LONG TERM RECONSTRUCTION OF COSMIC RAY FLUX

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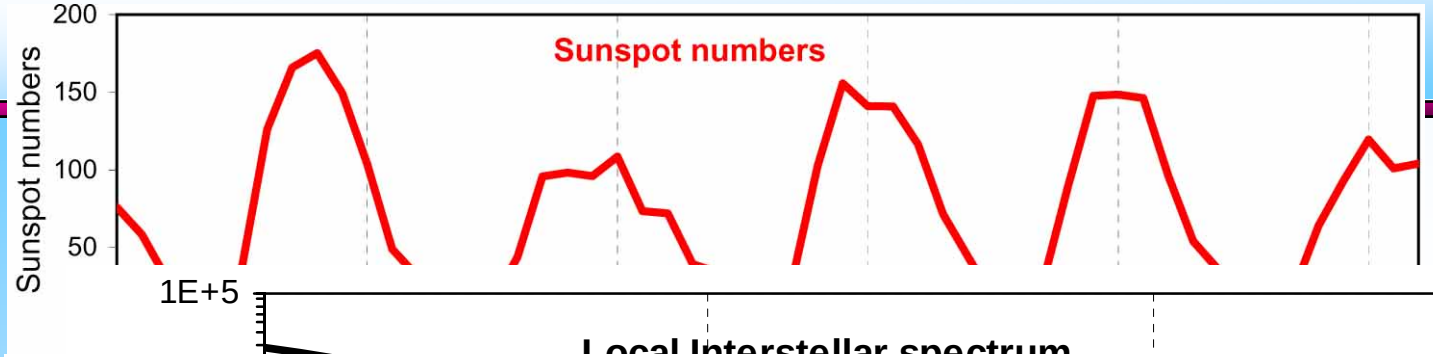
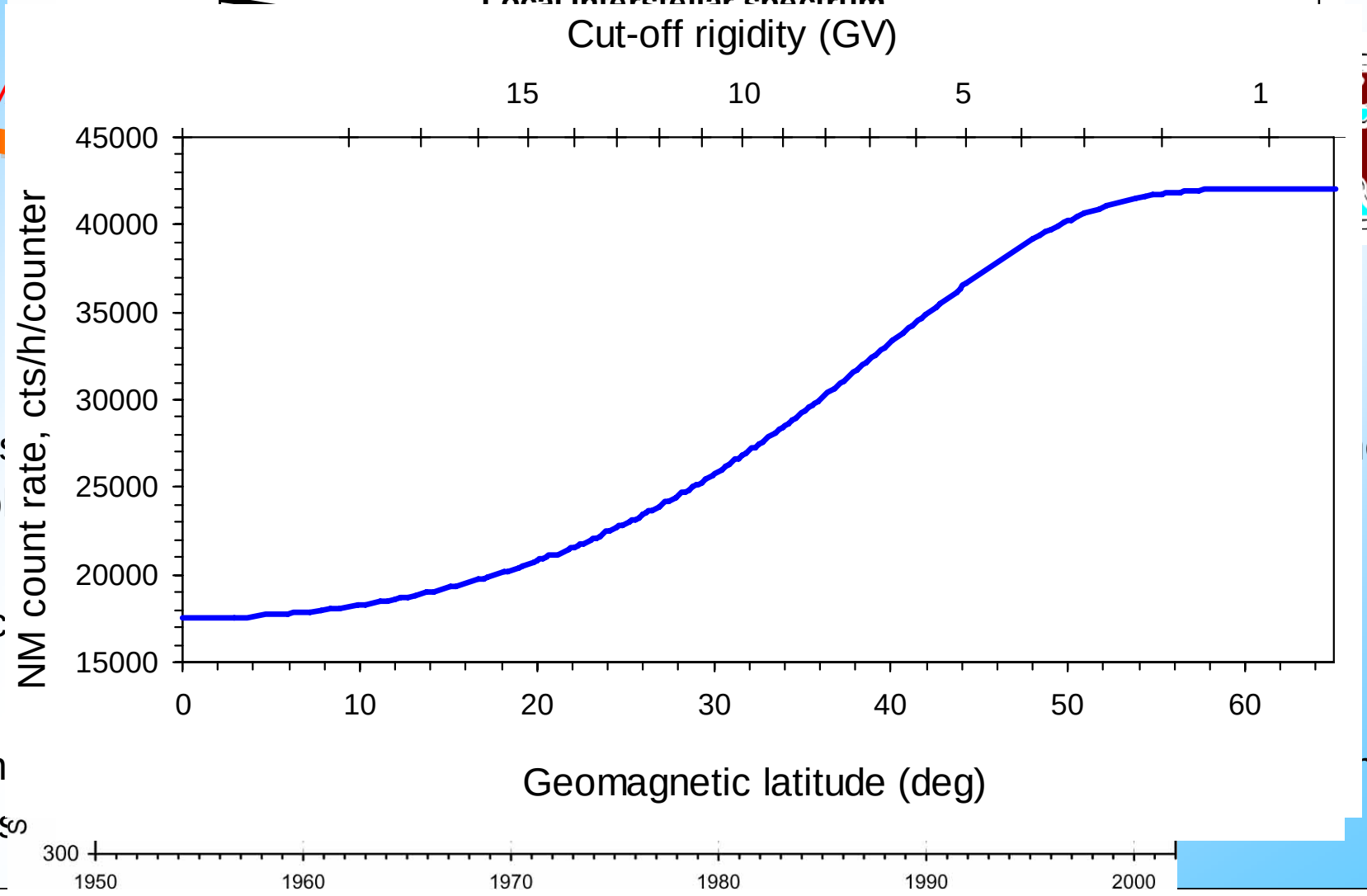




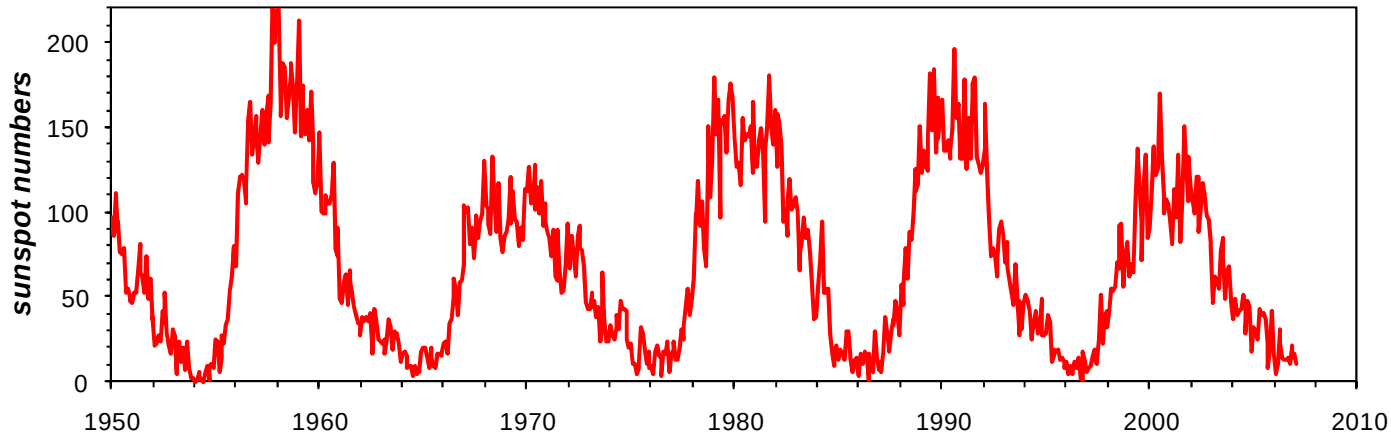
• Variable s etic field, interp

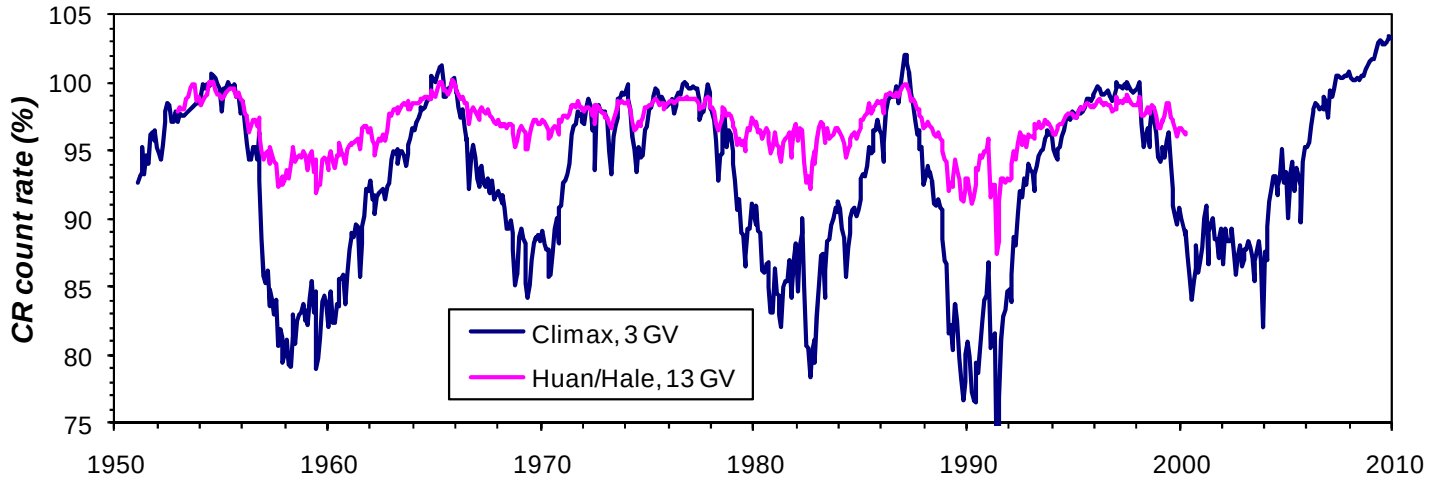
• Galactic c

• Geomagn ning cosmic rays

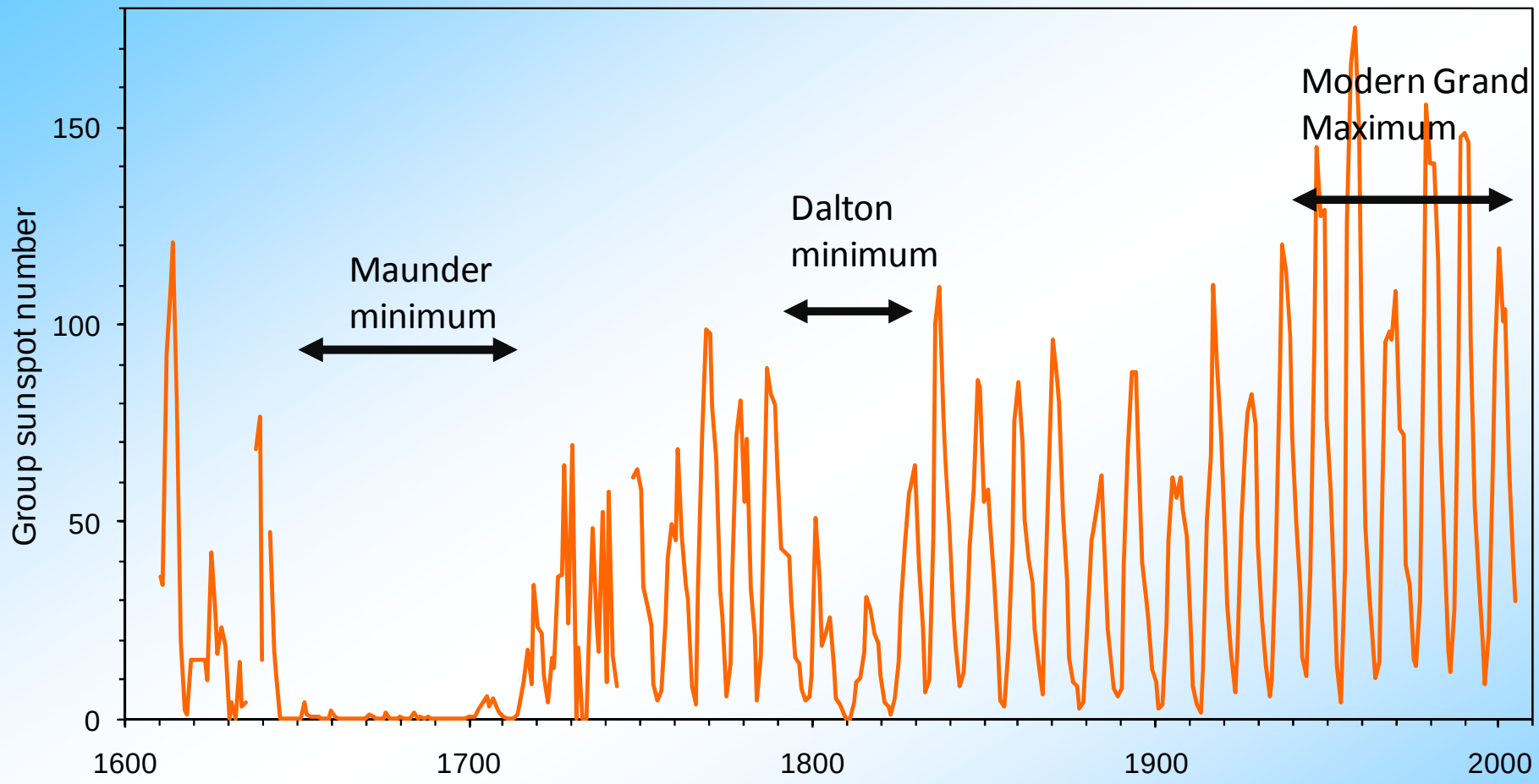
solar cycle variations

- 11-year cycle due to solar activity
- Weak 22-year cycle due to charge-dependent drift effects
- short-term fluctuations.
- Centennial variability?





Solar activity changes

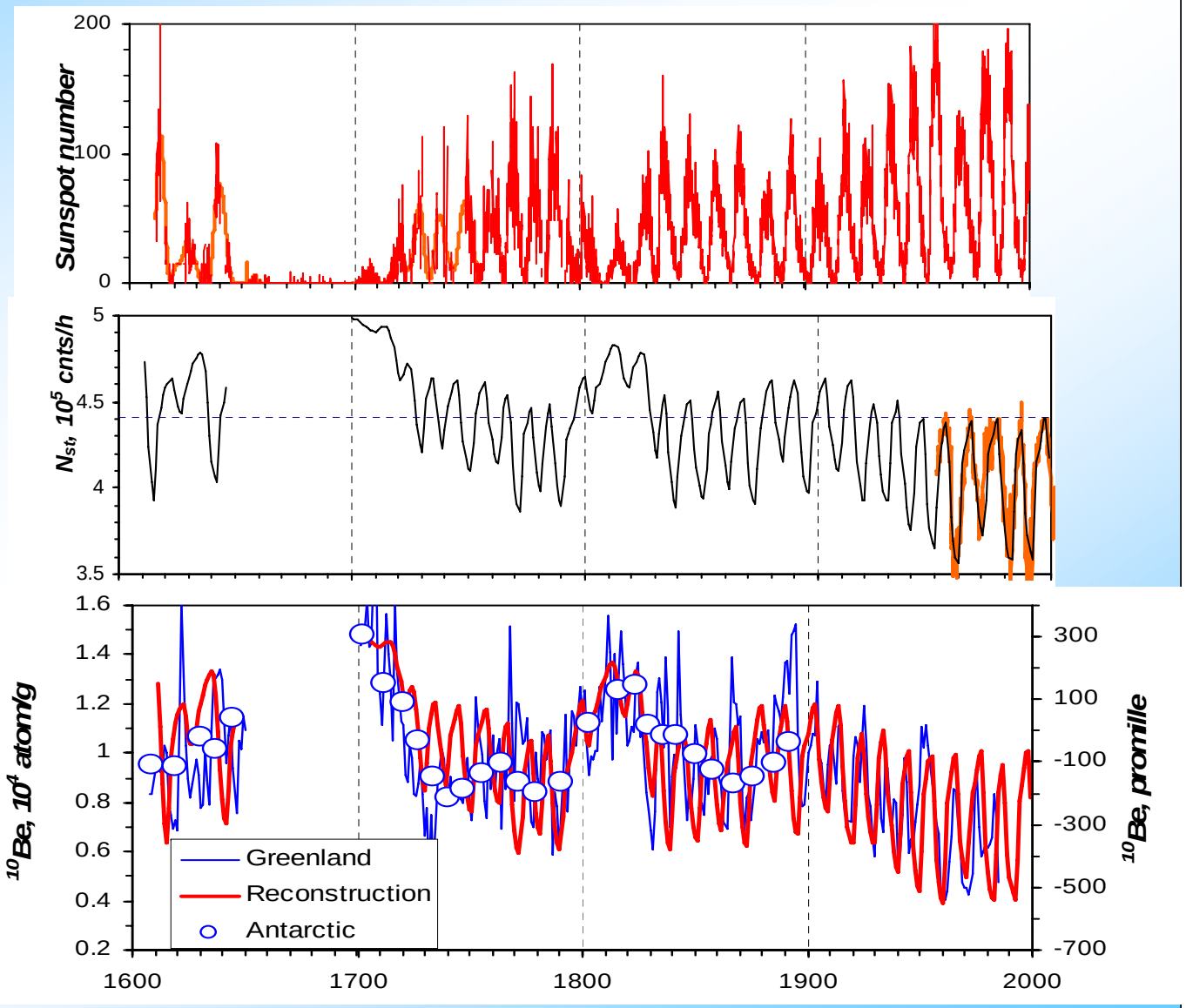


- 11-year solar cycle;
- Variable amplitude/envelope;
- Maunder minimum;
- The contemporary level is/was high;

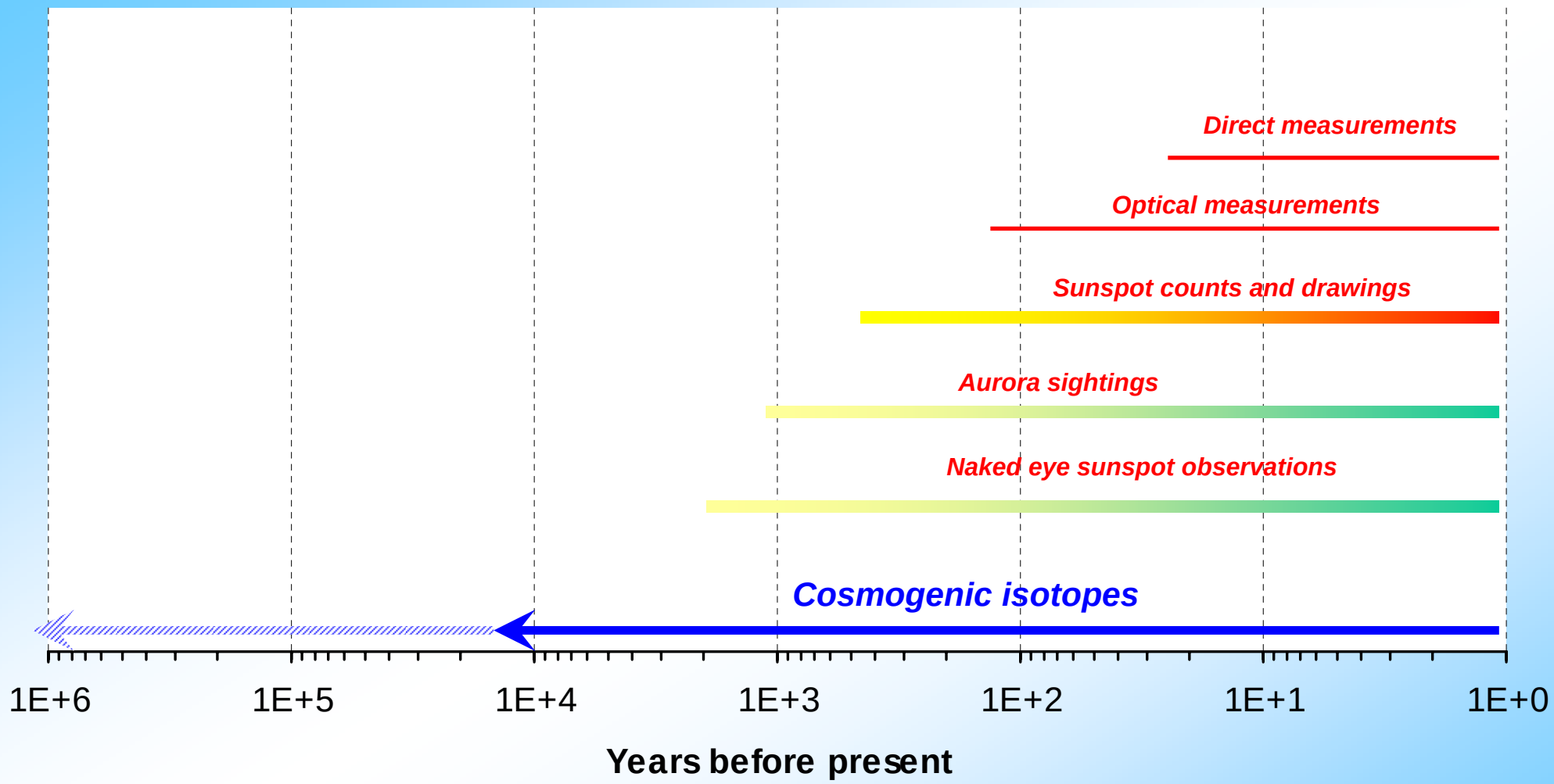
Long-term CR

Model computations:

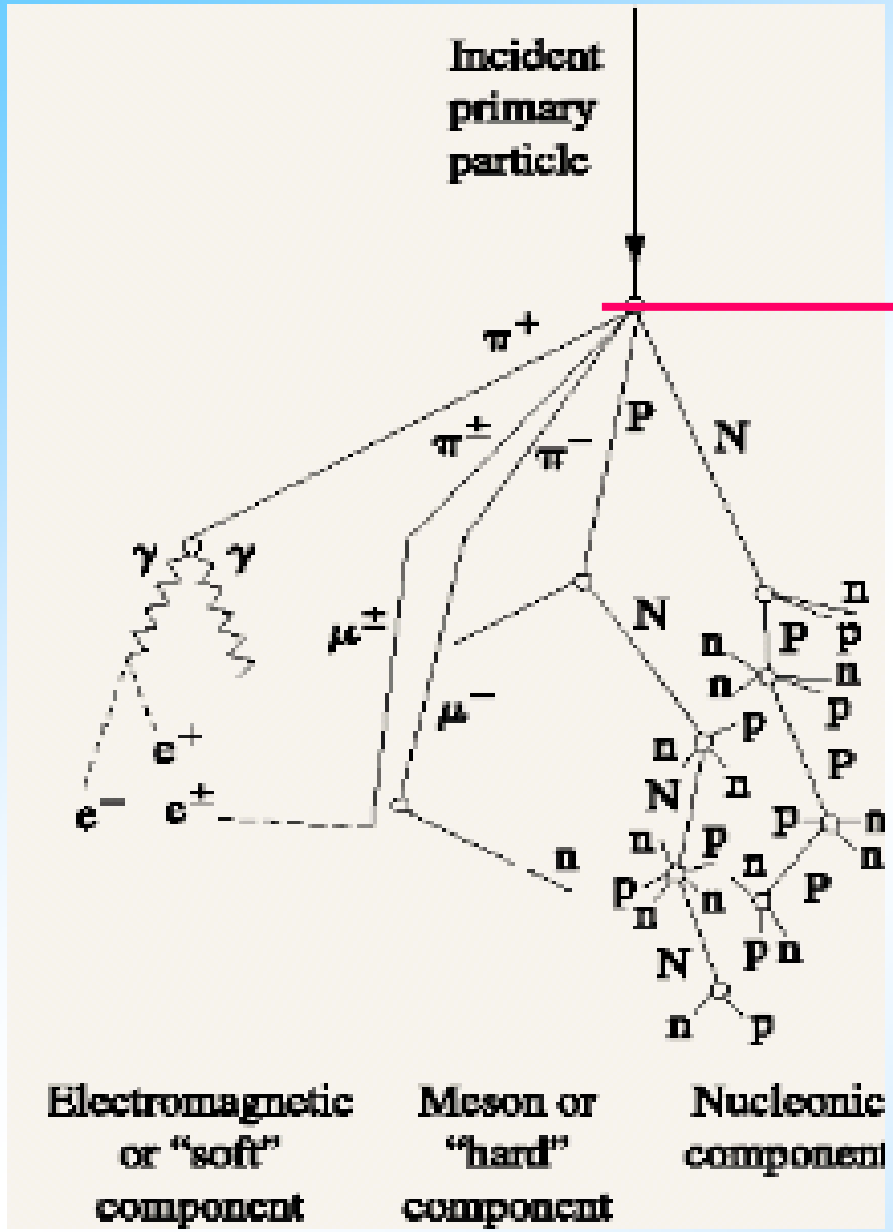
- SN -> open flux model (Solanki et al., 2002; Krivova et al., 2007);
- open flux -> CR (Usoskin et al., 2005);
- CR -> ^{10}Be (Usoskin & Kovaltsov, 2008)



Solar activity



Cosmogenic isotope production



Atmospheric cascade

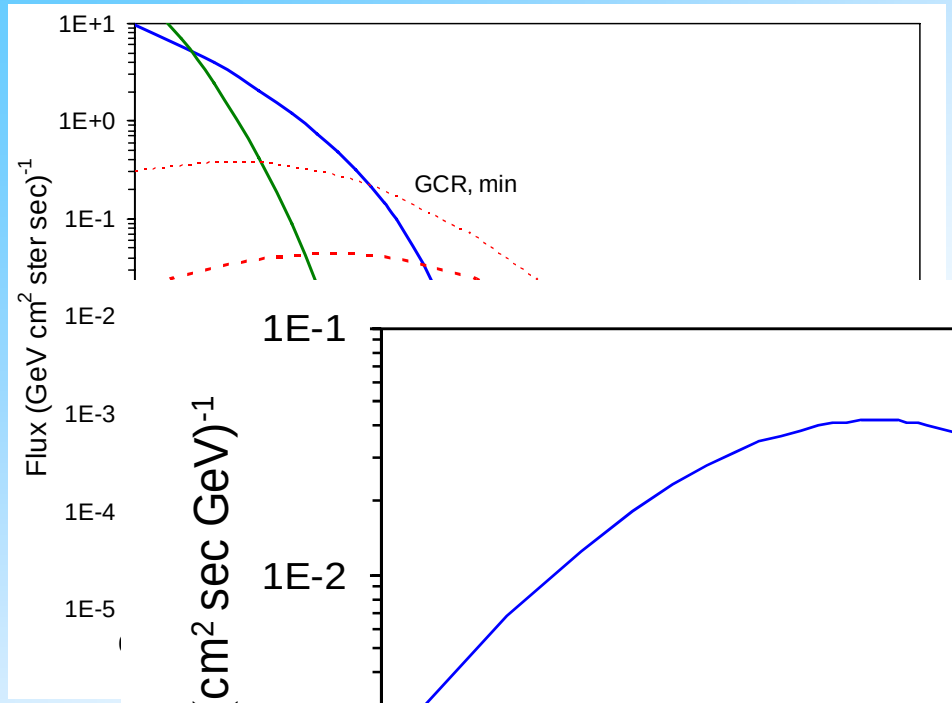
In the atmospheric cascade, nuclear reactions may take place, most important being:

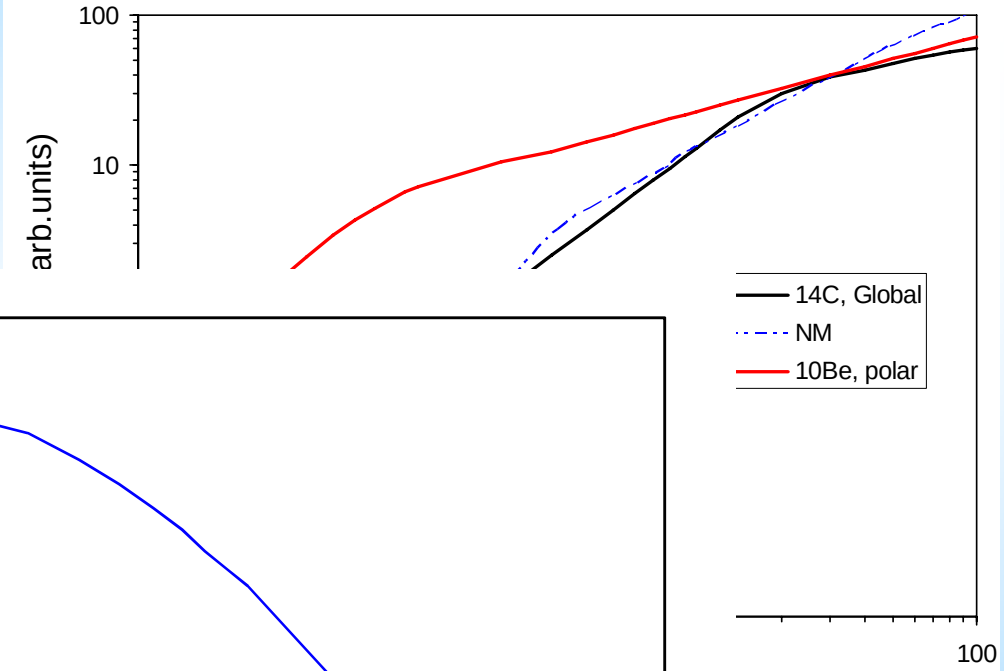
Spallation reactions on *O, N, Ar* → ^{7}Be, ^{10}Be, ^{22}Na, ^{36}Cl, *etc.*

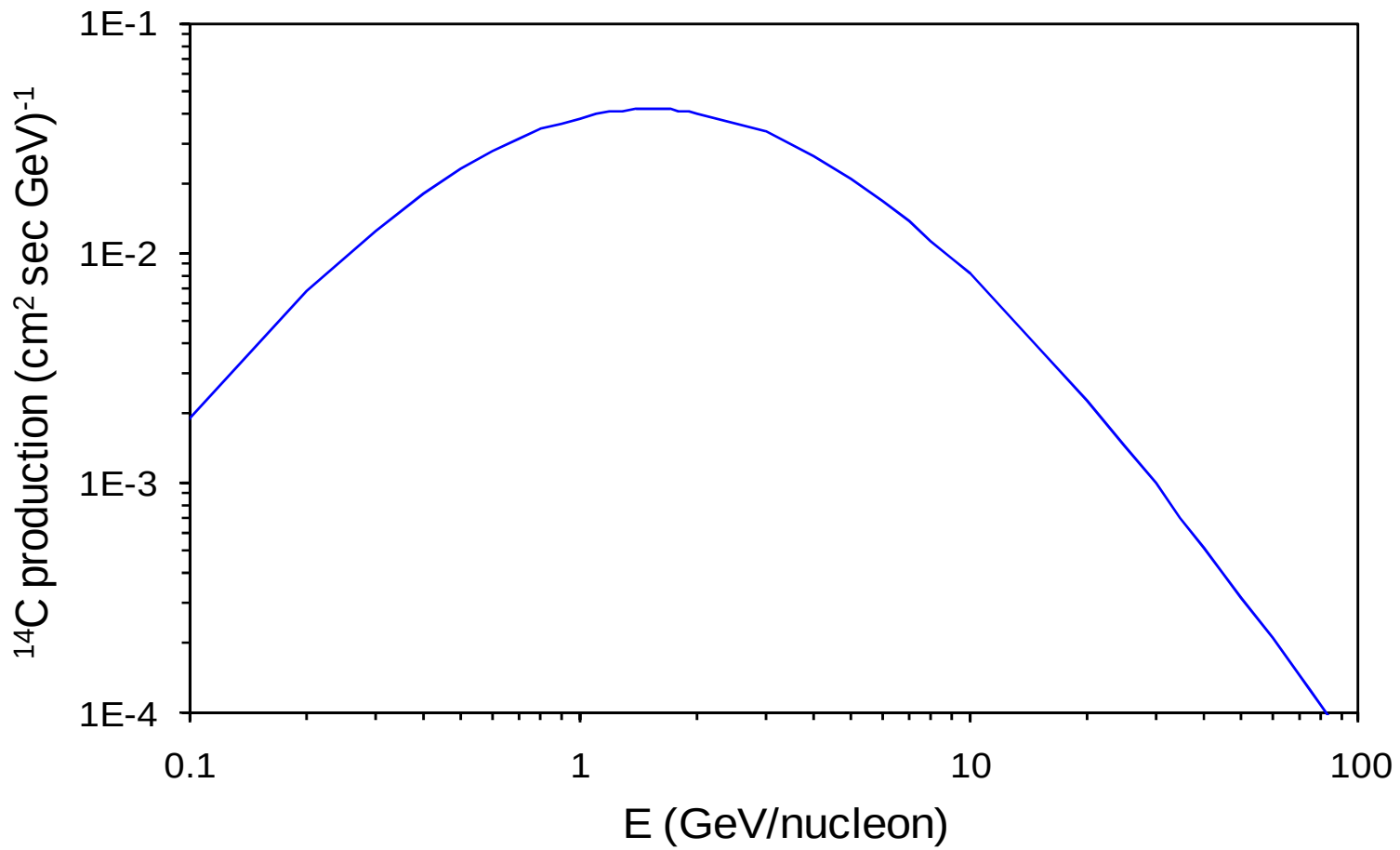
Neutron capture: $^{14}N+n \rightarrow {}^{14}C+p$

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

^{14}C production by GCR and SCR







The approach: Scheme

Direct problem (Usoskin et al. 2002)

Sunspot numbers

Model by Solanki et al. (2000), Krivova et al. (2007)

nonlinear

Sunspot activity ⟷ **open solar magnetic flux**

through IMF strength

Heliospheric parameters

Heliospheric model (Usoskin et al., 2002, 2005)

nonlinear

Open mag. flux ⟷ **CR intensity variations**

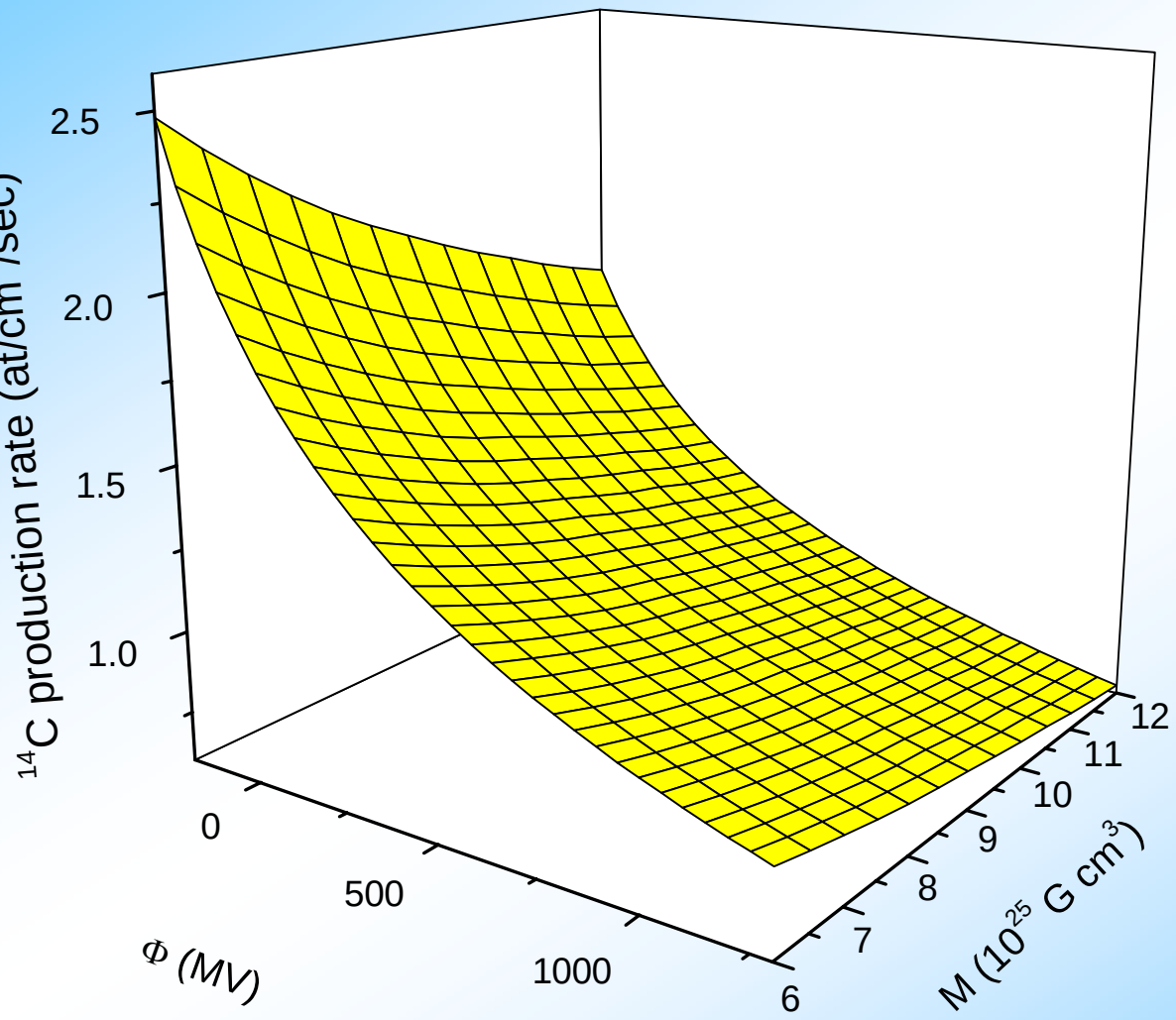
CR intensity

^{10}***Be*** (Masarik & Beer, 1999; Webber & Higbie 2003; Uoskin & Kovaltsov, 2010)

^{14}***C*** (Castagnoli & Lal, 1980)

cosmogenic isotopes in natural archives

14C production: a model



Model: ^{14}C production function – Castagnoli & Lal (1980);
Local interstellar spectrum – Burger et al. (2000);
1.5D cosmic ray transport in the heliosphere – Usoskin et al. (2002)

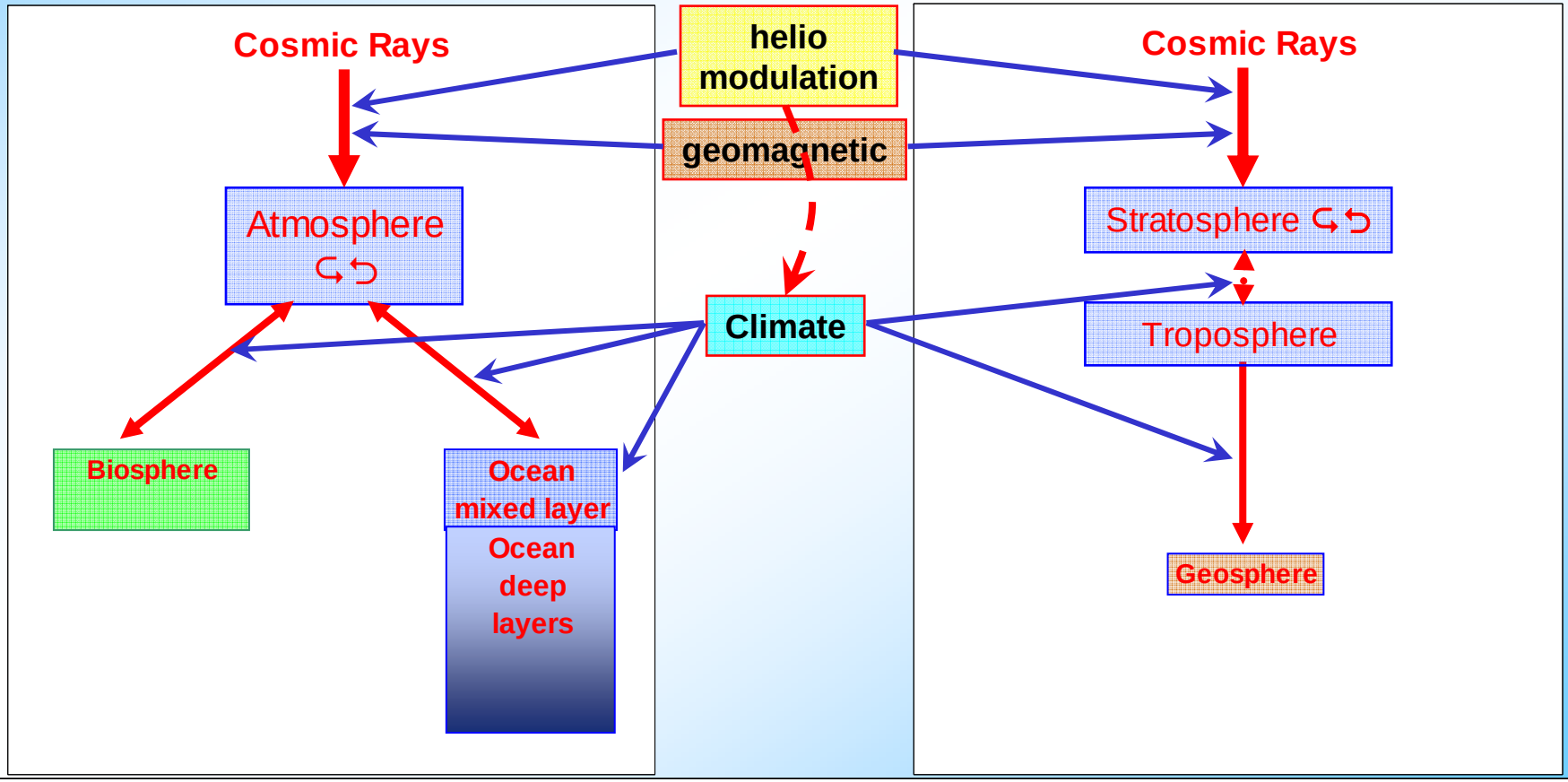
cosmogenic ^{14}C and ^{10}Be

$n + N \rightarrow {}^{14}C$
$CO_2 \rightarrow$ carbon cycle $\rightarrow$ tree rings

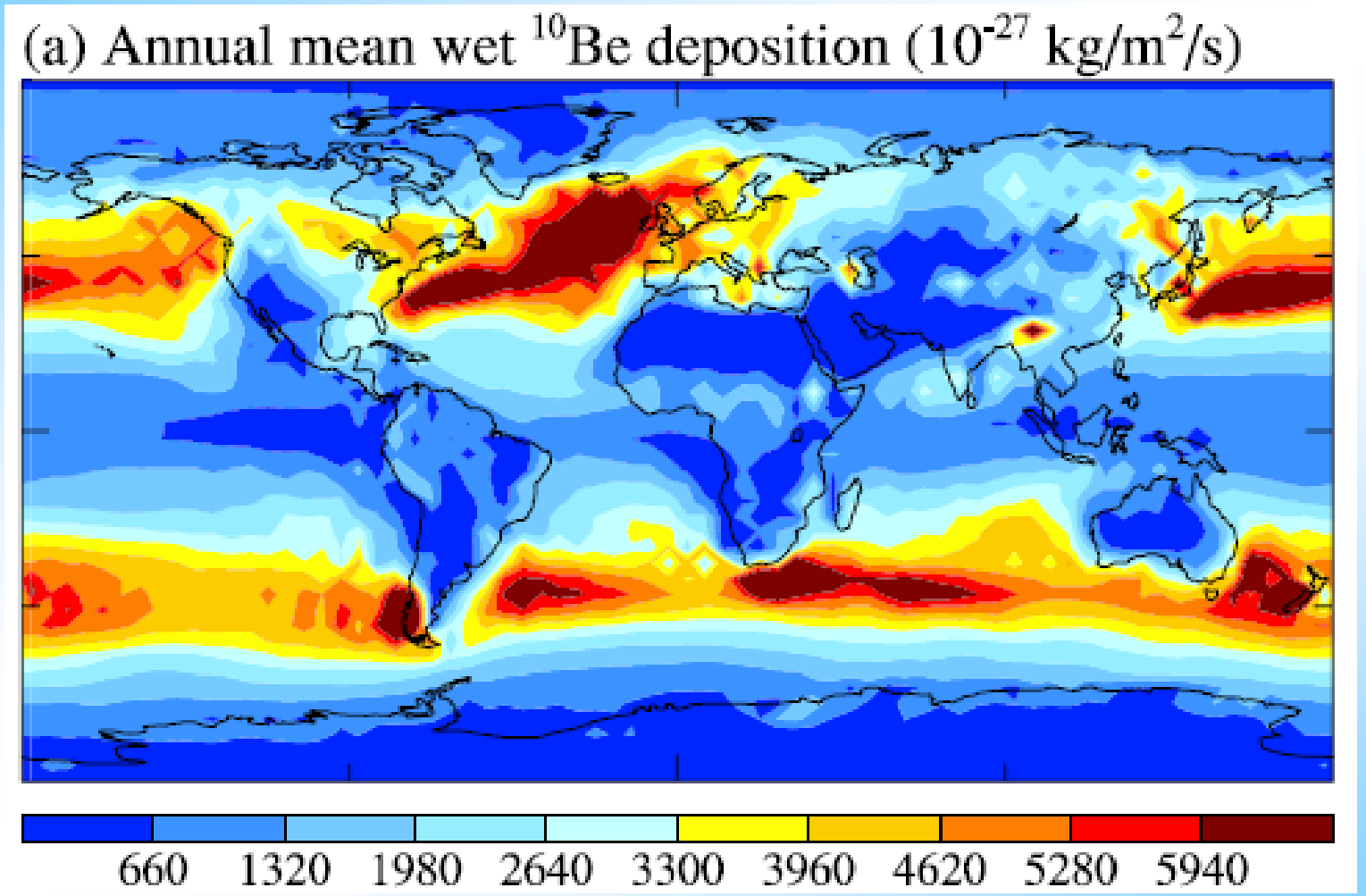
- Effective CR energy is ~ 3 GeV/nucleon;
- mean altitude: upper tropo, low stratosphere;
- measurements: normalized $^{14}C/^{12}C$ ratio

$CR + N,O \rightarrow {}^{10}Be$
aerosols $\rightarrow$ fall out

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

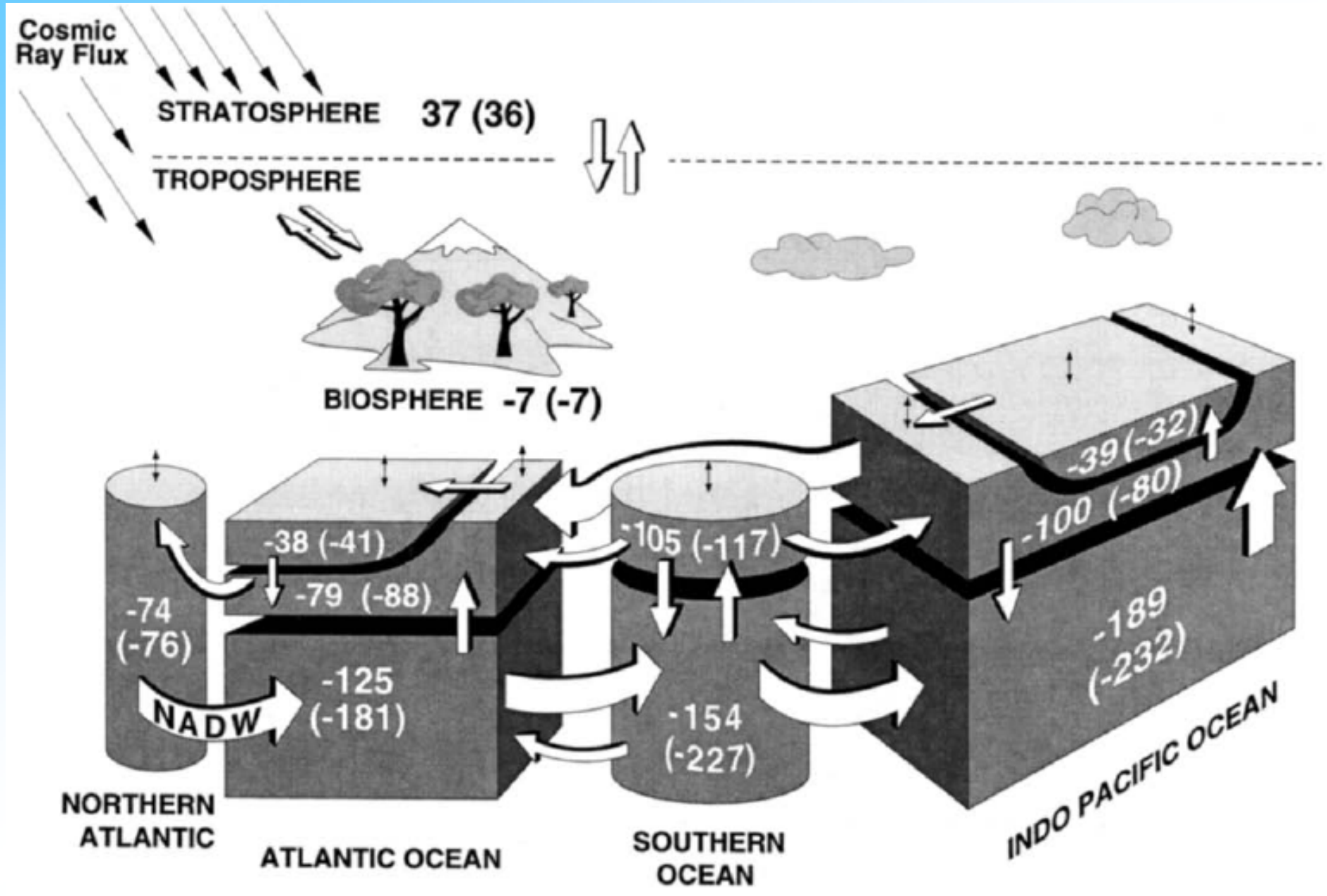


Atmospheric transport of ^{10}Be



Annual Mean Wet ^{10}Be Precipitation- Field et al (JGR, 2006)

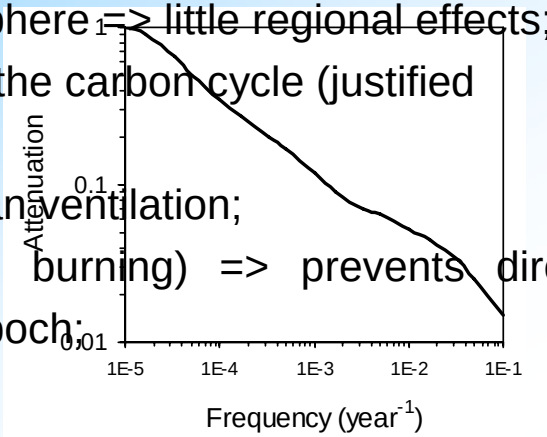
Carbon cycle (Pandora model)



Carbon cycle: from $\Delta^{14}C$ to Q

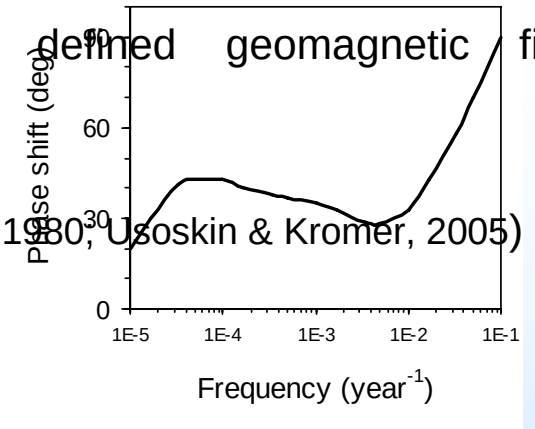
How to define Q from $\Delta^{14}C$?

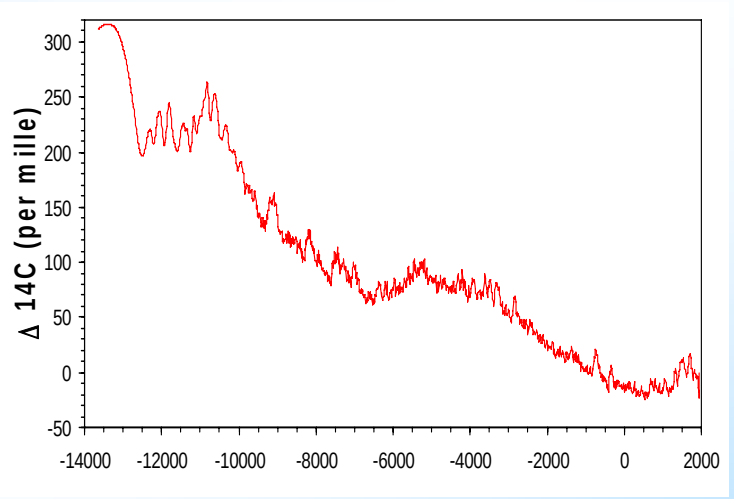
- Global mixing in the geosphere => little regional effects;
- assumption on stability of the carbon cycle (justified for Holocene);
- Most important is the ocean ventilation;
- Suess effect (fossil fuel burning) => prevents direct calibration to the modern epoch;

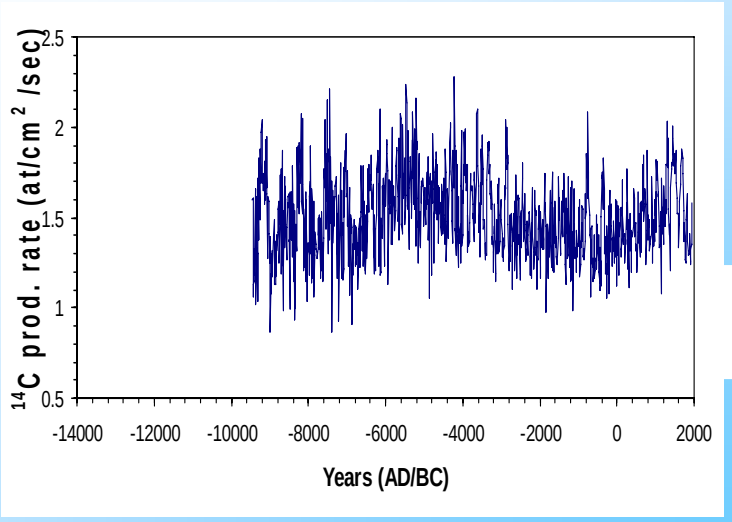


Knowledge of independently defined geomagnetic field variations is required;

Inversion method (Stuiver & Quay, 1980; Usoskin & Kromer, 2005)







Advantages and shortcomings

advantages – "OFF-LINE" type

- ✓ Primary archiving is done **routinely in a similar manner** throughout the ages.
- ✓ Measurements are done **nowadays** in laboratories. If necessary, all measurements can be repeated and improved.
- ✓ **Absolute independent dating** is possible (tree-rings, ice cores, marine sediments, etc.)
- ✓ As a result, a **homogeneous, of equal quality, data series** can obtained.

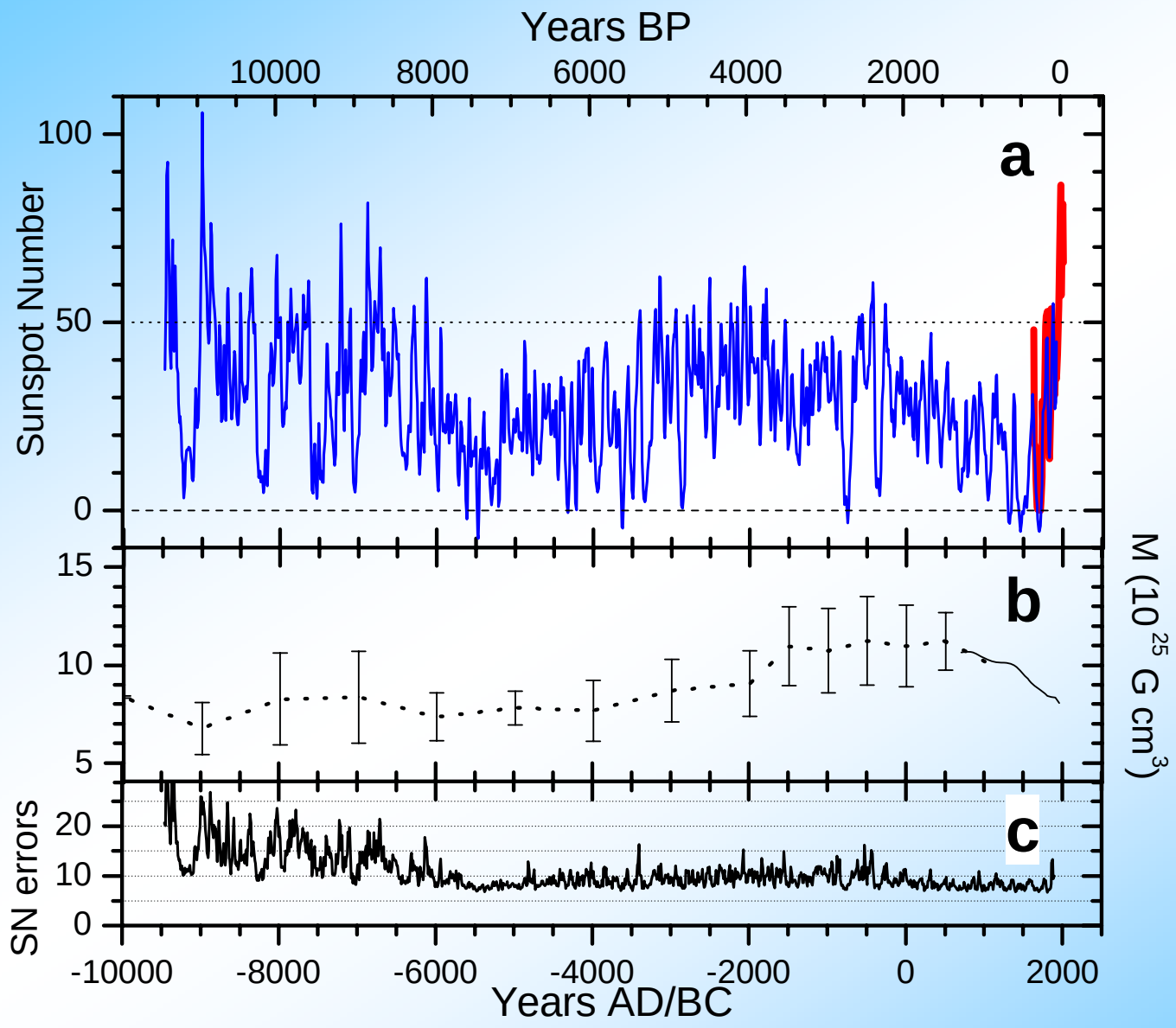
Shortcomings

- ✓ Redistribution in the geosphere and archiving may be affected by local and global climate/circulation processes which are to a large extend unknown in the past, thus justified only for the Holocene (since ca. 9500 BC)
  - ➢ ^{10}Be – unknown mixing; prone to short-term regional and long-term global transport variability
  - ➢ ^{14}C – global mixing; changes of ocean circulation (multi-millennial scales); Suess effect;

SOLUTION:

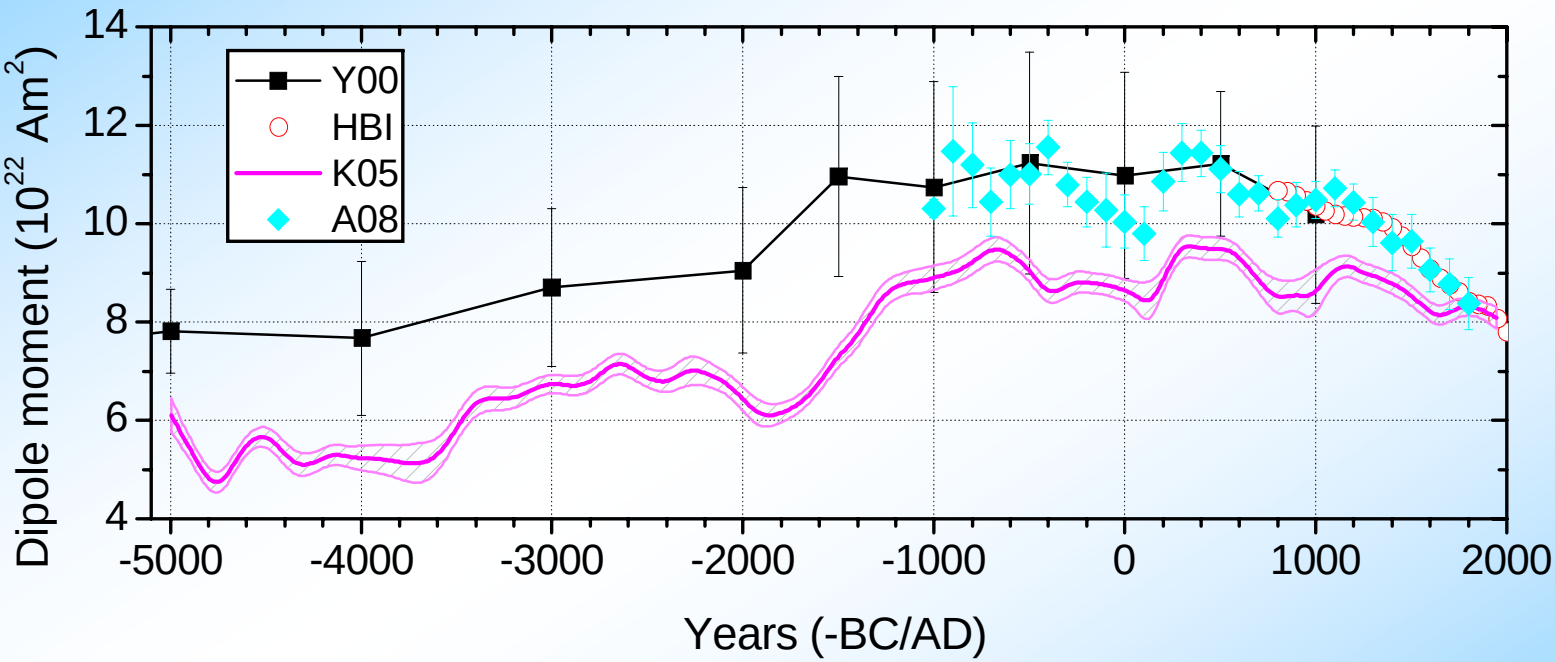
- ✓ Combined results from different nuclides, e.g. ^{10}Be and ^{14}C, whose **responses to terrestrial effects are very different** and may allow for disentangling external and terrestrial signals.
- ✓ Other proxy???

Solar activity throughout the Holocene

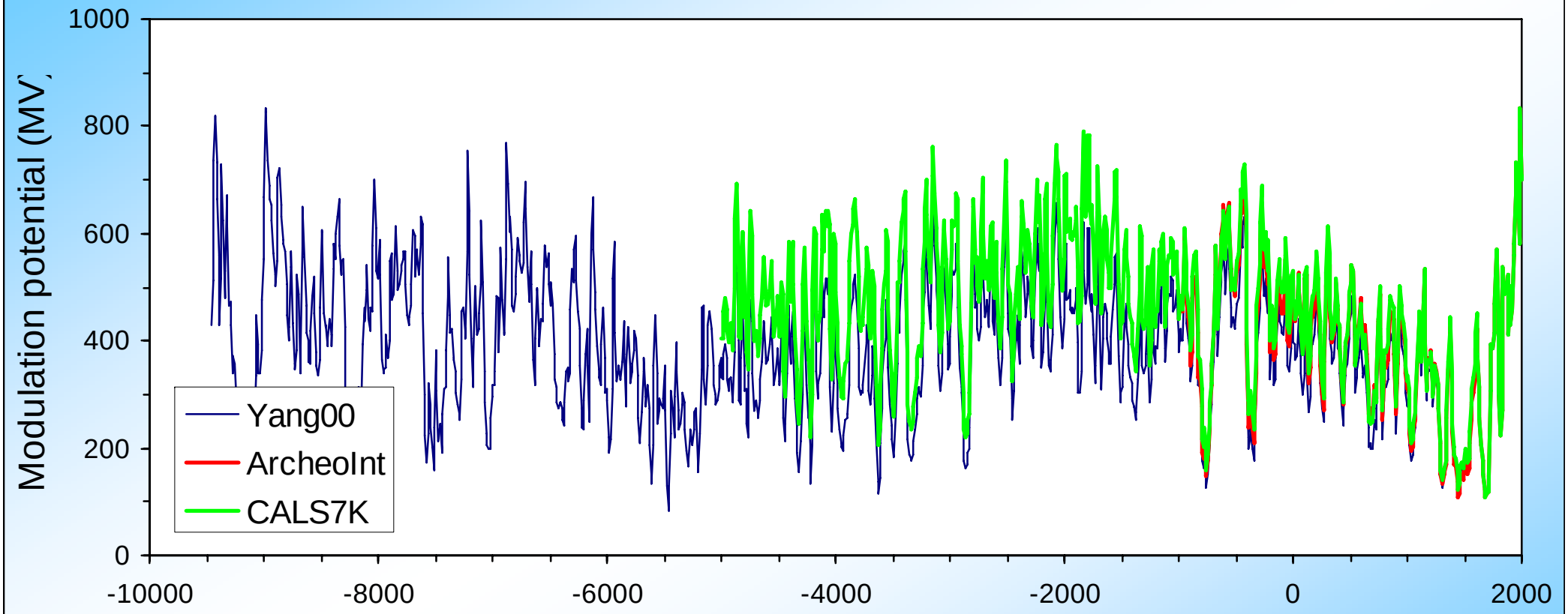


Solanki, Usoskin, Kromer et al., Nature, 2004

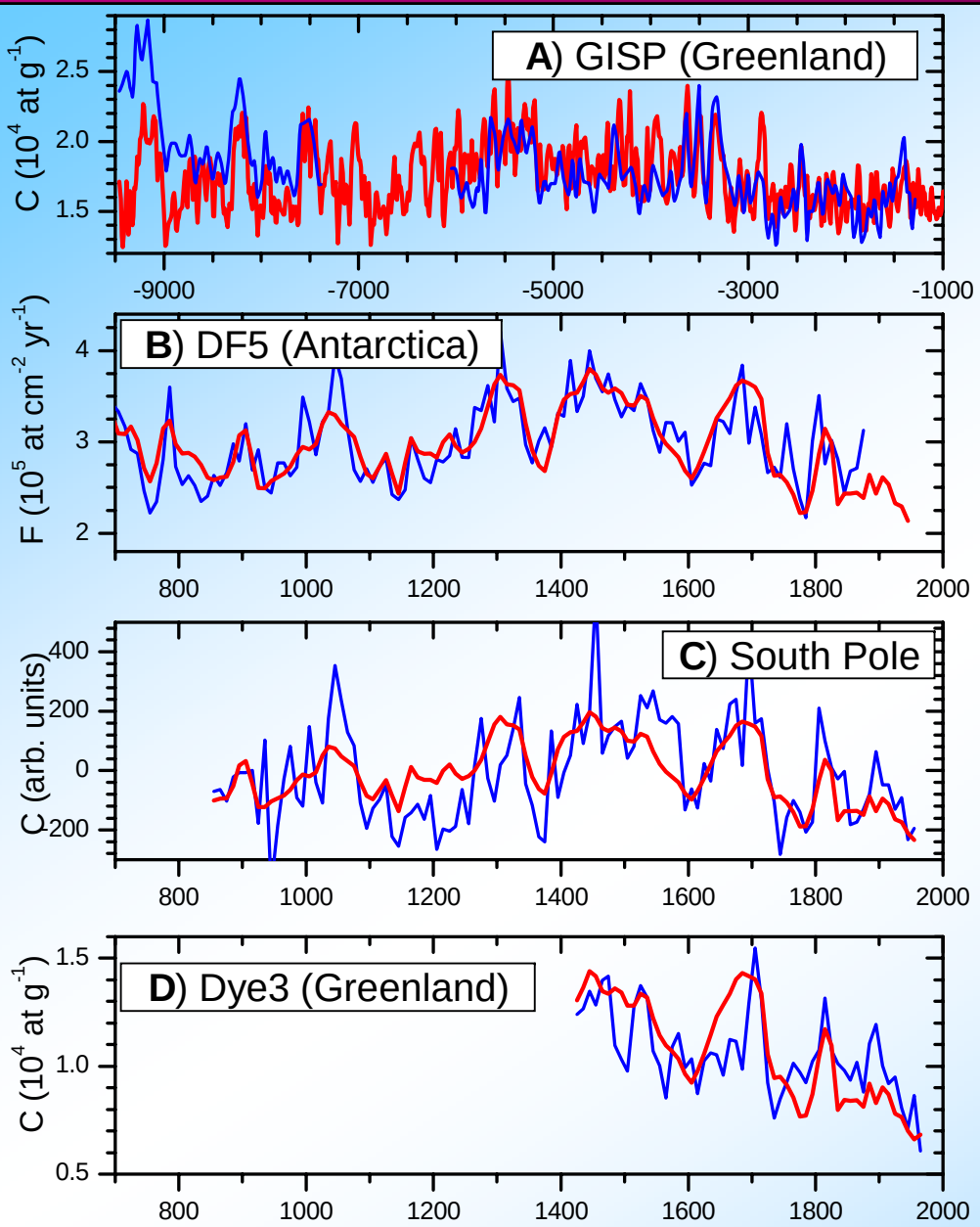
Geomagnetic dipole moment



Geomagnetic field effect



^{10}Be-vs-^{14}C



Usoskin et al. (JGR, 2009):

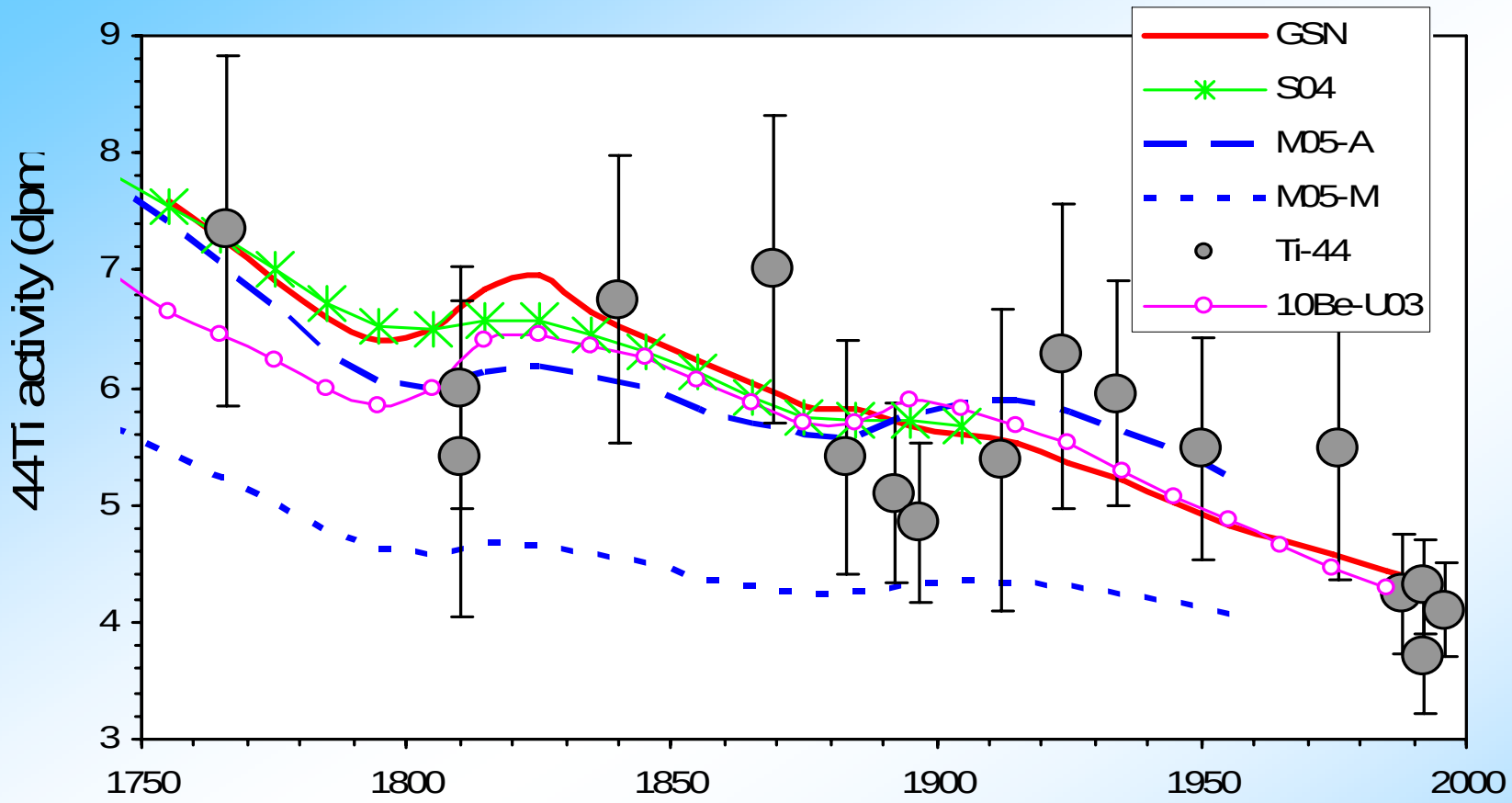
✓ ^{14}C and ^{10}Be data agree with each other (solar signal) at time scales 100-1000 year;

✓ Agreement between ^{14}C and any ^{10}Be series is BETTER than between individual ^{10}Be series.

✓ Shorter time scale – local climate in ^{10}Be data;

✓ Longer time scales – global climate (delayed effect of deglaciation).

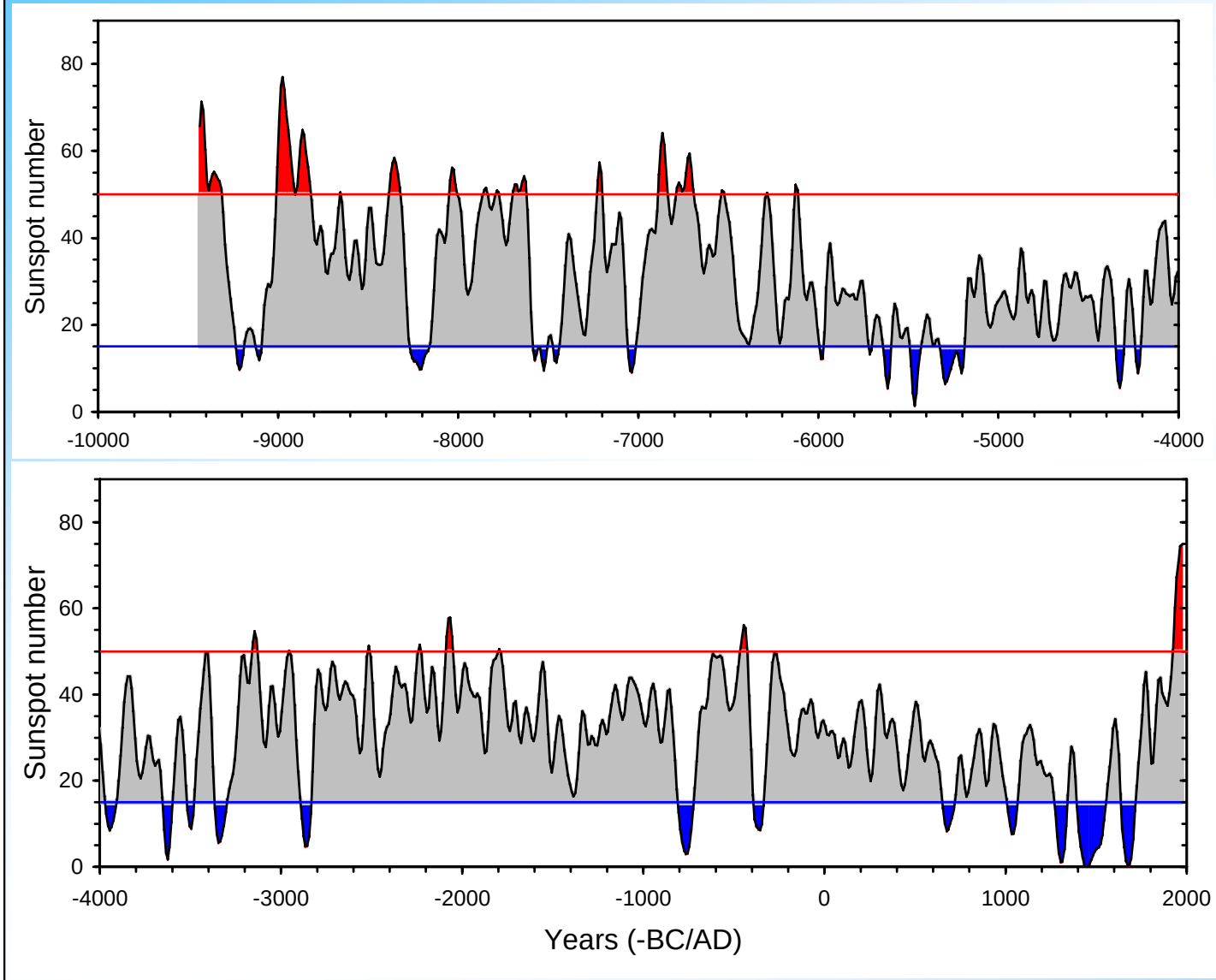
Ti-44 activity in meteorites: direct test



^{44}Ti ($\tau_{1/2}$=*60 yr)* measured in stony meteorites – direct test for CR reconstructions (Usoskin et al., A&A, 2006).

However, reconstruction from ^{44}Ti is impossible (time integration).

Reconstructed sunspot activity



27 Grand minima

19 Grand maxima

can be identified:

Minima (1880 yr – 17%)

Maxima (1030 yr – 9%)

Solanki, S.K., I.G. Usoskin, B. Kromer, M. Schuessler, J. Beer, *Nature*, 2004;
Usoskin, Solanki & Kovaltsov, A&A, 2007

Summary

- The main source of CR variability on time scales from days to millennia is the solar magnetic activity.
- The dominant is 11-year solar cycle but there is essential centennial-millennial variability.
- CR variations, via cosmogenic isotopes, is the only source of information on the solar/heliospheric activity in the past.
- CR/solar variability can be reliably reconstructed for the Holocene (last 11 millennia) from cosmogenic isotope data.
- The level of solar/heliospheric activity varies between Grand minima and Grand maxima.


THANK YOU !