Sunspot Number essentials:
A tortuous way from Galileo to Locarno

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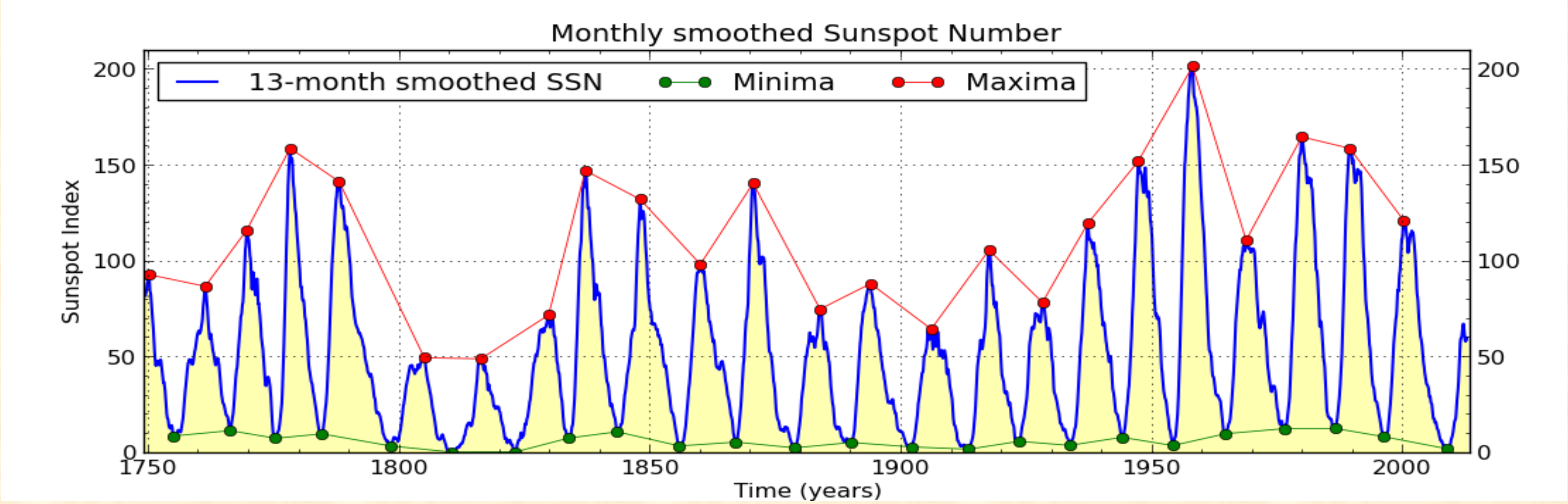
Outline

- Chronology of the Sunspot Number (SN) construction
- Other sunspot indices
- Matches and mismatches between series
- Conclusions

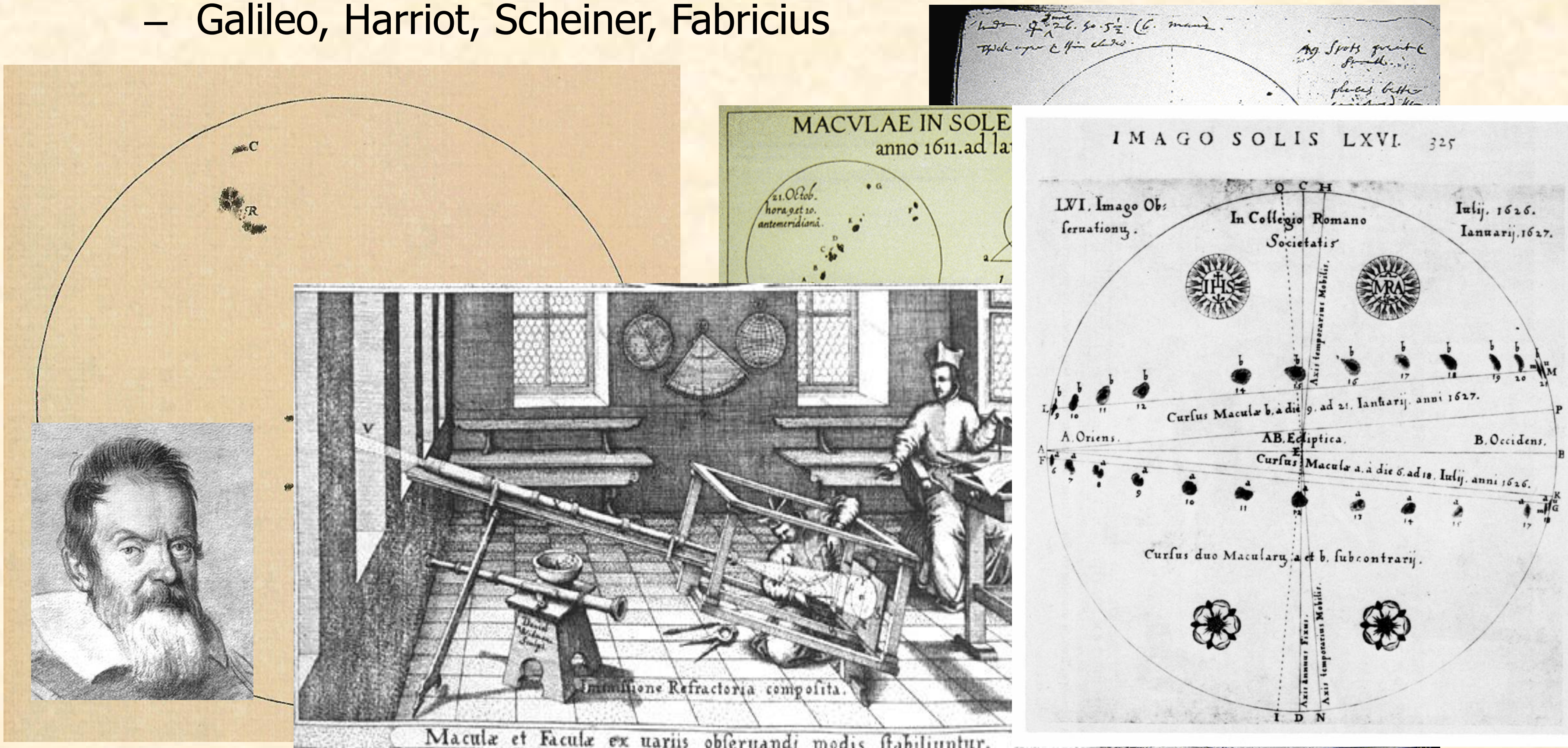
The Sunspot Number (SN): multiple roles

- Only direct multi-secular tracer of the solar cycle (404 years): synthetic index
- Constraint for solar dynamo models (11-year cycle, super-cycles, intermittency, grand minima)
- Quantitative reference for:
  - Solar irradiance and solar wind reconstructions
  - Cosmogenic radionucleides (access to millenia timescales)
  - Timebase for Sun-driven processes (geomagnetism, etc.)
- Tracer of the long-term solar influences on Earth:
  - Climate change
  - Atmospheric drag (spacecraft operations)
  - Cumulative GIC effects on infrastructures (e.g. pipelines).



Prehistory of the Sunspot Number

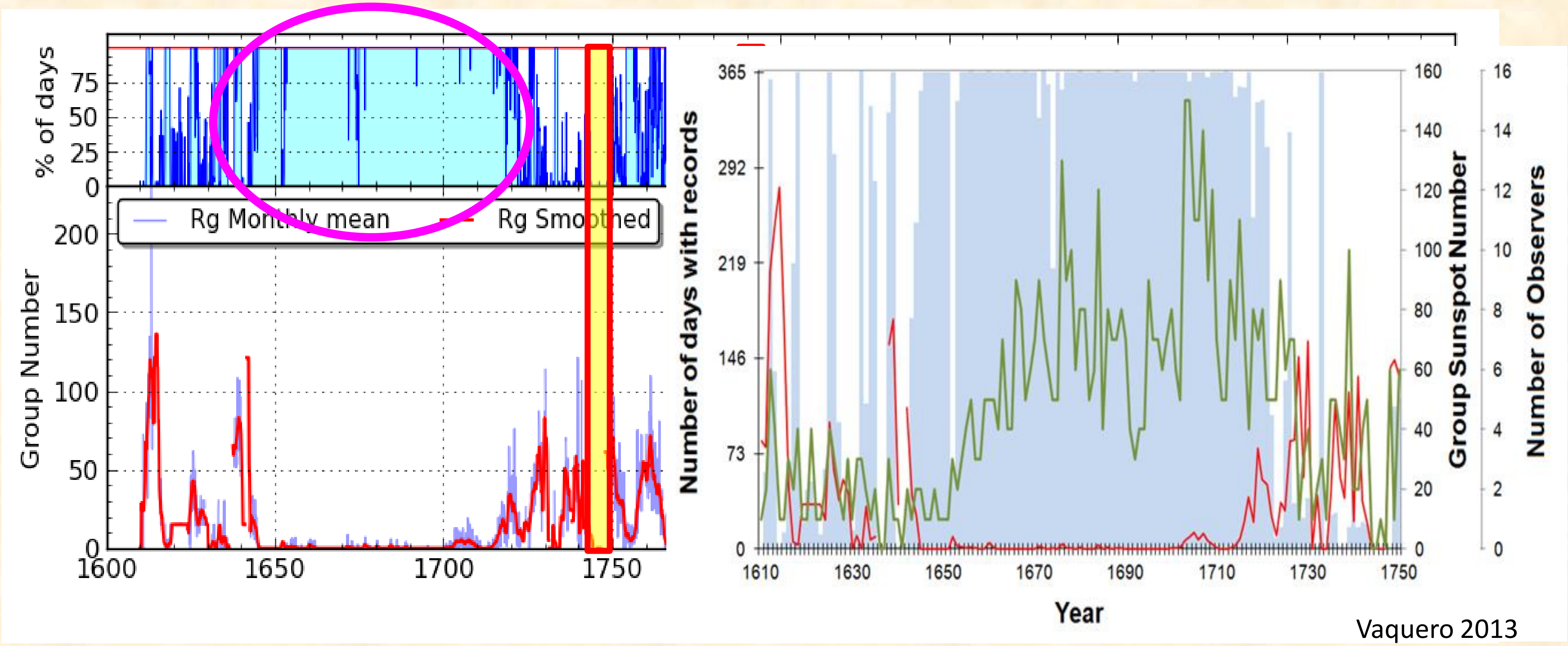
- Sparse pre-telescopic observations:
  - ⇨ Sunspots and the 11-year solar cycle existed centuries and millenia before Galileo
- Invention of the astronomical telescope: start of the sunspot record
  - – Galileo, Harriot, Scheiner, Fabricius



Prehistory of the Sunspot Number

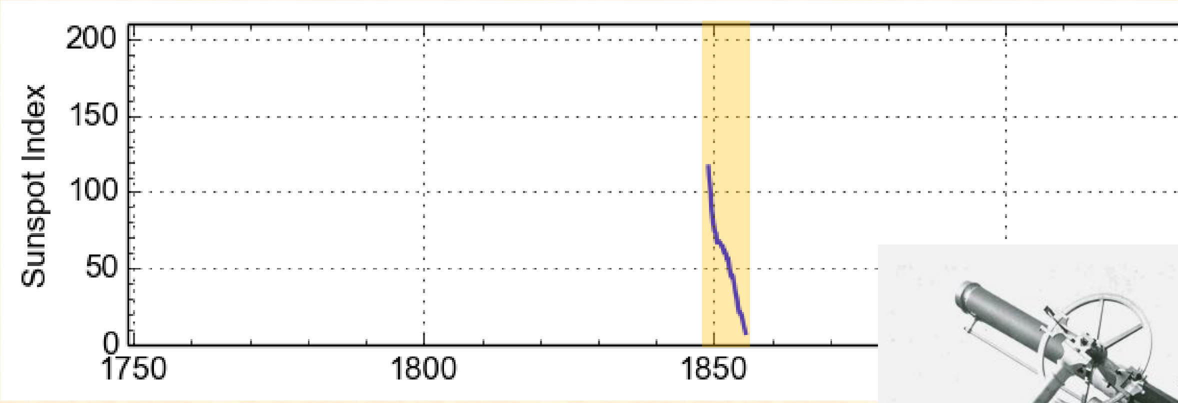
- The actual nature of sunspots is still unknown:
  - Debate: are those spots really on the Sun?
- Observations are not done for sunspot studies:
  - Astrometry (meridian distance, etc.)
  - Scattered in logbooks, among other observations
  - Some famous observers: Hevelius, Flamsteed, Herschel

➡ Very variable interest and time coverage: 18th century « gaps »



Vaquero 2013

The sunspot number: main episodes



R. Wolf in 1855 (1849-1893)

- R. Wolf: invention of the sunspot index (1851, 1856):

  W= k . (10 Ng + Ns)

- The 2 types of instruments:
  - **Standard «4-foot » Fraunhofer refractor** (fixed, Zürich Observatory)

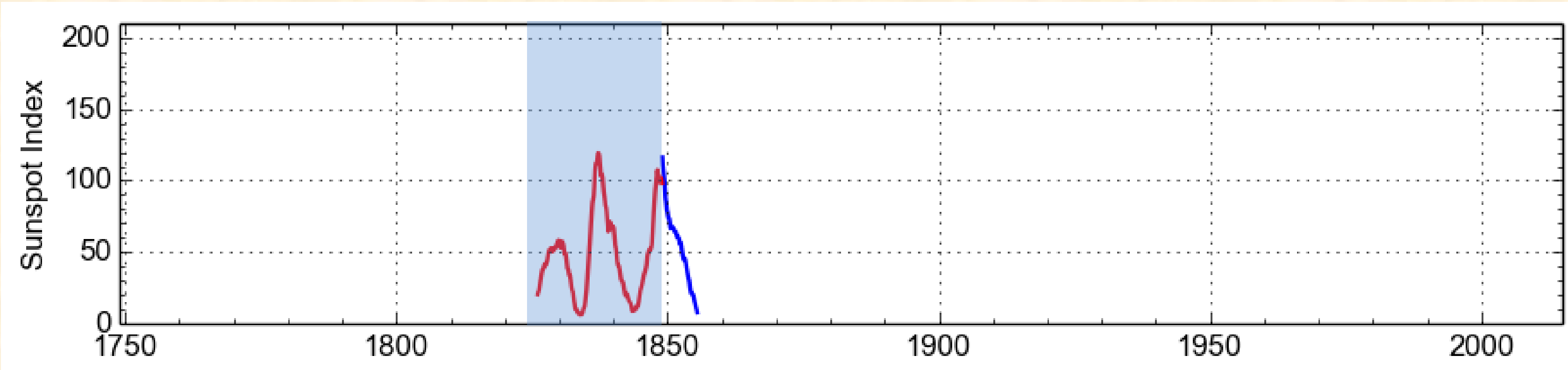
    D= 83mm, F= 1320mm Mag= 64x
  - **Small travel refractor** (portable):

    D= 43mm, F= 550mm, Mag= 29x
- Still in use now *(Thomas K. Friedli, Rudolf Wolf Society, Zürich)*

H.U. Keller and T. K. Friedli

Mid-1980's

The sunspot number: main episodes



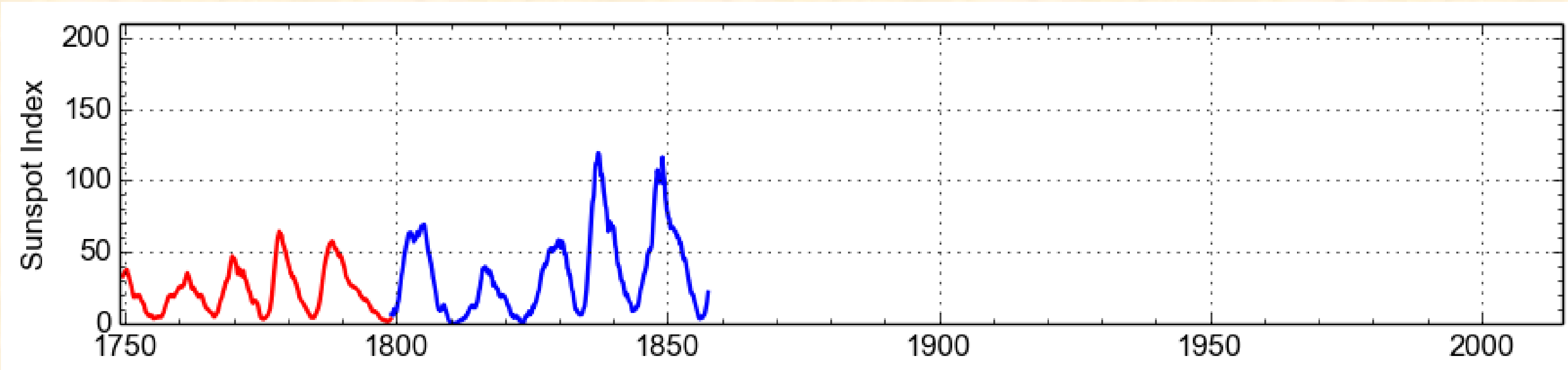
- Inclusion of past sunspot observers:
  - Samuel Heinrich Schwabe [1789-1875]:
    - Sunspot observations 1826 – 1867
    - Discoverer of the solar cycle (1844)

S. H. Schwabe

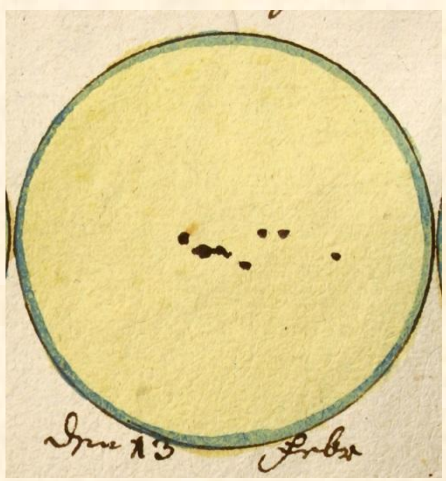
Zürich primary observers:

- Staudach 1749 - 1787
- Flaugergues 1788 - 1825
- Schwabe 1826 - 1847
- Wolf 1848 - 1893
- Wolfer 1893 - 1928
- Brunner 1929 - 1944
- Waldmeier 1945 - 1980

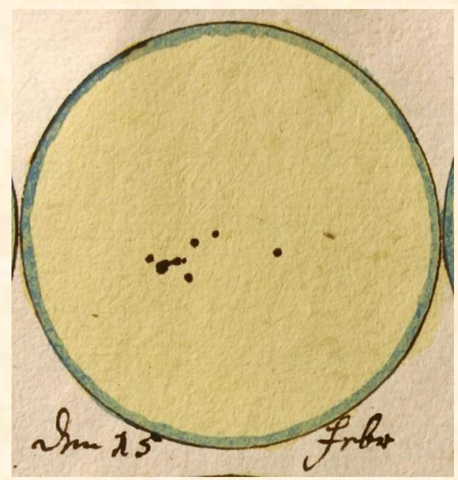
The sunspot number: main episodes



- 1857: adding Staudach: observations from 1749 to 1796

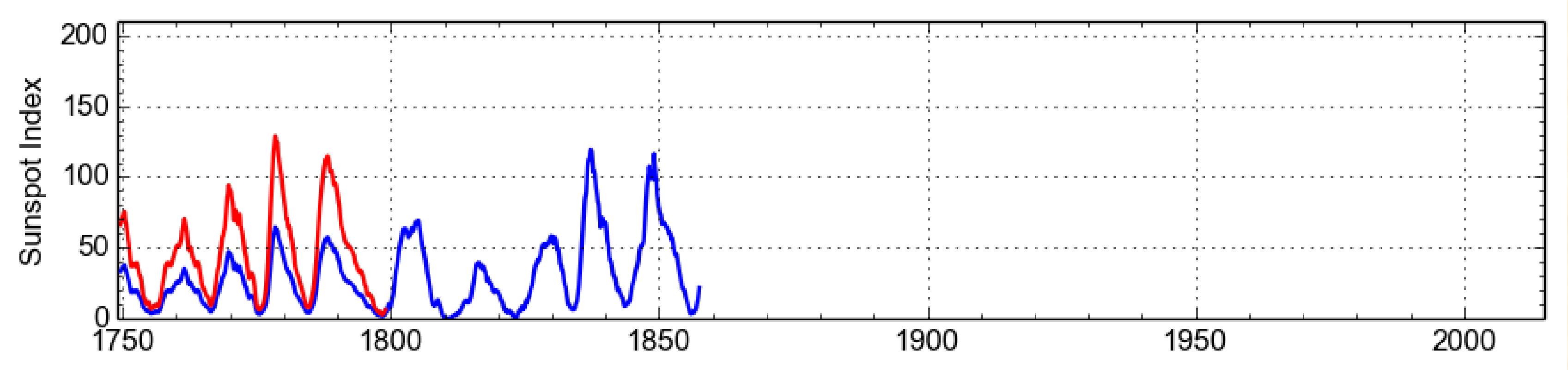


13/2/1760



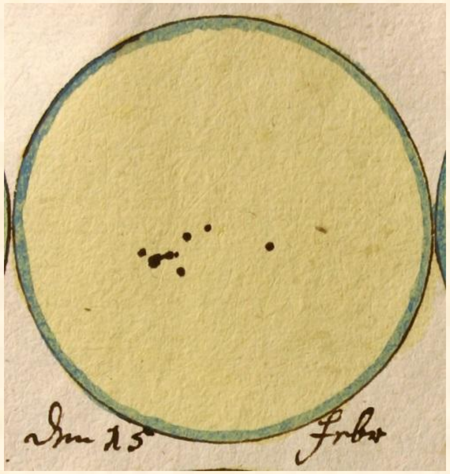
15/2/1760

The sunspot number: main episodes



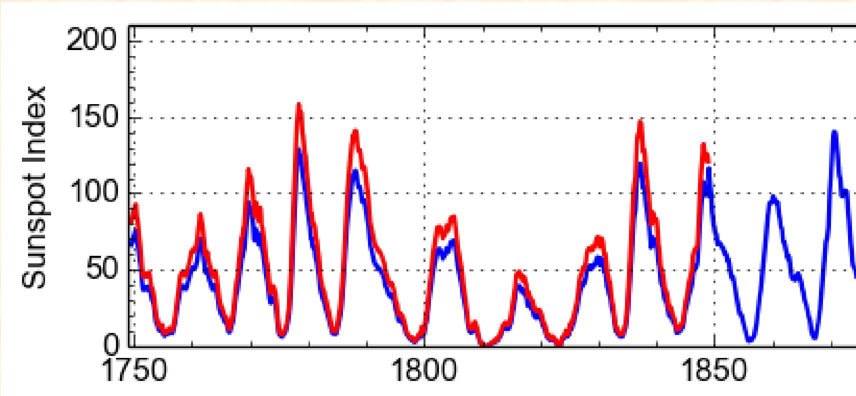
- 1861: magnetic needle corrections **Staudach data x 9/4**

13/2/1760



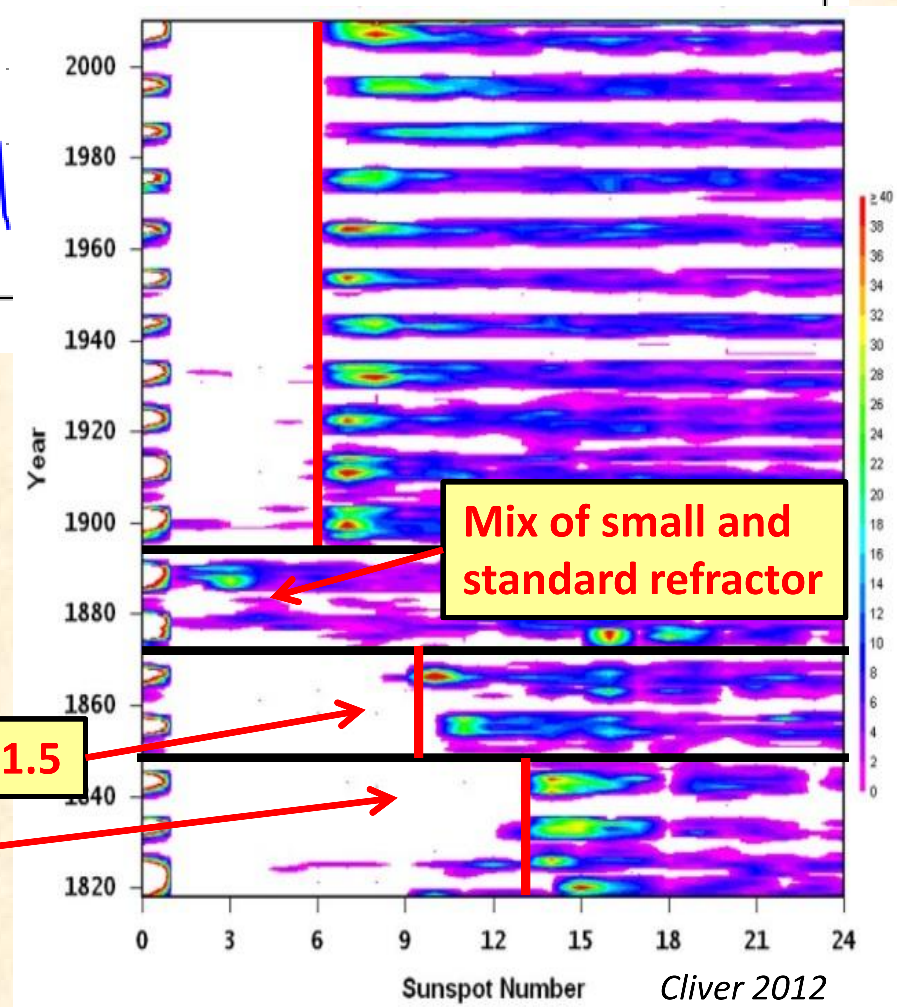
15/2/1760

The sunspot number: main episodes



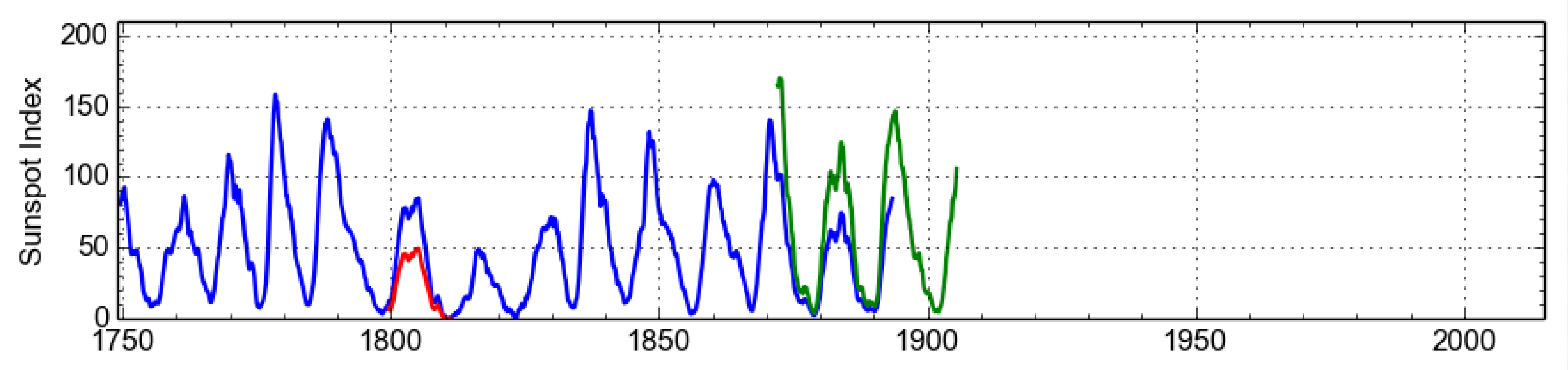
- Based on the analysis of English observations collected in 1861
  (Carrington, etc.)
- 1874: adding new data
  (Flaugergues, etc.)

All data before 1849 **x 1.23**



Record of these adjustments as seen in the lower end of the histogram of SSN values vs time

The sunspot number: main episodes



- 1902: Wolfer correction

  cycle 5 (1799-1810) x 0.58

- **Wolf-Wolfer transition** [1877 - 1893]

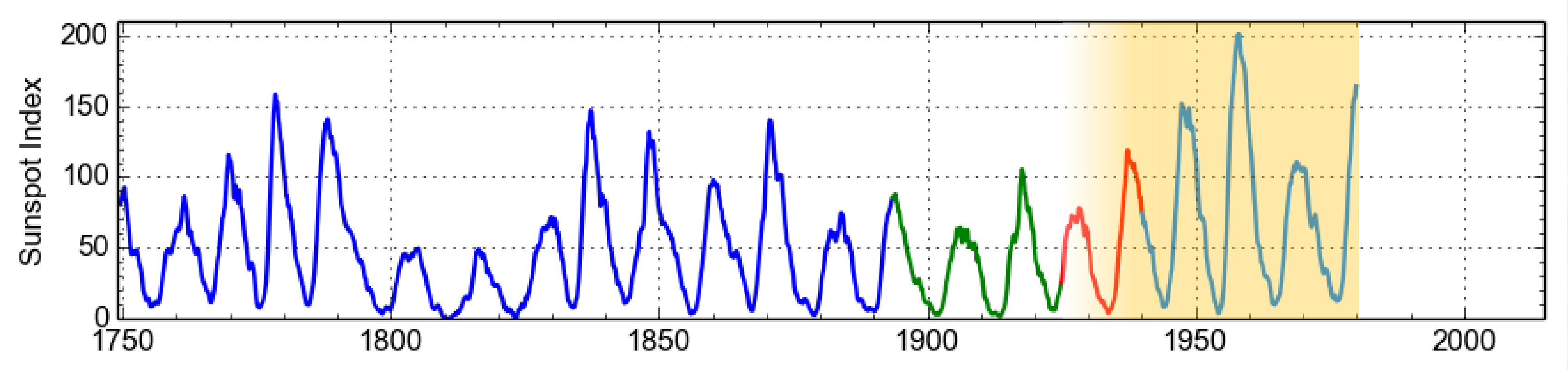
  New counting method:

  - All small spots included in count
  - Multiple umbrae in common penumbra counted as separate spots
  - 16 years of parallel Wolf-Wolfer counts

$R_Z = 0.6\ W_Z$

Alfred Wolfer (1877-1925)

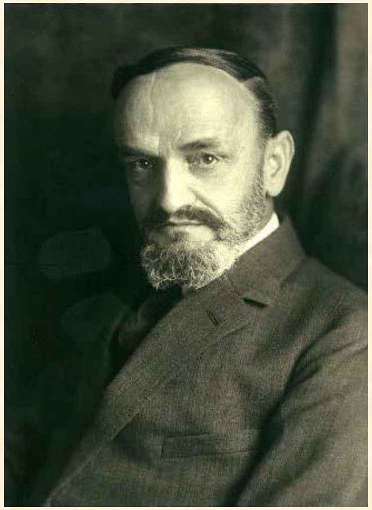
The sunspot number: main episodes



- Zürich period:
  - 3 directors

- **Sunspot weighting:**
  - Starting date uncertain: 1930's (W. Brunner) or ~1945 (M. Waldmeier)

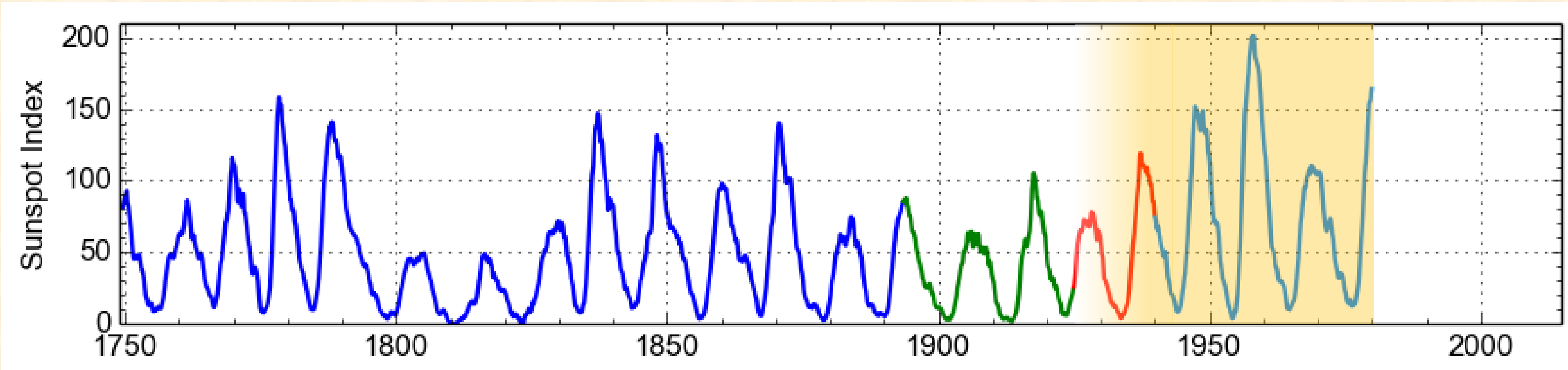
Alfred Wolfer (1877-1925)



William Brunner (1925-1944)

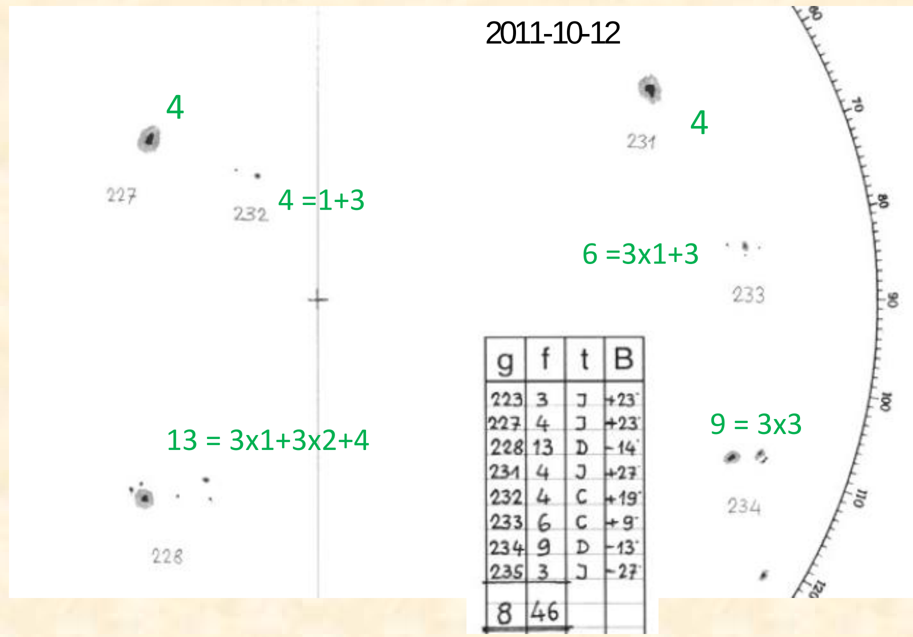
M. Waldmeier [1944 - 1980]

The sunspot number: main episodes

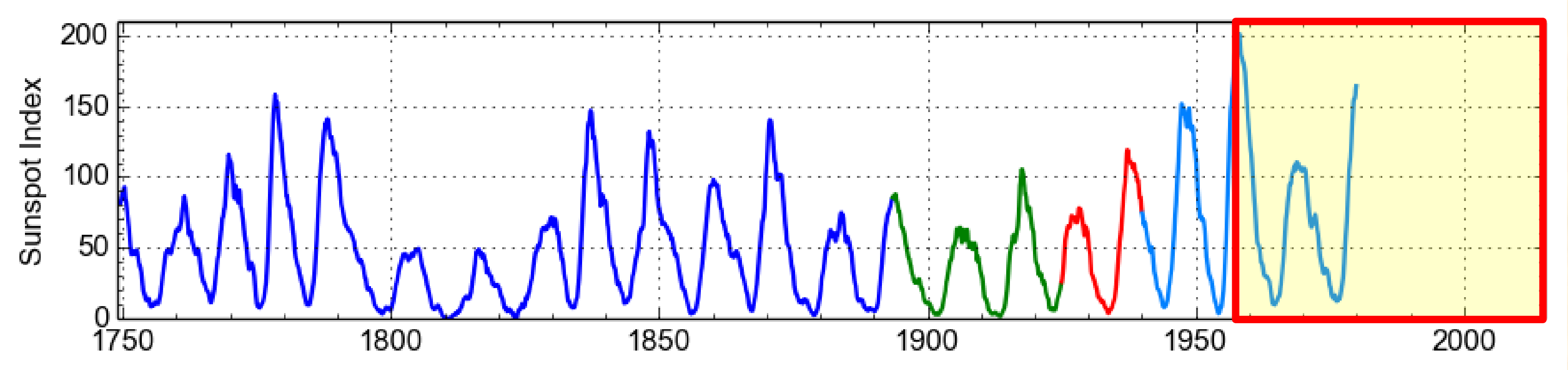


- Zürich period:
  - 3 directors

- **Sunspot weighting:**
  - Starting date uncertain: 1930’s (W. Brunner) or ~1944 (M. Waldmeier)
  - Large spots are counted >1 (up to 5)



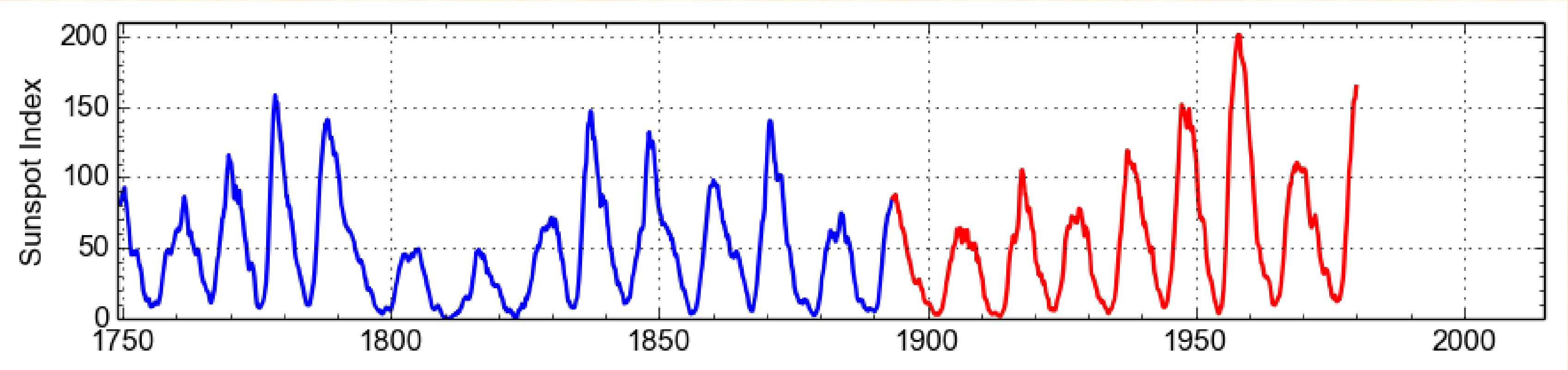
The sunspot number: main episodes



- Second base station [1957]: **Specola Solare, Locarno** (Ticino, SW)
  - Observer: **S. Cortesi** (now observing for 57 years!)
  - Trained to the Zürich method

S. Cortesi and M. Waldmeier circa 1972

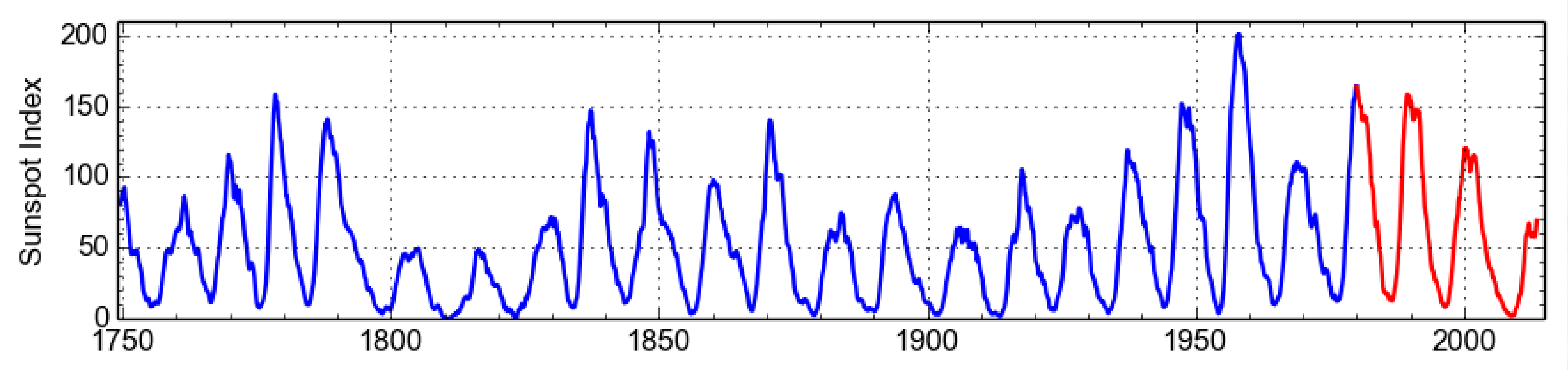
The sunspot number: main episodes



<u>The Zürich SSN computation</u>

- **SSN = Wolf number of the Zürich station**
- Daily gaps filled with average of auxiliary stations (10 to 40 stations)
- Scaling: yearly average k personal coefficients

The sunspot number: main episodes



- **1981: transfer of the WDC – Sunspot to Brussels (SIDC)**
  - New pilot station:
    Specola Solare Ticinese, Locarno
    (Primary observers: S. Cortesi, M. Cagnotti)
  - New global statistical determination of SSN using the full network
  - Extension of the worldwide observing network:
    from ~30 to ~80 stations

- Four Directors:
  - André Koeckelenbergh (1981 - 1991)
  - Pierre Cugnon (1992 - 2001)
  - Ronald Van der Linden (2002 - 2011)
  - Frédéric Clette (since 2011)
- None of them is a primary observer !

The current (living !) actors *(ROB, February 2011)*

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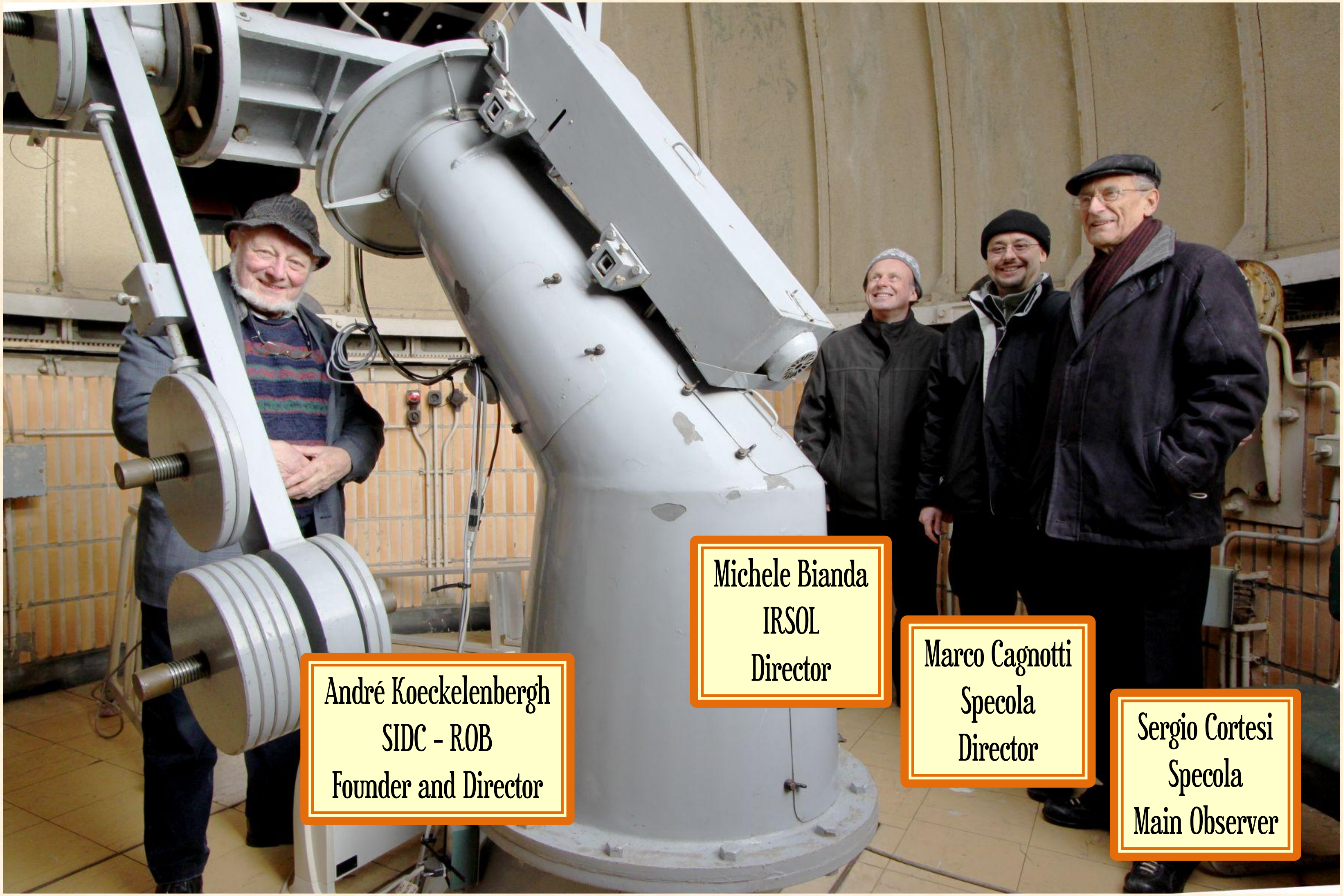
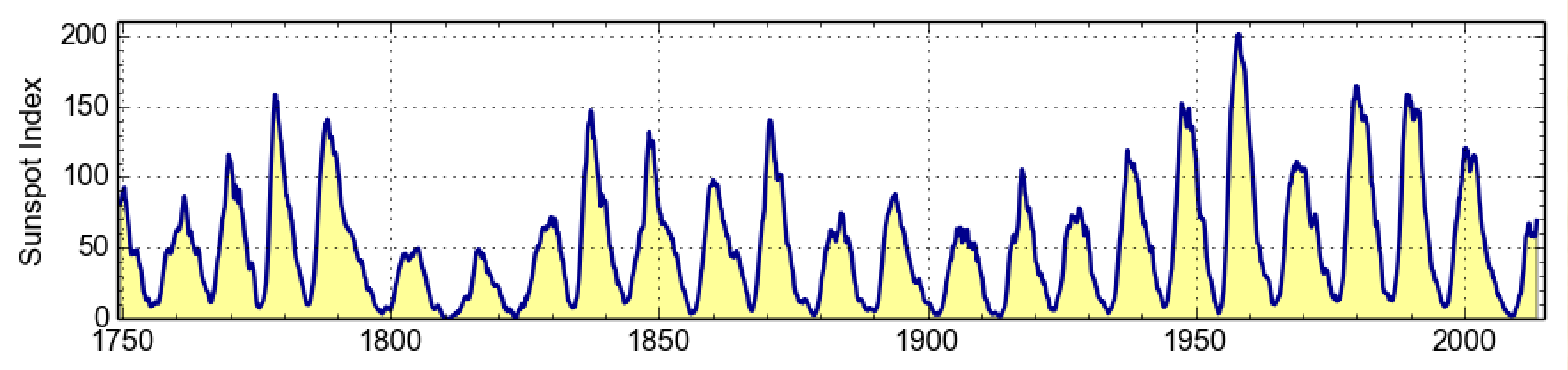
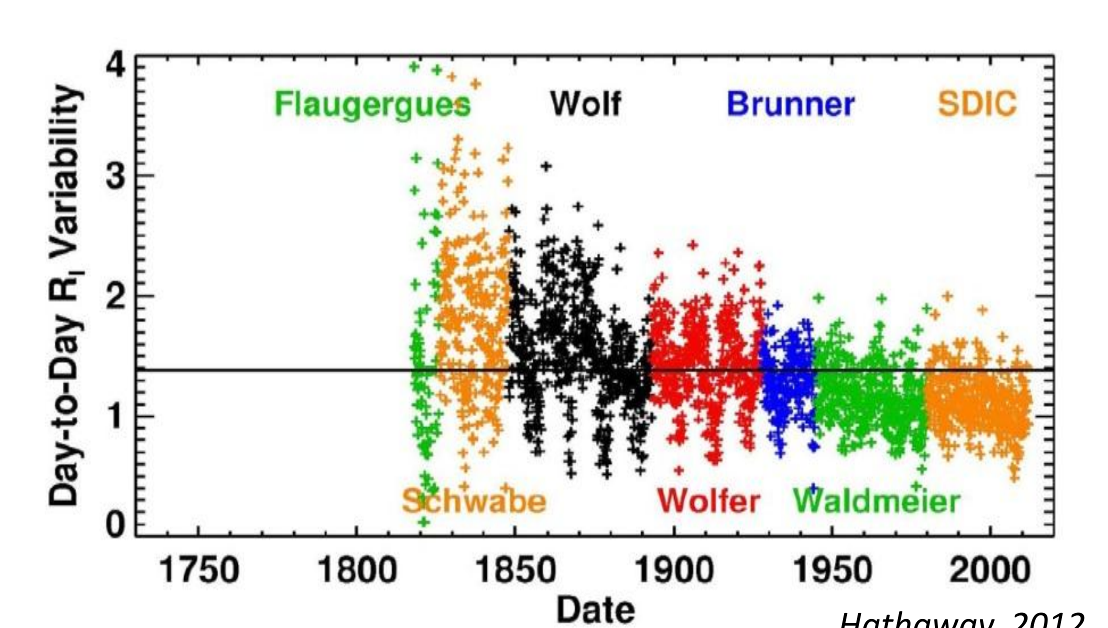


SN increasing precision



- Steady decrease of the daily variability
- Current rms dispersion of raw individual W_s values:
  - Daily: 8%
  - Monthly: 1.5%

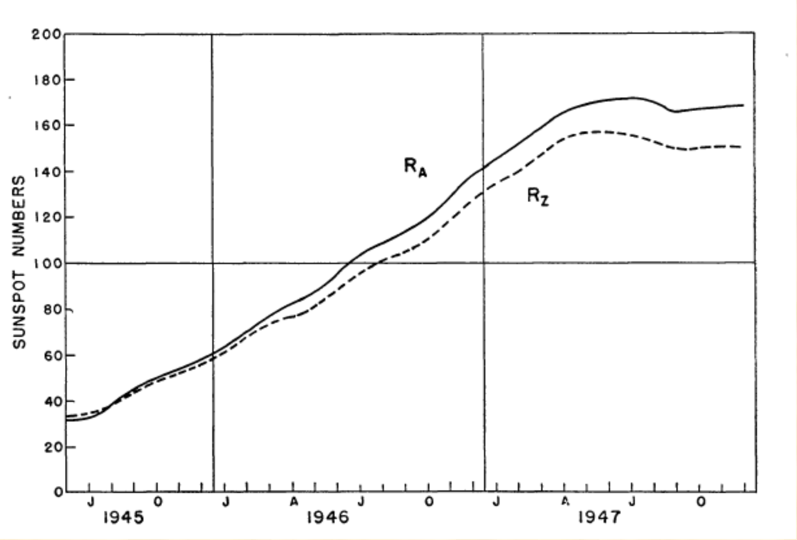


Hathaway, 2012

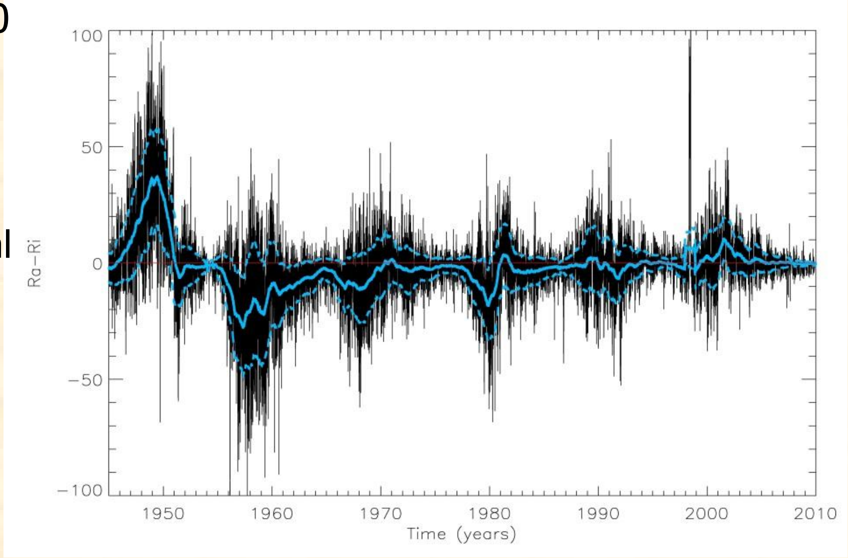
Other sunspot numbers

Other Sunspot Numbers: the AAVSO SN R_A

- Initiated during WWII by A.H.Shapley
- Handed over to the AAVSO in Dec. 1944
- Problem: R_Z and R_A are diverging
- ⇨ Harmful for the SN reputation:
  - Increases the conflicting relations with Waldmeier
  - Deepens the mistrust with the « subjective and outdated » visual sunpot number
  - ⇨ The continuation of R_Z treathened in 1980 (IAU WG involving A.Shapley & J.Eddy)
- Actual cause:
  - Flaws in R_A calculation:
    - « Inflation » effect due to the mathematical method for k coefficient calculation *(Hossfield 2002)*
  - Method fixed in 1997 *(Schaefer 1997)*
- But: original data lost !
- ⇨ R_A now reliable but valid only since ~1965

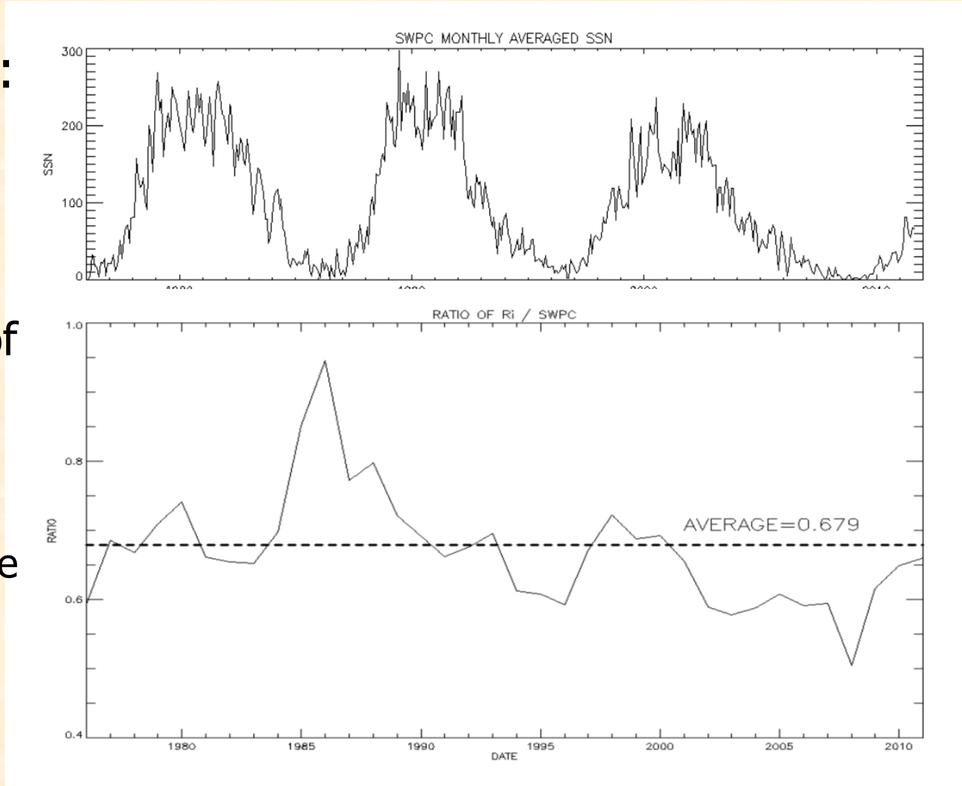


Shapley, 1949

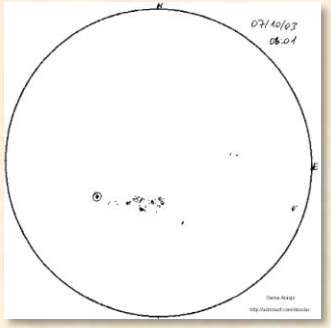


Other Sunspot Numbers

- The **Boulder sunspot Number**:
  - Based on the USAF SOON network and other US observatories (Boulder, Mt. Wilson, Sac. Peak)
  - Associated with the production of NOAA active region catalog
  - Meant for real-time applications
  - **No long-term calibration**
    - Contributing stations vary in time



- Other **amateur astronomer networks**:
  - SONNE (VDS, Germany), VVS Werkgroep Zon (Belgium), BAA Solar section (UK), etc.
  - Different calibrations or no calibration
  - **Duration limited (< last 30 years)**



Gema Araujo

The main alternate sunspot number: Group Number

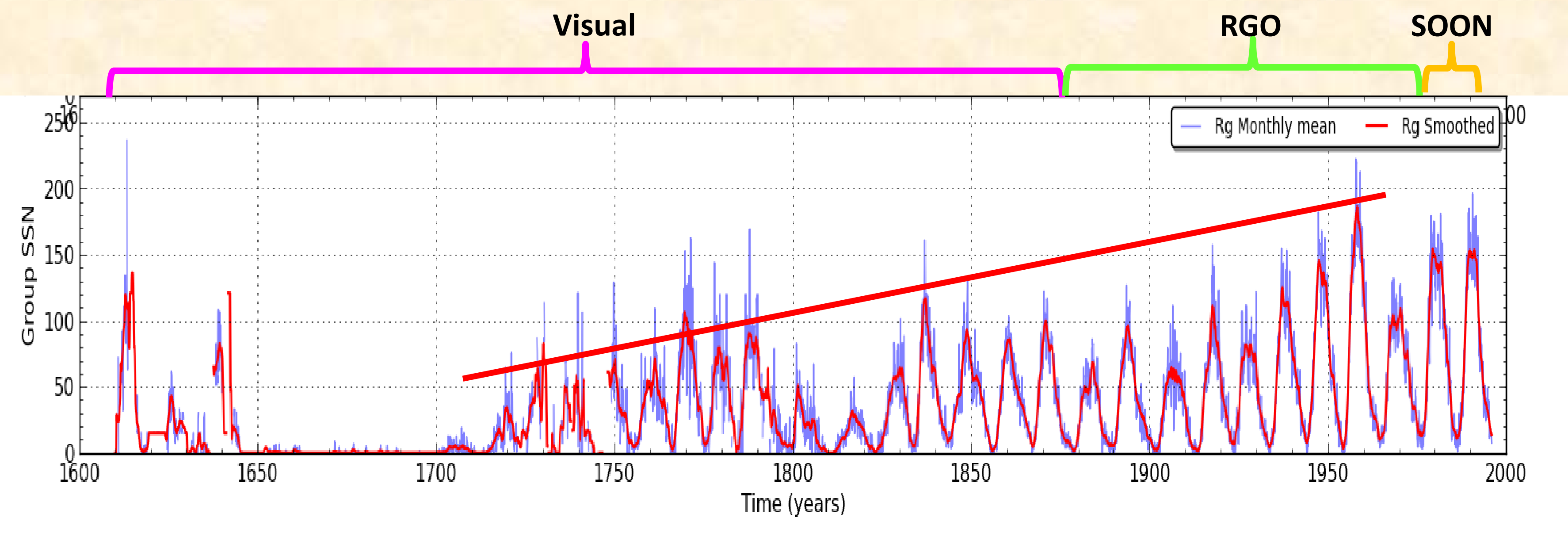
- Group Sunspot number R_g

  (Hoyt & Schatten 1998)
- Calibrated on R_Z over the 20[th] century**:**

$$R_G = \frac{12.08}{N} \sum k_i Ng_i$$

- With R_Z= 0.6 (10 N_g + N_s): N_s= 10.13 N_g

- Starts earlier than R_i: 1610 – 1995
- Base data:
  - 1610-1874: historical observers *(doubling of recovered records!)*
  - 1874-1976: RGO photographic plates
  - 1976-1995: SOON drawings



The Group Number

- Strengths:
  - R_g rests on a larger collection of observations.
  - Goes back to 1610 (1700 for Zürich SN)
  - Less dependant on visibility of small spots in the early observations
  - Processed as a complete set by the same person (no change of practices)
  - Calibration by backward propagation of cross-scaling factors (no use of external indicators, e.g. magnetic needle)

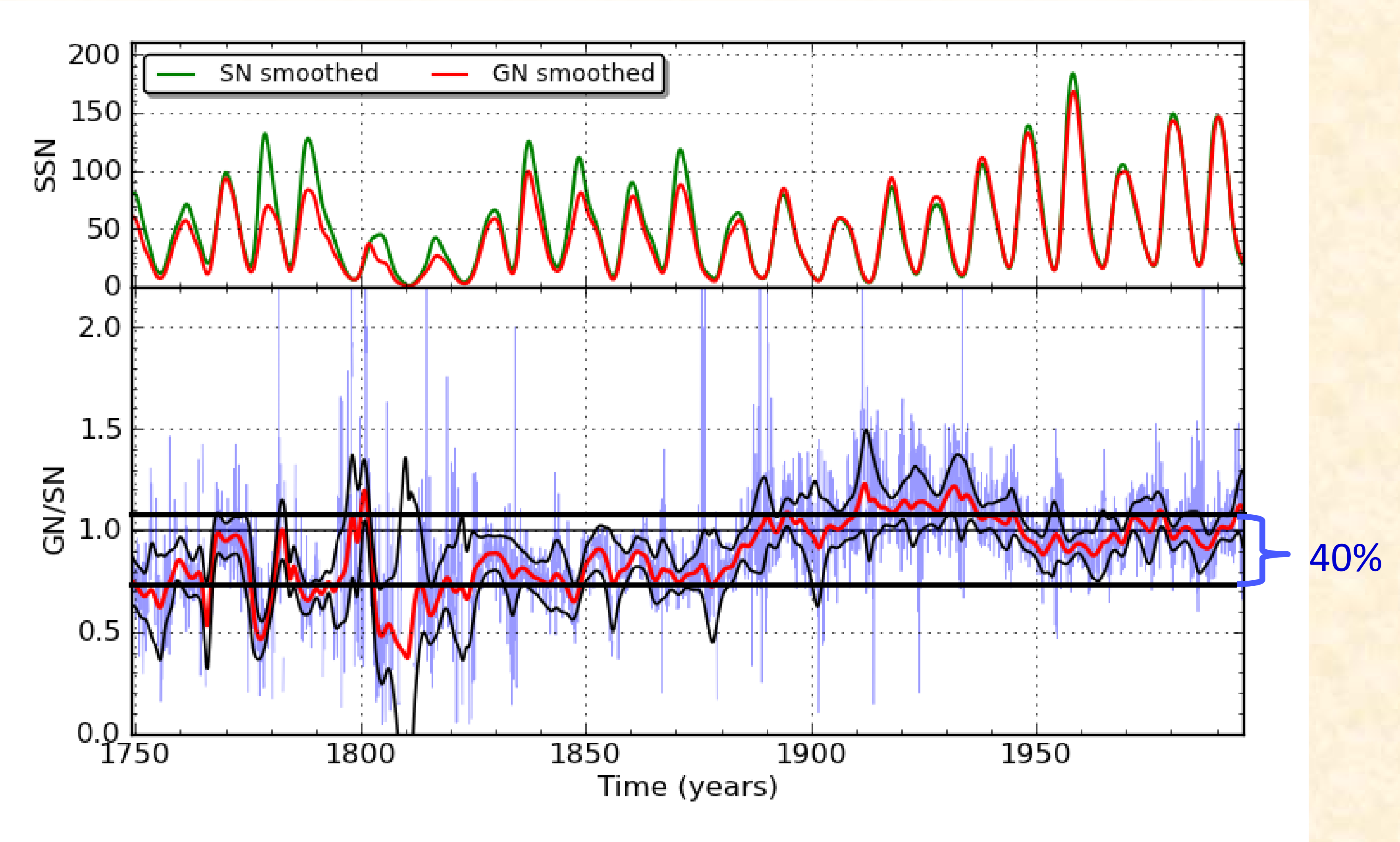
⇨ Often considered as the most reliable reference before 20th century :
  - Many applications: solar open magnetic flux, solar irradiance *(e.g. Krivova et al. 2007), etc.*

- Weaknesses:
  - assumes that the average sunspot/group ratio is constant over time and over the level of activity. Loss of the actual info on group size.
  - base calibration on a non-visual reference: RGO photographic plates

and ….

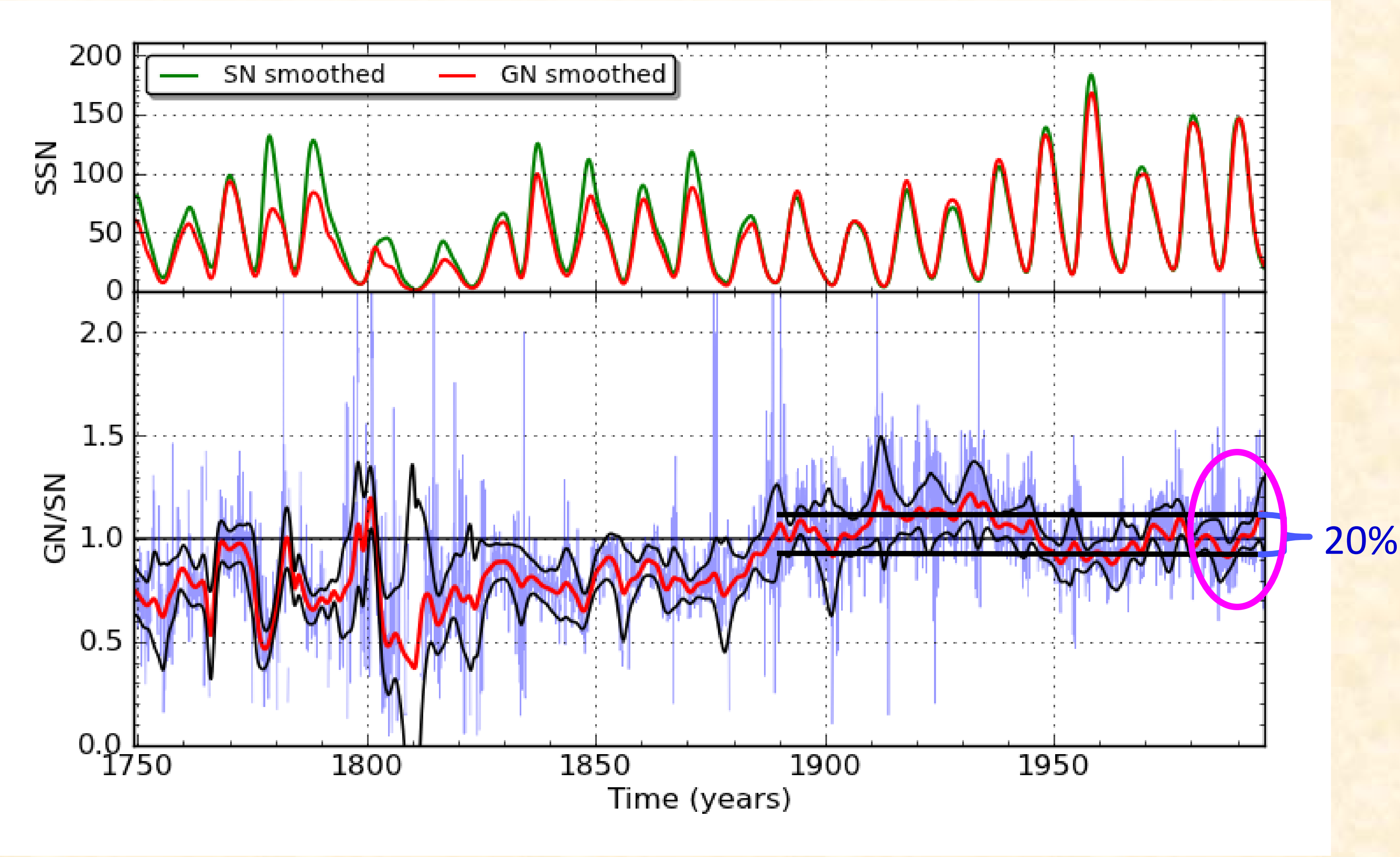
SN versus GN: a major disagreement

- All values before 1880 are 40% lower than the SN



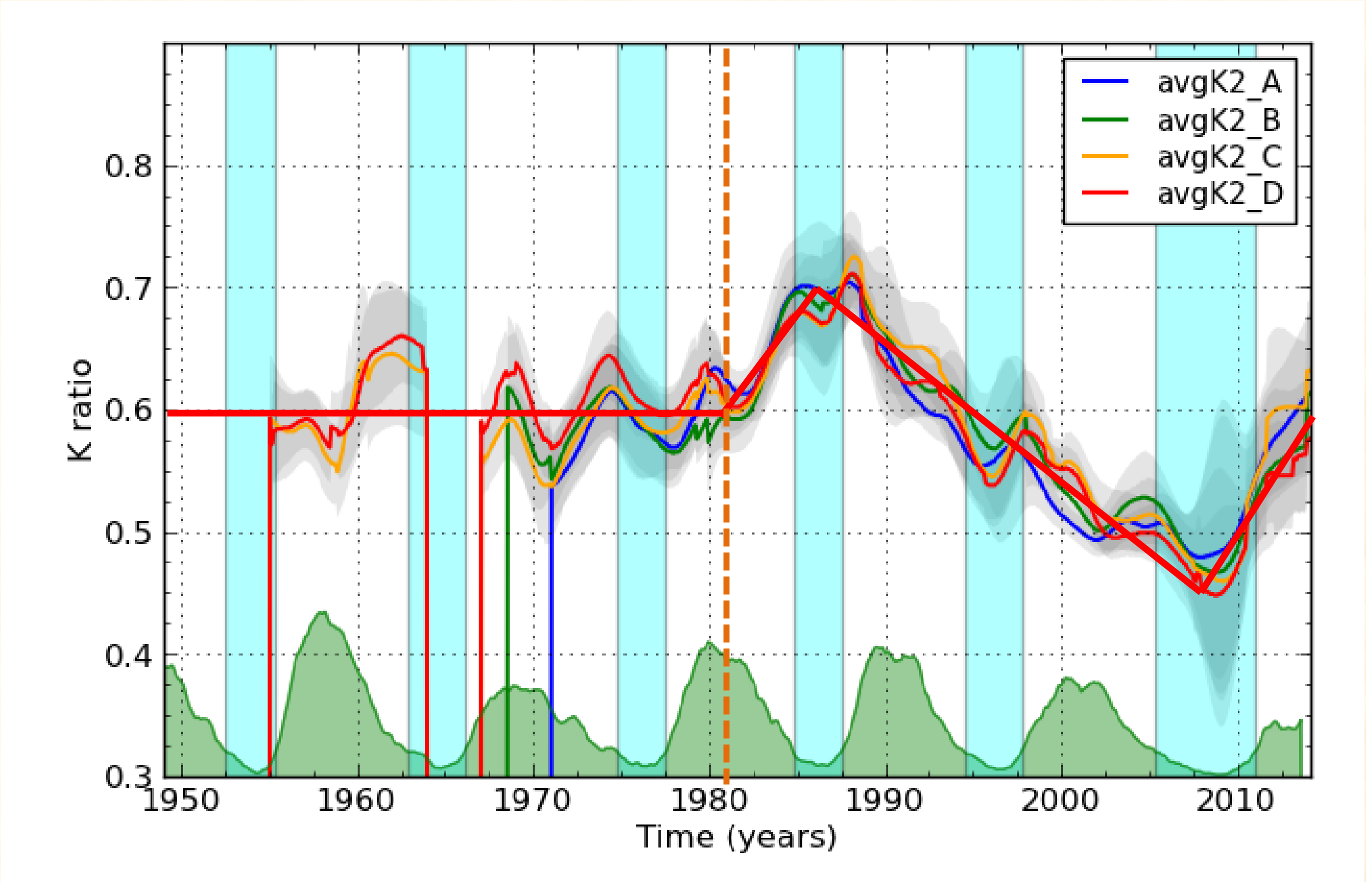
SN versus GN: a major disagreement

- 20% difference between the first and second half of the 20th century



Recent drifts in R_i (1981-2013)

- Global statistical analysis over the entire international sunspot network



- No trend before 1981 (Pilot station: Zürich)
- Variable drift starts with the transition to the new pilot station (Specola, Locarno)

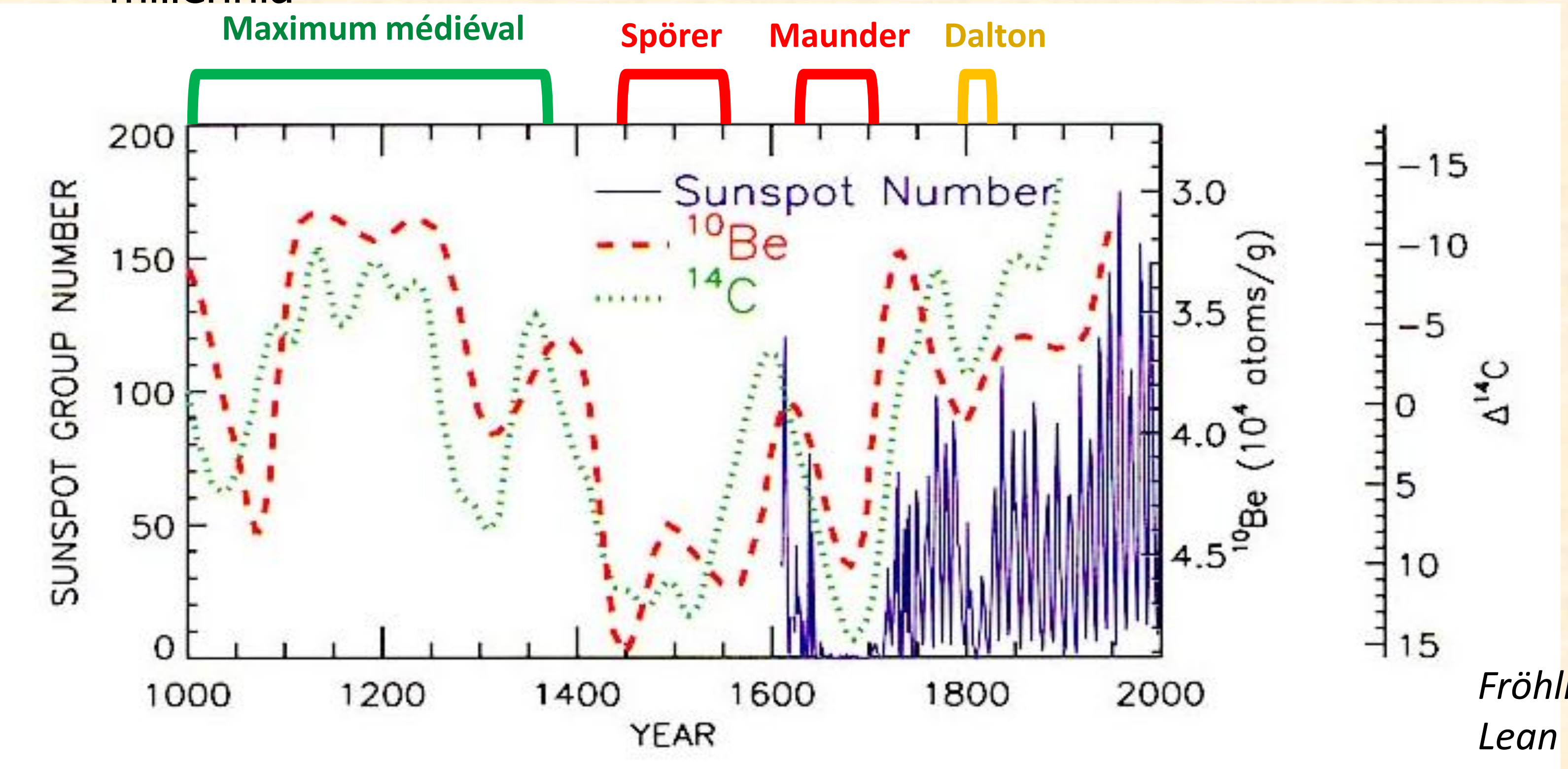
- All raw observations are preserved in the SILSO database

⇨ **R_i can be fully recomputed and corrected over the past 34 years !**

Other indirect long-term indices

SN and other long-term indices: cosmogenic isotopes

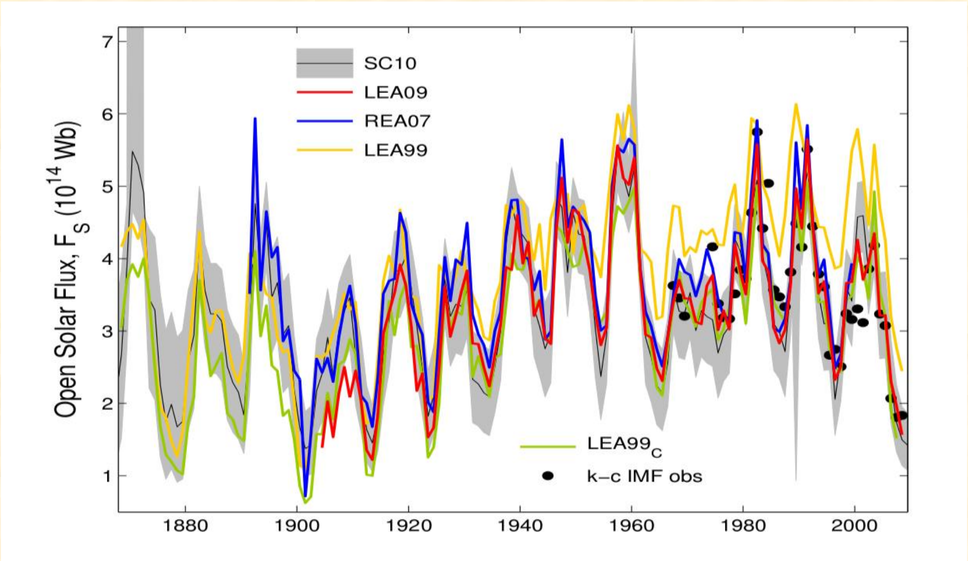
- ^{14}C (tree rings, sediments), ^{10}Be (ice cores):
  - Good correlation with long-term modulation of the SN
  - Allows extrapolation over millennia
- Limited time resolution
- Non-solar uncertainty factors:
  - Geomagnetism
  - Deposition processes and rates



Fröhlich & Lean 2004

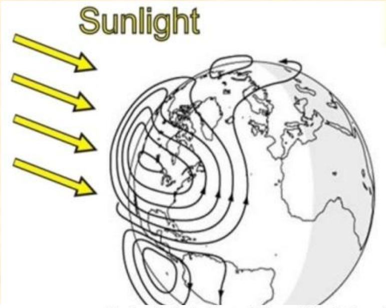
SN and other long-term indices: geomagnetic indices

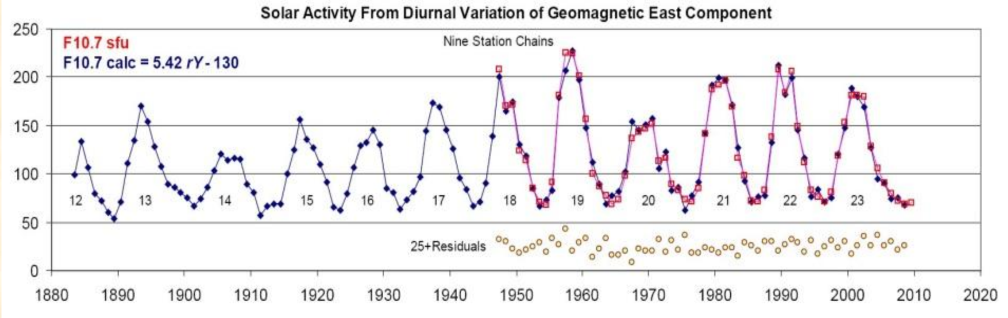
- Reconstruction of the solar open magnetic flux B:
  - Data starting in ~1835:
  - Influenced by evolution of Earth magnetic dipole
  - Change of observing stations



Lockwood 2013

- Diurnal variation of the E-W component of the geomagnetic declination: rY index (*Nevanlinna 1995, Svalgaard & Cliver 2007*) :
  - Ionospheric current system induced by daytime solar UV radiation
  - Indirect measure of solar UV irradiance variations
  - rY well correlated with F10.7 radio flux



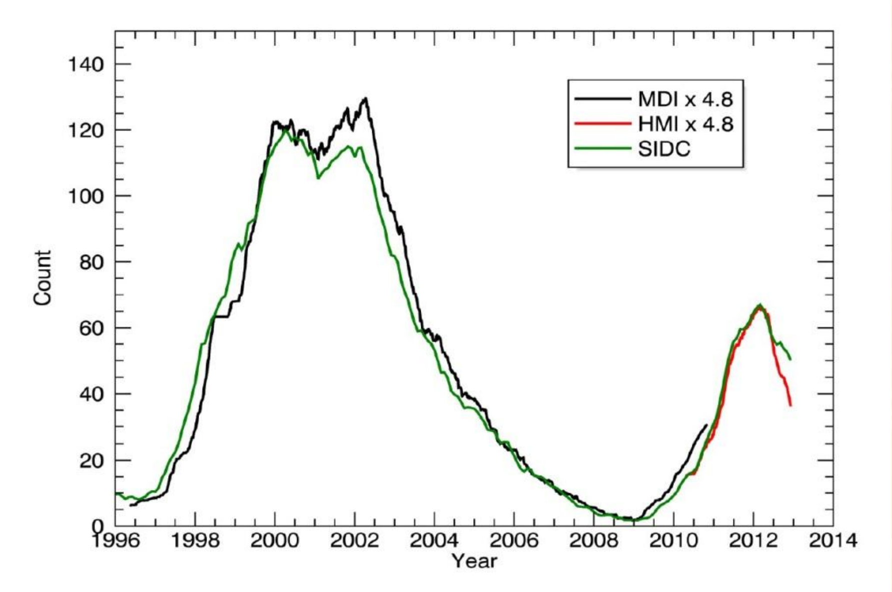


SN versus other modern solar indices

SN and other solar indices

- Photospheric indices:
  - Area, Mx, image-based counts
  - High linear correlations (R>95%):

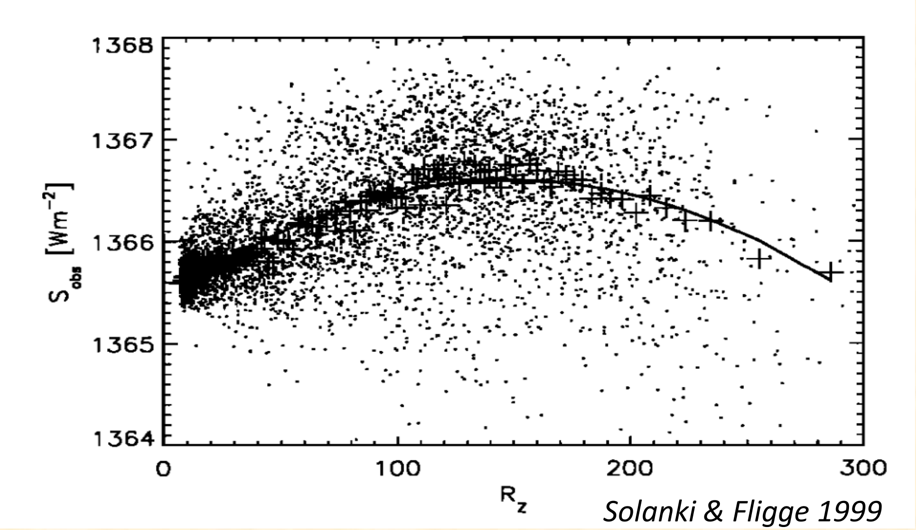
➡ SN is a quantitative index:
  - magnetic flux emergence *(Pretovay 2010, Stenflo 2012)*



STARA catalog; F. Watson, 2012

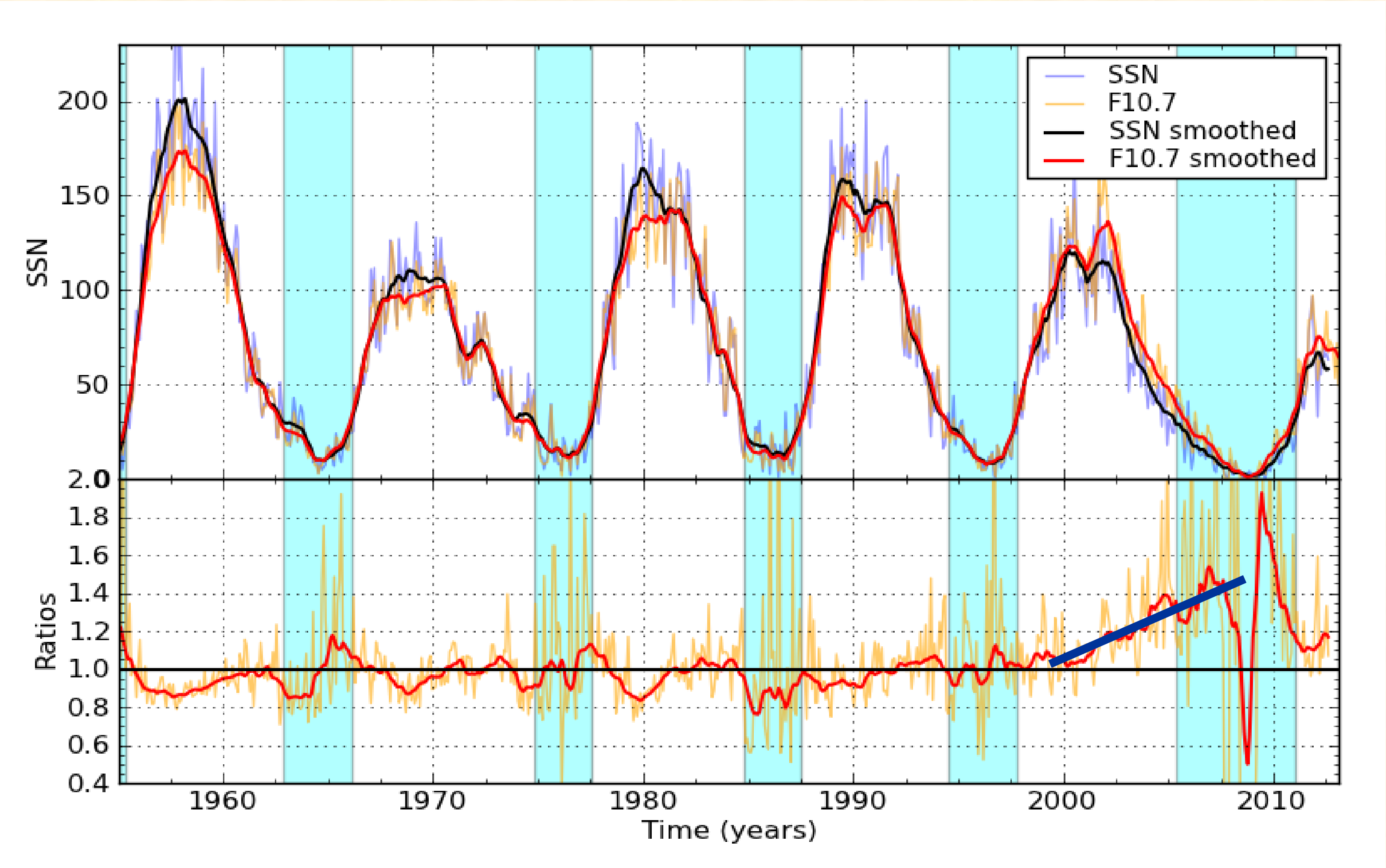
- Chromospheric and mixed indices:
  - TSI, CaII-K, MgII, $F_{10.7cm}$
  - Good correlations over long timescales:
    - Non-linear relation **(radiative mechanisms)**
    - Time lags **(magnetic decay and flux dispersal)**

➡ Different physics !



Solanki & Fligge 1999

Diverging indices in cycle 23



- New questions that can help interpreting past historical inconsistencies:
  - **Are small spots selectively vanishing in weaker solar cycles ?**
  - **Is the average number of spots per group constant over time ?**

Conclusions

- The SN series is a composite series (Successive « epochs »):
  - Different base data and number of observers
  - Different counting and processing methods
- Main parallel index : Group Sunspot Number
  - Major discrepancies between the series
  - GN homogeneity affected by different problems
- Other solar indices and indirect geomagnetic and isotope tracers can provide a useful validation:
  - Agreement provides confirmation
  - Relative reference over limited time intervals (last recourse to bridge gaps)
- The current modern SN is highly correlated with direct measurements of photospheric physical properties:

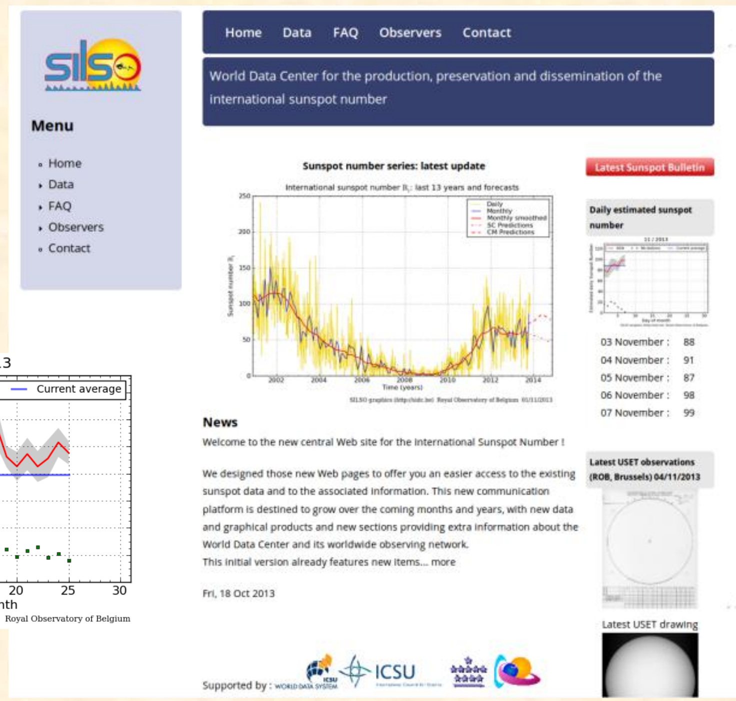
⇨ **Unique valid reference** to link our multiple modern but time-limited measurements with the long-term evolution of solar activity and Sun-Earth relations (Space climate)

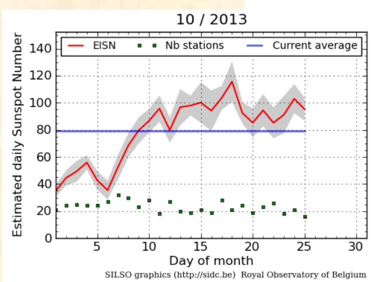
⇨ New demand for an homogeneous record retracing many solar cycles

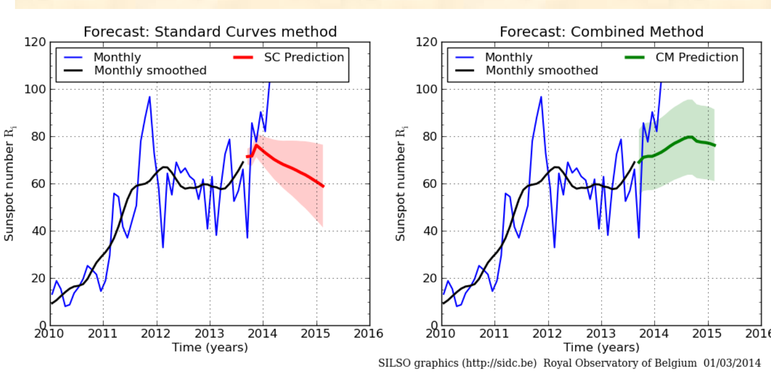
For the latest information, please visit …

WDC – SILSO Sunspot Index
and Long-term Solar Observations

http://sidc.be/silso







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