ROB STCE

Reconciling the Sunspot and Group Numbers

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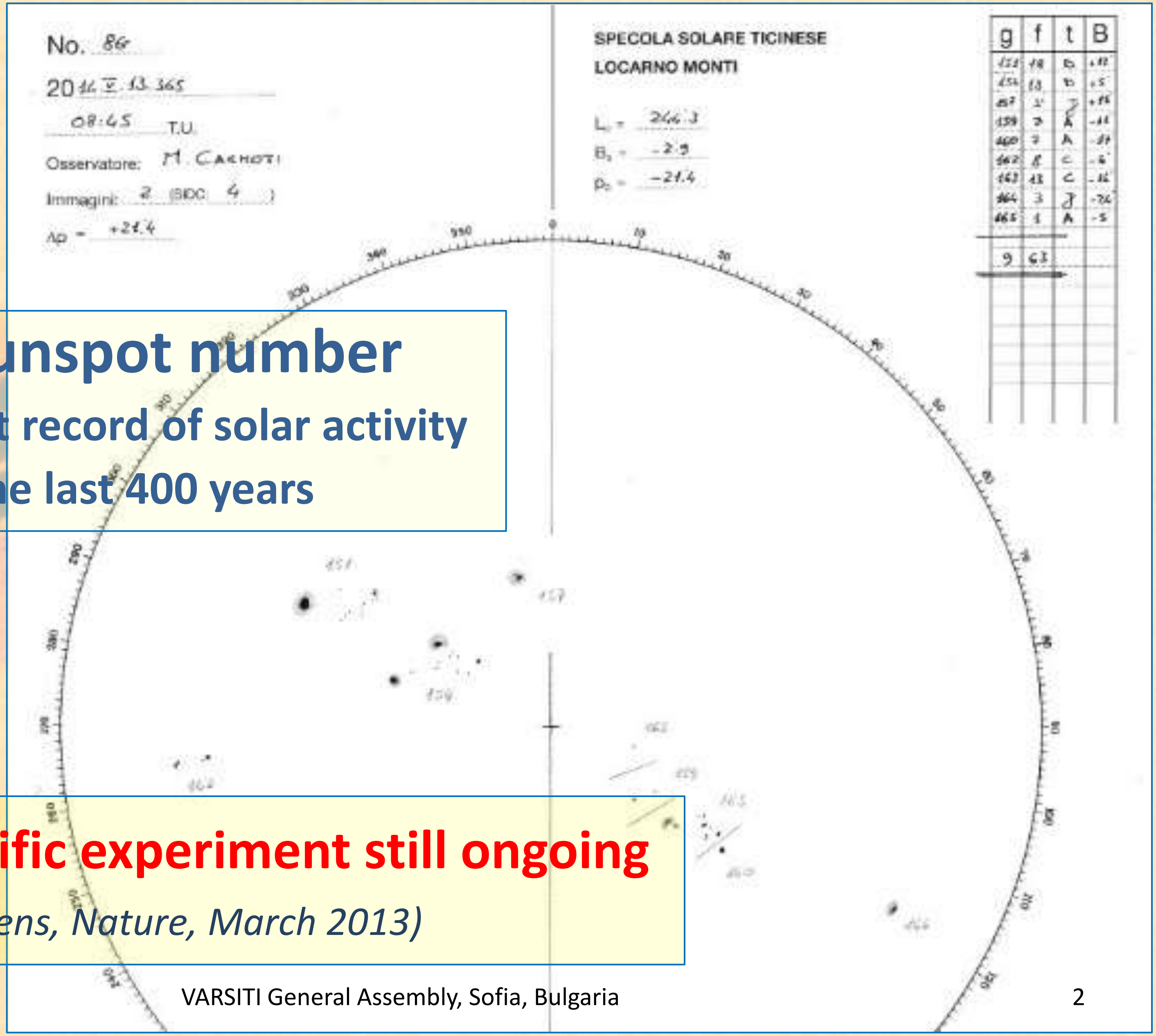
Multi-century solar activity reference



Visual sunspot number

Our only direct record of solar activity over the last 400 years

Longest scientific experiment still ongoing

(B.Owens, Nature, March 2013)

Two sunspot number time series

Sunspot Number

S_N= 10 Ng + Ns

- Measure of the number of active regions + their size
- Origin: R. Wolf (1849)
- Time interval: 1700 - now
- Production:
  - **1700-1849**: reconstruction from historical documents
  - **1849-1980**: Zurich Observatory
  - **1981-now**: World Data Center SILSO, Brussels
- Calibration: **pilot station**
  - **Zurich** Observatory (successive primary observers)
  - Specola Observatory **Locarno** (since 1981)

Sunspot group number

G_N= 20.13 Ng

- More basic but applicable to cruder early observations
- Origin: Hoyt and Schatten (1998)
- Time interval: 1610-1995
- Production:
  - Single recent reconstruction
  - Based on an **extended set of raw historical data**
- Calibration:
  - "Daisy-chaining" of observers backwards in time
  - **Starting reference: Royal Greenwich Observatory photographic catalog (1875-1975)**

- **Very good match after 1900**
- **Large disagreements before the 20th century:** G_N lower than S_N by up to 40%

A new impulse: Sunspot Number Workshops

NSO, Sac Peak, USA, Sept. 2011

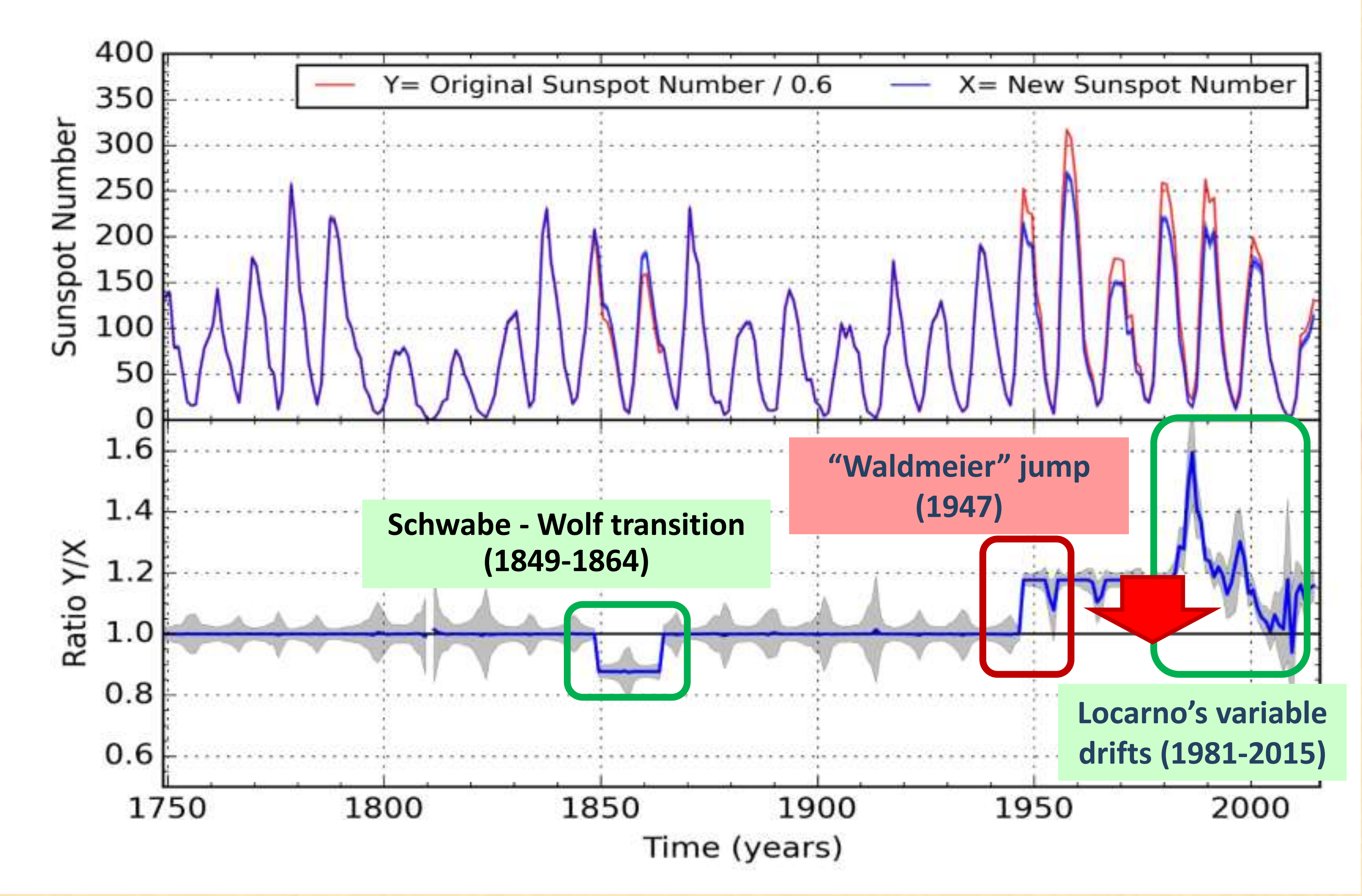
- Community effort started in Sept. 2011:
  - **4 Sunspot Number Workshops**:
  - > 40 participants
- **ISSI Team Meetings 2018-2019** *(www.issibern.ch/teams/sunspotnoser/)*:
  - Chairs M.Owens, F.Clette

ISSI Bern, Switzerland Jan. 2018

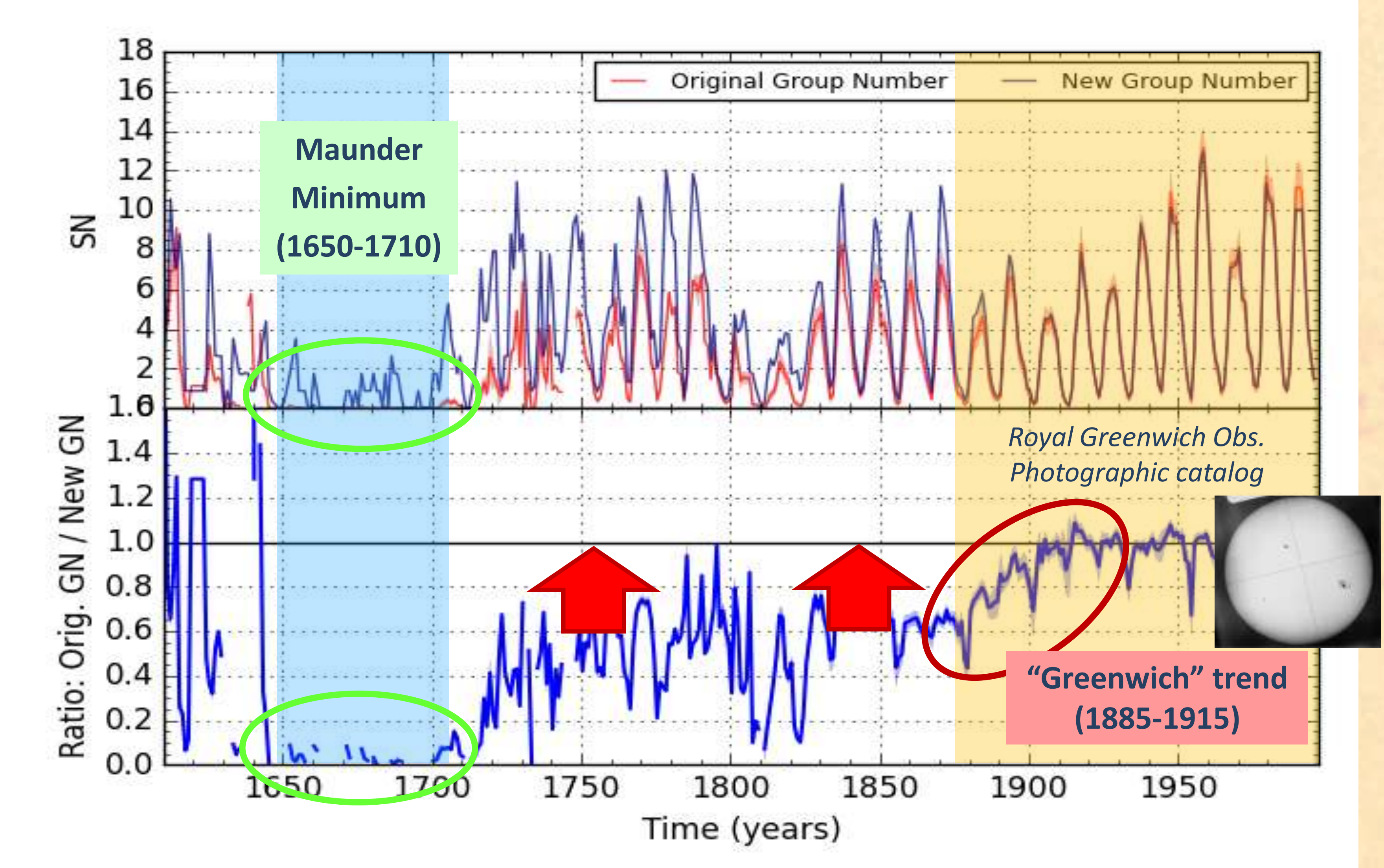
Synthesis in:

- Clette, F., Svalgaard, L., Vaquero, J.M., Cliver, E.W.: **Space Sci. Rev. 186, 35-103, 2014**
- **Solar Physics:** Topical Issue on « Recalibration of the Sunspot Number», **Volume 291 9-10, 2016**, Eds. Clette, Cliver, Lefèvre, Vaquero, Svalgaard, **35 articles**

Sunspot Number S_N version 2 *(released July 2015)*



“Backbone” Group Number G_N *(Svalgaard & Schatten, 2016)*



Two unrelated set of corrections

Sunspot Number

- Type of flaws:
  - **Inaccuracies in the k scaling coefficients** vs the pilot observer
  - **Drift of the single pilot station**
  - **Change of counting method:**
    - weighting according to spot size
- Methodological approach:
  - Statistics over **all available auxiliary observers** :
    - Replacing the single pilot … multiple stable lo… observers
  - **Doubl…**
    - …g the effect of the …ting of spots
  - ***…orrection factors applied to the original SN series***

Sunspot group number

- Type of flaws:
  - **Inhomogeneities in the photographic catalog** after 1875
  - **Backwards propagation … errors:**
    - Daisy-… …cient
- Meth… approach:
  - …ng the photographic data by multiple visual observers after 1875
  - Avoiding daisy-chaining:
    - Long-duration reference observers (**backbone observers**)
    - **Active-day fraction (ADF)**: scaling factor deduced from individual spotless days statistics
  - ***Full reconstructions from all raw data***

No attempt to make one series similar to the other one !

- **The problems have different causes and occur at different times**
- **The required correction methods and data were different and unrelated**

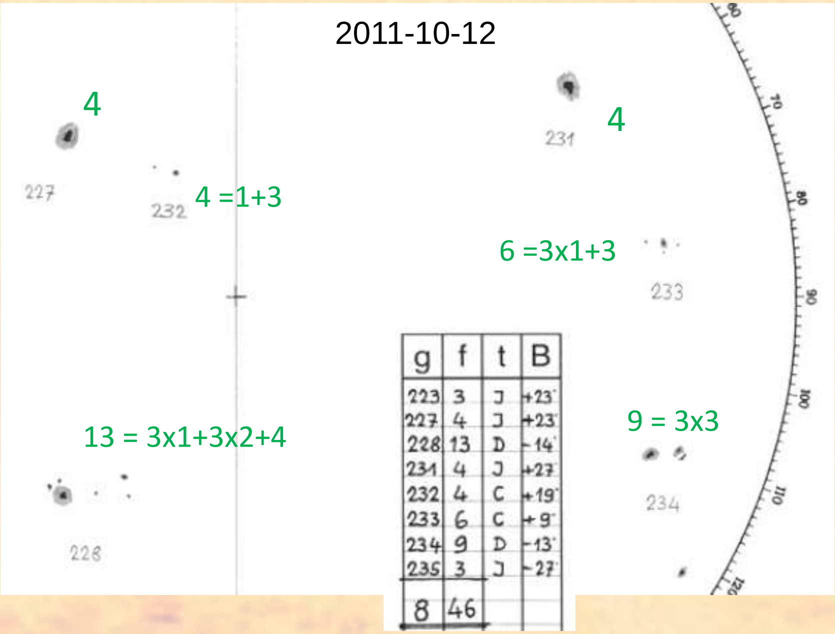
Sample corrections for S_N and G_N

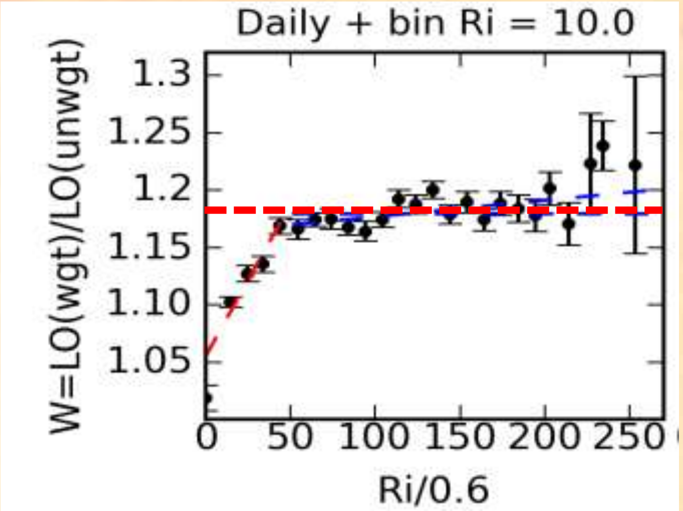
[S_N] The Waldmeier jump : probable cause

- **Sunspot weighting**:
  - Large spots are counted >1 (up to 5)
  - Introduced for Zurich assistants in the late 19th century *(Friedli 2016)*
  - Systematic application by the primary observer since 1926

- Locarno auxiliary station trained to the method (1955): **still in use !**
  - Blind test (2008 – 2014): comparison of simultaneous standard and weighted counts *(Clette & Lefèvre 2016, Svalgaard 2017)*:
  - **Variable inflation factor**
    - Constant at high activity: **1.177 ± 0.005**

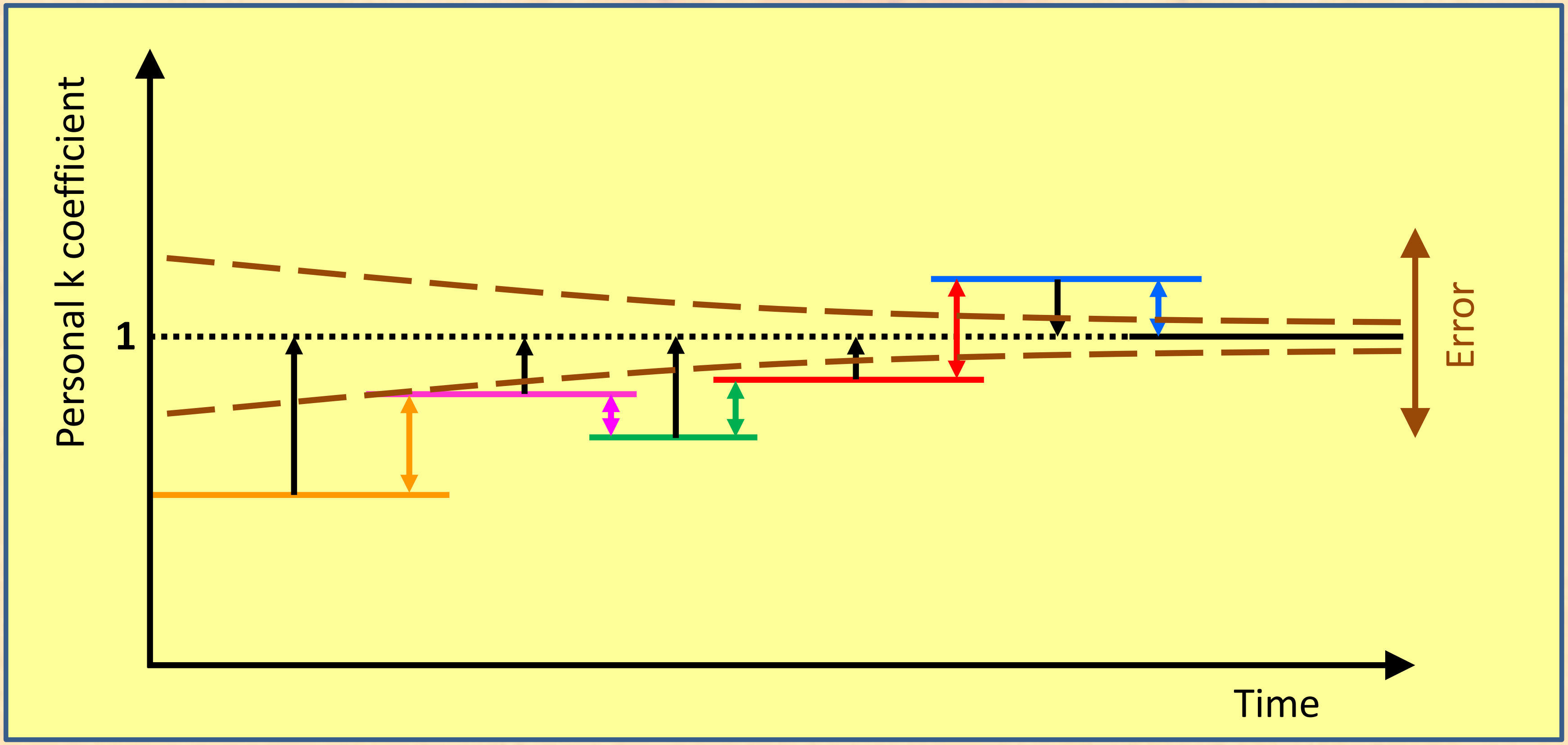
⇨ **Matches the amplitude of the 1947 jump**





G_N : criticisms and new results

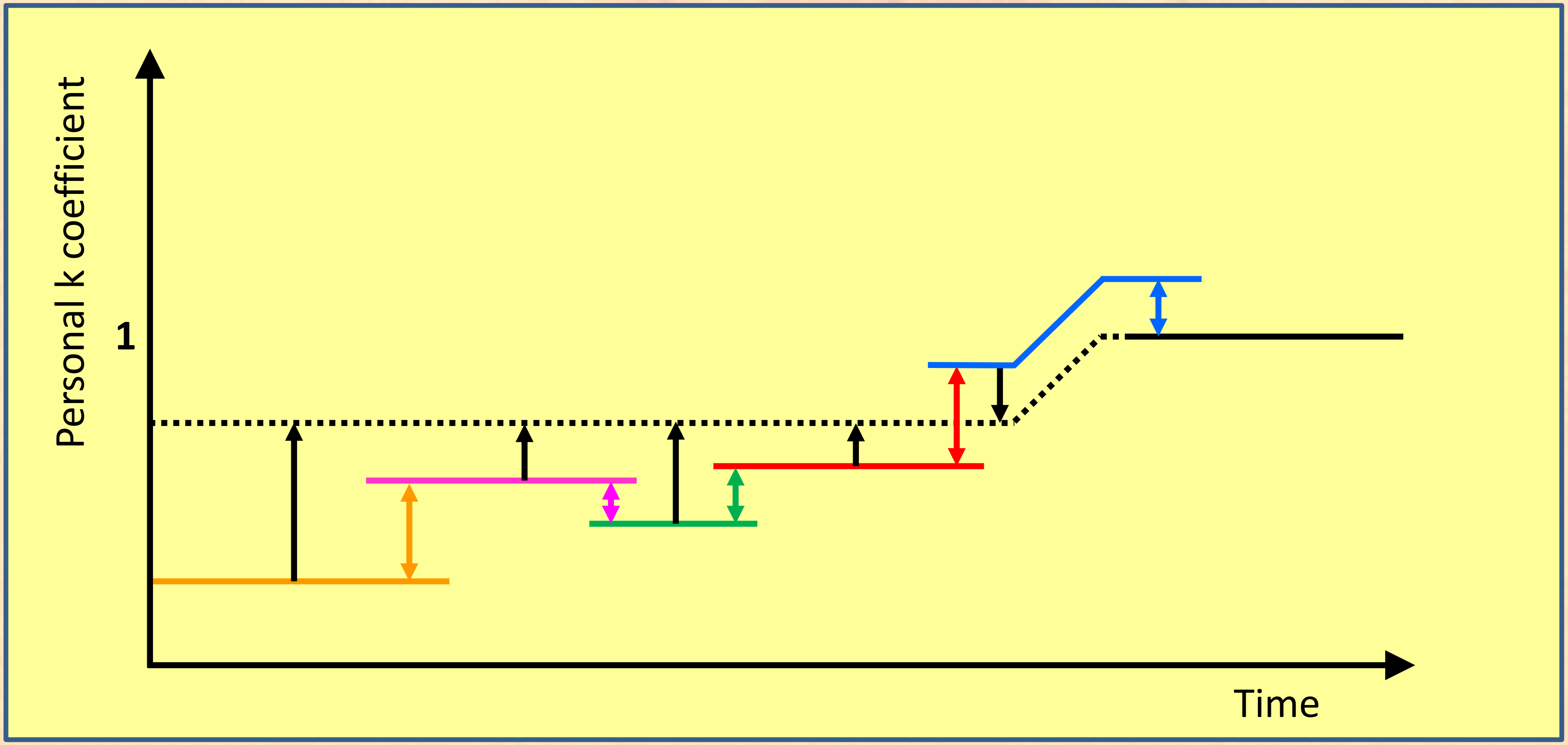
- Original G_N series *(Hoyt & Schatten 1998)*:
  daisy-chaining of k ratios between observer pairs
  - Backwards propagation of errors



G_N : criticisms and new results

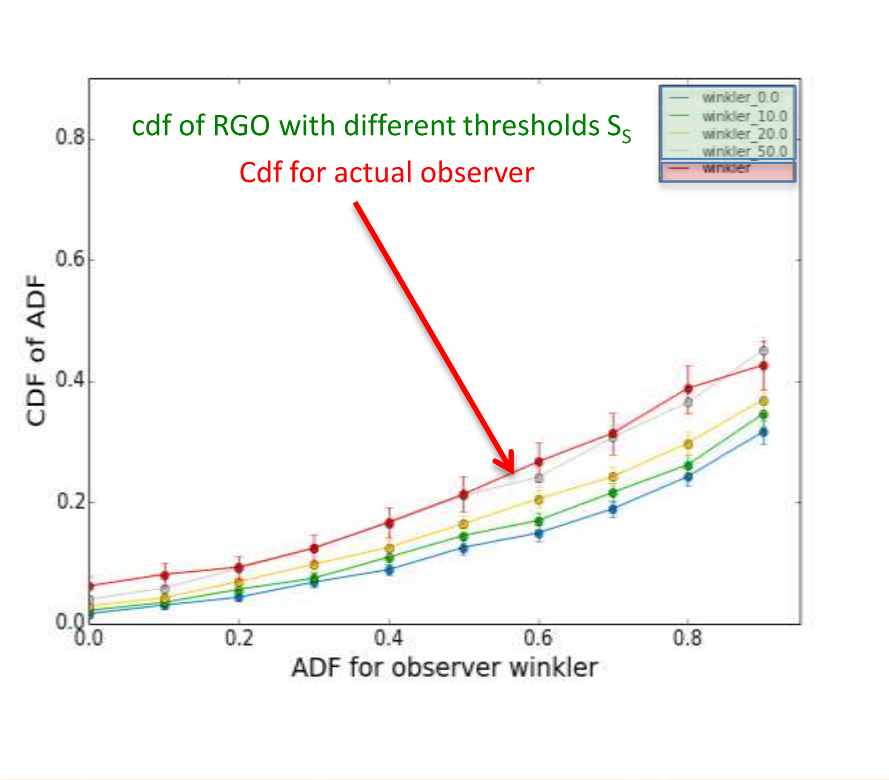
- 40% upward drift attributable to the use of photographic data after 1875 (Royal Greenwich Observatory catalogue)

Cliver & Ling 2016, Cliver 2017



[G_N] An alternate approach: active-days fraction

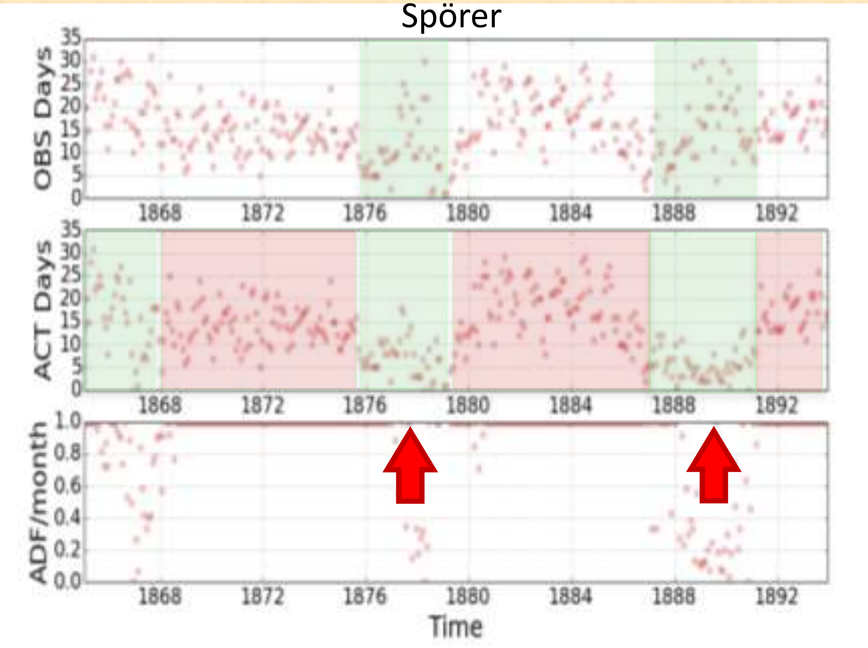
- **Statistics of spotless days** versus days with one group of spots or more = active days *(Usoskin et al. 2016)*
- **Model hypothesis**: differences in groups counts due to **acuity of observers**
- Construction of a standard **"perfect" observer: RGO catalogue** (1900-1975)
  - Acuity = groups eliminated below a **lower threshold in sunspot area** (S_S)
  - Matching the **cumulative distribution function (cdf) of the number of active days/month (ADF)** for the observer



Resulting series: similar to the original Hoyt & Schatten G_N (low in 19th century)

[G_N] Limits and failures of the ADF

- **Observer sampling can be varying with solar activity**:
  - ⇨ Strong positive bias on ADF **(underestimate of G_N)**
    Willamo et al. (2018)
- The method works only **when ADF is below 80%:**
  - Activity is below 5-6 groups (< 50% of peak of solar cycle)
  - Derived **scale is extrapolated for high activities** (cycle maxima)
- Base assumption does not consider **differences in group splitting** between observers:
  - **Important factor near cycle maxima**

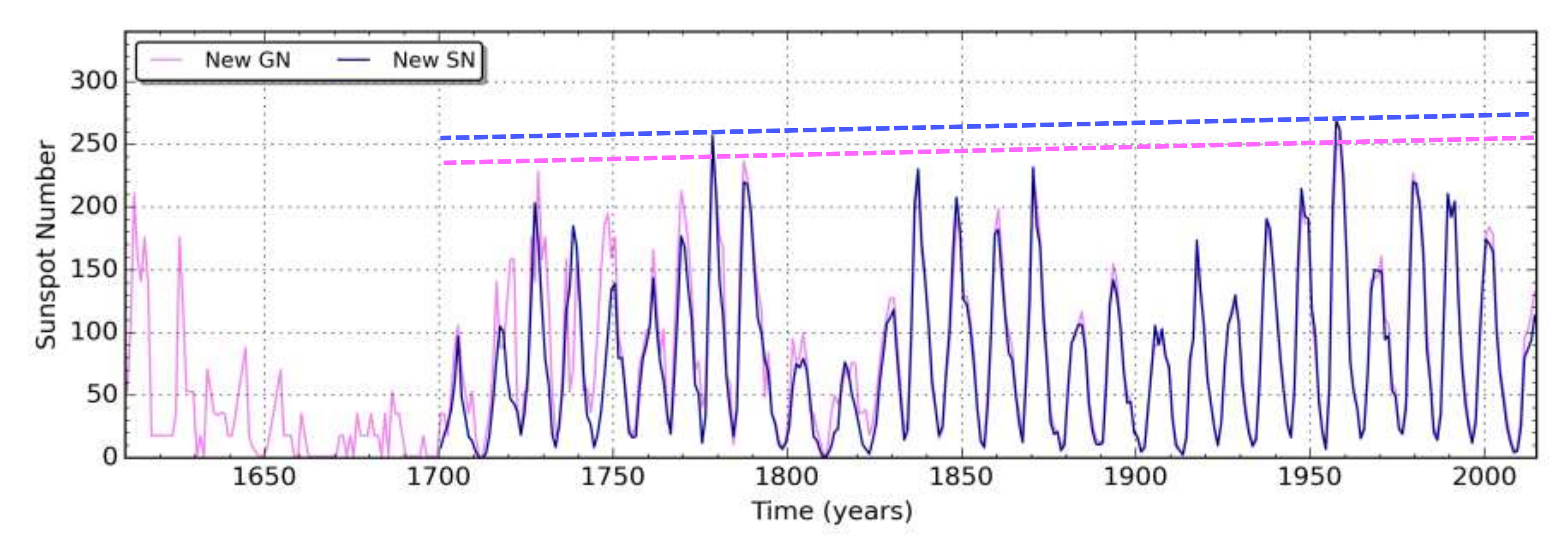


Staudacher, Feb. 13 1760
(Svalgaard 2016)

Post-correction assessment

Impact: new secular trends

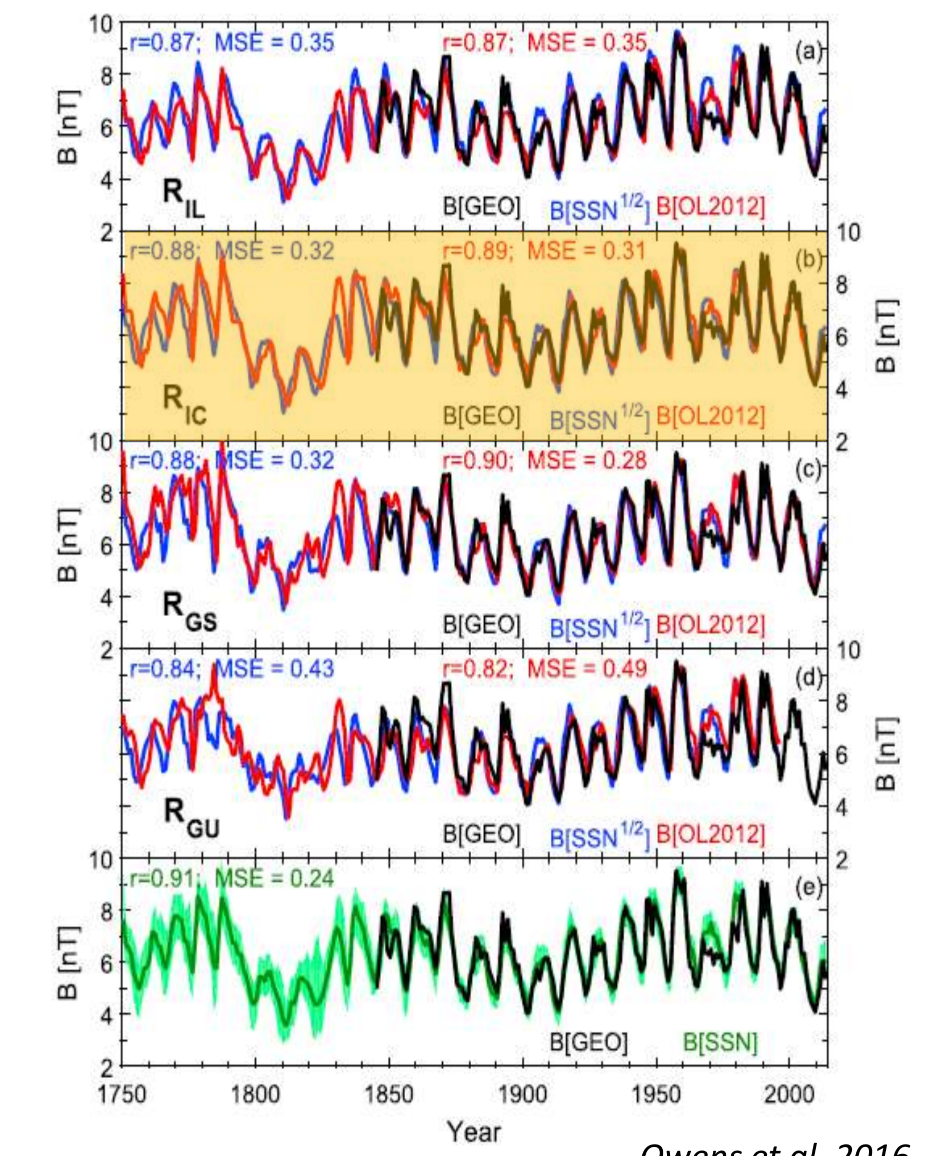
- Original series: strong upward secular trend over last 200 years ("Modern maximum", *Solanki et al. 2004, Usoskin 2013*):
  - GN: + 40% / century *(red)* SN : + 15% / century *(green)*
- New S_N and G_N are similar and have a **weak upward trend < 5 %/century**



External validation: geomagnetic record

- Comparison with the geomagnetic record: **solar open magnetic flux B reconstructions**
- Latest joint re-calibration (ISSI workshops) *(Owens et al. 2016)*
- **No trend between cycle maxima of mid-19th century and mid-20th century**

⇨ Best match with S_N version 2.0

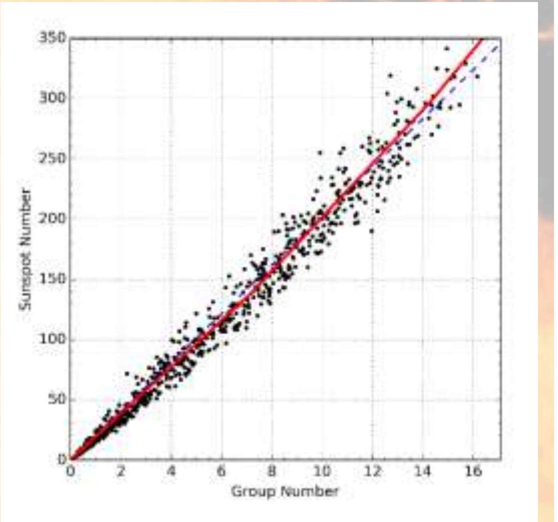


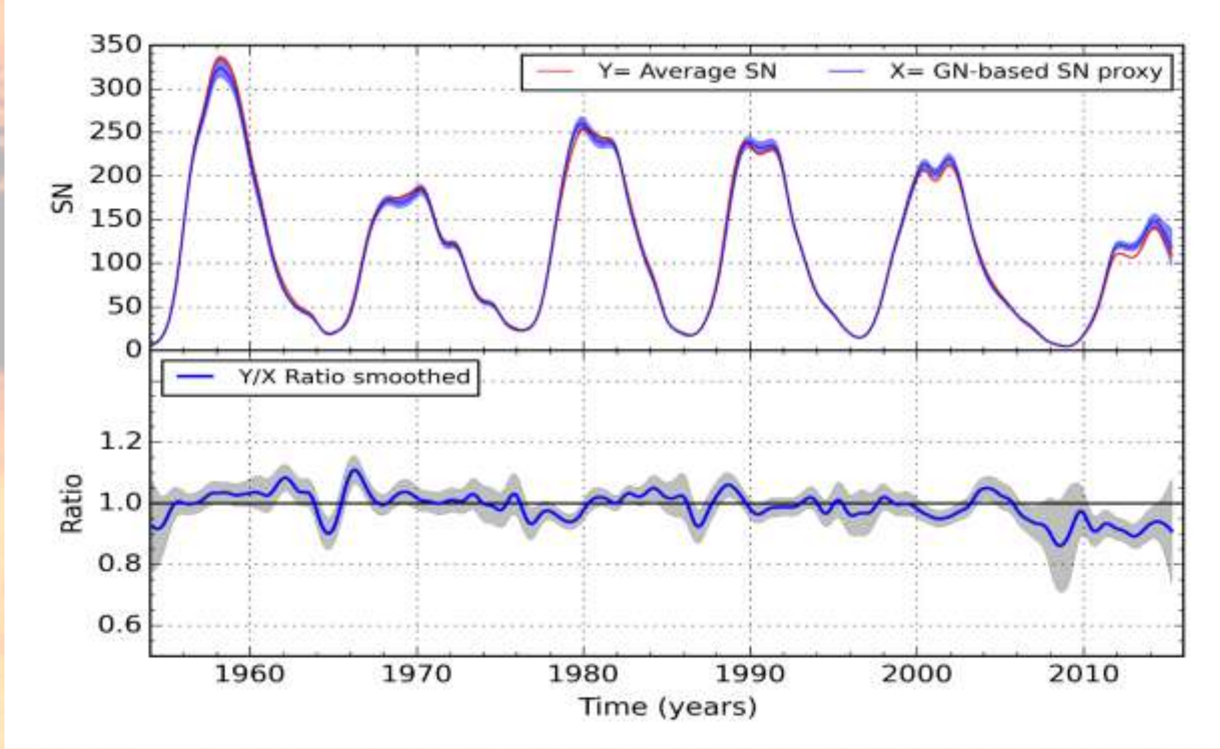
Owens et al. 2016

S_N and G_N remain distinct indices

- **Different measurements of emerging toroidal magnetic flux**
- Ratio between S_N and G_N values for the re-calibrated SN V2 series over 1945-2015 *(Clette & Lefèvre 2016)*:
- Single **non-linear relation valid for multiple cycles**
- Consequence of the **varying contribution of large and small sunspot groups** *(Tlatov 2013, Georgieva et al. 2017)*

$$S_N = 17.11(\pm 0.13)\ G_N^{1.07(\pm 0.010)}$$





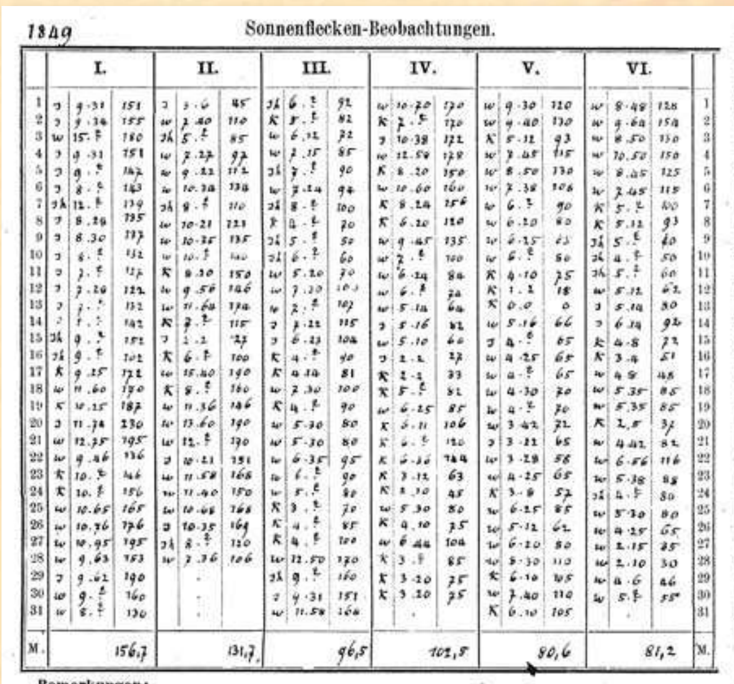
Building a full sunspot database

Key action: S_N observation database

- Next S_N version (V3):

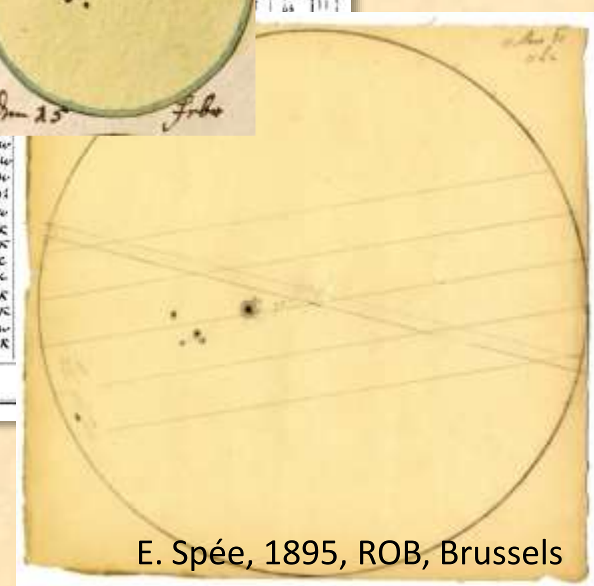
  Recalculation from all available raw source data

- Recovery of personal logbooks, printed tables, drawings



Wolf's sourcebooks

Staudacher, Feb. 13 and 15 1760 *(Svalgaard 2016)*

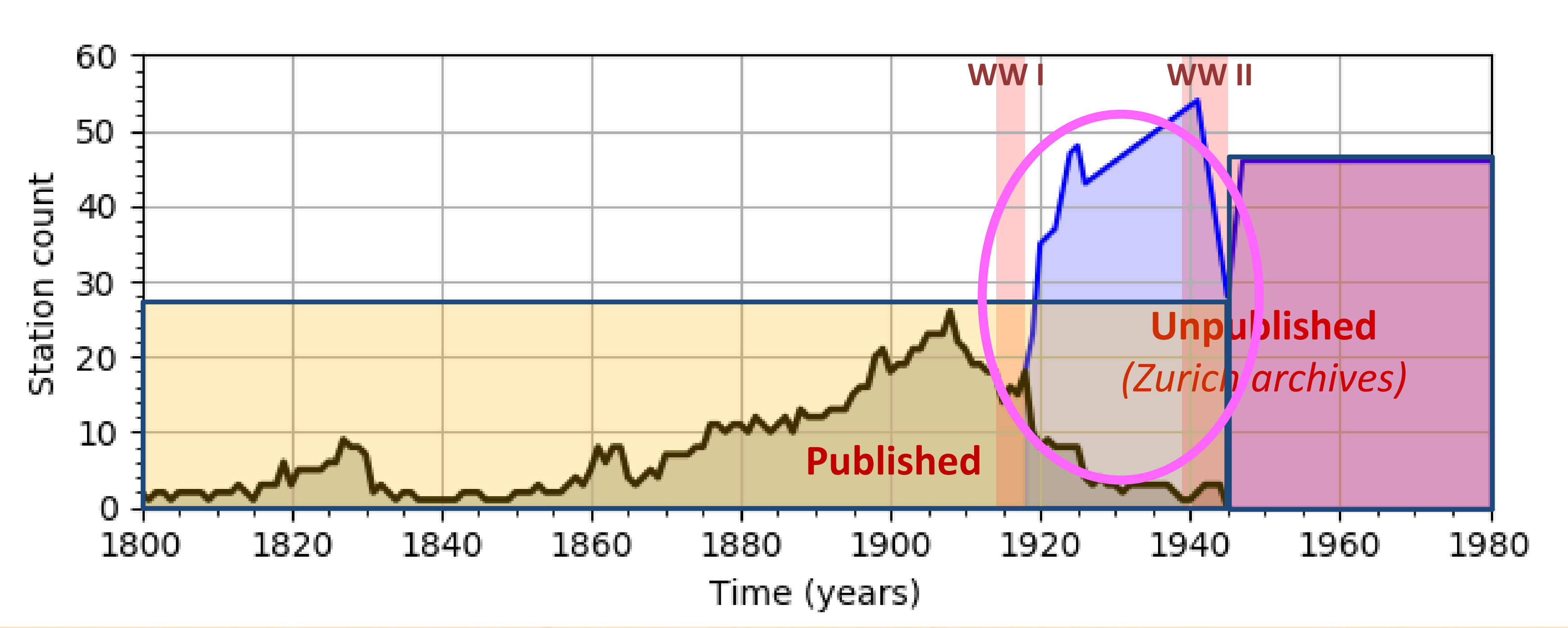


E. Spée, 1895, ROB, Brussels

Key action: S_N observation database

- **Recovering all raw input data from Zurich** (internal + auxiliary stations) *(Astronomische Mittheilungen der Sternwarte Zurich)*:
  - Now encoded **up to 1945 (WDC-SILSO)**
  - Not all data published after 1919 (external stations missing)
  - **No data published after 1945**

⇨ **Original sourcebooks recovered** at the Specola Observatory (Locarno) in June 2018: **all source data between 1945 and 1970**



Remaining issues and next goals

Sunspot Number

- Status:
  - The **main corrections** are included in Version 2
  - **Consensus on the amplitude of the Waldmeier jump correction**
- Remaining improvements:
  - Modern period (1849-today)
    - Mostly small local deviations: < 10%, less then 1 solar cycle
  - **Early period (18th and early 19th century)**:
    - Lower accuracy and sparse data
- Ongoing database construction
  - Recovery of lost Zurich sourcebooks

Sunspot group Number

- Status:
  - Consensus on flaws in the original H & S series
  - **Several incompatible reconstructions**
  - **Flaws identified in all new methods**
- Ongoing method evaluation:
  - Common new G_N database *(Vaquero et al. 2016)*
  - **Coordinated testing of methods:**
    - Joint work: ISSI workshops
    - Focused topical working groups
- Goal:
  - Consensus for each separate issue
  - Single optimal reconstruction

Full end-to-end reconstruction from all original data

Combination of different methods: Best method for each problem and epoch

Conclusions

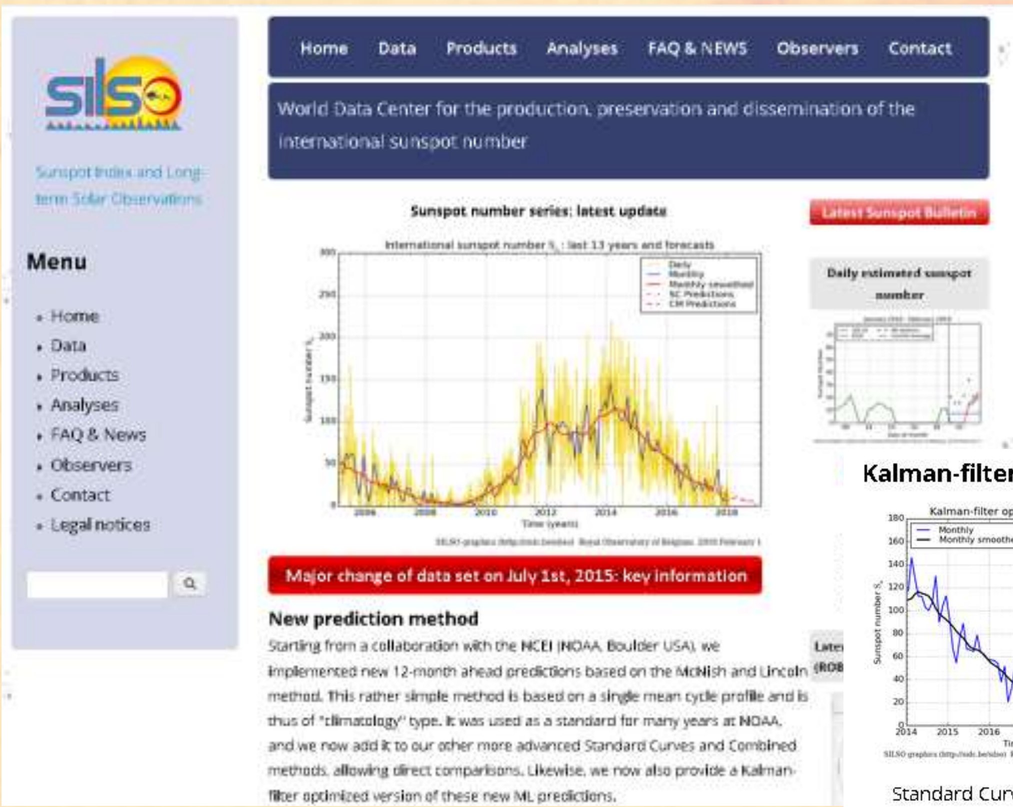
- **The study of the past sunspot record is completely revived**
- **S_N and G_N were and will be calibrated independently**
- **The S_N and G_N time series are now evolving data sets!**

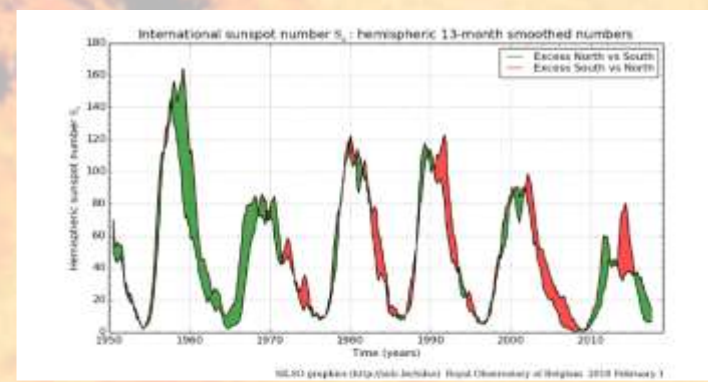
Stay tuned ….

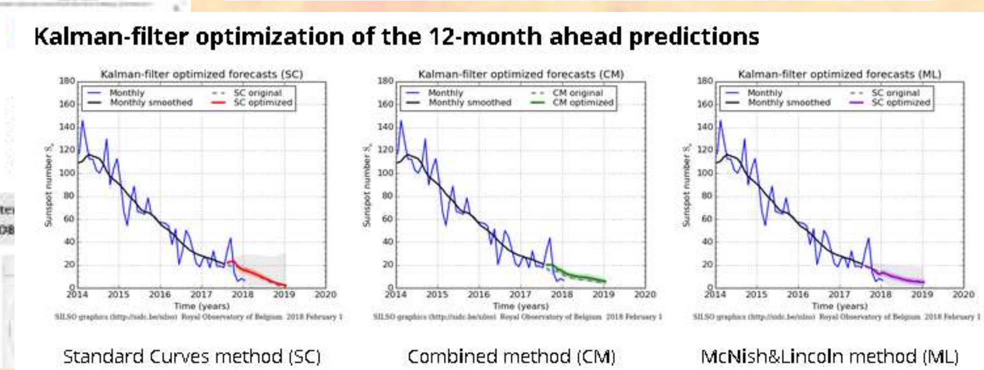
World Data Center – SILSO

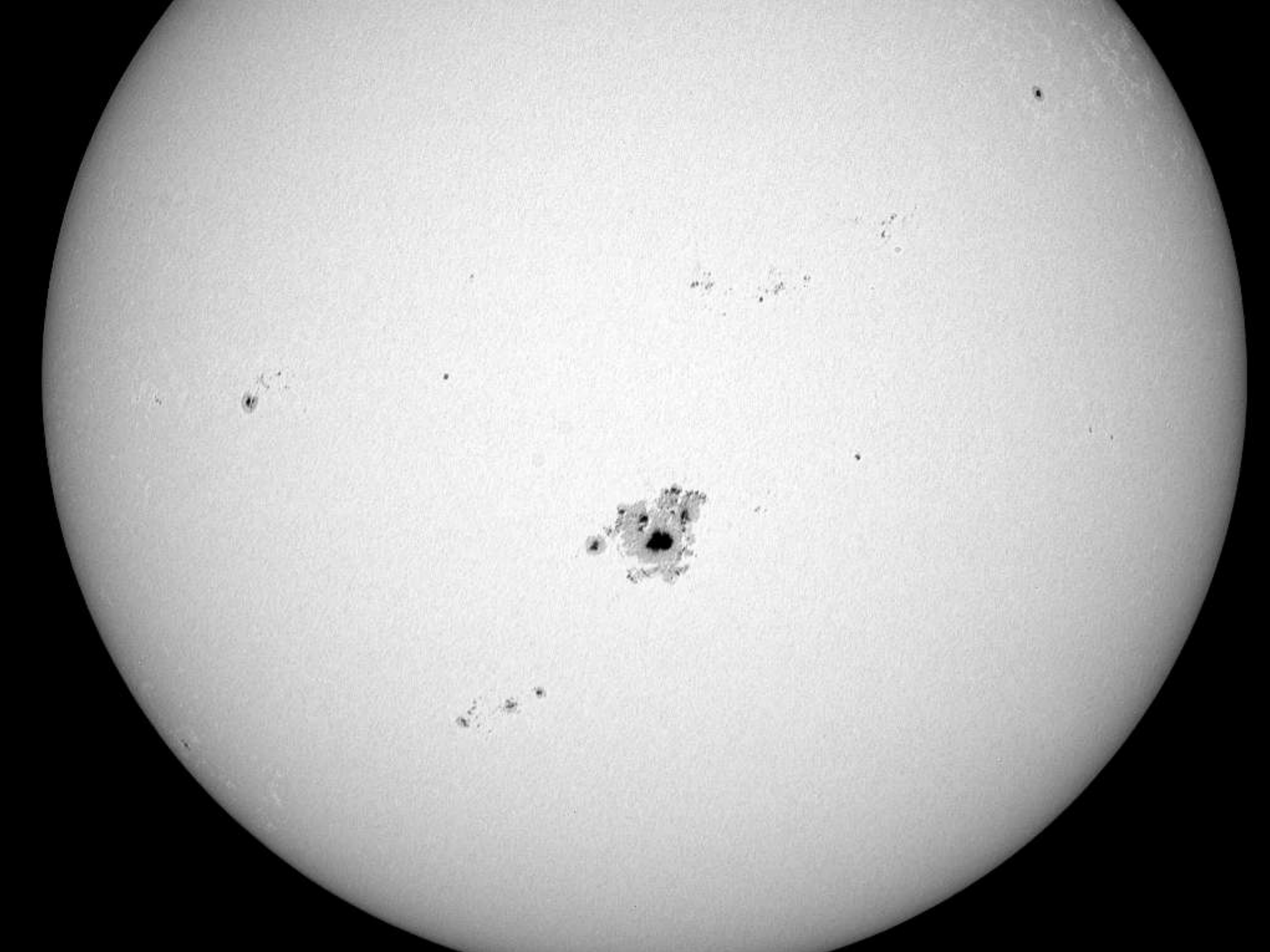
Sunspot Index and Long-term Solar Observations

http://sidc.be/silso





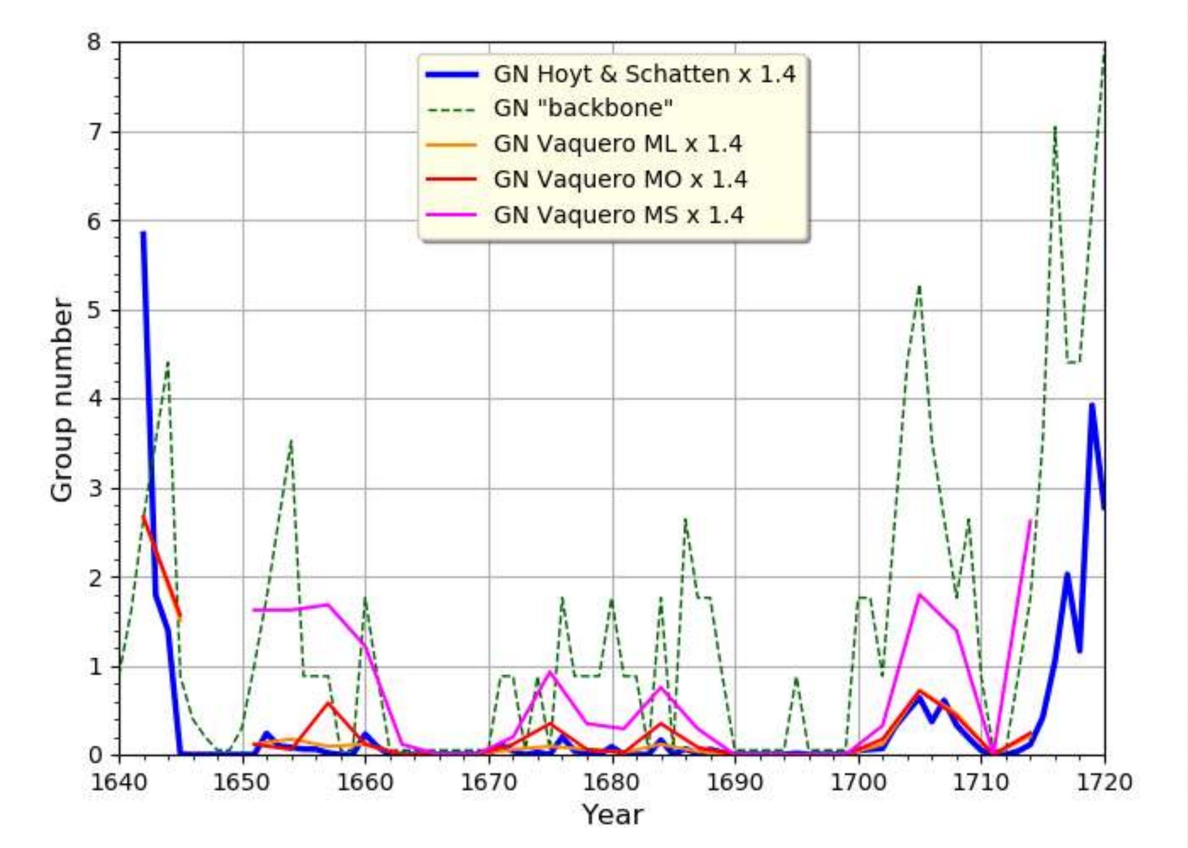




G_N: new database and Maunder minimum

- **Full revision of the original G_N raw data archive** *(Vaquero et al. 2016)*

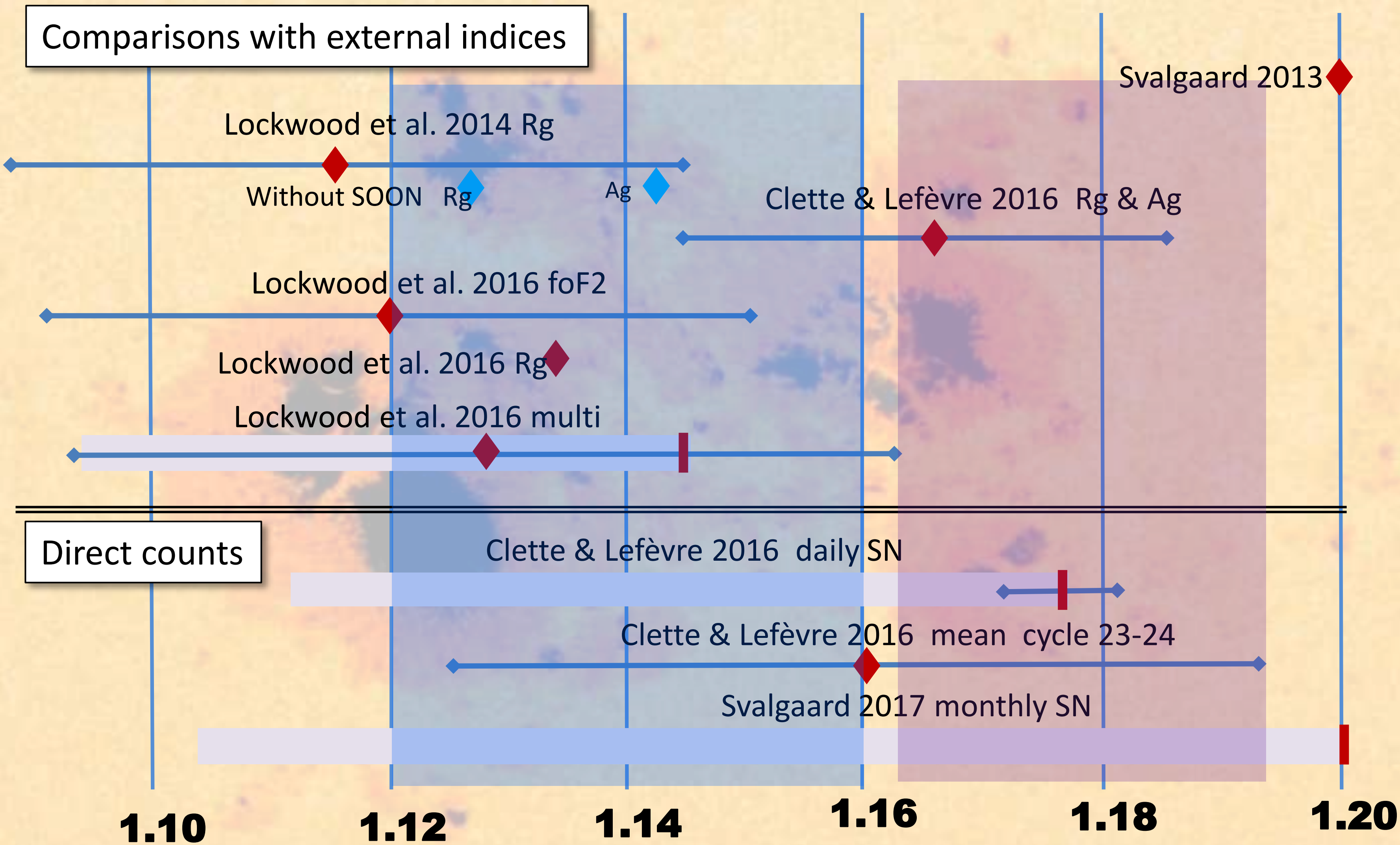
⇨ **Many null values unduly interpolated by Hoyt & Schatten** *(1998)*



⇨ Higher activity levels in Maunder minimum: a weak solar cycle persists (South hemisphere)

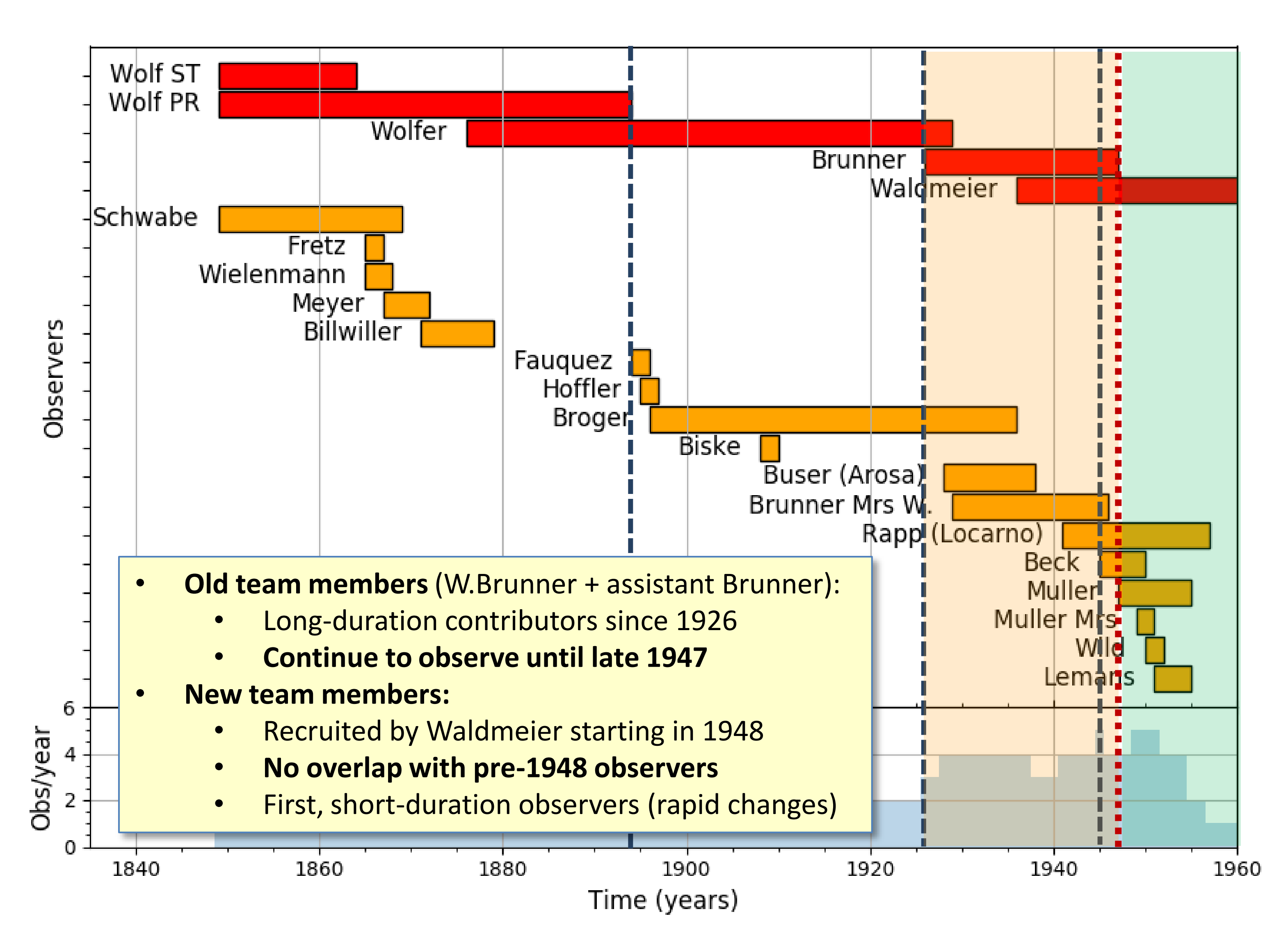
GN « Original », Hoyt & Schatten 1998
GN « Backbone », Svalgaard & Schatten 2016
GN Vaquero et al. 2015 A&Ap
ML « Loose » model
MO: « Optimum » model
MS « Strict » model

S_N criticisms: narrowing in on a common value



Distinction between **mean ratio** ♦ **: 1.14 +/- 0.02** and **peak ratio** ▌**: 1.177 +/- 0.005**

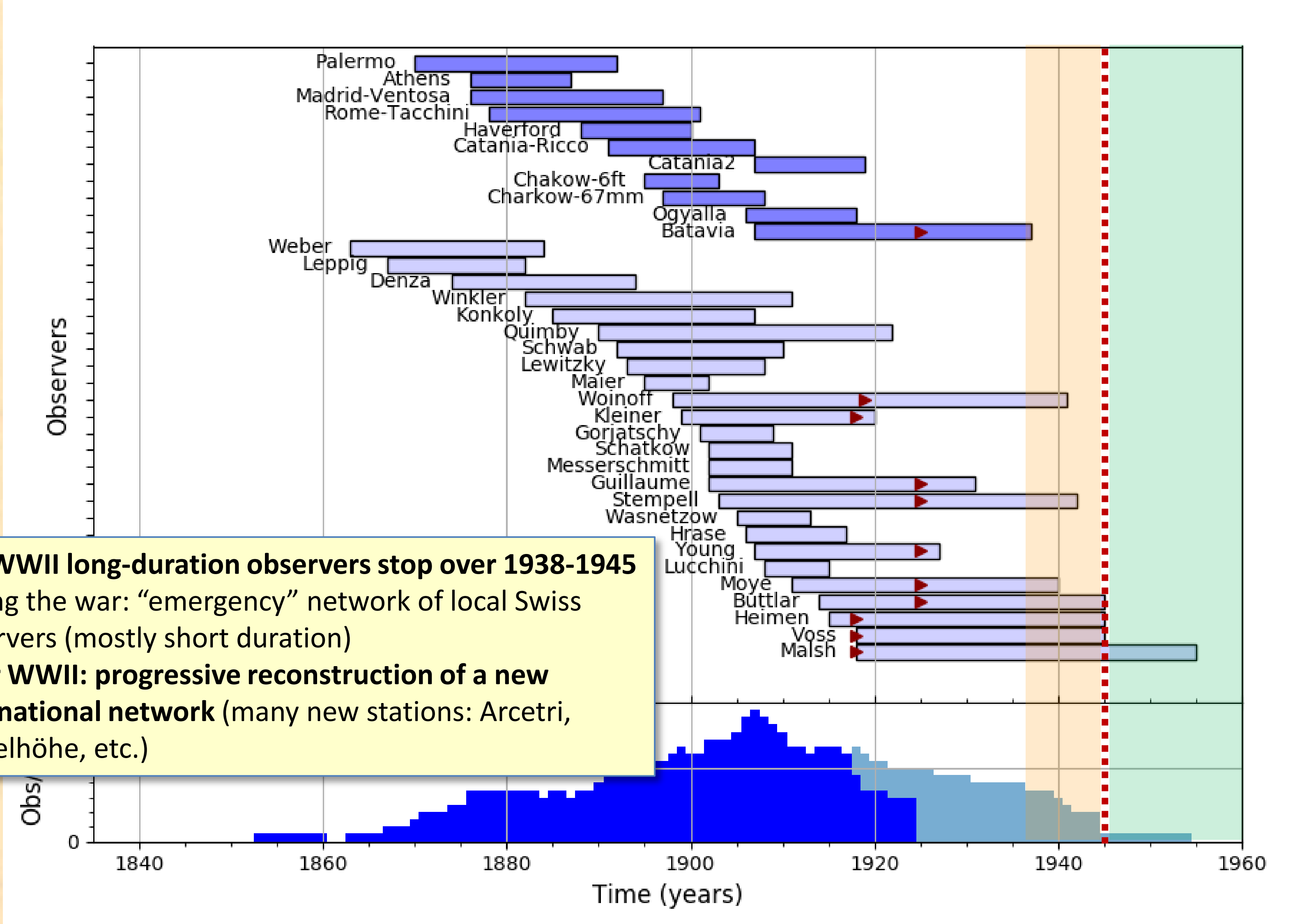
[S_N] Zurich observers



- **Old team members** (W.Brunner + assistant Brunner):
  - Long-duration contributors since 1926
  - **Continue to observe until late 1947**
- **New team members:**
  - Recruited by Waldmeier starting in 1948
  - **No overlap with pre-1948 observers**
  - First, short-duration observers (rapid changes)

(Plot based on the Mitteilungen der Eidgenösisches Sternwarte Zürich)

[S_N] Long-duration stations (> 1 solar cycle)

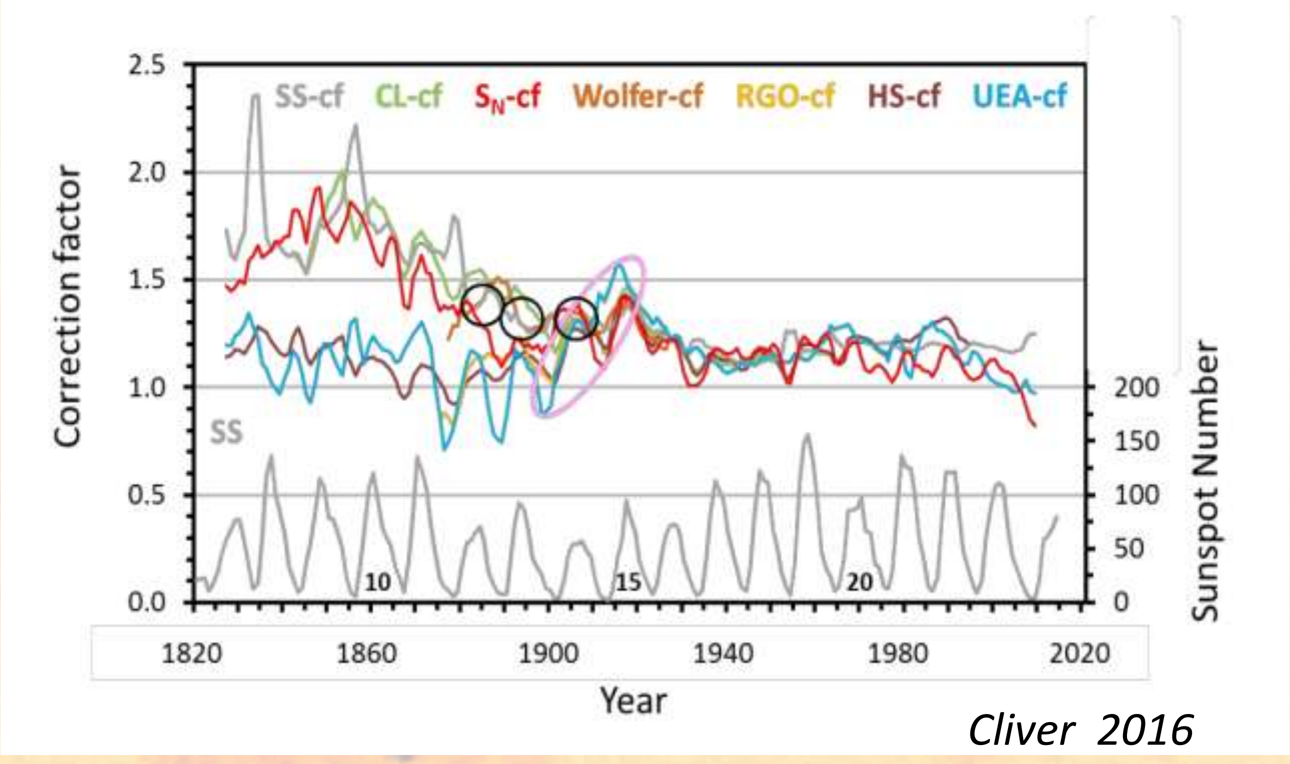


- **Pre-WWII long-duration observers stop over 1938-1945**
- During the war: "emergency" network of local Swiss observers (mostly short duration)
- **After WWII: progressive reconstruction of a new international network** (many new stations: Arcetri, Kanzelhöhe, etc.)

(Plot based on the Mitteilungen der Eidgenösisches Sternwarte Zürich)

[G_N] Uncorrected series: a comparison

- **Ratios with a non-calibrated series** (raw un-normalized numbers)



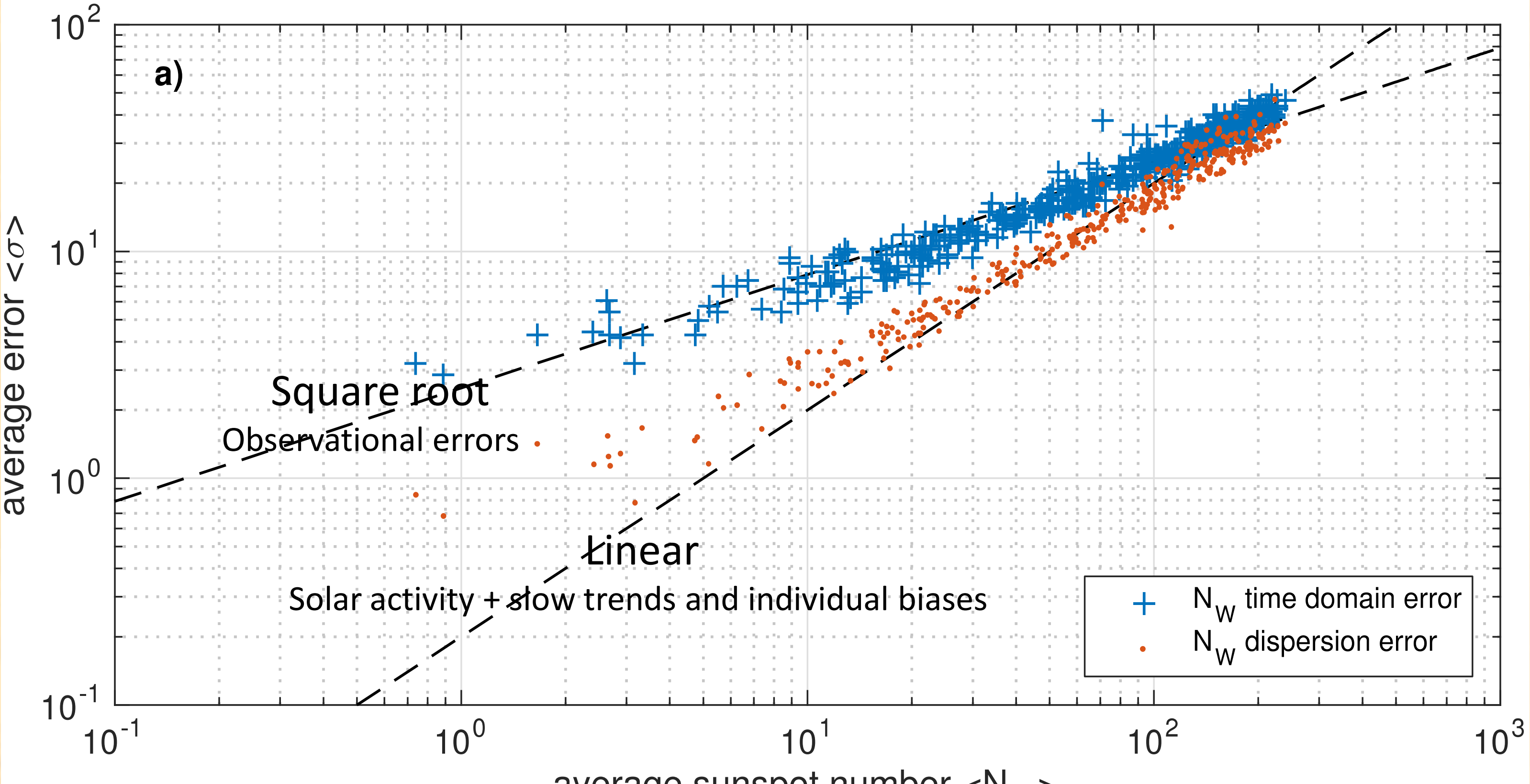
  - High values before 1900: S_N V2, backbone G_N, Cliver&Ling G_N
  - Low values before 1900: original H&S G_N, ADF G_N

⇨ Constant or rising ratio (low series) imply a constant or degrading quality of the observations

  - **Inconsistent with known progresses of astronomical instruments**

Non-Gaussian errors and uncertainties

- Global statistics based on the SILSO database (1981-now, > 550.000 data)
- **Two components in random errors** *(Dudok de Wit et al. 2016)*:

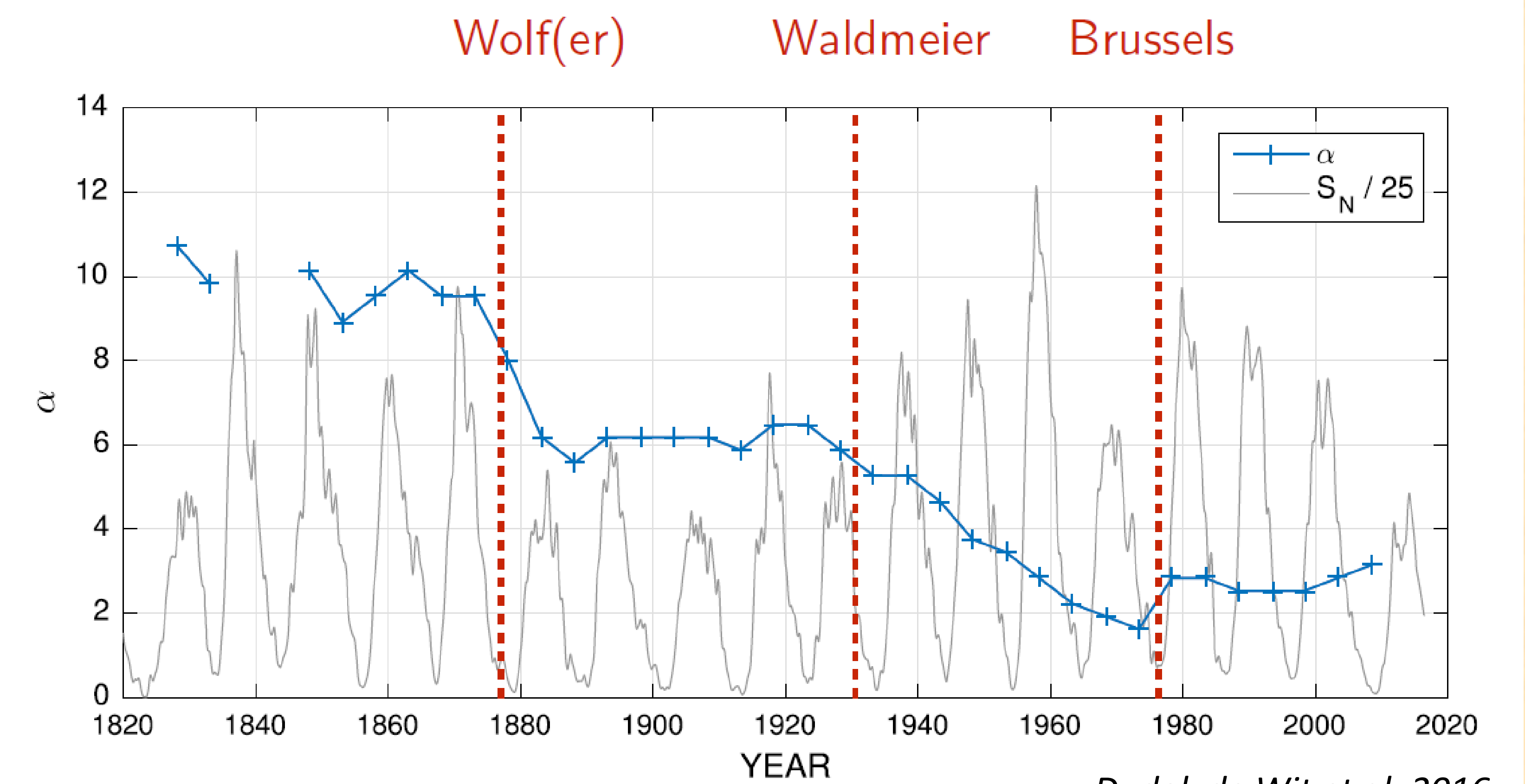


Dudok de Wit et al. 2016

Non-Gaussian errors and uncertainties

- Long-term variations of observer errors:
  decreasing dispersion in the resulting S_N

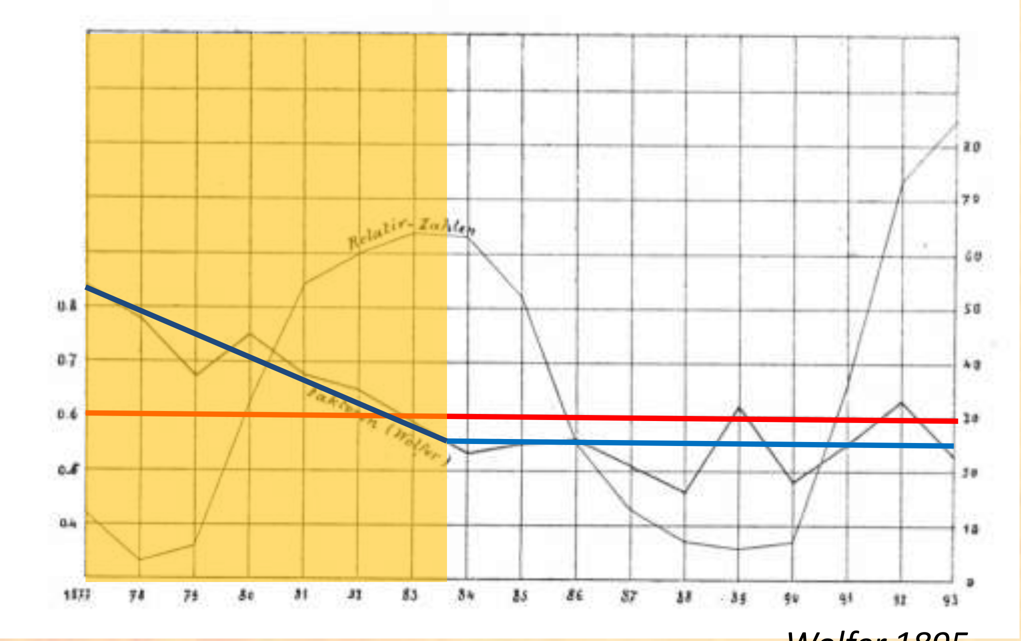
⇨ Steady improvement of the S_N index precision



Dudok de Wit et al. 2016

The Wolf-Wolfer transition (1877-1893)

- Unique interval in the SN series:
  - SN number is the **average between two observers** (Wolf+Wolfer)
- Critical **double transition**:
  - From
    Wolf 40mm portable refractor to
    Wolfer with 82mm refractor
  - New counting rules: small spots, multiple umbrae



Wolfer 1895

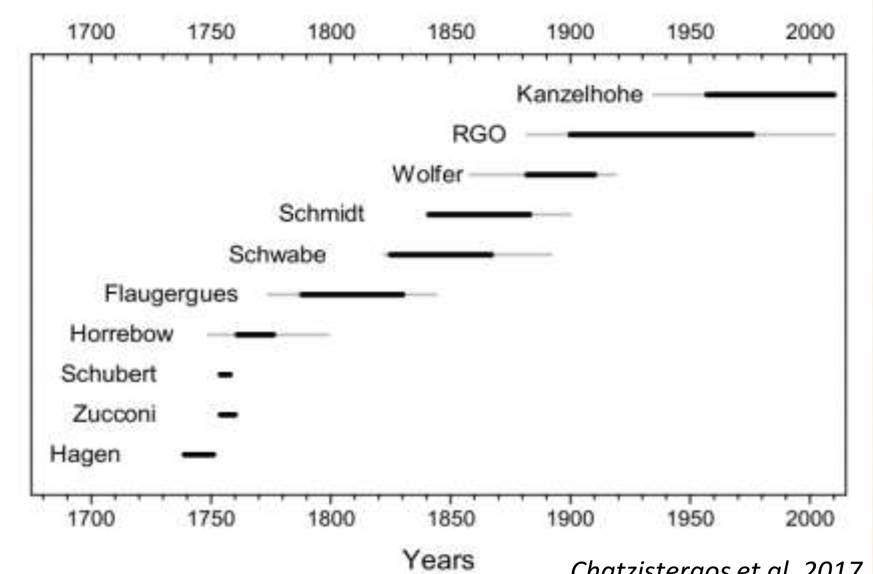
- k coefficient 0.6 between Wolf series (1700-1893) and modern series (1893-now)
- **Trend over 1876-1883**:
  - Wolfer gaining experience (counting progressively more spots)
  - Mix with other assistants (mutual influence?)
- 1883-1893 gives a **correction factor of about 0.55** (< 0.6)
  - Should the Wolf series before 1876 be raised by 10%?

$[G_N]$ Improving the backbone method

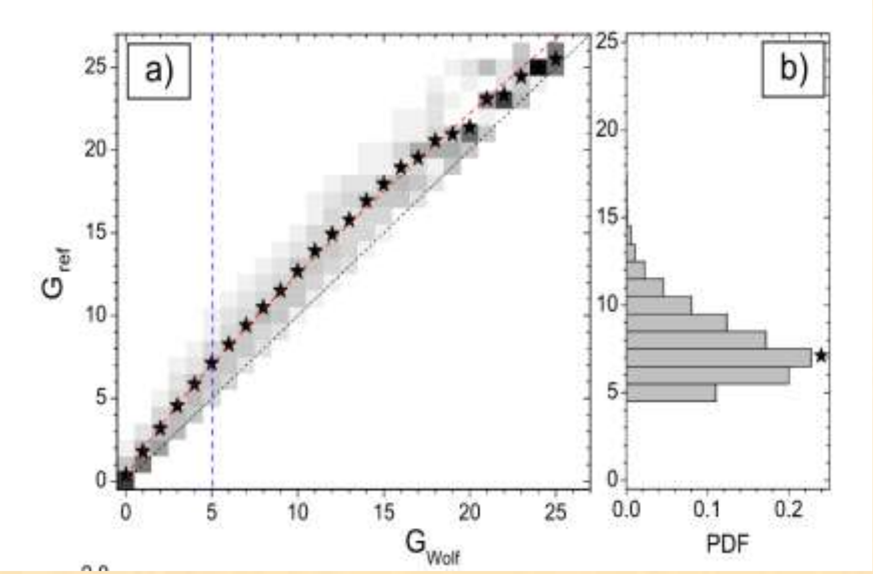
- New "backbone" reconstruction *(Chatzistergos et al. 2017)*:
  - **More backbone observers**: directly overlapping
  - Use of **daily values** instead of yearly mean values
- Non-parametric scaling between observers :

  correspondence matrices
  - Cross-observer probability distribution functions
  - Provides the means and dispersion of the estimated corrected value (panel b)

Intermediate scale in 19th century:
- Lower than original backbone G_N
- Higher than ADF G_N

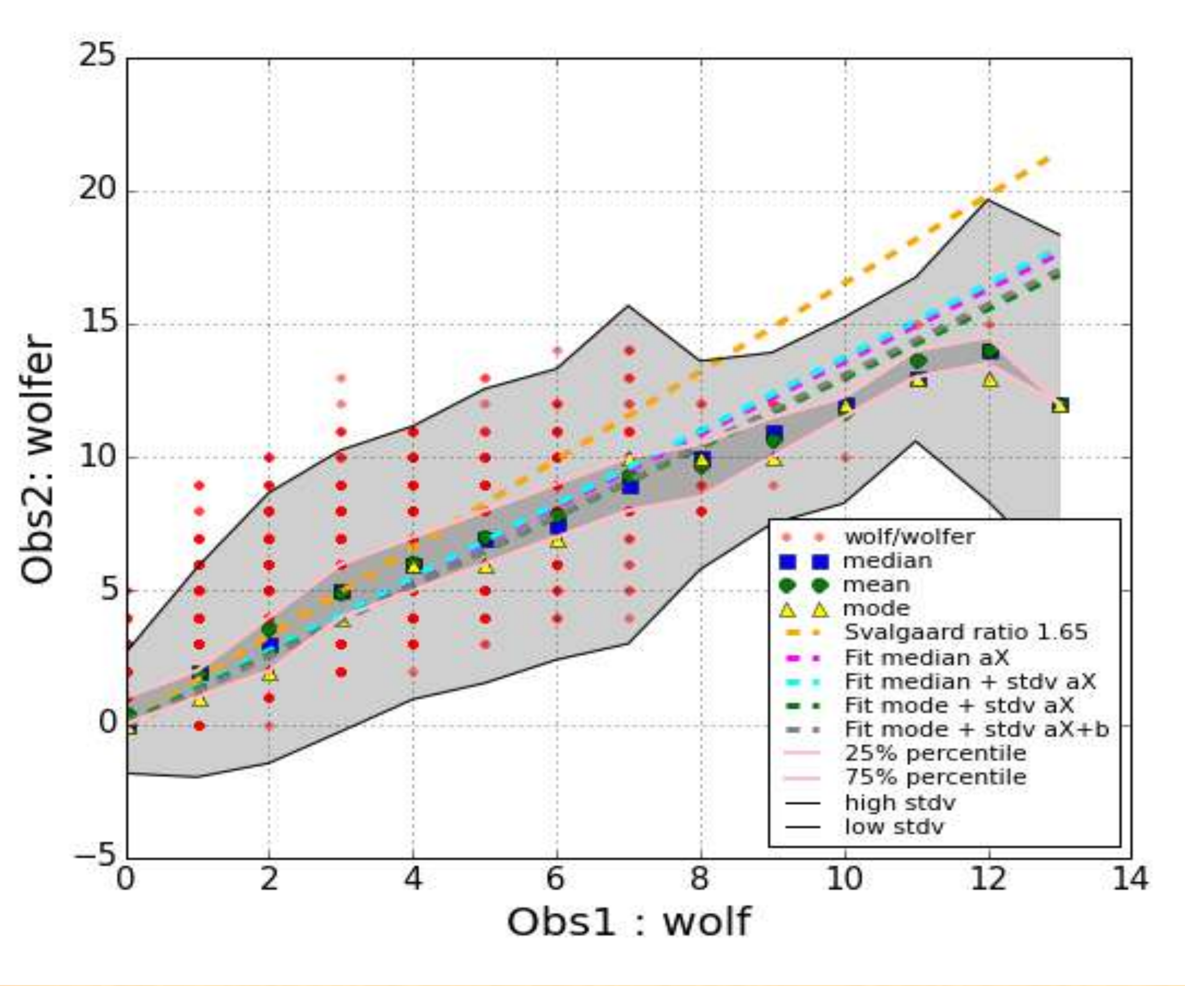


Chatzistergos et al. 2017



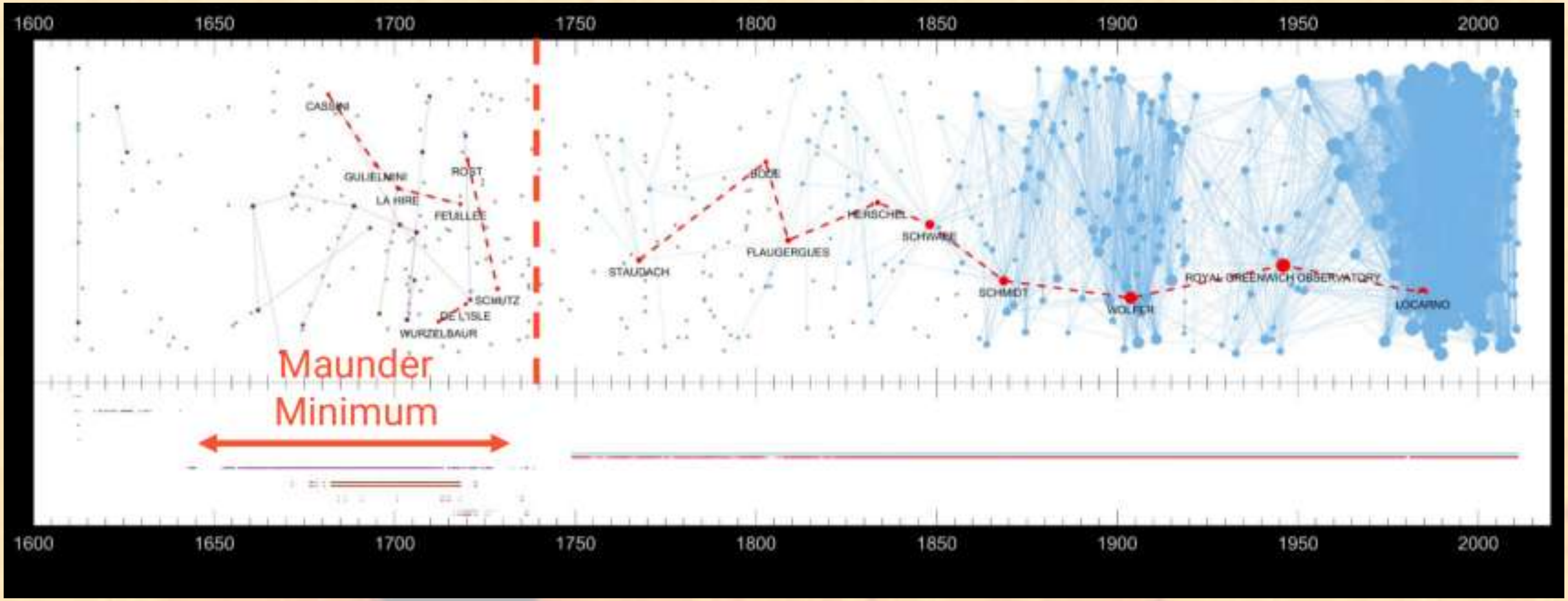
[G_N] Towards a solution ?

- **Correspondence matrices**: nice non-parametric tool
- Very few data points at moderate and high GN values:
- ⇨ Lower slopes (k factors) or non-linearity of fits are barely significant



- **Best approach:**
  combination of classical k-ratios and correspondence matrices

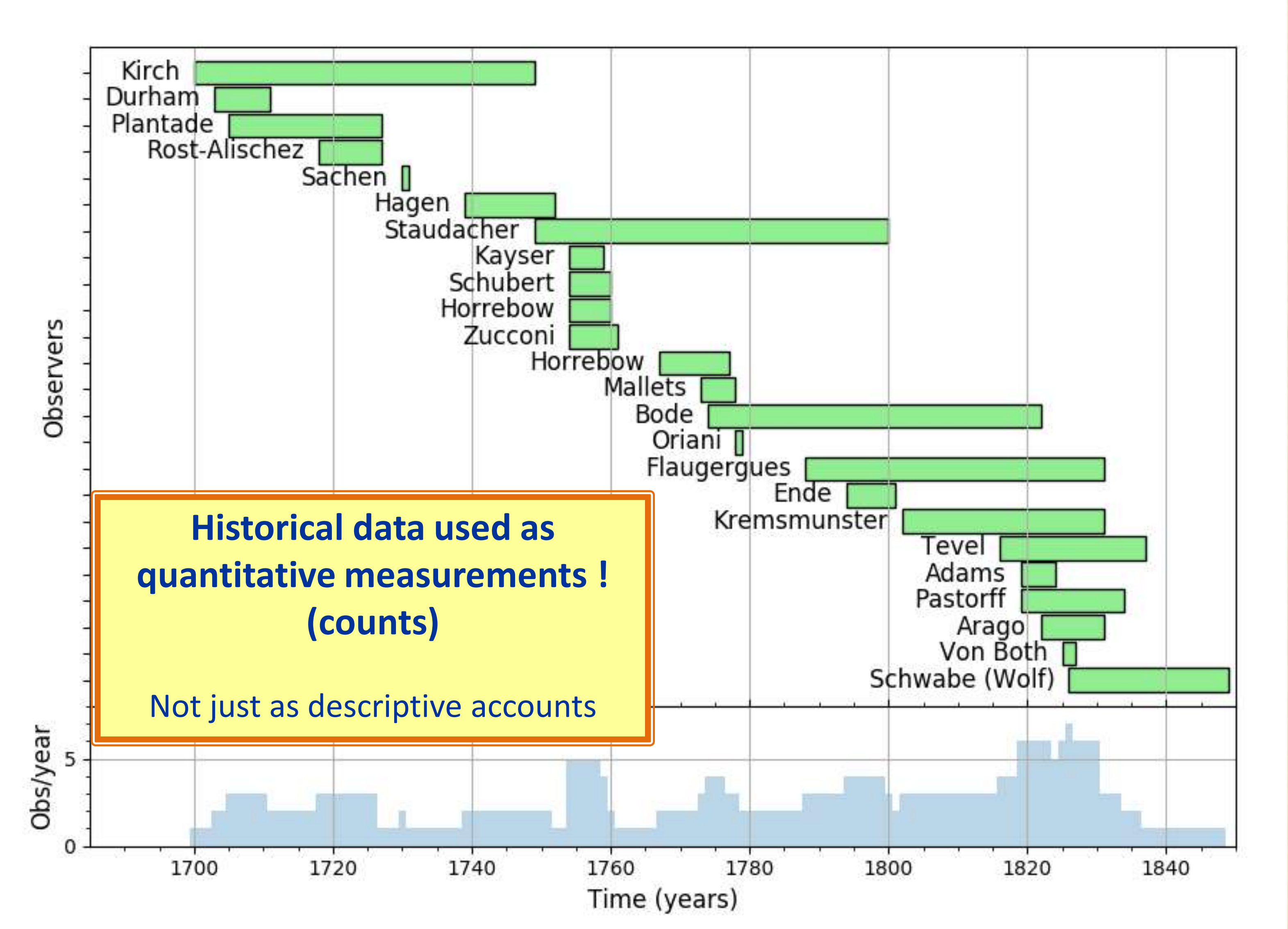
Future big challenge: continuity in early data



- Optimal choice of the reference- observer chain *(A. Muñoz-Jaramillo 2018)*: linking best observer pairs
  - Recovering new "forgotten" observations: e.g. East Asia (Hayakawa et al. 2019)
  - Advanced data-mining methods for sparse time series
  - Exploitation of detailed information in sunspot drawings
  - Use of geomagnetic indices to bridge short gaps to link "loose ends"

Dudok de Wit et al. 2017

Wolf's historical observers: timeline



Historical data used as quantitative measurements ! (counts)

Not just as descriptive accounts

Two distinct base data sets

Sunspot Number

- Reference data sets:
  - Zurich observers and auxiliary stations before 1980
  - SILSO database
    - 280 stations
    - > 550,000 numbers
  - + a few new recovered time series (1950-2015)
    - Archived reports to Zurich

Sunspot group number

- Reference data sets:
  - Original Hoyt & Schatten group number database (1610-1995)
  - Extension with new observations:
    - 20^{th} century (Wolfer, Koyama, Luft, etc.)
    - SILSO database (1980-2014)
  - Corrections and extension of early historical data, including the Maunder Minimum
    - *Vaquero et al. 2016*

[G_N] Towards a solution ?

- A compromise between old stitching methods and correspondence matrices