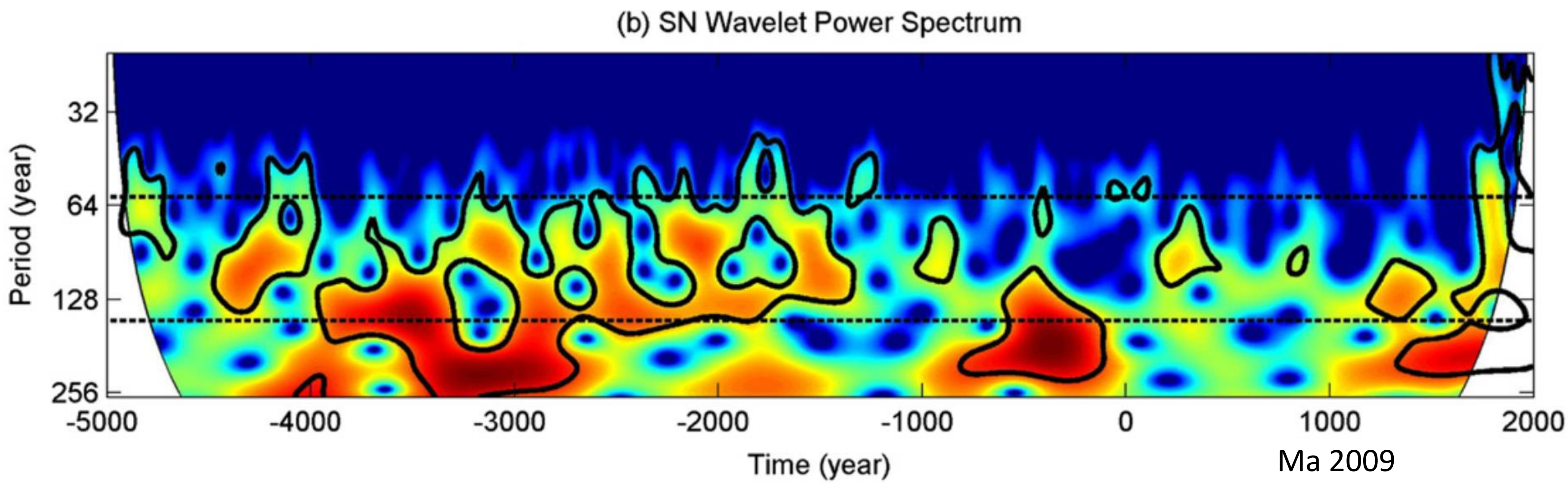


Usoskin 2017

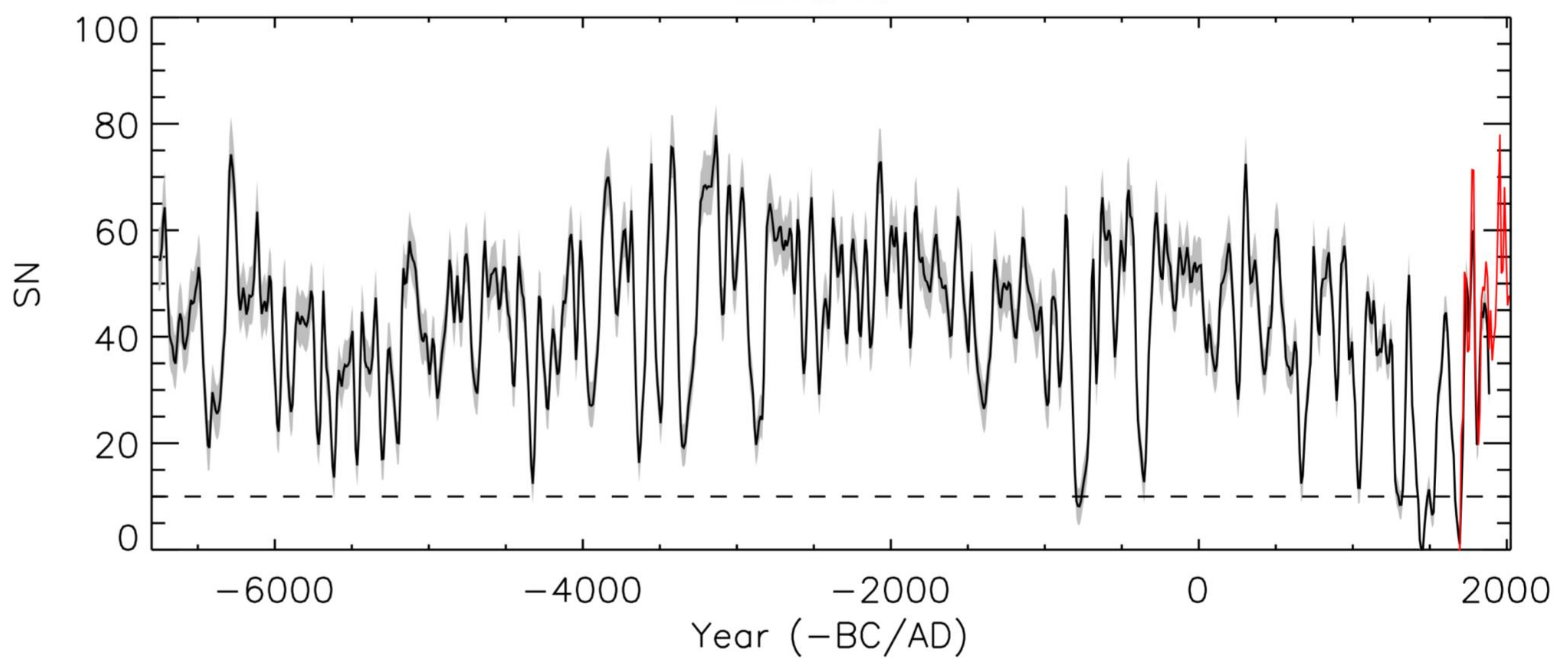


Wu et al. 2018

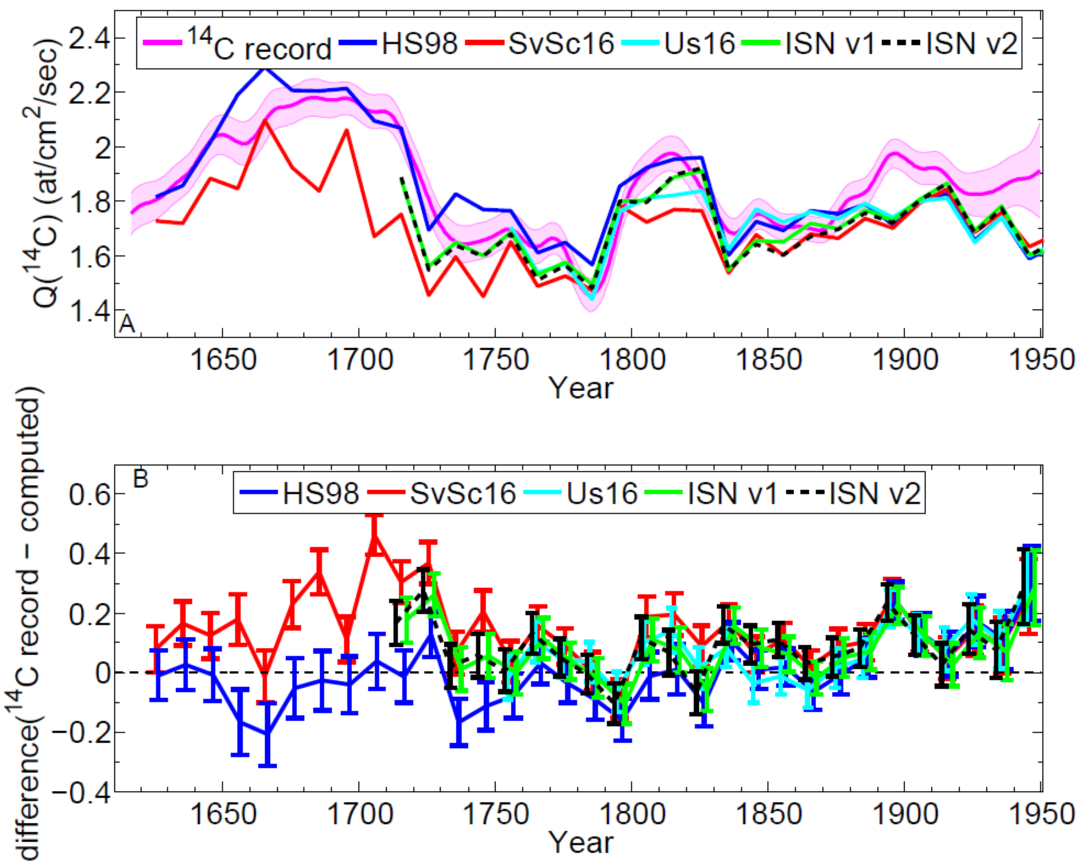
Gleissberg cycle 60-120 yrs
Suess/de Vries cycle 205-210 yrs
Eddy cycle 600-700 or 1000-1200 yrs
Hallstatt cycle 2000-2400 yrs



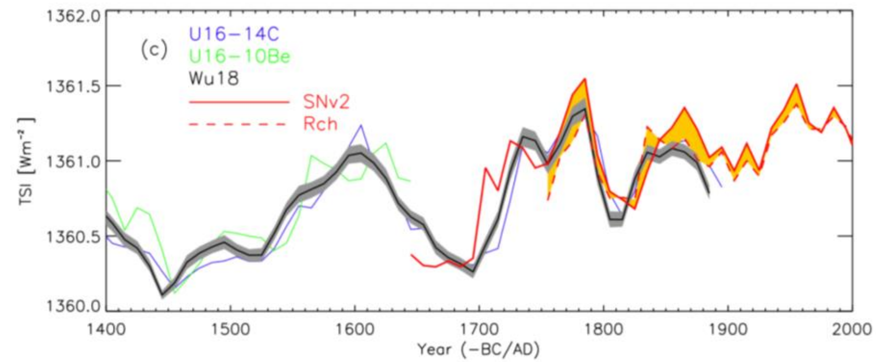
Ma 2009



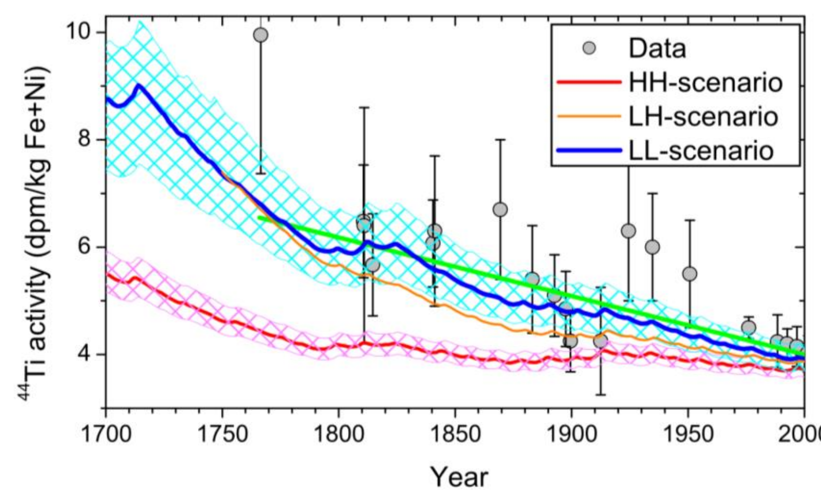
Comparing Sunspot series to cosmogenic isotope data



Asvestari, 2016



Wu et al., 2018



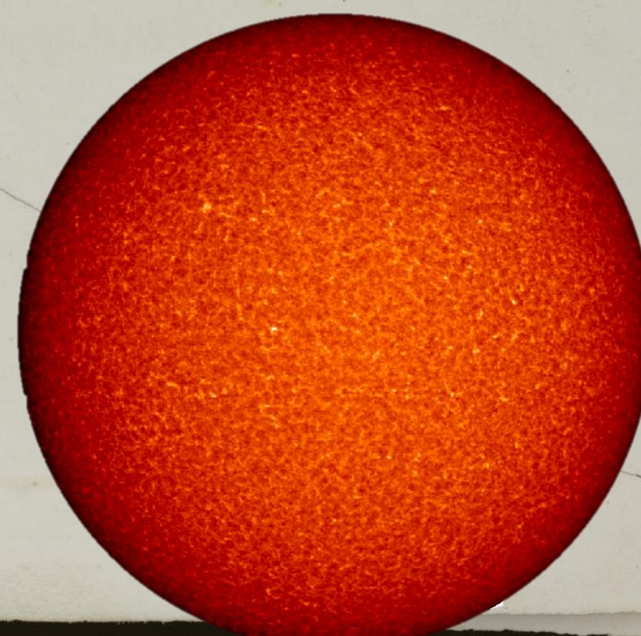
Asvestari et al., 2017

Cosmogenic radioisotopes favor sunspot number series closer to the one by Chatzistergos et al. 2017

Faculae/plage area series

Solar Maximum

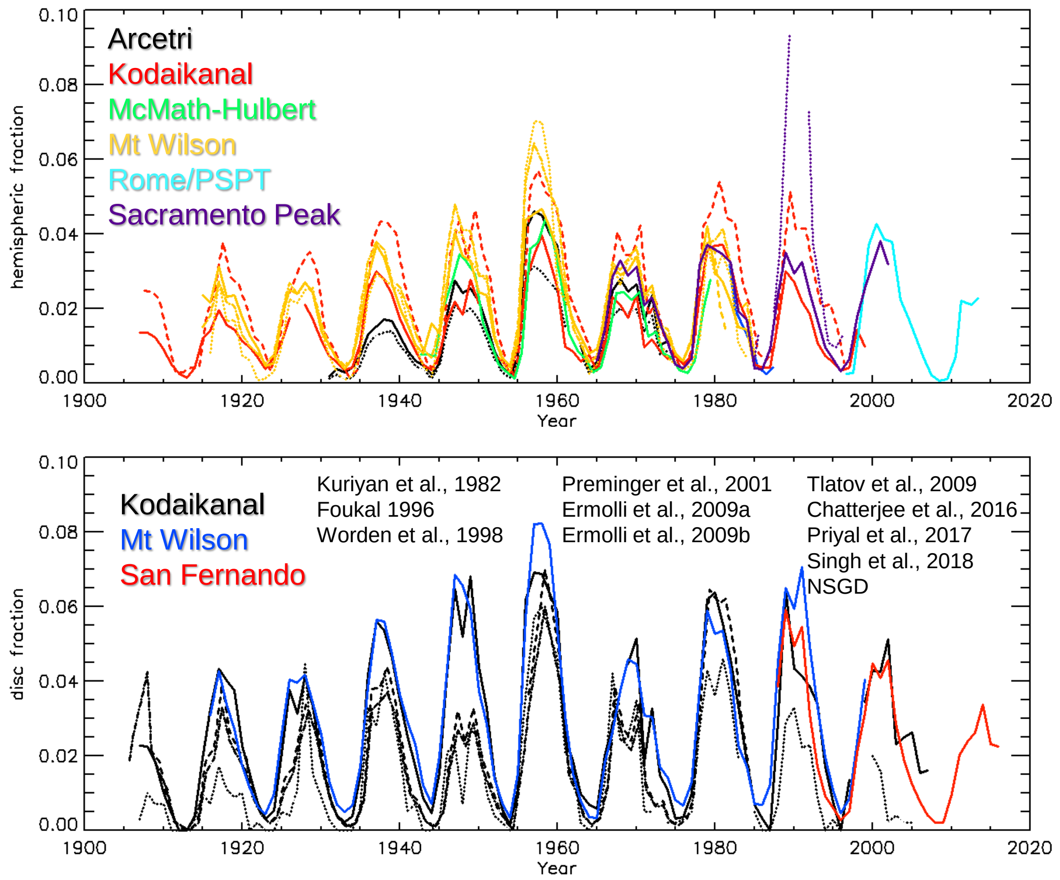
Solar Minimum



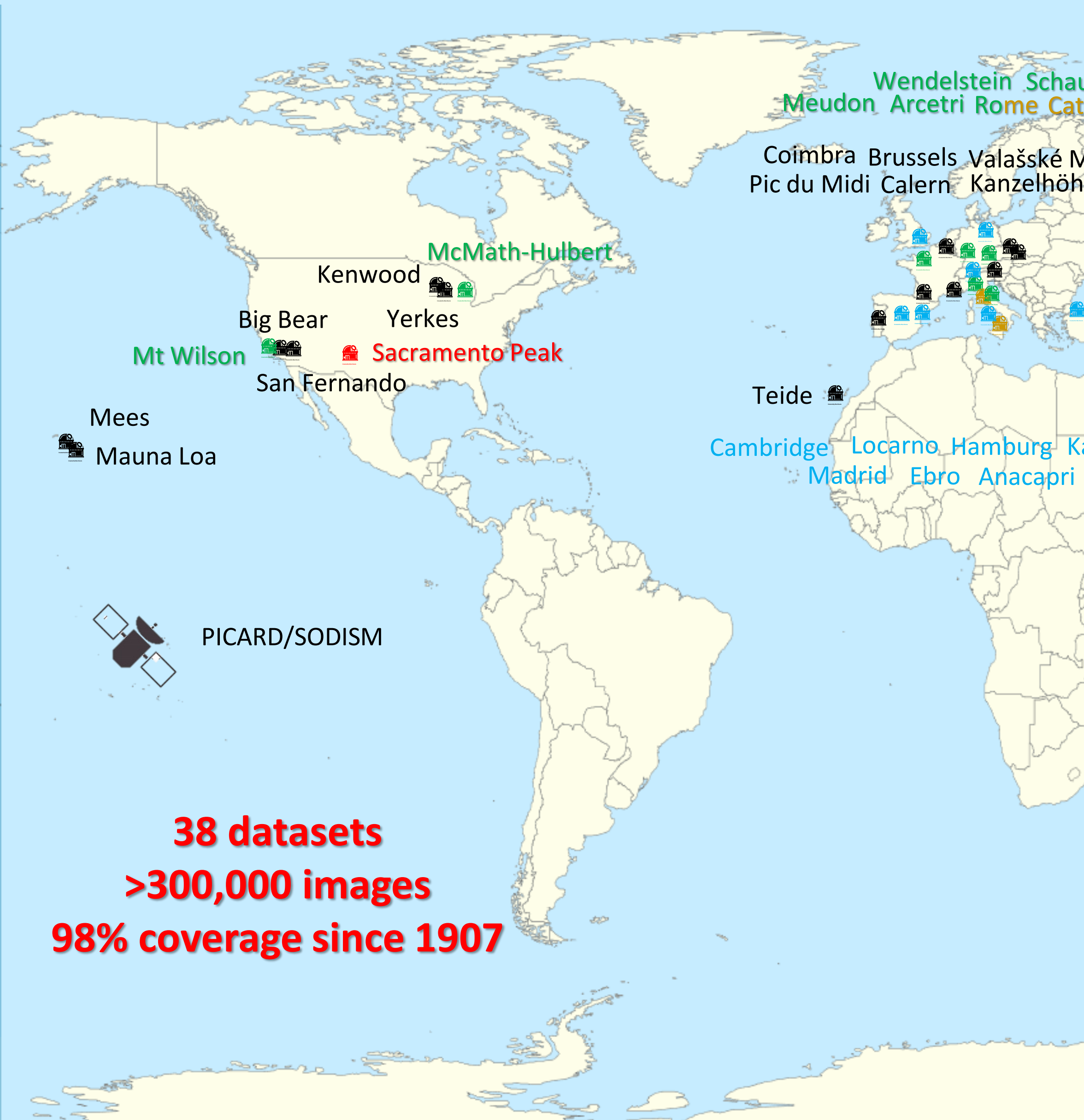
Available plage area series

Most studies:

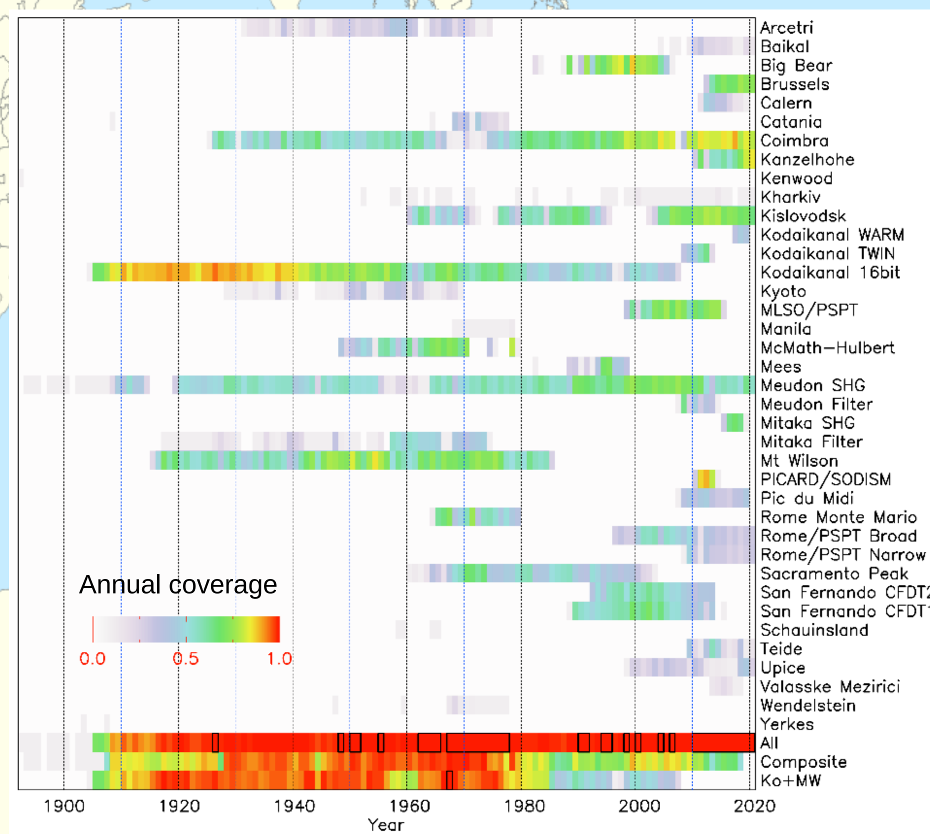
- Use of single archive
- No photometric calibration
- Different processing techniques
- Segmentation manually adapted
- No accuracy estimation of processing
- ….



Ca II K archives

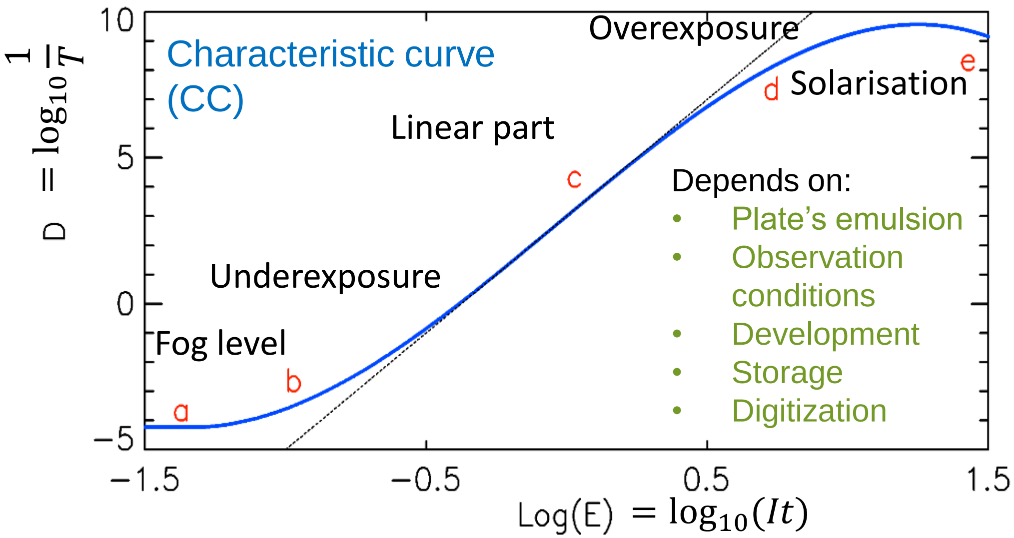


38 datasets
>300,000 images
98% coverage since 1907

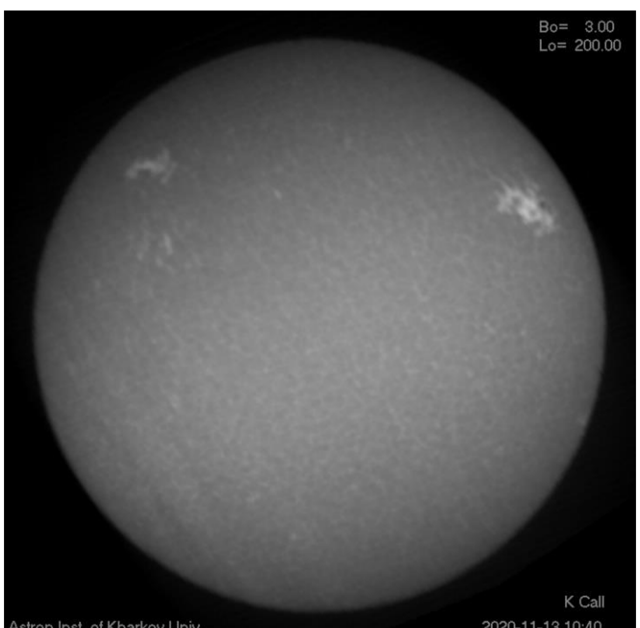


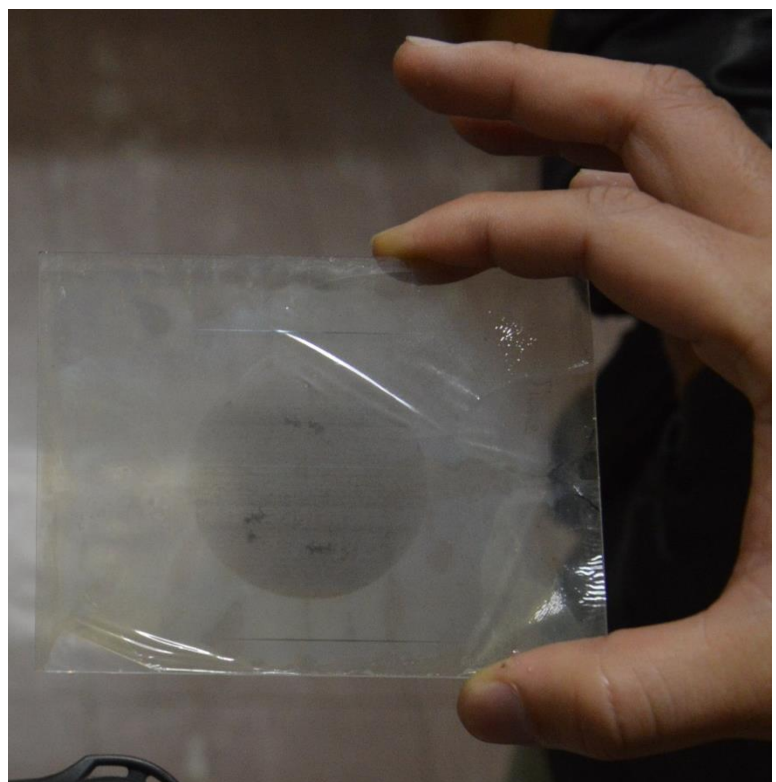
Chatzistergos et al., 2019a, A&A 625
Chatzistergos et al., 2019b, Sol. Phys. 294 10
Chatzistergos et al., 2019c, Il Nuovo Cimento 42C
Chatzistergos et al., 2020a, Journal of Physics: Conference Series
Chatzistergos et al., 2020b A&A 639

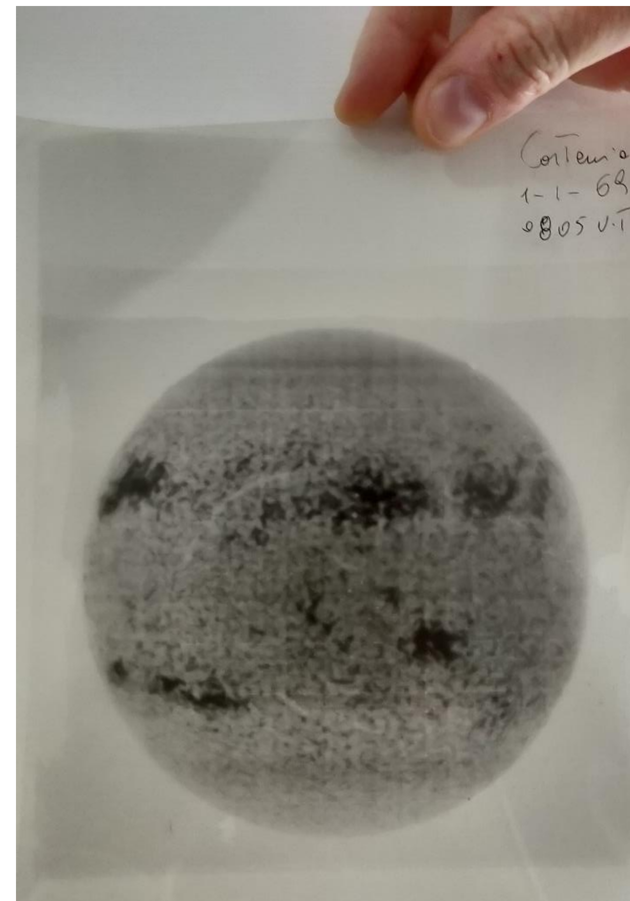
Photographic plates ≠ linear detectors

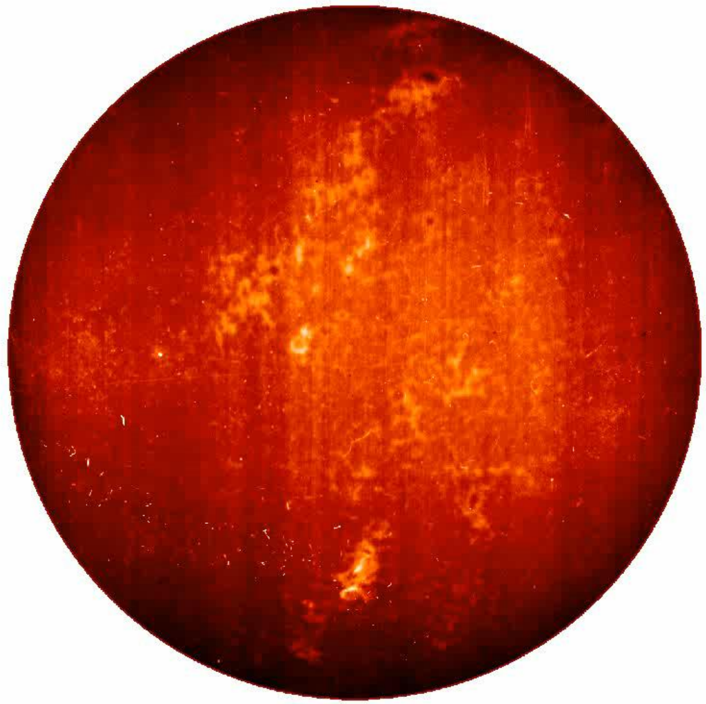


Chatzistergos et al., 2018

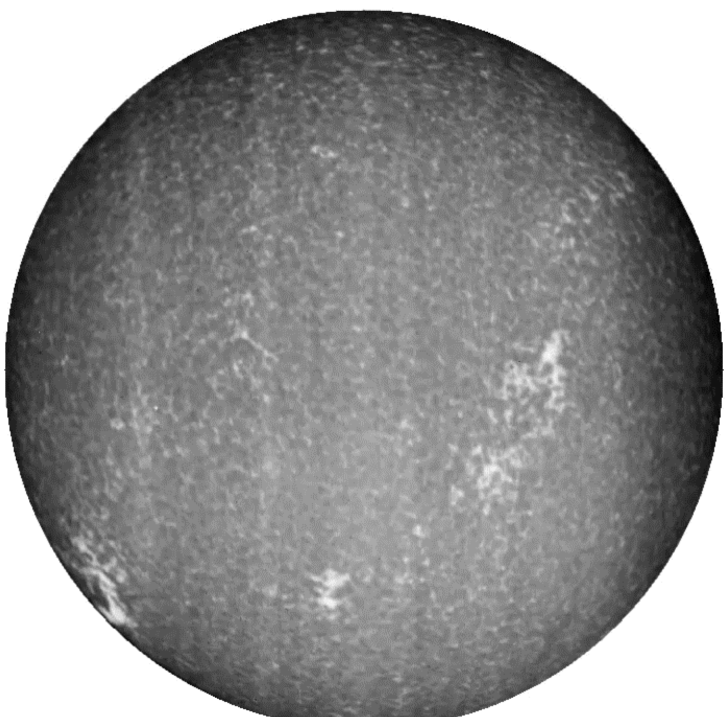




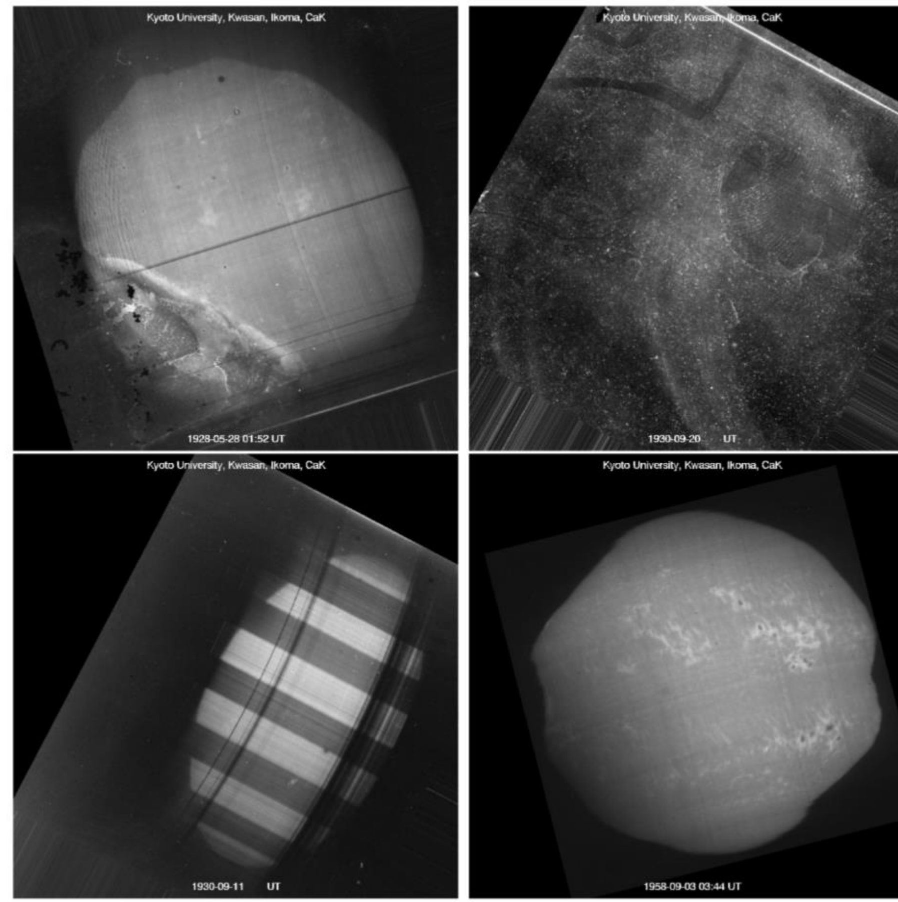


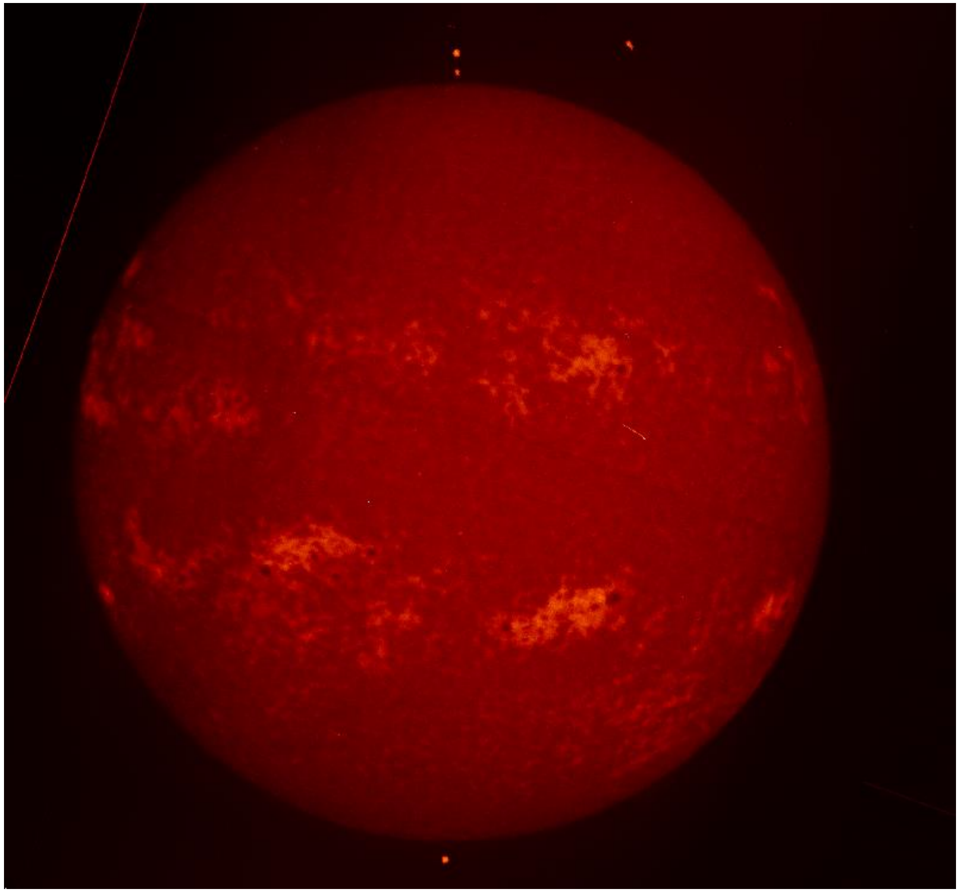
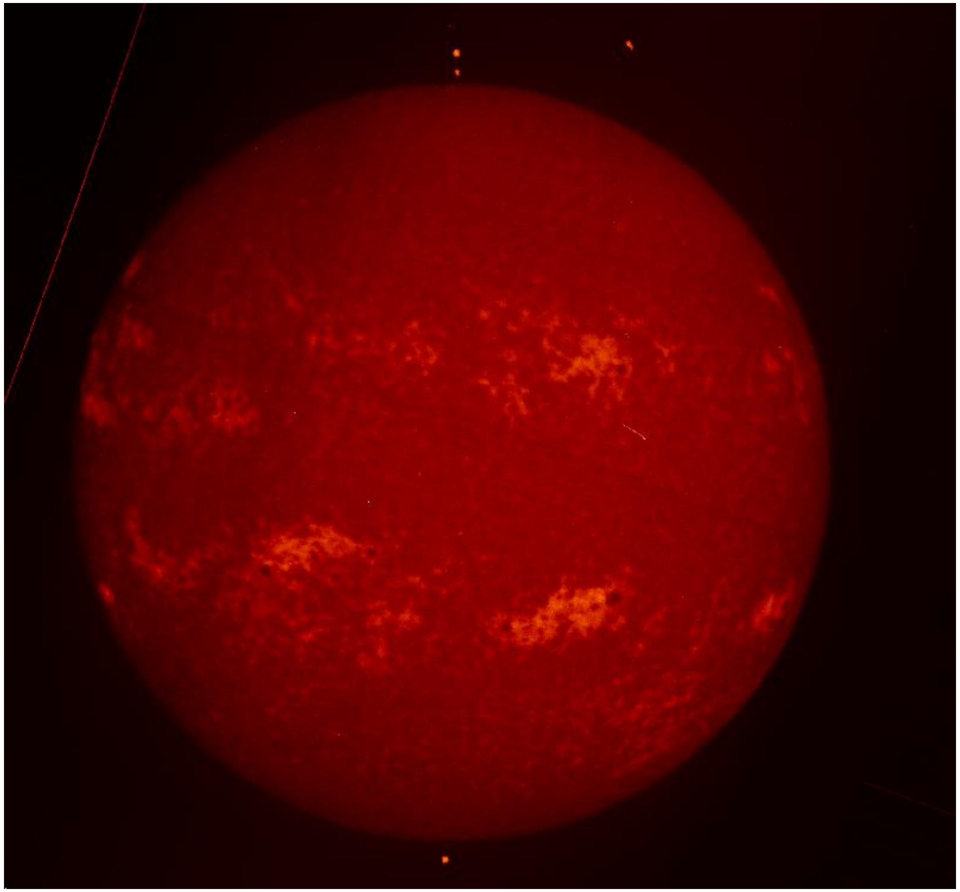


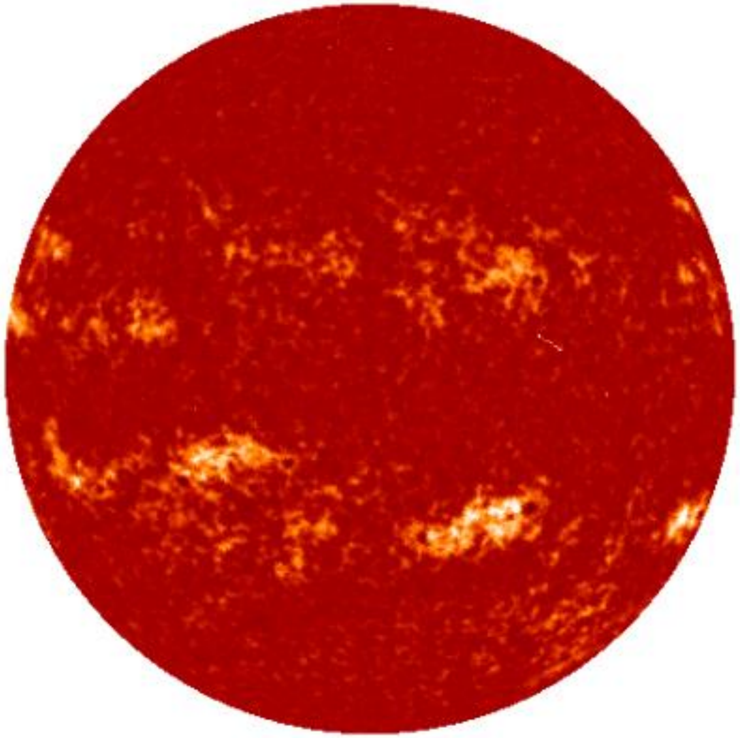
05/01/1950 00:00:00



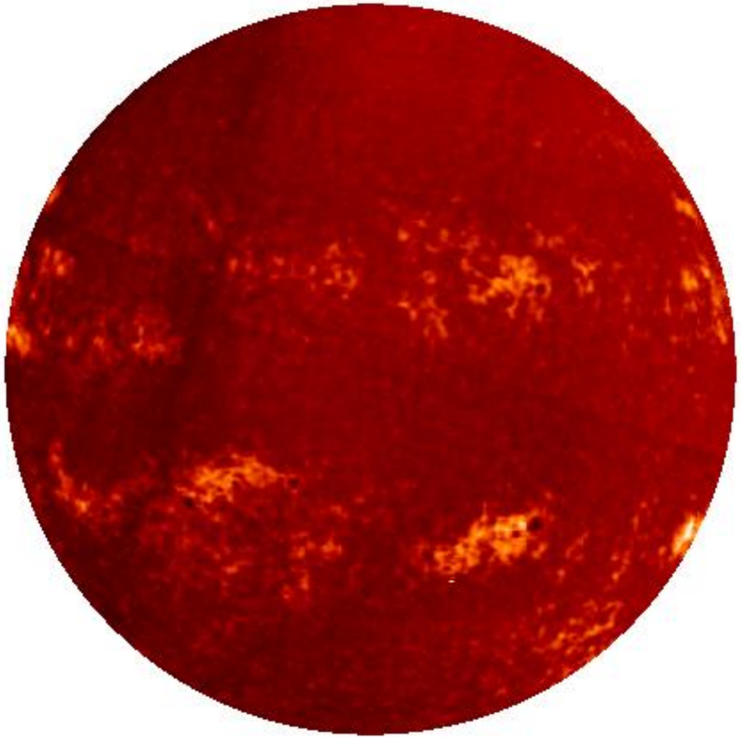
01/01/1915



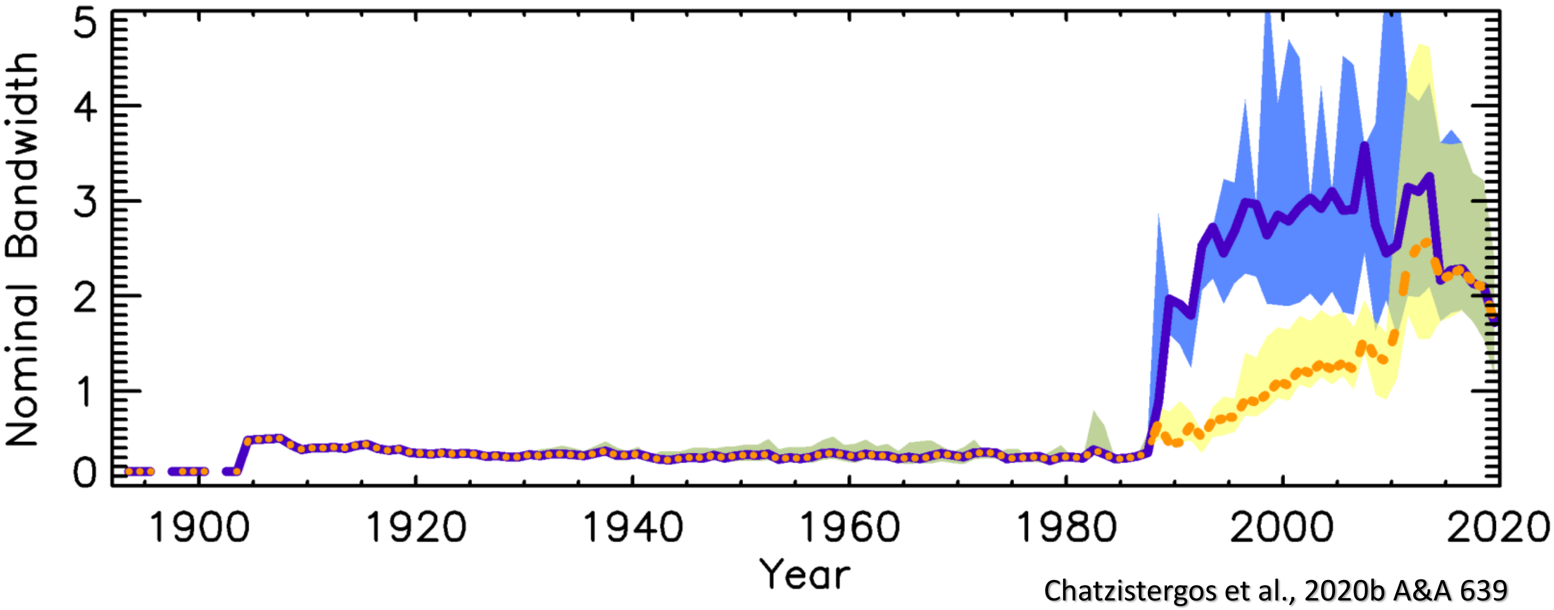


Chatzistergos et al. 2018



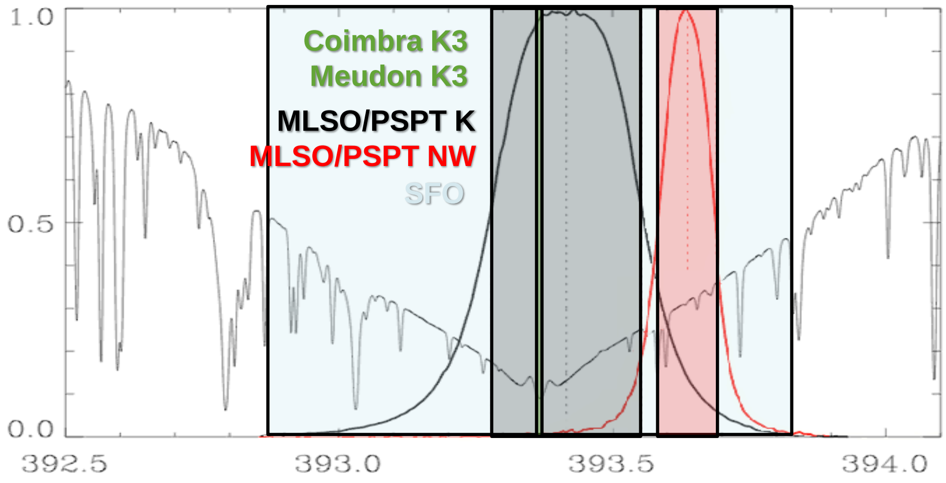
Priyal et al., 2017

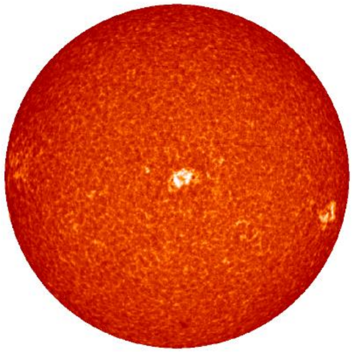
Ca II K observations



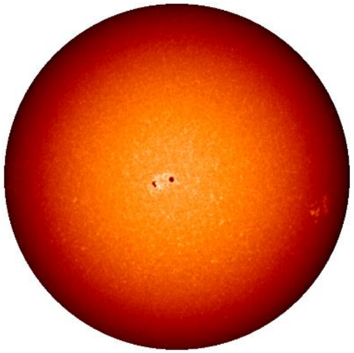
Chatzistergos et al., 2020b A&A 639

Bandwidths change among archives





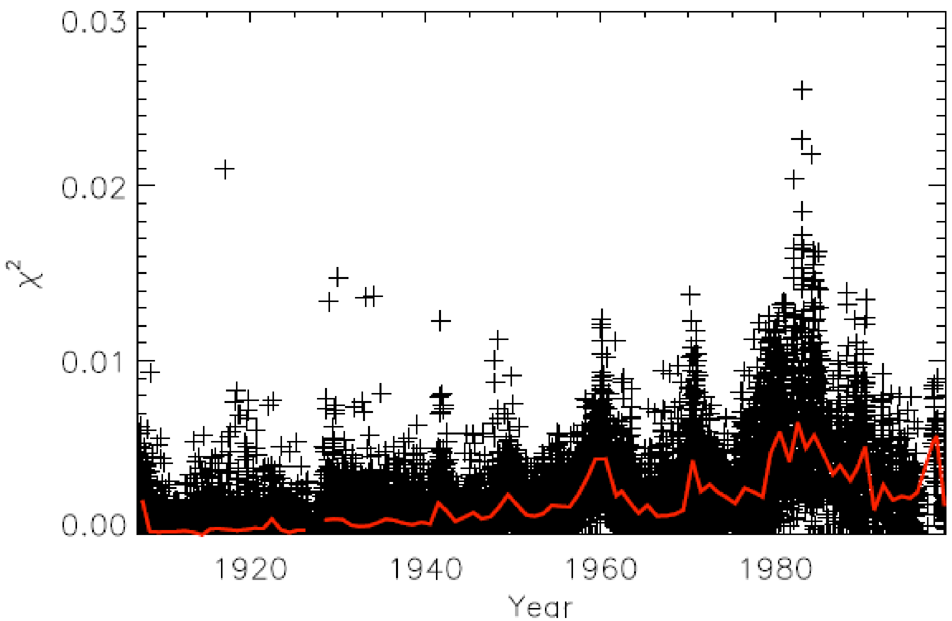
Meudon



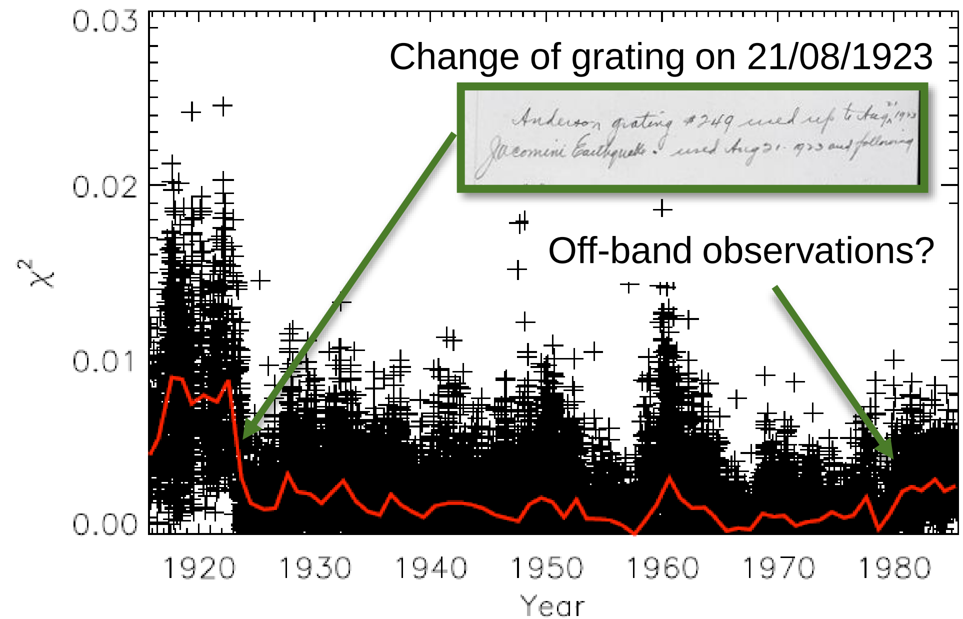
SFO

Archives' inconsistencies

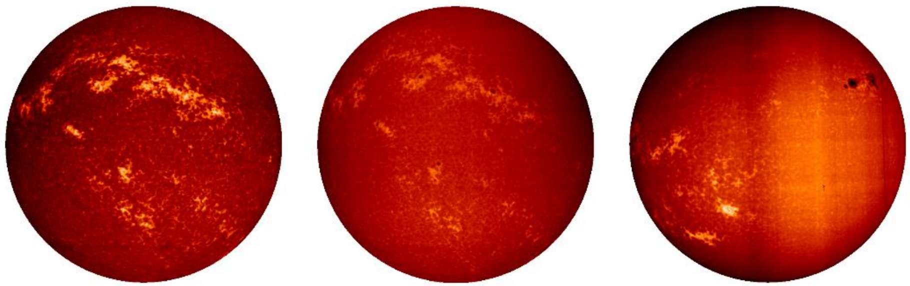
Kodaikanal



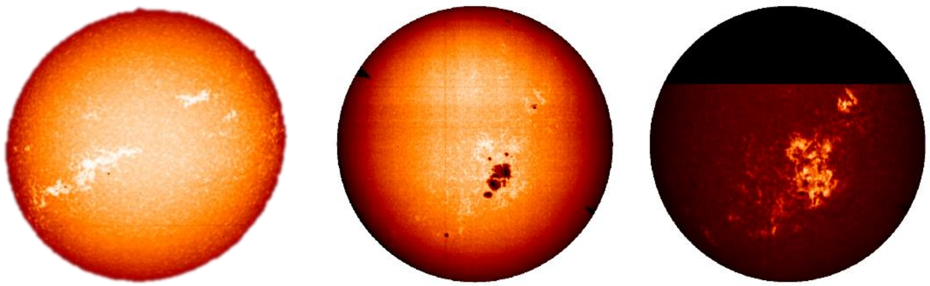
Mt Wilson



19/04/1969 19/04/1969 16/11/1990

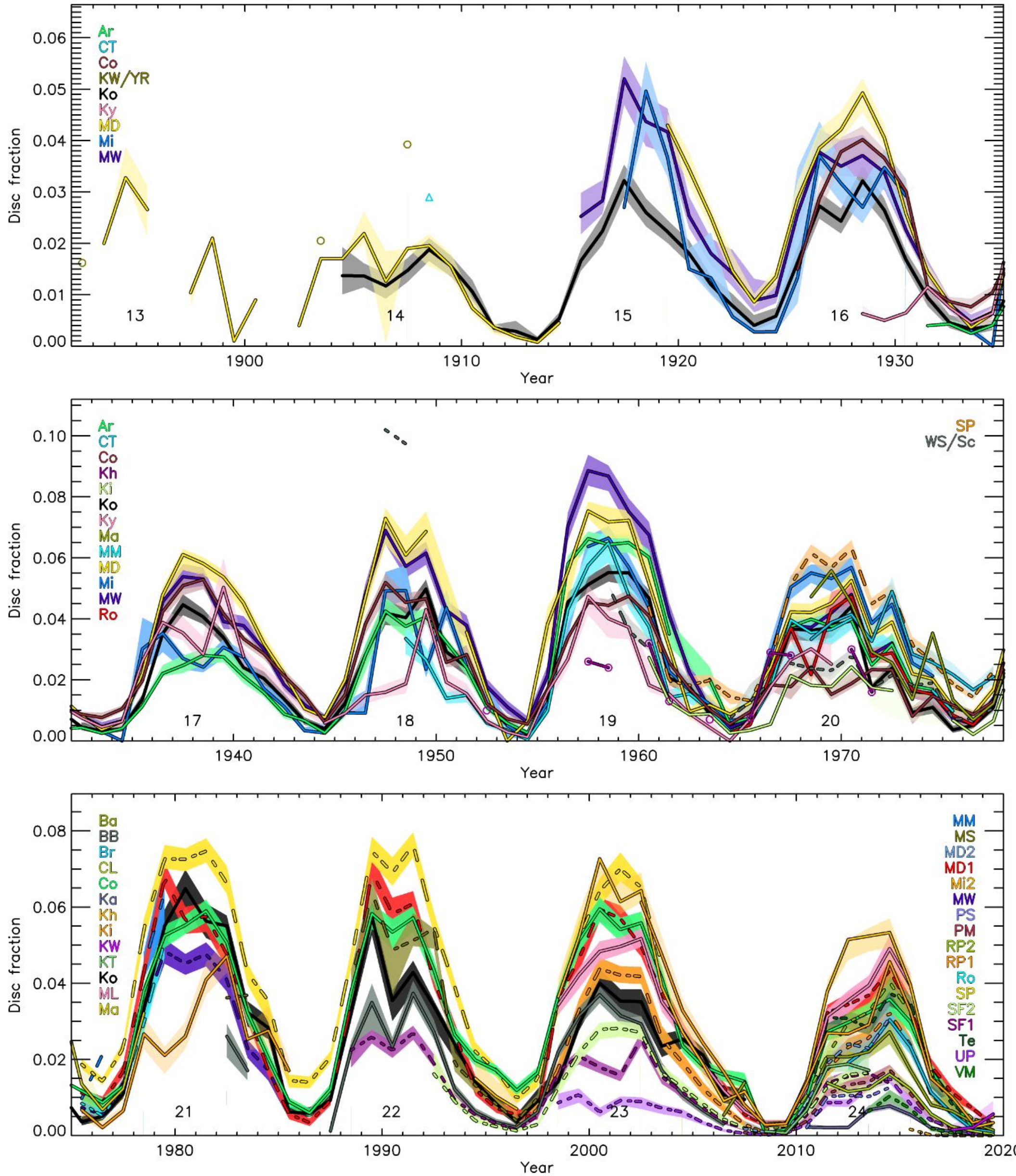


15/03/1921 16/05/1951 16/05/1951

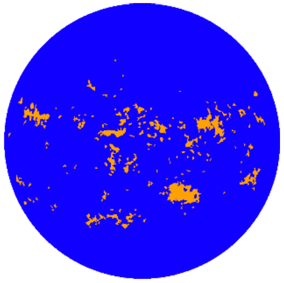


Chatzistergos et al., 2019a, A&A 629

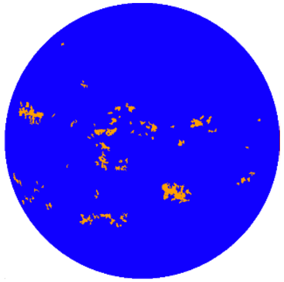
Plage coverage over the 20th century

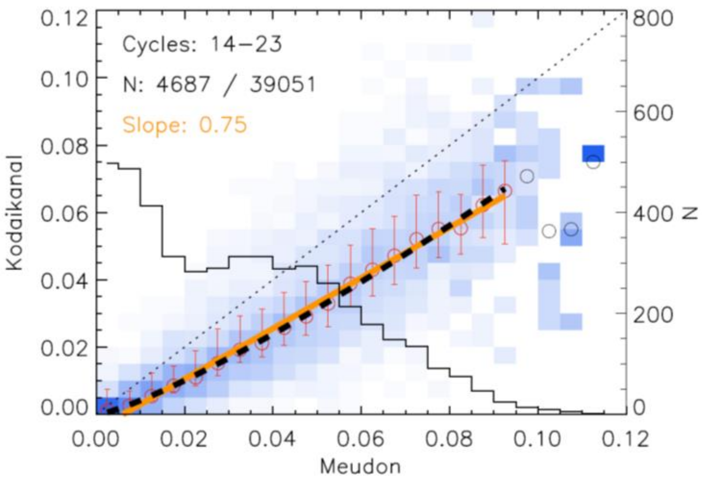


Meudon
0.015nm



Kodaikanal
0.05nm

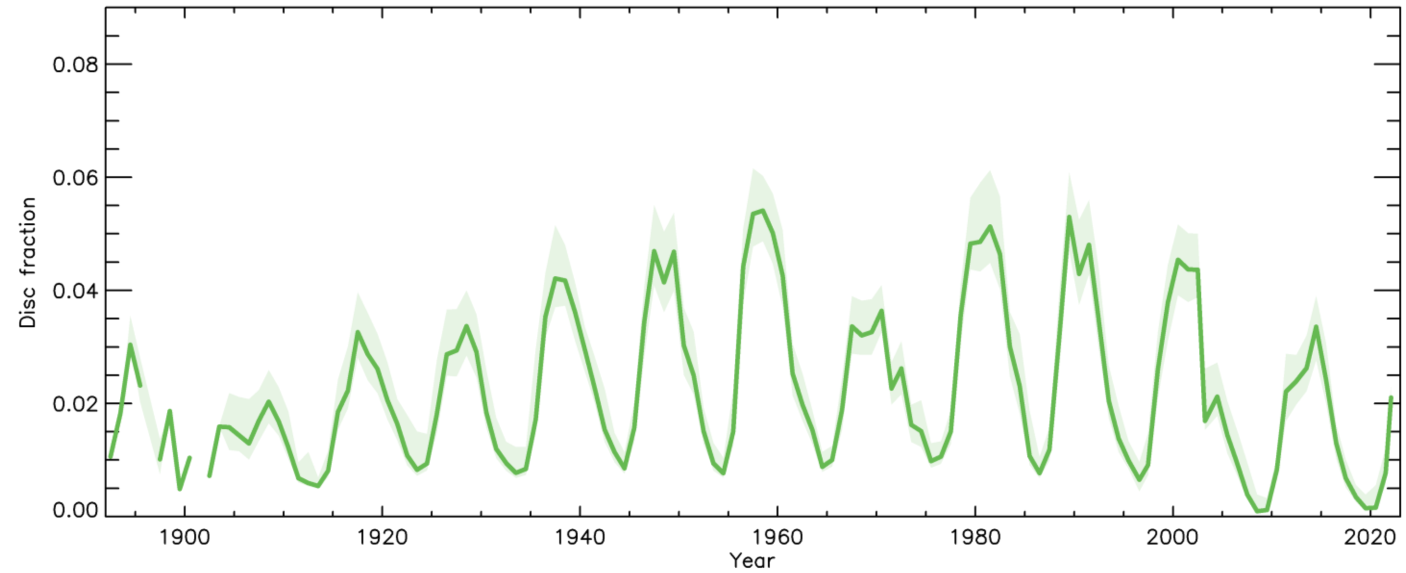




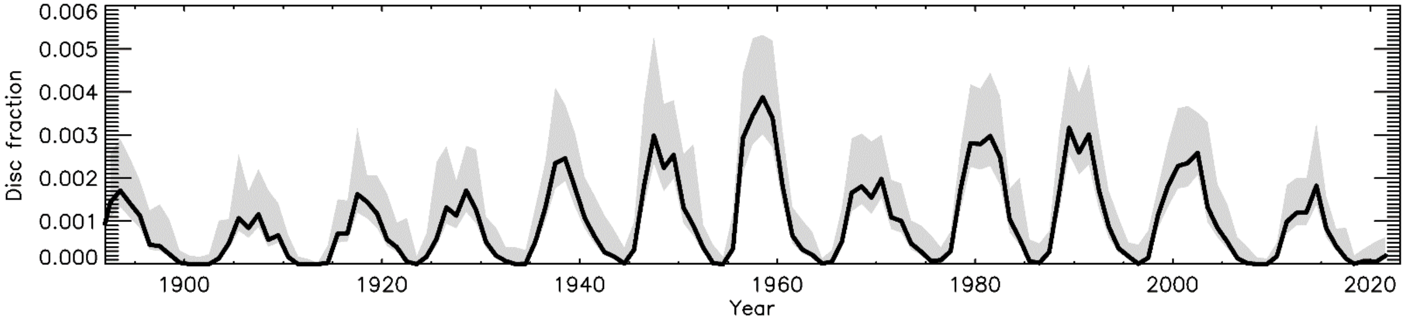
Chatzistergos et al., 2020, A&A 639

Plage coverage over the 20th century

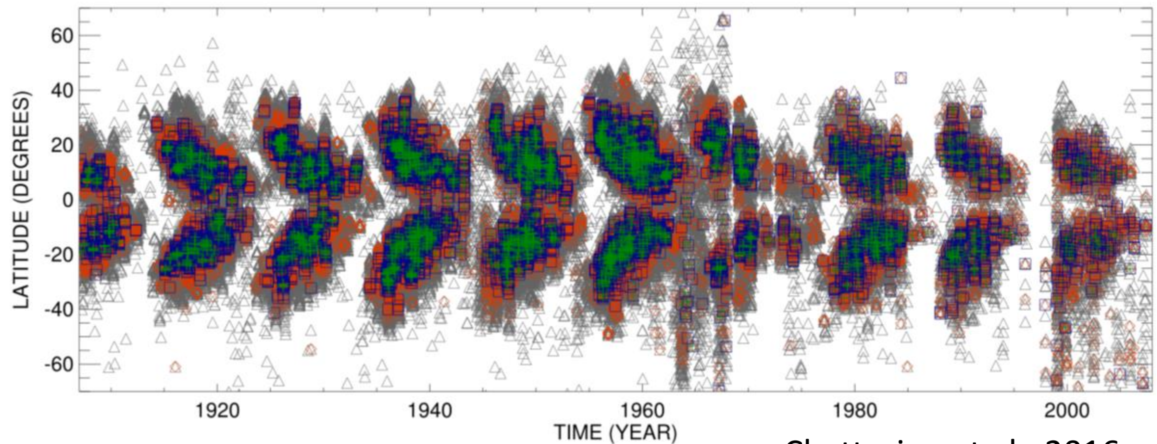
Plage fractional areas



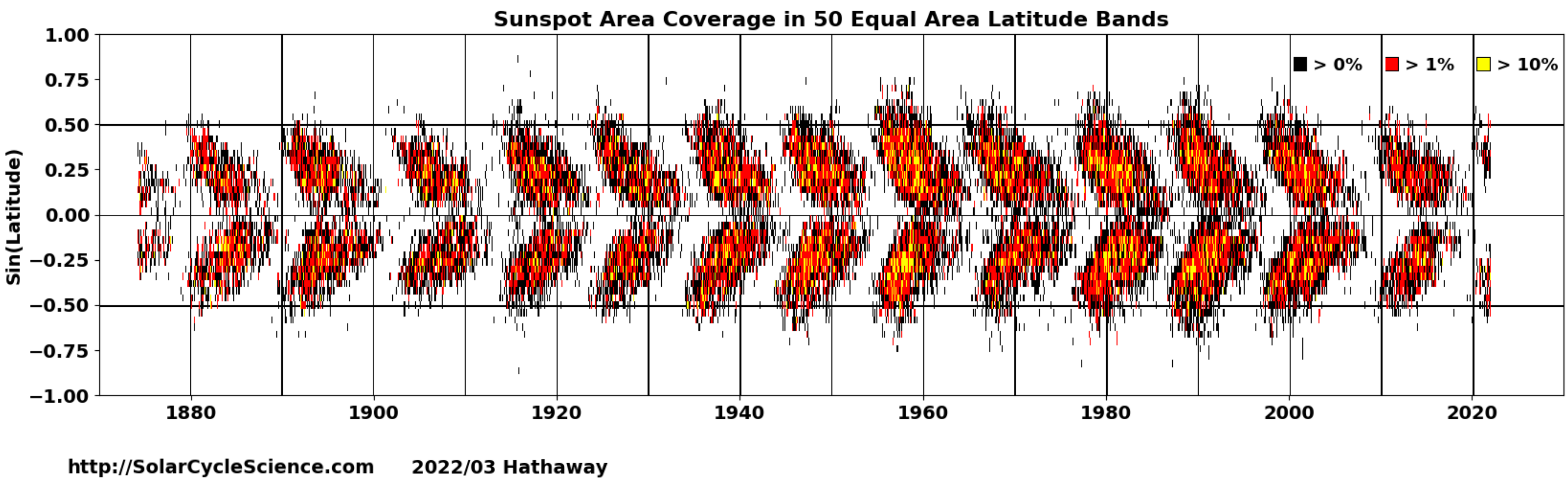
Sunspot fractional areas



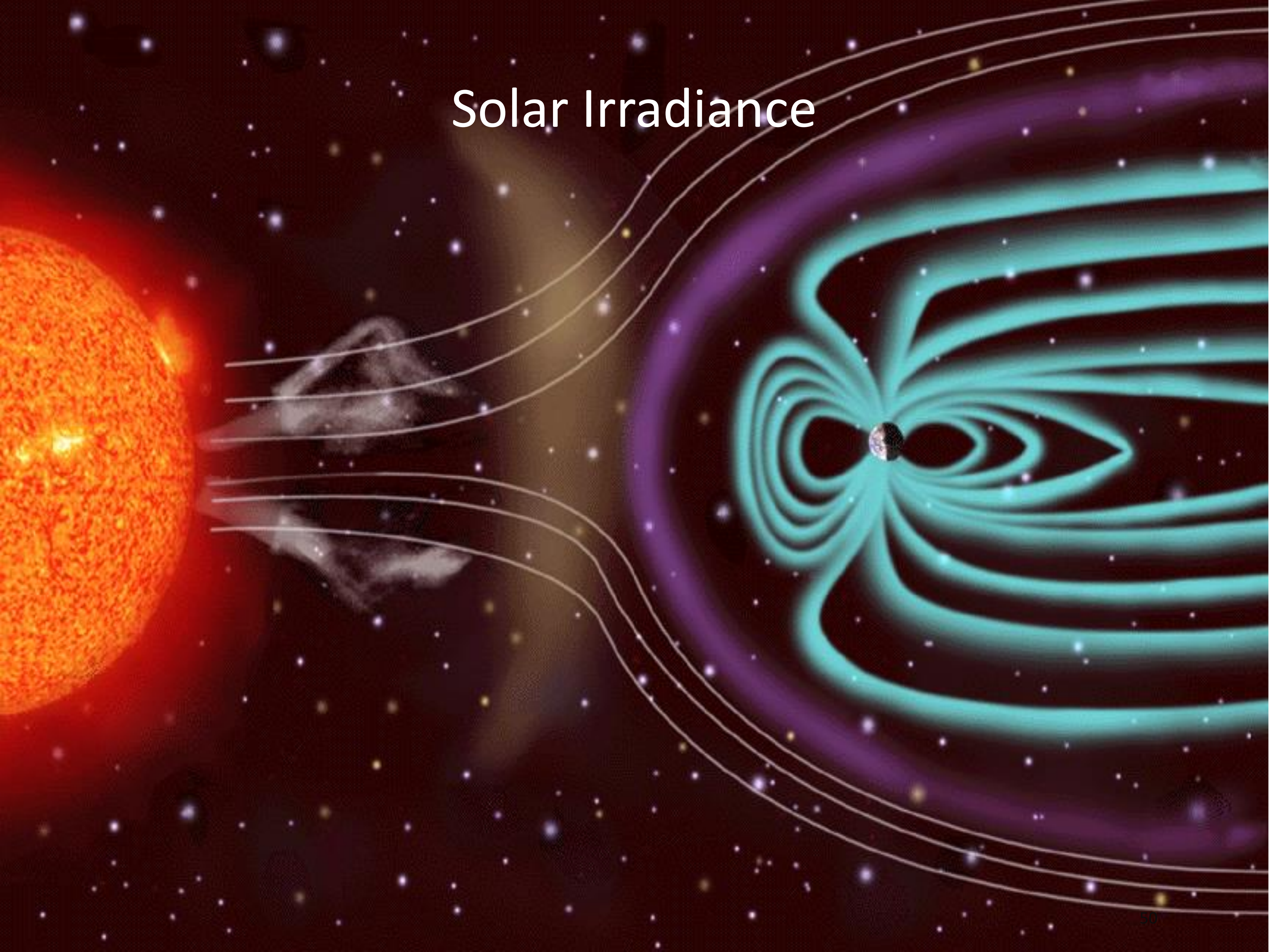
Chatzistergos et al., 2020, A&A 639



Chatterjee et al., 2016



Solar Irradiance

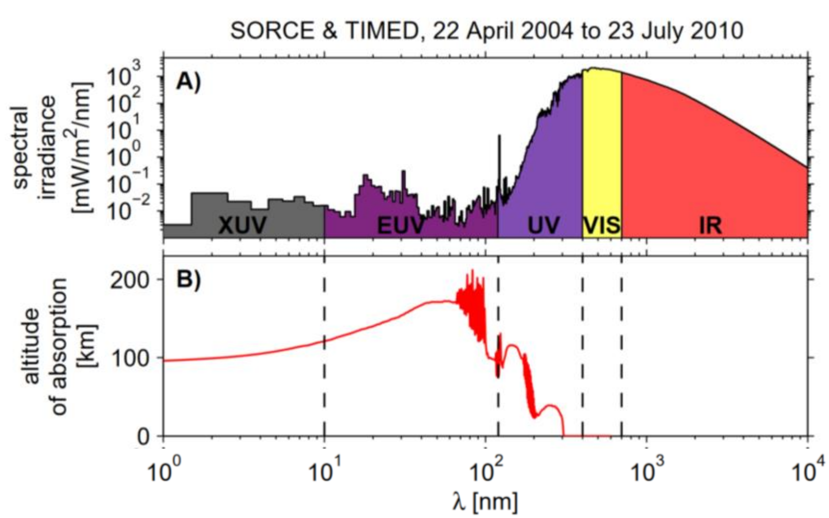


Solar Constant

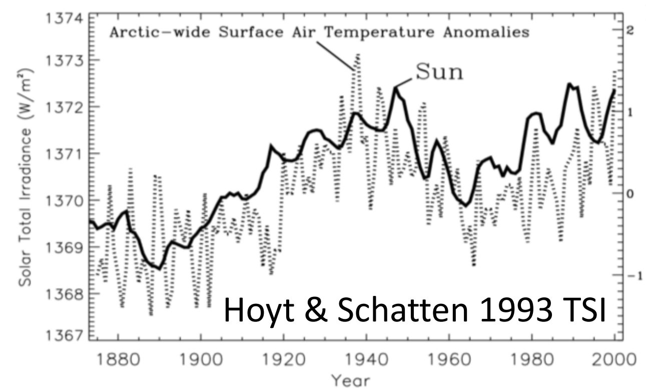
- Claude Poullet (1837) 1227 W m^{-2}
- John Hershel (1837)
- Sam Langley (1881) 2903 W m^{-2}
- Charles Abbot (1958) 1465 W m^{-2} (±0.1%)
- Labs and Neckel (1971) 1360 W m^{-2} (±1%)

Energy source	Flux density [W m^{-2}]	Uncertainty or range [W m^{-2}]	Relative to total solar irradiance
Solar irradiance	**340.2**	**±0.12**	**1.000**
Earth's interior heat flux	0.09	±0.006	2.6×10^{-4}
Infrared radiation from the full Moon	0.01	8.7×10^{-3} to 0.0113	2.9×10^{-5}
Combustion of coal, oil, and gas in the United States	0.0052	–	1.5×10^{-5}
Magnetic storm dissipation	0.00362	1.0×10^{-5} to 1.0×10^{-3}	1.1×10^{-5}
Reflected radiation from the full Moon	0.0018	1.57×10^{-3} to 2.03×10^{-3}	5.3×10^{-6}
Solar atmospheric tides	0.00168	–	4.9×10^{-6}
Lightning discharge energy	4.95×10^{-4}	9.0×10^{-5} to 9.0×10^{-4}	1.5×10^{-6}
Auroral emission	3.7×10^{-4}	1.0×10^{-5} to 1.0×10^{-3}	1.1×10^{-6}
Zodiacal irradiance	5.67×10^{-5}	5.65×10^{-5} to 5.68×10^{-5}	1.7×10^{-7}
Lunar tides	1.96×10^{-5}	–	5.8×10^{-8}
Total radiation from stars	6.78×10^{-6}	5.62×10^{-6} to 7.94×10^{-6}	2.0×10^{-8}
Cosmic microwave background radiation	3.13×10^{-6}	$\pm 2.62 \times 10^{-9}$	9.2×10^{-9}
Dissipation of energy from micrometeorites	1.1×10^{-6}	1.9×10^{-8} to 2.0×10^{-6}	3.2×10^{-9}
Additional external sources			
Airglow emission	0.0036	–	1.1×10^{-5}
Galactic cosmic rays	8.5×10^{-6}	7.0×10^{-6} to 1.0×10^{-5}	2.5×10^{-8}
Earthshine	1.93×10^{-7}	–	5.7×10^{-10}

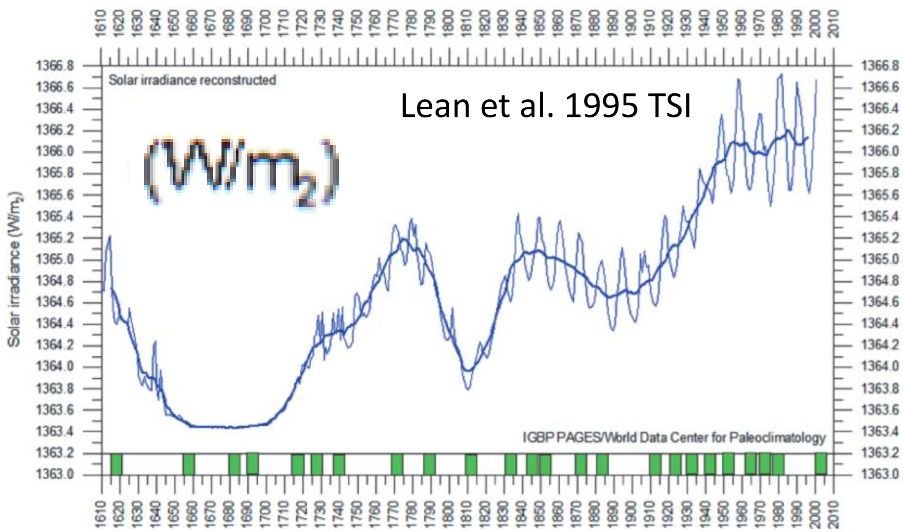
Kren et al. 2017

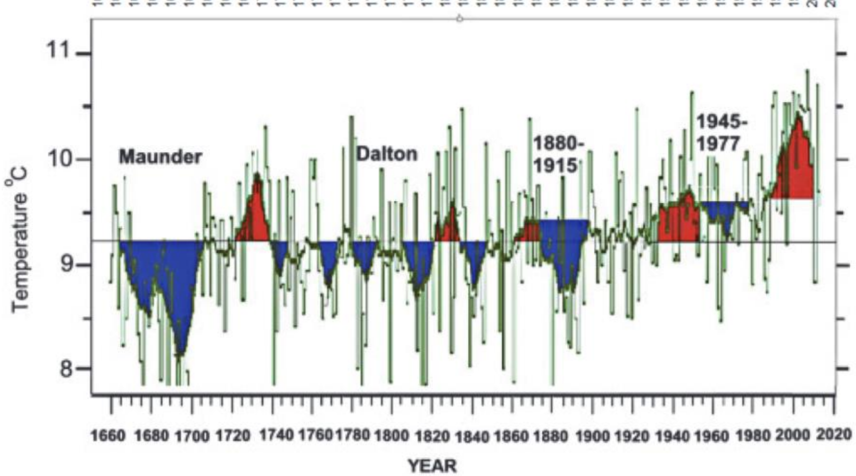


Ermolli et al. 2013

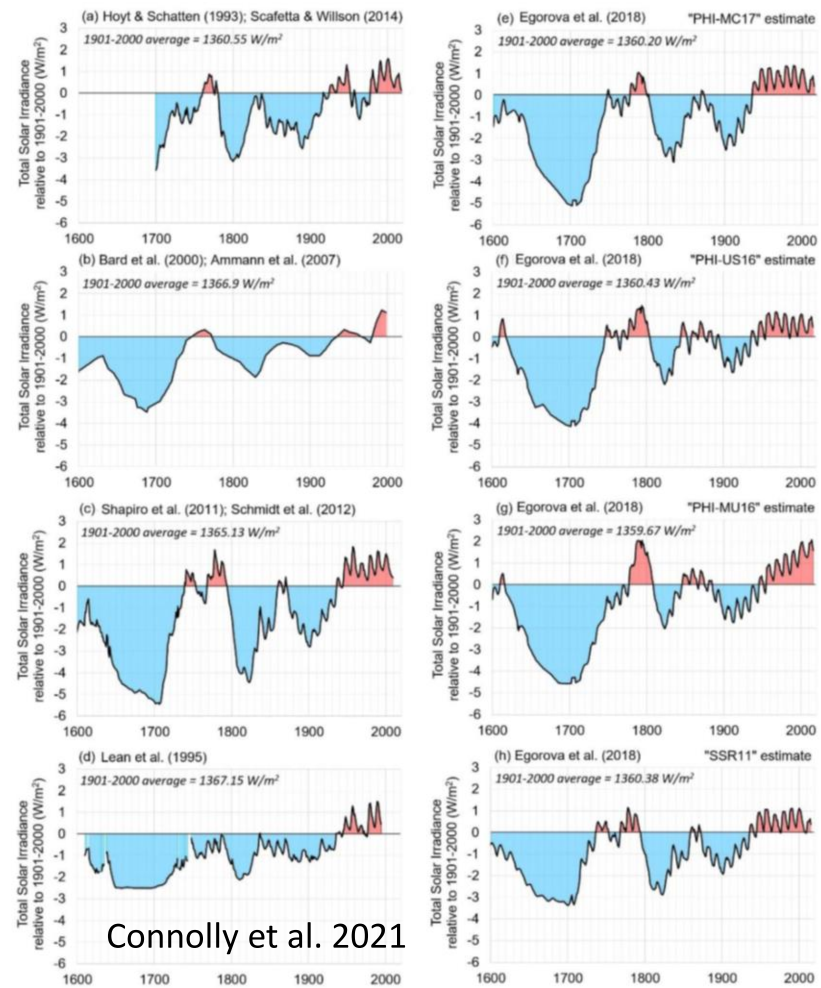


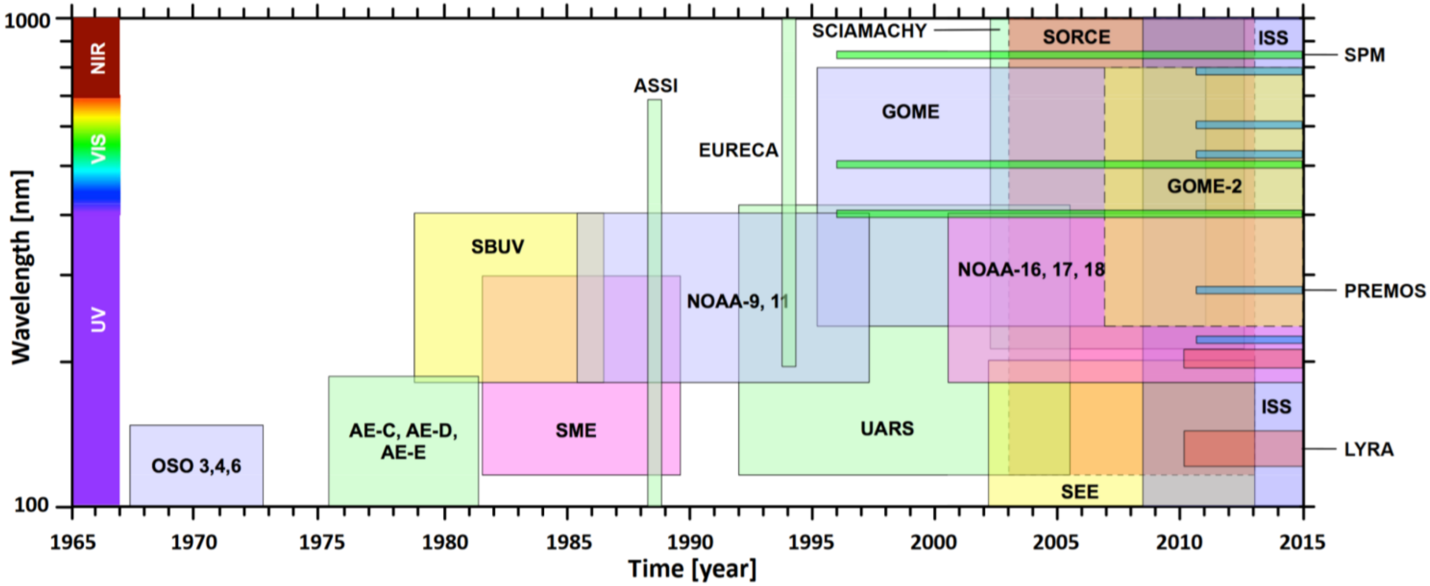
Soon 2005



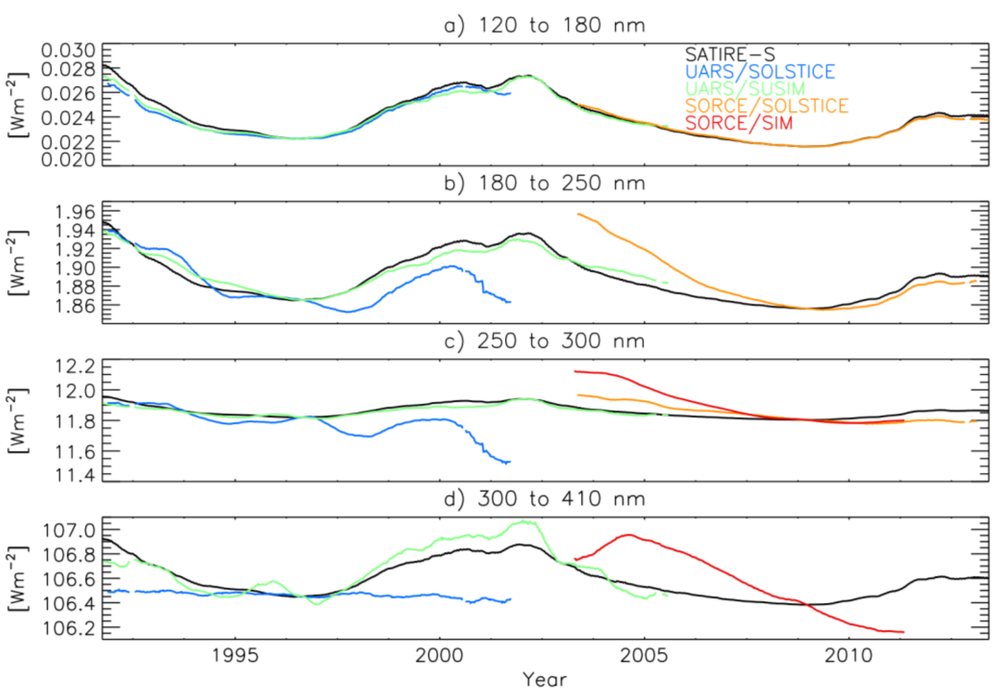


Zharkova 2021

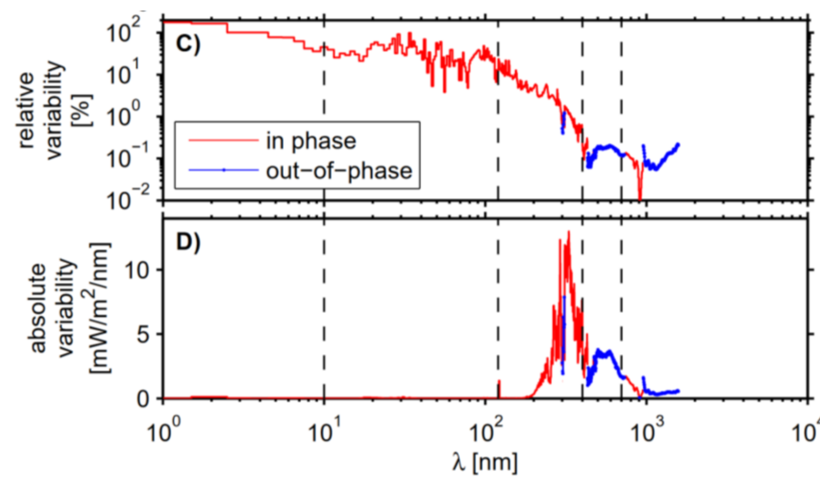




Ermolli et al. 2013



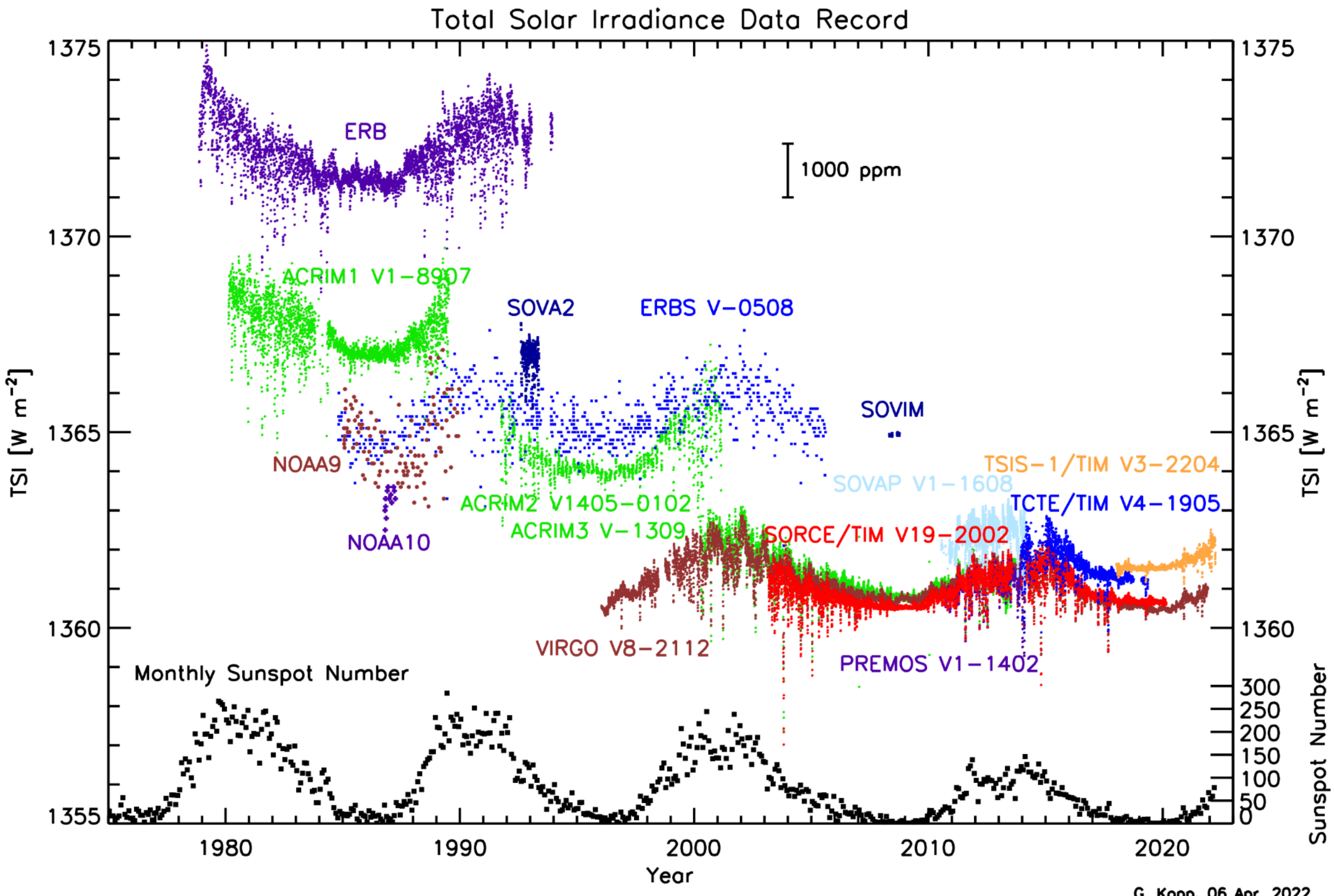
Yeo et al. 2015



Ermolli et al. 2013

ACRIM gap

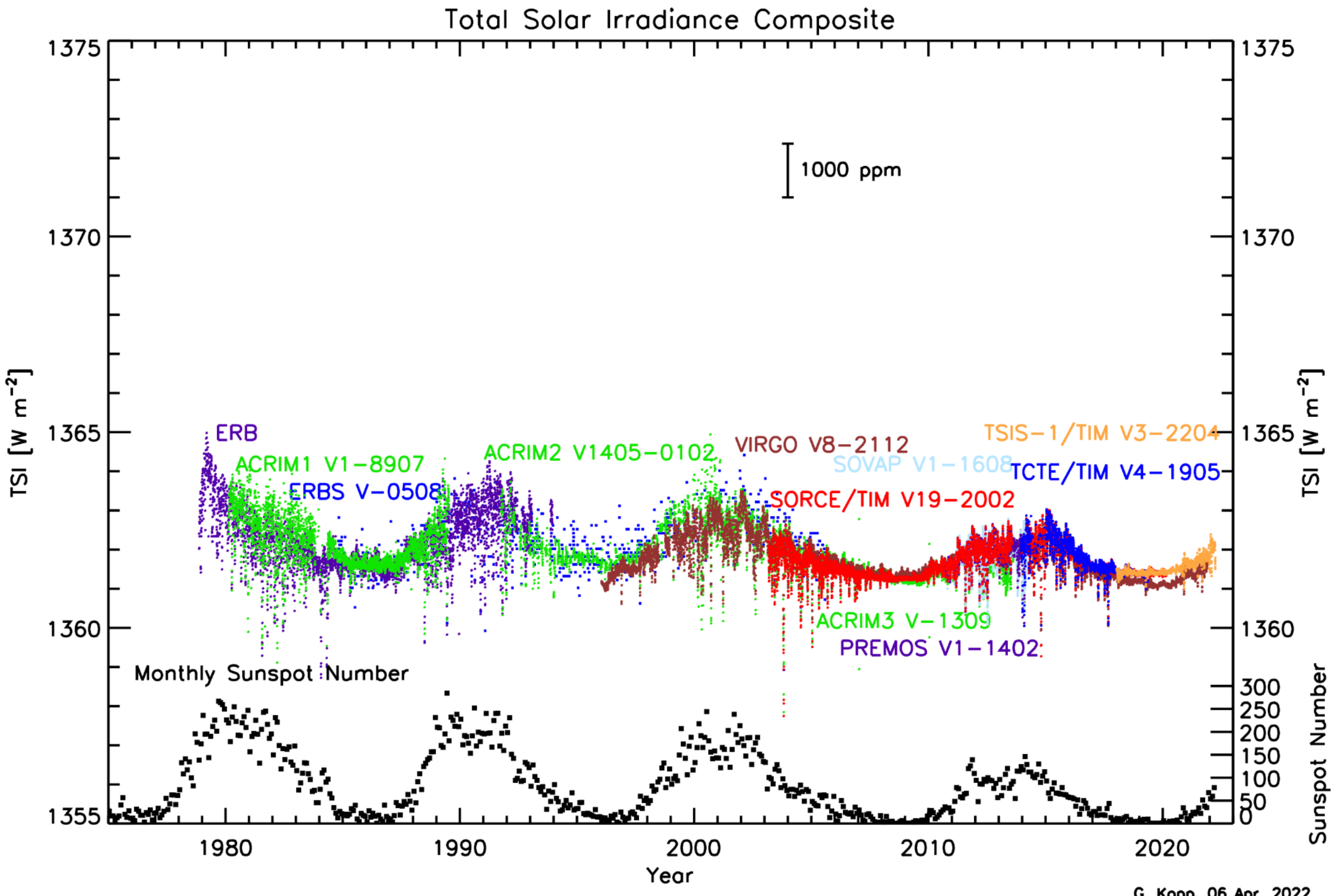
Space-based measurements of TSI



https://spot.colorado.edu/~koppg/TSI/

ACRIM gap

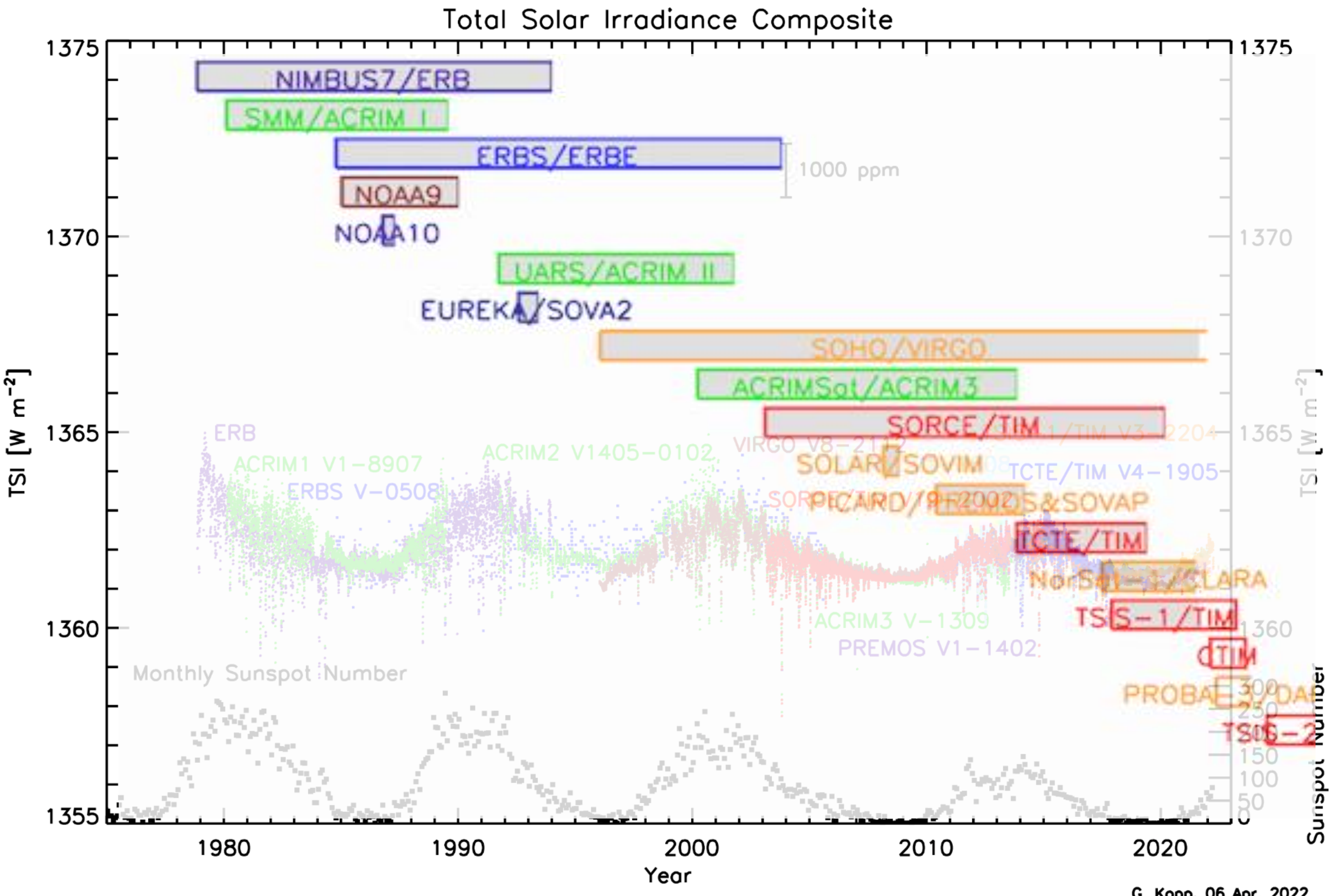
Space-based measurements of TSI



https://spot.colorado.edu/~koppg/TSI/

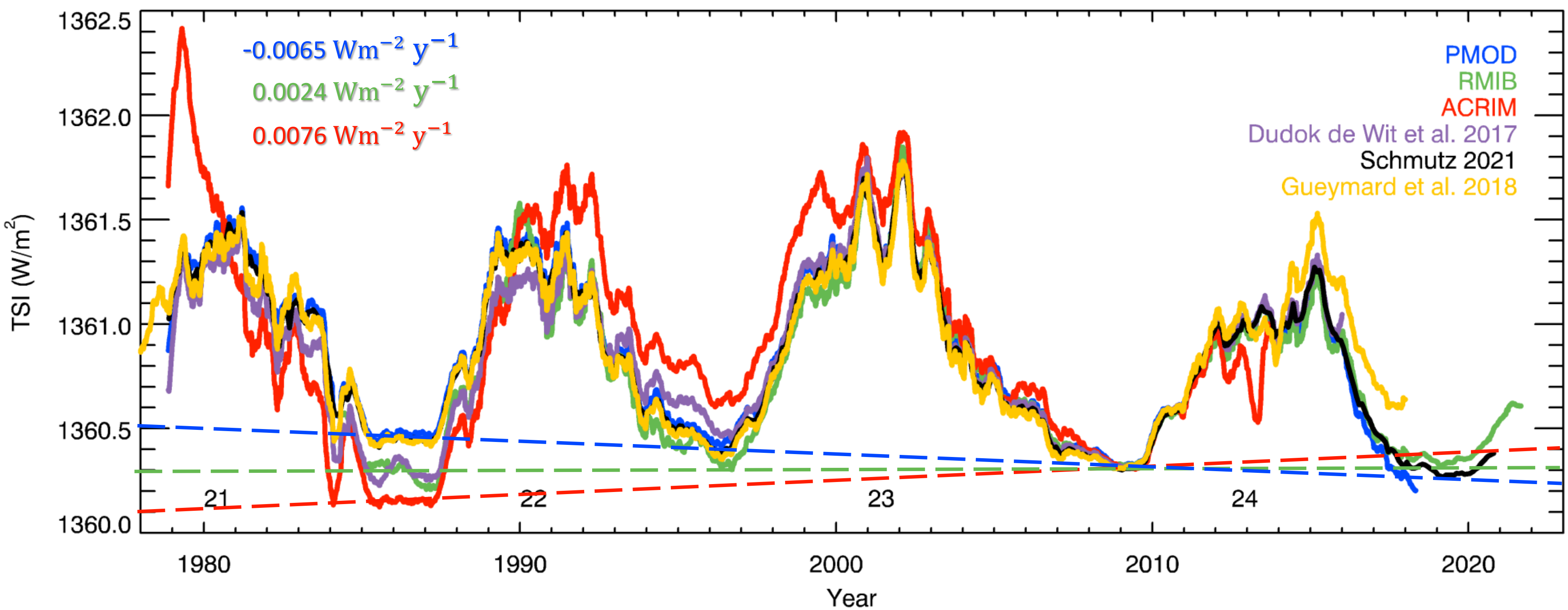
ACRIM gap

Space-based measurements of TSI



https://spot.colorado.edu/~koppg/TSI/

ACRIM gap



Composites show different long-term trends

Empirical

Regressions between facular/sunspot and irradiance data

- **Naval Research Laboratory Total Solar Irradiance (NRLTSI)** (lean 2018)**,**
- **EMPirical Irradiance REconstruction (EMPIRE)** (Yeo et al. 2017)
- **Photometric Sums** (Chapman et al. 2013, Chatzistergos et al. 2020)

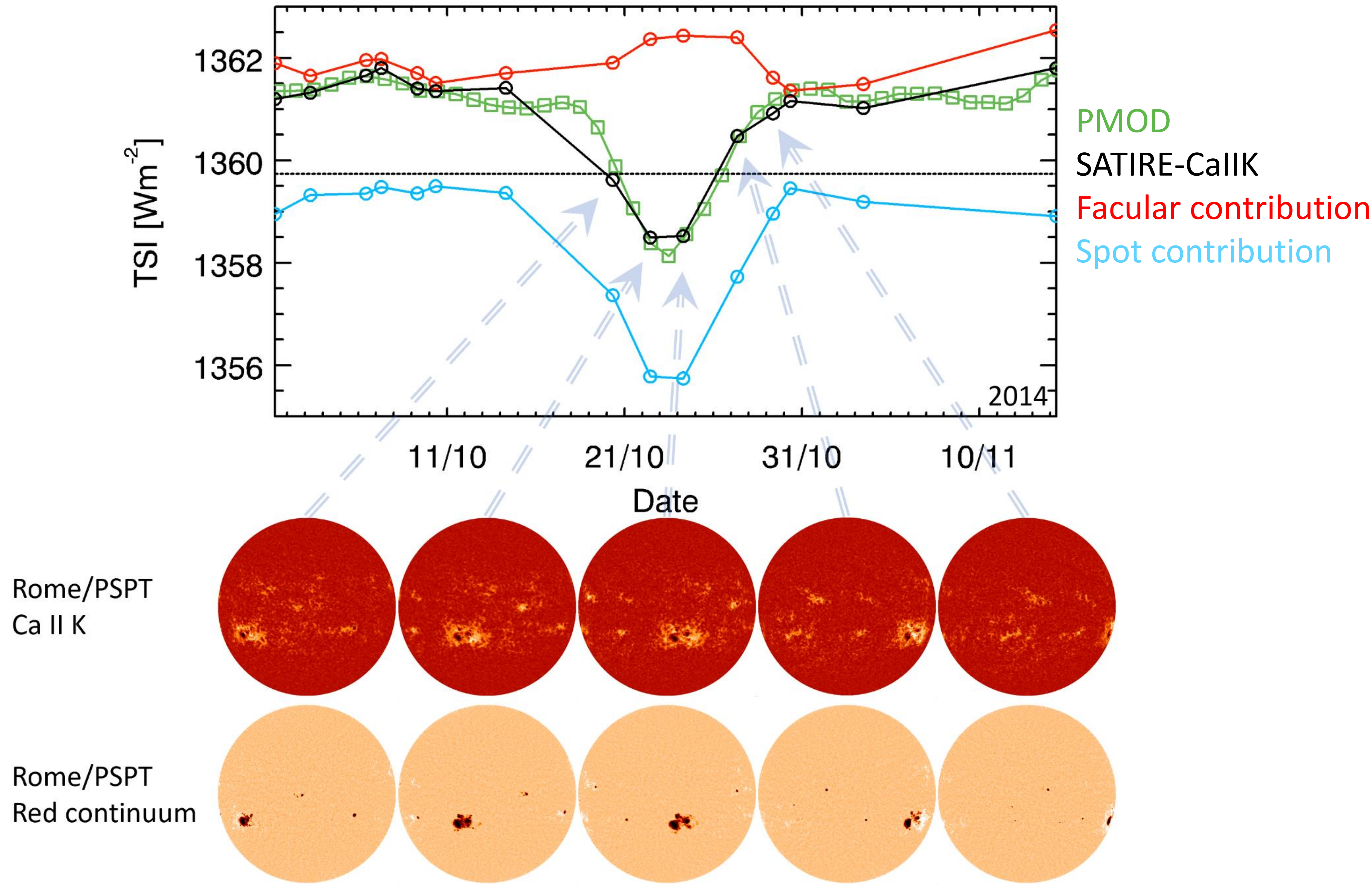
Semi-empirical

Surface-coverage-weighted Intensity spectra (I) computed from corresponding model atmospheres and radiative transfer codes

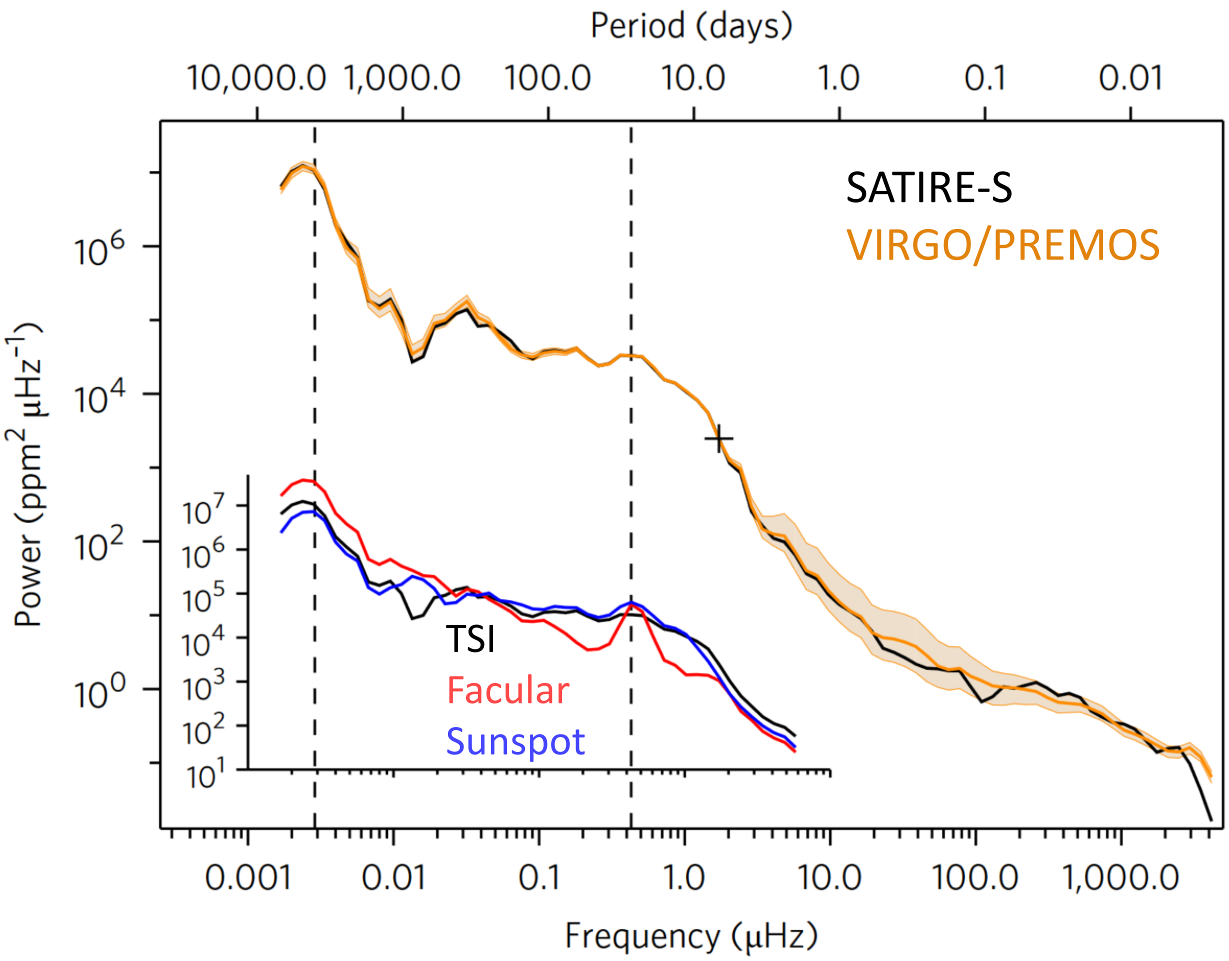
- **Spectral And Total Irradiance Reconstruction (SATIRE)** (Krivova et al. 2003 A&A 399)
- **Solar Radiation Physical Modelling (SRPM)** (Ermolli et al. 2013)

Sunspots Faculae Quiet Sun

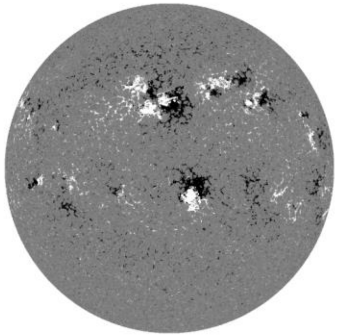
$$S(t) = \int \left(\sum_{i,j} a_s(i,j,t) I_s(i,j,\lambda) + a_f(i,j,t) I_f(i,j,\lambda) + a_{QS}(i,j,t) I_{QS}(i,j,\lambda) \right) d\lambda$$



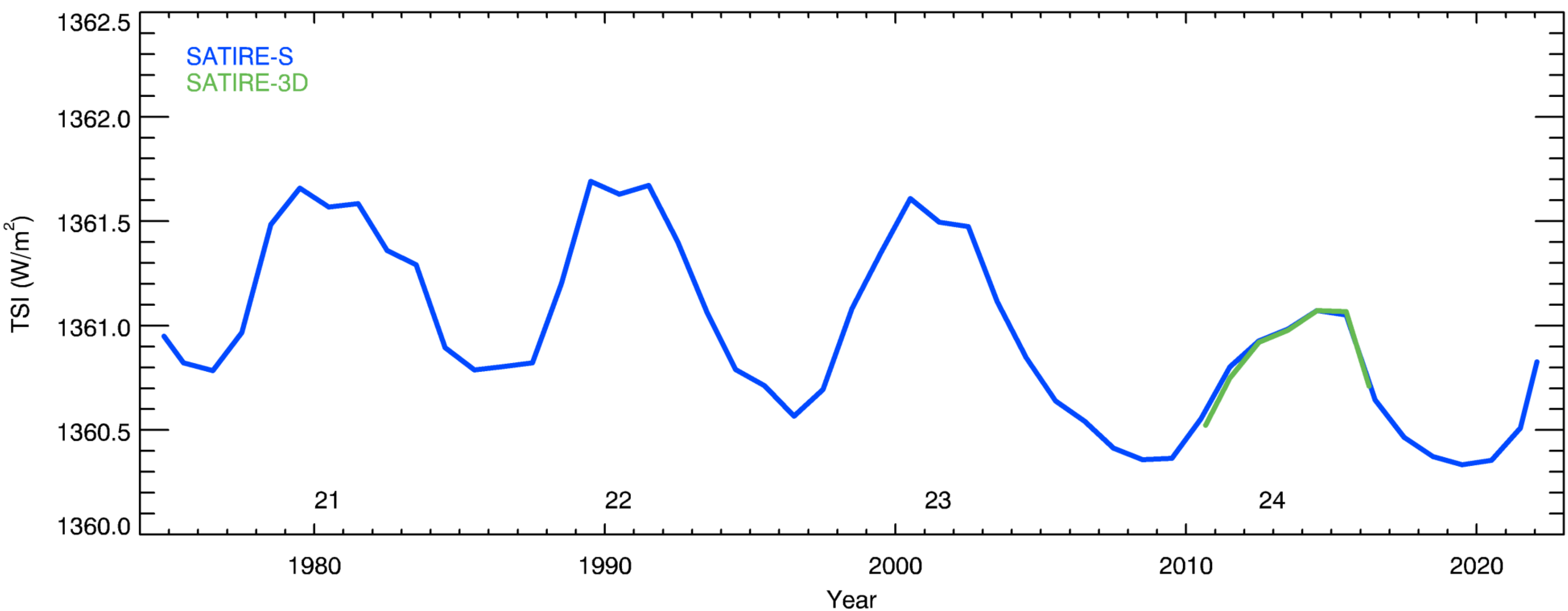
1362
1360
1358
1356
TSI [Wm^{-2}]
2014
11/10
21/10
31/10
10/11
Date
PMOD
SATIRE-CaIIK
Facular contribution
Spot contribution
Rome/PSPT
Ca II K
Rome/PSPT
Red continuum

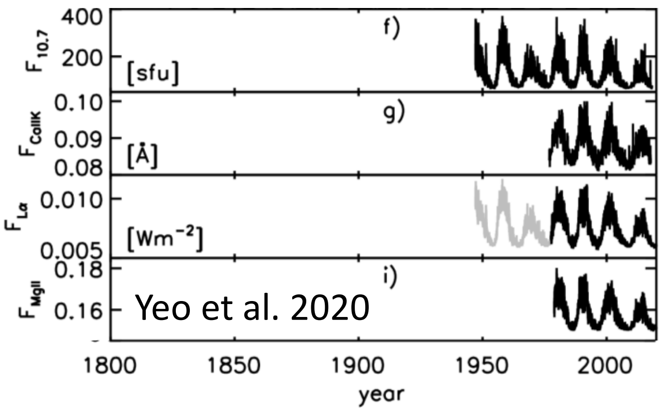


Shapiro et al. 2017

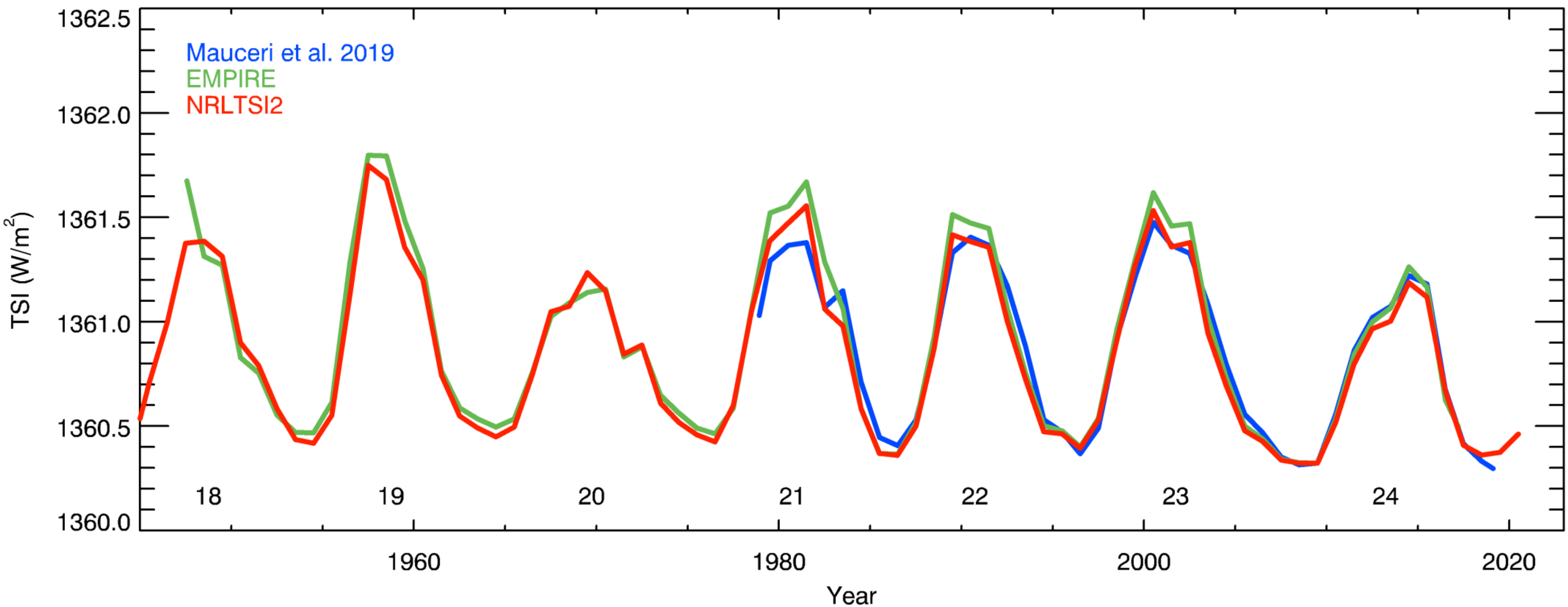


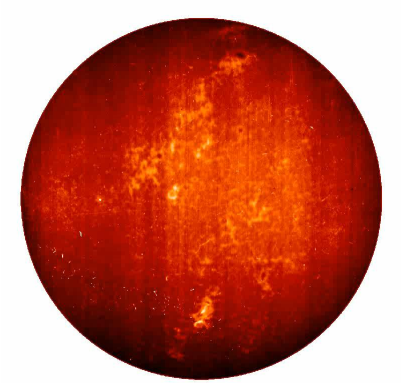
Magnetograms / MHD simulations



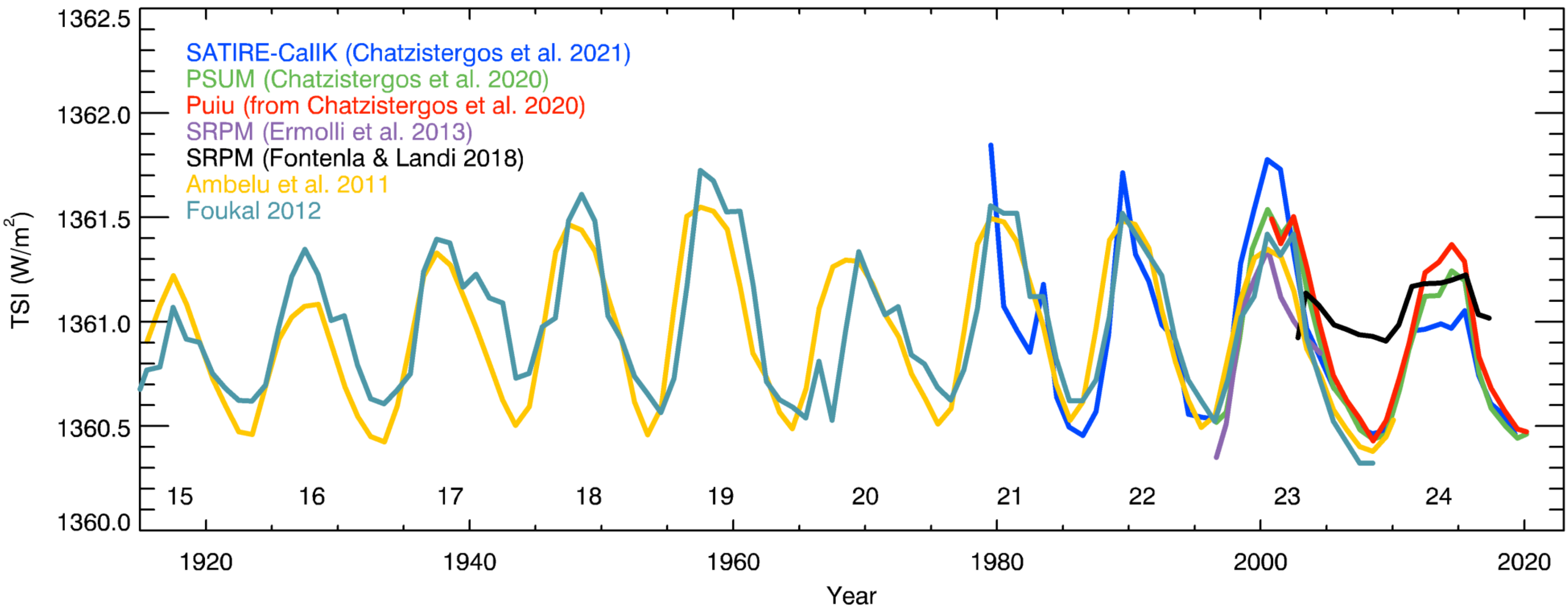


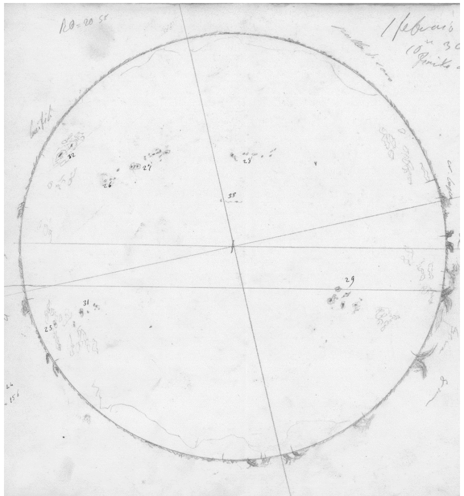
Disc-integrated indices
F10.7 / Mg II / Lyα



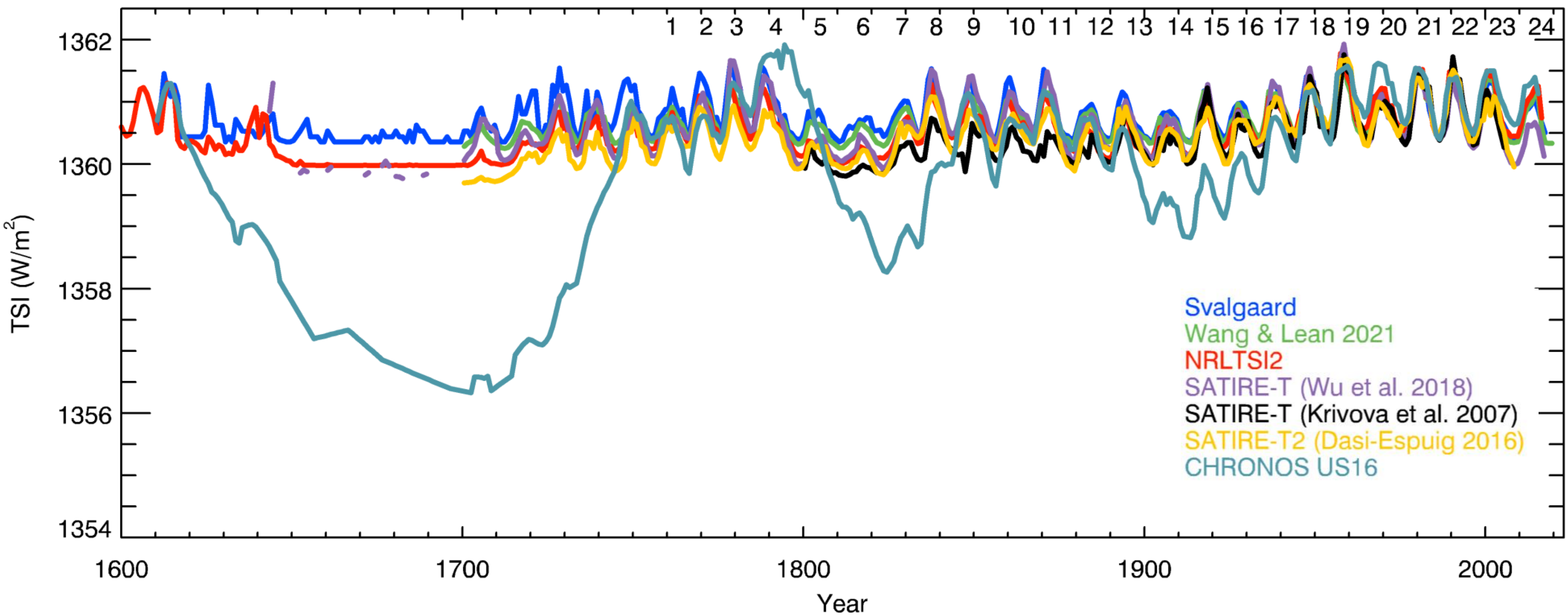


Ca II K observations





Sunspot data

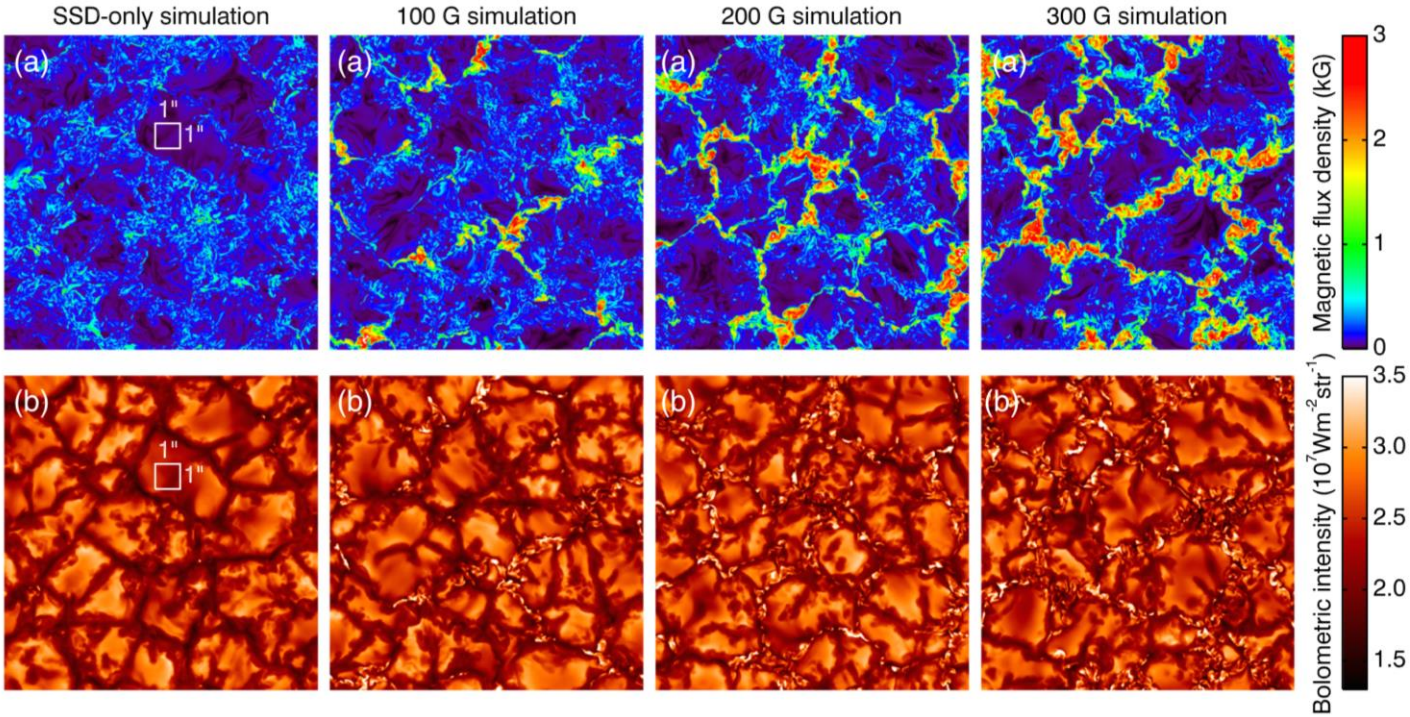


SATIRE-3D

Use 3D simulations of the solar atmosphere to produce TSI variations.

- Solar magnetic field maintained by global and local dynamo action.
- Sunspot records indicate global dynamo is weak during grand minima.
- Recent studies suggest local dynamo is not coupled to the global dynamo and invariant with time (Lites, 2011; Rempel, 2014).

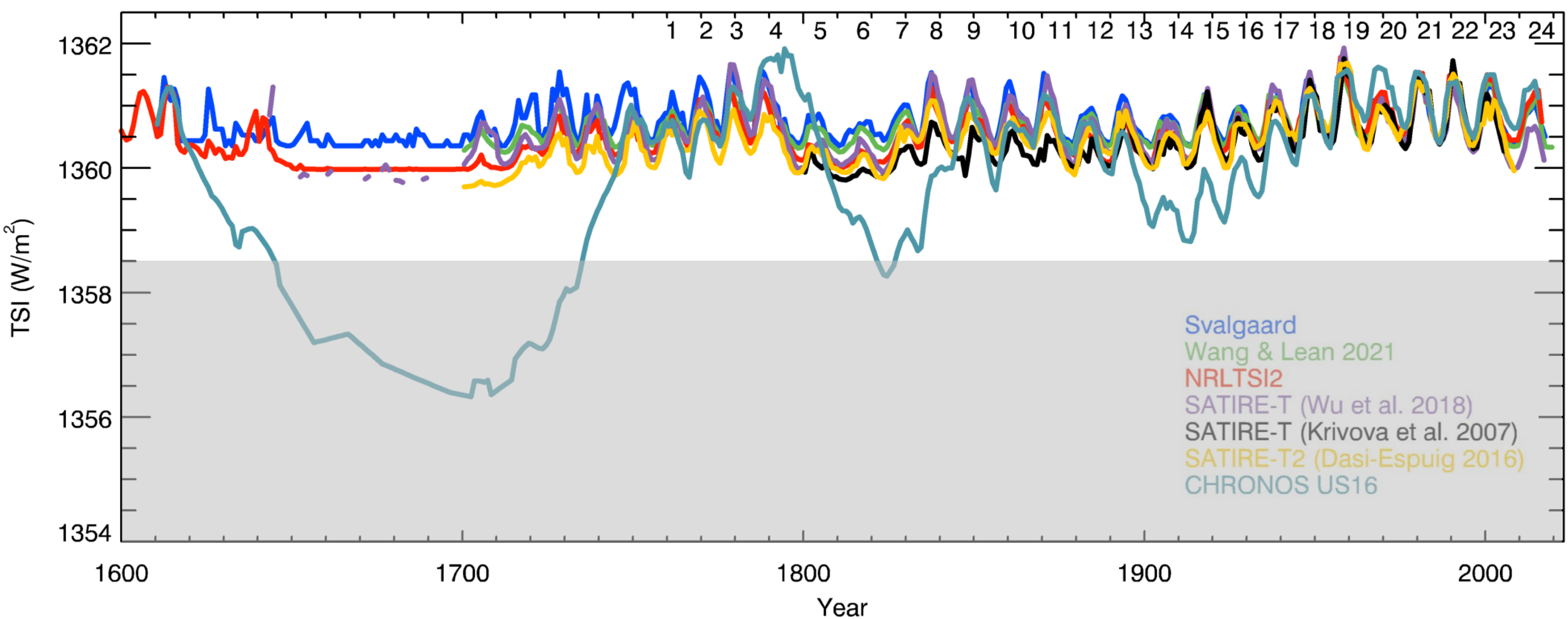
Minimum TSI at grand minima emerges from the model by considering scenario where entire solar surface resembles simulation of local dynamo.



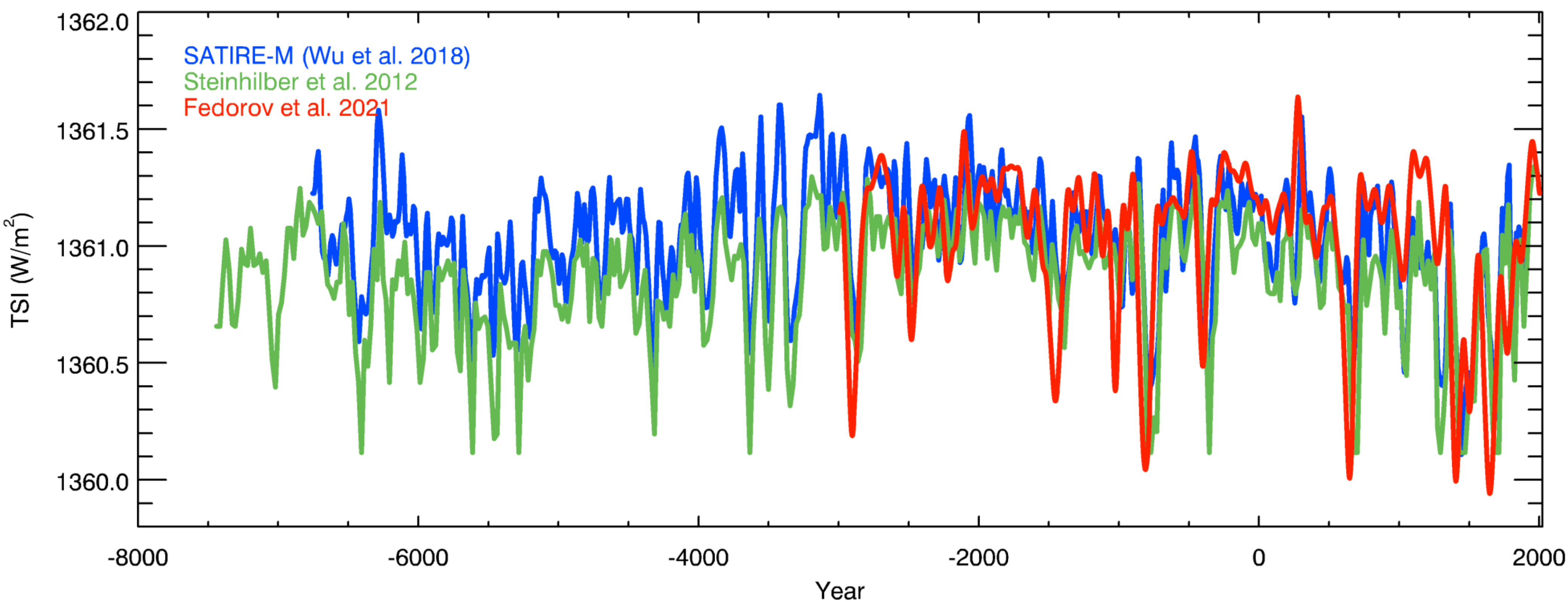
Yeo et al. 2020

Minimum TSI at grand minima = 2.0±0.7 Wm^{-2} below 2019 level.

- ΔTSI since Maunder Minimum cannot be greater than 2.0±0.7 Wm^{-2}
- Restricts role by solar forcing in driving global warming.

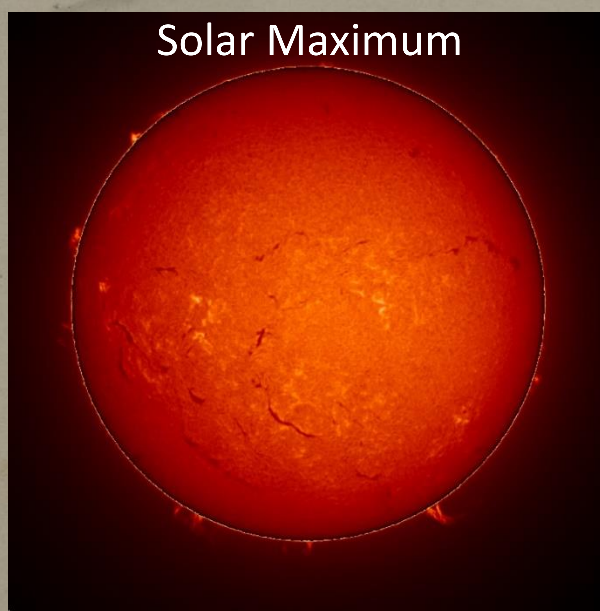


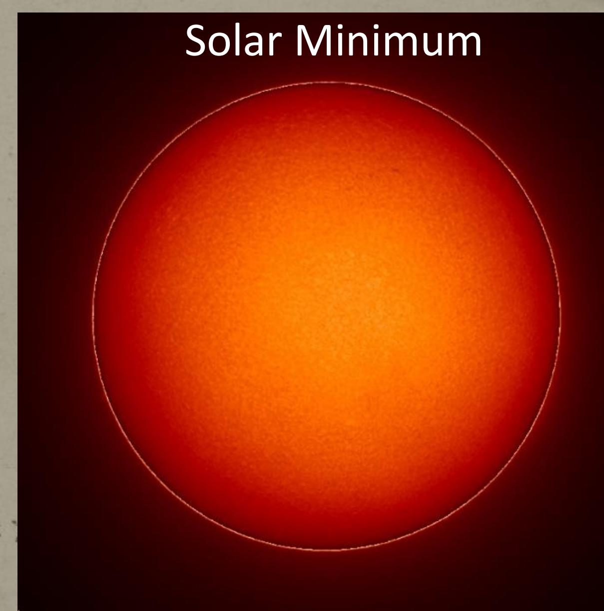
Cosmogenic radioisotopes: ^{10}Be, ^{14}C

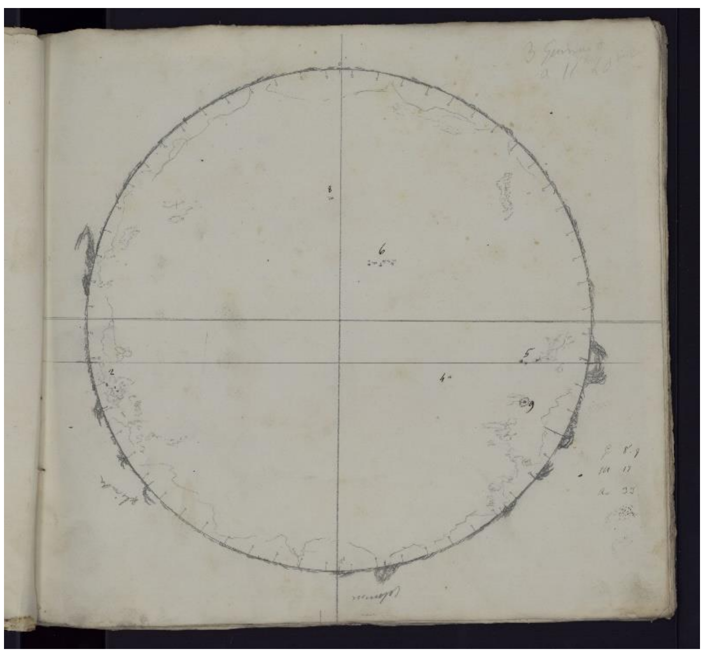


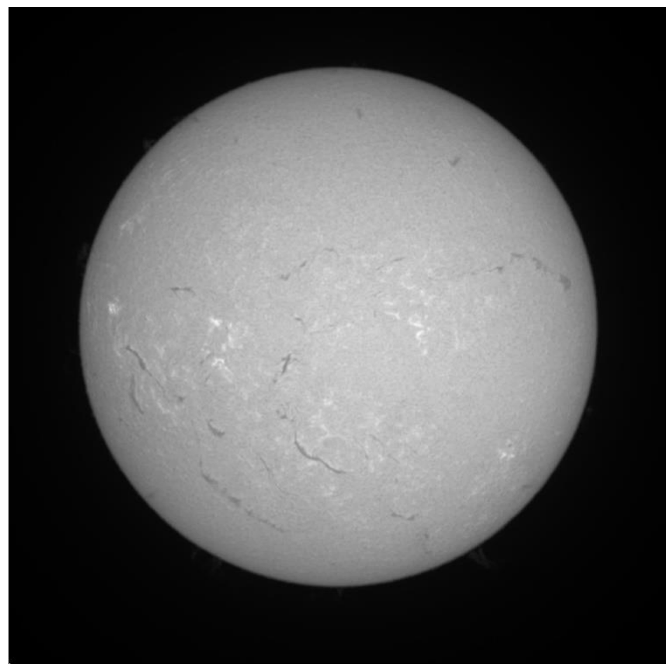
Thank You!

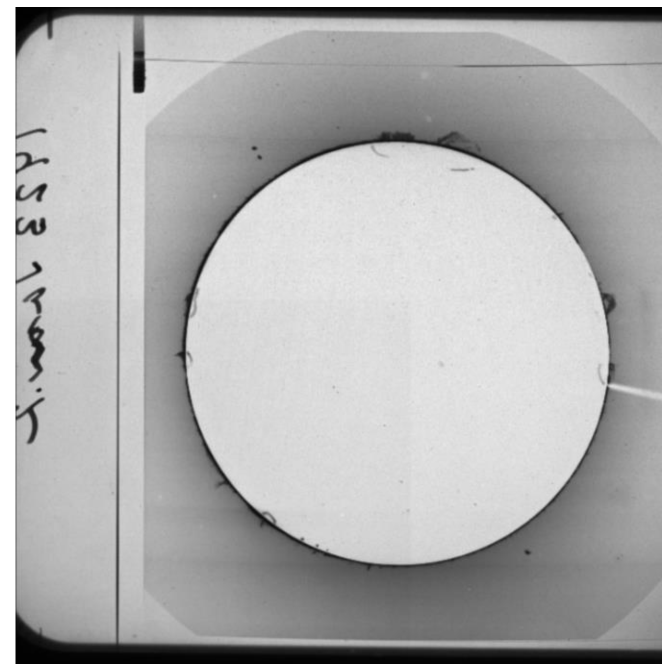
Filaments/Prominences

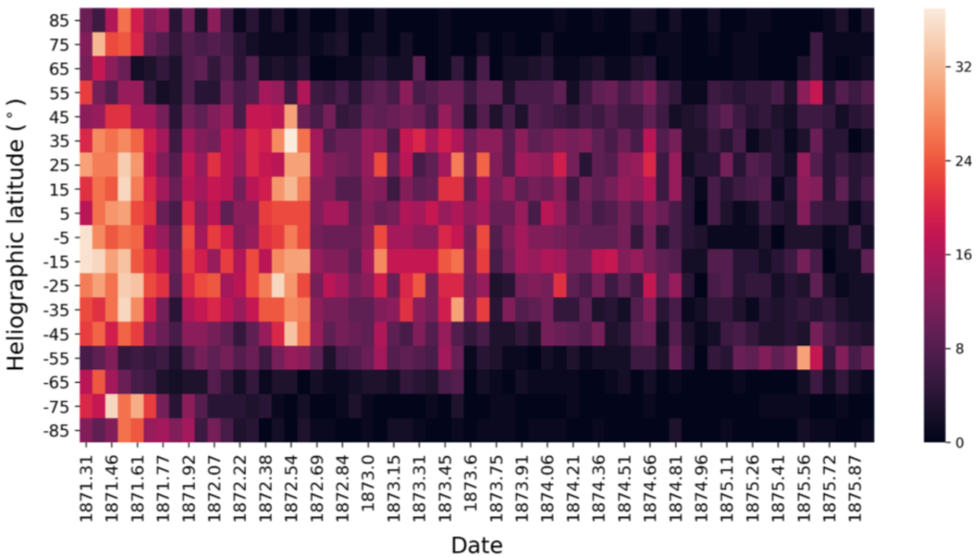




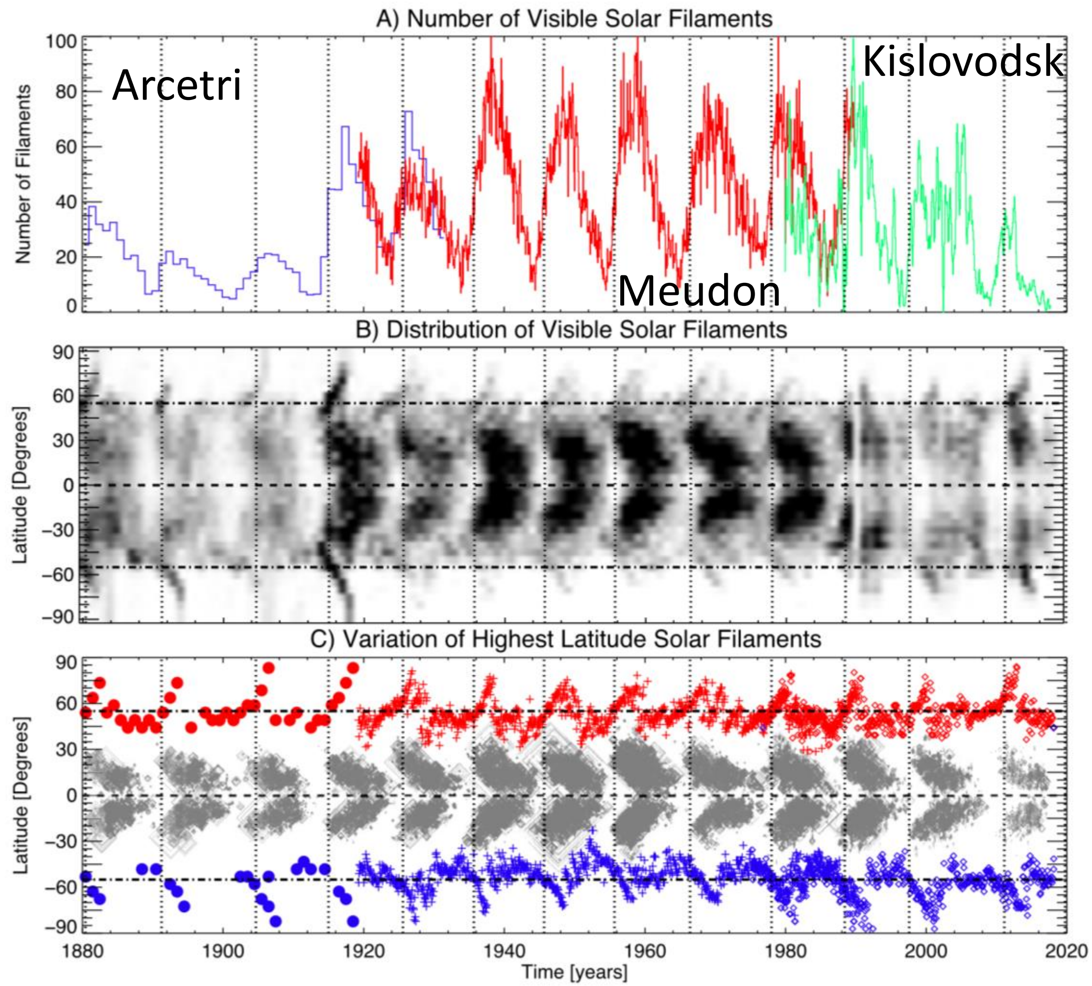




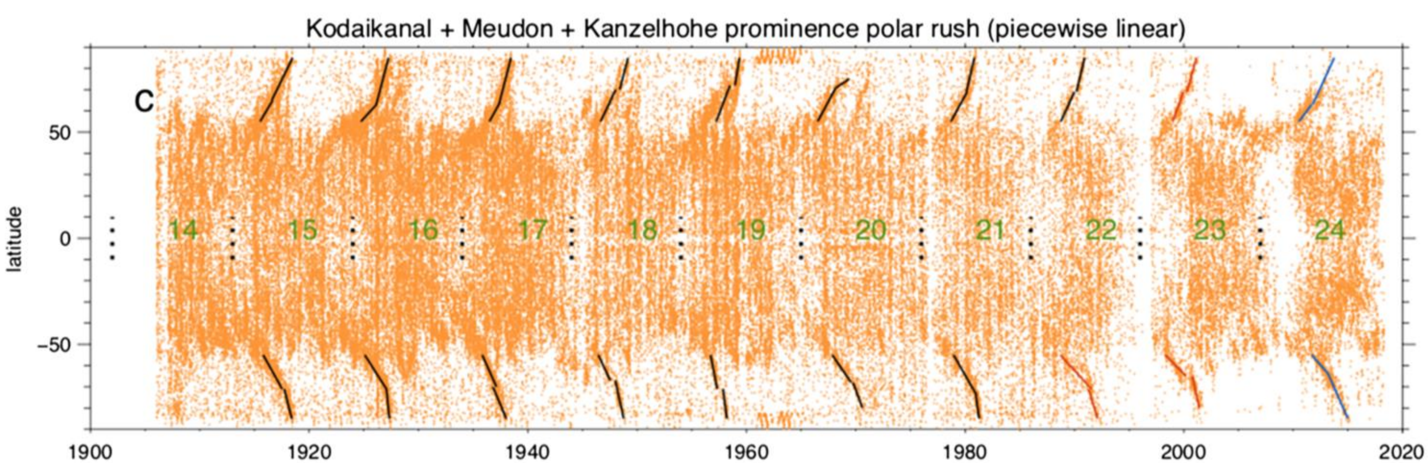




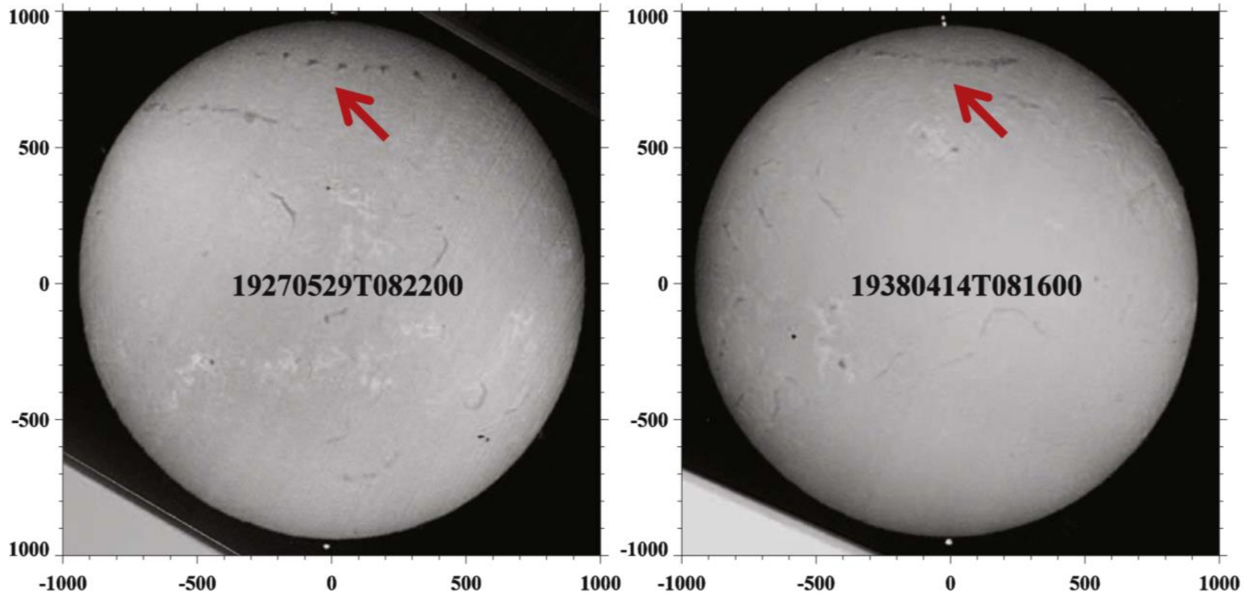
Carrasco et al., 2021

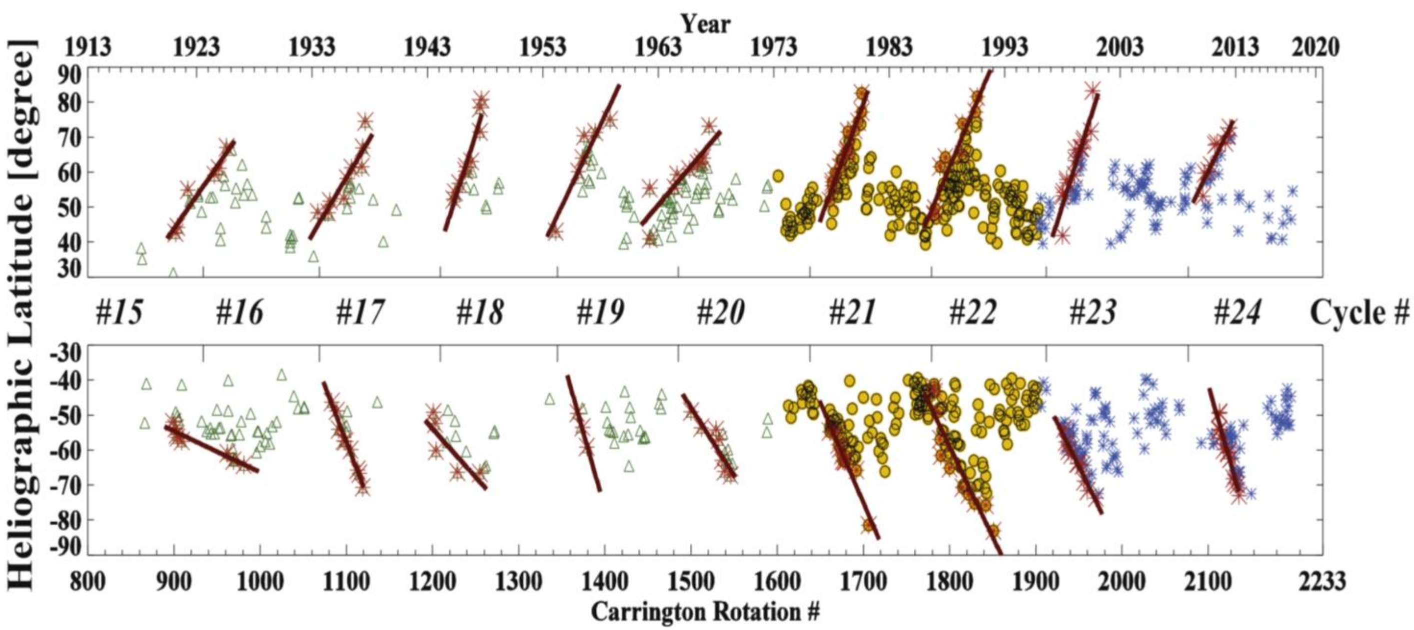


McIntosh et al., 2019

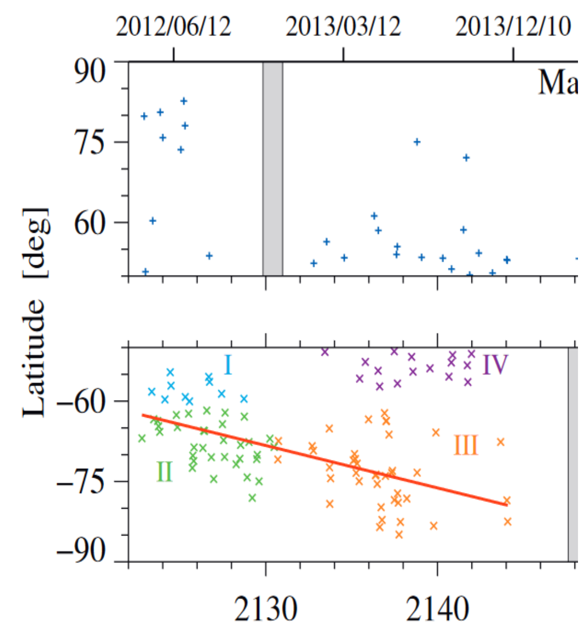


Chatterjee et al., 2020





Xu et al. 2021



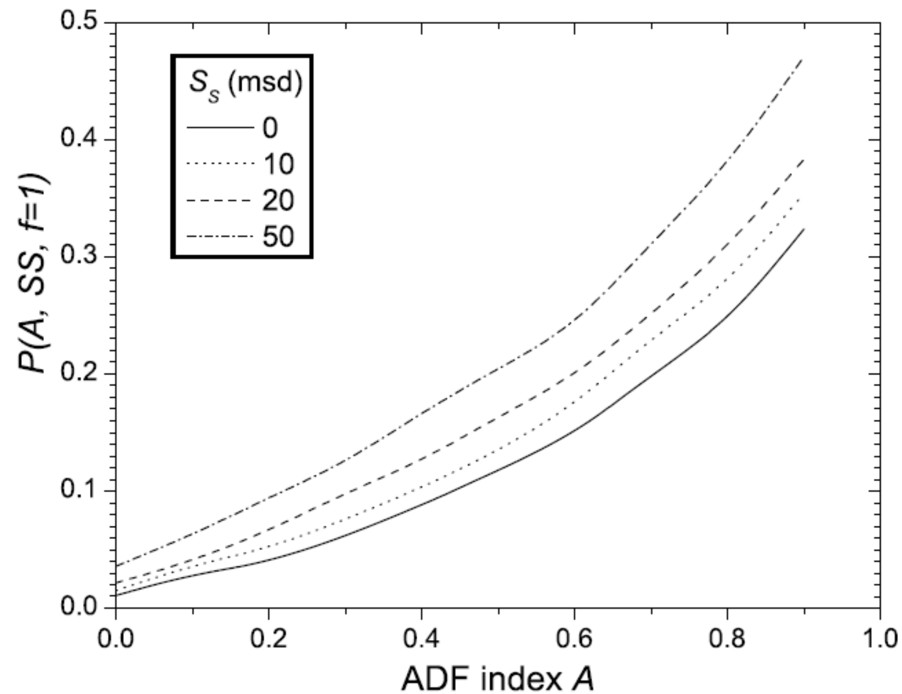
Diercke et al. 2019

Active day fraction (ADF) = monthly ratio of days with spots to spotless days.

For each observer cumulative PDF of ADF

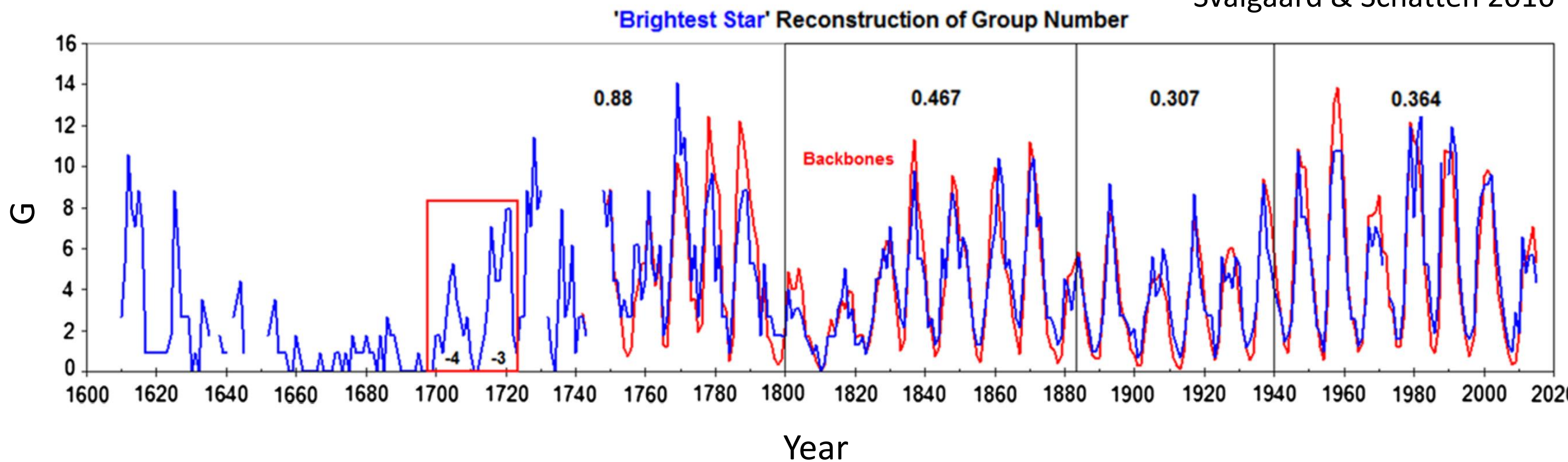
Calibration curve is determined by comparing ADF PDF to those from RGO synthetic data

Bias for observers that did not leave records for spotless days.

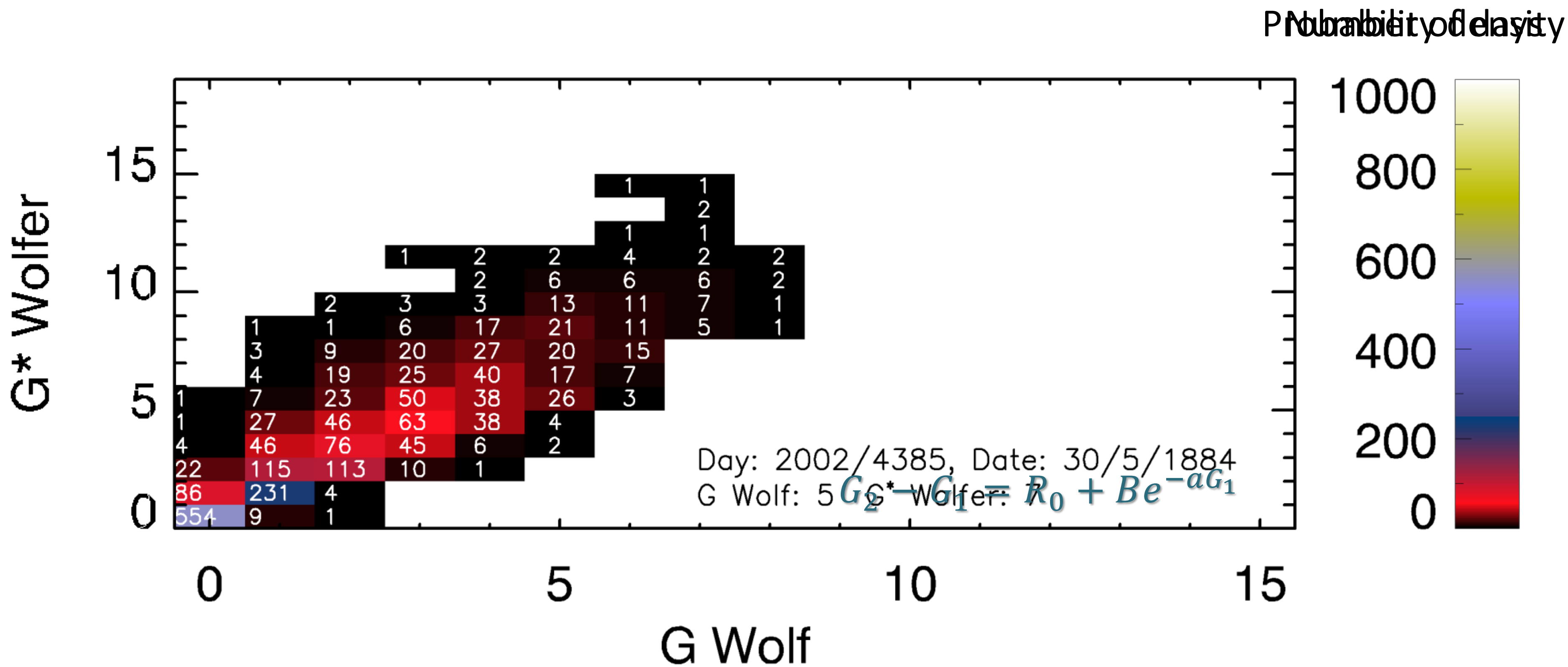


Usoskin et al. 2016

Svalgaard & Schatten 2016



Synthetic data



$$G_2 - G_1 = R_0 + Be^{-aG_1}$$