Reevaluation of the 400-Year Sunspot Record

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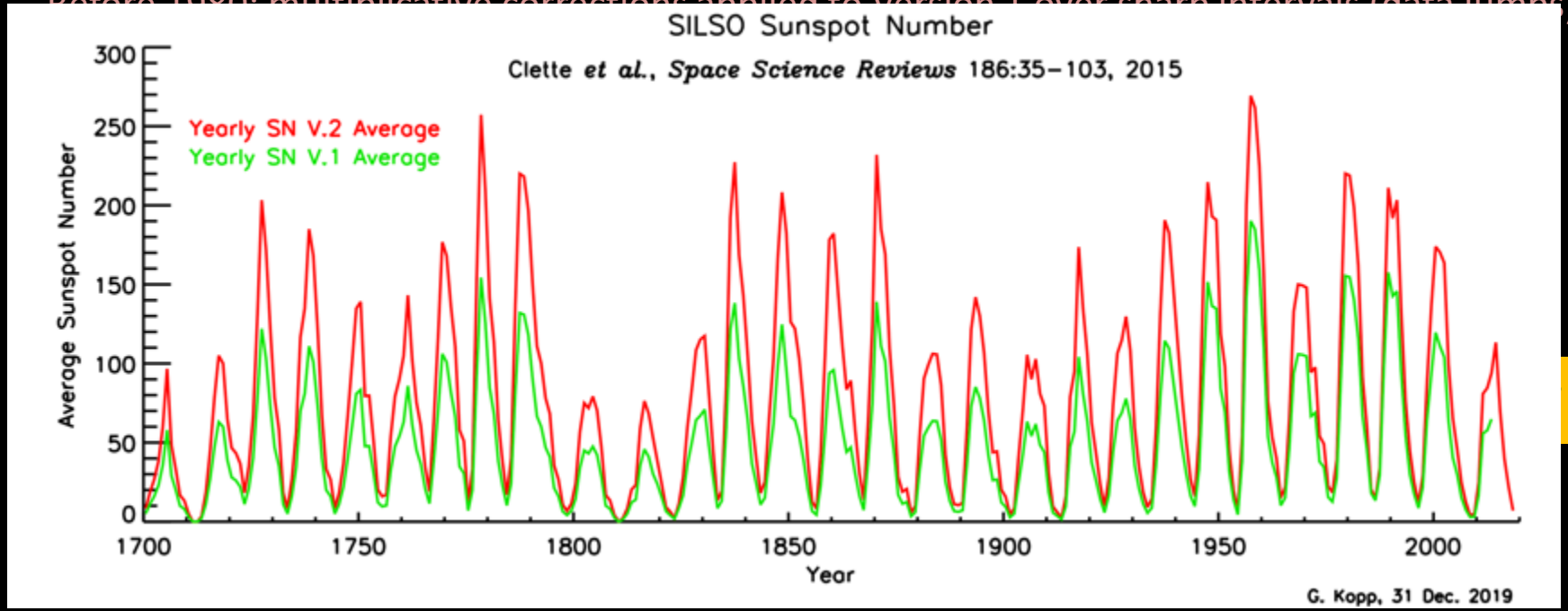
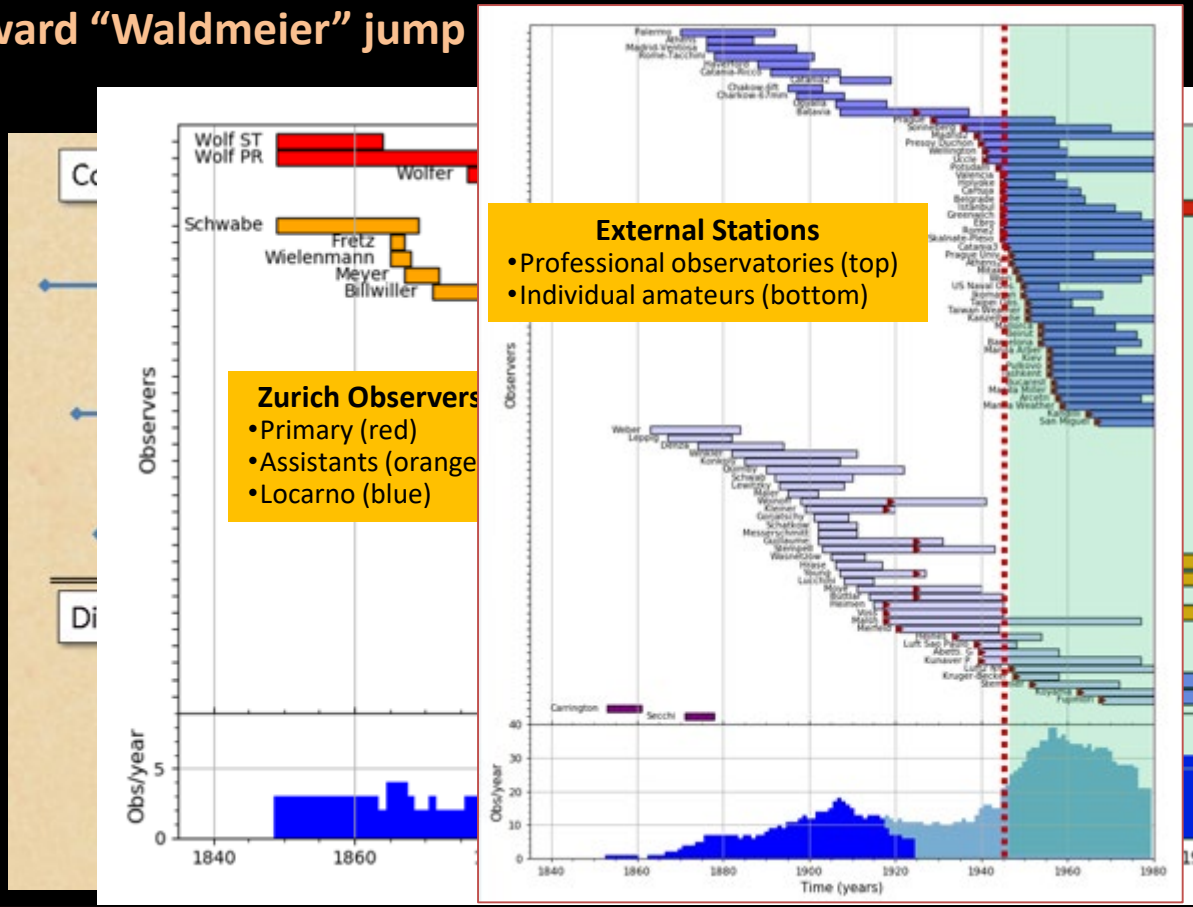
The Sunspot Number: A Different Construction

- Version 1: based almost entirely on intra- and inter-calibrated reference stations
  - Schwabe (1826-1849), Zurich (1849-1980), Locarno (1981-present)
- Version 2 *(Clette et al. 2015)*: new reconstruction after 1980 (SILSO network database)
  - Before 1980: multiplicative corrections applied to Version 1 over sharp intervals (data jumps)



The Sunspot Number: A Different Construction

- **Main correction: 1947 onward "Waldmeier" jump**
- Consensus reached on the amplitude:
  - Mean: 1.14 +/- 0.02
  - Cycle maxima: 1.177 +/- 0.005
- Probable cause identified
  - Disruption in source data between 1946 and 1947
  - Full renewal of the Zurich team and of the international network of auxiliary stations



Time-Series Reconstruction Methods

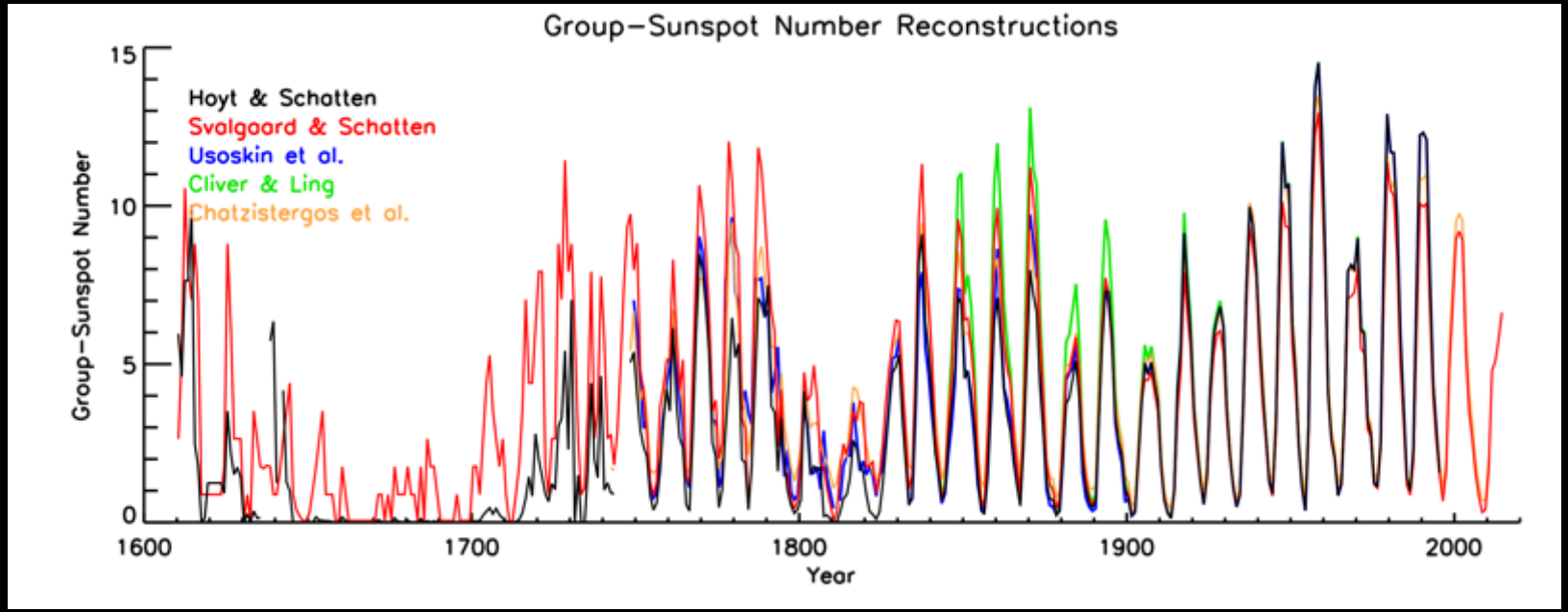
Overlap Methods

- Daisy Chaining (includes Backbone)
- Probability Distribution Function (PDF)
- Expectation Maximization

Non-Overlap Methods

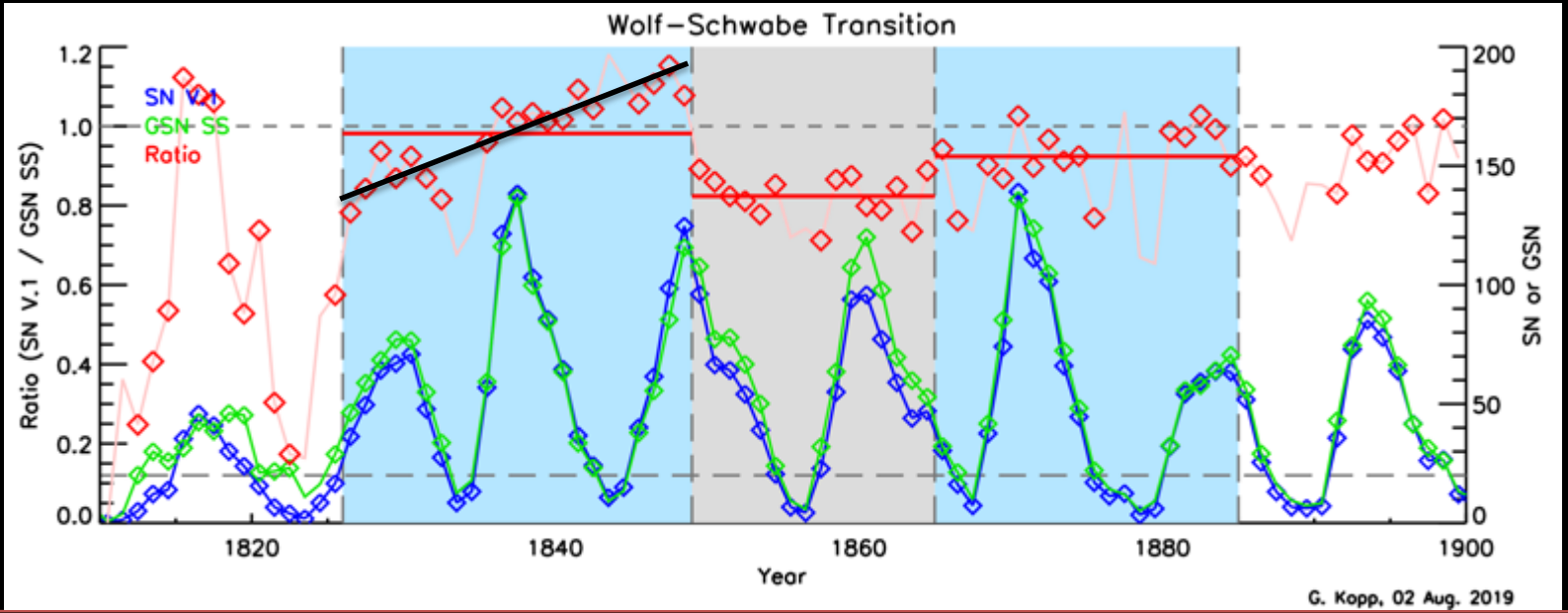
- Statistics-based
- Active-Day Fraction (ADF)
- Proxy-based

Application to Group Sunspot Number



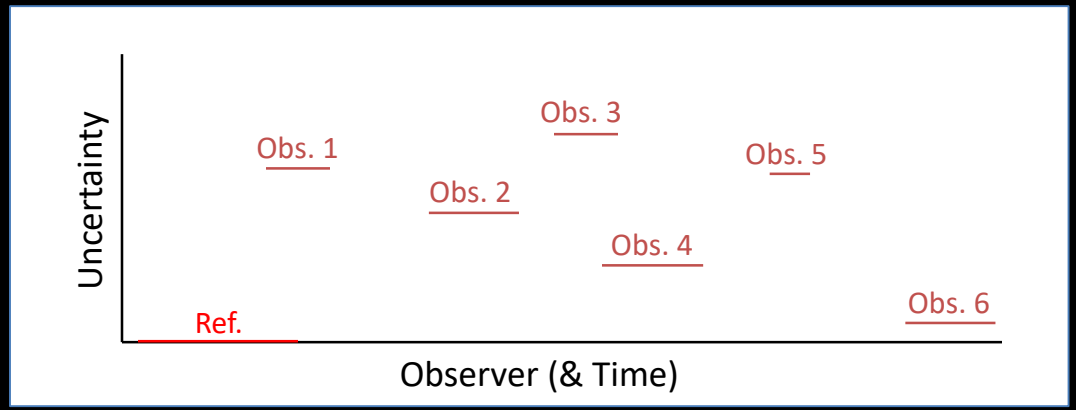
Overlap-Method Uncertainties Increase Monotonically

- Uncertainties increase monotonically forward and backward from any given time (or observer)
  - Observer sensitivity may change
  - Connecting one observer to another adds additional uncertainty
  - No current methods inherently correct for differing time-dependent trends between observers



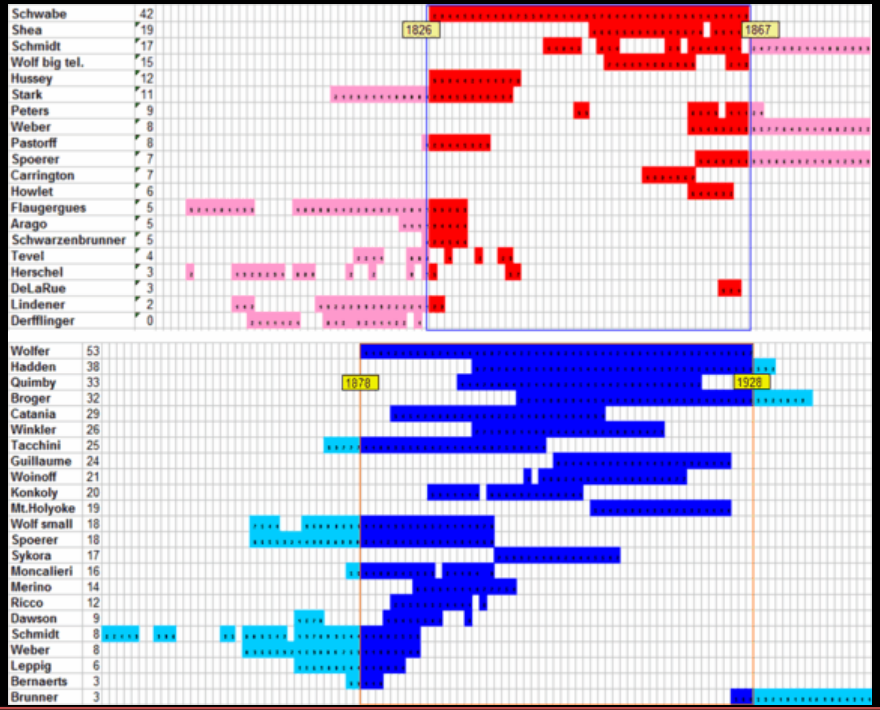
Non-Overlap-Method Uncertainties Are Largely Time-Independent

- Uncertainties depend on observers (and solar-activity levels)
  - Relative uncertainties are not necessarily three-way commutative
  - Does not inherently allow for time-dependent changes in observer sensitivity



Daisy-Chaining Reconstruction Methods (Includes Backbone)

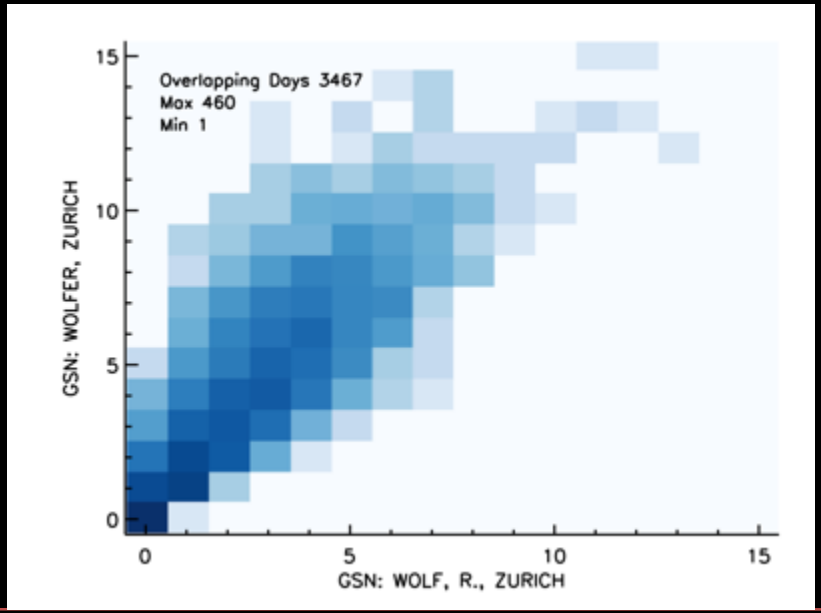
- Linear, non-linear, parametric, or non-parametric fits required to estimate uncertainties
- Single observer must be selected vs. time
- Does not inherently allow for time-dependent changes in observer sensitivity



Svalgaard & Schatten 2016

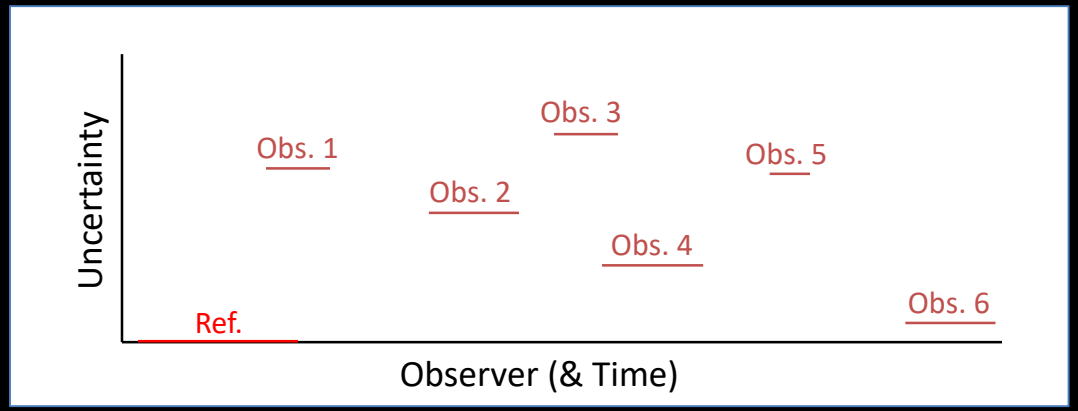
PDF Reconstruction Methods

- Does not require parameterization
- Estimates uncertainties via statistics (i.e. via Monte Carlo)
- Single observer must be selected vs. time (but can be statistically driven and less subjective)
- Does not inherently allow for time-dependent changes in observer sensitivity
- Uses only co-temporal daily data (in Theo's implementation)
  - Yearly (and even monthly) time-averages can be misleading



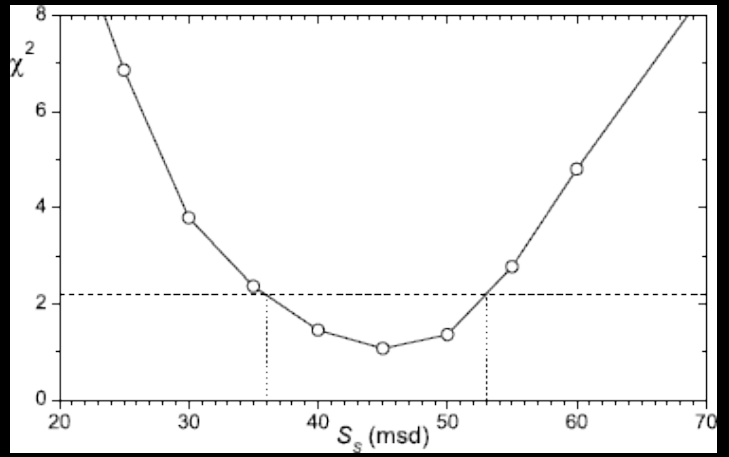
ADF and Statistics-Based Reconstruction Methods

- Uncertainties are independent of temporal separation
- Uncertainties are dependent on observers and solar activity level
- Does not inherently allow for time-dependent changes in observer sensitivity
- Does not require parameterization



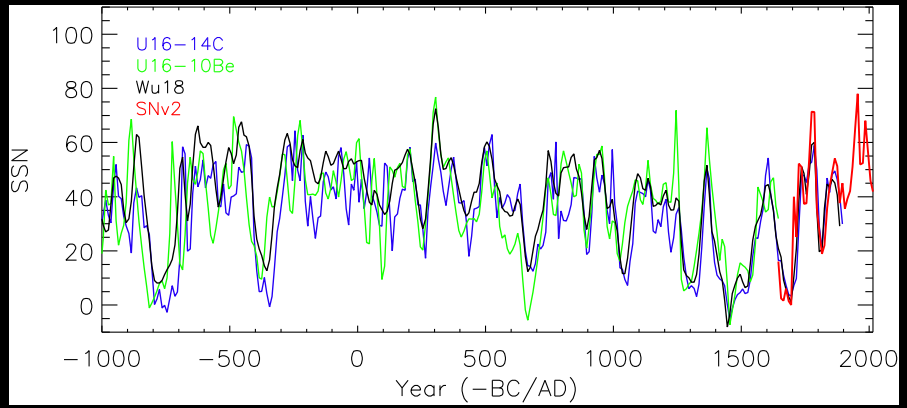
- But (ADF-implementation limitations)
  - Uses a synthetic "perfect observer" (model)
  - Assumes sampling is independent of solar-activity level

Usoskin *et al.* 2016



Proxy-Based Reconstructions

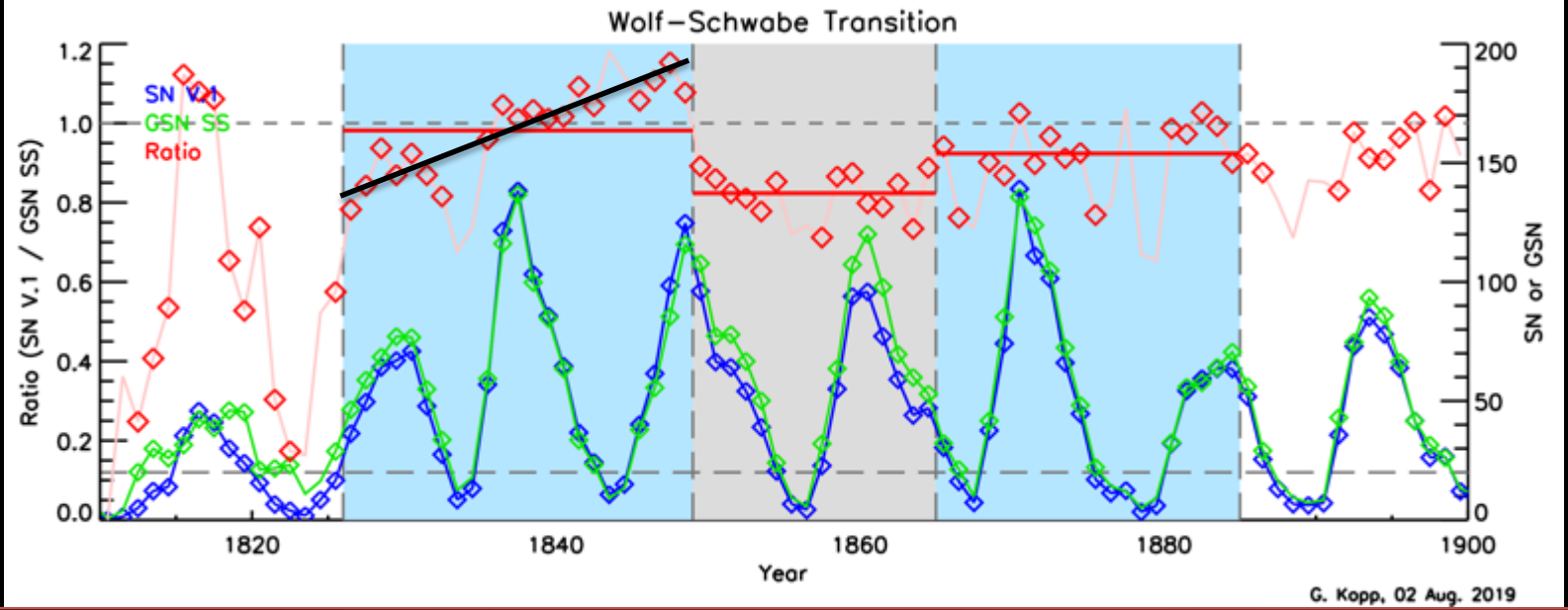
- Use solar proxies to reconstruct sunspot records
  - Examples: geomagnetic indices; ionosondes; isotopes (^{10}Be, ^{14}C); aurora
  - Advantages: Independent tracers of solar activity, some with very long durations
  - Disadvantages: often driven by open solar flux (not closed); influenced by non-solar processes; limited temporal resolution (> 11 years)
- May only be used as "consistency check" of sunspot-number reconstructions
  - Greg's (TSI) Rule: "Consistency is comforting, but agreement does not necessarily indicate accuracy"
- Allows the extension of the solar-activity record prior to the last 400 years



Wu *et al.* 2018

Need to Account for Trends in Observers' Records

- Observer sensitivity may change
- No current methods inherently correct for differing time-dependent trends between observers



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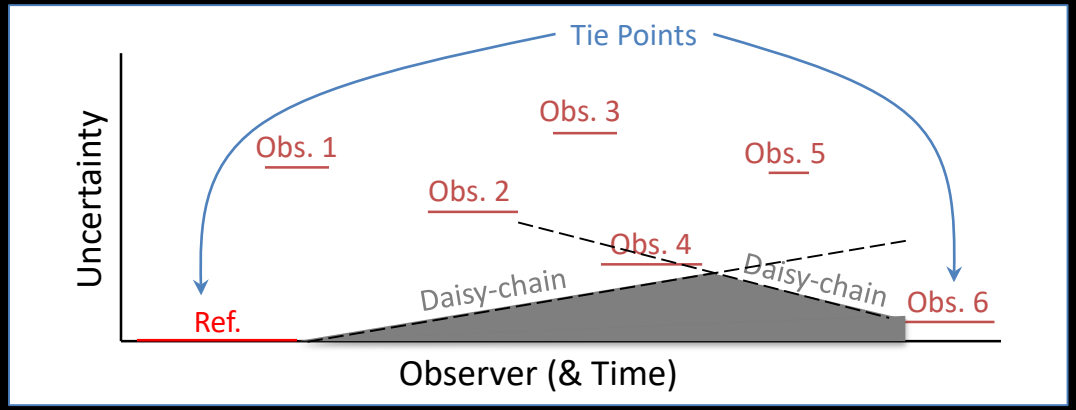
Methodology	Inherent Uncertainties	Req. Para-meterization	Spans Gaps or Sparse Data	Weights All Data in Result	Inherent Trend Detection	Maturity (low = good)
Daisy-chaining	no	yes	no	no	no	1
Rank/Tied-Rank	not yet	no	no	no	no	5
Expectation-Maximization	yes	no	maybe...	yes	possible	6
PDF	yes	no	no	no	no	2
ADF	not yet	no	yes	no	no	4
Proxies	no	no	yes	no	possible	3

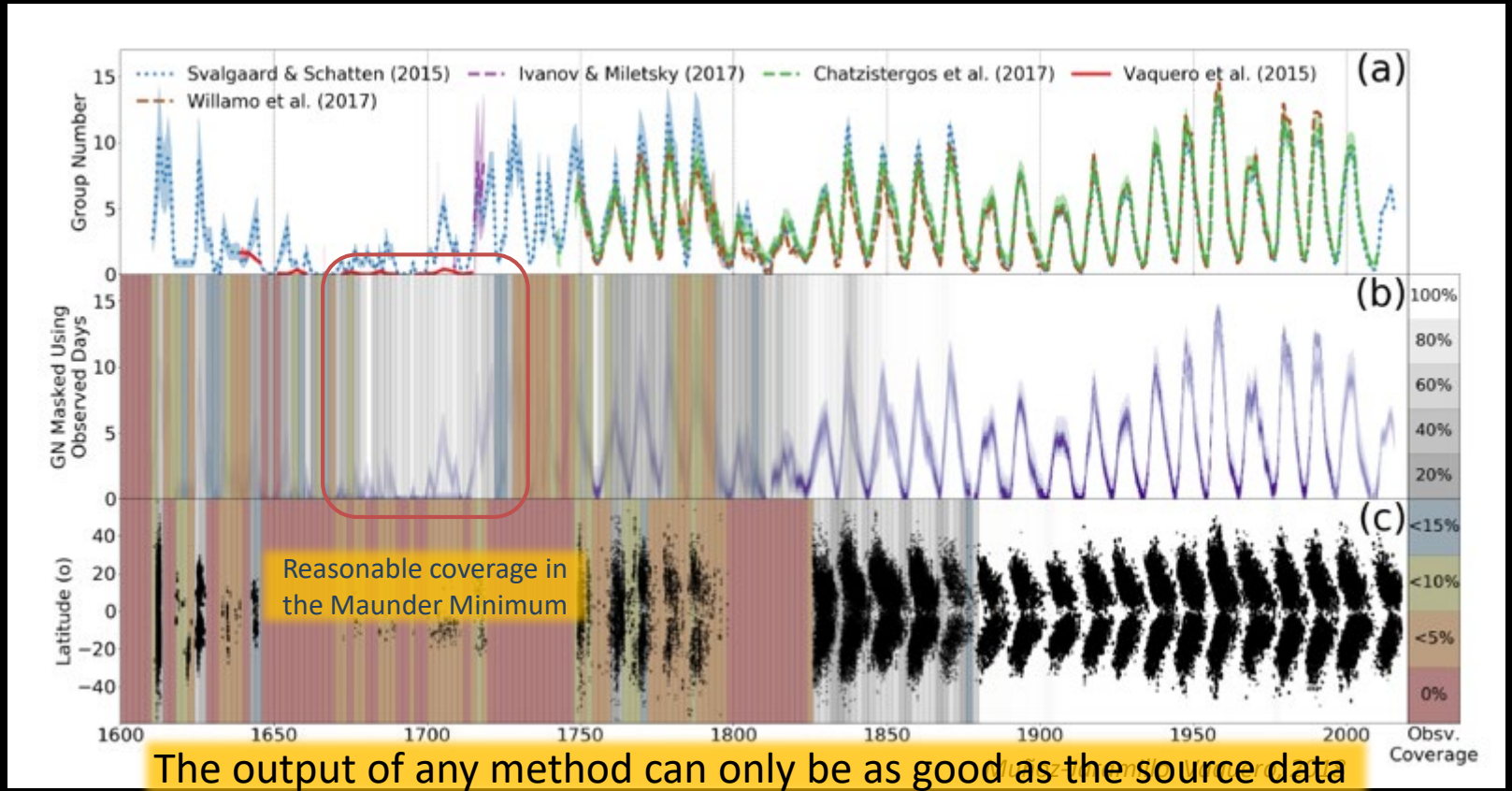
Suggestions on Reconstruction Methods

- Combine different reconstruction methods over time as is most beneficial for point-to-point uncertainties
  - Overlap methods are generally best short-term and when there are multiple sequential observers
    - Co-temporal measurements generally give low uncertainties and allow cross-calibration approaches
  - Non-overlap methods have advantages long-term and when observations are sparse
    - Preferred when monotonically-increasing overlap-method uncertainties exceed non-overlap (i.e. ADF) uncertainties between two observers
    - Applies even if observation continuity is possible



The Quest for More Data

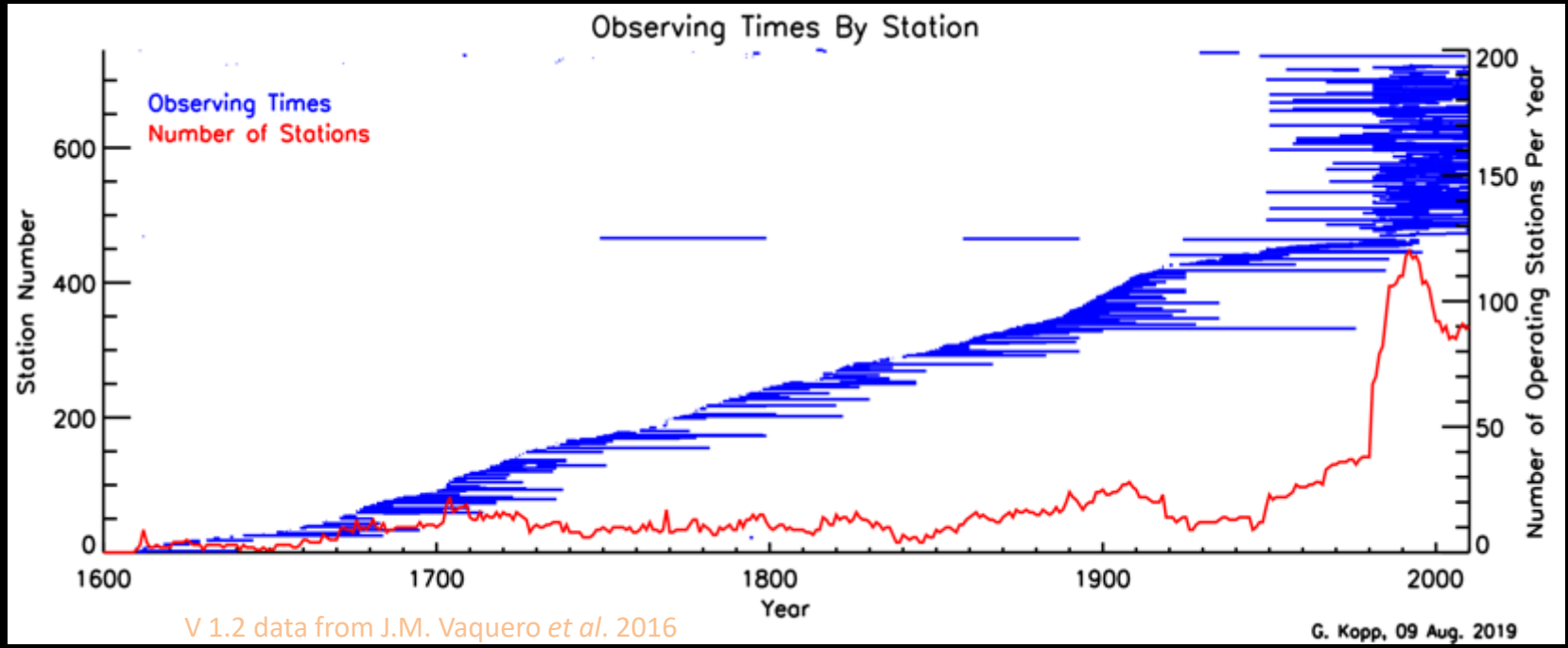
Sparse observations and occasional long gaps in early data (< 19th century)



The output of any method can only be as good as the source data

The Quest for More Data: Group Number Database

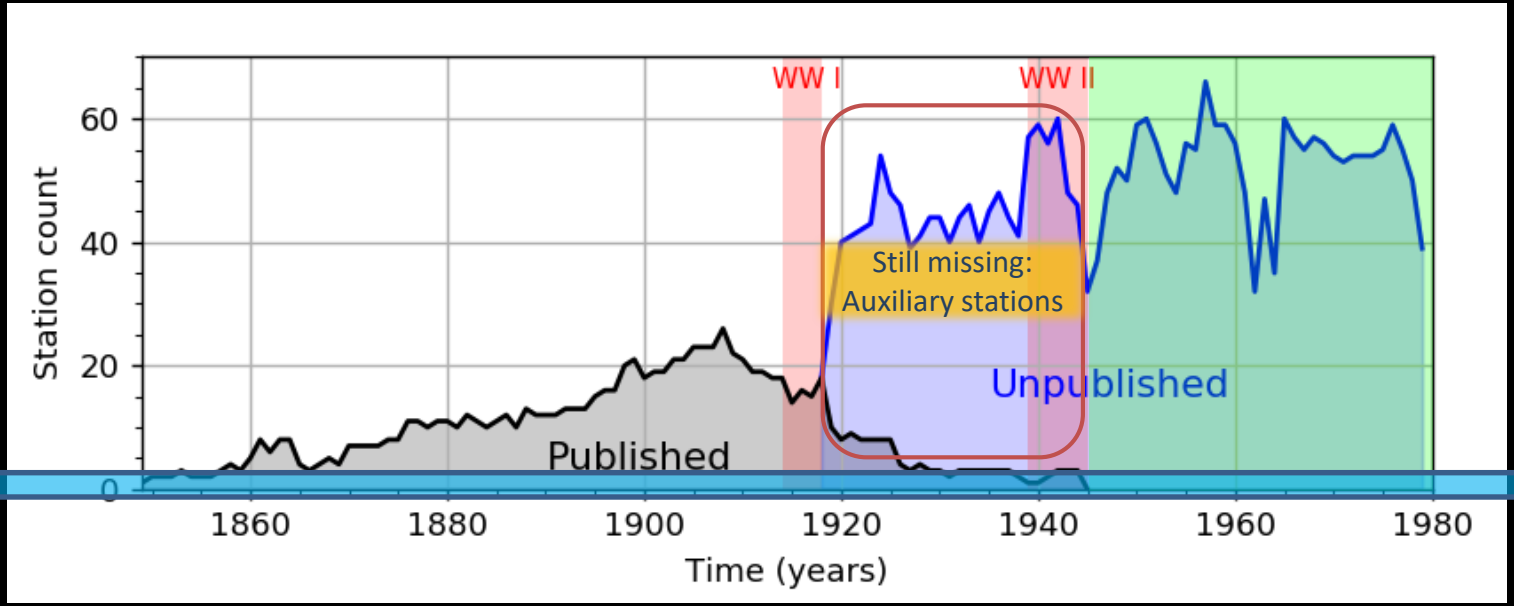
- Corrections of misinterpreted data in the Hoyt & Schatten 1998 original database
- Newly-recovered series and drawings in 17th and 18th centuries (incl. observers in Asia)
- New version (V 1.3) in preparation (Vaquero, Carrasco, Gallego)



V 1.2 data from J.M. Vaquero *et al*. 2016

The Quest for More Data: The Sunspot Number Database

- Long-lost archive of Zürich source data from 1945 to 1980 fully recovered in 2018
- Full digitization of the source data in the Zürich *Mittheilungen* almost completed (2020)



Major advances towards continuous data coverage from 1826 to the present

Basis data for the first full reconstruction of the SN series (Version 3)

Summary and Future Plans

- **Methodology Recommendations**
  - All methods need quantified time-dependent uncertainties
  - Keep *GSN* and S_N time series independent of proxies
  - Use the best of different methodologies and their appropriate time ranges
    - E.g. **Expectation-maximization** or **PDF** short-term (continuity) and **ADF** for long-term tie points (span gaps)
    - Let uncertainty analyses drive the methodology
  - Consider new methods to detect and account for trends
  - Most issues are associated with changes in observer-processing methods rather than in the source data
  - *SN* time series (Version 3): from single pilot station to a full reconstruction from source data
- **Historical Data Recommendations**: Continue improvements and expansion
  - Importance of studying original historical documents: understand changes in observing practices or in the observers themselves (jumps!)
  - Group-number database update (Version 1.3) in preparation: concentrate on continuity gaps
  - Sunspot-number database improvements
    - Before 1945: published data fully digitized; now under quality control; release by mid-2020
    - 1945-1980: source tables fully recovered; connecting the Zurich series with the contemporary data (SILSO)