

Long-Term Solar Activity Reconstruction: Grand Minima and Maxima

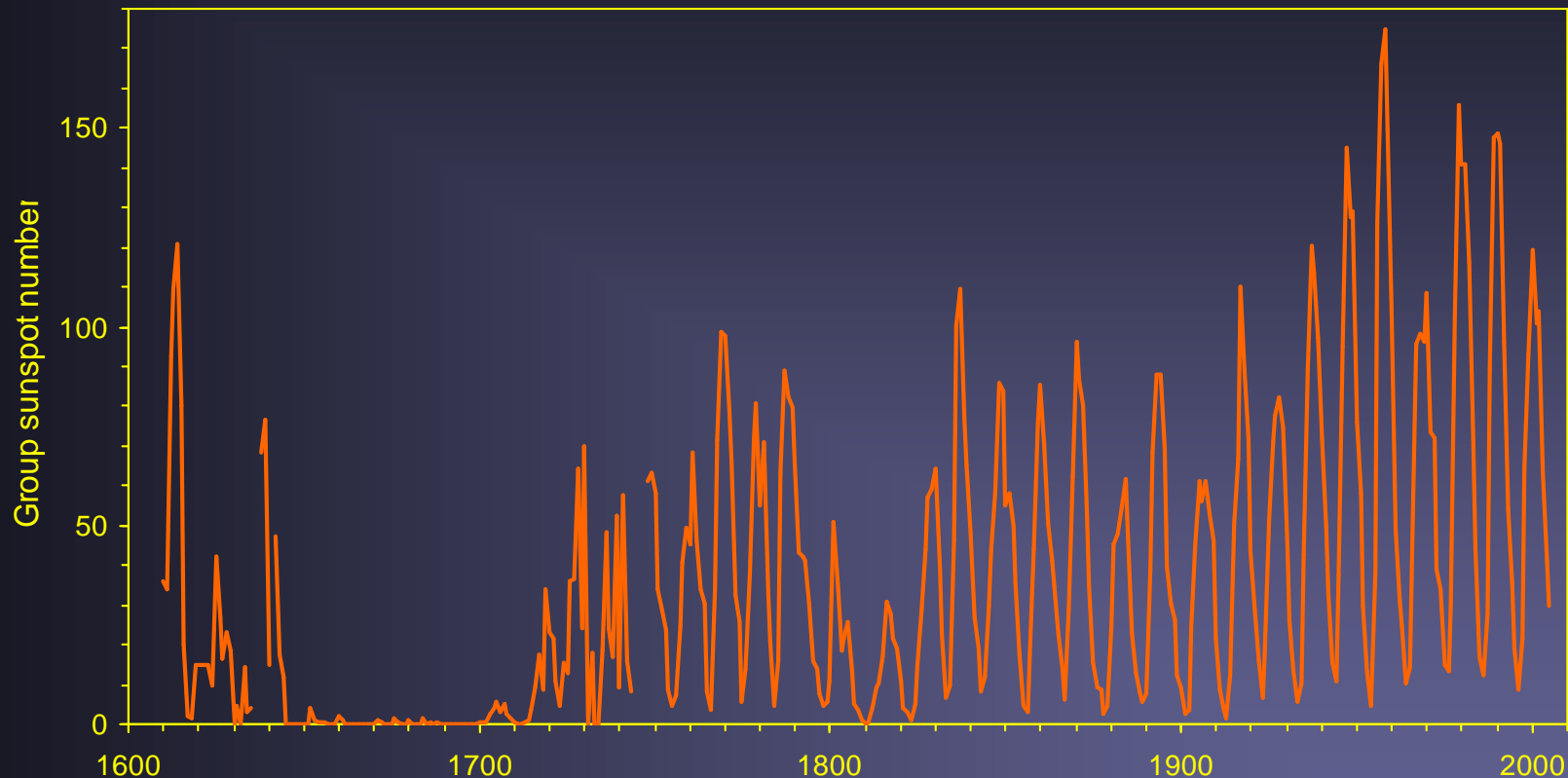
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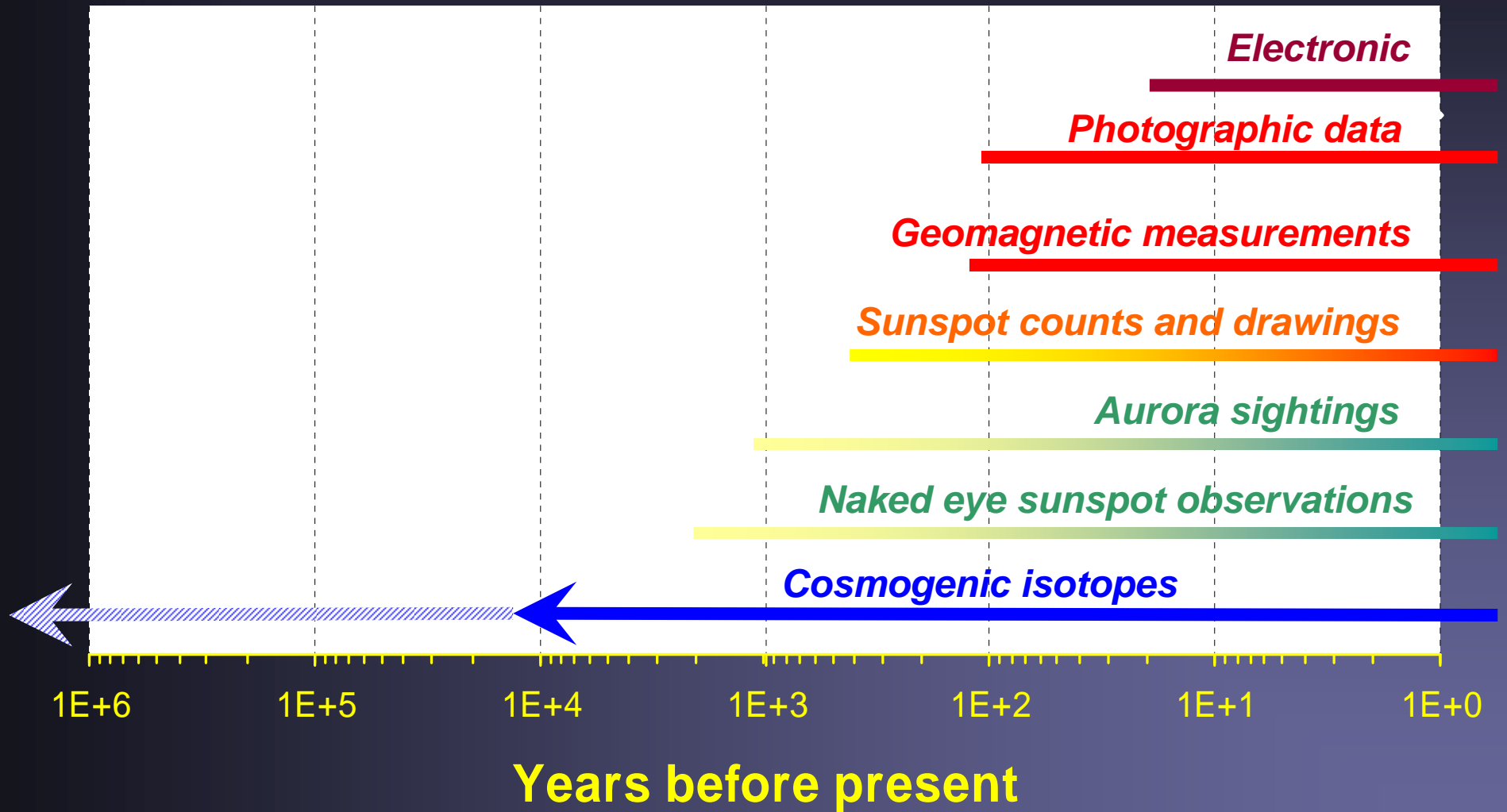
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Solar activity variations: telescopic sunspot number record

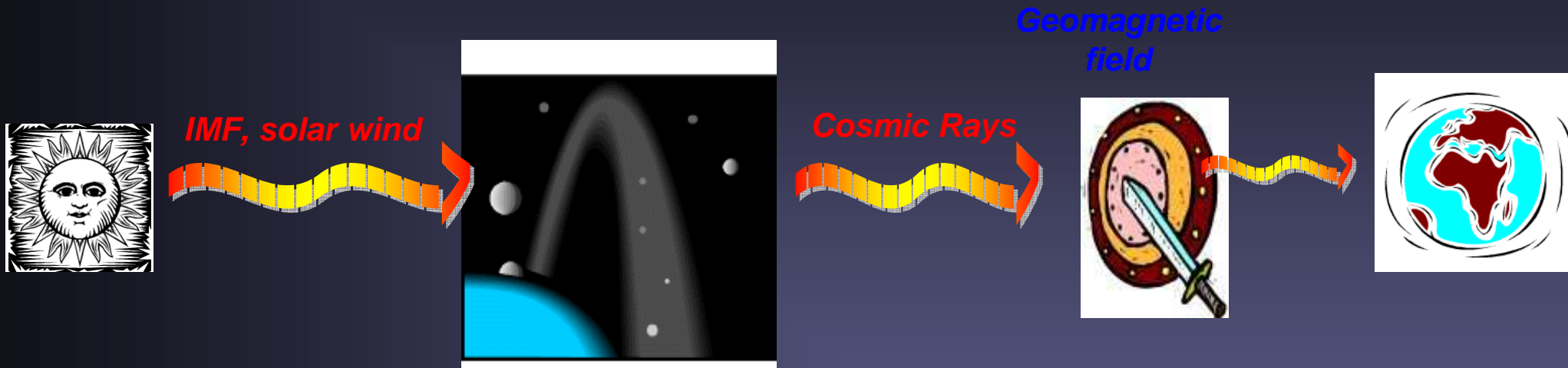


- 11-year solar cycle (Christian Horrebaw 1770s; Schwabe 1843)
- Variable amplitude/envelope (Gleissberg 1944);
- Maunder minimum (Hivelius; Eddy 1976);
- The contemporary level is high

Solar activity in the past



Proxy of SA: Cosmogenic isotopes



- Variable solar activity expands to the Heliosphere: solar wind, interplanetary magnetic field, interplanetary transients (CME, corotation regions), etc.
- Galactic cosmic rays are modulated by IMF, magnetic inhomogeneities, solar wind;
- Geomagnetic field partly shields the Earth (mid- and low-latitude regions) from incoming cosmic rays;
- This process is well understood and can be properly modelled (Beer, Space Sci. Rev., 2000; Usoskin et al., Phys. Rev. Lett., 2003; Solanki et al., Nature, 2004)

SN reconstruction from ^{14}C or ^{10}Be

e.g. Model by Solanki et al. (2002)

Sunspot number  open magn. flux

e.g. Model by Usoskin et al. (2002a)

Modul. strength  CR intens. variations

Deposition models, paleomagnetic models

^{10}Be : *Webber & Higbie*, ^{14}C : *Usoskin & Kromer*

B_{\oplus} : *Yang et al. (2000)*, *Korte & Constable (2005)*

Sunspot numbers



Heliospheric params



CR intensity

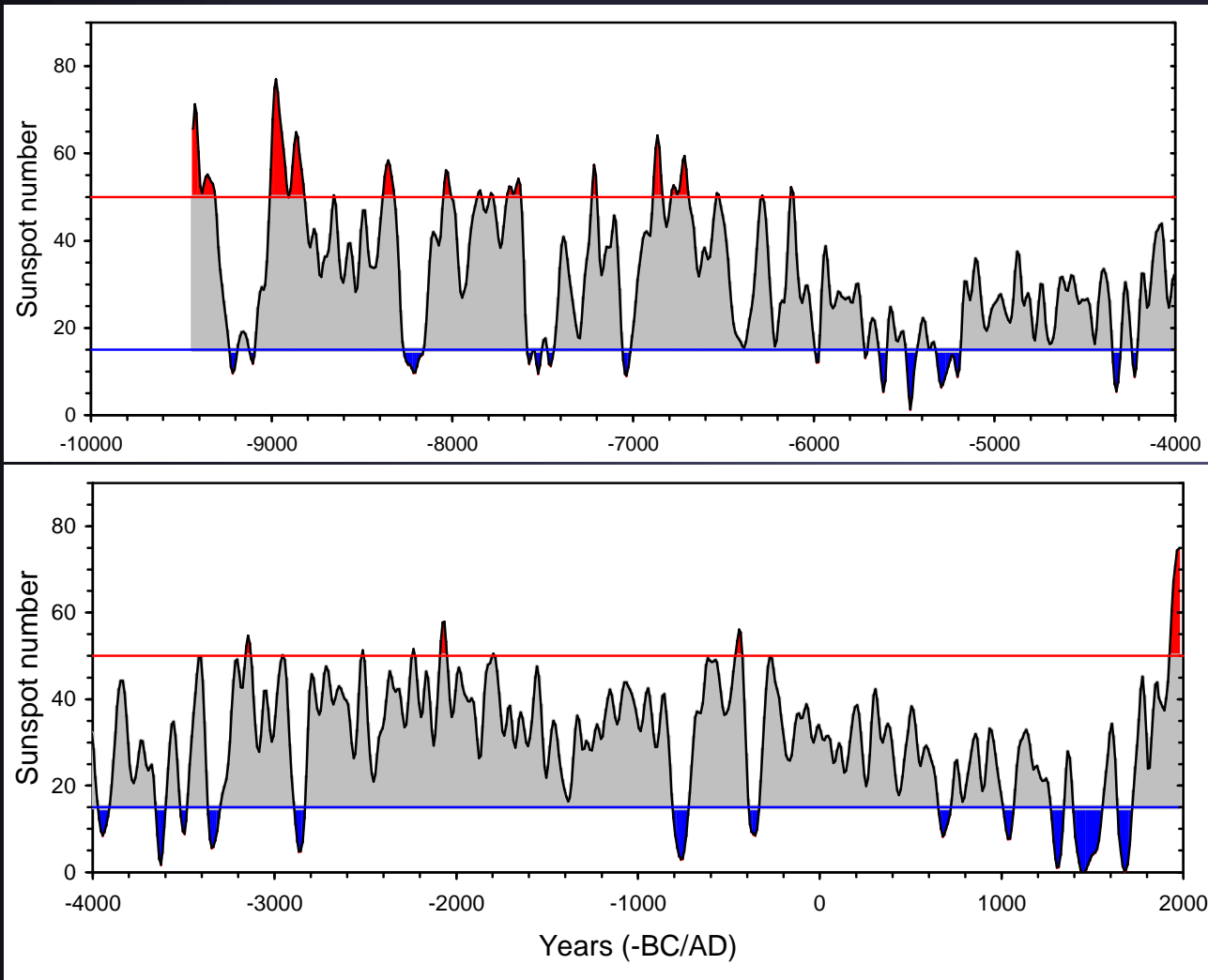


Cosmogenic isotopes
in natural archives

Usoskin et al. (2002b)

Solanki et al. (2004) , Usoskin et al. (2004, 2007)

Sunspot number reconstructed from ^{14}C



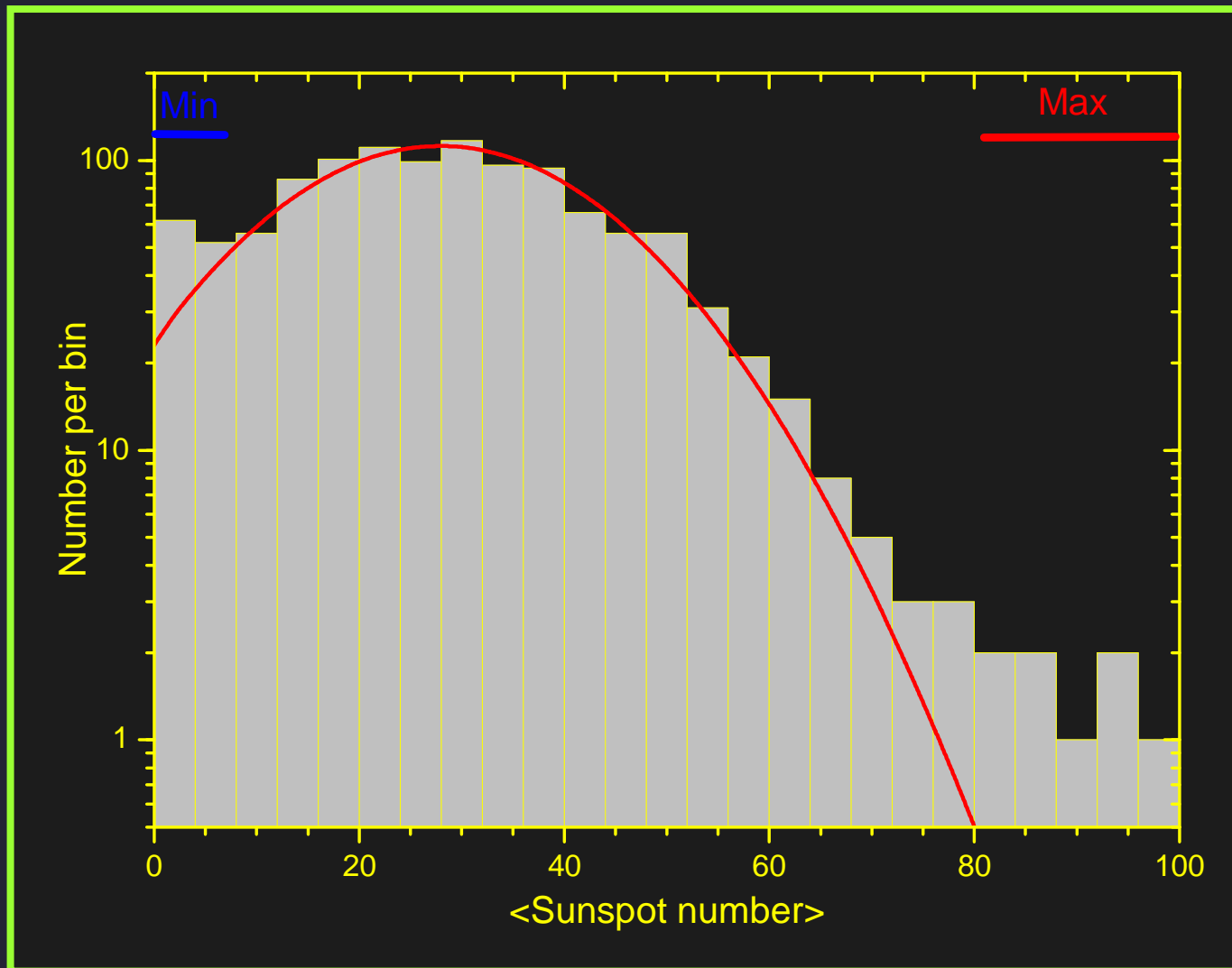
Smoothed Sunspot number over 11400 yr

27 Grand minima
19 Grand maxima
can be identified.

Minima cover
1880 yr \approx 17% of time
Maxima cover
1030 yr \approx 9% of time

Solanki, Usoskin, Kromer, Schüssler, Beer, *Nature*, 2004
Usoskin, Solanki & Kovaltsov, *A&A*, 2007

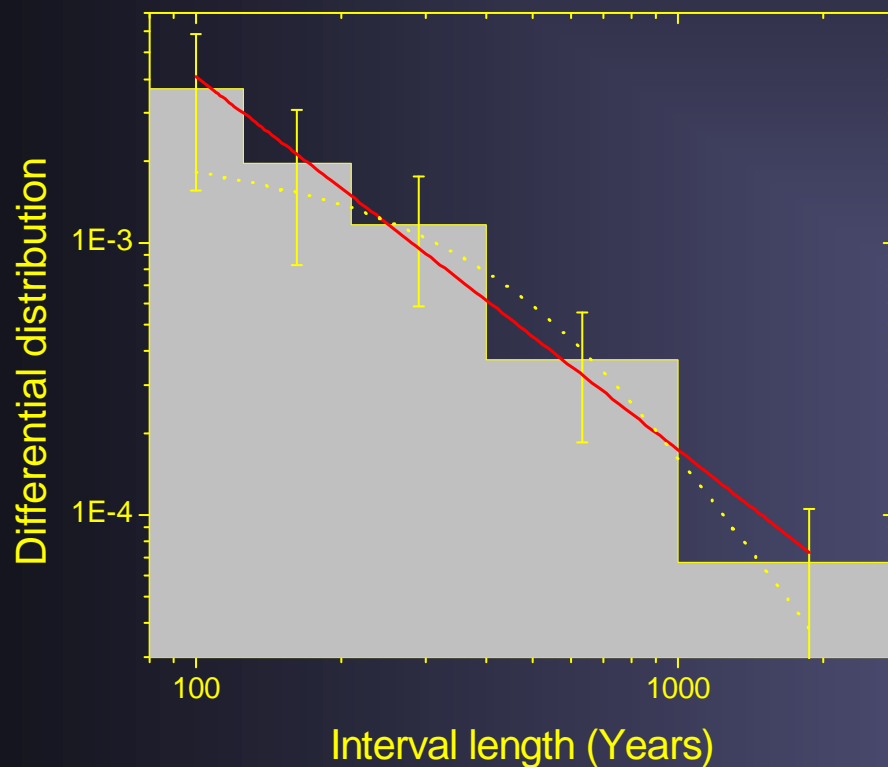
Sunspot number statistics



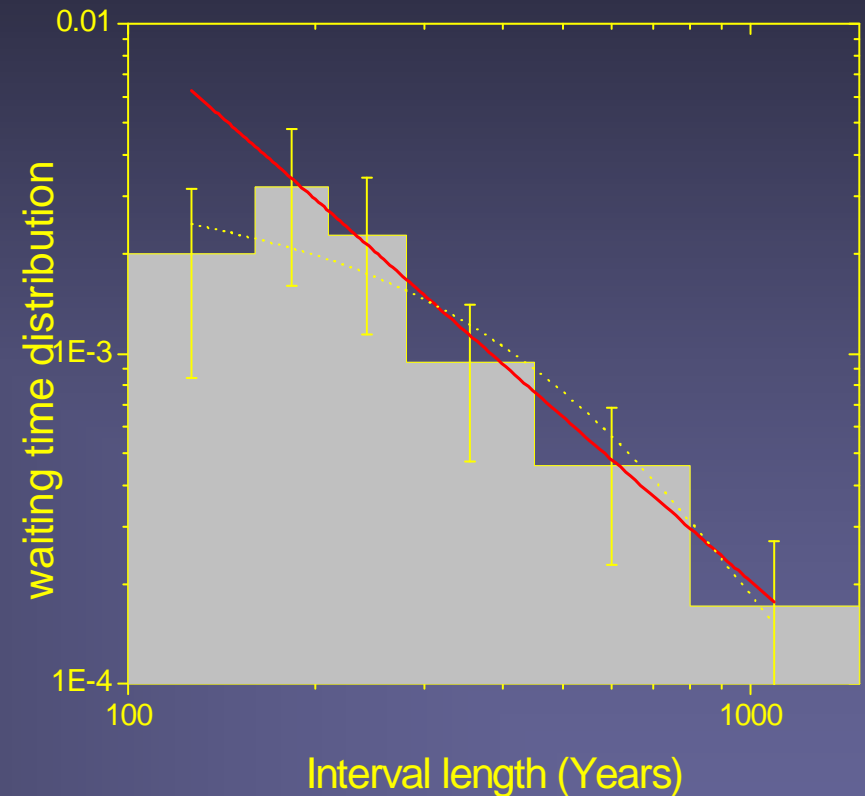
Red curve: best-fit normal distribution

Waiting time distribution

Grand minima



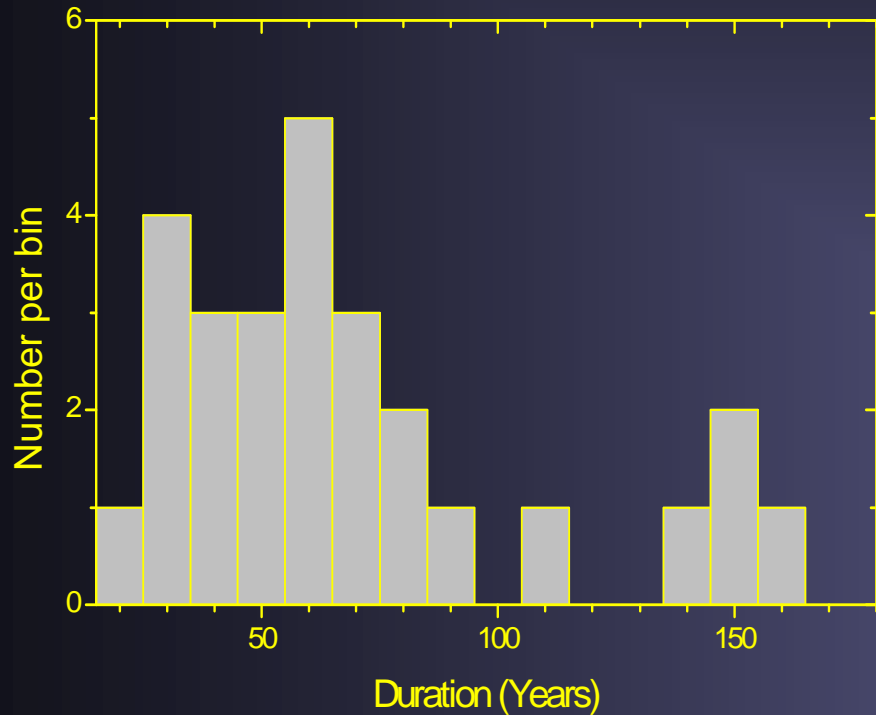
Grand maxima



Closer to power law (red lines) than to exponential (dotted yellow lines) → waiting time tends to show clustering of **Min** and **Max**

Durations of Minima & Maxima

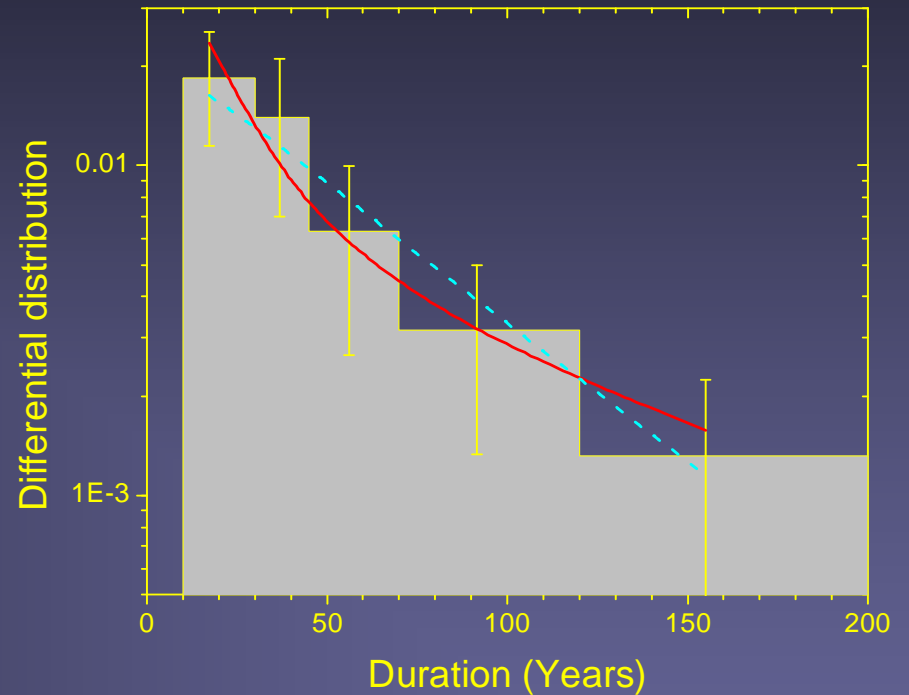
Grand minima



Maunder ←→ Spoerer

Quasi-Bimodal

Grand maxima



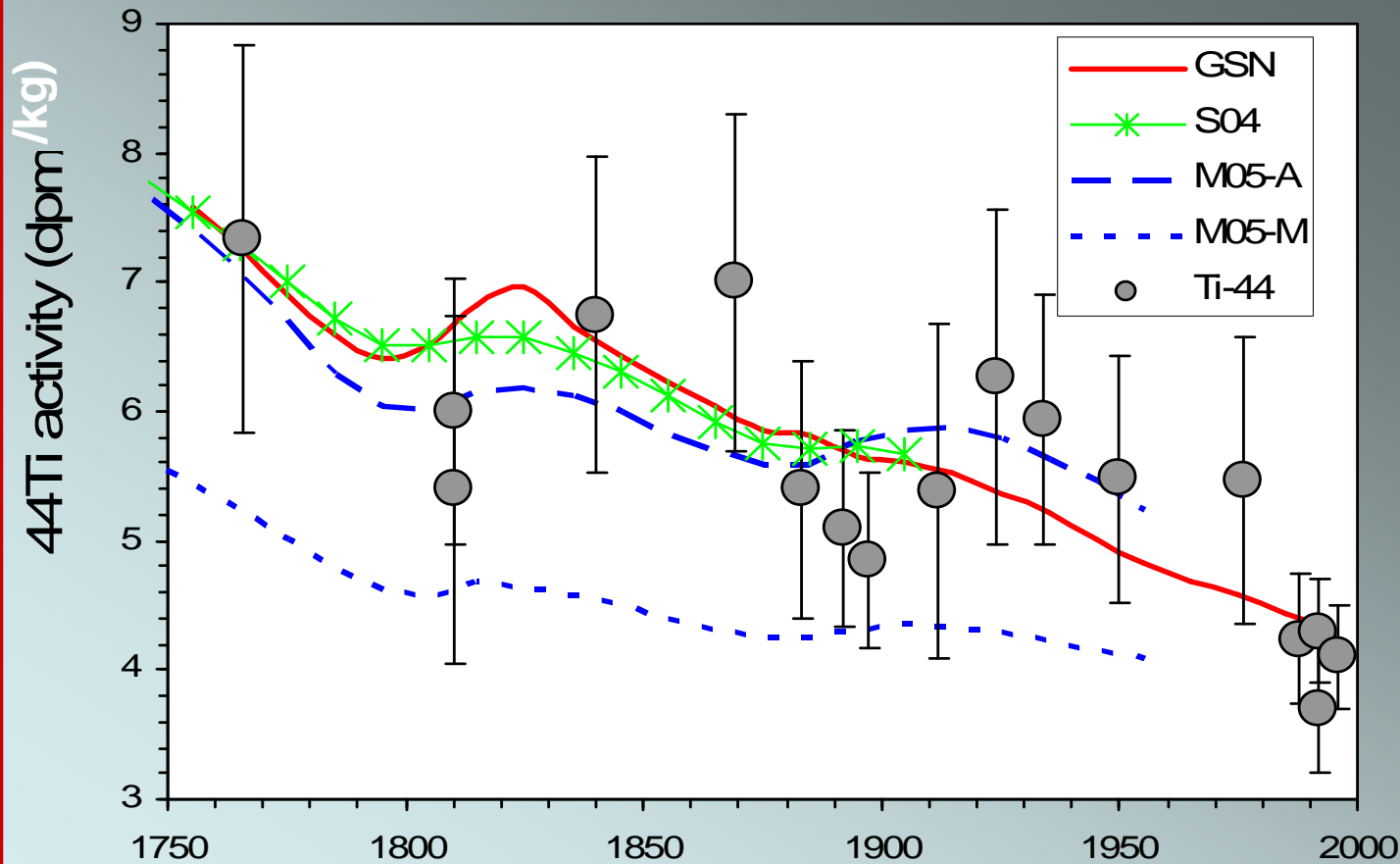
Exponential

Conclusions

- The Sun spends 17% of the time in **grand minima**, 9% in **grand maxima**. Currently the Sun is in a grand maximum.
- Grand **minima/maxima** are not due to long-term cyclic variations but rather to stochastic/chaotic processes.
- Waiting time distribution of occurrence of **grand minima** and **maxima** deviates from an exponential distribution → typical of non-Poisson processes with, e.g., self-organized criticality or processes related to accumulation and release of energy.
- **Grand minima** can be classified into two different types: short minima of **Maunder type** and long minima of **Spörer type**.
- Duration of **grand maxima** exponentially distributed → leaving a **grand maximum** is a random process, unlike for **grand minima**







Ti-44 activity: measurements vs. model

Preliminary results!

New data are currently being finalized and analyzed

Model	χ^2 (DoF)	Confid. level
GSN	7.55(17)	98%
S04	2.44 (8)	97%
M05-M	20.5 (11)	4%
M05-A	4.4 (11)	95%