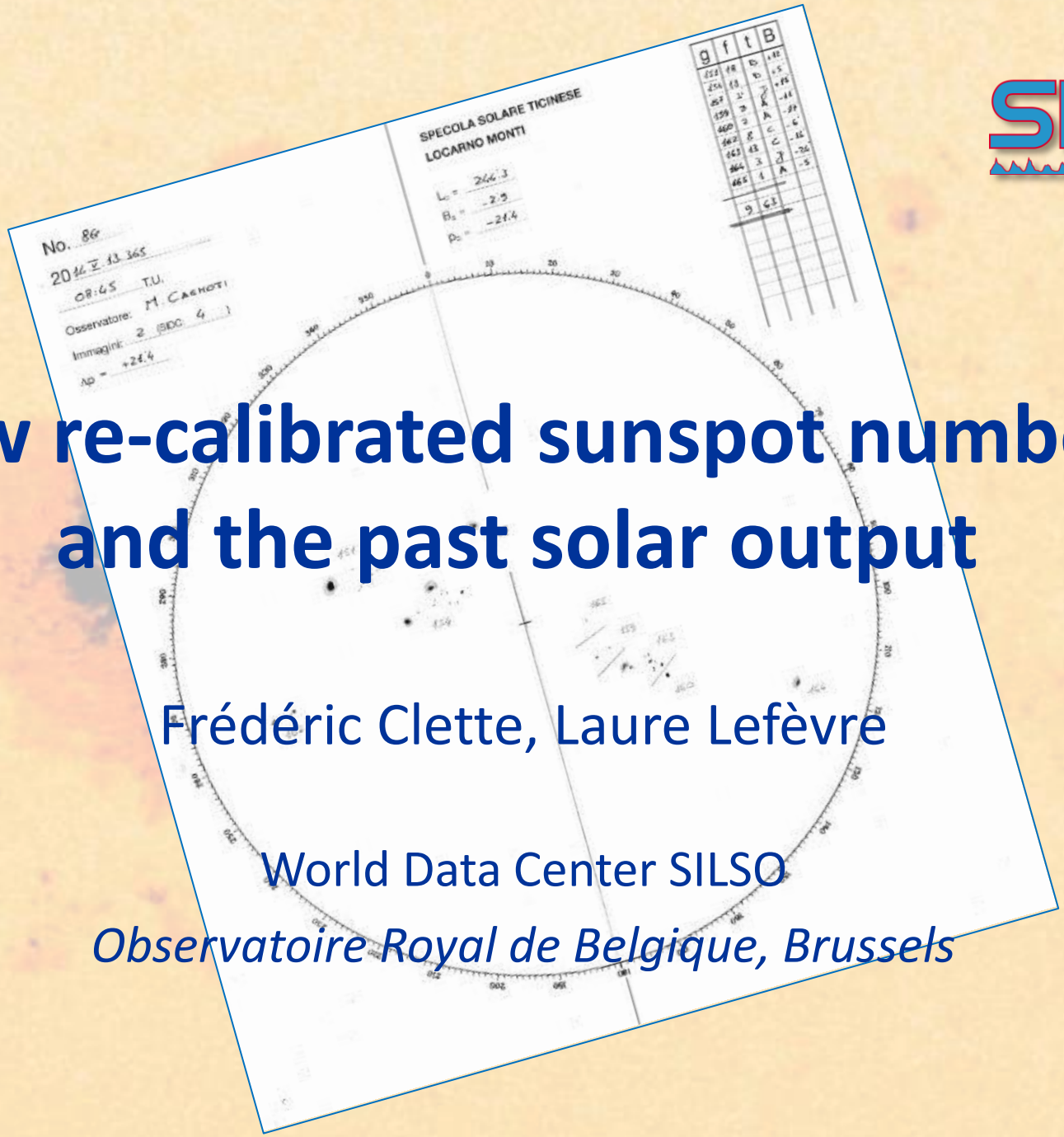


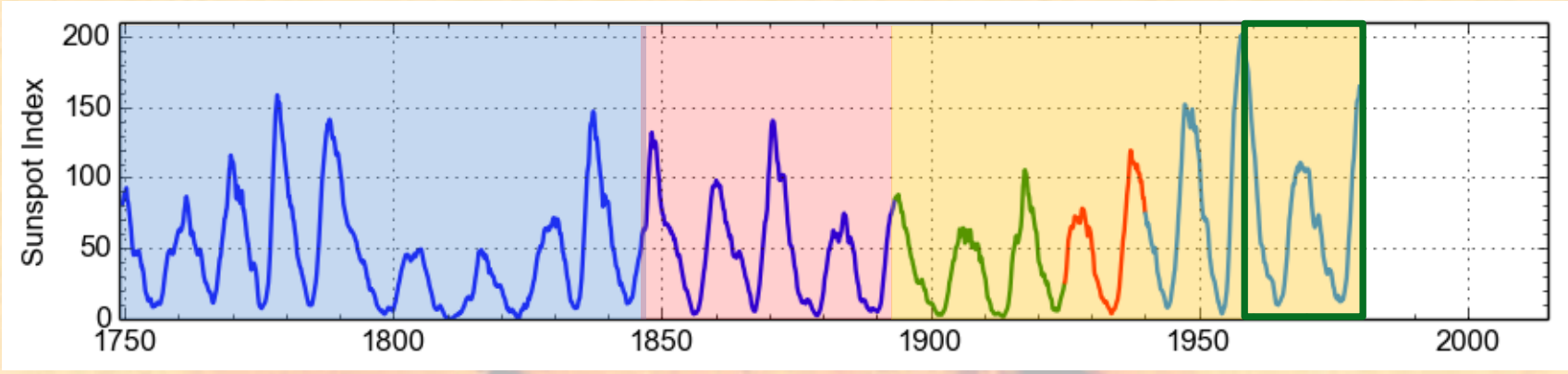
New re-calibrated sunspot numbers and the past solar output

Frédéric Clette, Laure Lefèvre

World Data Center SILSO

Observatoire Royal de Belgique, Brussels

Sunspot Number: a composite series



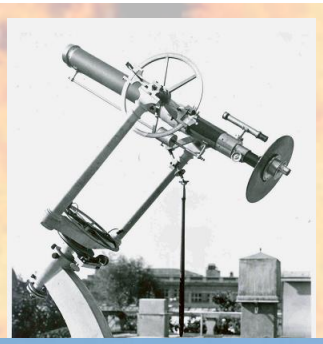
Historical reconstruction (1749-1849):

- Scale adjusted to Wolf's observations

Primary Wolf observations (1849-1893):

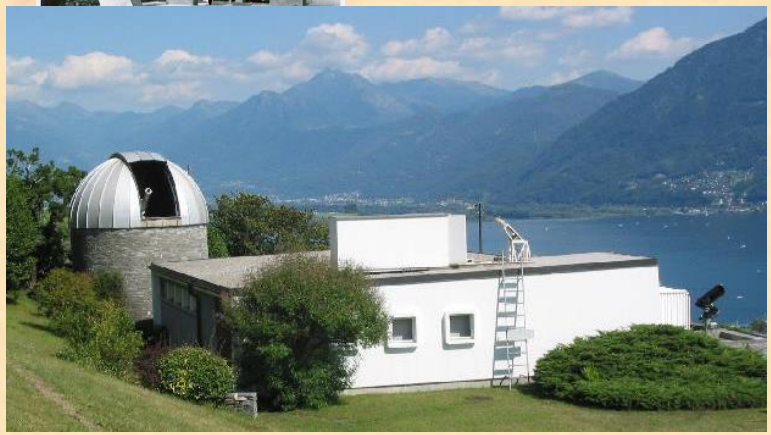
- Standard 83mm refractor
- Small 40mm travel telescopes

$$R = k(10.N_G + N_S)$$



Zürich period (1894-1980):

- 3 reference observers: Wolfer, Brunner, Waldmeier
- New counting method: **0.6 factor**
- 1957: Zürich + Specola (Locarno) stations



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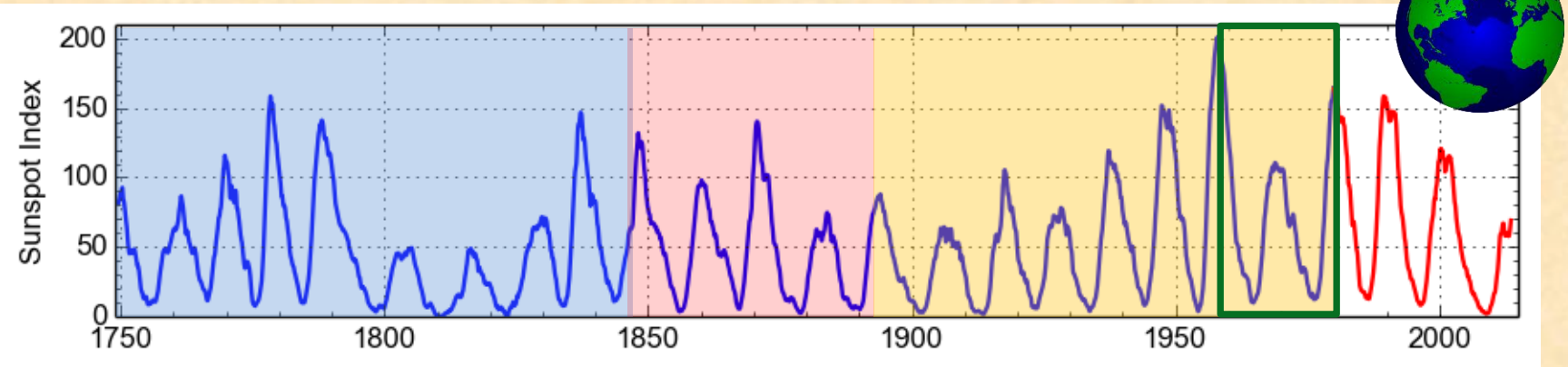

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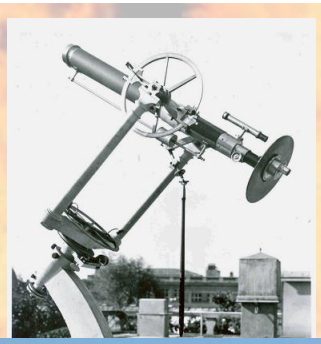

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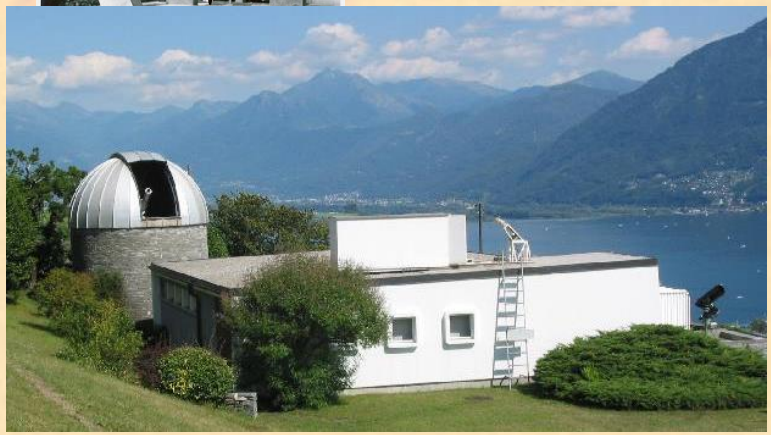


Brussels period (1981-now):

- New pilot station: Specola (Locarno)
- Statistics over worldwide network

Sunspot Number versus modern measurements

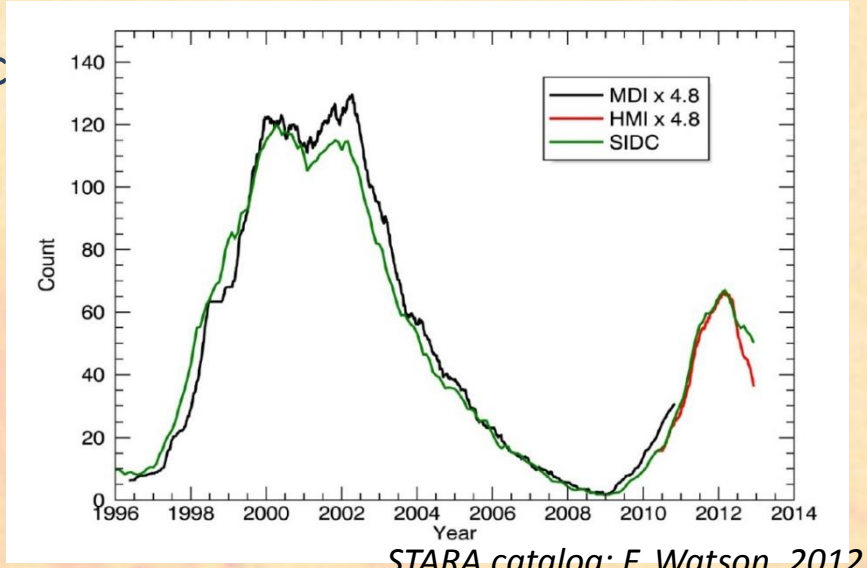
- High correlation with photospheric parameters:
  - automated counts (MDI,HMI), sunspot area, **emerging magnetic flux Mx**

⇨ Quantitative measure

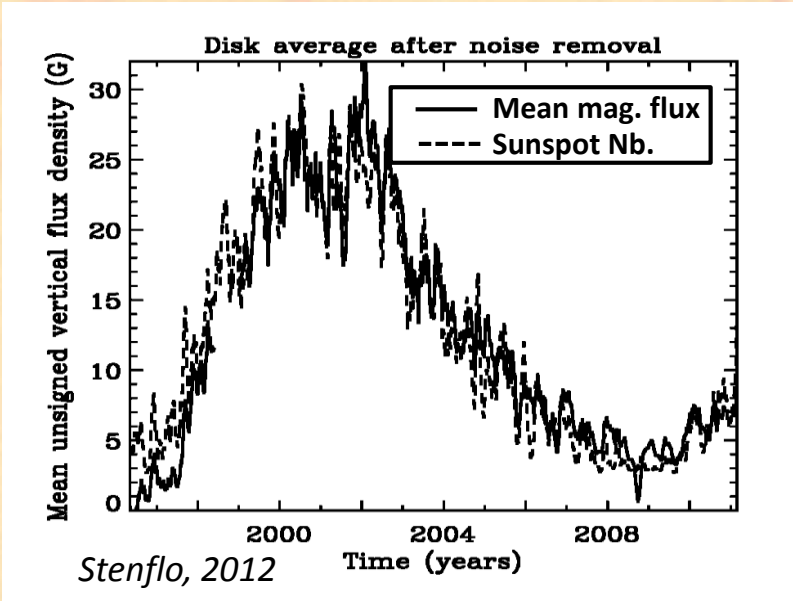
- Lower correlation with chromospheric and coronal indices ($F_{10.7cm}$, CaII K, MgII, TSI)
  - Additional component: magnetic decay (plages, network)

⇨ Non-linearity, time lags

Are those relations stable over long durations ?



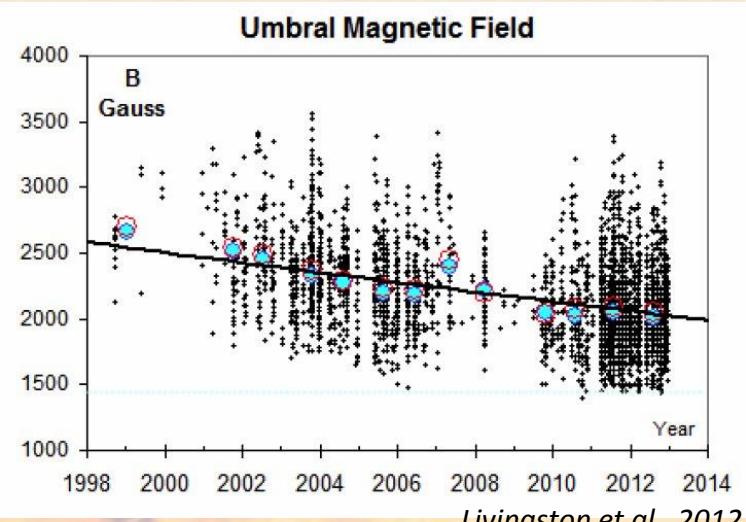
STARA catalog; F. Watson, 2012



Stenflo, 2012

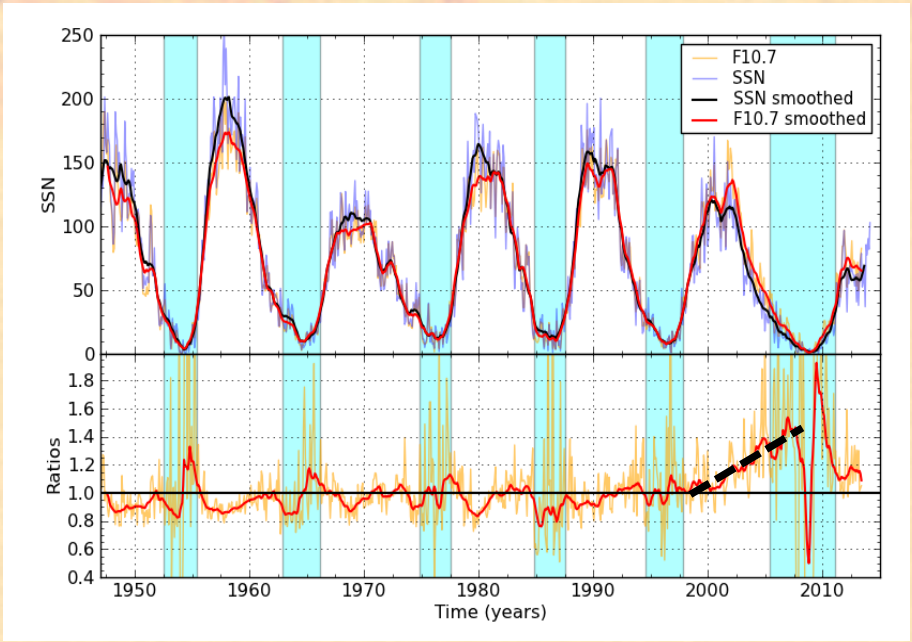
Cycle 24: Unexpected mismatches

- Unexpected late and weak cycle *(Pesnell 2008, 2012)*
- Decline of mean umbral magnetic field *(Livingston & Penn 2009, 2012)*
- Selective deficit of small sunspots: factor 2 (*Lefèvre & Clette 2011 2012, Kilcik et al. 2011, Nagovitsyn 2012)*



Livingston et al. 2012

- Failure of several proxy relations:
  - Drop of SN versus $F_{10.7cm}$ after 2000 : up to -20% *(Svalgaard & Hudson 2010, Lukianova & Mursula 2011, Clette & Lefèvre 2012)*

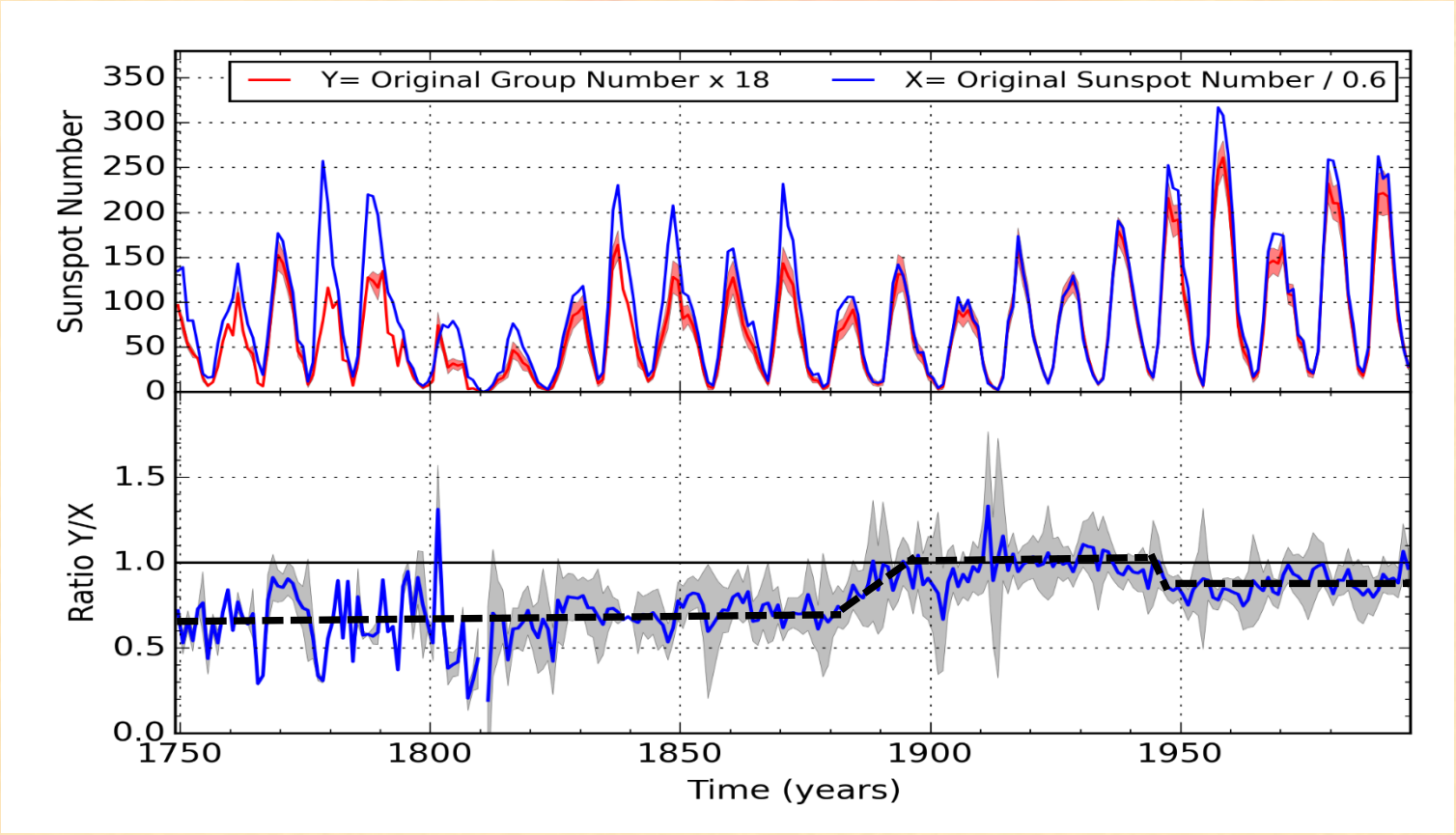


Two incompatible sunspot records

- Only alternate series:
  Group Number (Hoyt & Schatten 1998)
  - Larger data set, back to 1610
  - Only groups: more immune to cruder early observations

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

⇨ **Large persistent discrepancies between the series (up to 40%)**

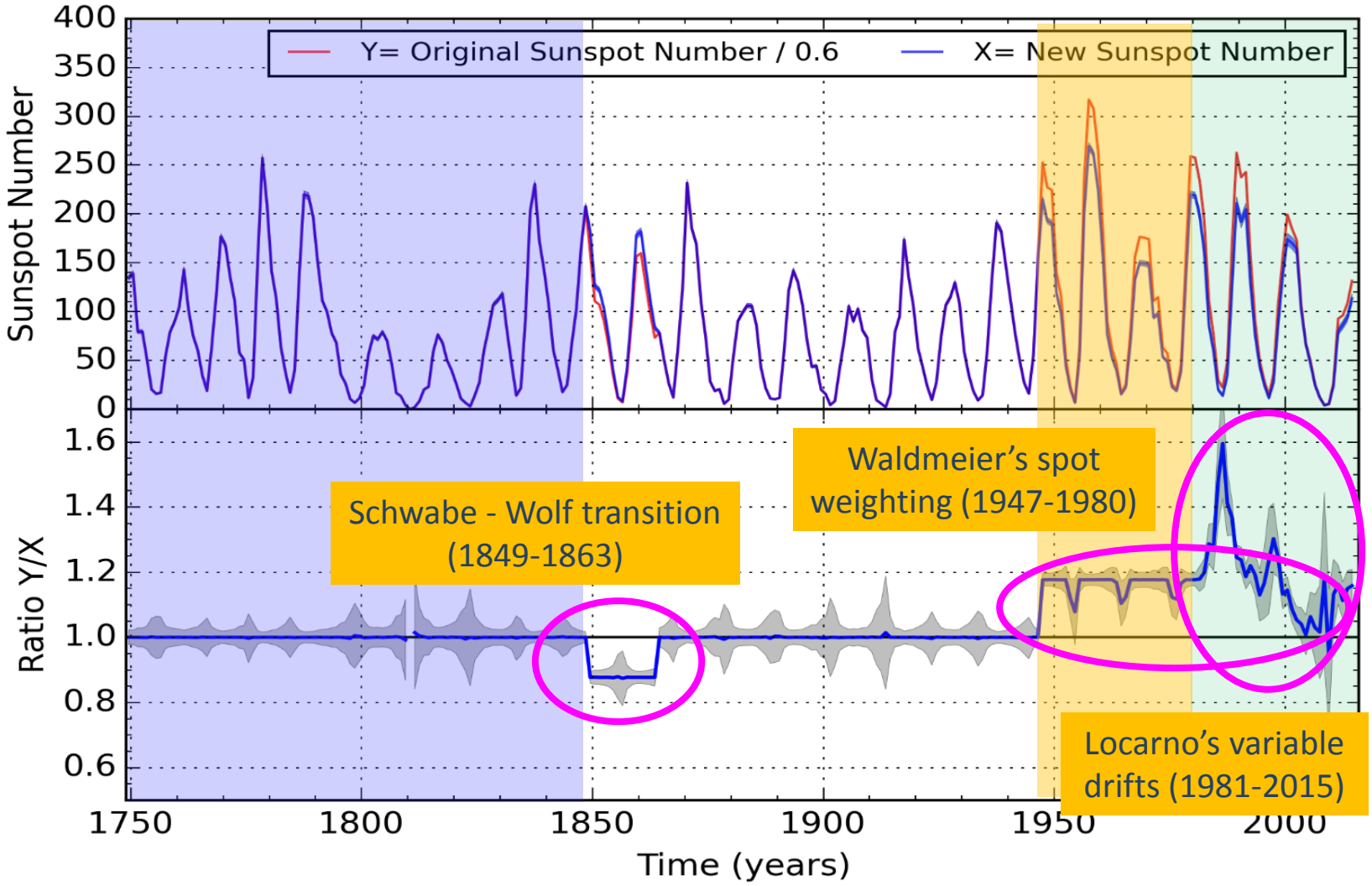


A necessary revision: Sunspot Number Workshops

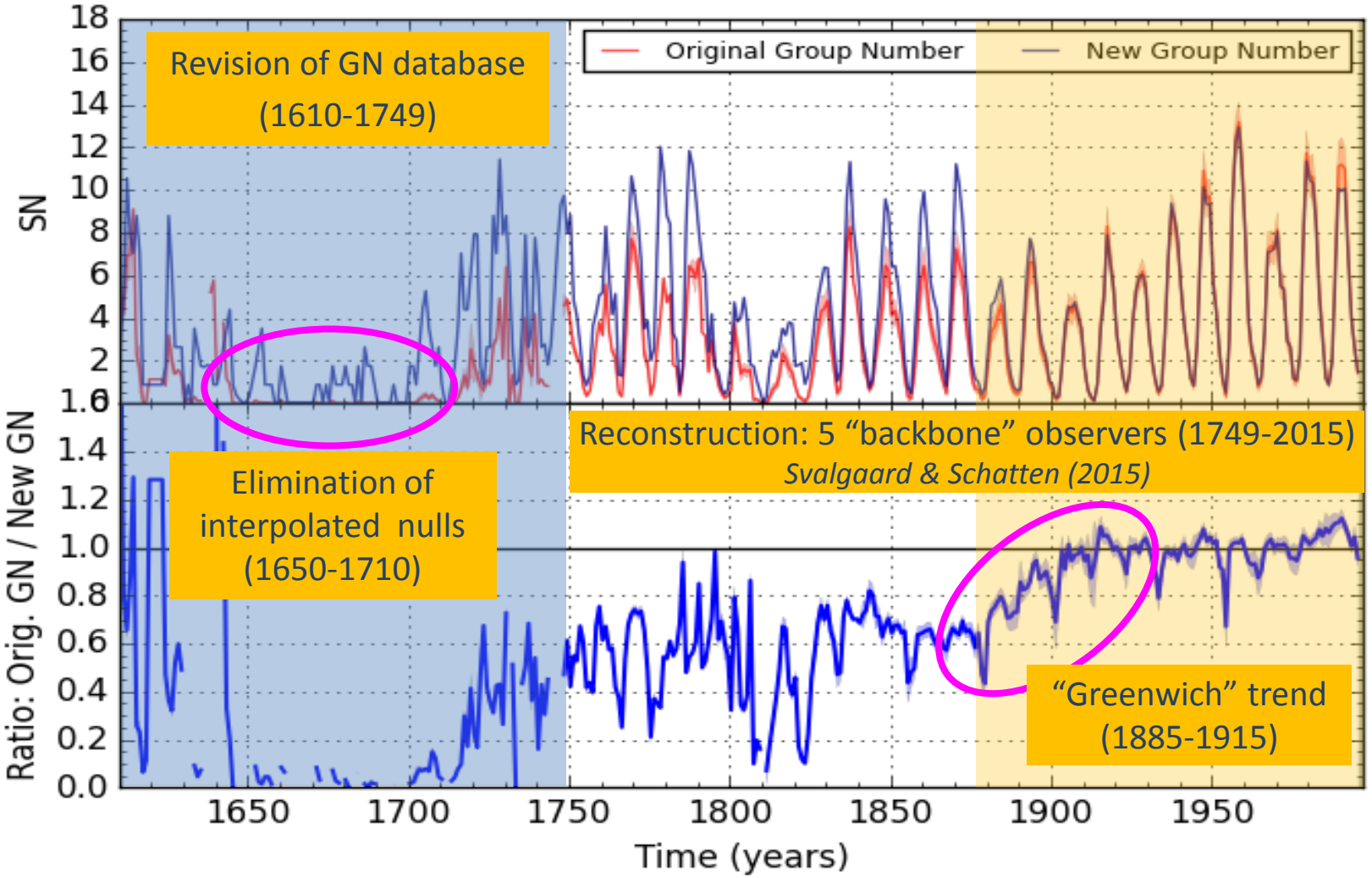
- 4 workshops (2011-2014): Sac. Peak, Brussels, Tucson, Locarno
- Multiple diagnosed problems in the SN and GN:
  - Clette, F., Svalgaard, L., Vaquero, J.M., Cliver, E.W.: 2014, *Revisiting the Sunspot Number. A 400-Year Perspective on the Solar Cycle*. **Space Sci. Rev. 186, 35-103**
  - **Solar Physics topical issue (early 2016):**

Clette & Lefèvre (New Sunspot Number) , Svalgaard & Schatten (New Group Number)

Sunspot Number corrections: overview



Group Number correction: overview

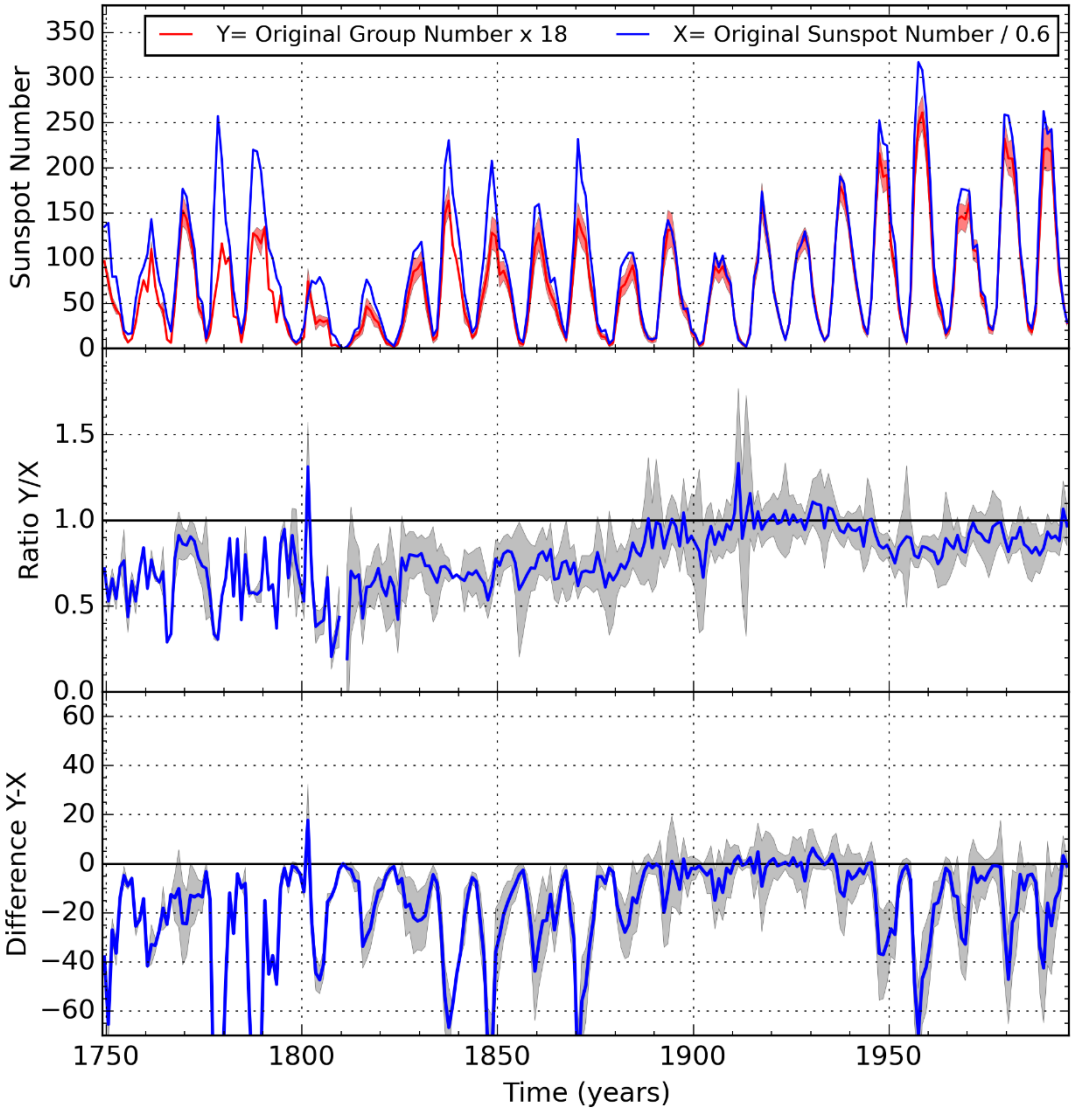


Combining all corrections: matching SN and GN

Original series:

SN / 0.6

GN x 18.



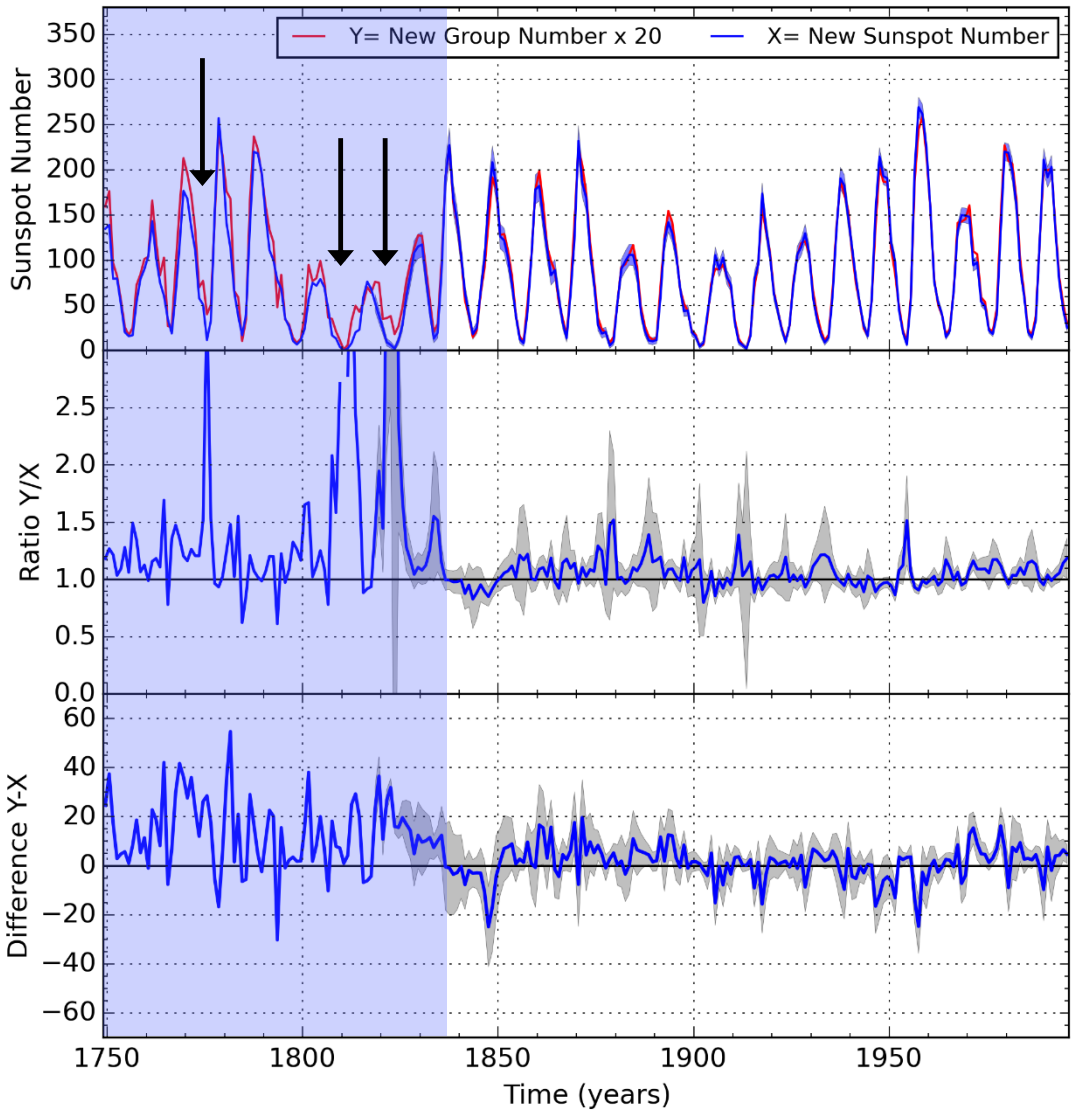
Combining all corrections: matching SN and GN

Close agreement over the entire interval 1826-2015

Still significant differences before 1826:

(10% – 20%):

➡ Target for next upgrade !

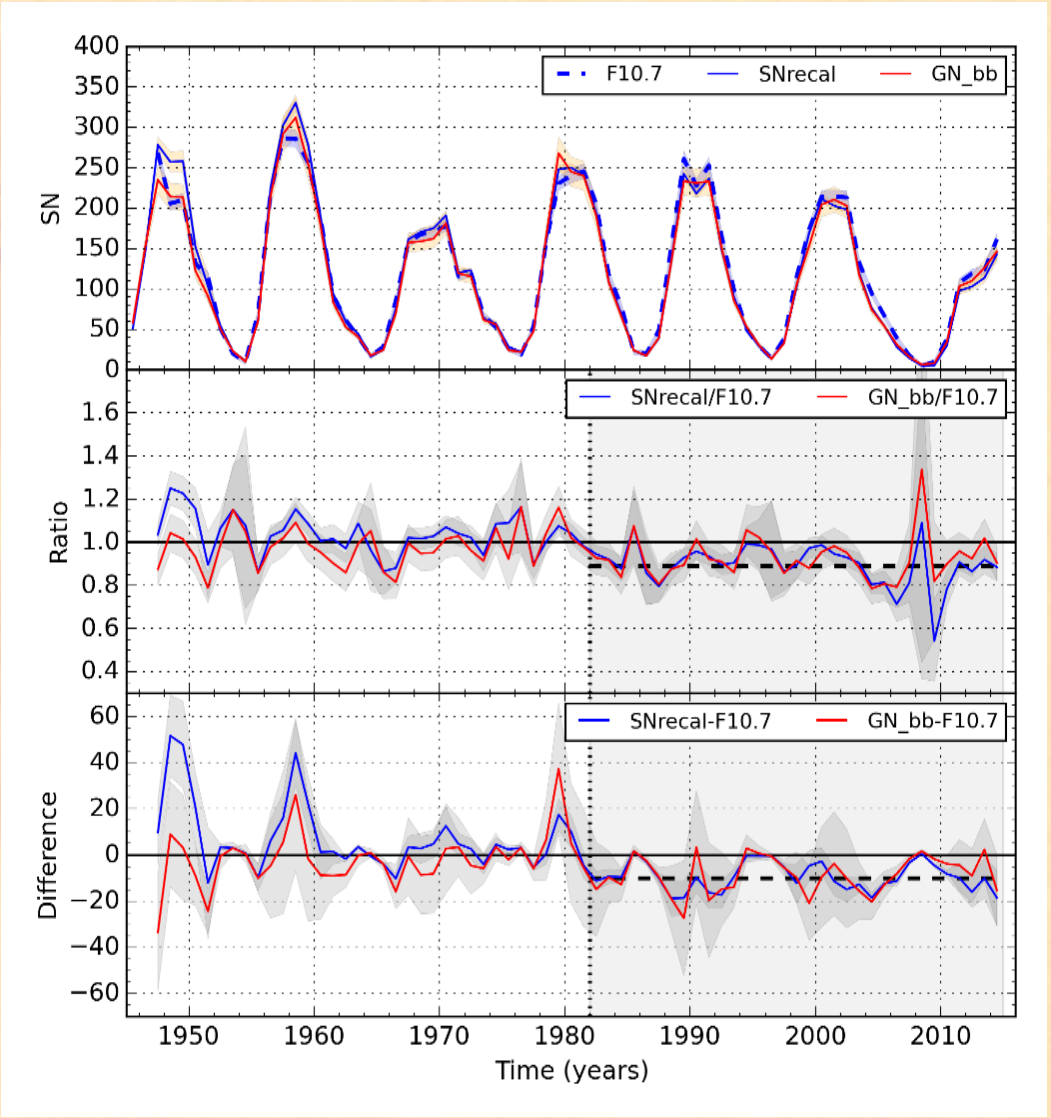


Better agreement with modern solar indices

- New comparison of $F_{10.7}$ with the corrected SN and "backbone" GN (1945-2015)

⇨ No anomaly after 2000

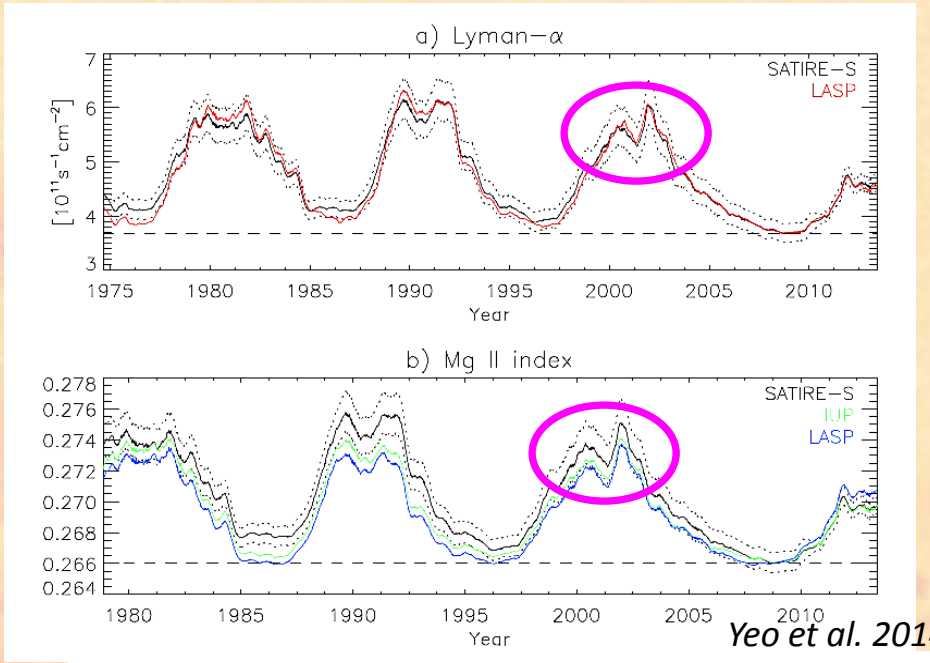
⇨ $F_{10.7}$ is too high by 10% after 1983



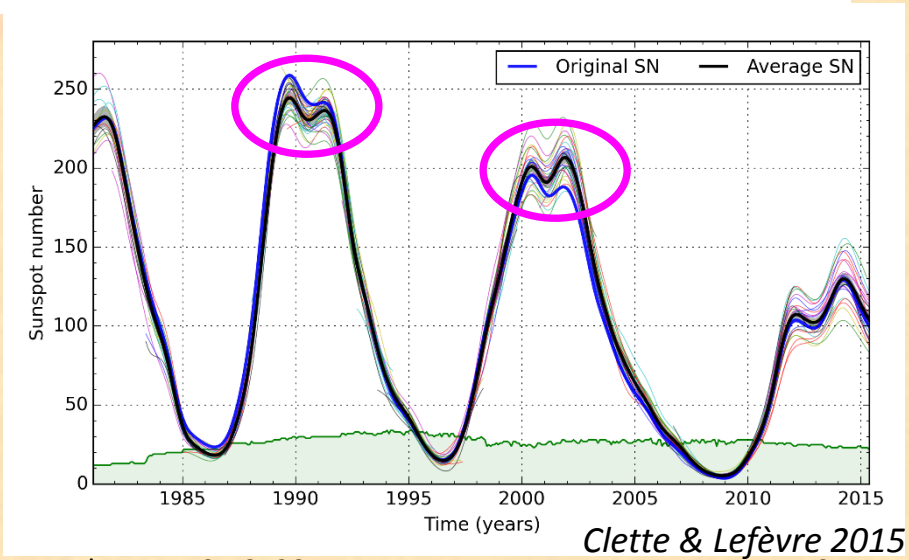
Better agreement with modern solar indices

- Amplitude and shape of recent solar cycle maxima:
  - Mismatch between original SN and solar irradiances (TSI, MgII, Lyα, total sunspot magnetic flux)
- Second peak in cycle 23 (November 2001) now higher than first peak (July 2000)

➡ **Main unexplained discrepancies are eliminated.**



Yeo et al. 2014

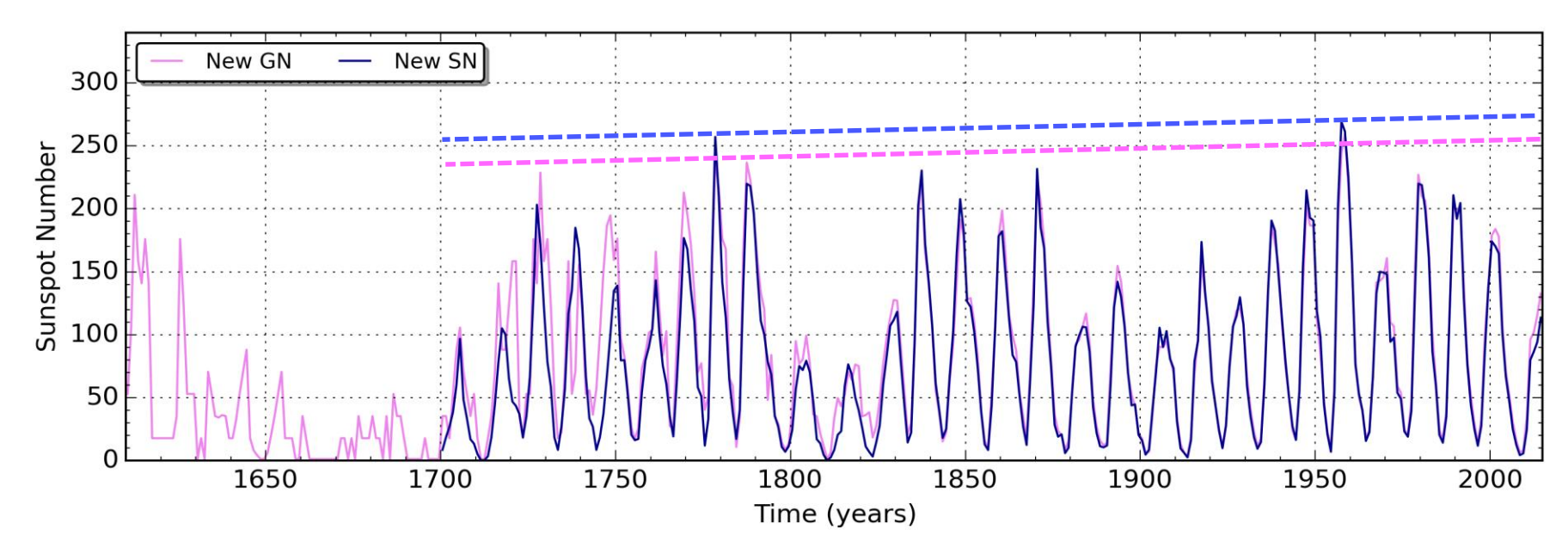


Clette & Lefèvre 2015

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**



Conclusions: lessons learned

- Most diagnosed problems in SN and GN due to:
  - Improper processing methods
  - Method changes deviating from an original definition

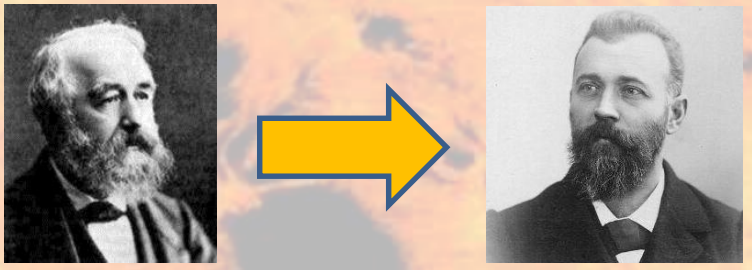
⇨ **Processing methods have a bigger impact than random errors in the data**

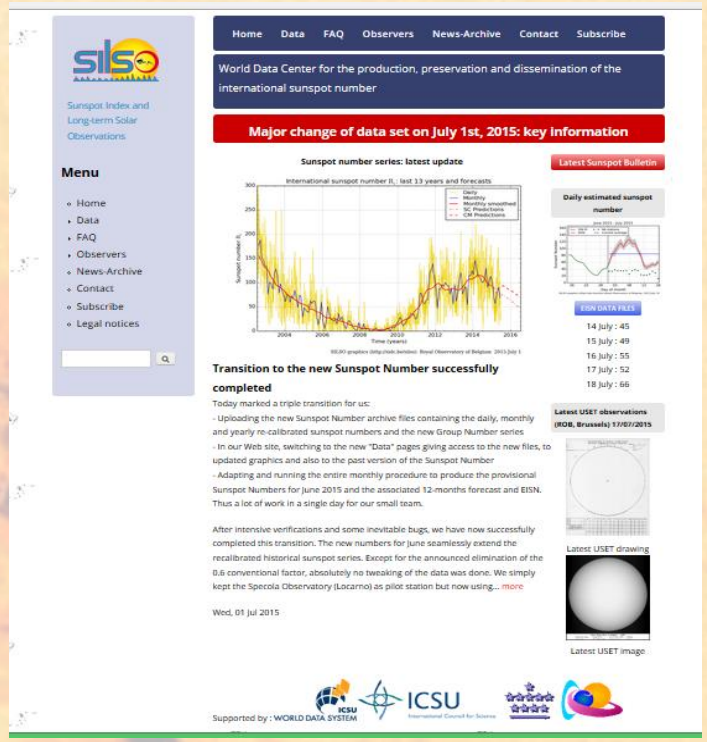
- **Defects diagnosed in the SN recalibration may still influence irradiance reconstructions** (SATIRE, NRLTSI):
  - Trends in **RGO photographic group areas and counts** *(Balmaceda et al. 2009)*
  - **Imbedded semi-empirical models** based on the uncorrected Hoyt & Schatten Group Number series:
    - Cosmogenic isotopes and **open solar magnetic flux** *(Solanky et al. 2002, Usosking et al. 2005, Lockwood et al. 2014)*
    - **Magnetic flux transport** *(Wang , Lean & Sheeley 2005)*

⇨ **Using the new SN as direct input parameter is not sufficient**

Conclusions and next steps

- **SN Version 2.0 + new GN** released on the new SILSO Web site**: July 1st 2015**
- **New conventions:** R_i ⇨ **S_N symbol**
  - Elimination of Zürich factor : **SN / 0.6**
    New reference = **A. Wolfer (1893-1926)**



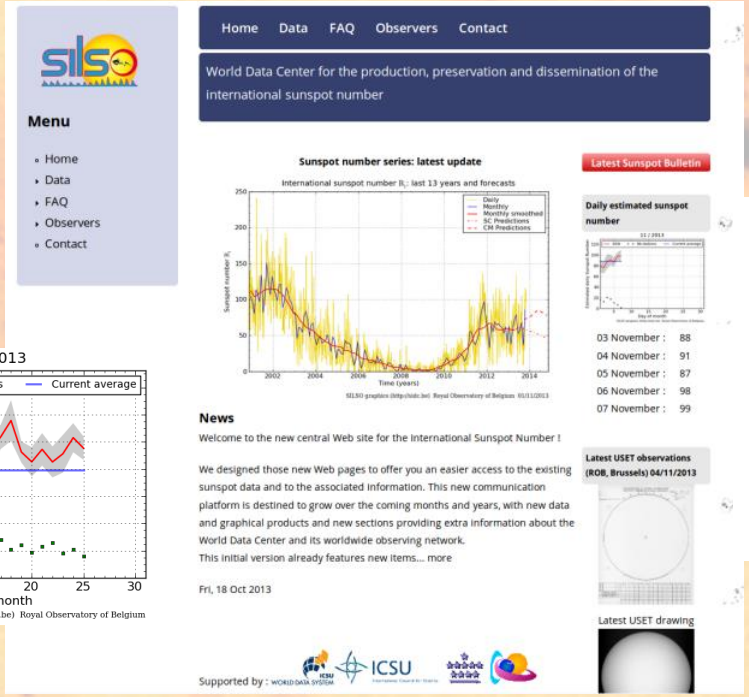


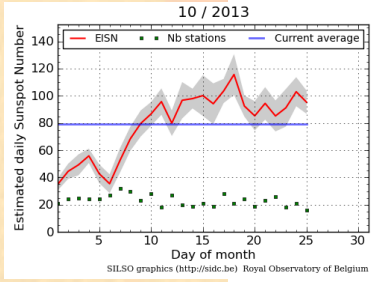
- **From a locked archive to a living data series:**
  - Open to future improvements (IAU supervision)
  - Archive of past versions
- Recent wave of interest for the past solar record
- Next developments (Version 3!):
  - **Advanced methods for sparse data and time-variable uncertainties** (PCA, ARMA, multiscale, Bayesian approaches)
  - **Full SN reconstruction (1981 – 2015)**

Stay tuned ….

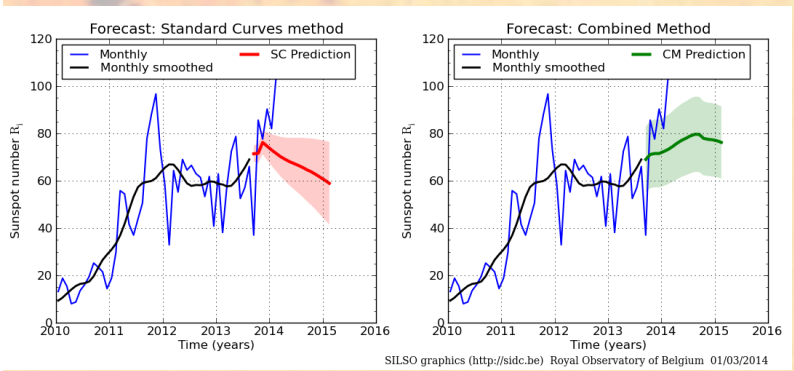
World Data Center – SILSO

Sunspot Index and Long-term Solar Observations





http://sidc.be/silso



SN workshops: http://ssnworkshop.wikia.com/wiki/Home