Cosmogenic radionuclides: an index of Solar activity

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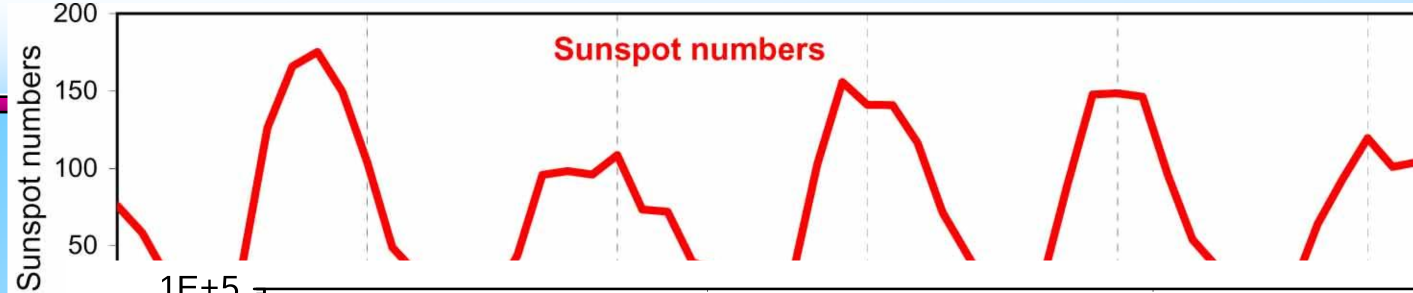

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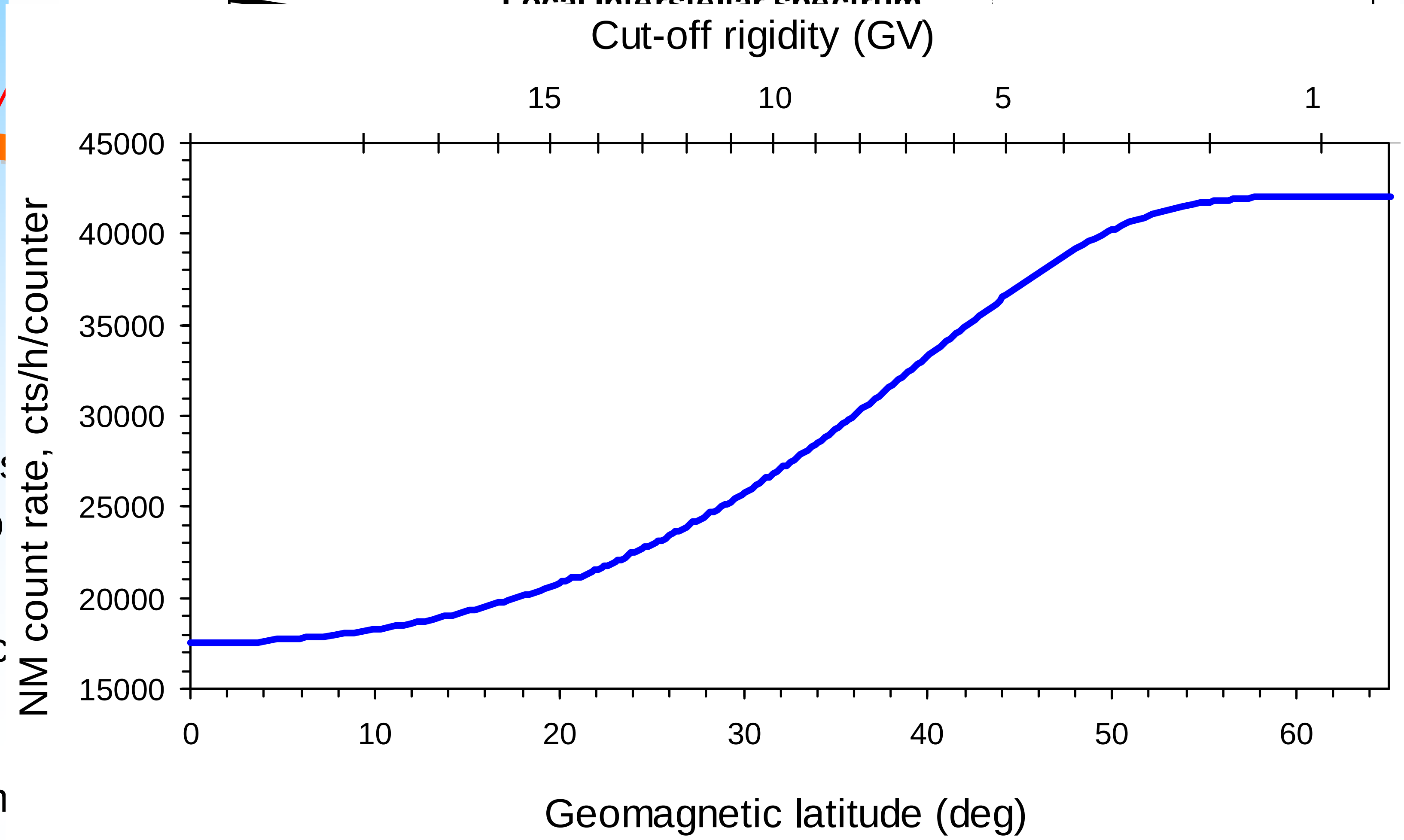
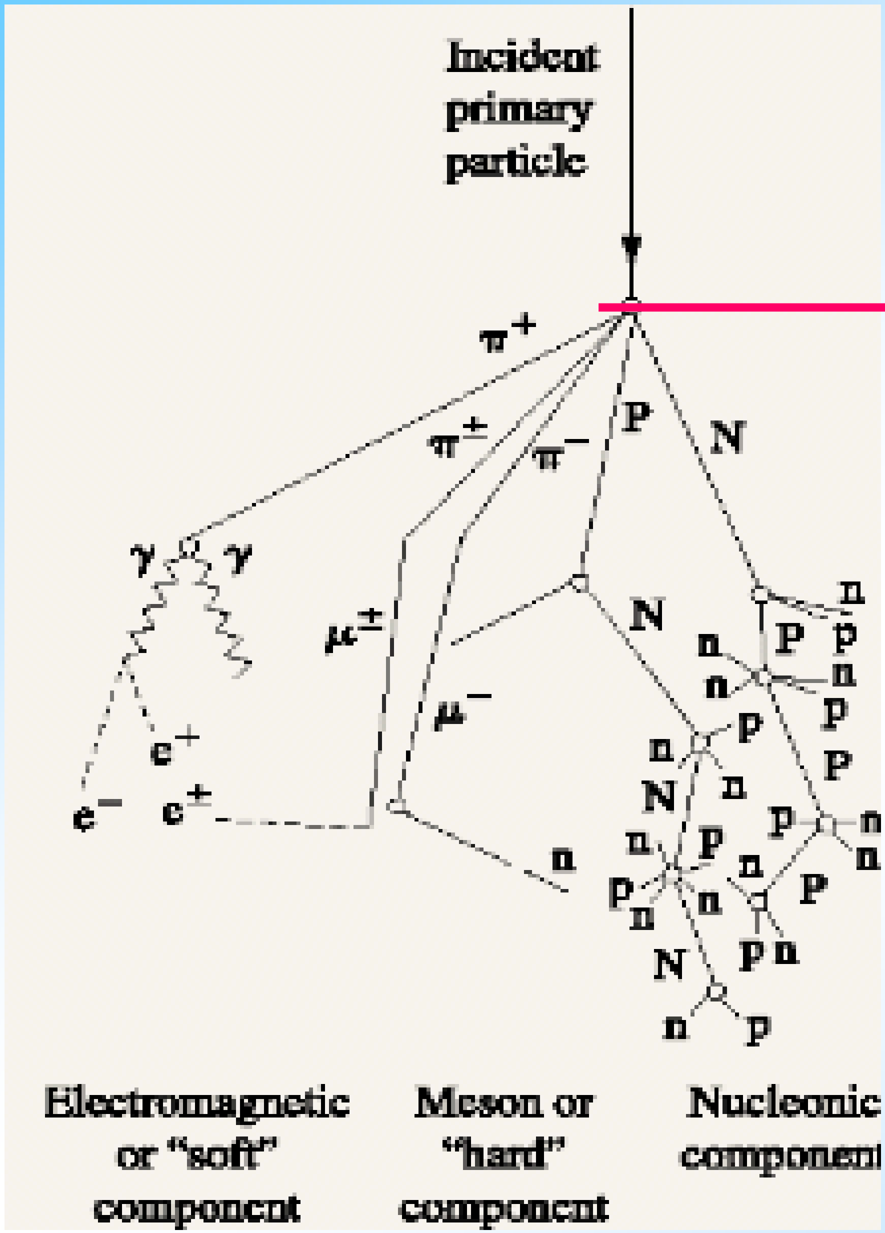


• Variable … netic
field, interp…

• Galactic c…

• Geomagn… ning
cosmic rays

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

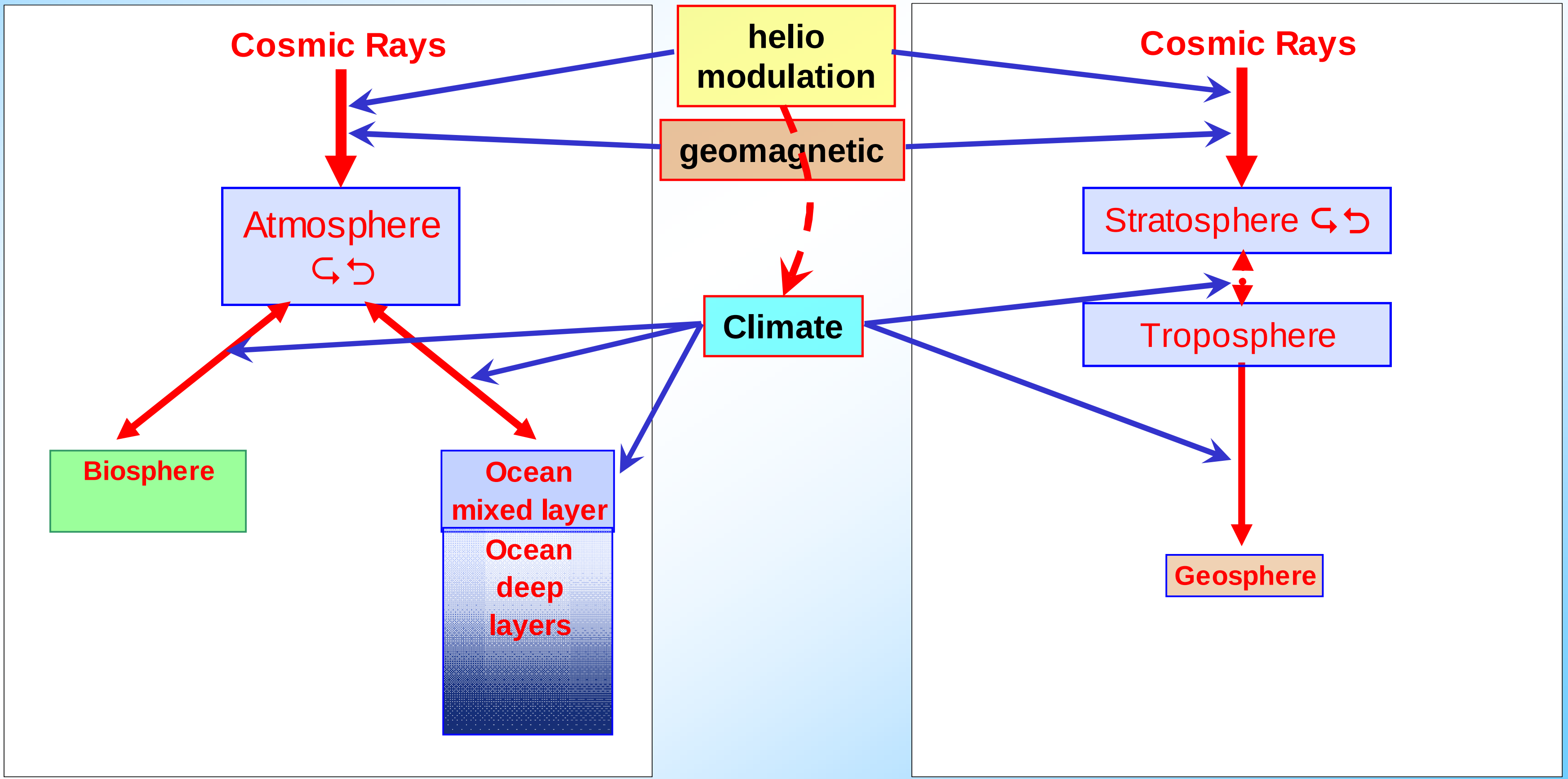
cosmogenic ^{14}C and ^{10}Be

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

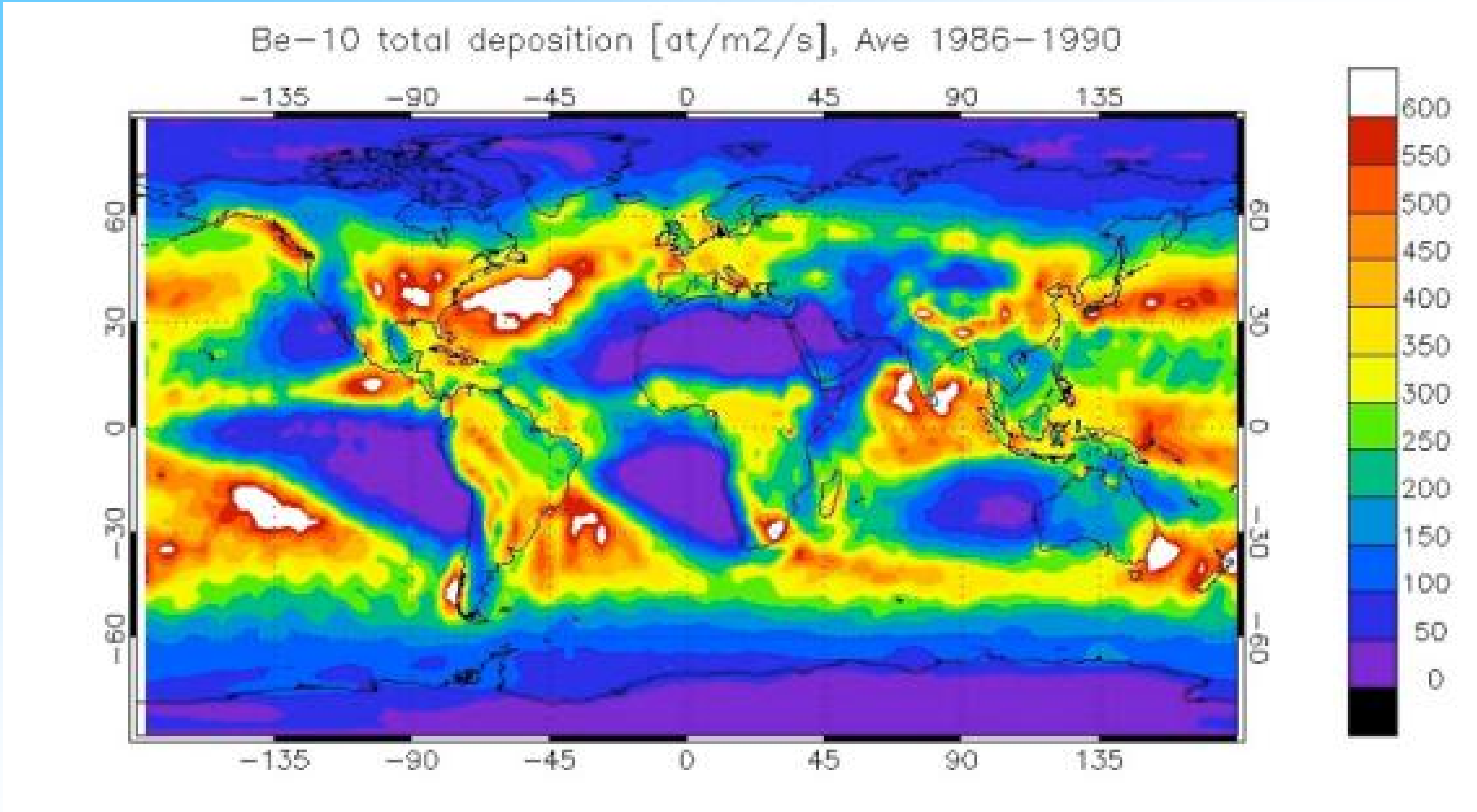
- Mode CR energy is ~ 3 GeV/nucleon;
- mean altitude: upper tropo, low stratosphere;
- measurements: normalized $^{14}C/^{12}C$ ratio

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

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

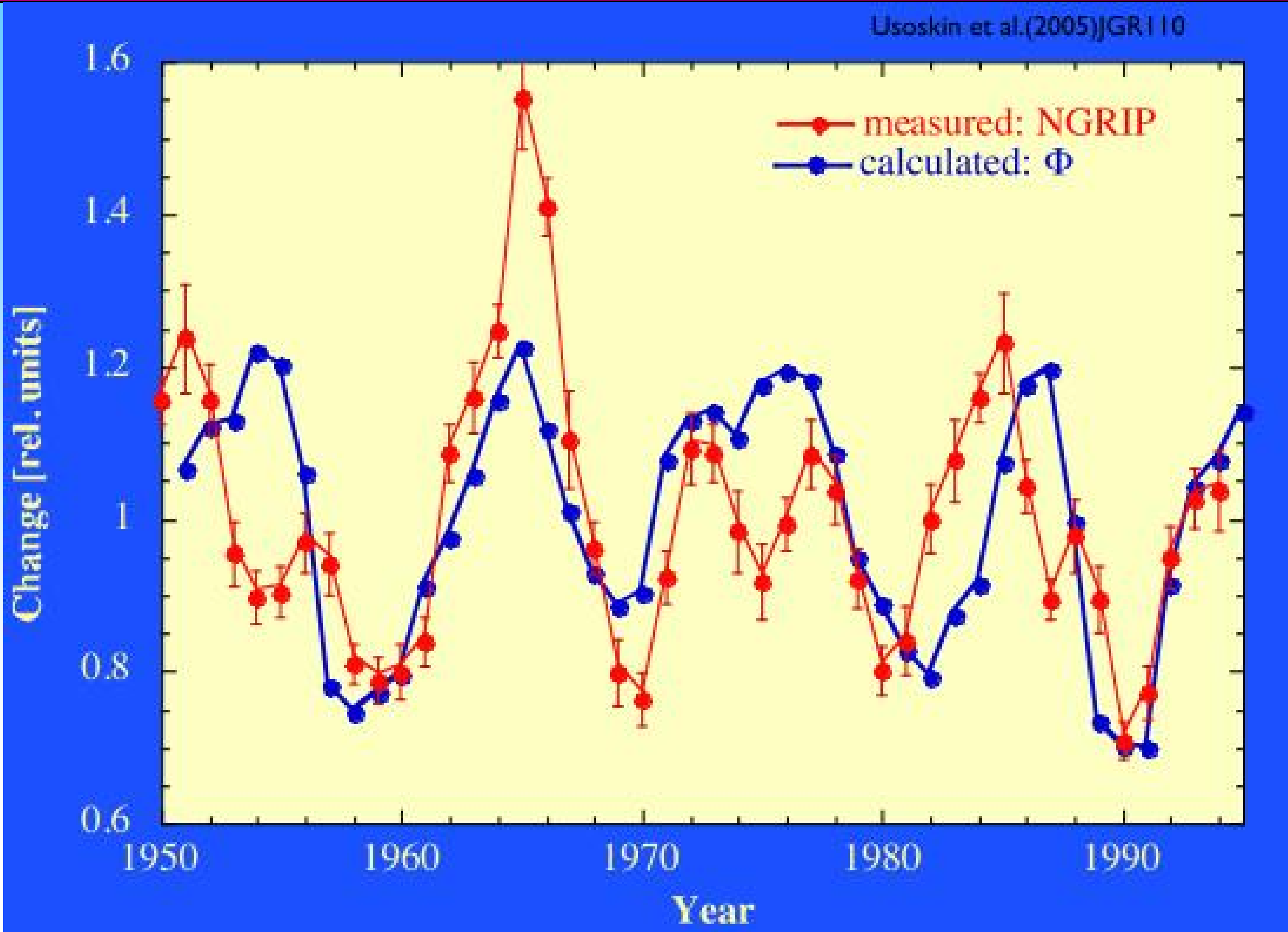


Atmospheric transport of ^{10}Be

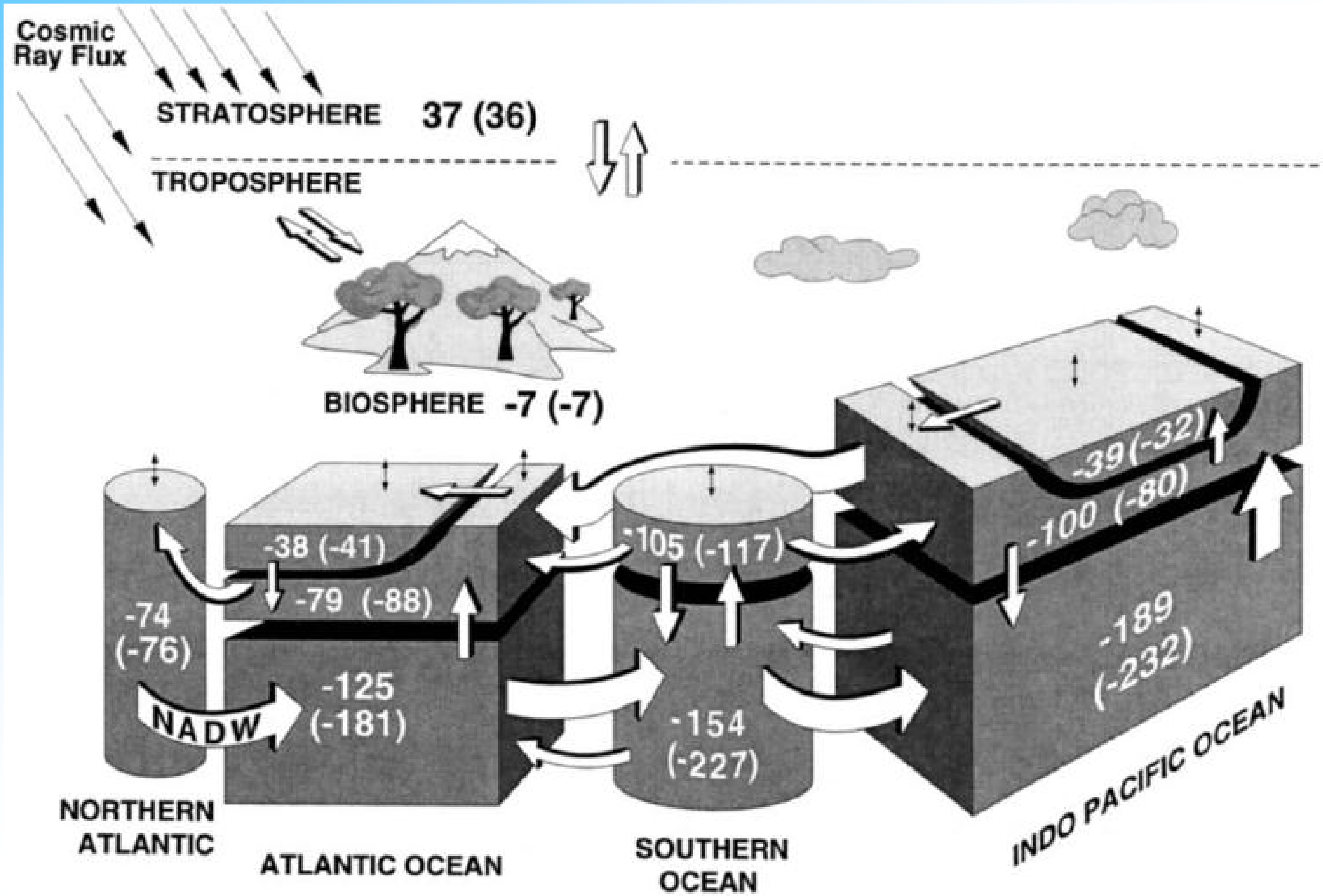


Annual Mean ^{10}Be Flux [at/m2/s] – Heikkilä (2007), Field et al (JGR, 2006)

Solar cycles in 10Be



Carbon cycle (Pandora model)



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.

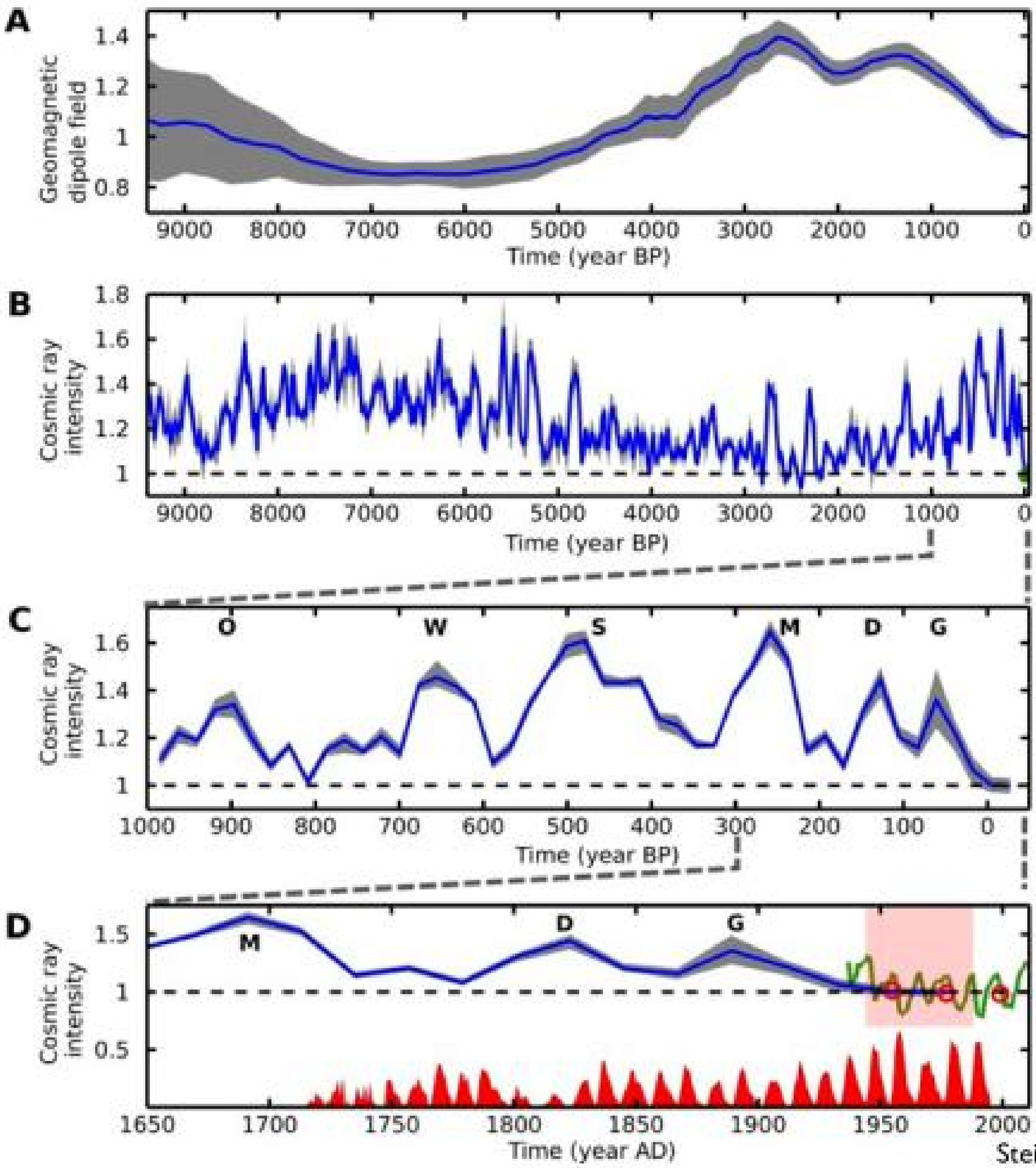
Shortcomings

- ✓ 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:

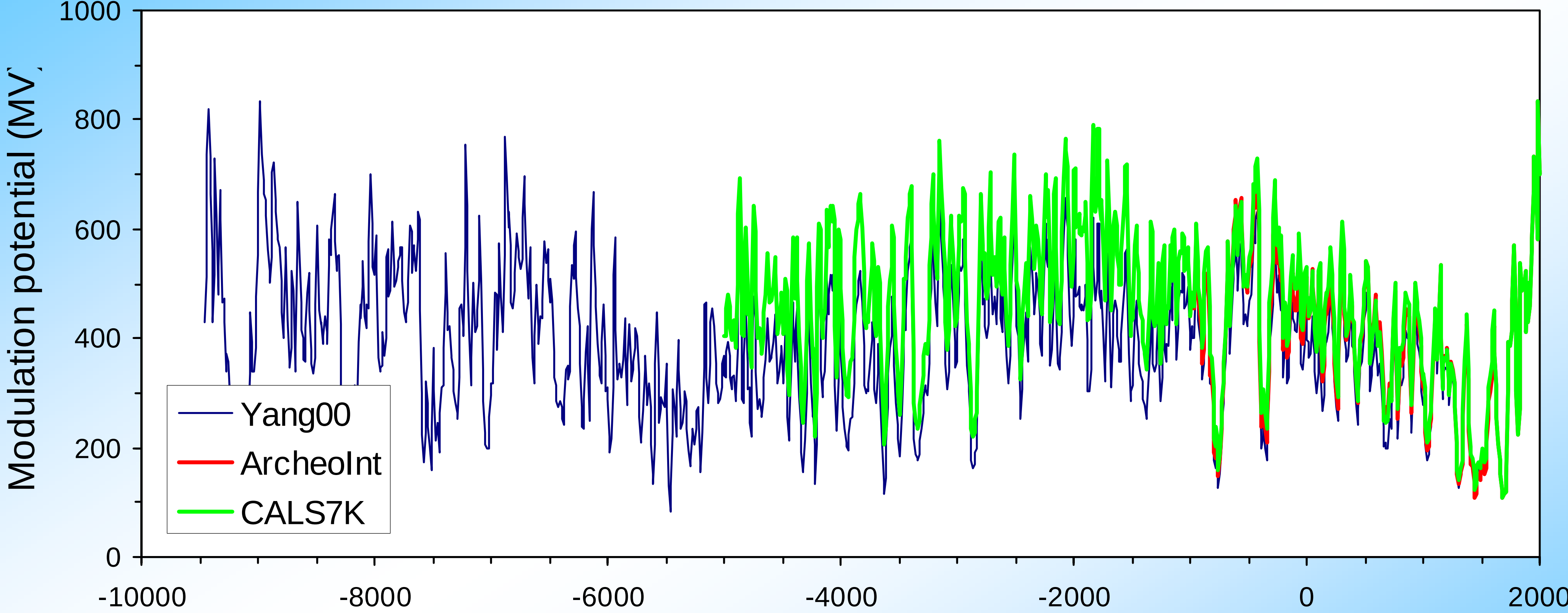
- ✓ Combined results from different nuclides, e.g. ^{10}Be and ^{14}C, whose **responses to terrestrial effects are very different** and may allow for disentangling external and terrestrial signals.
- ✓ Other proxy???

Combined record

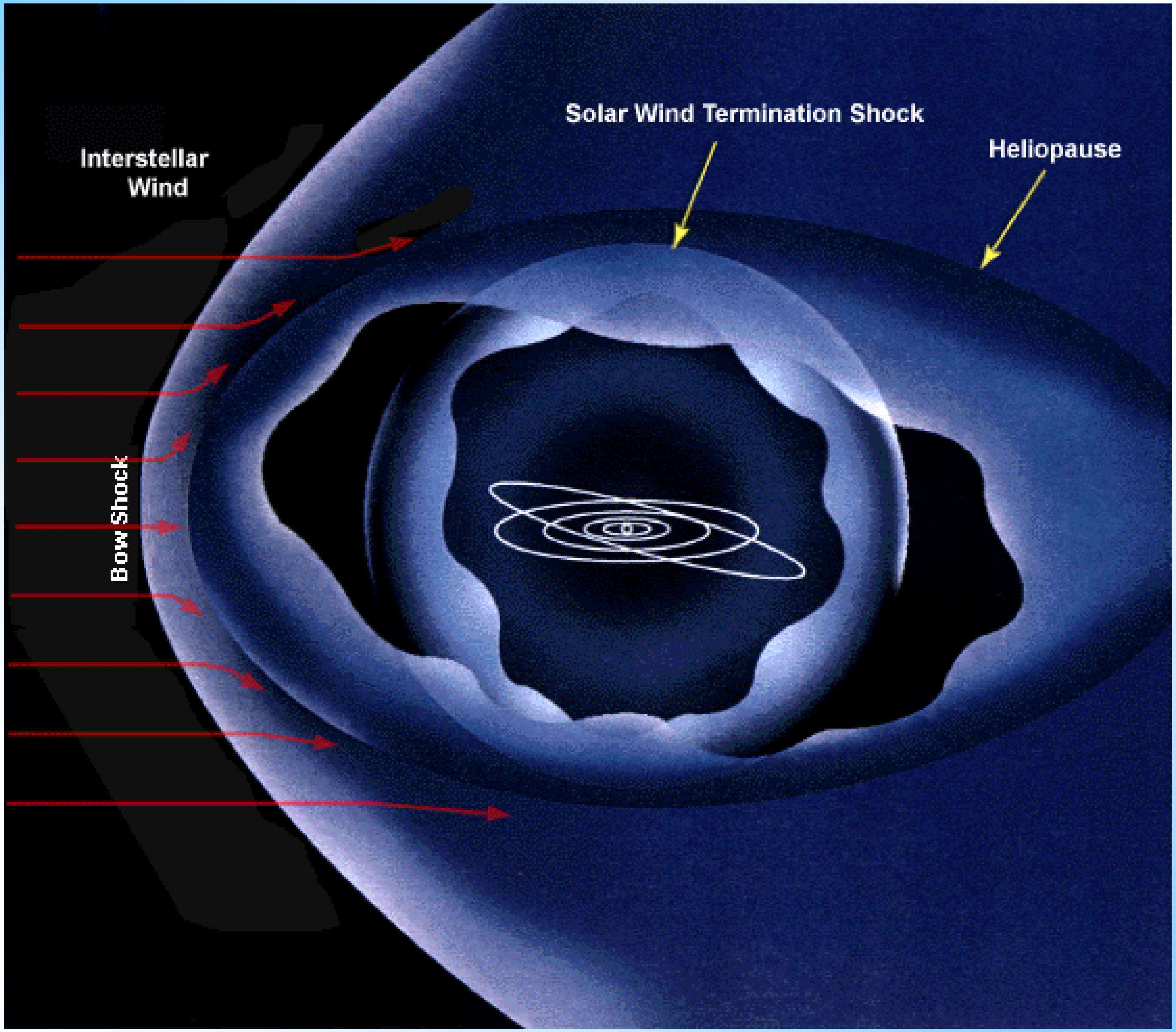


Steinhilber et al, PNAS,2012

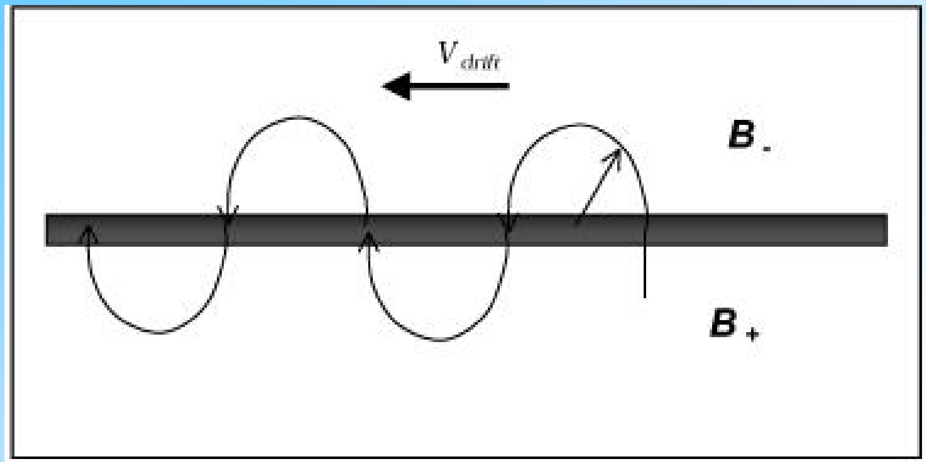
Geomagnetic field effect



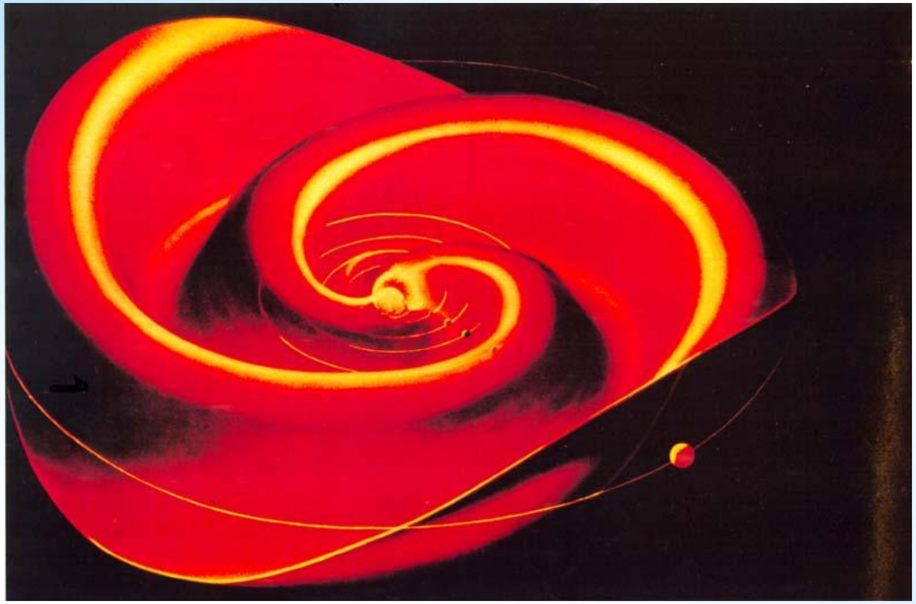
The heliosphere

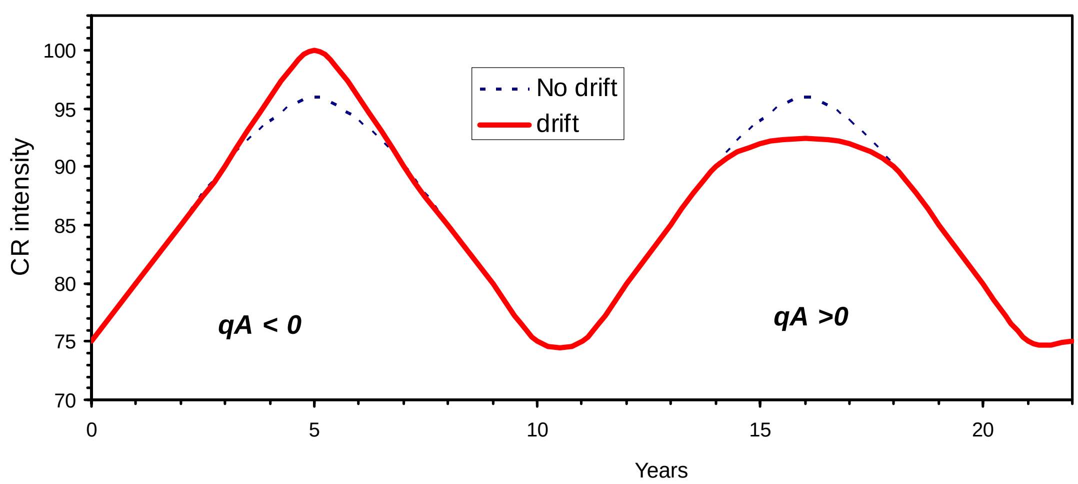


HCS drift

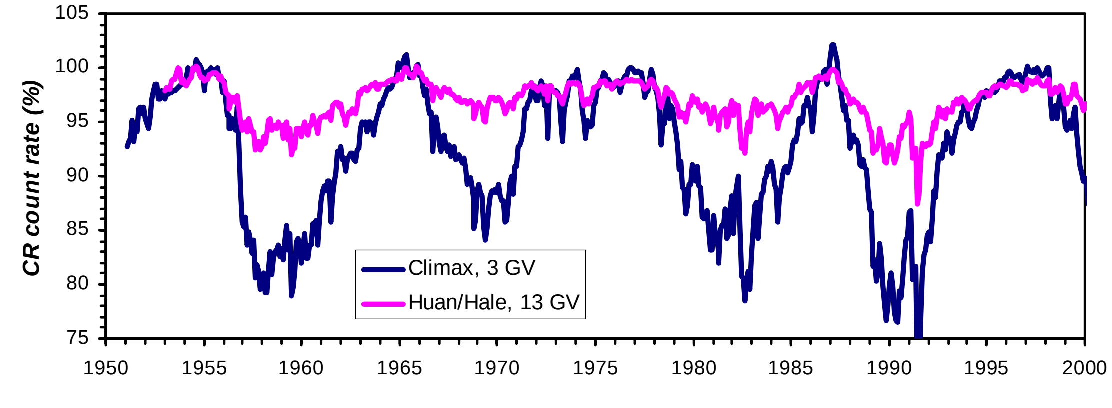


V drift
B -
B +





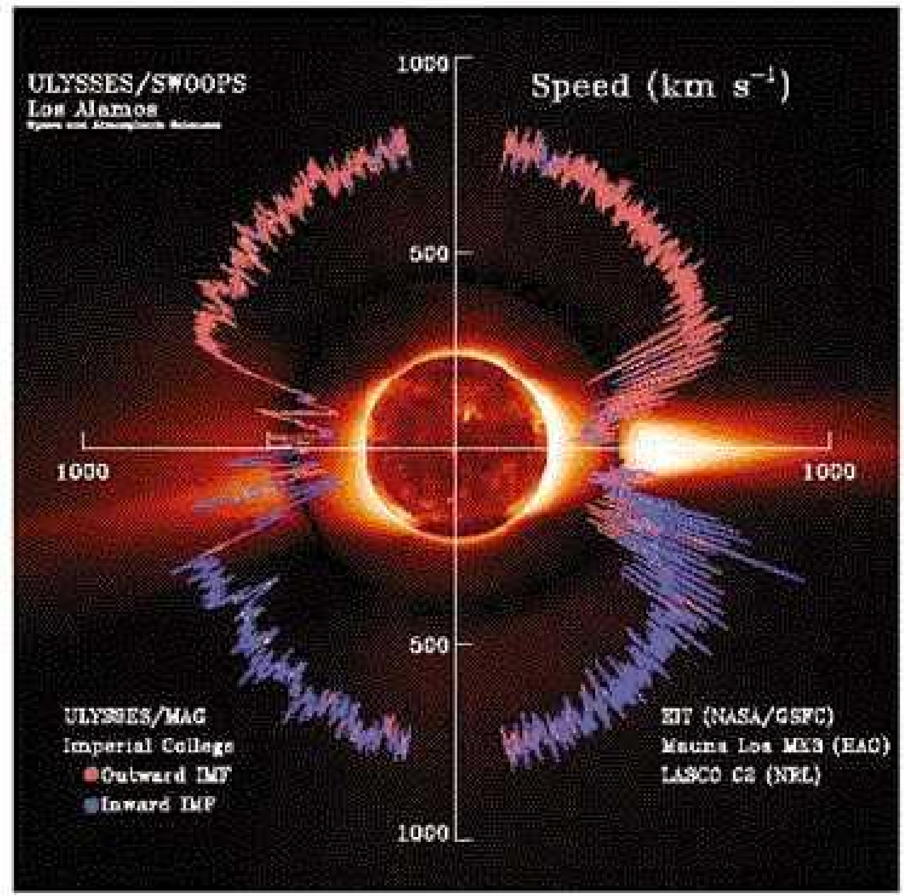
CR intensity
Years
No drift
drift
qA < 0
qA >0



CR count rate (%)
Climax, 3 GV
Huan/Hale, 13 GV

Heliospheric data

- Most of direct data exist for the ecliptic plane:
  - » IMF → can be approximated assuming the regular Parker's field;
  - » Solar wind → little variability over the solar cycle;
- Latitudinal scans (ULYSSES):
  - » latitudinal variability of the solar wind;
- Solar observations:
  - » HCS tilt angle; CMEs;
- Distant missions:
  - » Discovery of the termination shock;



McComas, D.J., et al., Geophys. Res. Lett., 25, 1-4, 1998

Quality and quantity of data decrease backwards in time.

Force-field approximation

Under some simplifying assumptions, the force-field (FF) approximation of CR transport equation is:

$$\frac{\partial f}{\partial r} + \frac{VP}{3\kappa} \cdot \frac{\partial f}{\partial P} = 0$$

Solution: $P = P_{LIS} - \Phi$

$$j_{1\mathrm{AU}}(T) = j_{LIS}(T + \Phi)\frac{P^2}{(P+\phi)^2}$$

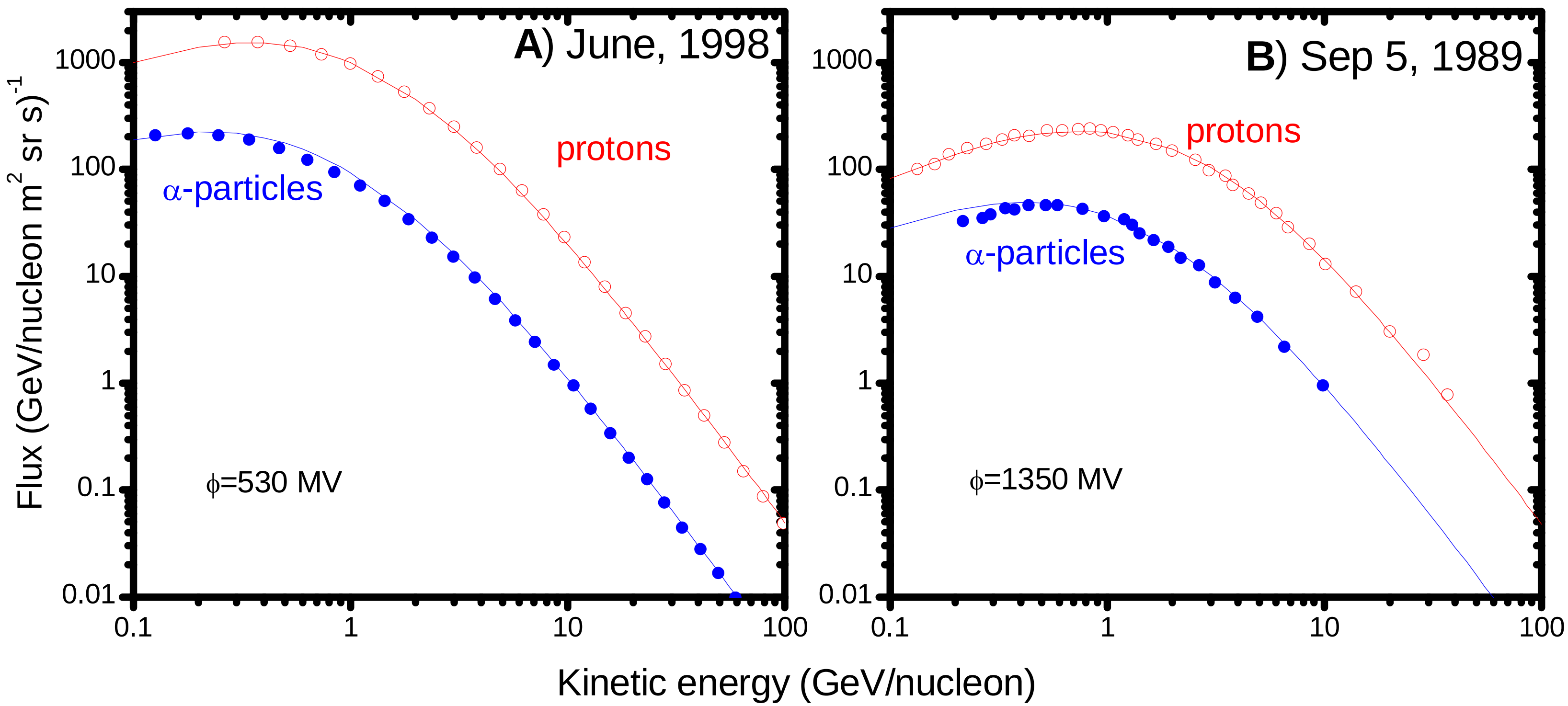
where $j = P^2 f$ and

$$\Phi = \frac{eZ}{A}\phi$$

is the modulation strength (in MV)

variable parameter and **fixed parameter LIS**

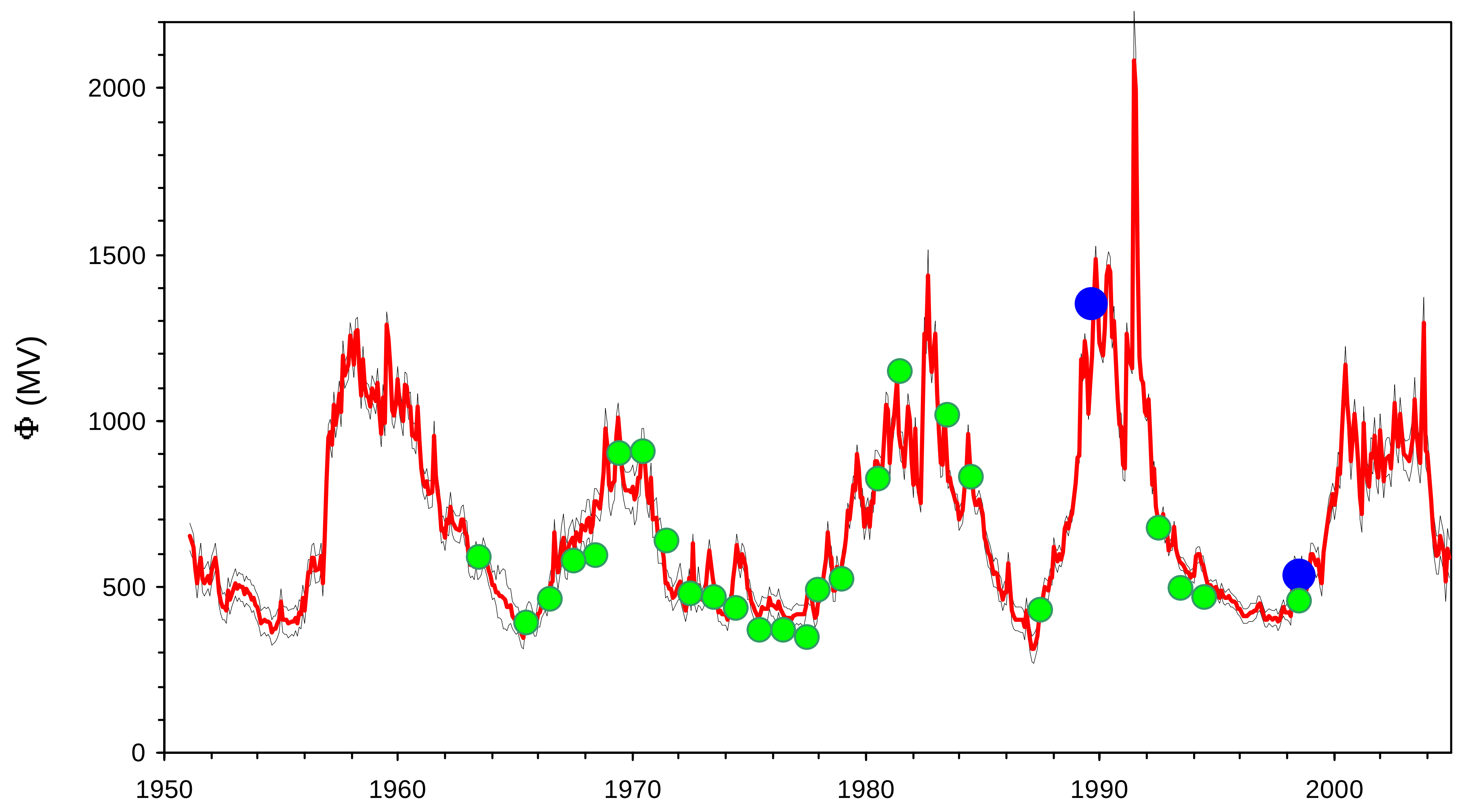
Spectrum parameterization



Measured GCR (p and α) spectra can be well fitted with the single parameter in a wide range of the modulation strength.

LIS from Burger, Potgieter & Heber, JGR, 105, 27447, 2000.

ϕ reconstruction since 1951



Usoskin et al., JGR, 110, 2005.

Cosmic ray variability

Short time scale (days): transients

Mid time scale (months-years): all modulation processes (diffusion, convection, drifts)

Long time scales (decades-centennia): diffusion-dominated 1D model (force-field), heliosphere size,

Very long time scales (millennia): solar modulation + geomagnetic field

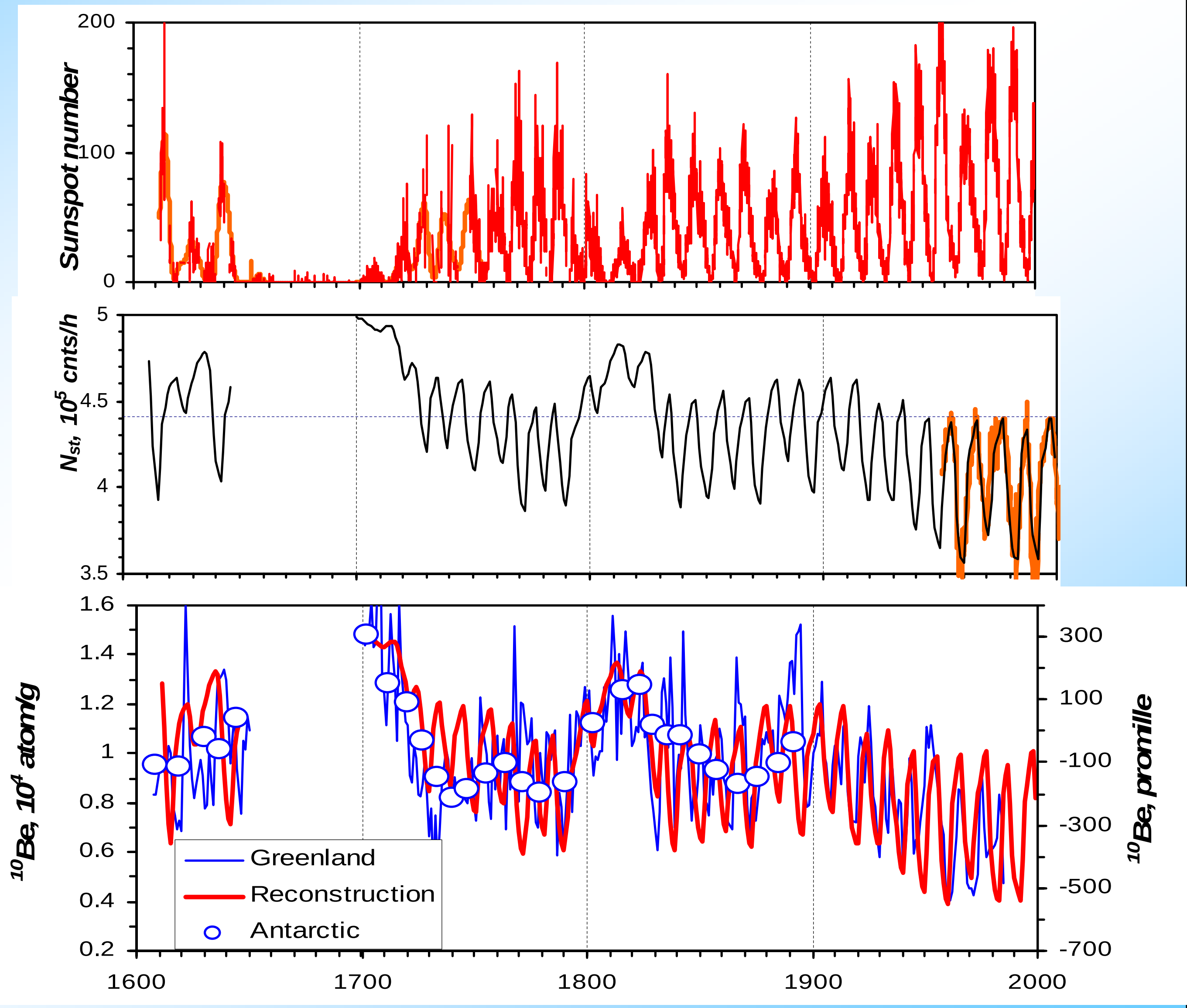
Extra long time scales (> 10^4 years): geomagnetic field – lunar samples → constant solar modulation

Geological time scale (>10^8 years): local galactic surroundings

Long-term CR

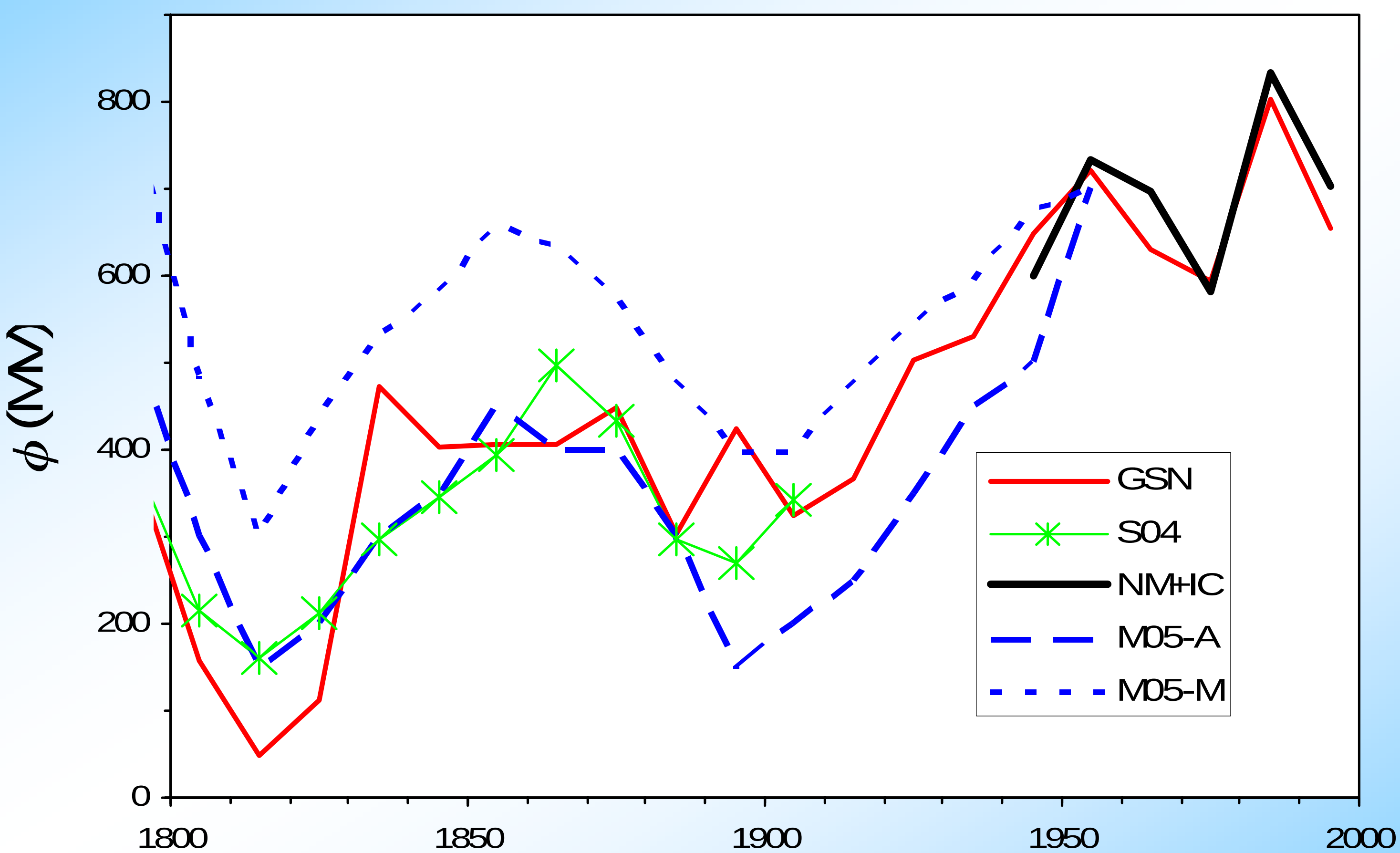
Model computations:

- SN -> open flux model (Solanki et al., 2002; Krivova et al., 2007; Vieira et al., 2011);
- open flux -> CR (Usoskin et al., 2005);
- CR -> ^{10}Be (Kovaltsov & Usoskin, 2010)

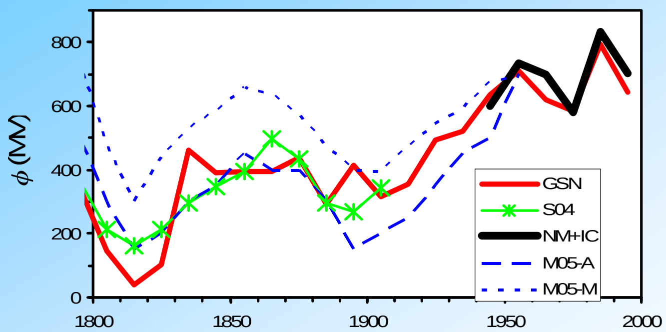


^{44}Ti in meteorites: A direct test

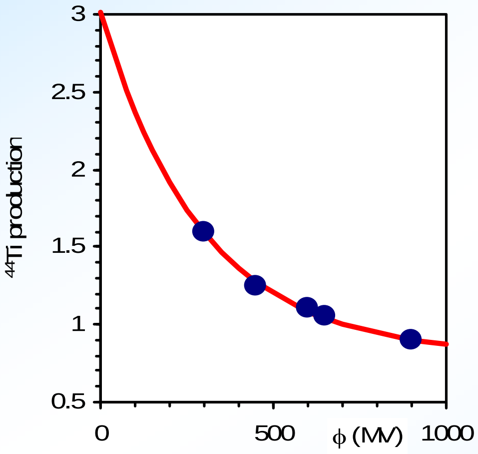
Modulation potential: reconstructions

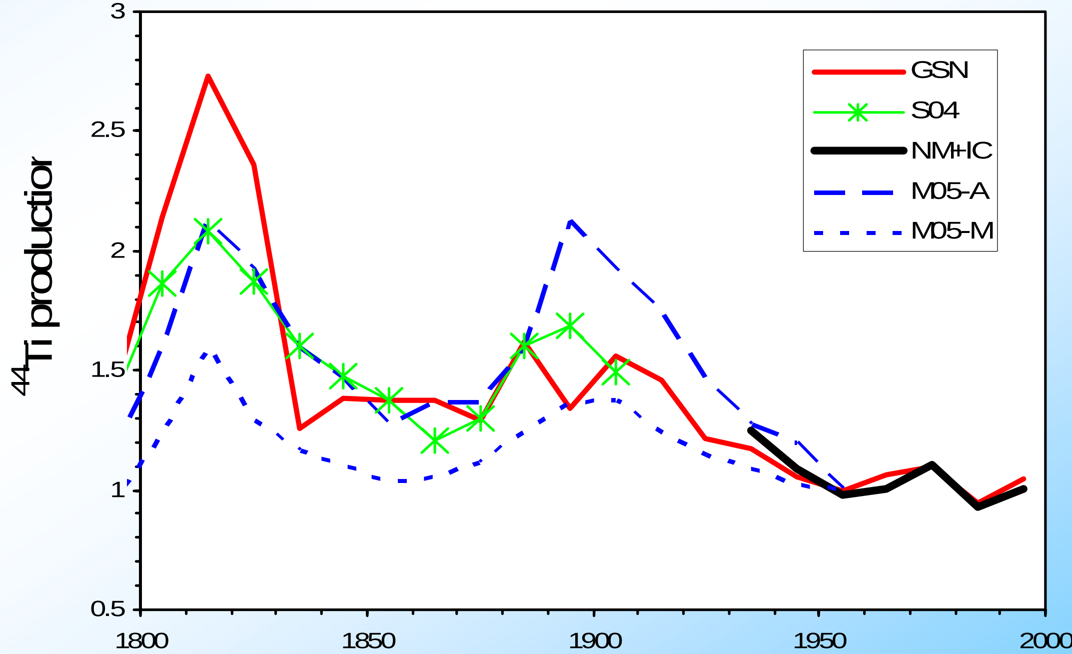


44Ti production rate, Q_{Ti}



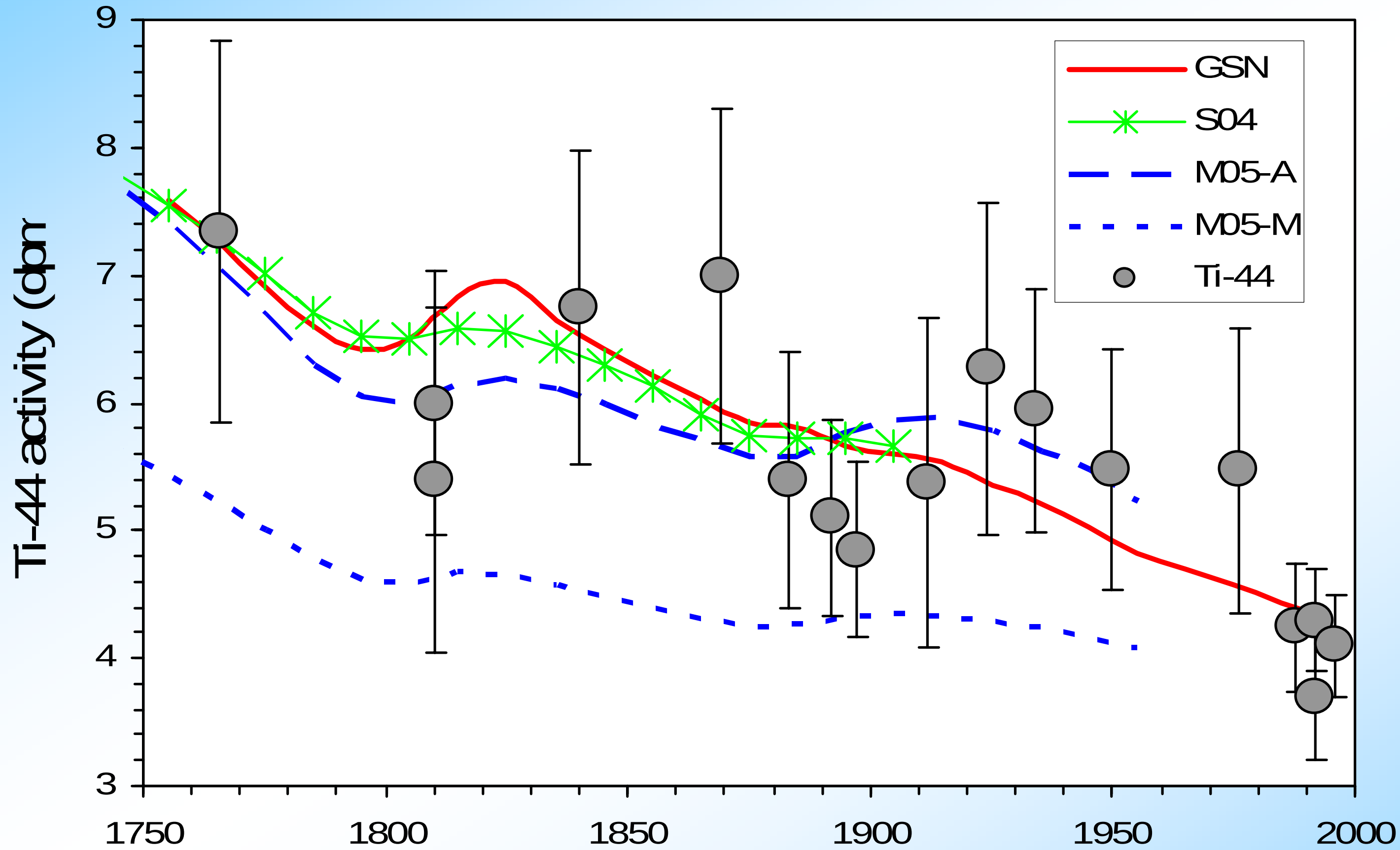
X





Michel & Neumann, Earth Planet. Sci., 107, 441, 1998

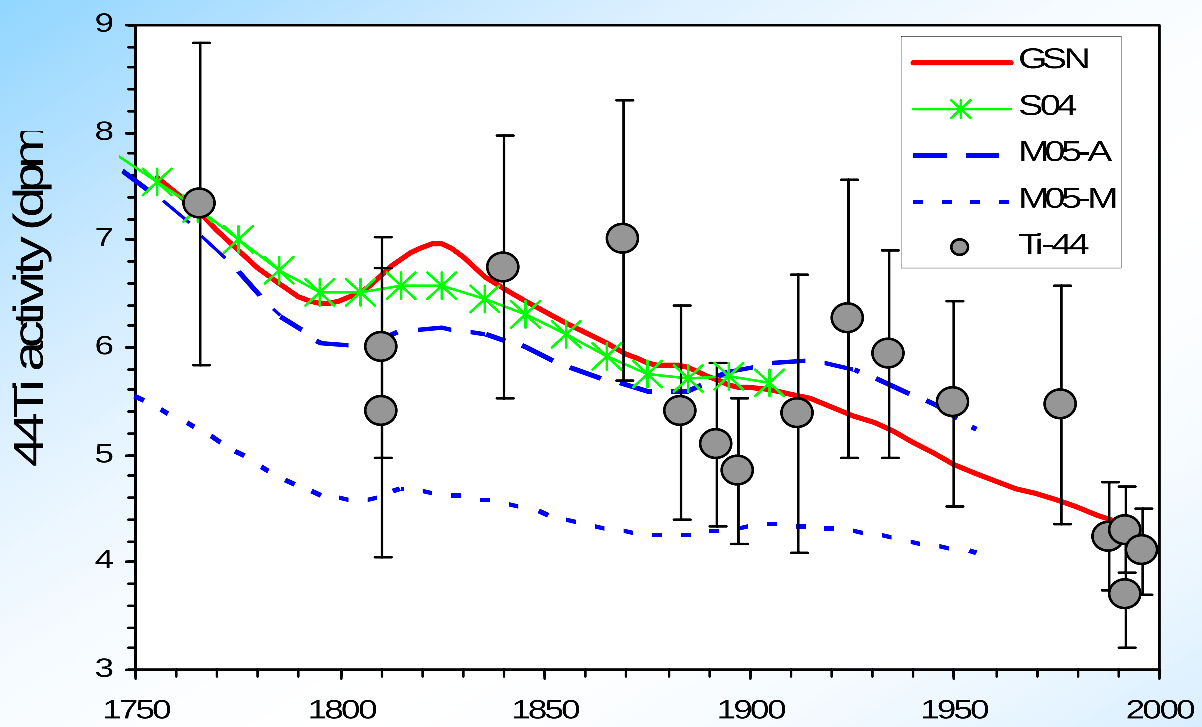
Ti-44 activity: model-vs-measurements



Integration/decay => measured activity :

$$A(t) = \frac{1}{\tau} \int_{-\infty}^{t} Q_{Ti}(\tau) \cdot \exp\left(\frac{t - x}{\tau} \right) d\tau$$

Ti-44 activity: model-vs-measurements

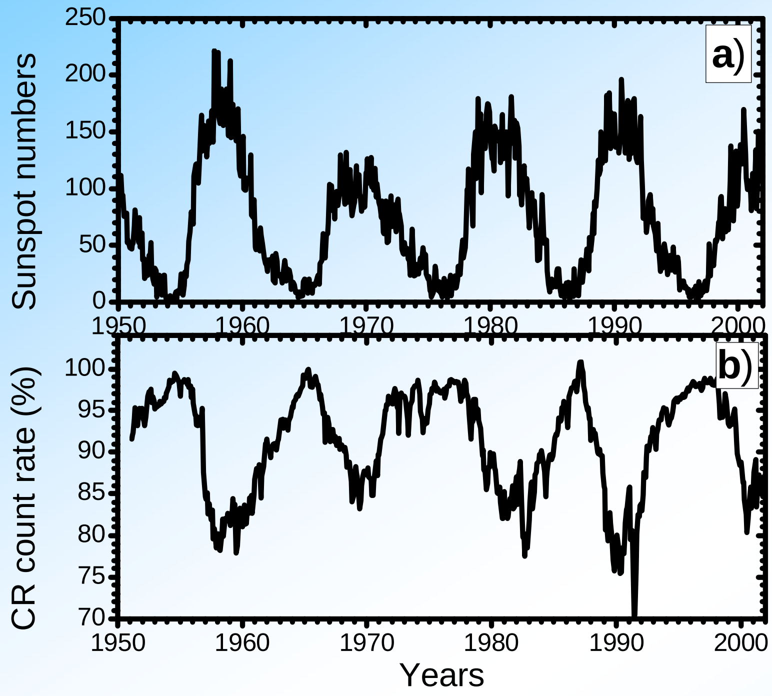


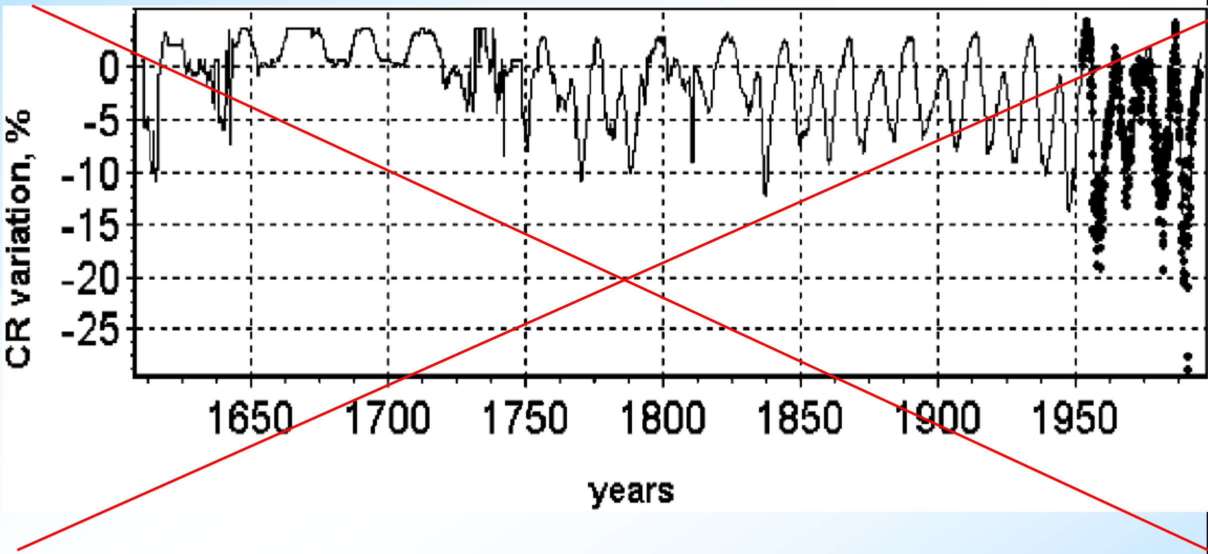
Model	x^2 (DoF)	Sign. level
GSN	7.55(17)	2%
S04	2.44 (8)	3%
M05-M	20.5 (11)	96%
M05-A	4.4 (11)	4%

A word of warning on regressions

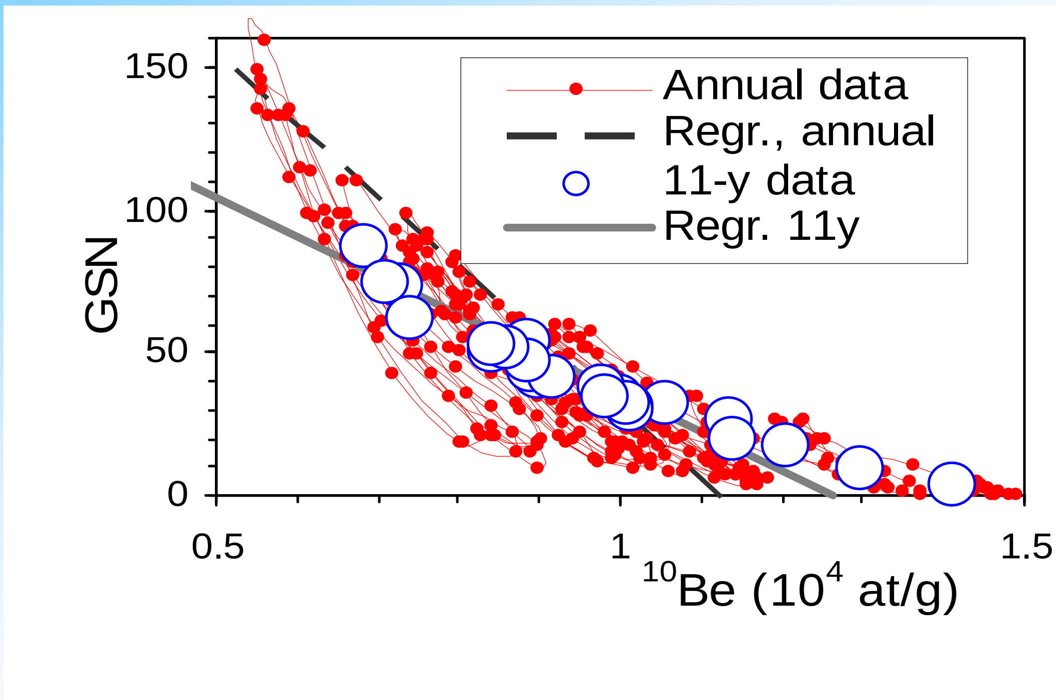
Regressions?

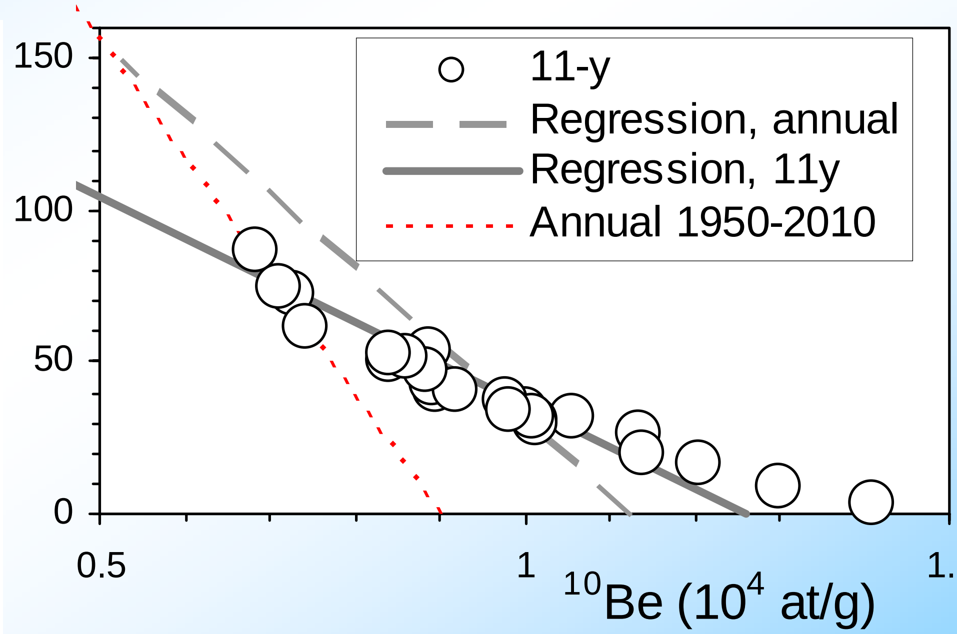
Belov et al., JASTP, 2006

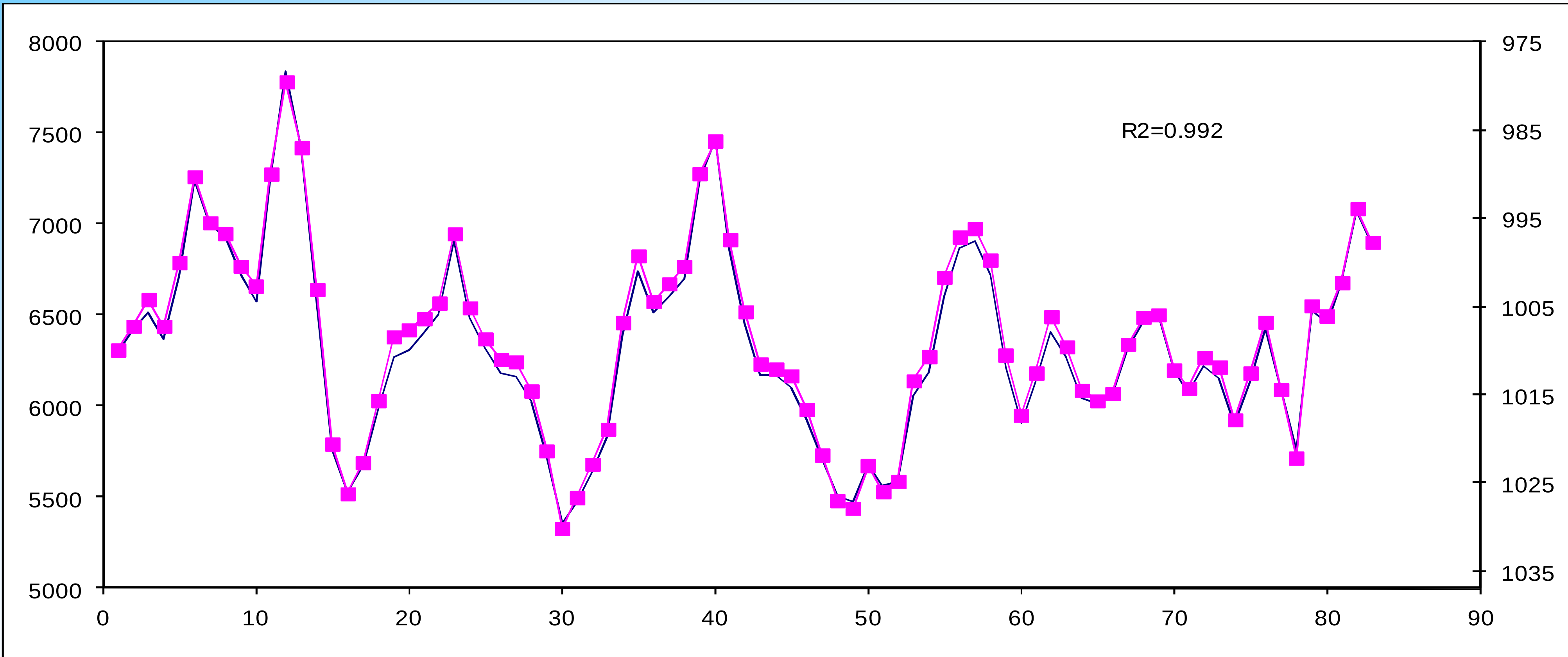


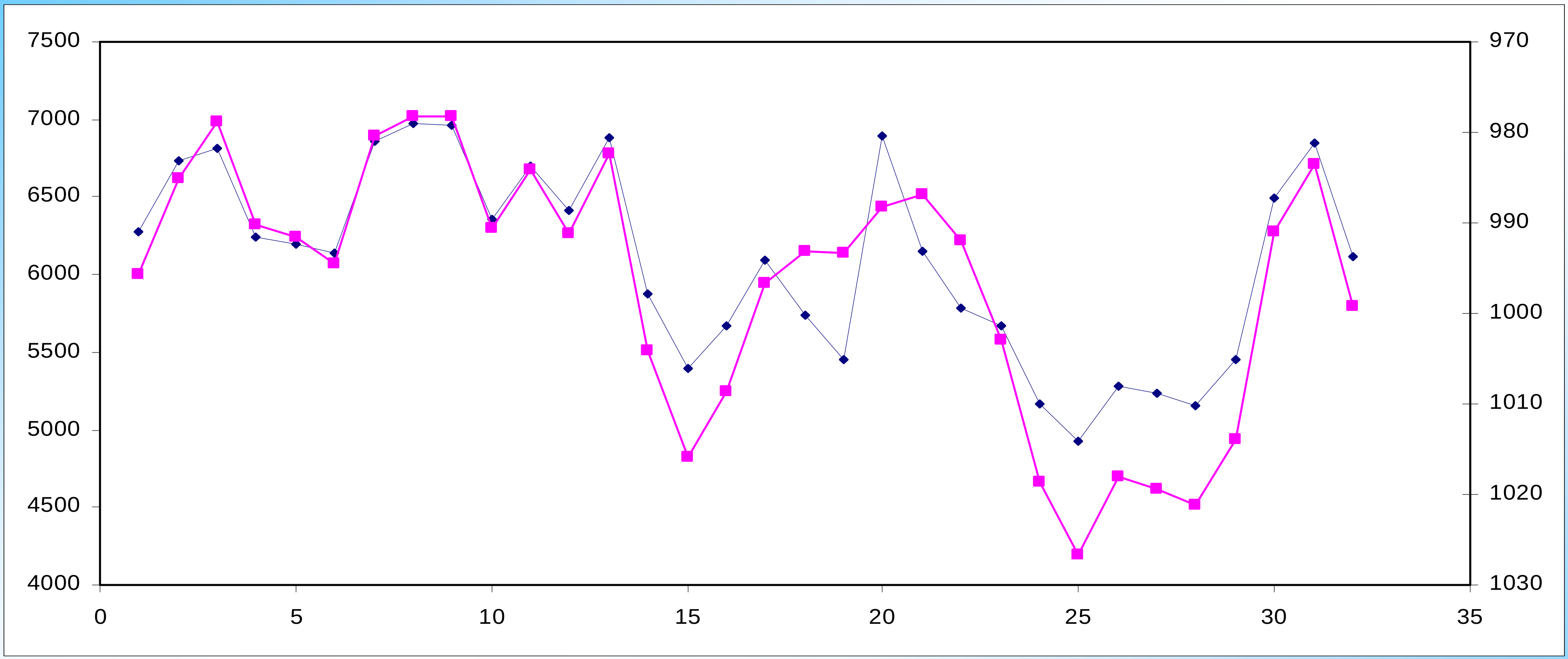


Regressions






8000
7500
7000
6500
6000
5500
5000
975
985
995
1005
1015
1025
1035
0
10
20
30
40
50
60
70
80
90
R2=0.992



7500
7000
6500
6000
5500
5000
4500
4000
970
980
990
1000
1010
1020
1030
0
5
10
15
20
25
30
35

- Series #1 – a neutron monitor count rate.
- Series # 2 – barometric pressure;
- Period #1 – Jan-Mar 2008 (quiet);
- Period #2 – Jan 2005 (GLE + 2 FDs)

NM is a bad barometer, but the long-term relation is lost,

barometer is NOT a NM

Conclusions

- Cosmogenic isotopes form a reliable proxy for solar magnetic activity (HMF+solar wind – not ecliptics) on decadal-centennial-millennial time scale.
- Centennial variability of SA is robustly confirmed.
- ^{44}Ti in meteorites confirms large centennial variability during the last 150 years.
- As we know from cosmogenic data – linear regression does NOT work. The relation between SA and cosmogenic data is essentially non-linear.

THANK YOU !