The new Sunspot and Group Numbers
A full recalibration

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The 400-year sunspot record

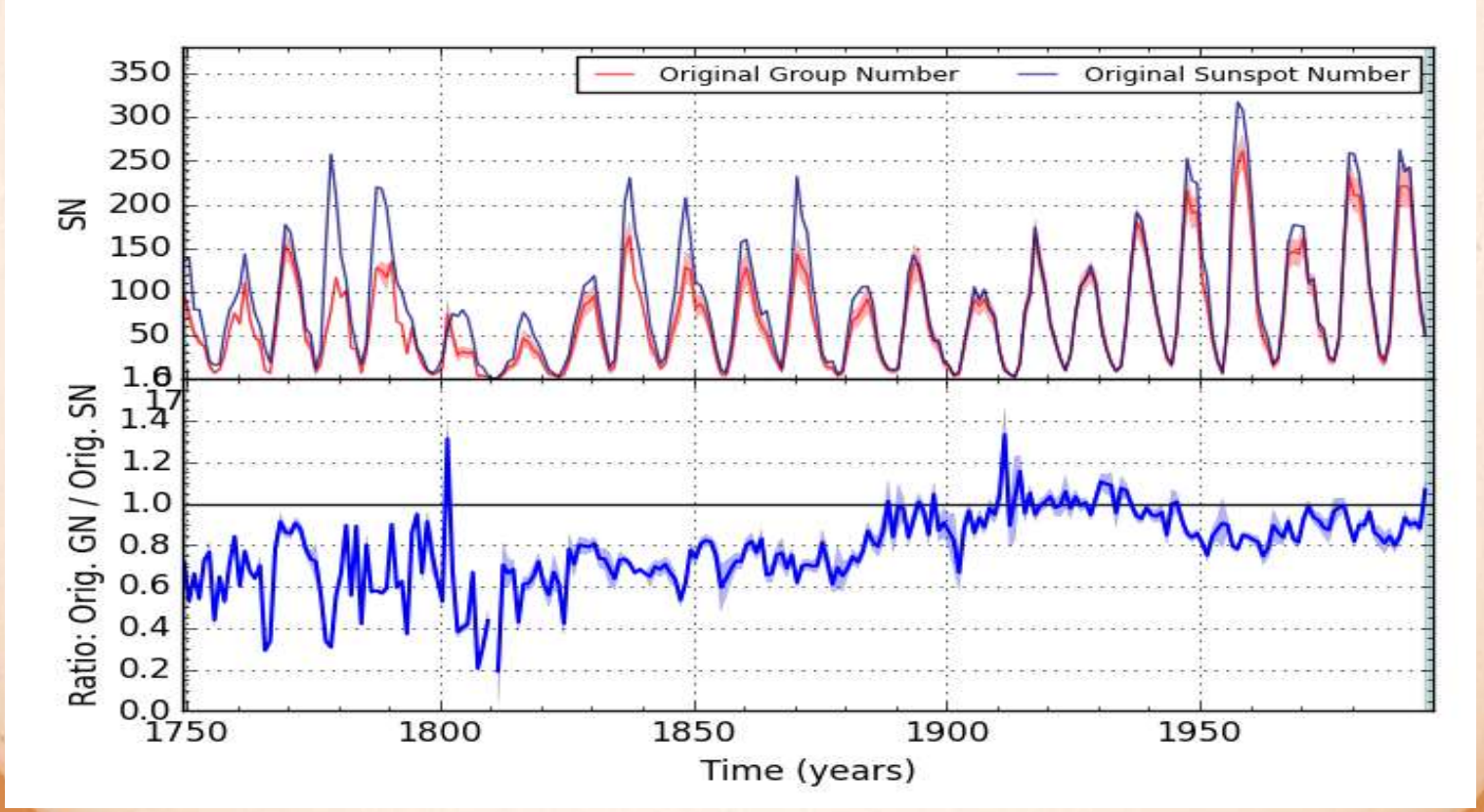
- Only direct record of the evolution of the solar cycle over multiple centuries
- Longest scientific experiment still ongoing *(B.Owens, Nature, March 2013)*
- Multiple applications:
  - Solar dynamo modelling
  - Long-term irradiance reconstructions
  - Calibration of the cosmogenic isotopes (^{14}C, ^{10}Be)
  - Earth climate change
  - Infrastructure maintenance (pipelines, electrical power grid)
- > 100 scientific publications / year
- Part of public culture and astronomy education
  - > 150 000 Google hits on “sunspot number”:

A necessary revision

- No critical revision of the Sunspot Number series since its creation by R. Wolf in 1849
- Only alternate series: the **Group Number**
  (Hoyt & Schatten 1998)
- **Large discrepancies between the series (up to 40%)**

$$R = \frac{1}{N}\sum_i k_i \left(10 Ng_i + Ns_i\right)$$

$$G_N = \frac{12.08}{N}\sum_i k_i Ng_i$$



A new impulse: Sunspot Number Workshops

- Community effort started in Sept. 2011:
  - 4 Sunspot Number Workshops: Sac. Peak, Brussels, Tucson, Locarno
  - 40 participants:
    - Core group working on the SN
    - Input concerning other parallel solar tracers:
      CaII-K, magnetograms, TSI, geomagnetic indices

Synthesis in:

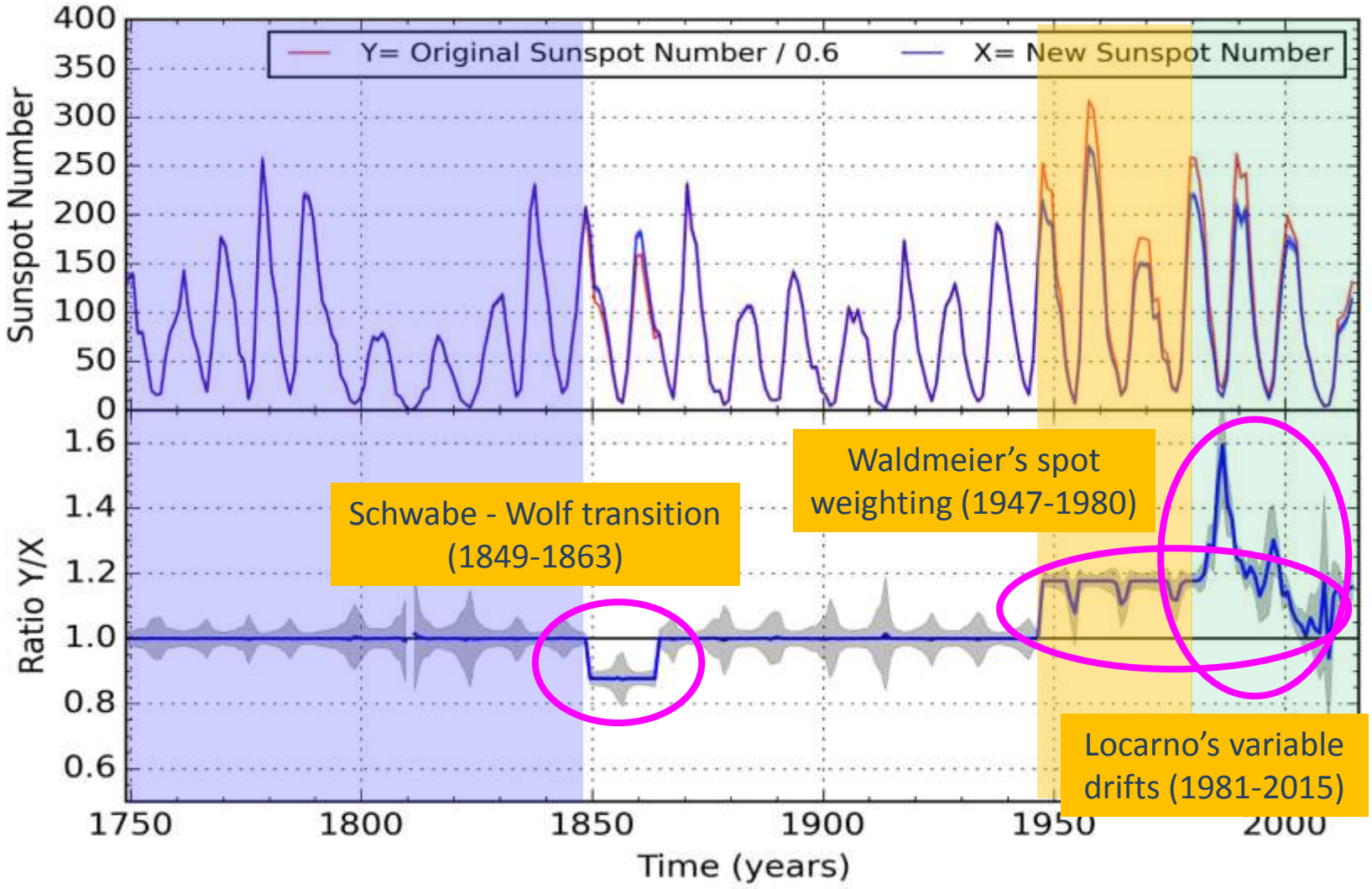
Clette, F., Svalgaard, L., Vaquero, J.M., Cliver, E.W.: 2014,

Revisiting the Sunspot Number. A 400-Year Perspective on the Solar Cycle.

Space Sci. Rev. 186, 35-103

DOI: 10.1007/s11214-014-0074-2

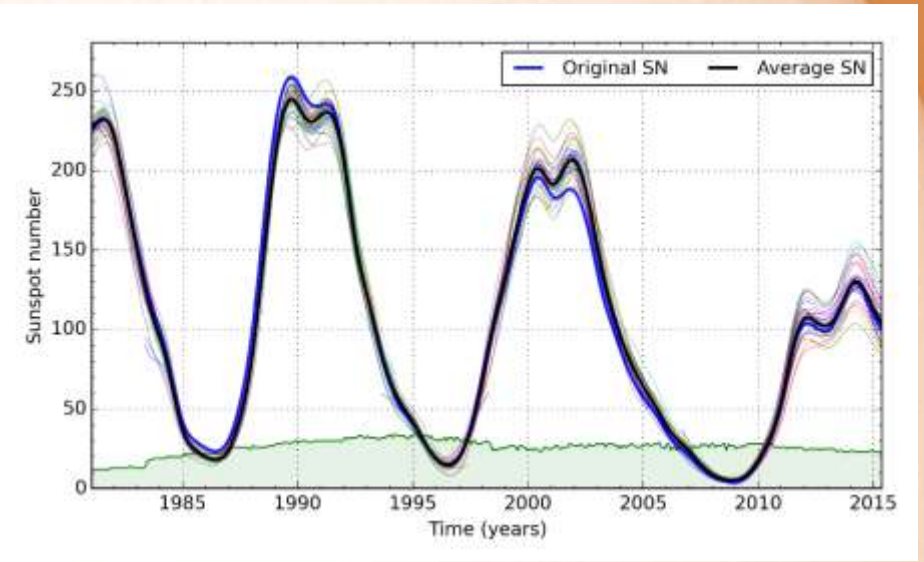
Sunspot Number corrections: overview

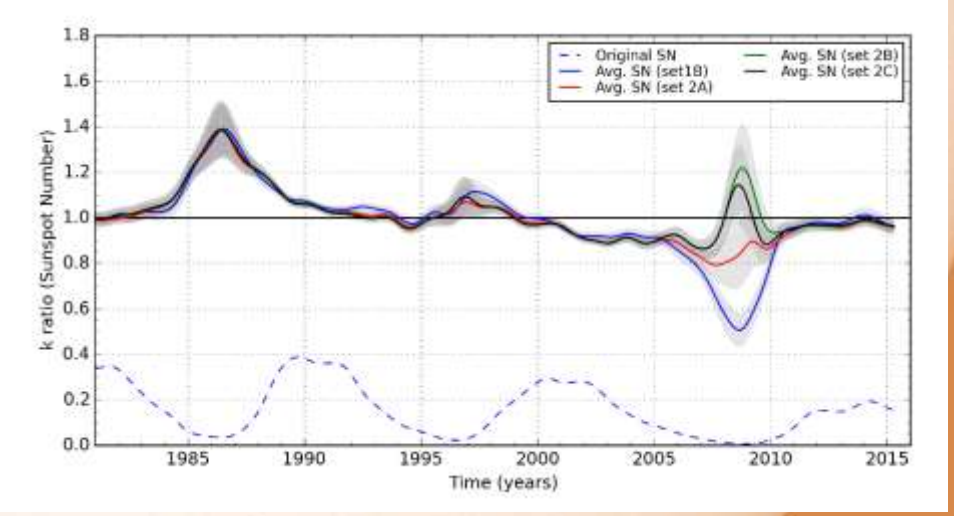


Locarno's variable drift (1981-2015)

- After the 1981 Zürich-Brussels transition: changing trends found in the SN from the Locarno pilot station *(Clette et al. 2014)*

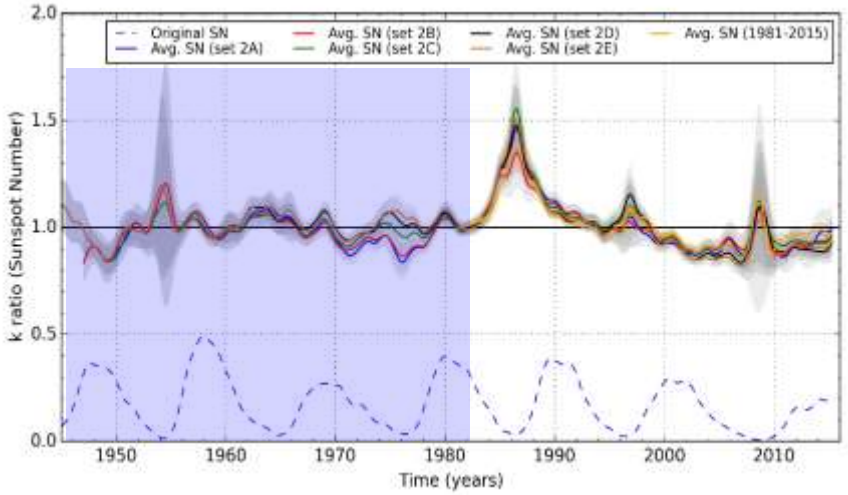
- **Direct reconstruction of the SN from a subset of 42 long-duration** and stable **stations** in the WDC – SILSO database:
  - Correction factor: monthly mean k ratio with the original SN series
- Causes
  - Loss of the Zürich Observatory as reference : initial overestimate over 1983-1995
  - Slow aging of primary observer (S. Cortesi)
  - Recovery with arrival of a new observer (M. Cagnotti, 2005)
  - Minor role by the sunspot weighting factor



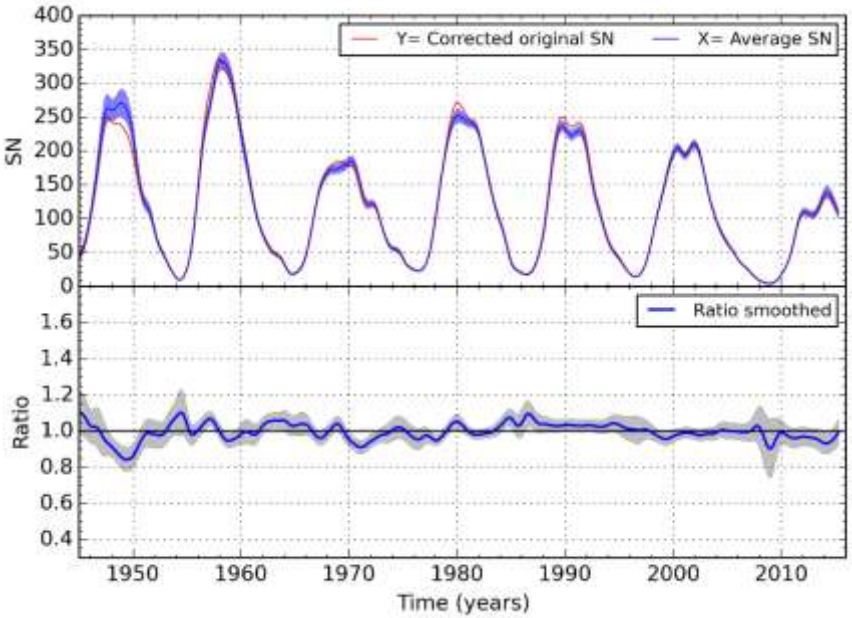


Locarno's variable drift (1981-2015)

- **Long reconstruction 1945-2015**: 17 long-duration series covering the 1981 transition

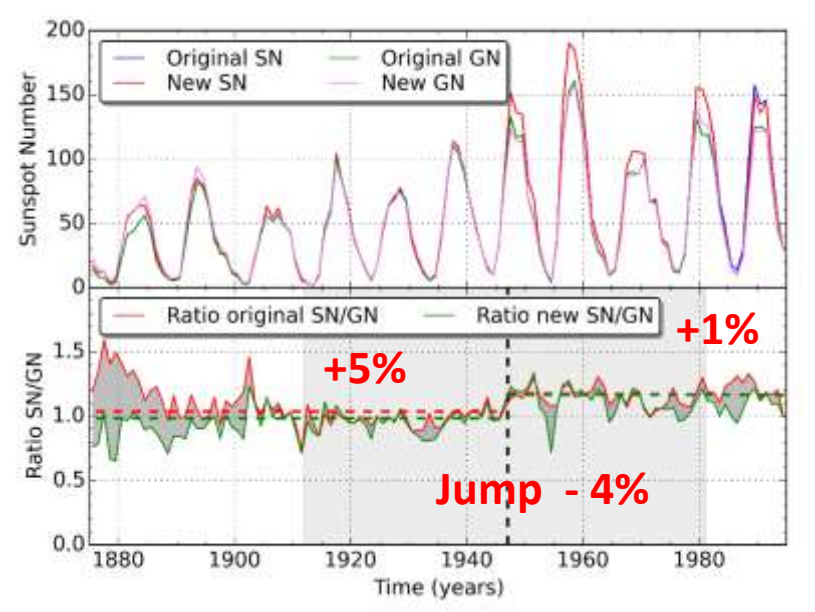


- After correction by the k factor over 1981-2015:
  - Constant ratio between the reconstructed series and the corrected original series
  - ⇨ Average ratio before and after 1981 are equal:
    - Scale factor = 1.00 +/- 0.012

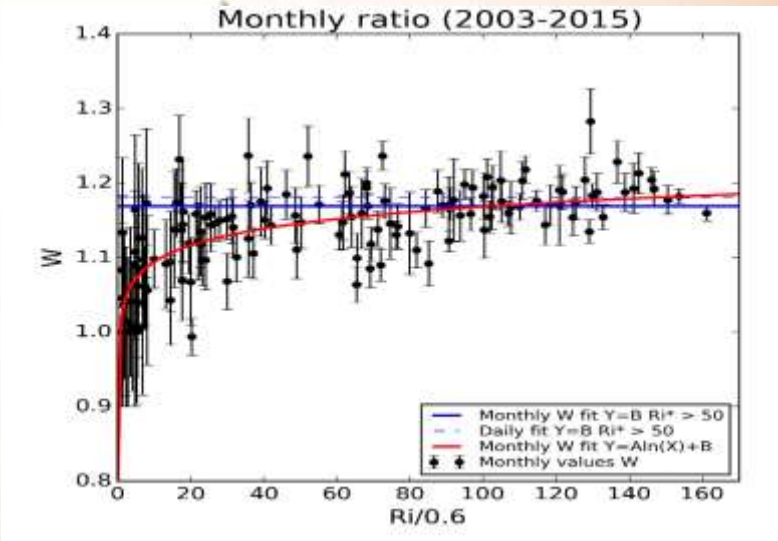


Waldmeier's weighted number (1947-1980)

- 1947: new counting practice: large spots counted as >1 (2 to 5) according to penumbral size
- **Inflation factor range: 1.15 to 1.25**
- One low value: 1.126 *(Lockwood (2014)*, but improper data:
  - Original series SN and GN containing other uncorrected biases (before 1915 and after 1980)



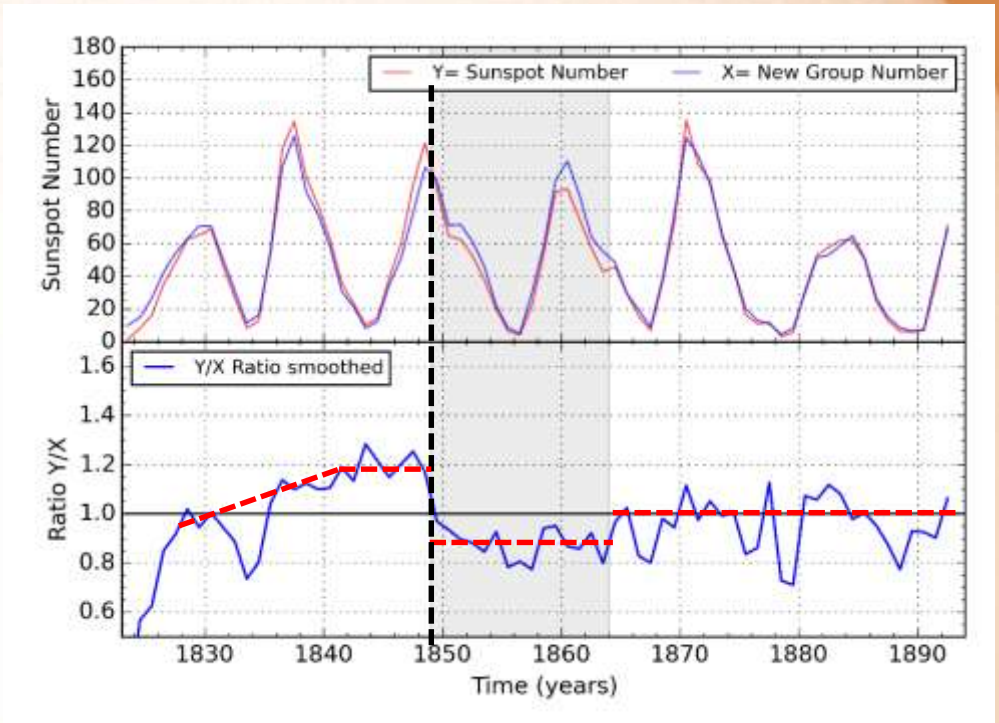
- Most robust determination: **double counts, weighted and standard, done at the Locarno station**:
  - Mean ratio in cycle 24: 1.165 +/- 0.035
  - Existence of a maximum asymptotic mean value: **1.177 +/- 0.005**
  - *See also Svalgaard 2015, Sol. Phys.*



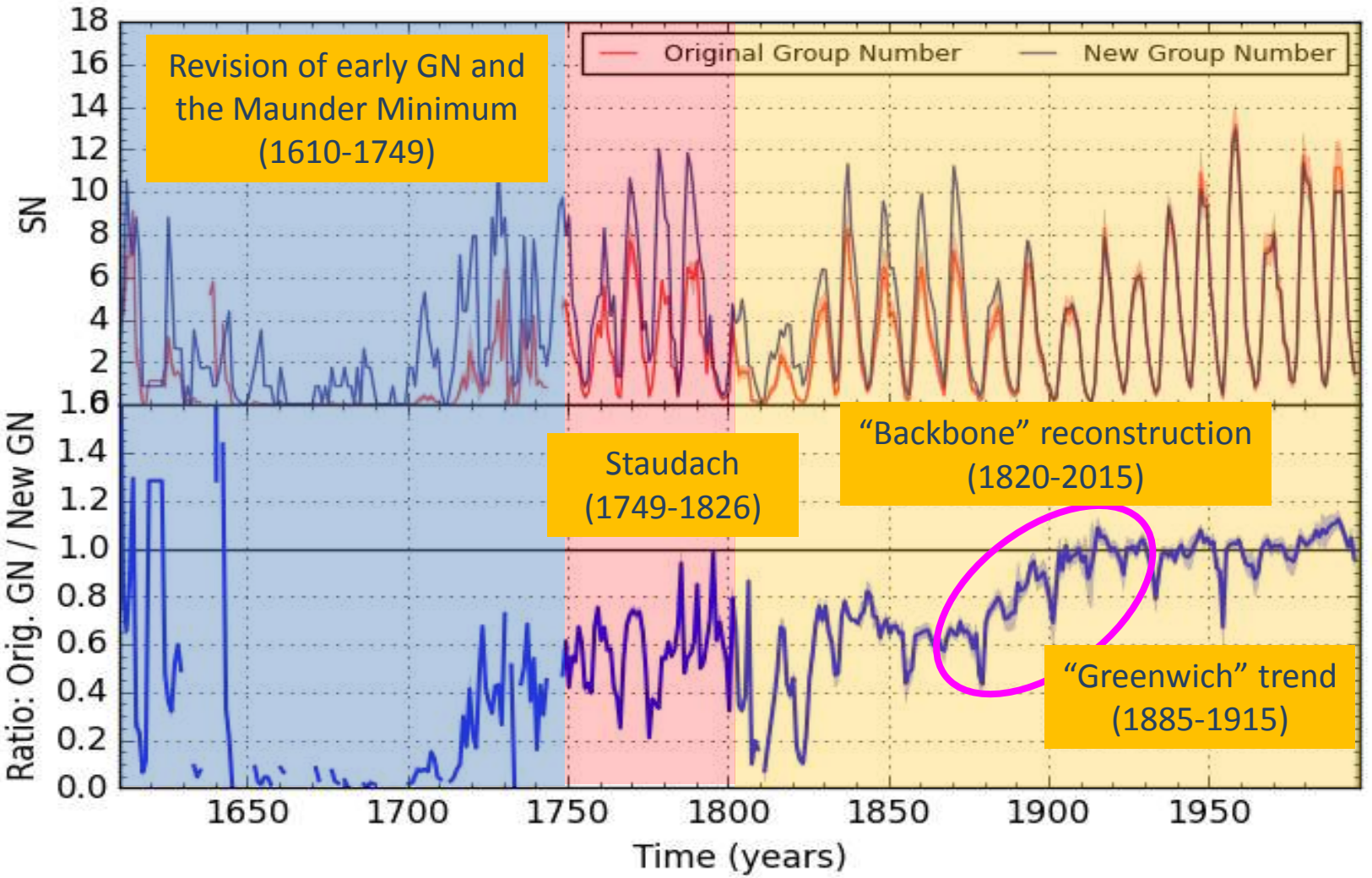
The Schwabe- Wolf transition (1849-1863)

- **1849: 20% downward jump** in the SN relative to the original Schwabe numbers *(Leussu et al. 2013)*
- By comparison with the Group Number over a wider time interval:
  - Schwabe upward trend 1826-1840
  - **14% upward jump in 1863**
  - ⇨ Equal scale before 1826 and after 1863
- A probable cause:
  - Wolf initially mixed the raw Schwabe numbers with his own observations (small portable refractors).
    - Distinct markers only appear in published tables by 1863
    - Standard 80mm Zürich refractor delivered in 1864
- ⇨ Time-limited correction:

  SN increased by 1.14 (+/- 0.02) over 1849-1863



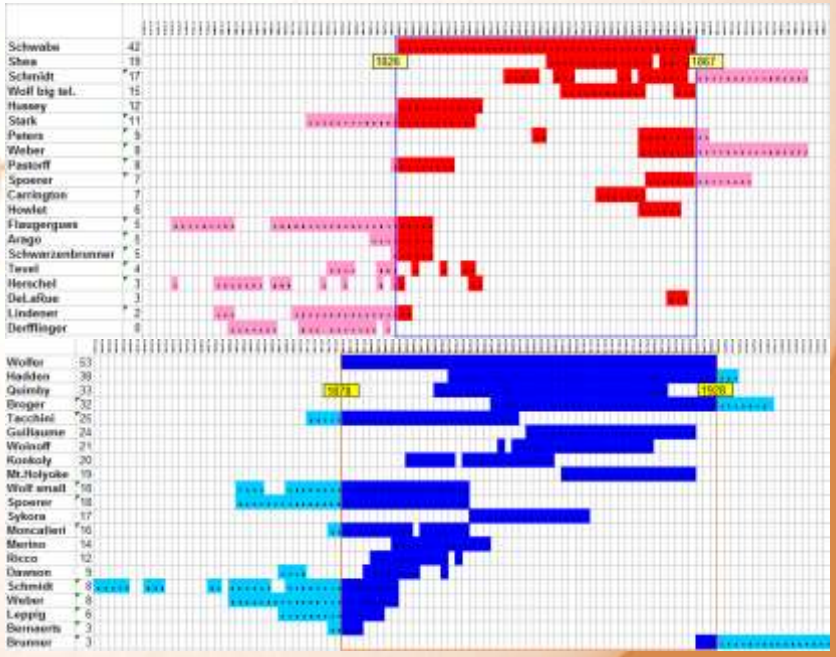
Group Number correction: overview



The “backbone” Group Number (1749-2015)

- Original method **(Hoyt& Schatten 1998)**:
  - daisy chaining of k coefficients between parallel observers, working backwards in time
  - **Non-visual reference after 1875**: photographic catalog from the Royal Greenwich Observatory
  - **Includes a 42% trend (1885-1915)** *(Clette et al. 2014)*
- **New approach for linking the scale of observers over centuries** *(Svalgaard 2012, Clette et al. 2014, Svalgaard & Schatten 2015)*:
  - “Backbone” provided by **5 long-duration observers to which other observers are normalized.**
  - Overlapping backbones are cross-calibrated
  - Only visual sunspot observers are used, including in the 20th century

Backbone observer	Main interval	Full interval	Nb Obsevers
Staudach	1749 - 1787	1740 - 1822	15
Schwabe	1826 - 1867	1794 - 1883	20
Wolfer	1878 - 1928	1841 - 1944	21
Koyama	1947 - 1993	1920 - 1996	36
Locarno	1957-2015	1950 - 2015	22

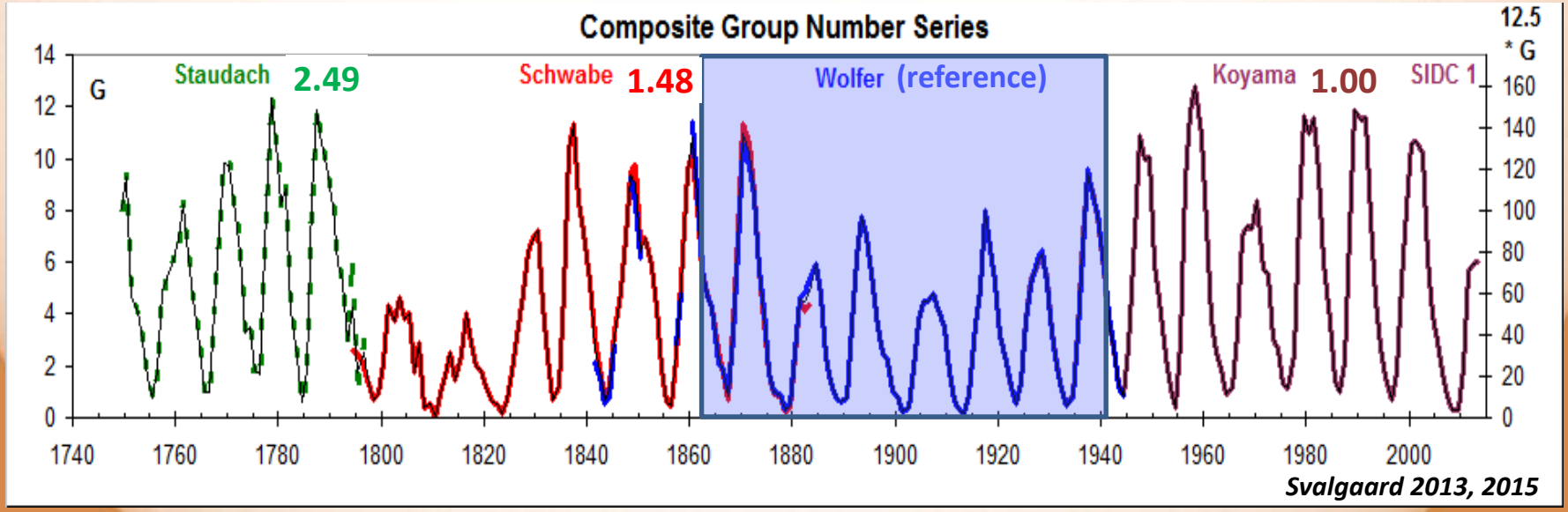


The "backbone" Group Number (1749-2015)

- First Staudach backbone (1749-1787):
  - Insufficient group splitting: unrealistically large groups
  - Full recounting from original drawings *(Svalgaard 2015)*
- GN increased by 1.68 relative to Schwabe

Staudach, Feb. 13 and 15 1760

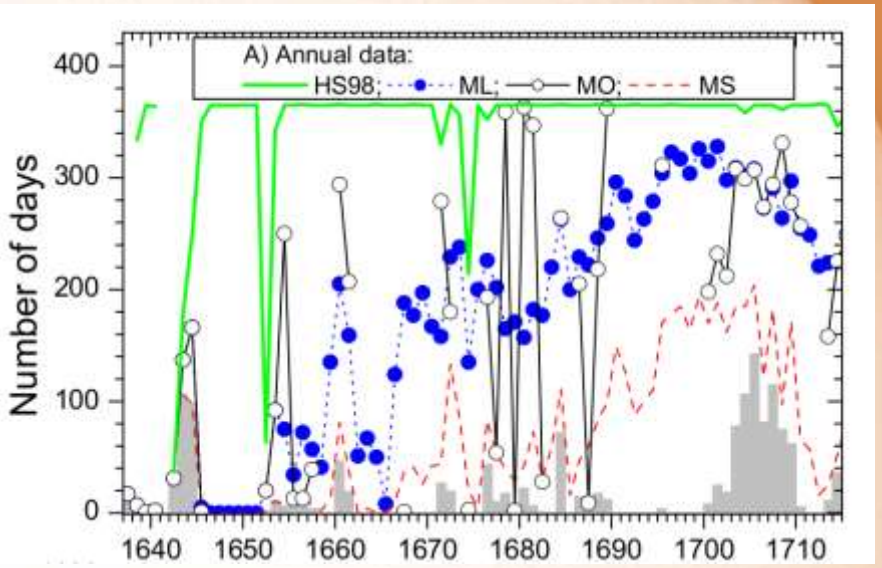
- Final 1749-2015 composite backbone:
  - Base reference: A. Wolfer (standard counts, standard refractor)



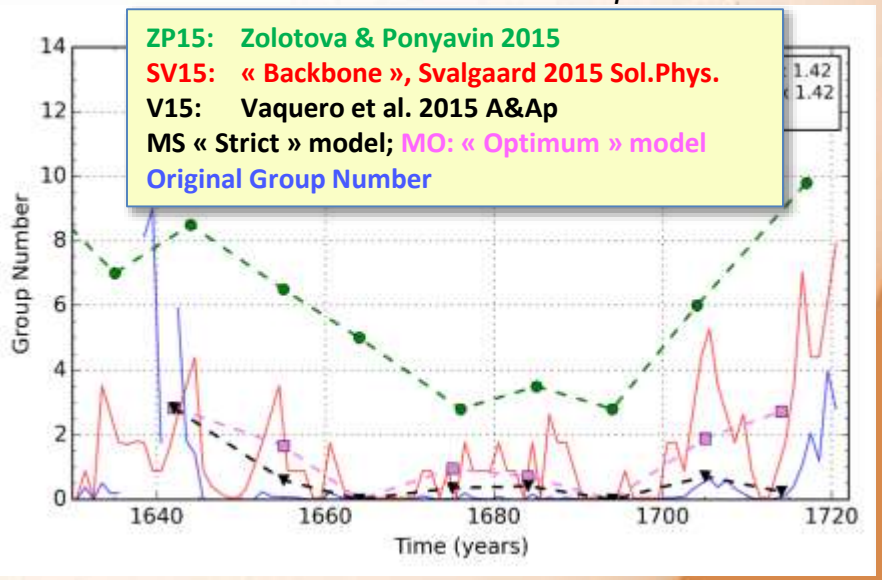
Revisiting the Maunder Minimum

- **Elimination of many interpolated null GNs in meridian transit observations** *(Vaquero & Gallego 2014, Clette et al. 2014, Vaquero et al. 2015 in press):*
- Reduction of the actual coverage from ~100% down to ~60%
- **A new hypothesis** *(Zolotova & Ponyavin 2015)*: spots that did not look like round transiting planets were systematically ignored.
  - Only non-null observations are used
  - **Contradicted by several alternate approaches like the "active days" method** *(Vaquero et al. 2015, Usoskin et al. 2015)*

⇨ **Slight increase in the sunspot numbers during the MM:**
  - **Short 9-year solar cycles**



Vaquero et al. 2015

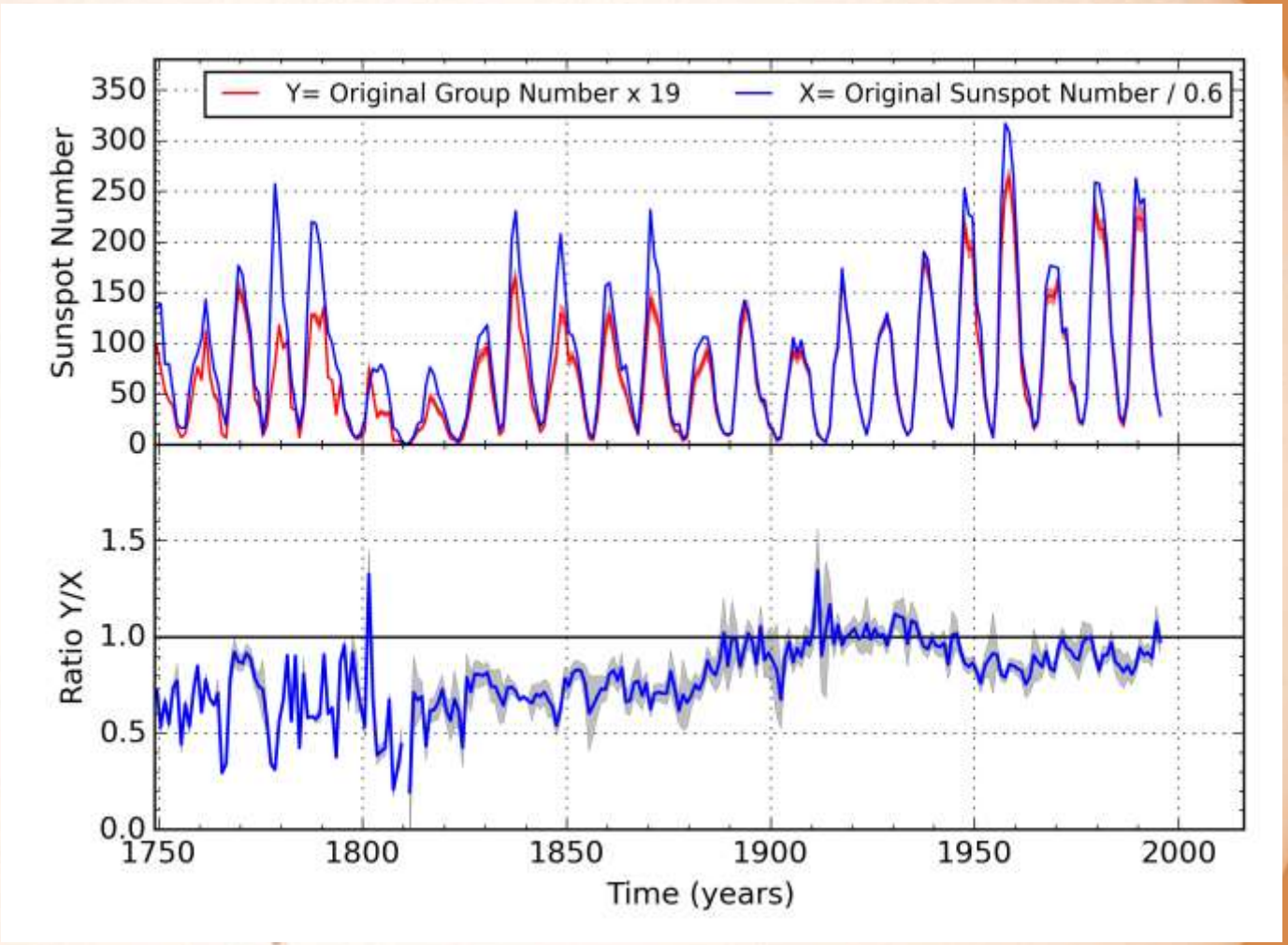


Combining all corrections: matching SN and GN

Original series:

SN / 0.6

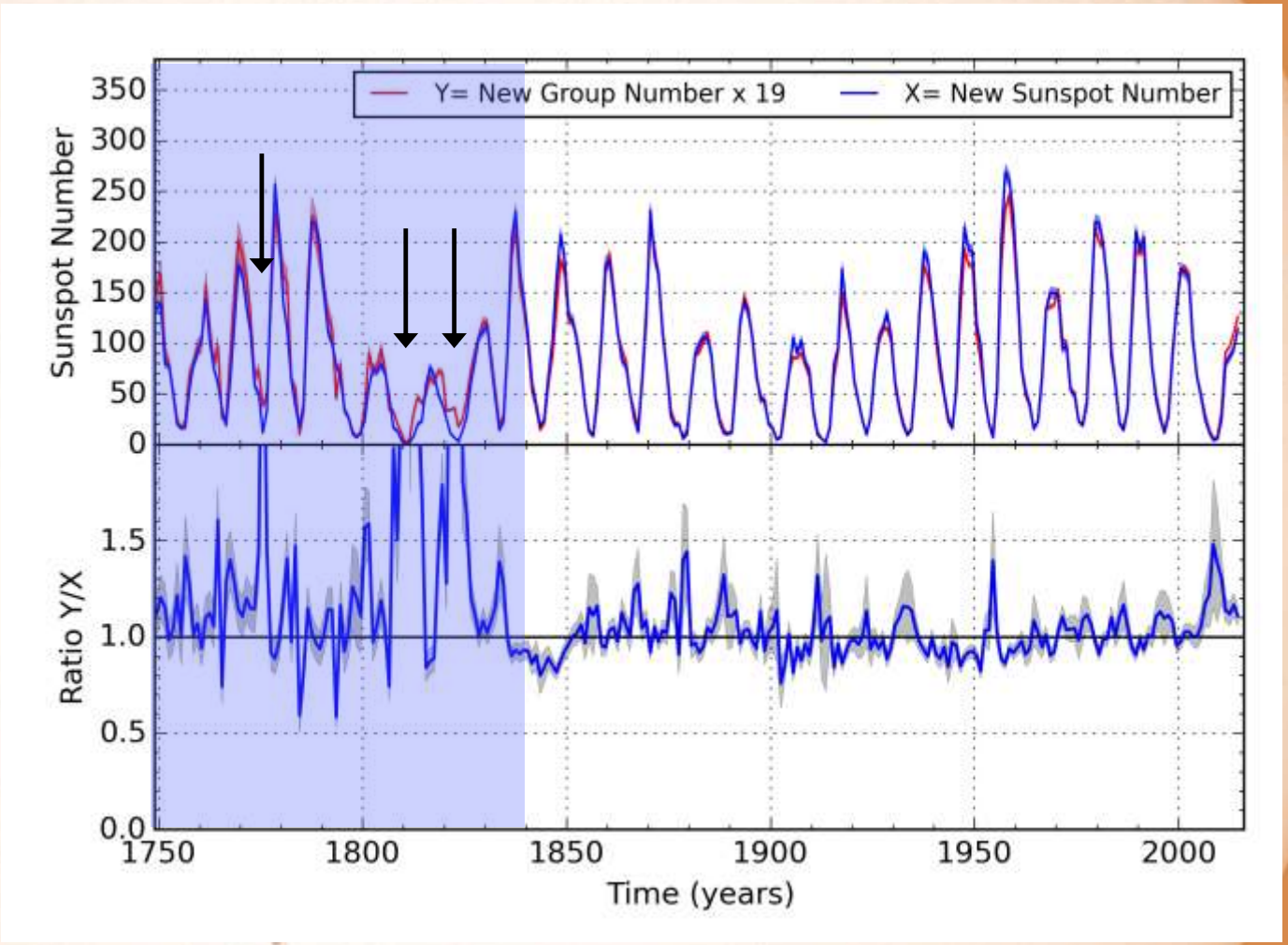
GN x 19.



Combining all corrections: matching SN and GN

Close agreement over the entire interval 1826-2015

Still significant differences before 1826: more work is needed !



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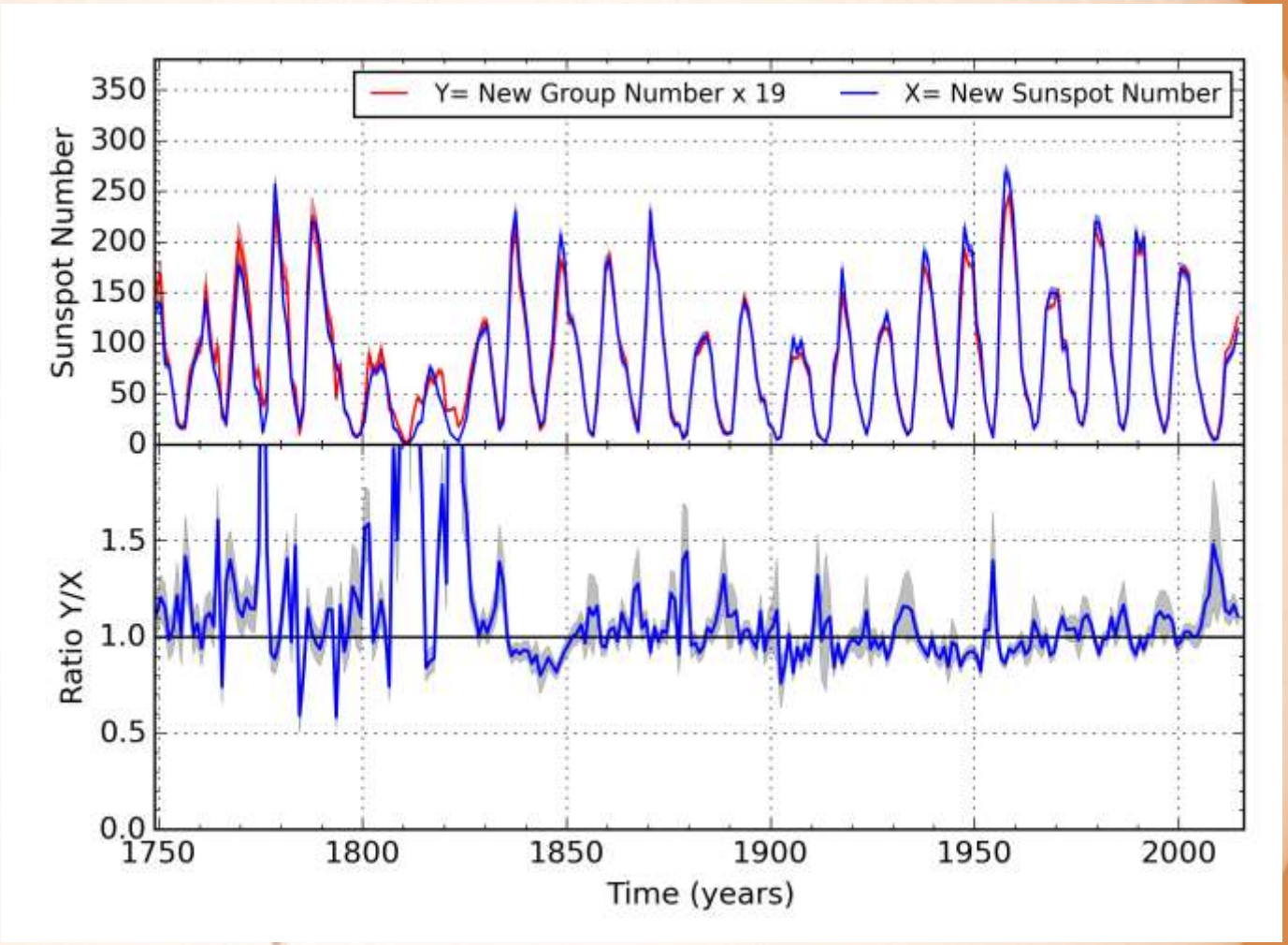
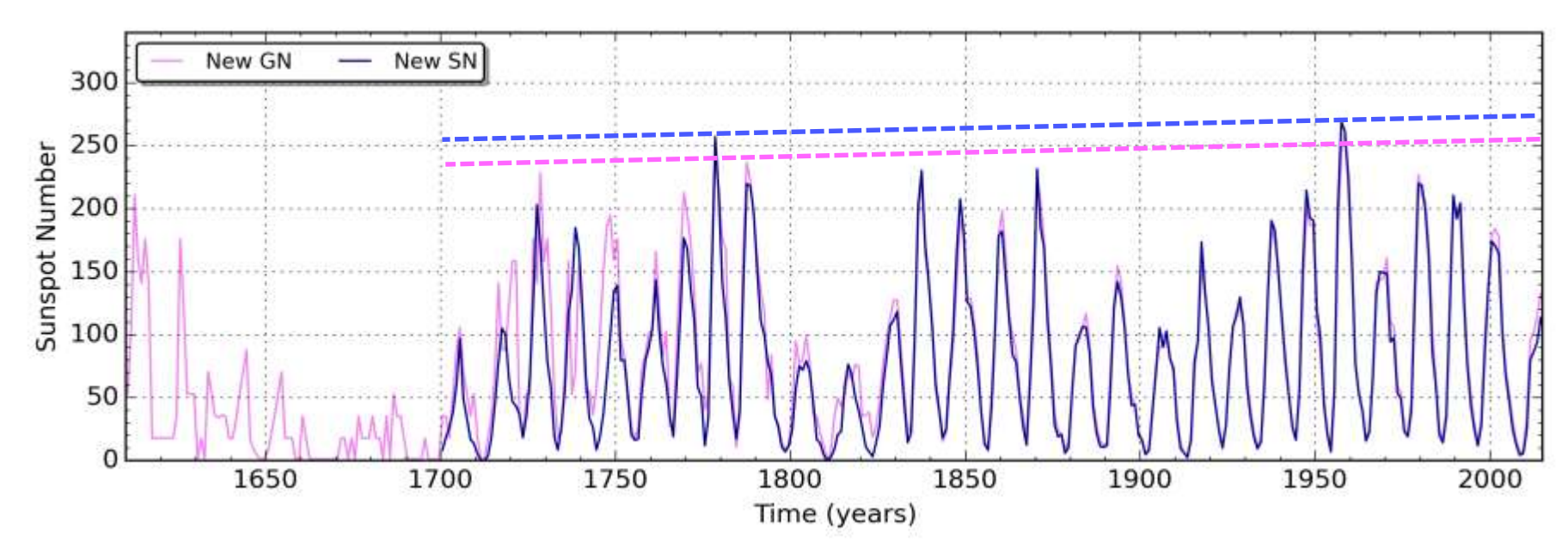


- **The improved agreement gives a strong final confirmation of the validity of the corrections**

Uniform peak cycle amplitudes over last 3 centuries

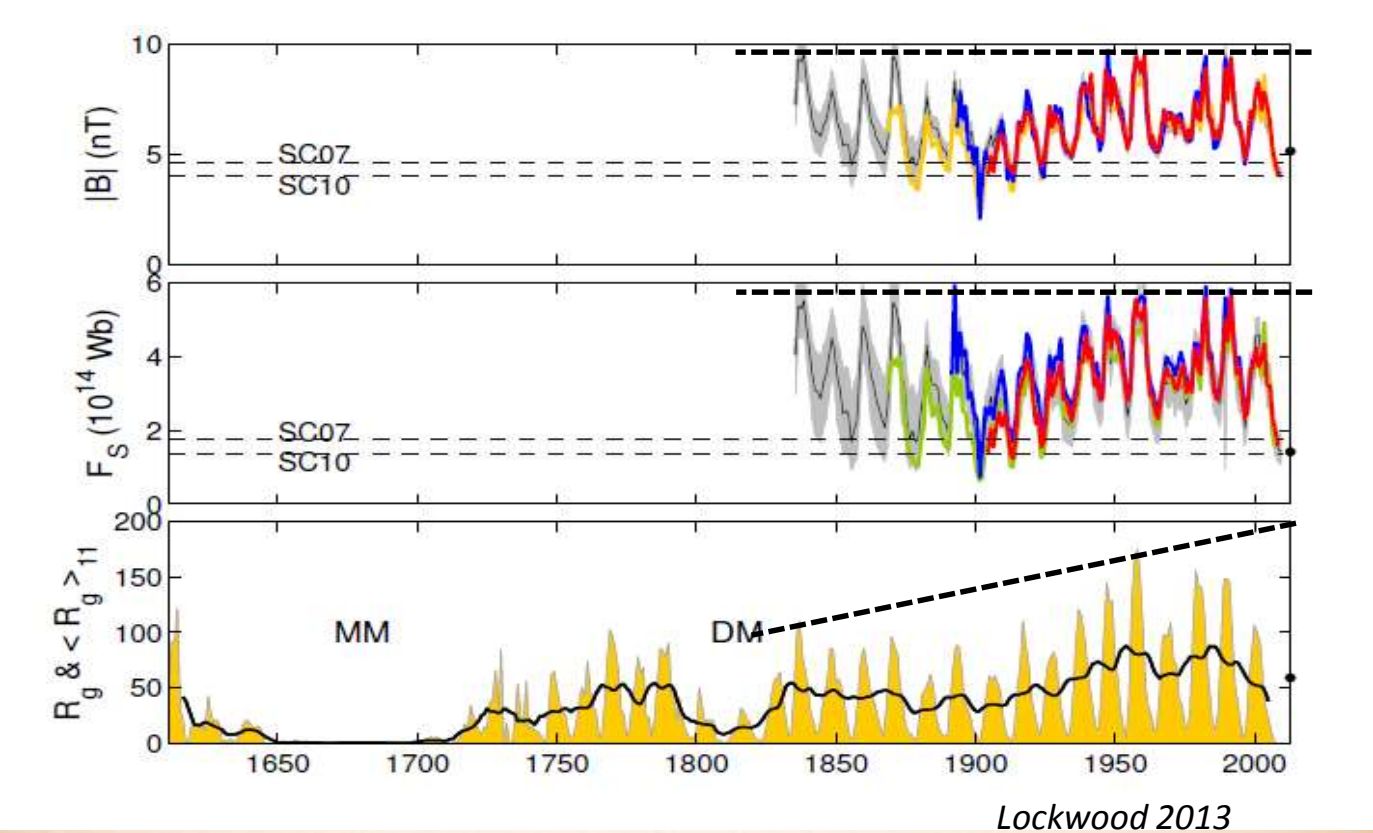
- Original series: strong upward secular trend from the end of the Maunder Minimum to the mid 20th century ("Modern maximum", *Solanki et al. 2004, Usoskin 2013*):
  - GN: + 40% / century *(red)* SN : + 15% / century *(green)*
- New SN and GN= similar **very weak upward trend < 5 %/century** *(blue, purple)*

➡ **Soon after the Maunder Minimum , solar activity returned to high levels equivalent to recent cycles of the 20th century**



Comparison with indirect indices of solar activity

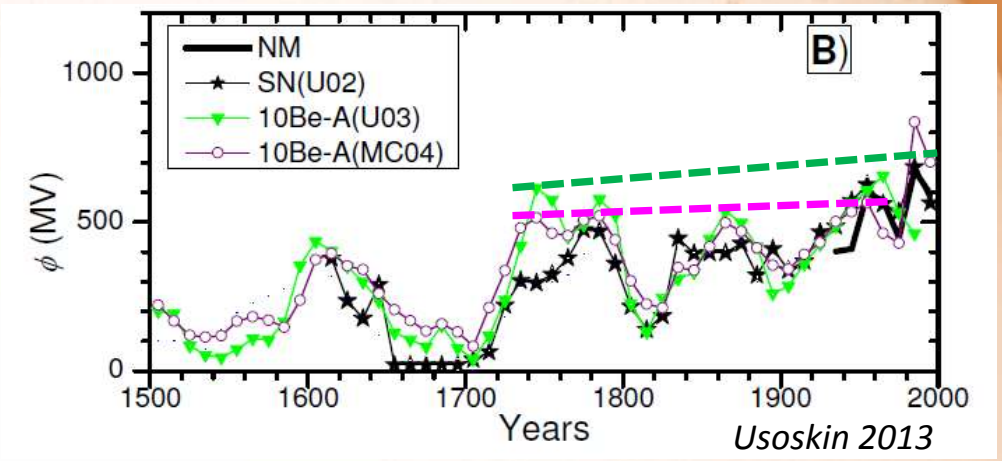
- Geomagnetic indices: reconstructed open magnetic flux over the last 180 years *(Lockwood et al, 2013)*
  - Recent reconstructions show identical cycle amplitudes between the mid-19th century and the 20th century



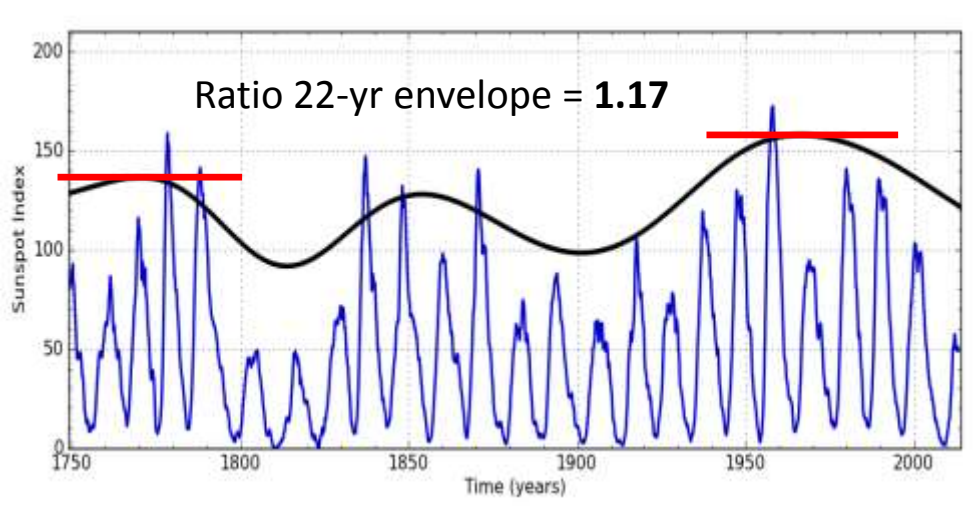
Lockwood 2013

Comparison with indirect indices of solar activity

- **Cosmogenic isotopes** (^{10}Be, ^{14}C):
  - contradictory results between different samples and models (modulation potential ϕ):
    - Upward trend *(Usoskin et al. 2002, Solanki et al. 2004)*
    - No trend *(Muscheler 2007, Usoskin et al. 2015)*
  - Limitations: complex deposition processes, evolution of Earth magnetic field
- **Time integration of ϕ** (20 to 40 years)
  - Low-pass filtering of SN series (22 years):
  - Upward trend but weaker
- The longer sequence of strong cycles in the 20th century gives a higher solar signal without stronger solar cycles



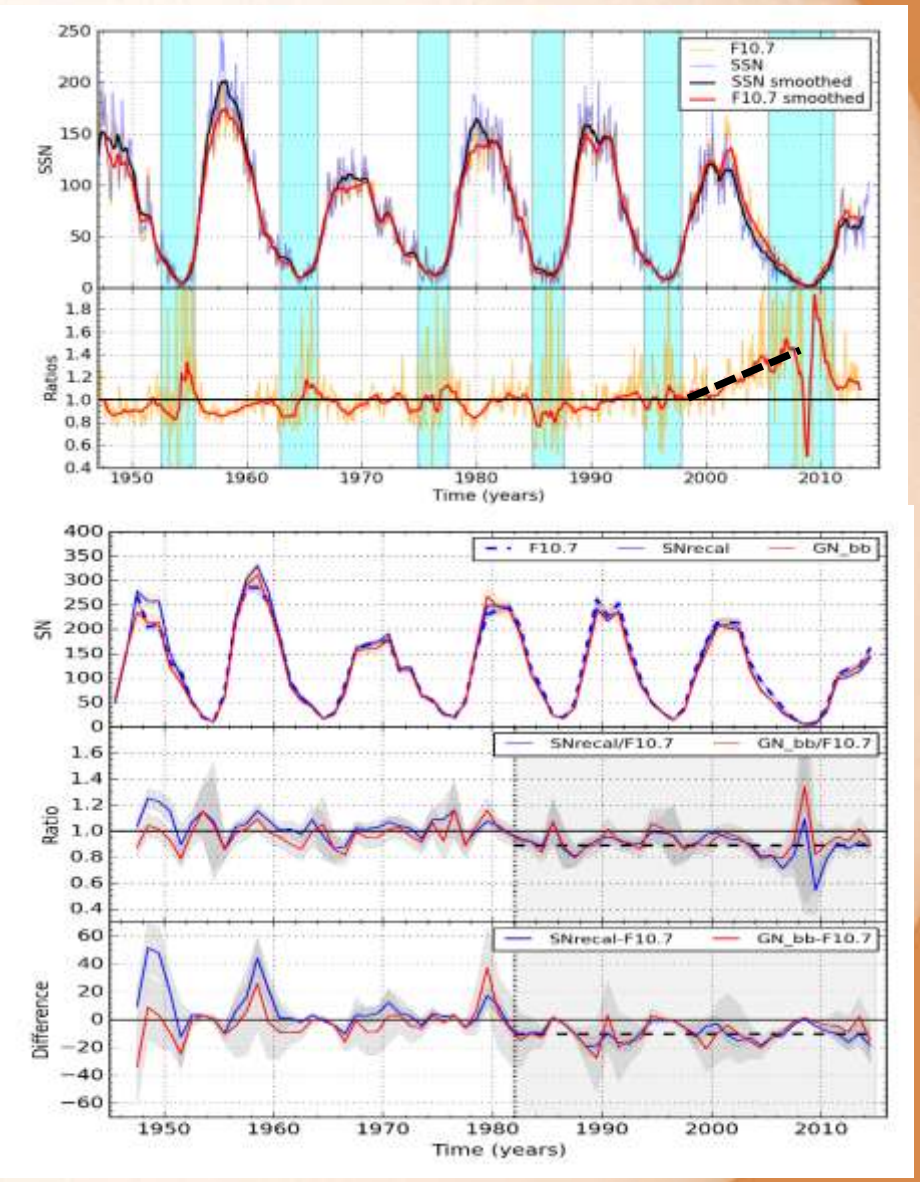
Usoskin 2013



Better agreement with modern solar indices

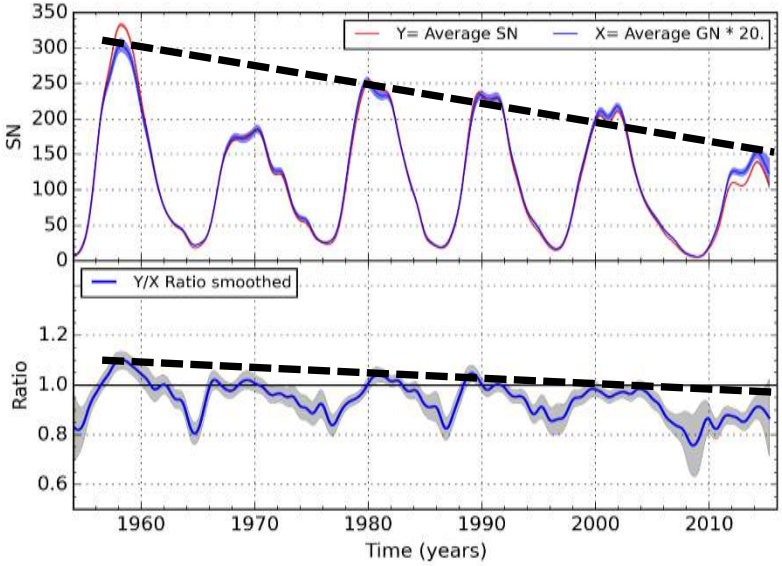
- Original SN too low versus the $F_{10.7}$ radio flux after 2000 *(Svalgaard & Hudson 2010, Lukianova & Mursula 2011, Clette & Lefèvre 2012)*

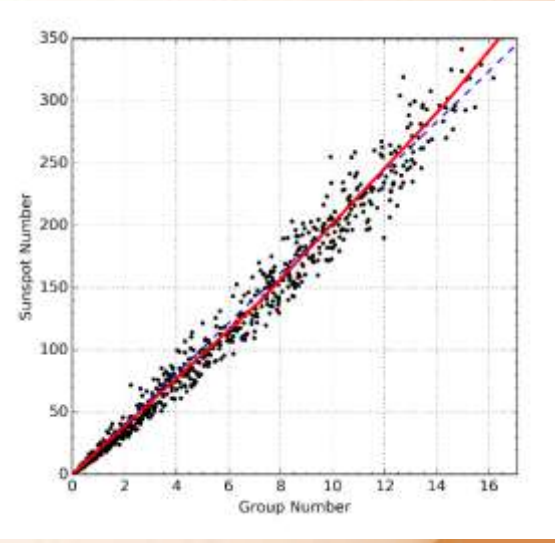
- Using the reconstructed SN and the "backbone" GN over 1945-2015
  - no more anomaly after 2000
  - $F_{10.7}$ is too high by 10% after 1983 !



A sunspot deficit in recent solar cycles?

- Decline in the average number of spots per group over past cycles, enhanced after after the maximum of solar cycle 23: *(Tlatov 2012, Clette, Lefèvre 2012 ,Svalgaard 2013, Clette et al. 2014)*
- **Reconstruction of SN and GN from the same base set of stations** (SILSO network) over 1945-2045 *(Clette et al. 2015)*:
  - Cycle modulation in the ratio
  - Trend in the ratio follows the maxima of successive cycles



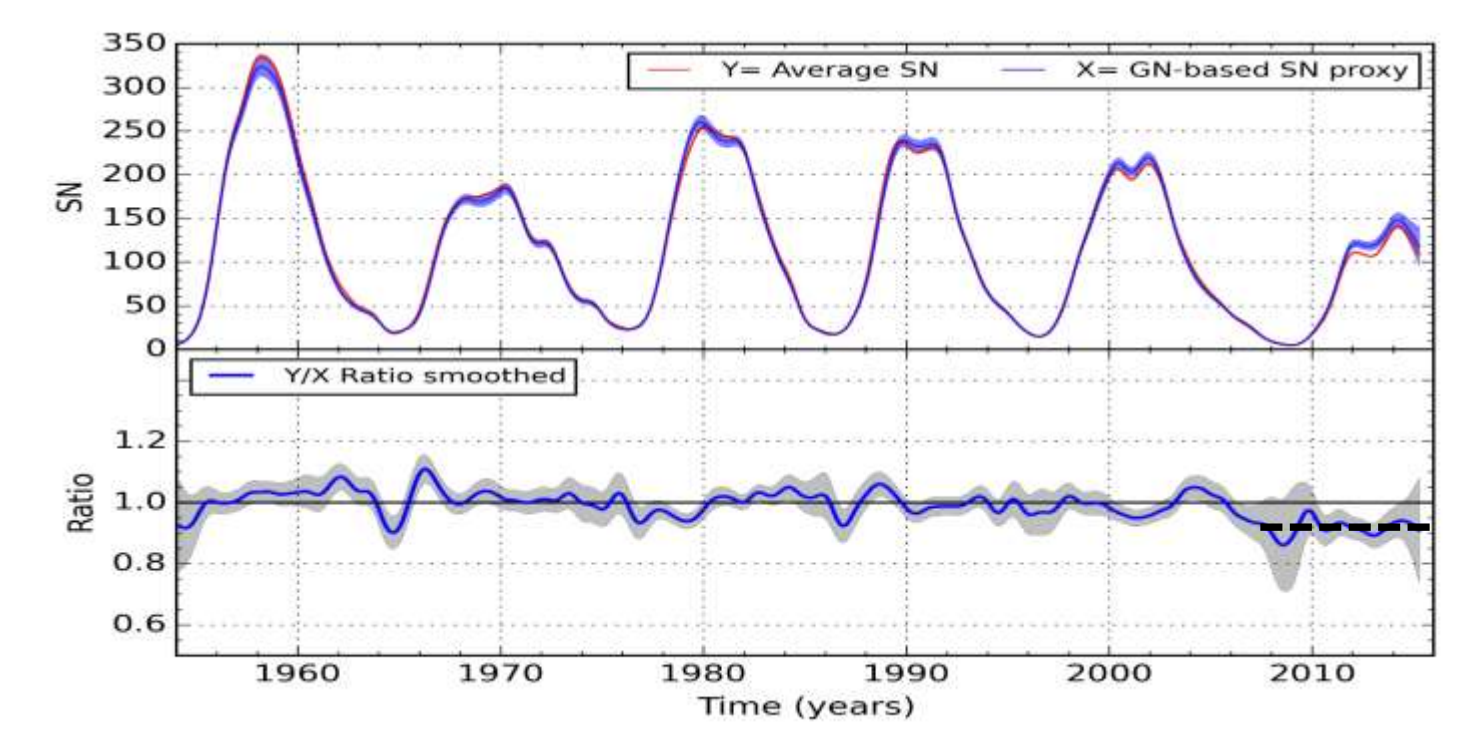


➡ **Constant non-linear relation**

(degree 2 polynomial):

$$S_N = 17.8(\pm 0.4) \times G_N + 0{,}21\ (\pm 0.03) \times G_N^2$$

A sunspot deficit in recent solar cycles?



- GN-based proxy of the SN :
  - No more cycle modulation: constant ratio over 1945 - 2008

⇨ The average number of spots per group obeys a constant relation

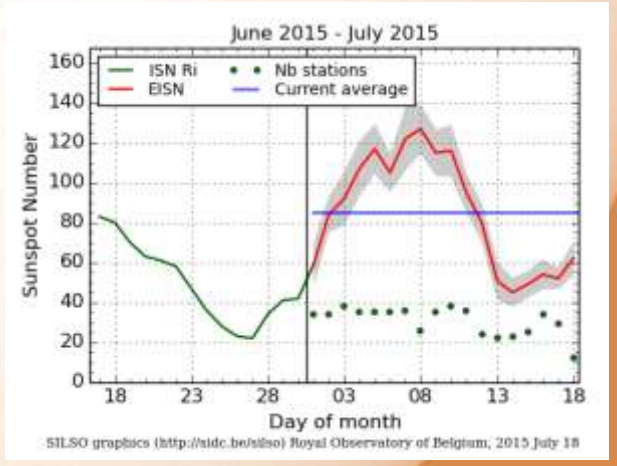
  - The recent spot deficit is a natural consequence of the activity decline

⇨ 10% deficit only starts in cycle 24

Upgraded data distribution and production

- **New SILSO Web site**: portal for all SN products **on-line since early 2014:**
  - Ready for future extensions (versions, info)

- **Operational transition to the new SN:**
  July 1st, 2015
  - Archive: Version 1 files replaced by Version 2.0
  - Adaptation of entire software for all SILSO products: **hemispheric numbers, daily estimated SN (EISN), 12-month predictions**
  - **Unchanged base method for the total SN** but:
    - **Pilot station: Specola, Locarno un-weighted counts** (original Wolf formula)
    - **Factor 0.6 set to 1.0**



New conventions

- **Elimination of the 0.6 Wolf-Wolfer correction factor**:
  - Based on 17 years of parallel observations by Wolf and Wolfer (1876-1893)
  - New modern counts set to Wolf's scale (small 40mm refractor)
    - Does not make sense after 123 years of modern SN
    - Source of confusion: SN was always too low compared to raw counts of current observers
  - **New reference: A. Wolfer (1893-1926)**
- New symbols: **S_N** and **G_N**
  - Coexistence of several denominations: R, R_Z, R_i
  - Clear distinction with the original "heritage" series
- **Elimination of the 0-11 jump rule**
  - emulation of a single-station Wolf number
- **New file formats: standard errors**

R. Wolf in 1855 (1849-1893)

Alfred Wolfer (1876-1925)

New version management

- Objectives:
  - Structured scheme for future additions and improvements to the SN series
  - **Past versions remain available** for re-analyses of past published studies
  - **Complete incremental documentation**
- Implementation:
  - **"Archive" section** in SILSO Web site
  - Filenames with a **2-digit version number: Vn.i**
    - **n**: for each major change to the SN values
    - **i**: for minor changes (e.g. isolated typos) or side modifications (e.g. error estimates, file format).
  - Links to info files + publications
- Supervision:
  - Data curation: **World data System (ICSU)**
  - Scientific: creation of an advisory committee **(IAU, Division E)**
    - Solar physicists and data processing specialists

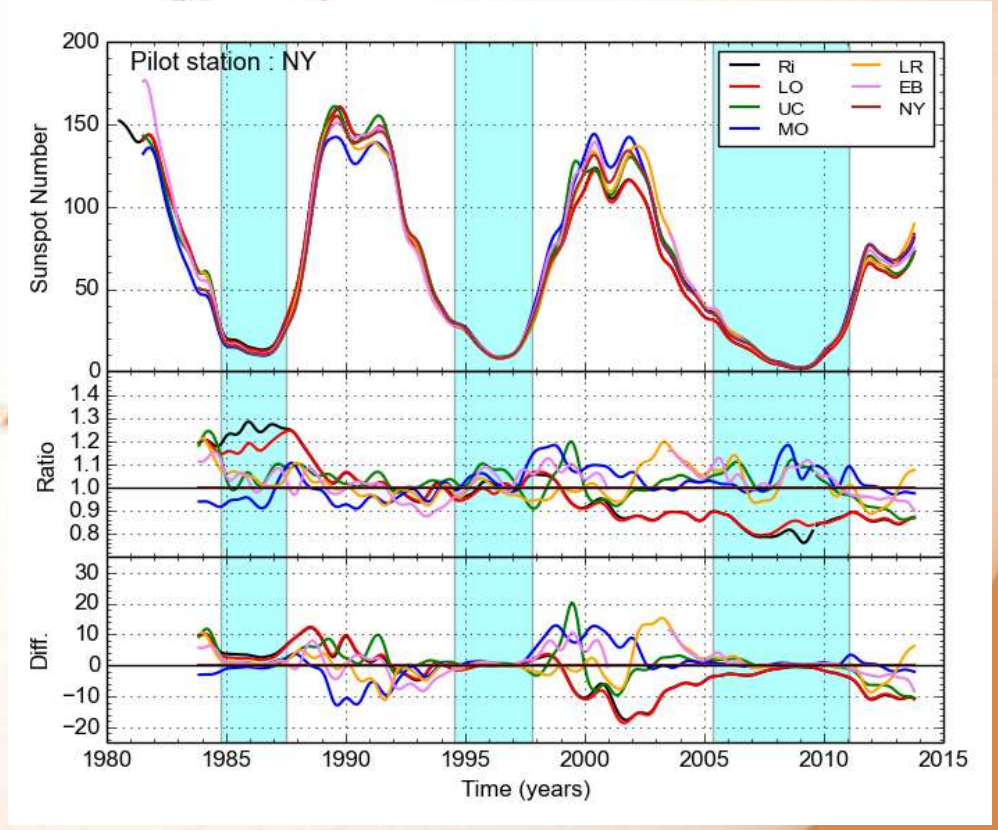
The future

- Development of a **new operational method**
  - Implementation of a multi-station reference

➡ **Full re-calculation of the SN since 1981**

➡ Routine production of the **Group Number**

- Application of more advanced statistical methods:
  - sparse data with gaps and null values (ARMA)
  - station assessment and classification (Bayesian PCA, total linear regression)

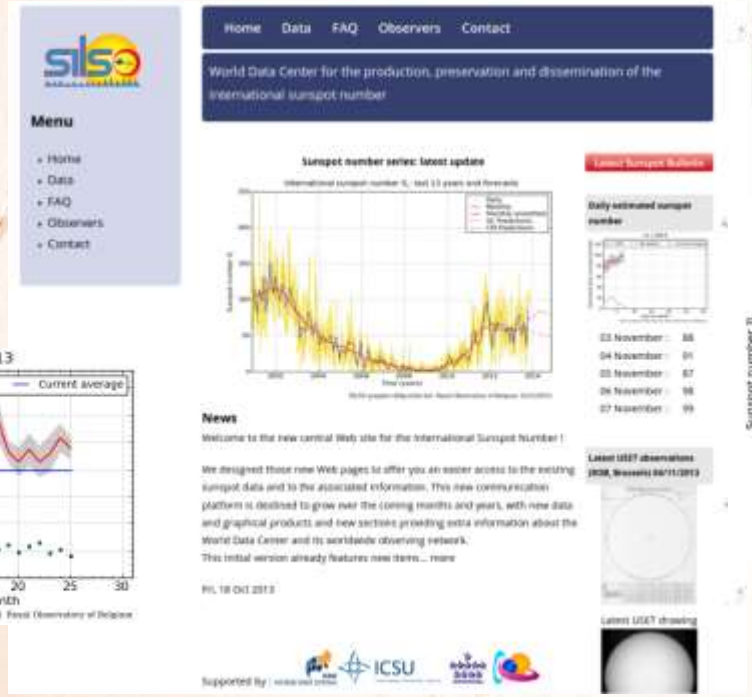


Conclusions

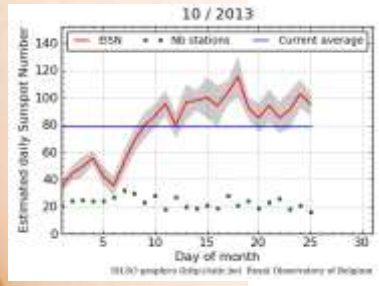
- Major corrections to the SN and GN series
  - The new SN and GN now largely agree
- **From a static heritage to a living data series**: long overdue!
  - "Cultural" shock for the scientific community
- Multiple implications:
  - Same levels of solar activity from Maunder Minimum to 21st century
  - Variable average number of spots per group: decline in cycle 24
  - ⇨ **Opening new research paths**
- Renewed interest for the long-term sunspot record:
  - **Recent wave of new publications**
  - **Topical issue of Solar Physics** (> 40 papers)
- **Base for a new Sunspot Number production:**
  - open to future additions and improvements
  - new digital archive for historical sunspot observations HASO
    (J. Vaquero, Univ. Extremadura, Merida)

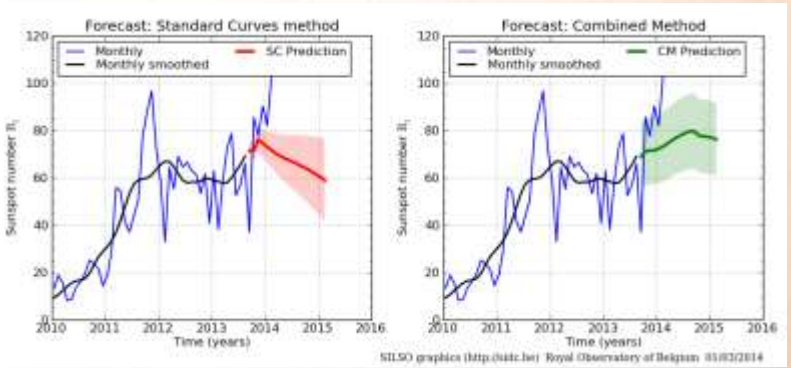
For the latest information, please visit …

WDC – SILSO Sunspot Index and Long-term Solar Observations



http://sidc.be/silso





Sunspot Workshops http://ssnworkshop.wikia.com/wiki/Home

Historical Archive of Sunspot Observations http://haso.unex.es/