

Cosmic-ray variability over millennia: A new multi-proxy reconstruction

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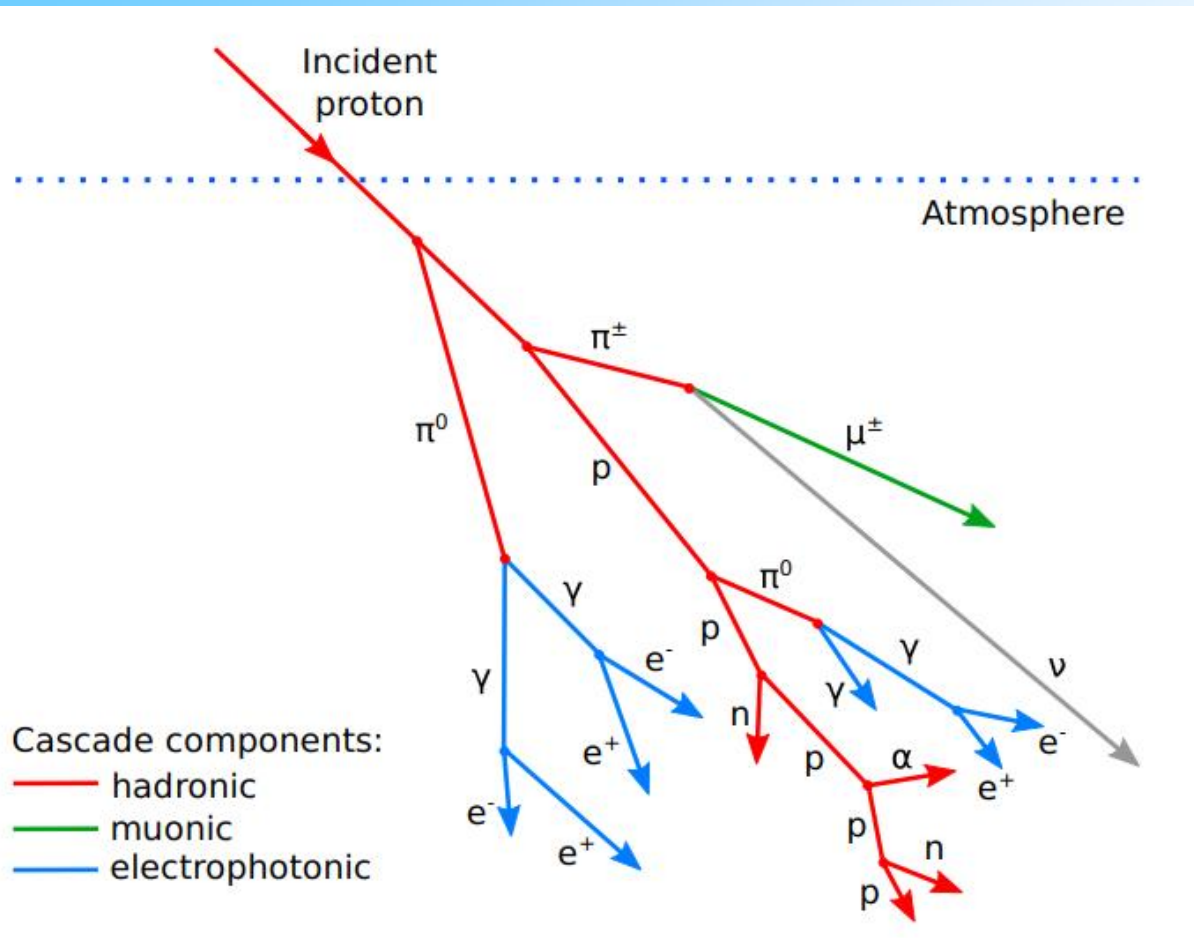
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Cosmogenic isotope production



In the atmospheric cascade, nuclear reactions may take place, most important being:

Spallation reactions on O , N , Ar \rightarrow 7Be , ^{10}Be , ^{22}Na , ^{36}Cl , etc.

Neutron capture: $^{14}N+n \rightarrow ^{14}C+p$

Storage in natural independently dated archives: ice-cores, tree trunks, sediments, corals

cosmogenic ^{14}C and ^{10}Be



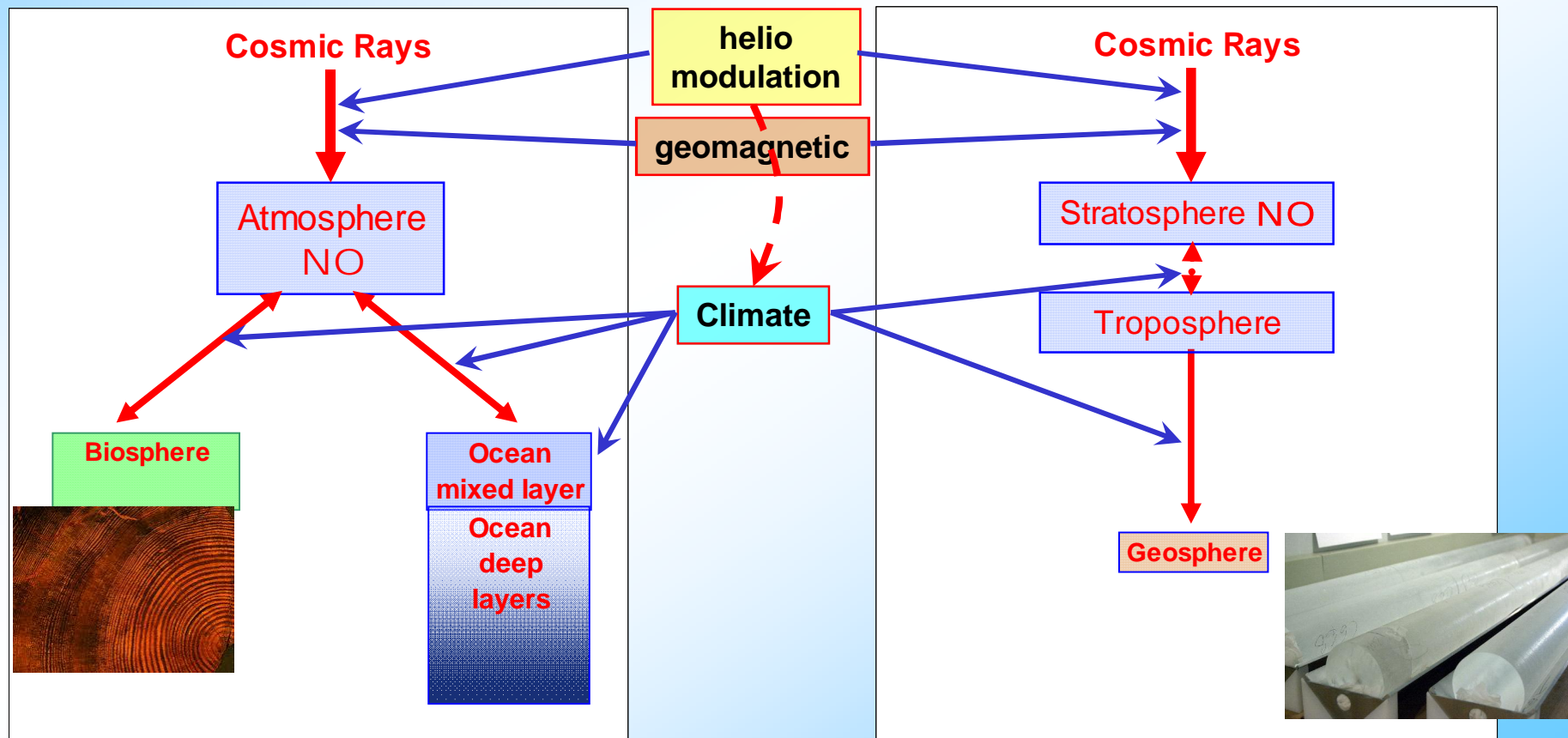
$\text{CO}_2 \rightarrow$ carbon cycle \rightarrow tree rings

- Effective CR energy is ~ 3 GeV/nucleon;
- mean altitude: upper tropo, low stratosphere;
- measurements: normalized $^{14}\text{C}/^{12}\text{C}$ ratio

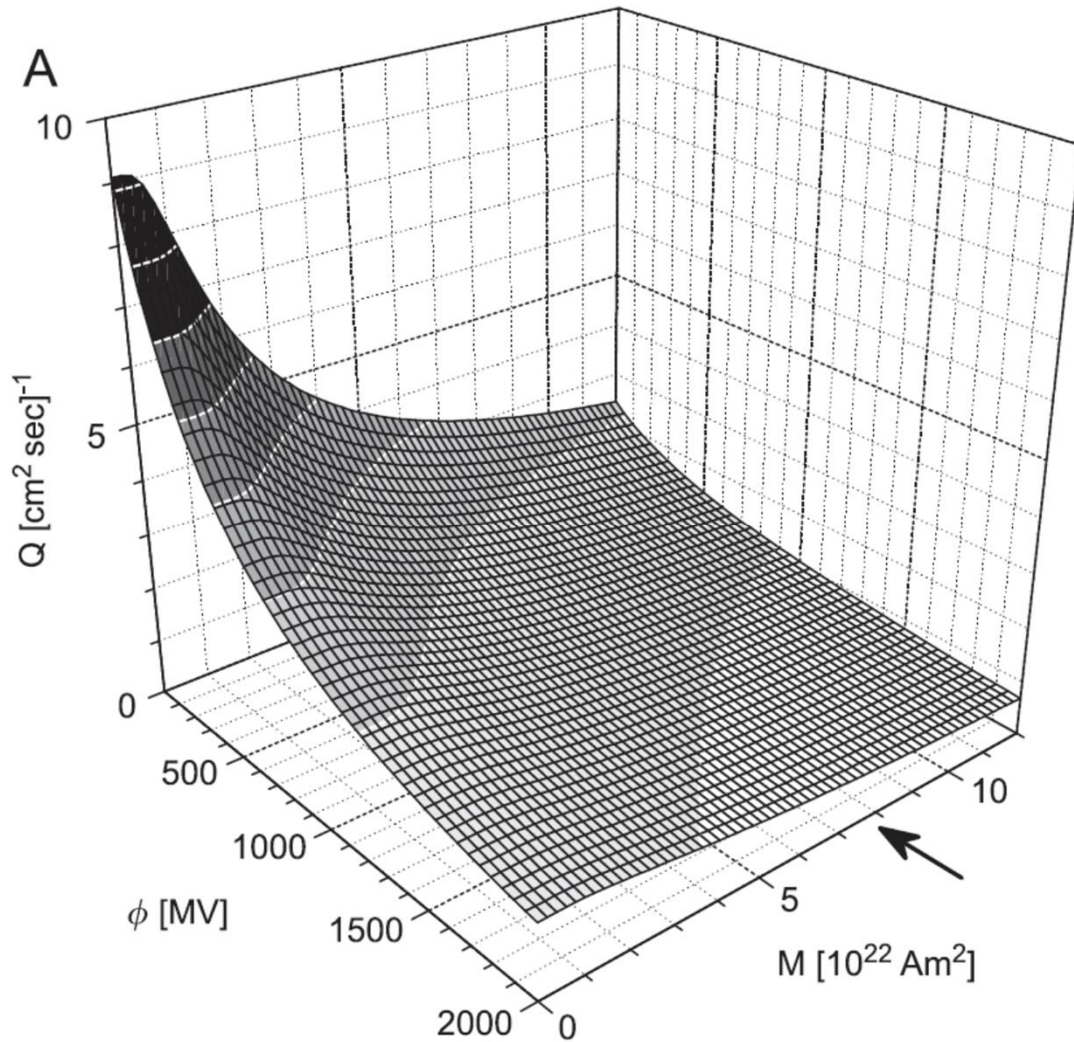


aerosols \rightarrow fall out

- Effective CR energy is 1–2 GeV/nucleon;
- mean altitude: upper tropo, lower stratosphere;
- measurements: abundance



Production model

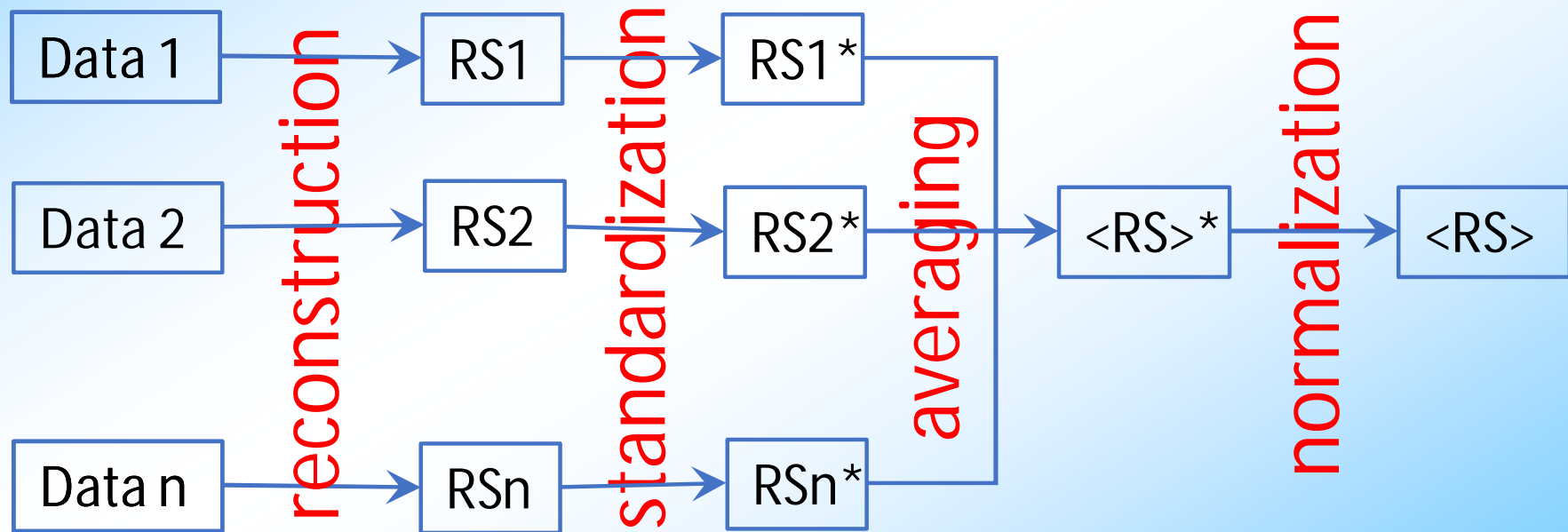


Kovaltsov, Mishev & Usoskin (EPSL, 2012);
Poluianov et al. (JGR, 2016)

- Full range of GCR energy (0.01-1000 GeV);
- Heavier species included explicitly;
- Calibration to direct in-situ GCR measurements (PAMELA, AMS experiments)
- Accuracy 1-2%

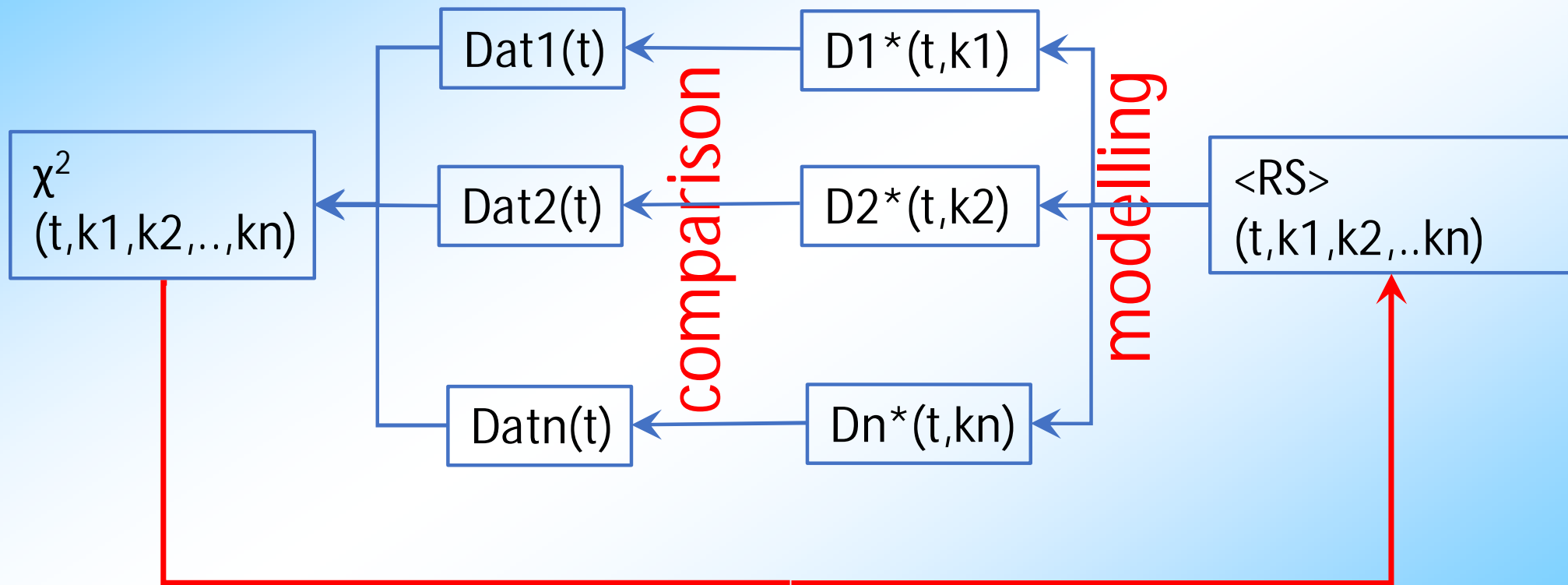
Multi-proxy composite

- Production models are precise (Poluianov et al., 2016) à ~1-2%
- Transport is less precise:
 - » ^{10}Be à local/regional deposition pattern $\pm 20\%$;
 - » ^{14}C – uncertainties in the preindustrial content, within 15% (full range);
- Standard composites (Steinhilber et al., 2012; Inceoglu et al., 2015; Usoskin et al., 2016)

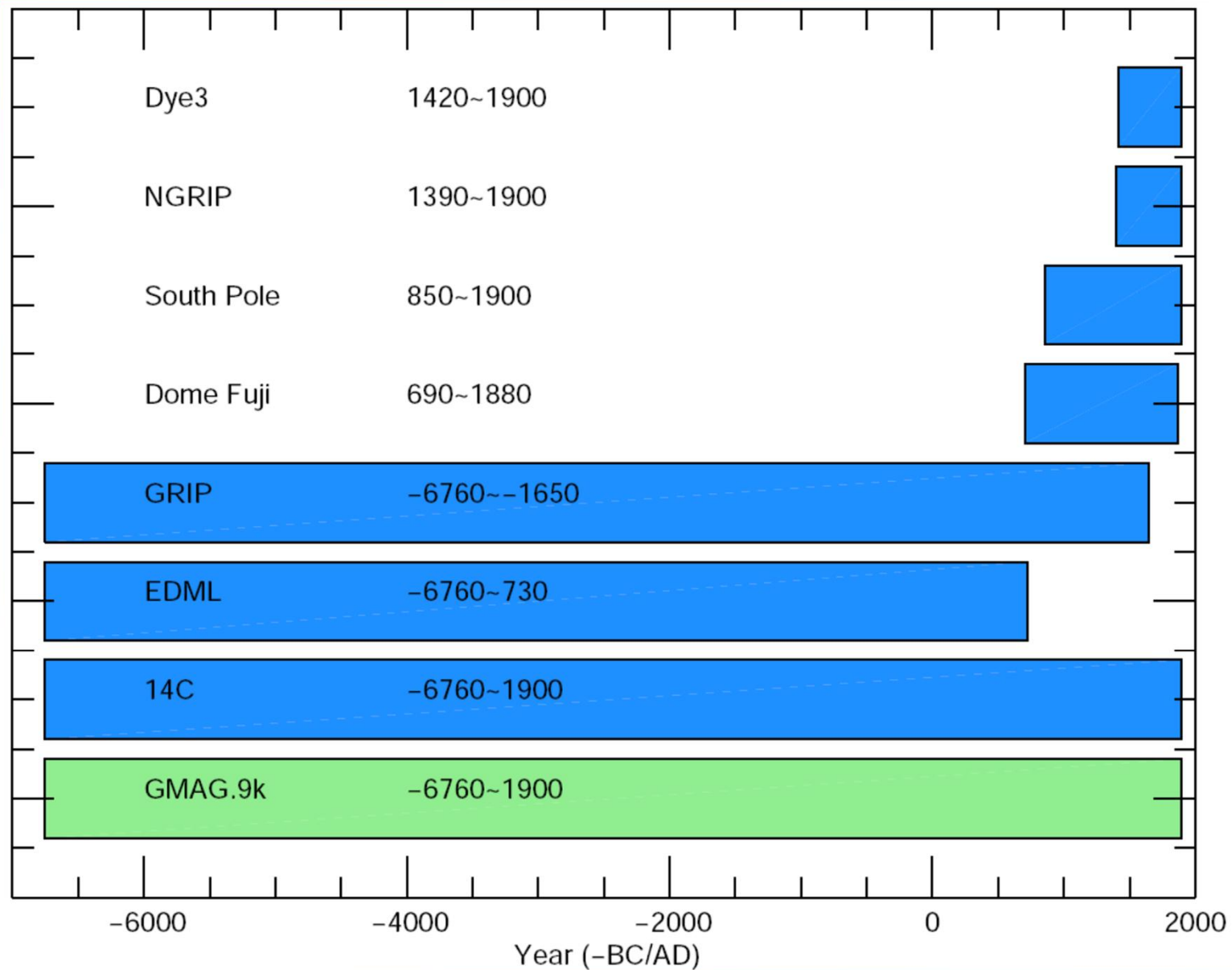


Multi-proxy composite (Bayesian)

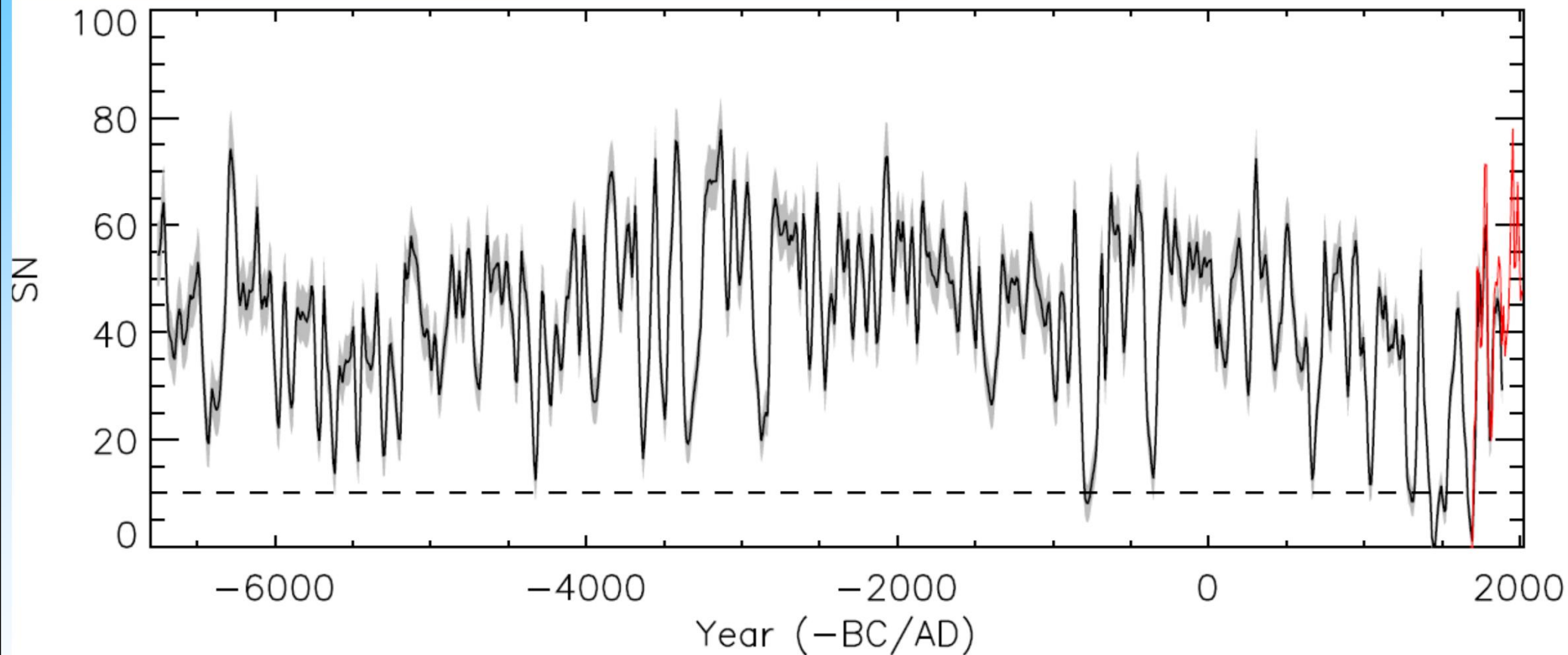
- Bayesian composite (Wu et al., 2018)



Datasets

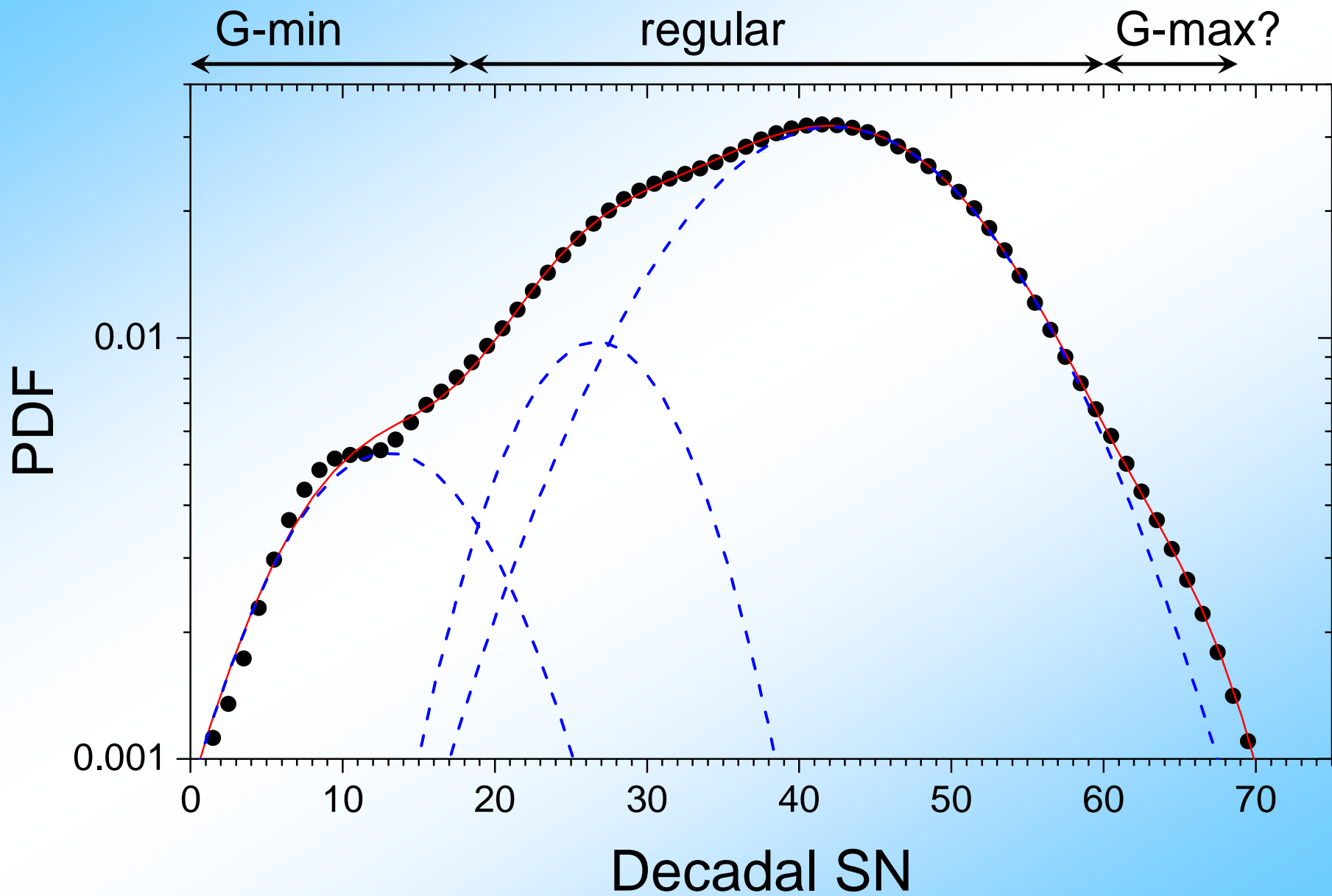


SN reconstruction

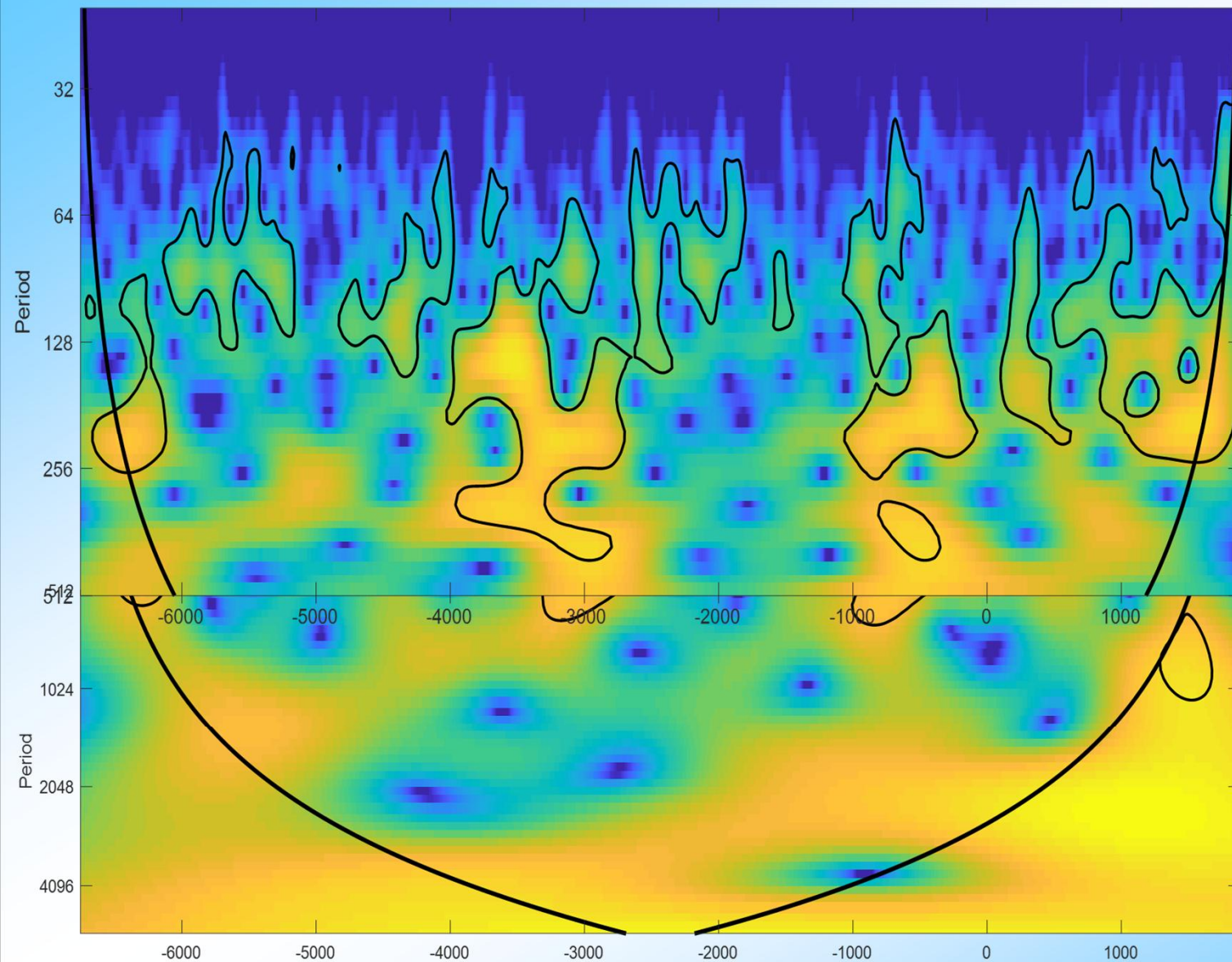


Wu et al. (A&A, 2018)

PDF 10 kyr



Cycles



β **Gleissberg**
(60-130 yr)

β **Suess/de Vries**
(~210 yr)

β **Eddy** (~1000 yr ?)

β **Halstatt** (~2400 yr)
– origin unknown

6000-yr (only in 14C),
likely climatic

Summary

- CR variations, via cosmogenic isotopes, is the only source of information on the solar/heliospheric variability over the Holocene (last 11 millennia).
- The Sun spends $\sim 3/4$ of the time at moderate activity (normal mode), $1/6$ in a grand minimum and $1/10$ in a grand maximum state (is it a special mode?).
- The Modern grand maximum is over, the Sun returns to the normal activity mode.
- Several intermittent cycles can be found: Gleissberg (60-140 yr), Suess/de Vries (~ 210 yr), Hallstatt (~ 2400 yr, origin unclear); other cycles are insignificant.

THANK YOU !