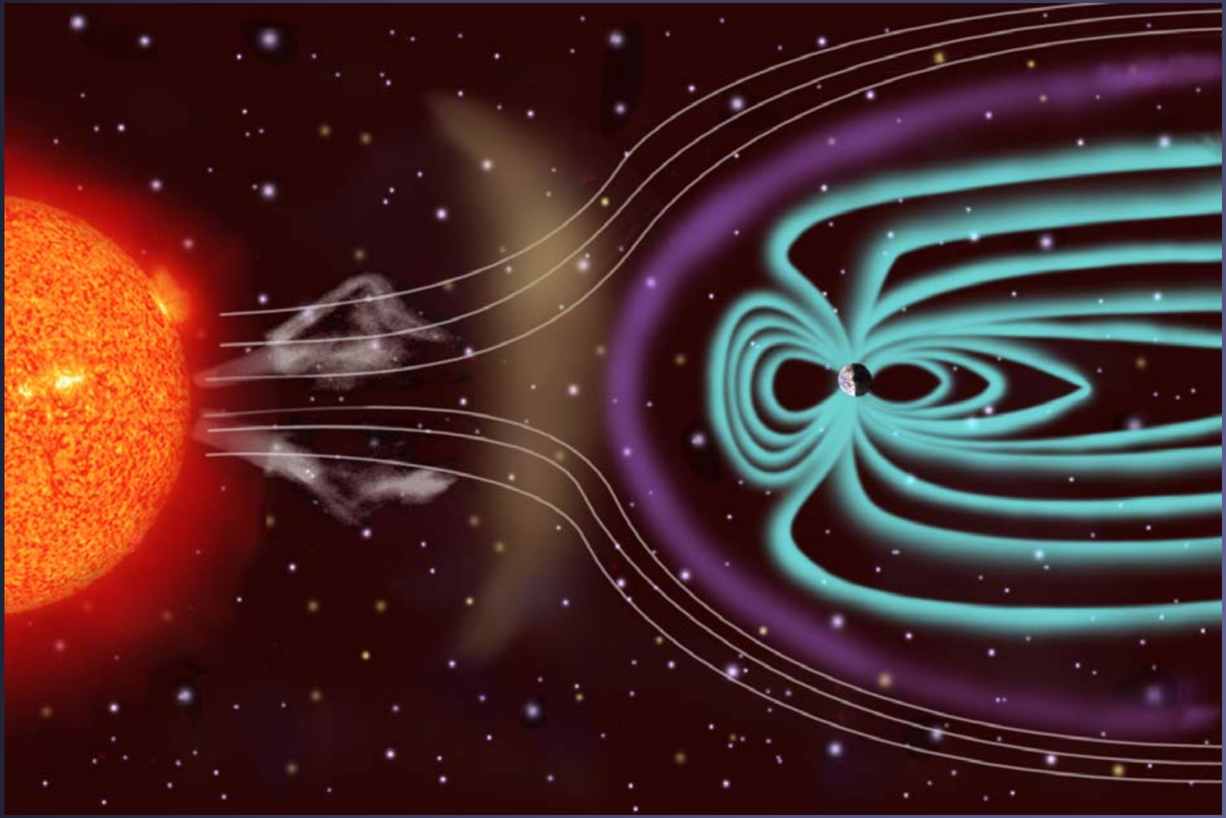
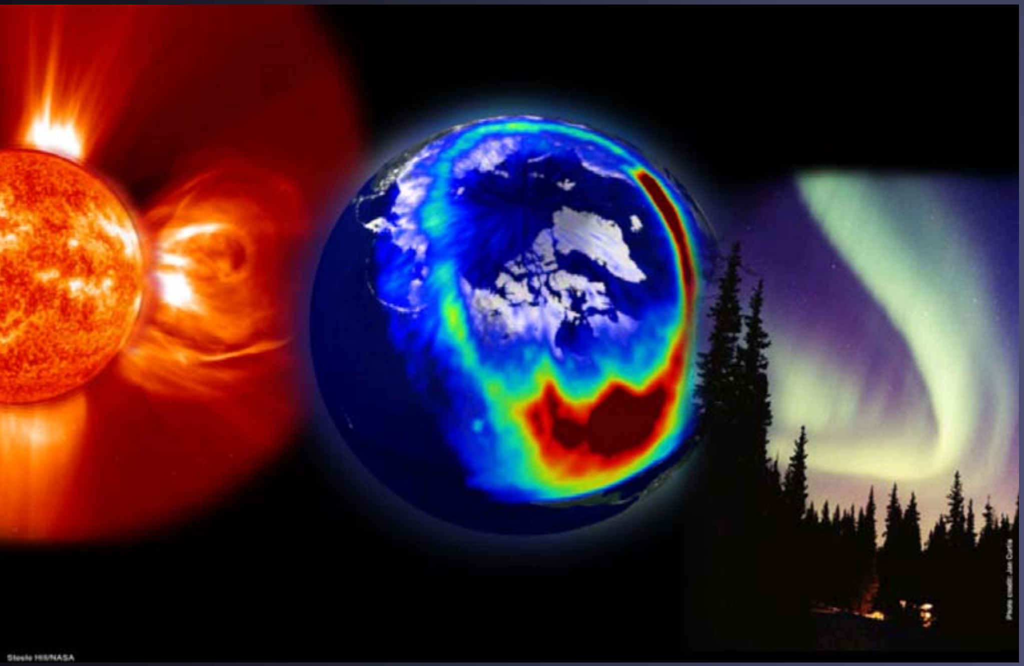
The Sun-Earth Connection



Solar influence on Earth

The variable activity of the Sun affects Earth in many ways:



short

- "Space weather": Disturbances in the Magnetosphere, Ionosphere, Upper atmosphere
- Satellite systems, Communication and Energy supply

long

- Global climate change
- Modulation of galactic cosmic rays hitting Earth

Space Weather

- Cause: variability of Sun & solar wind
- Solar components: solar energetic electro-magnetic (UV, X-rays, γ-rays) & particle radiation (eV to MeV)

↓

- Affected natural systems: Earth’s magnetosphere, ionosphere, thermosphere, stratosphere
- Technical systems in space & partly on Earth affected
- Potential health hazard: astronauts, airplane passengers & crew, inhabitants at high latitudes (ozone hole)

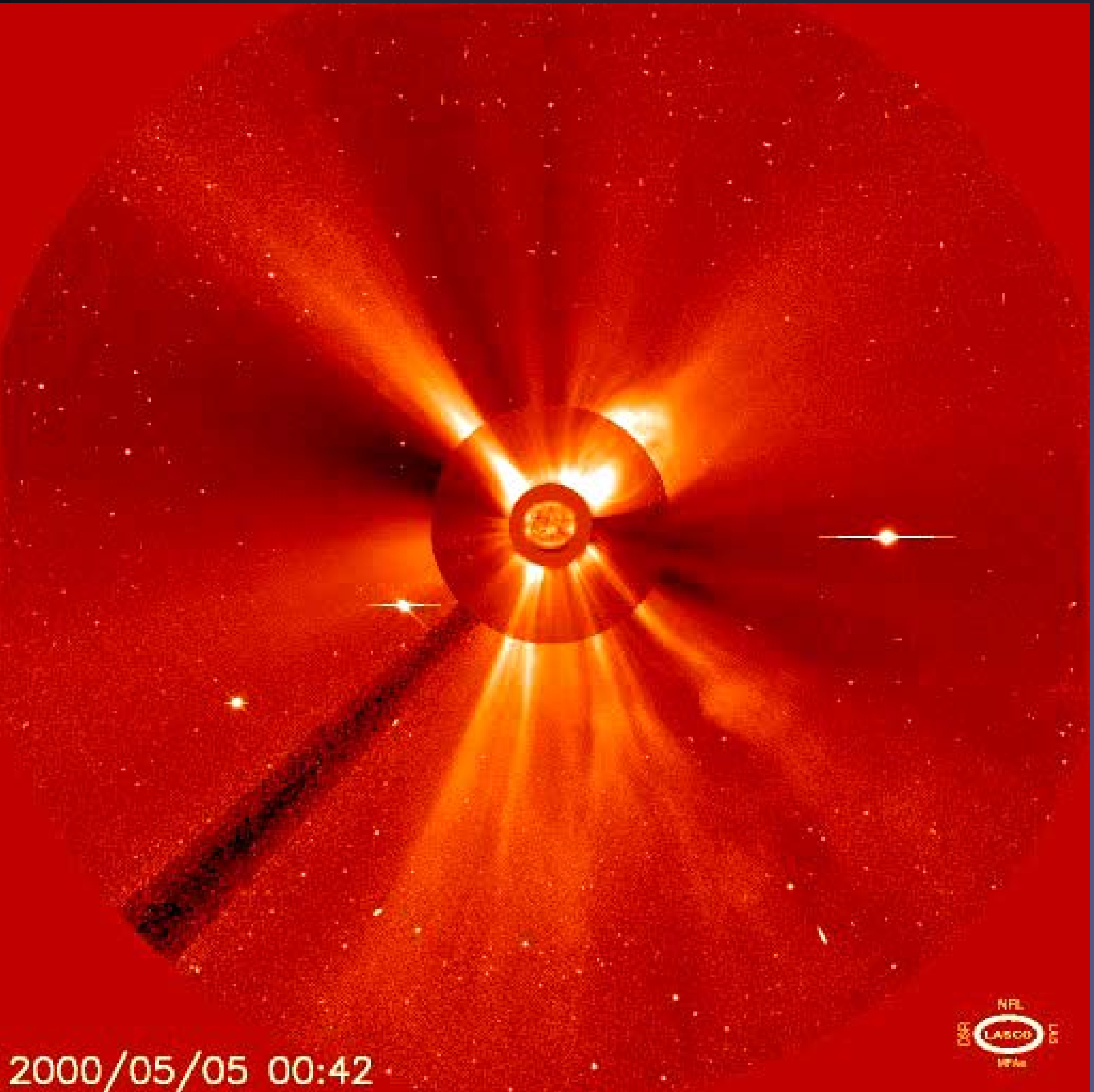
Causes of Space weather

- Variations of the solar electromagnetic radiation, in particular UV and X-radiation
- Solar wind
- Suprathermal particles (particle energies of eV)
- Energetic particles (keV to MeV)
- Cosmic rays (MeV to GeV)
- Meteorides, interplanetary dust, galactic Gamma-Ray-Bursts, etc.

From Sun

Other sources

The Sun and Space Weather: CMEs



Composite of Sun and its extended corona (LASCO C2 + C3 EIT 304 Å)

Bright, overexposed dots are planets (Mercury, Venus, Jupiter, Saturn), fainter background objects are stars

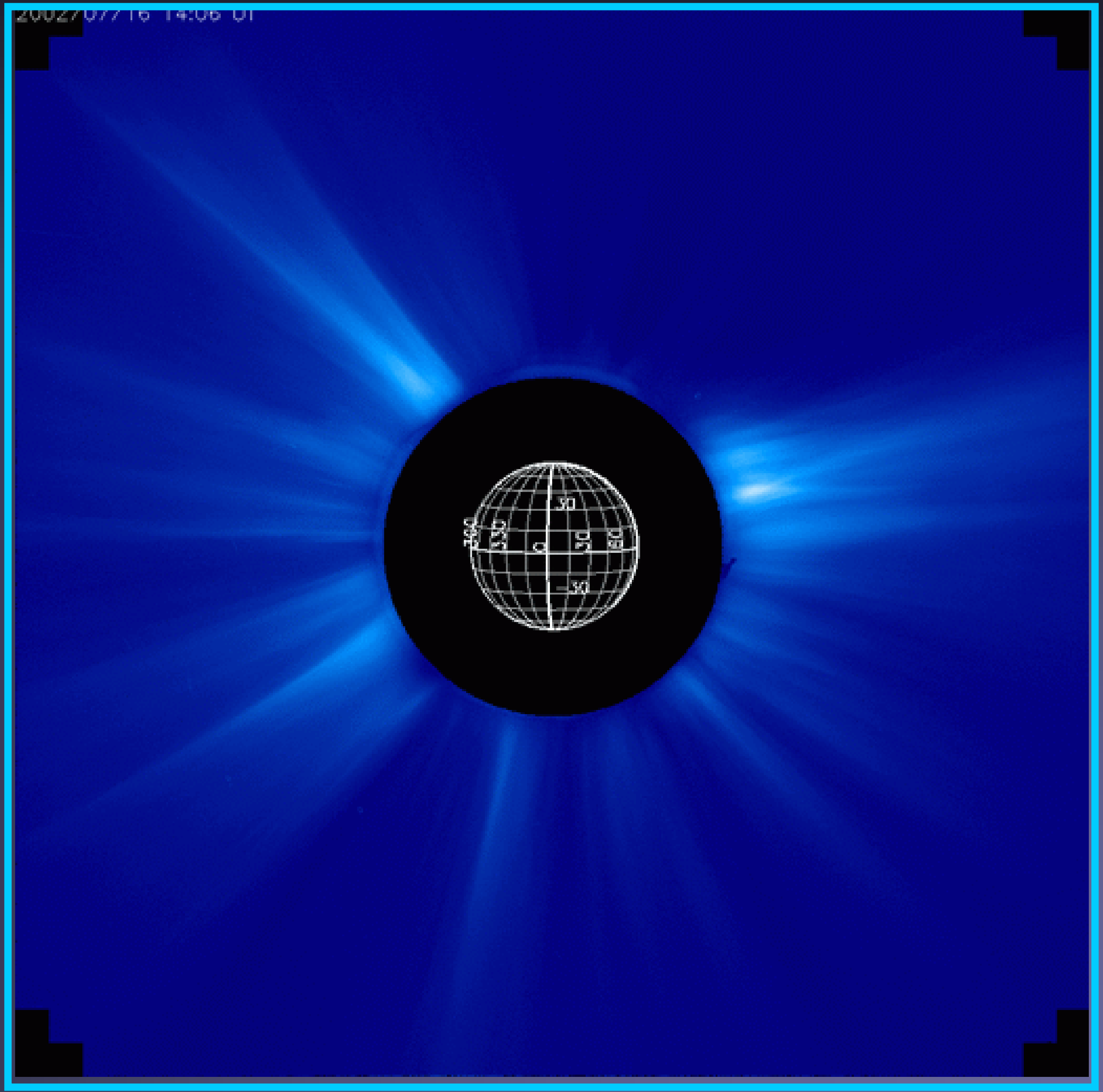
R. Schwenn

Halo CMEs

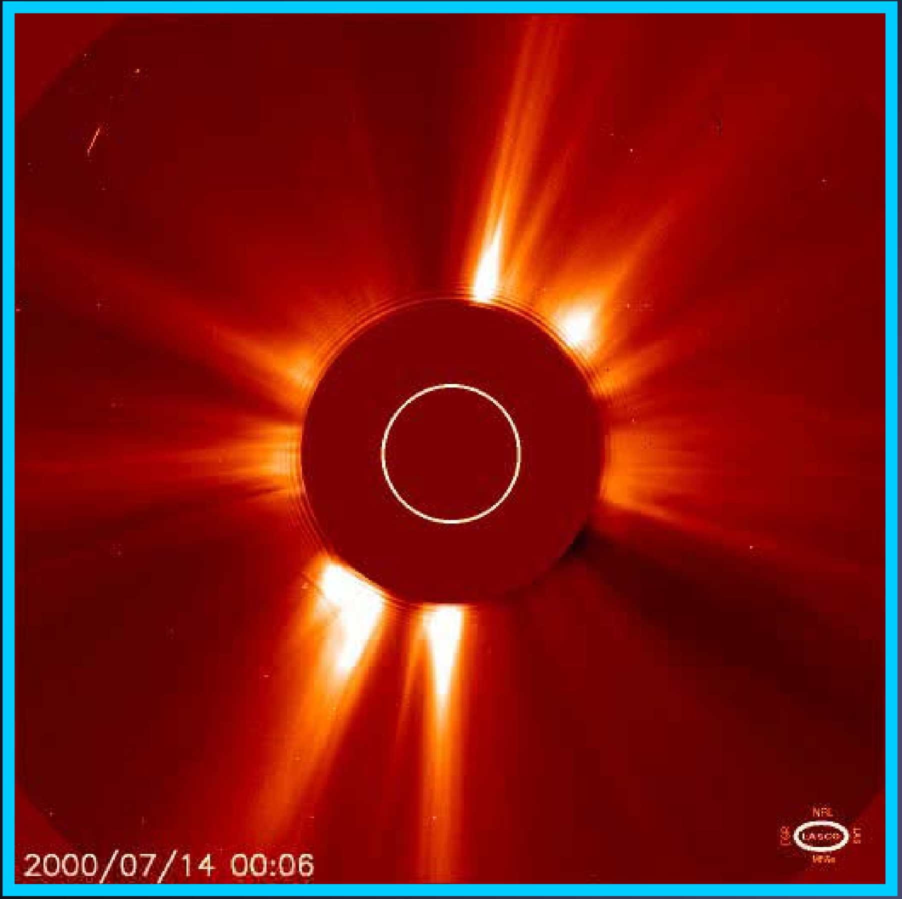
Halo CMEs:

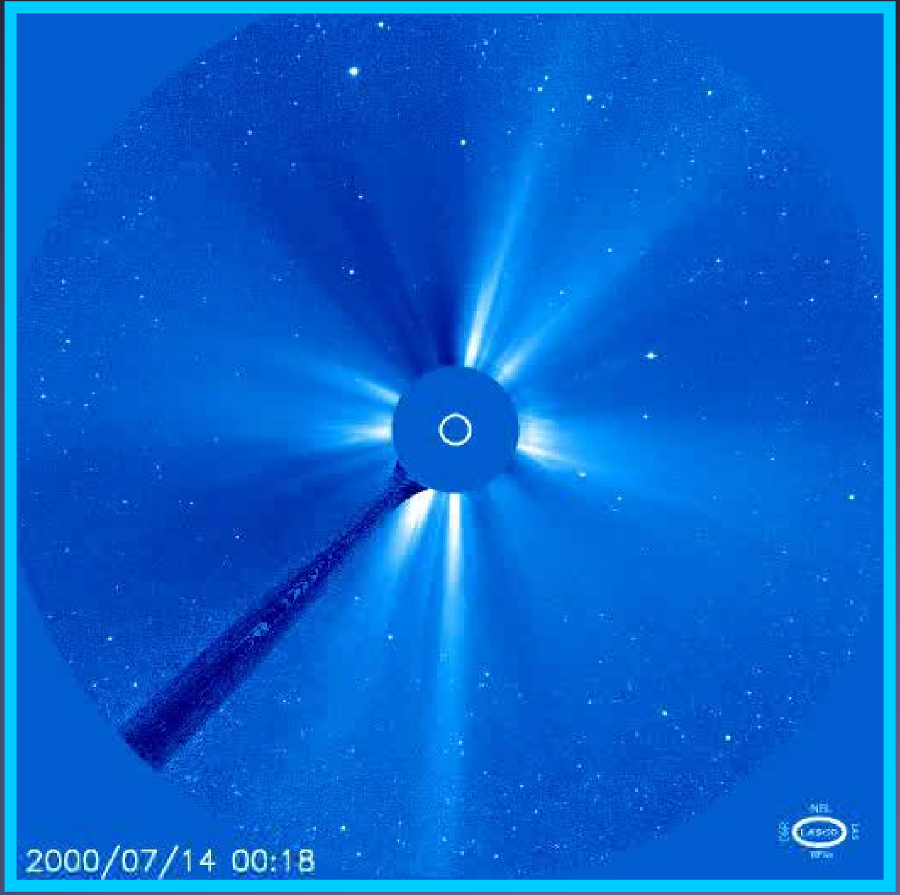
CMEs directed towards (or away from) Earth. The main cause of Space Weather.

Most difficult to detect! Most difficult to predict propagation speed.



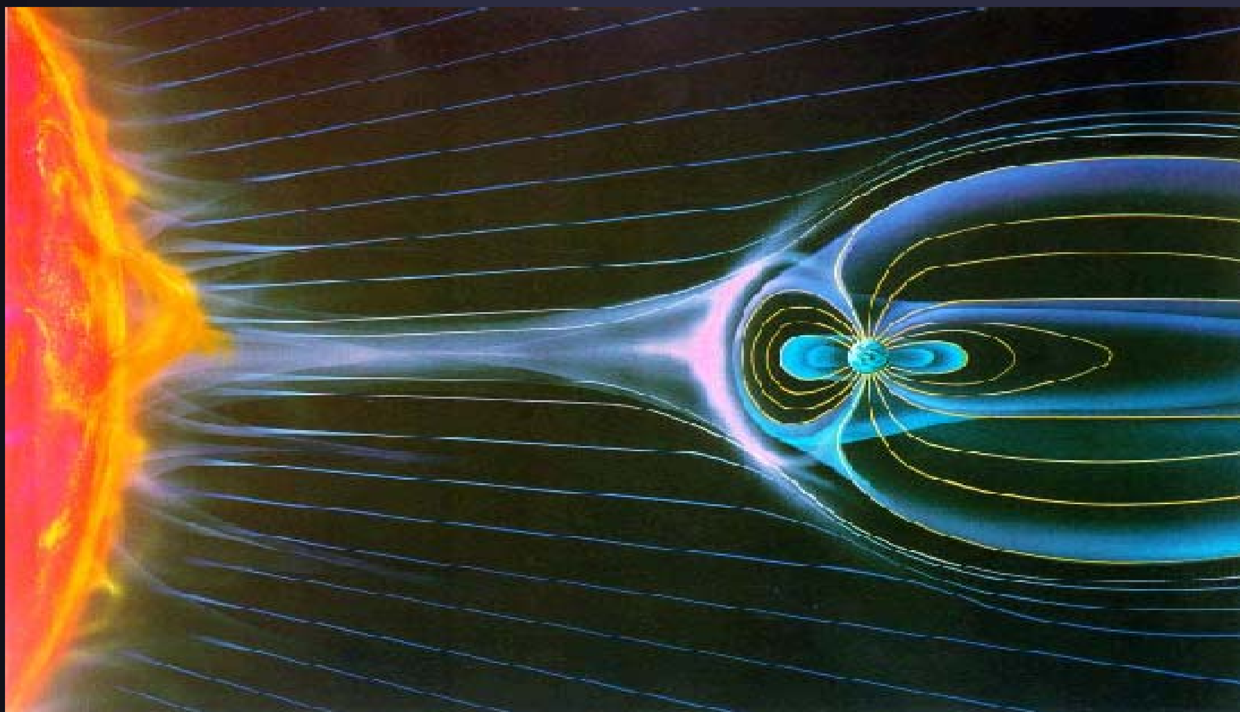
Effect of a CME directed to Earth





The largest solar particle events appear to result from shock associated coronal mass ejections (CMEs)

Interaction of Solar Wind with Magnetosphere of Earth



North

IMF - B_z Earth - B

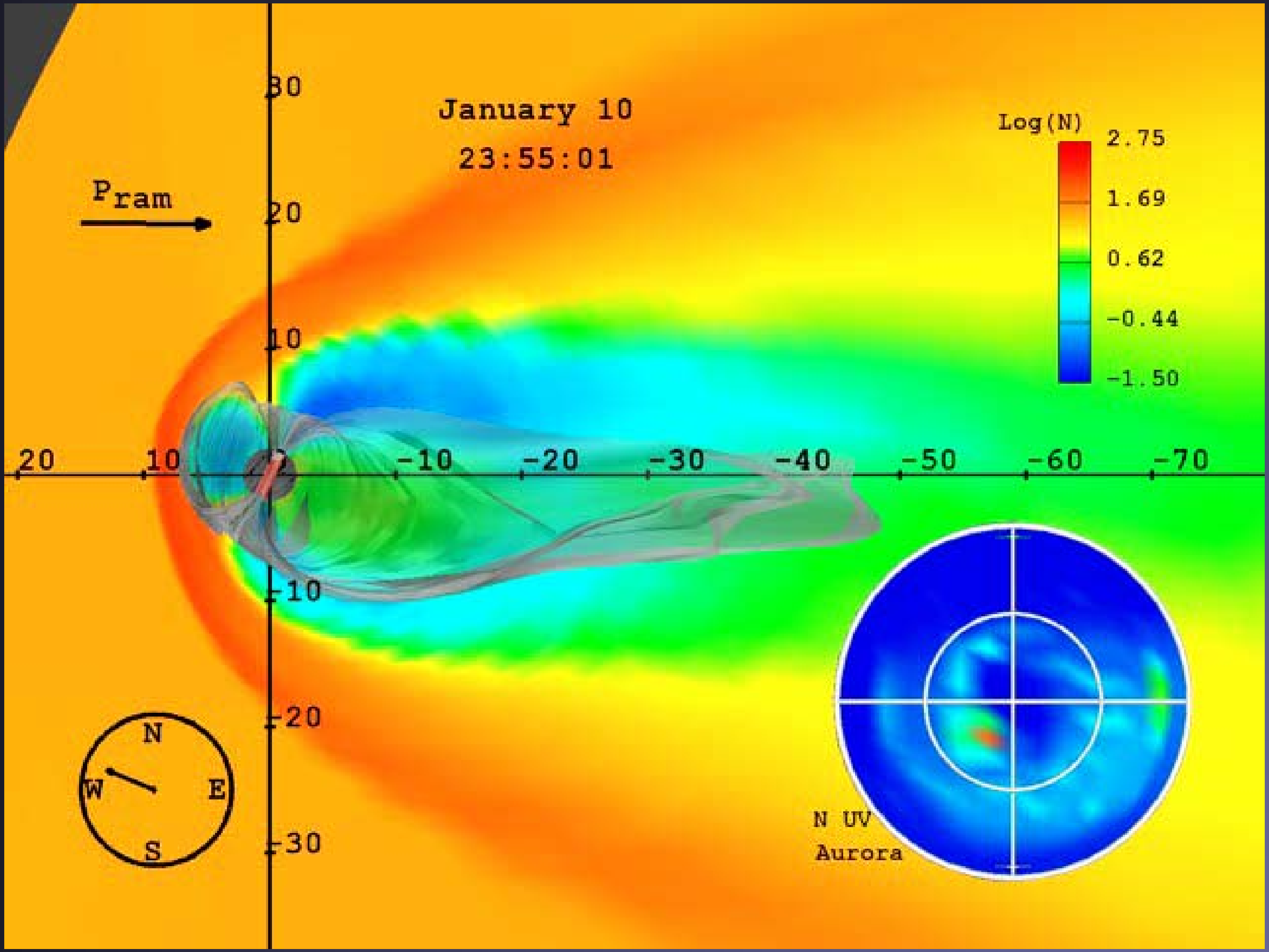
South

Induced electric field: $\underline{E} = - \underline{V} \times \underline{B}$

Effective energy transfer into Magnetosphere in presence of southward component of IMF (e.g. through CMEs, CIRs, waves)

Geomagnetic Storm

Simulation of reaction of magnetosphere to passage of CME launched 6.1.97

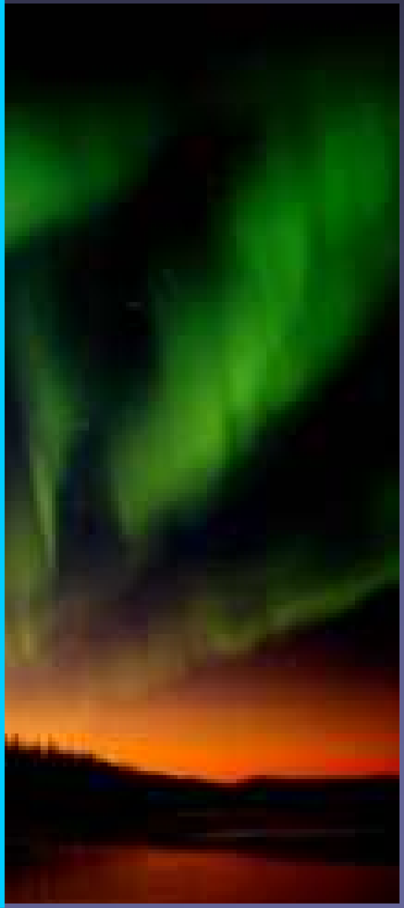


IMF B direction

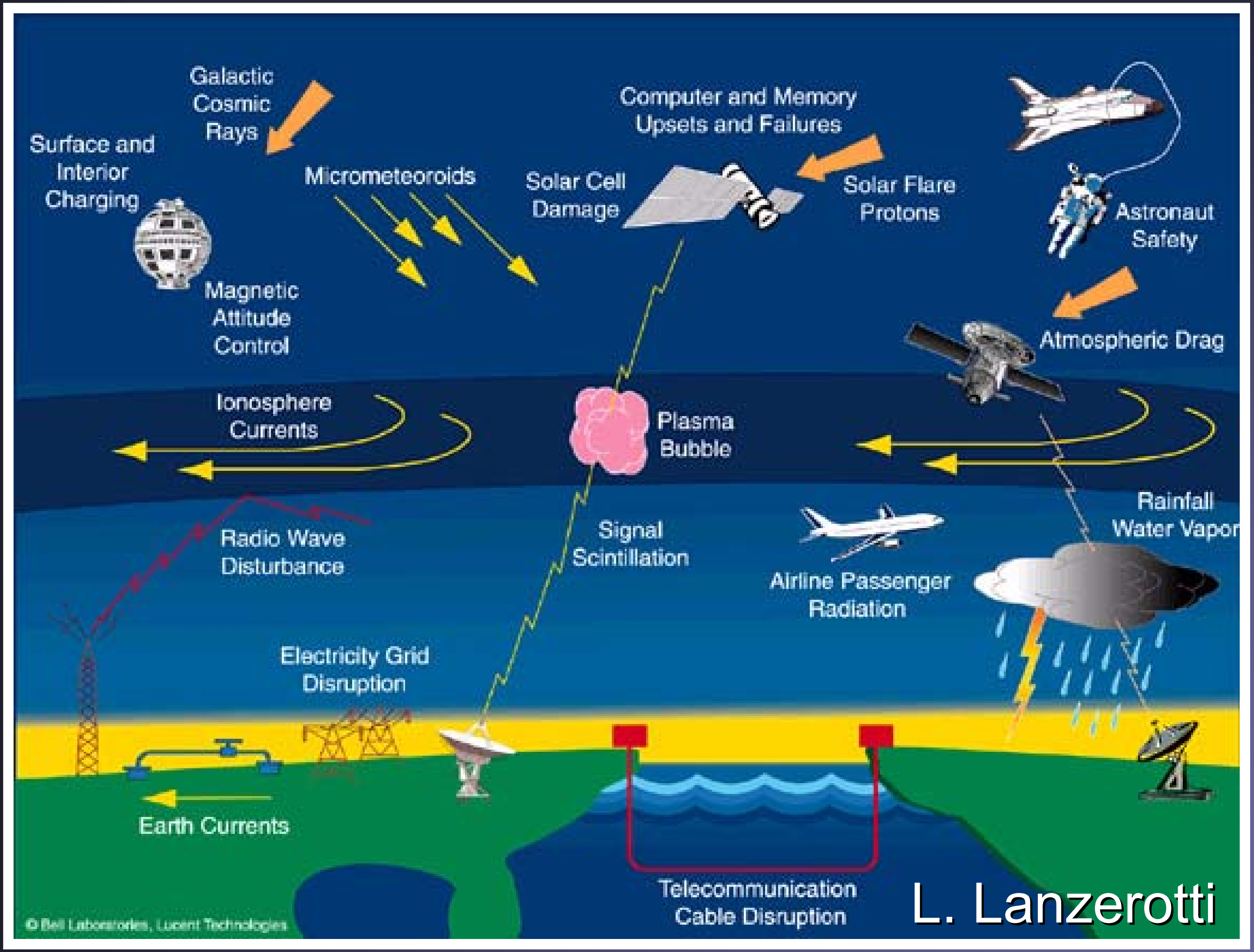
Avge. solar wind speed: 410 km

Goodrich et al. 1998 GRL

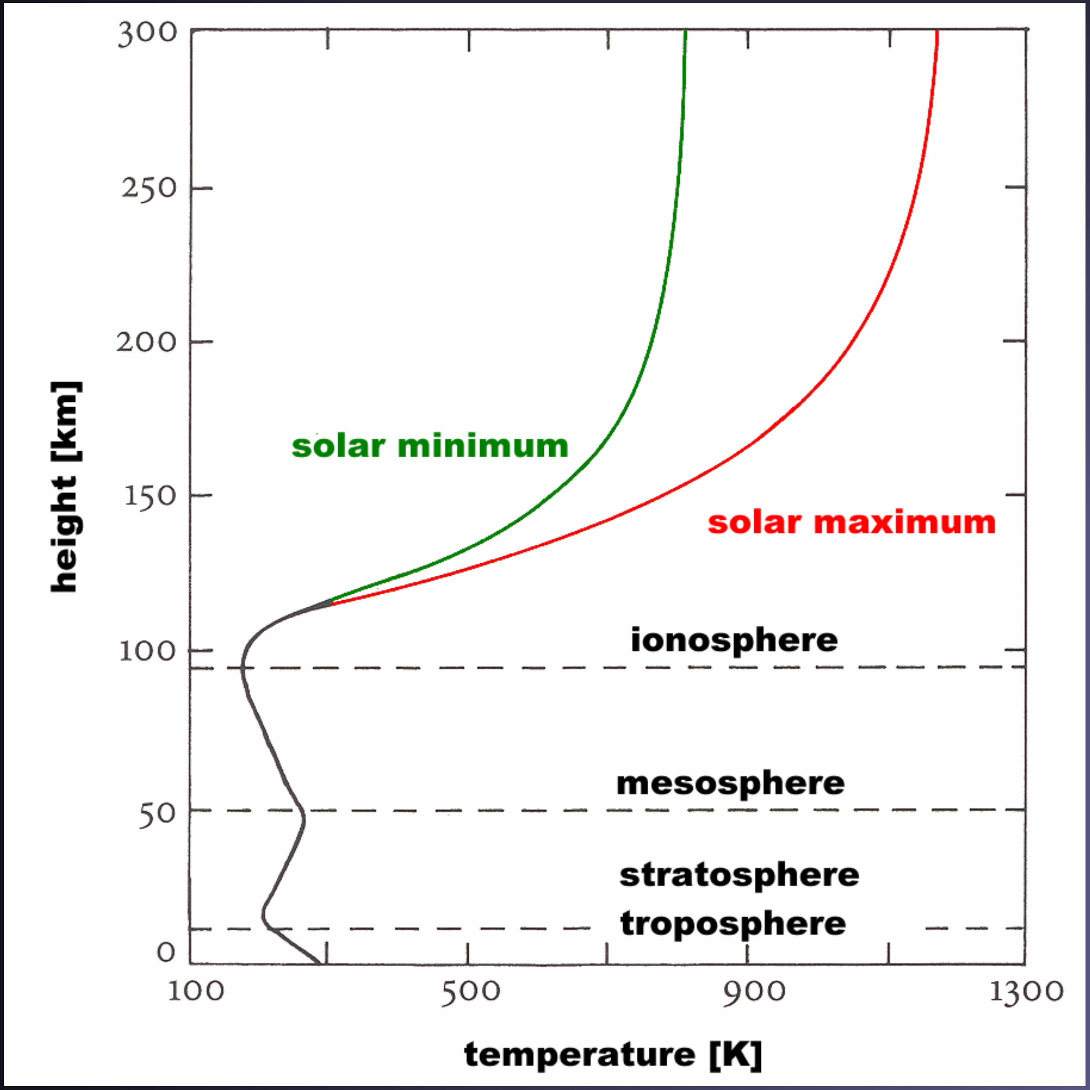
Space Weather: the Aurora



Influence of Solar Activity on Technical Systems



Ionospheric heating by UV radiation

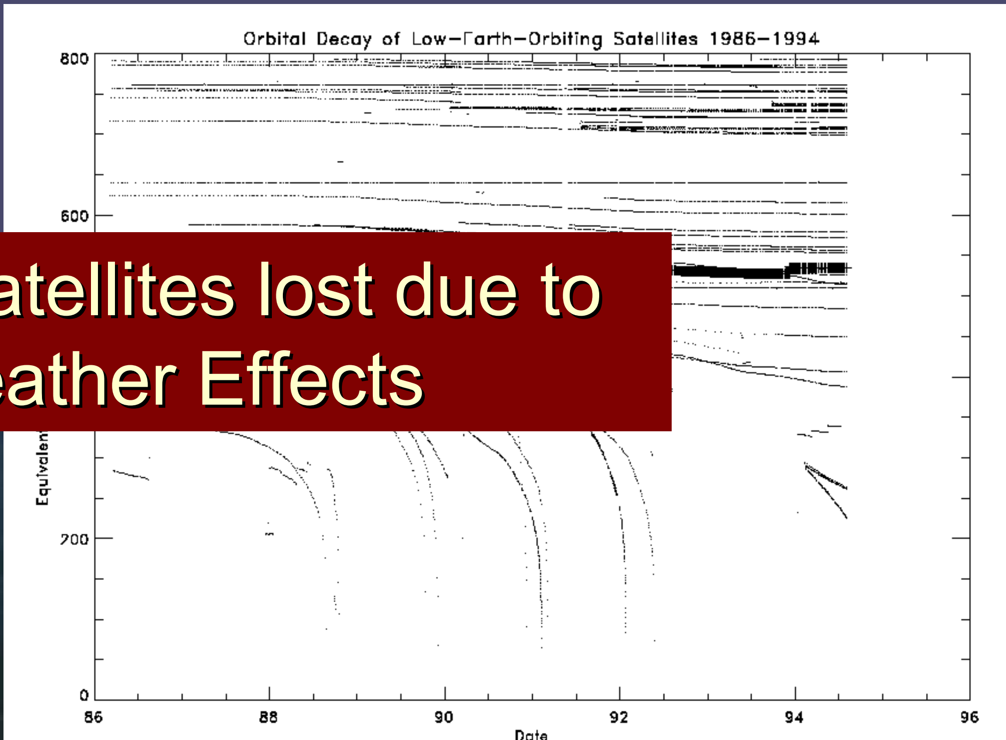


Most important solar radiation component is Lyα, whose strength changes by roughly a factor of 2 over a solar cycle.

Larger temperature means larger scale height: ionosphere expands

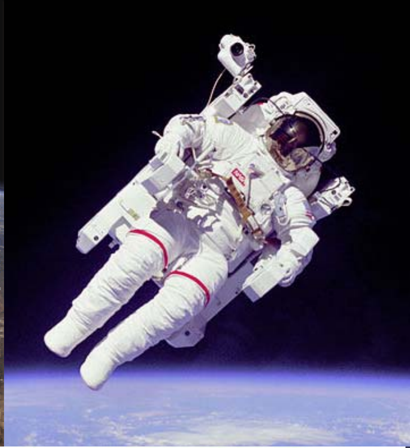
Increased Drag on Satellites

- Expanding atmosphere causes increased drag on low orbit satellites. They loose altitude & non-symmetrical satellites can start tumbling
  - Skylab re-entered several years earlier than planned
  - Hubble Space Telescope drops 10-15 km per year (Re-boosted by the Shuttle



More than 12 satellites lost due to Space Weather Effects

Astronaut safety



- Astronauts are particularly at risk
- The Earth's magnetosphere helps to protect the astronauts on, e.g. the ISS.
- Astronauts travelling to the moon etc. are very much at risk, however.

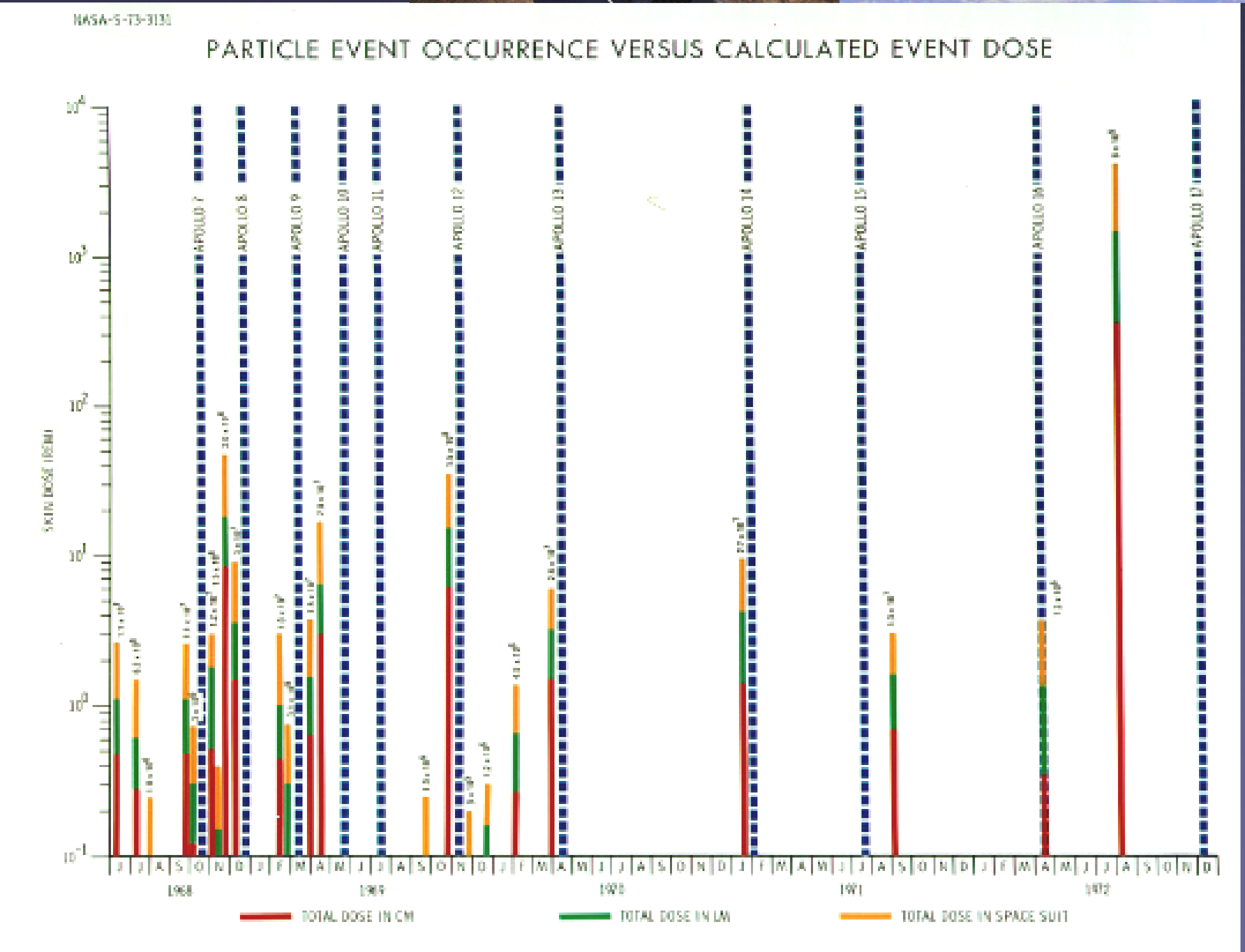
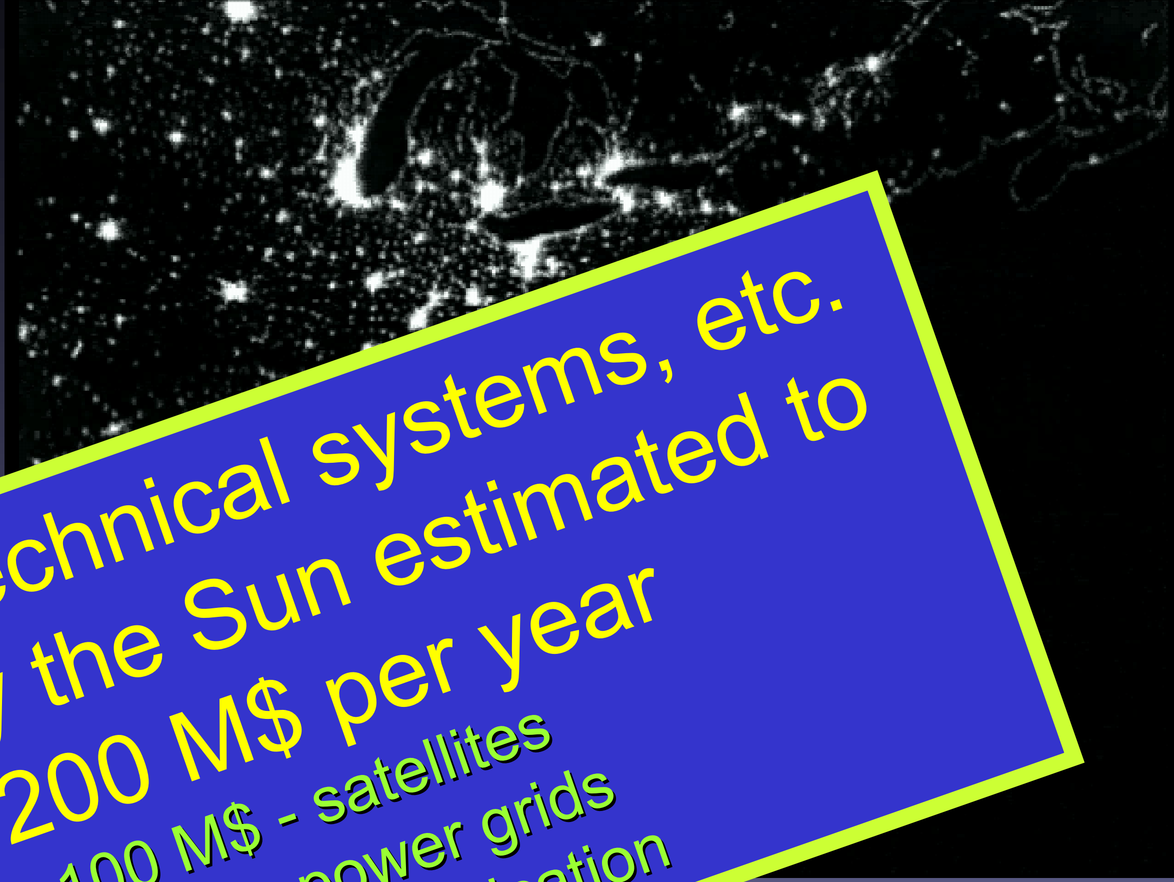


Figure 10. Solar proton events during the Apollo Program.

Bright Sun causes dark night



Blackout in C...
and N...
sc...
tra...
last...

Damage to technical systems, etc. produced by the Sun estimated to be > 200 M$ per year

100 M$ - satellites
100 M$ - power grids
10 M$ - communication

- Sa... ...ations growing most rapidly
- Na... ...argely satellite based: GPS, Galileo
- Sate... ...oads increasingly sensitive
- Humans in Space: more and longer manned missions
- **Importance of Space Weather warnings will increase**

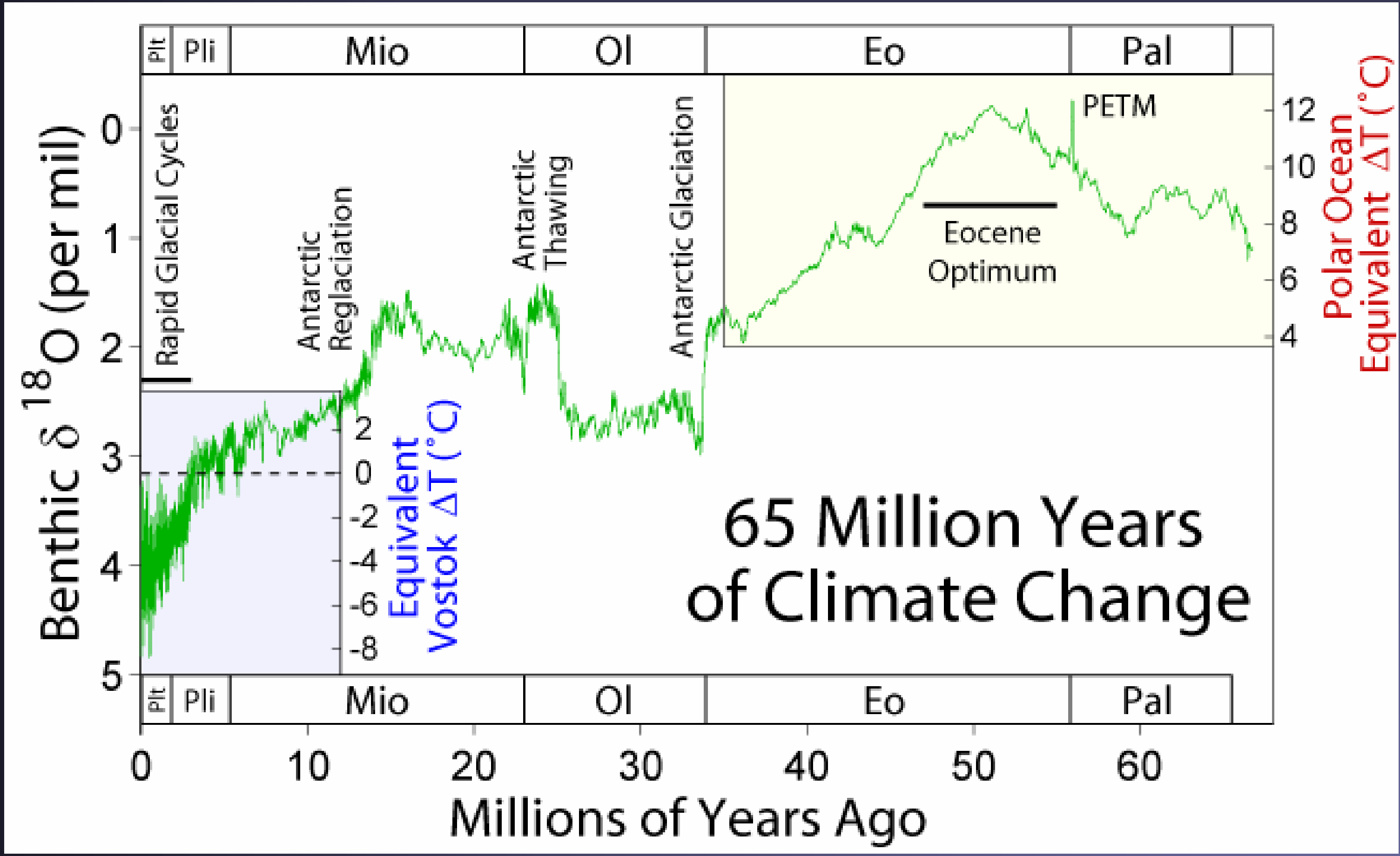
Does the Sun influence climate?

Answer depends on the considered time scale

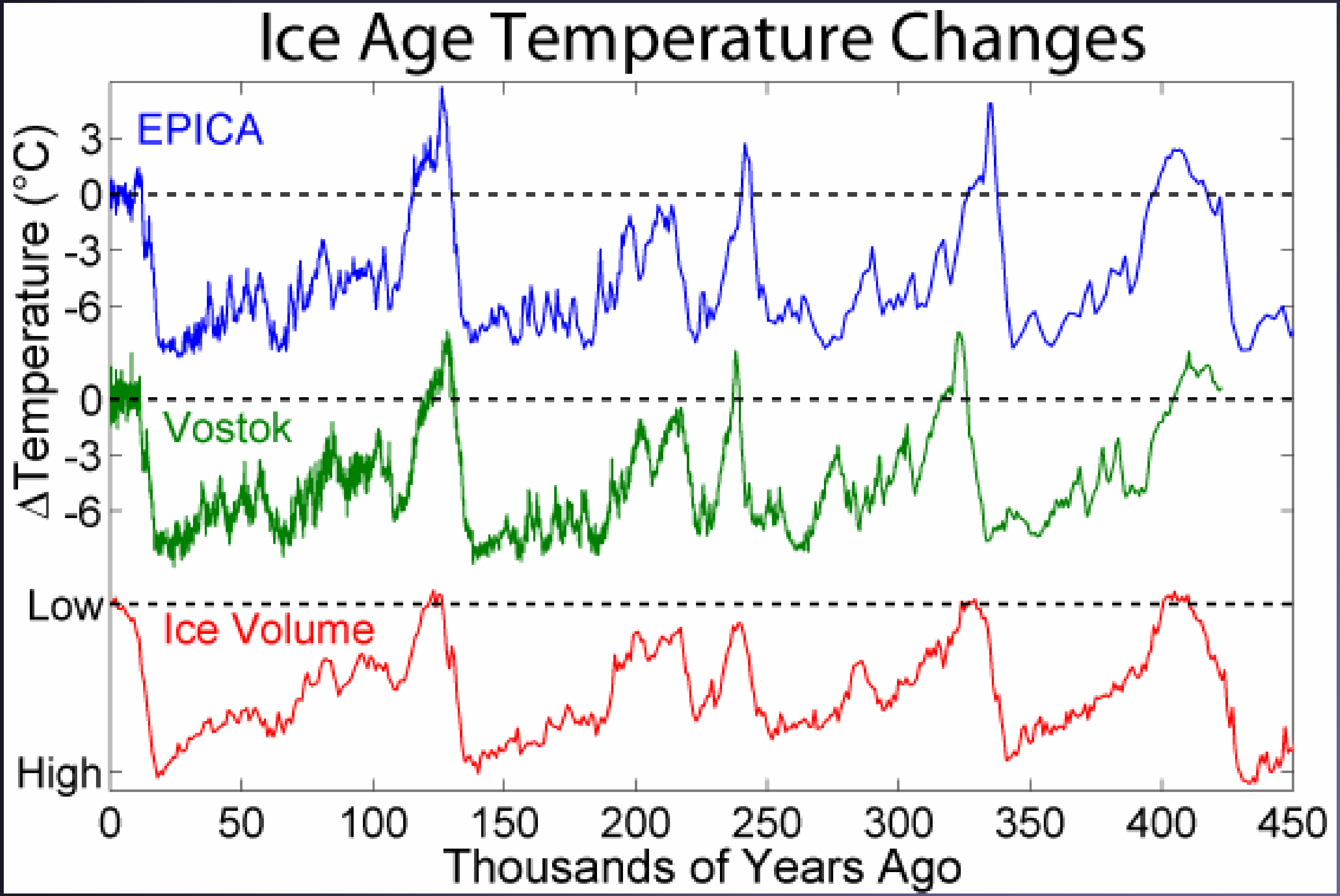
- Time scales of billions of years: yes! The Sun’s evolution makes it increasingly brighter (see sect. on solar interior)
- Time scales of 10^5-10^6 years: Ice ages are probably caused by changes in the Earth’s orbital parameters (although changes in the Sun’s radiative output may play a role).
- Time scales of centuries to millenia: there are increasing indications of a solar contribution to global climate change
- Shorter time scales: unclear

Climate evolution: the broader view

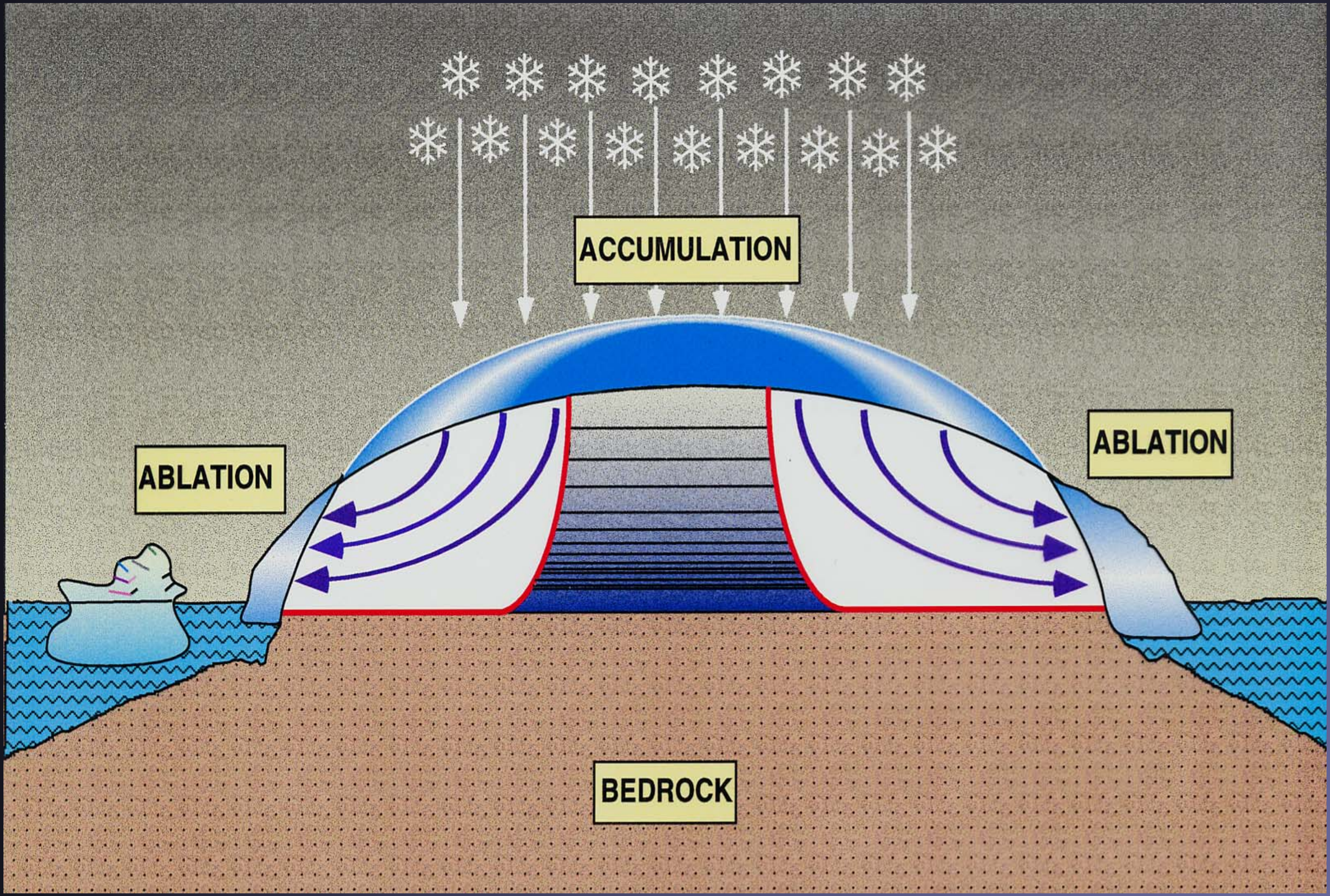
- The Earth today is cooler by 4-6 K than it was 10 Myears ago



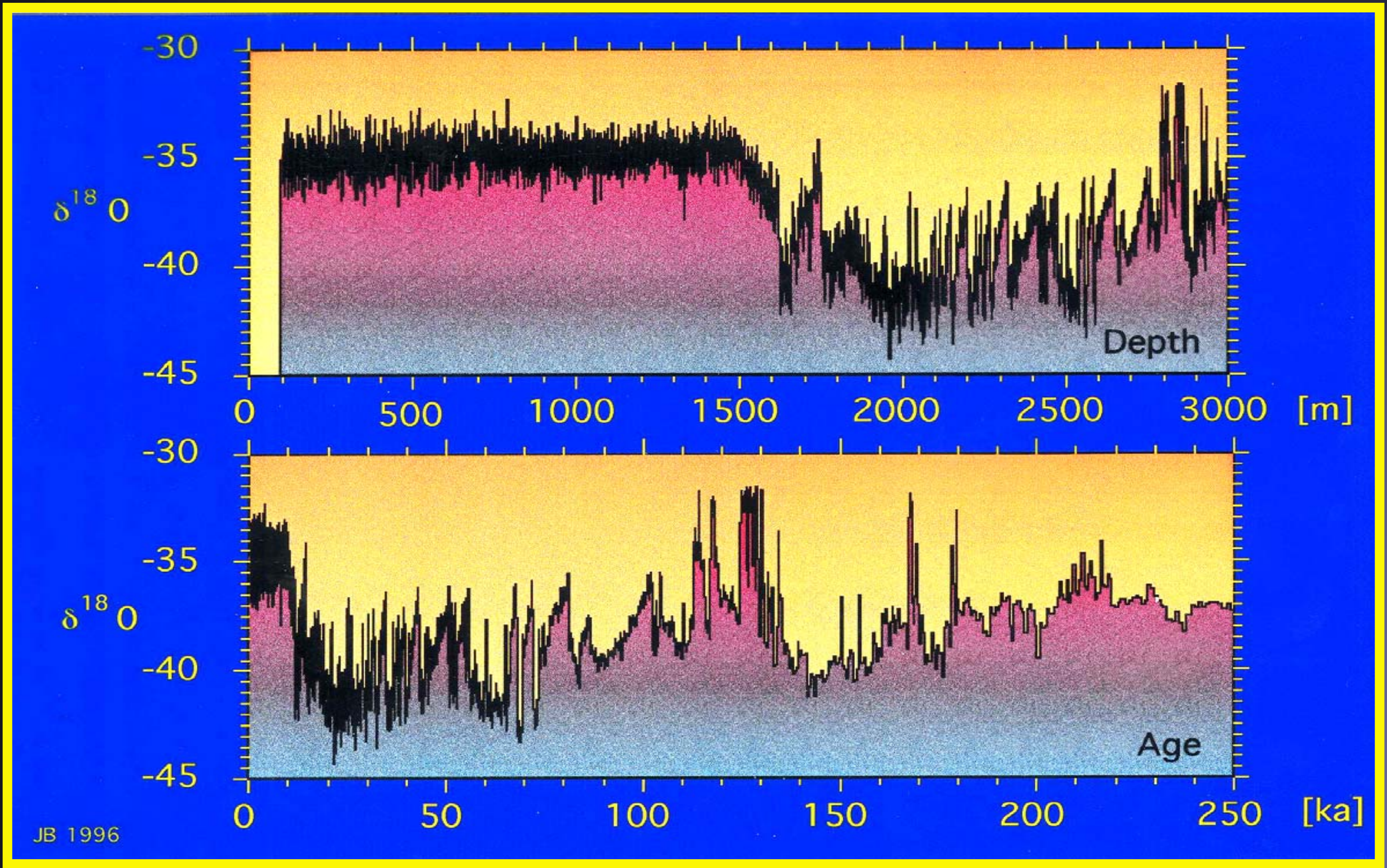
Ice ages and warm periods



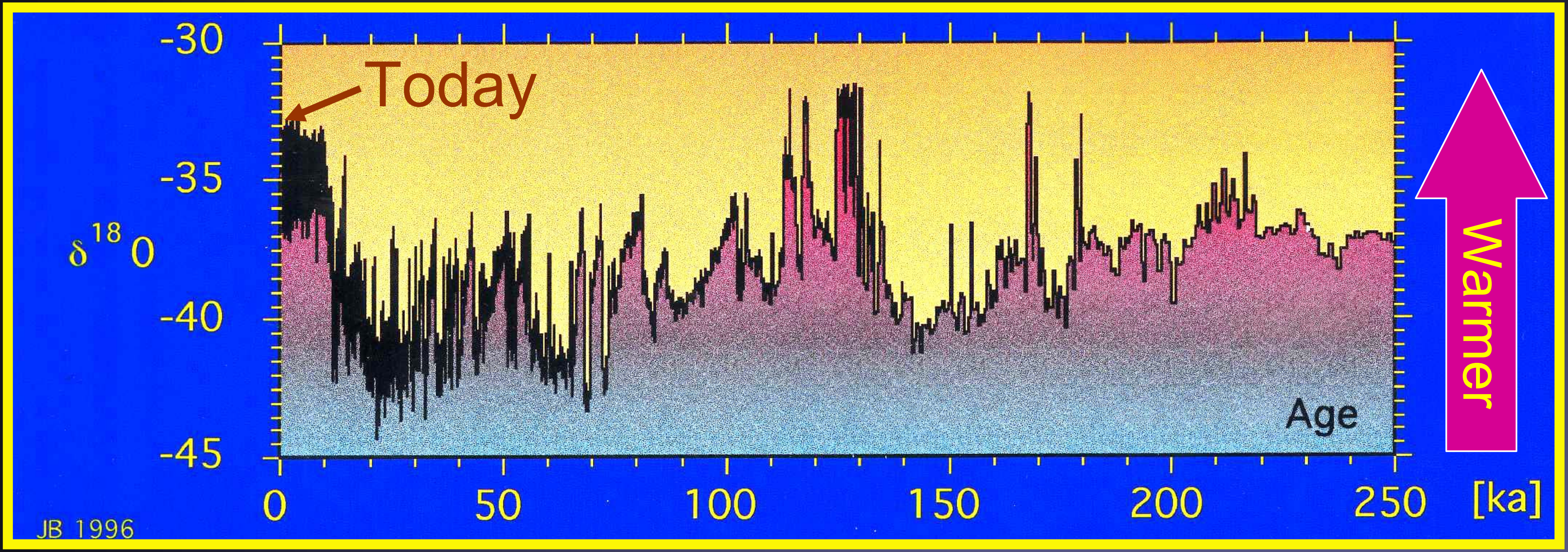
Accumulation of $\delta^{18}O$ in Greenland ice



$\delta^{18}O$ signatures in Greenland ice



Ice ages and warm periods II



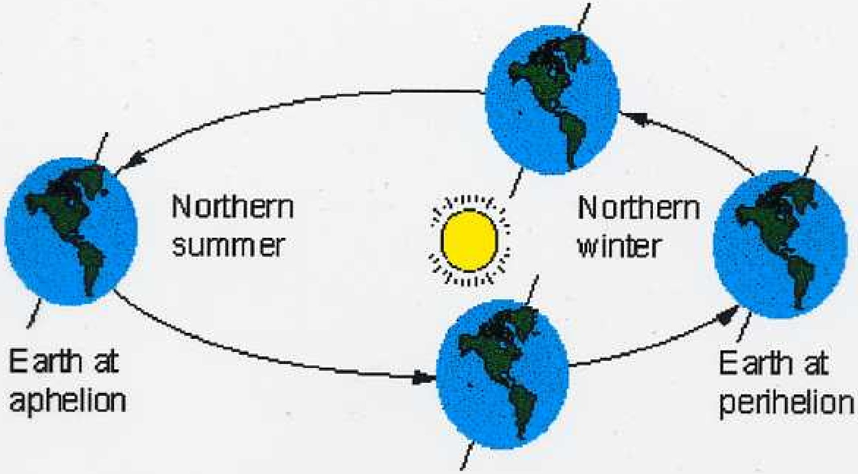
We live in a (rare) warm period (Holocene ≈ 12000 yrs) in times dominated by ice ages. Transitions are abrupt.

Milankovich-Theory: Changes in Earth's orbital parameters cause ice age cycles. Abrupt Transitions?

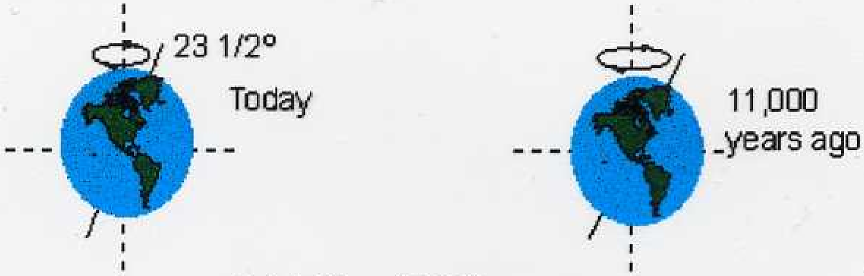
Cause of Ice ages

Milankovitch Theory

Ice ages are due to variations of the Earth's orbit.



Precession of the equinoxes 19,0000-23,000 years



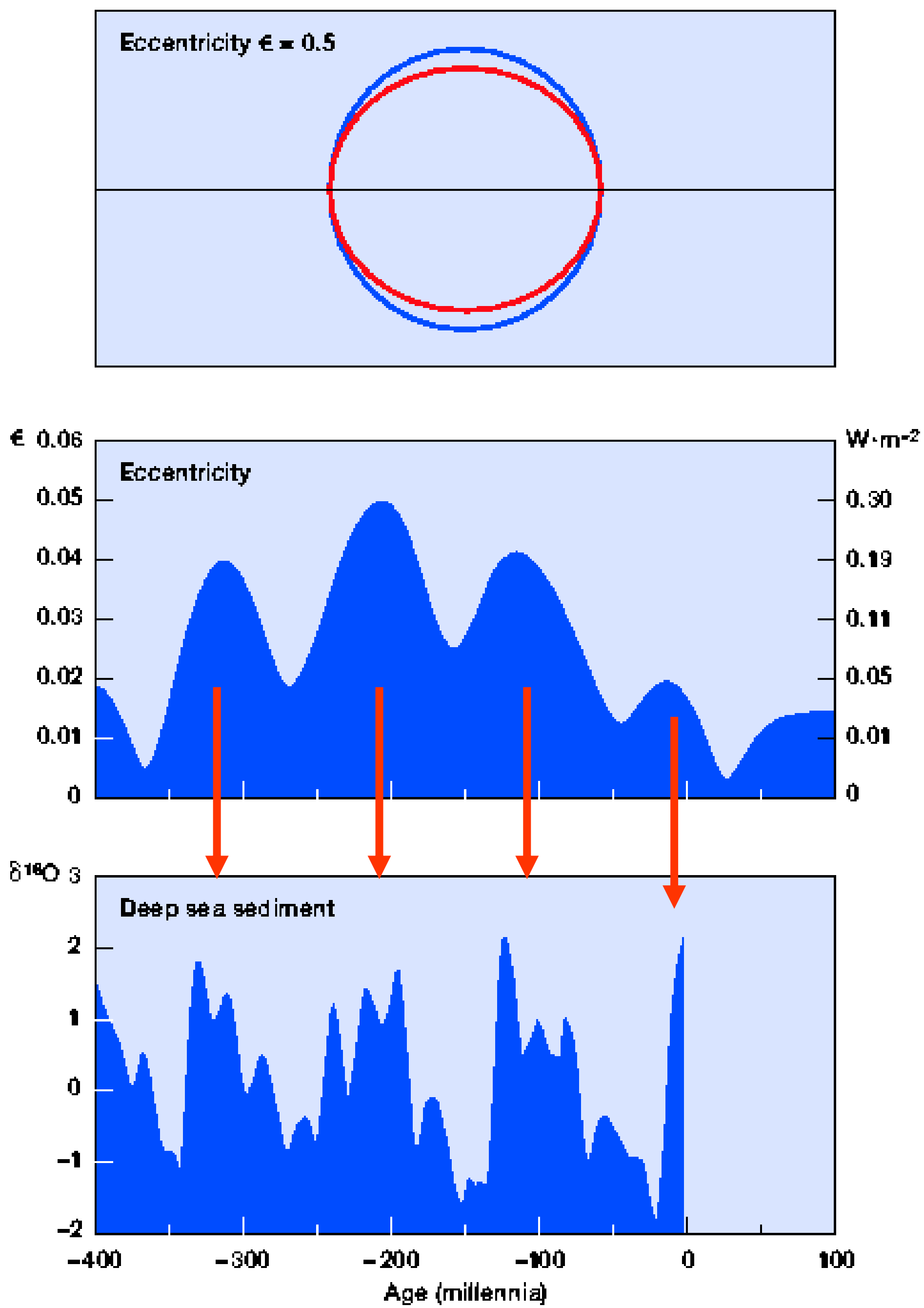
Axial tilt 41,000 years

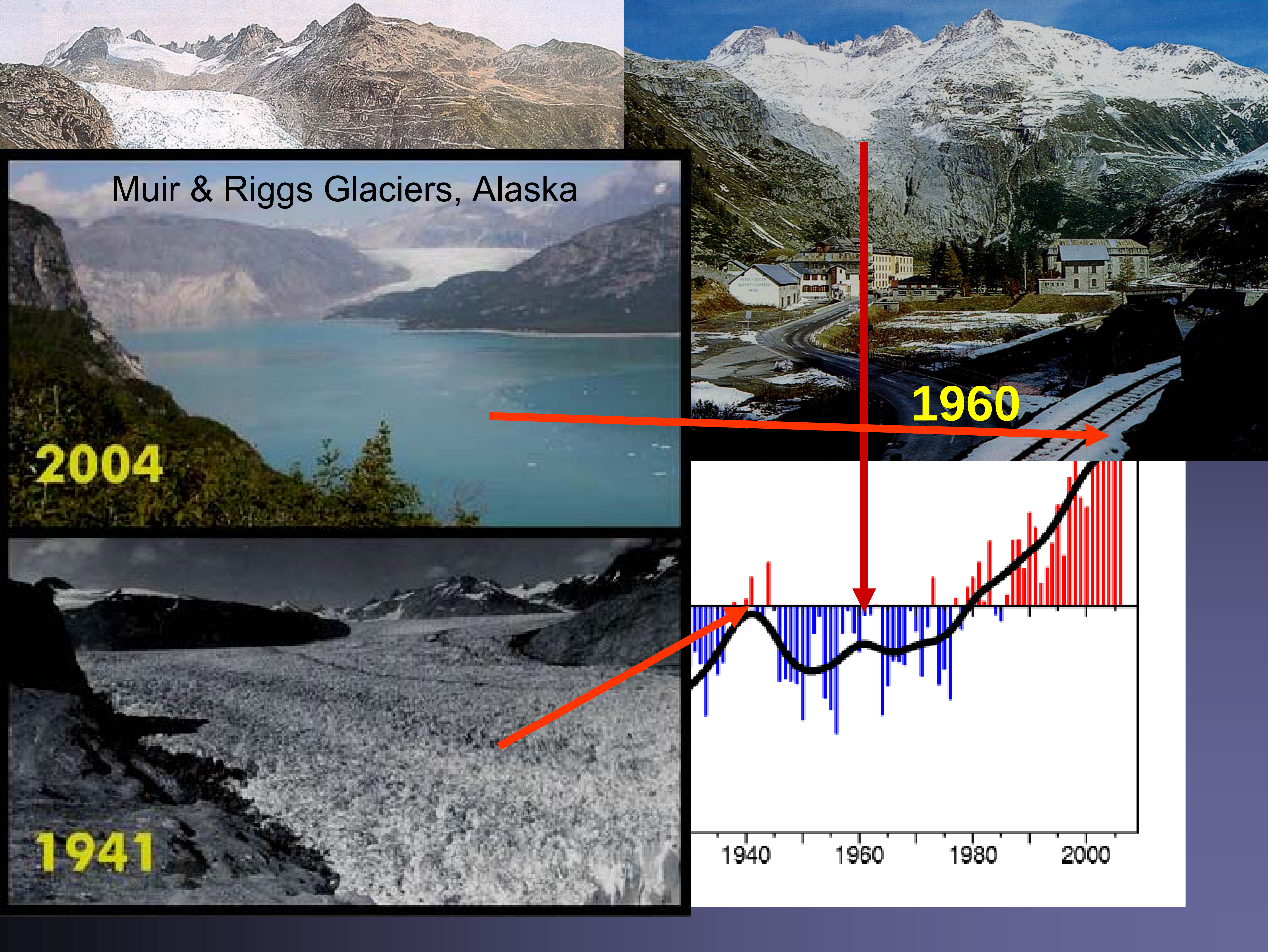
Ellipticity of the earth's orbit 90,000-100,000 years

Cause of Ice ages

Standard theory: Milankovic theory of orbital parameter changes of Earth, combined with non-symmetric distribution of continents.

Effect of the change of the eccentricity of the Earth's orbit on temperature on Earth: direct evidence

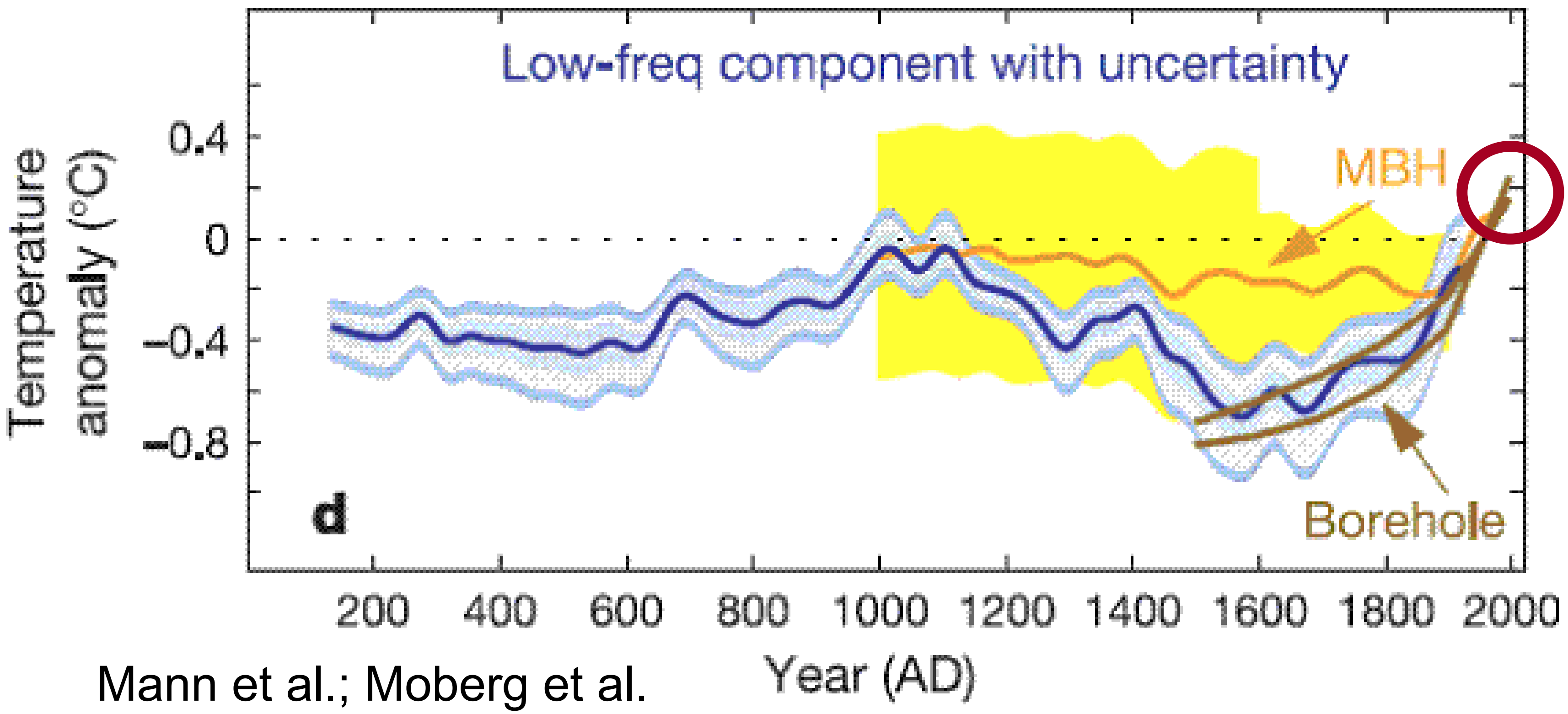




Muir & Riggs Glaciers, Alaska
2004
1941
1960
1940
1960
1980
2000

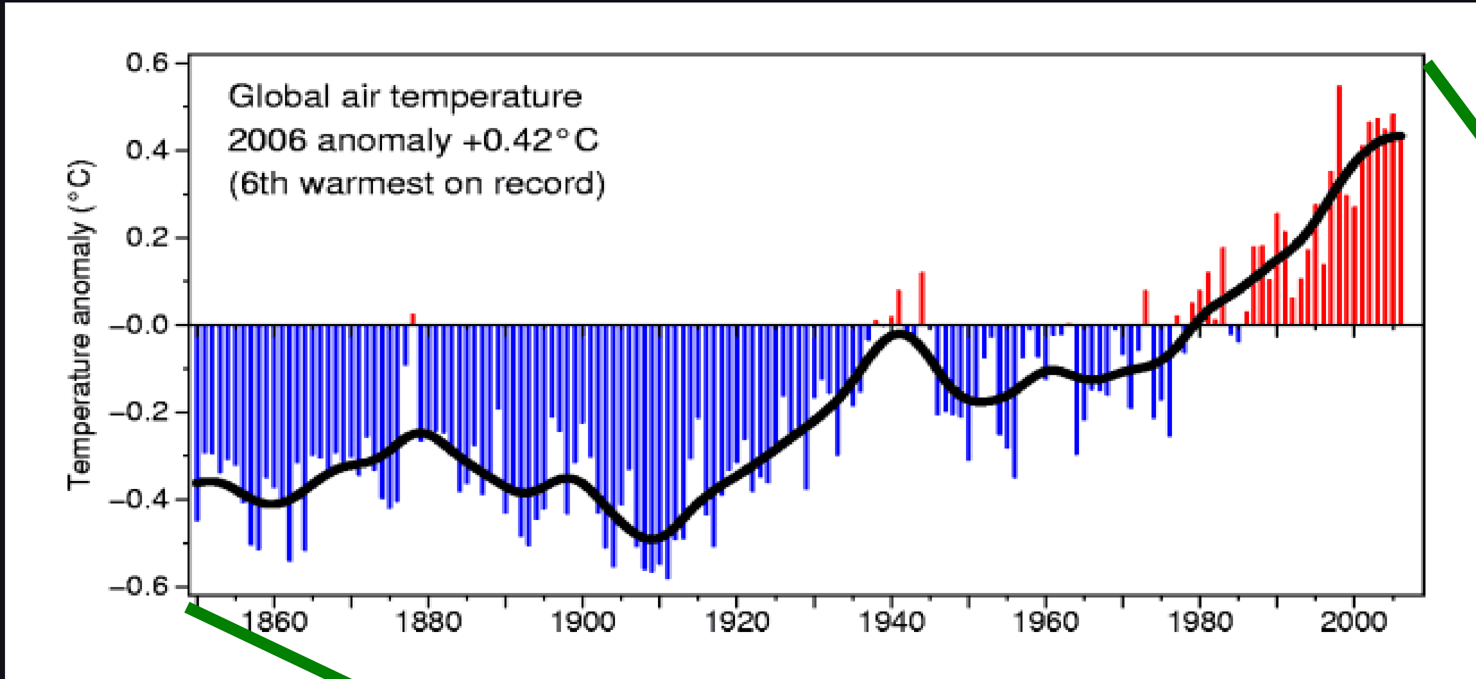
Is the Recent Temperature Rise Extraordinary?

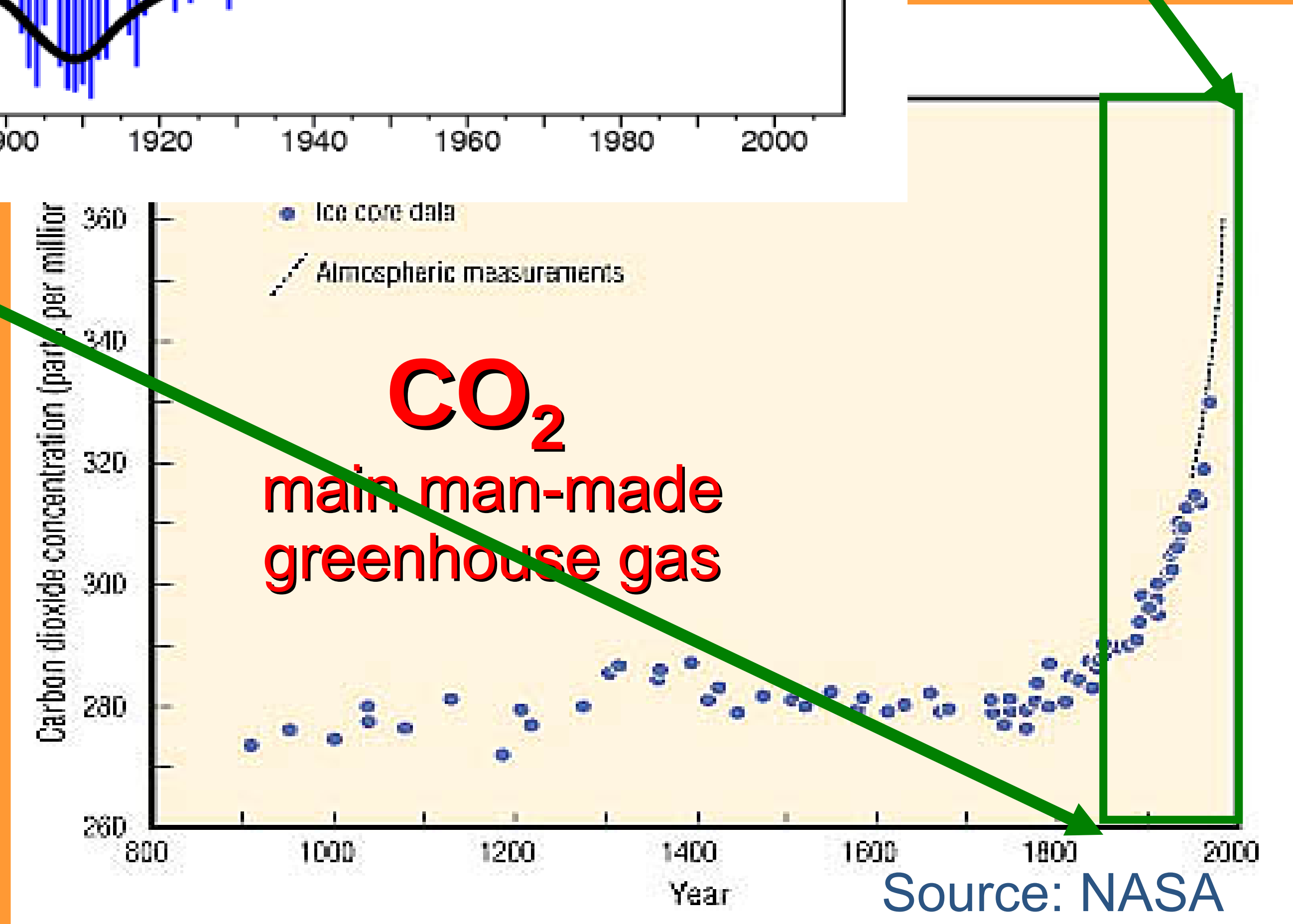
Various temperature reconstructions suggest that the Earth is hotter now than in the last 2000 years



Mann et al.; Moberg et al.

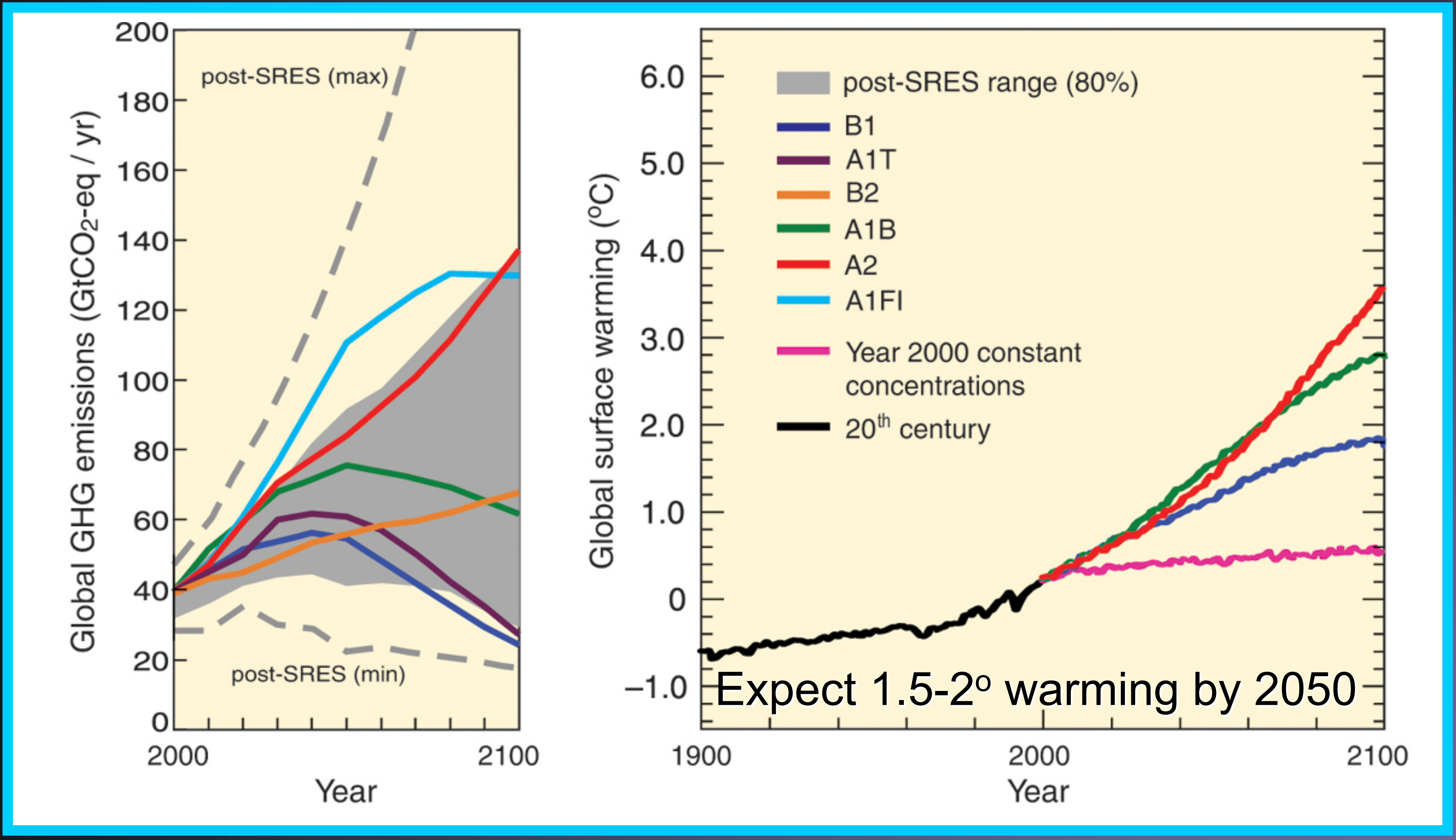
Is Global Warming Man-made?



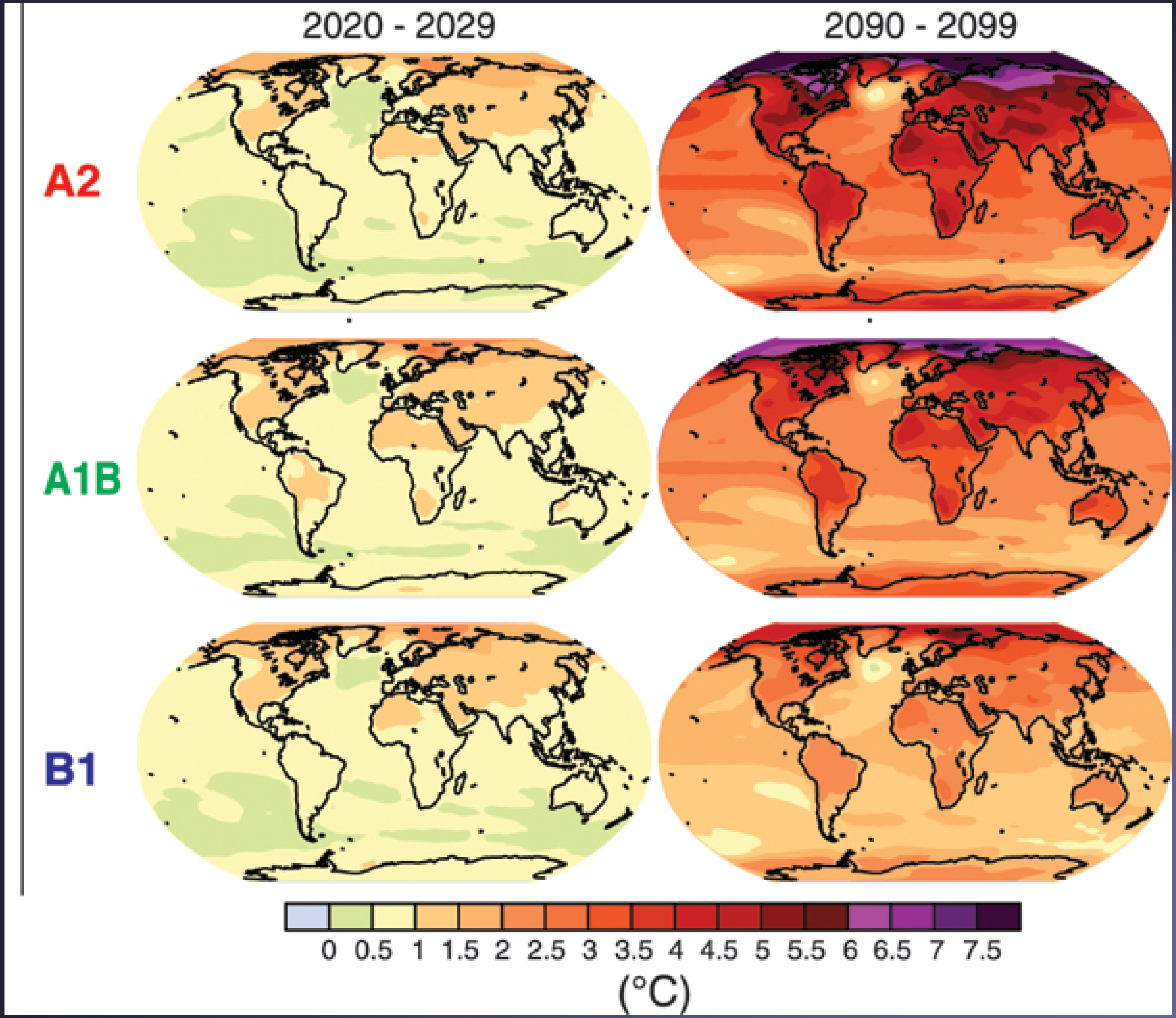


IPCC Predictions until 2100

Scenarios for emission of Greenhouse Gases → Predicted temperature over next 100 years

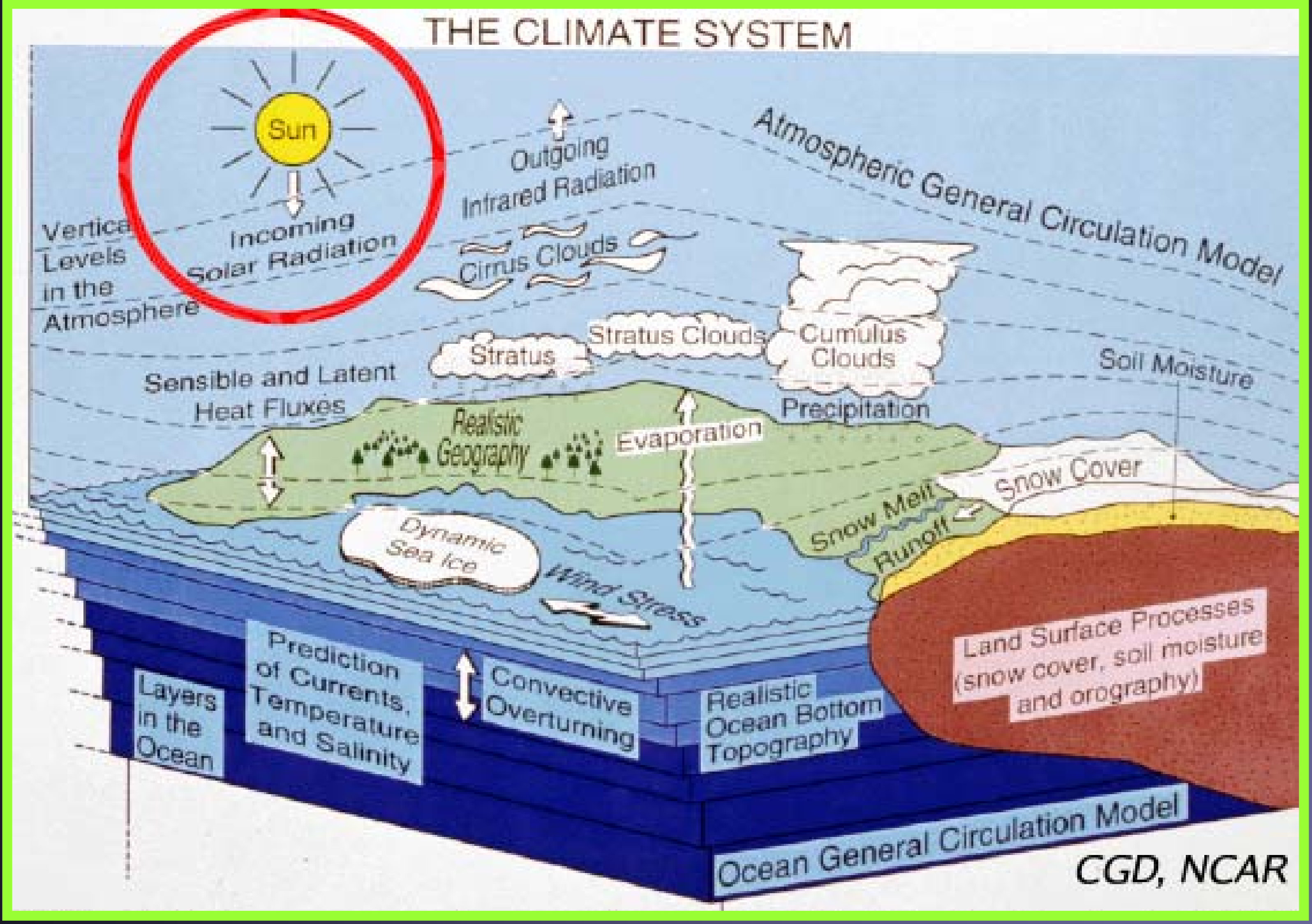


Warming is uneven over the globe



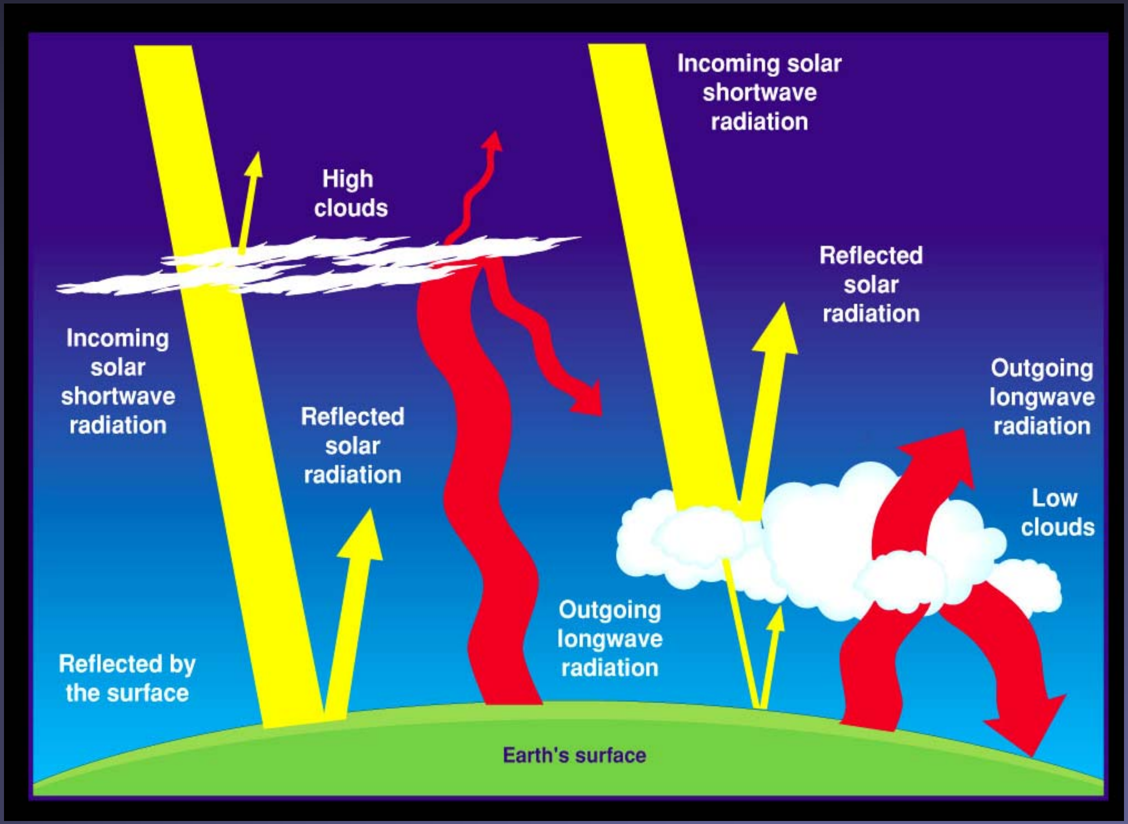
Some Consequences of Global Climate Change

Is everything understood?



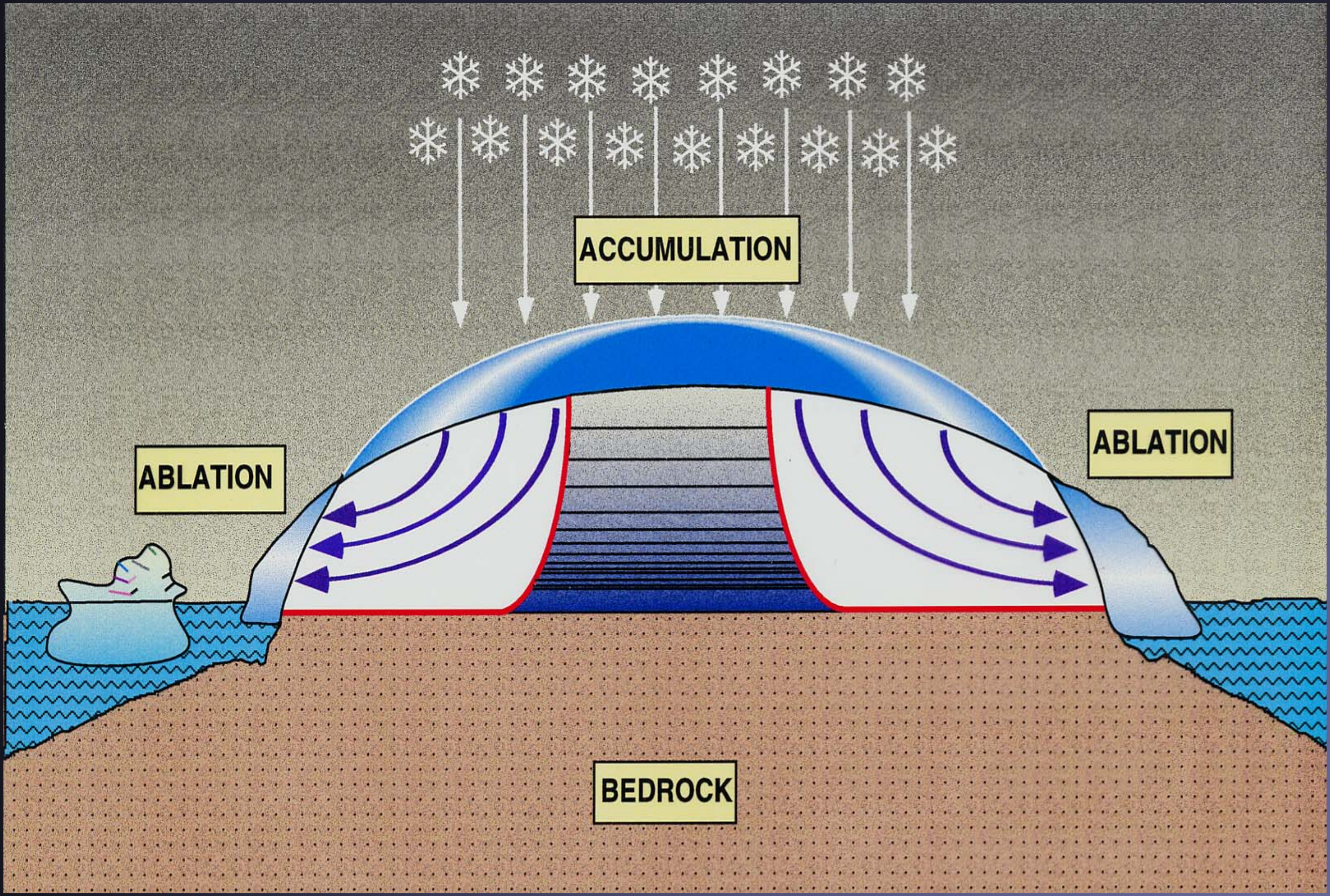
Could the Sun be to blame?

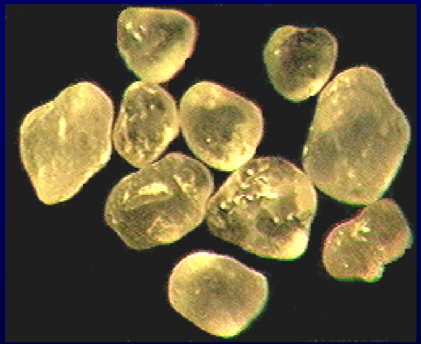
- The Sun delivers 1.36 kW / m^2. We get ≈ 1 kW / m^2 (at equator, at noon, if no clouds)
- In 20-30 min the Sun provides to Earth the yearly energy needs of Humanity

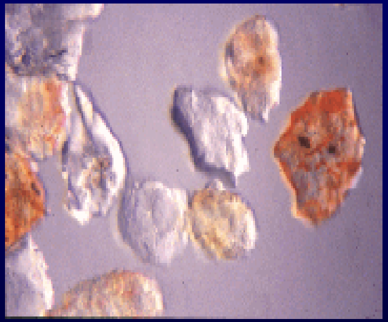


Without sunlight, no life (Our atmosphere would cool to below -200° C within weeks)

The life story of Greenland ice II





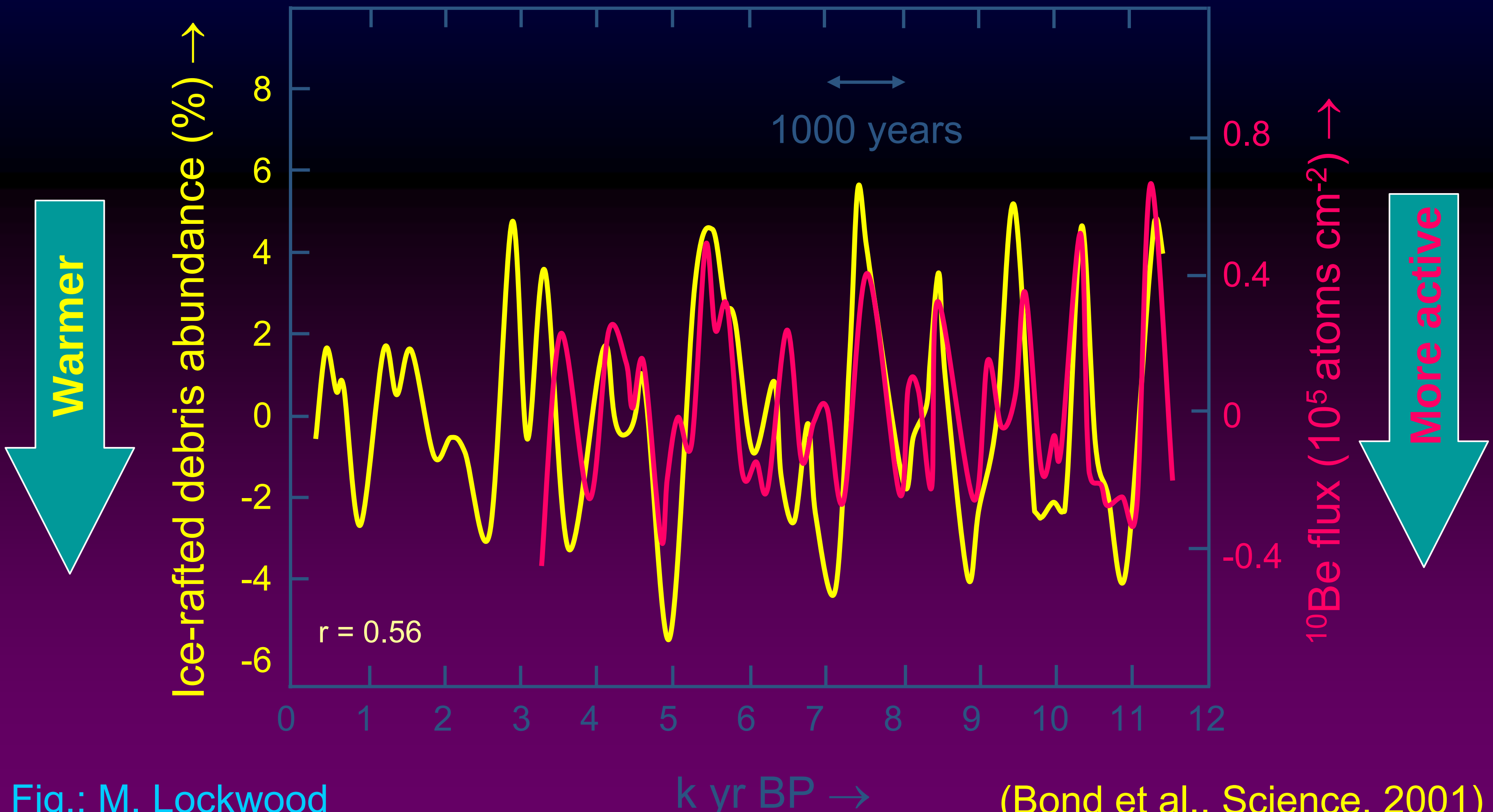
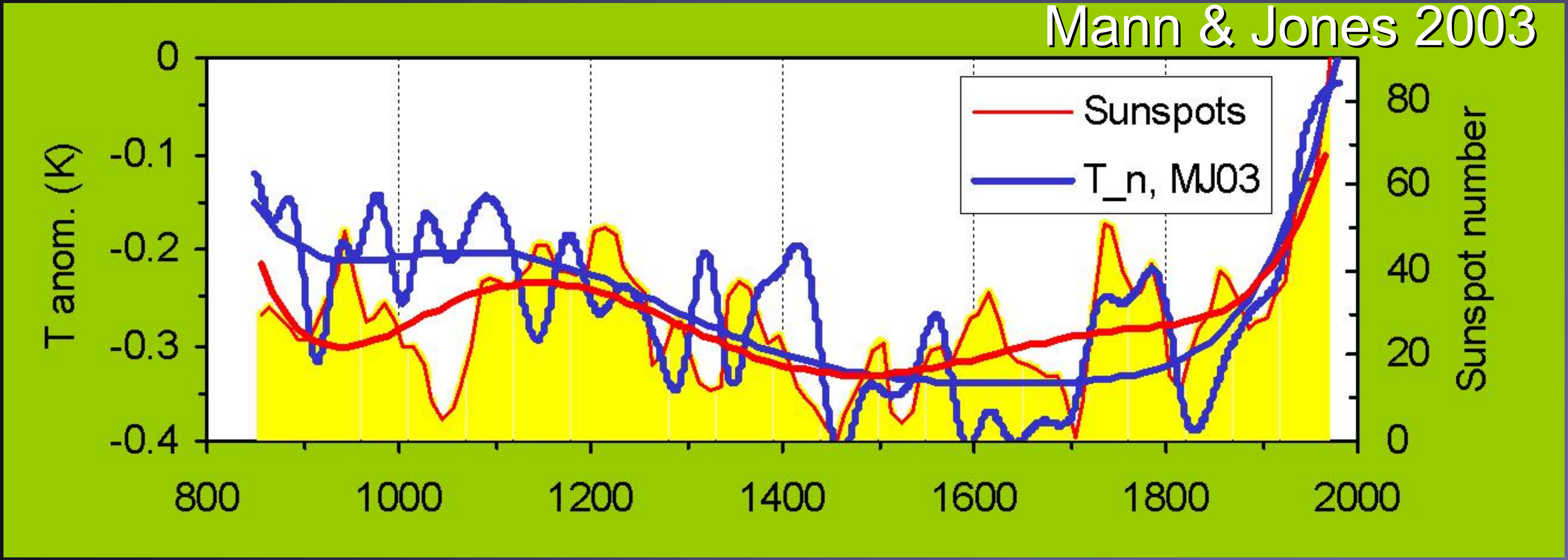


Fig.: M. Lockwood

(Bond et al., Science, 2001)

Sunspots and Climate over Last 1150 Years

- Sunspot numbers reconstructed over past 1150 years from ^{10}Be correlate with NH climate at 98% significance level.
- Mainly due to "hockey stick" shape, also seen in solar data!
- Analysis excludes last 25 years, when Sun did not behave like climate (Solanki & Krivova 2003)

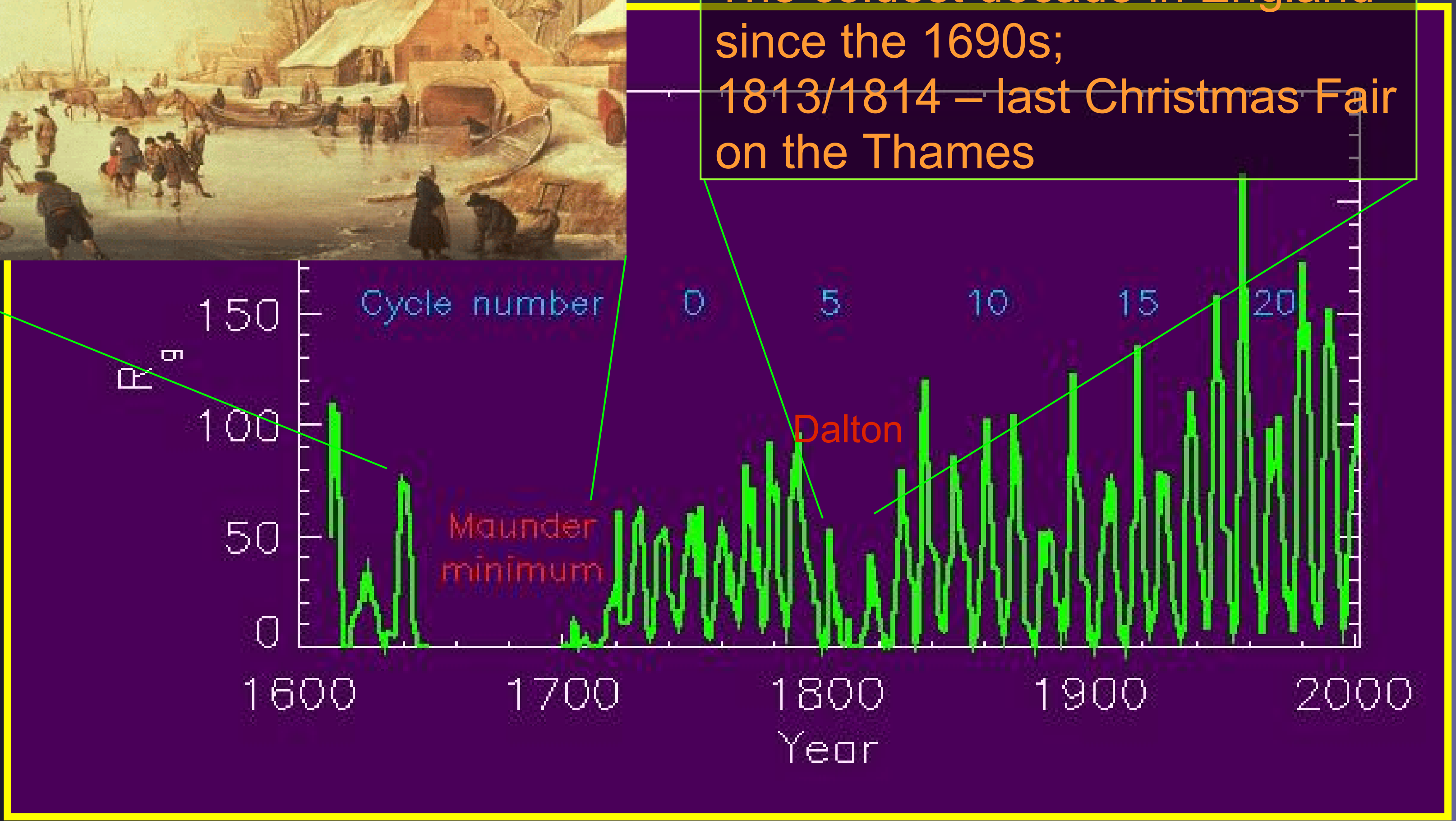


Usoskin, Schüssler, Solanki, Mursula 2004

Maunder Minimum & Little Ice Age

The Maunder Minimum corresponded to the Little Ice Age: Is there a connection?

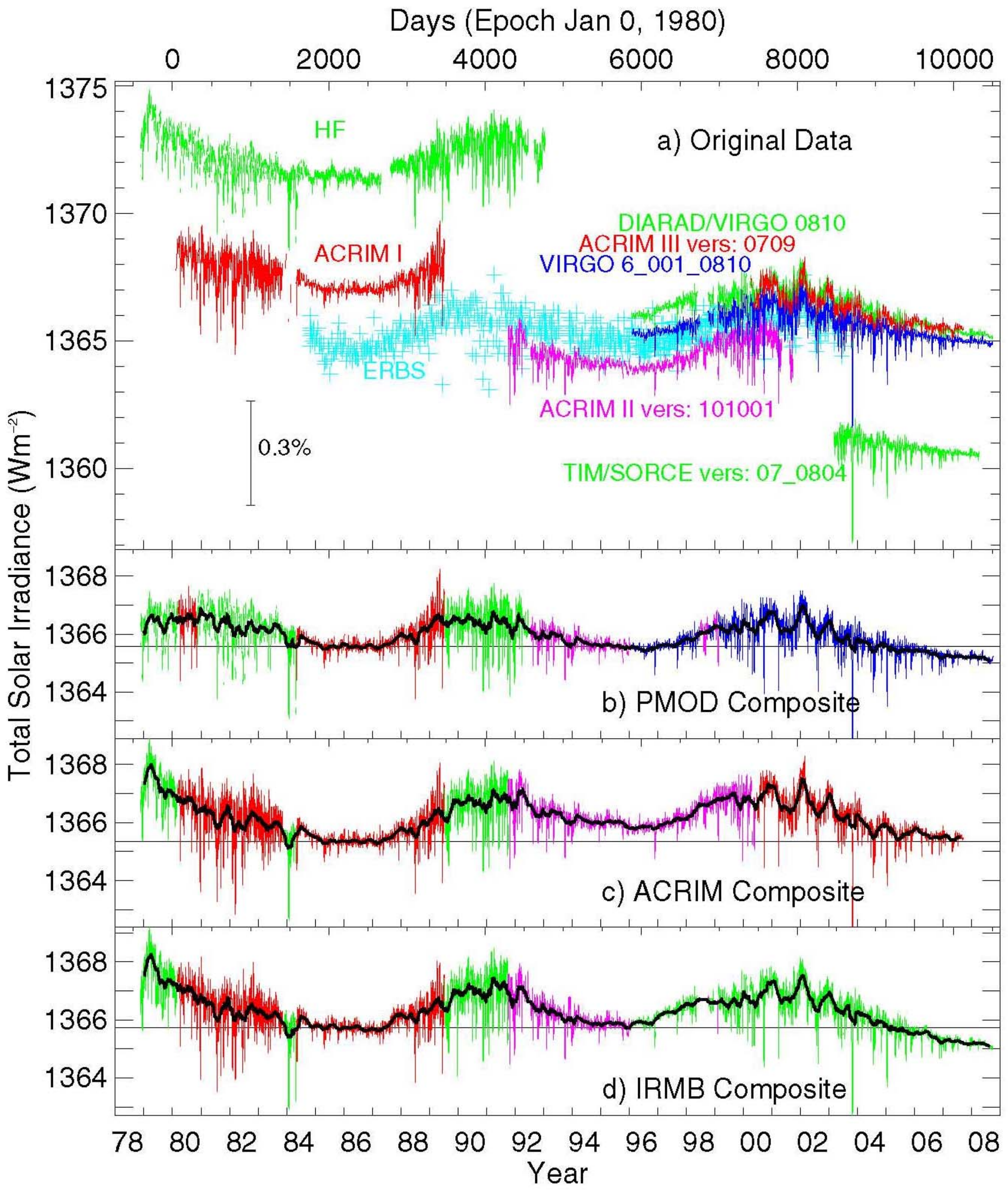
The coldest decade in England since the 1690s;
1813/1814 – last Christmas Fair on the Thames



Paths by Which Sun Affects Climate

- Variations of total irradiance: change in total energy input to Earth's atmosphere [irradiance] = W/m^2 = flux at 1AU (above Earth's atmosphere)
- Variations of UV irradiance: influence on atmospheric chemistry (e.g. stratospheric ozone production and depletion)
- Modulation of cosmic rays: has been proposed to affect cloud cover.
- Energy carried by particles at 1 AU 0.002 W/m^2 (mainly protons and electrons) vs. 1365 W/m^2 from radiation

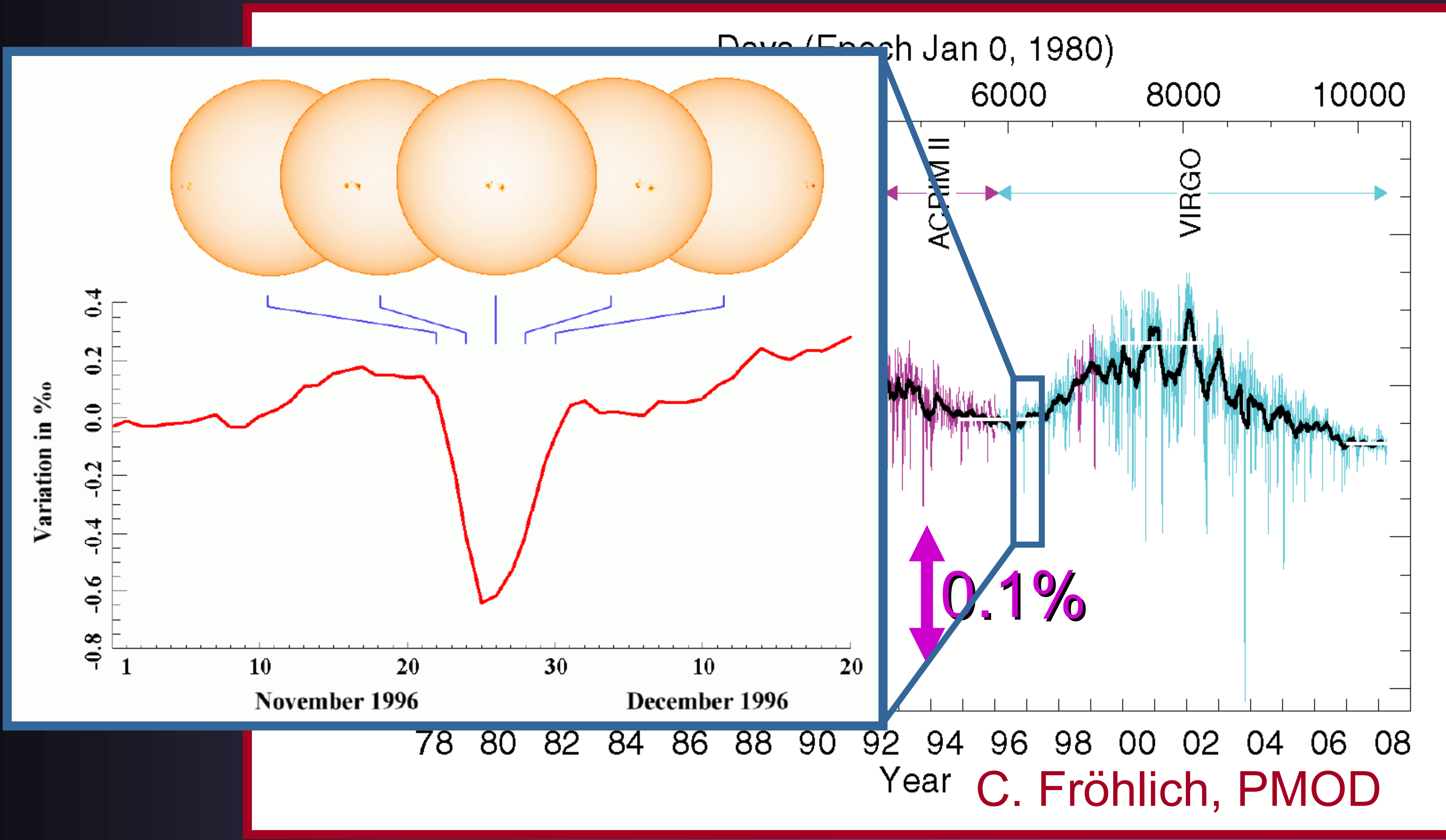
Measured Total Irradiance

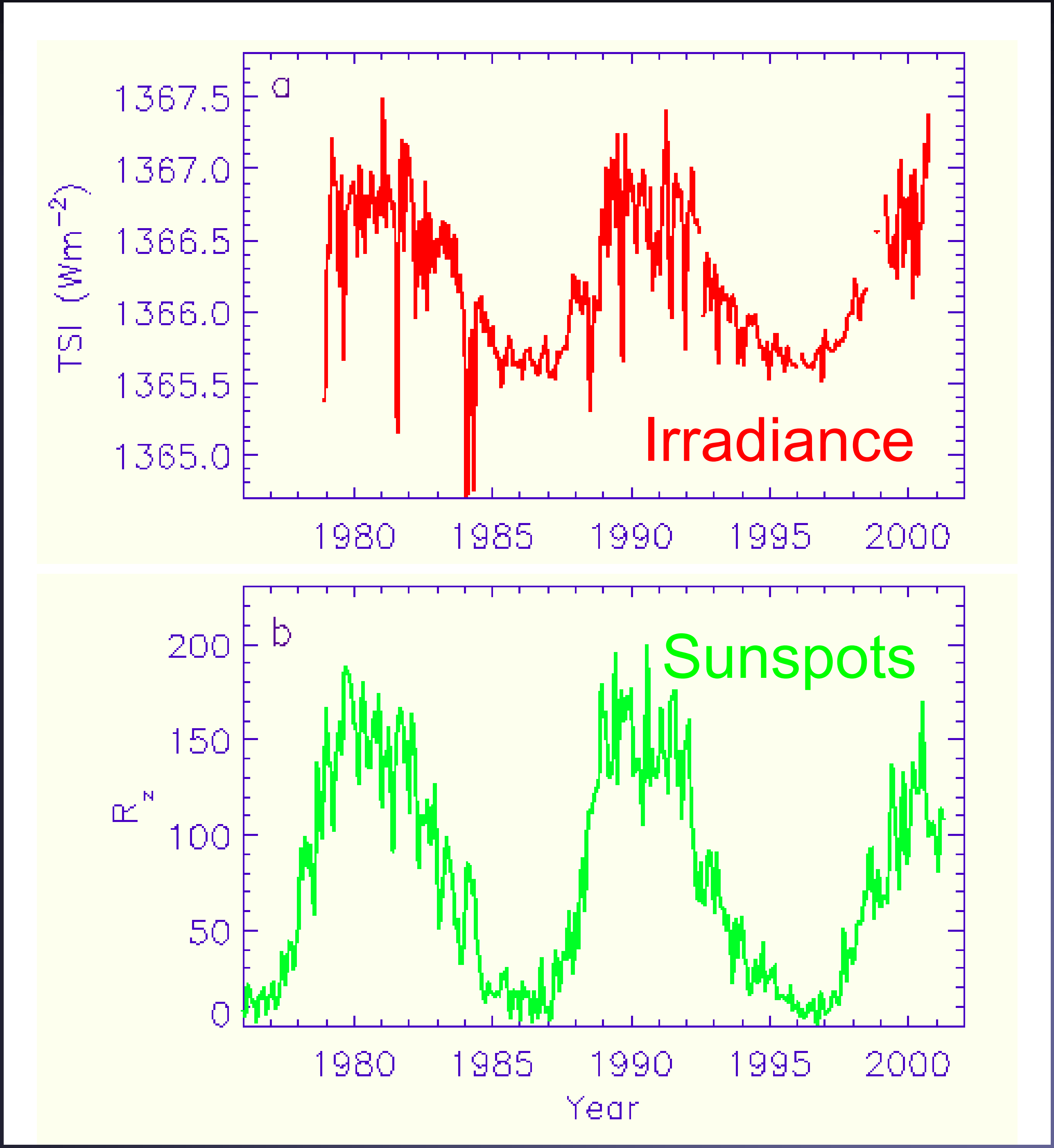


8 different TSI radio-meters have been used, with offsets. Trend in composite depends on introduced corrections

PMOD homepage 2008

Measured total irradiance

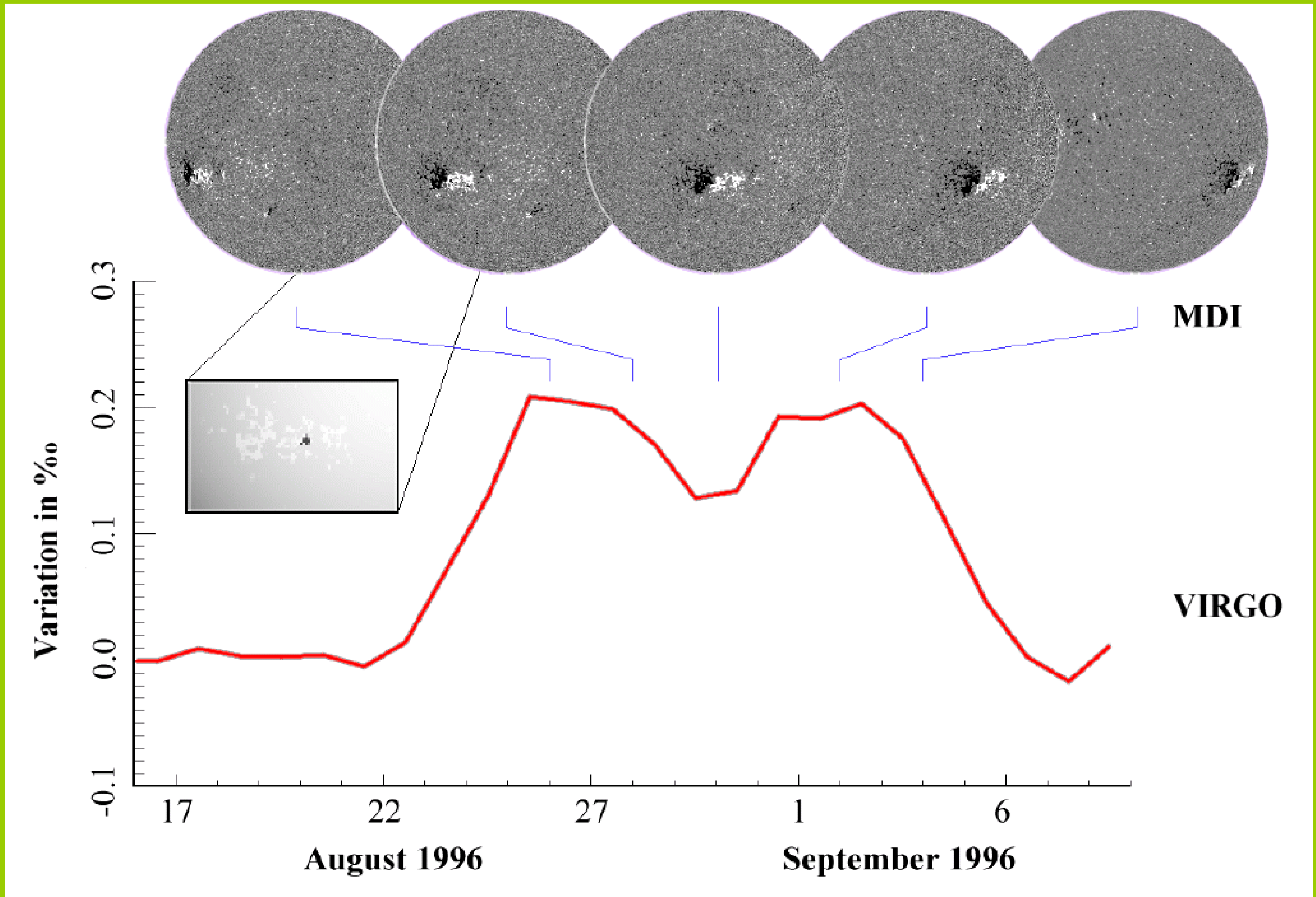



a
1367.5
1367.0
1366.5
1366.0
1365.5
1365.0
TSI (Wm^{-2})
Irradiance
1980
1985
1990
1995
2000
b
200
150
100
50
0
R_z
Sunspots
1980
1985
1990
1995
2000
Year

Faculae and Plage

Area increase of faculae from activity min to max is factor of 10-20 greater than of sunspots

Passage of a Facular Group



3- Component Model

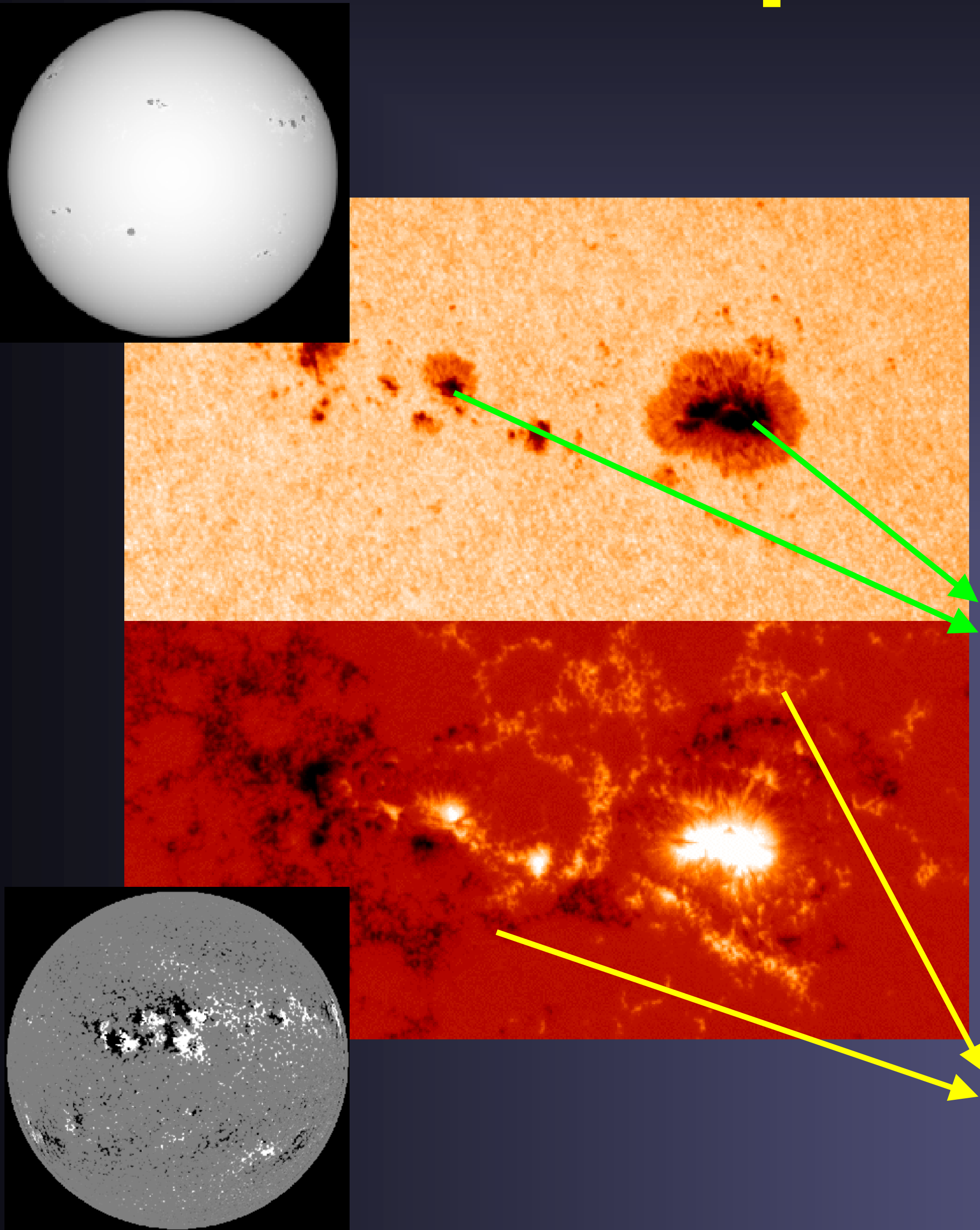
- Assume that variation in irradiance is exclusively due to magnetic field at solar surface (for time scales day-decades)
- Total flux $F(\lambda,t)$ then depends on the intrinsic fluxes of each of the different types of magnetic features and the area fraction α that each covers
- Flux at 1AU = irradiance
- Magnetic features:
  - sunspots: subscript "s"
  - faculae: subscript "f"
- Background: field-free quiet Sun: subscript "q"

Total flux emitted by Sun

- Sum of filling factors = 1
- F_s , F_f and F_q are the fluxes that one would measure if that feature were to cover the whole Sun

$$\begin{aligned} F(\lambda, t) = & \; \alpha_s(t) F_s(\lambda) \\ & + \alpha_f(t) F_f(\lambda) \\ & + \left(1 - \alpha_s(t) - \alpha_f(t)\right) F_q(\lambda) \end{aligned}$$

3- Component Model



$F(\lambda)$ quiet Sun flux
(Fontenla et al. 1993)

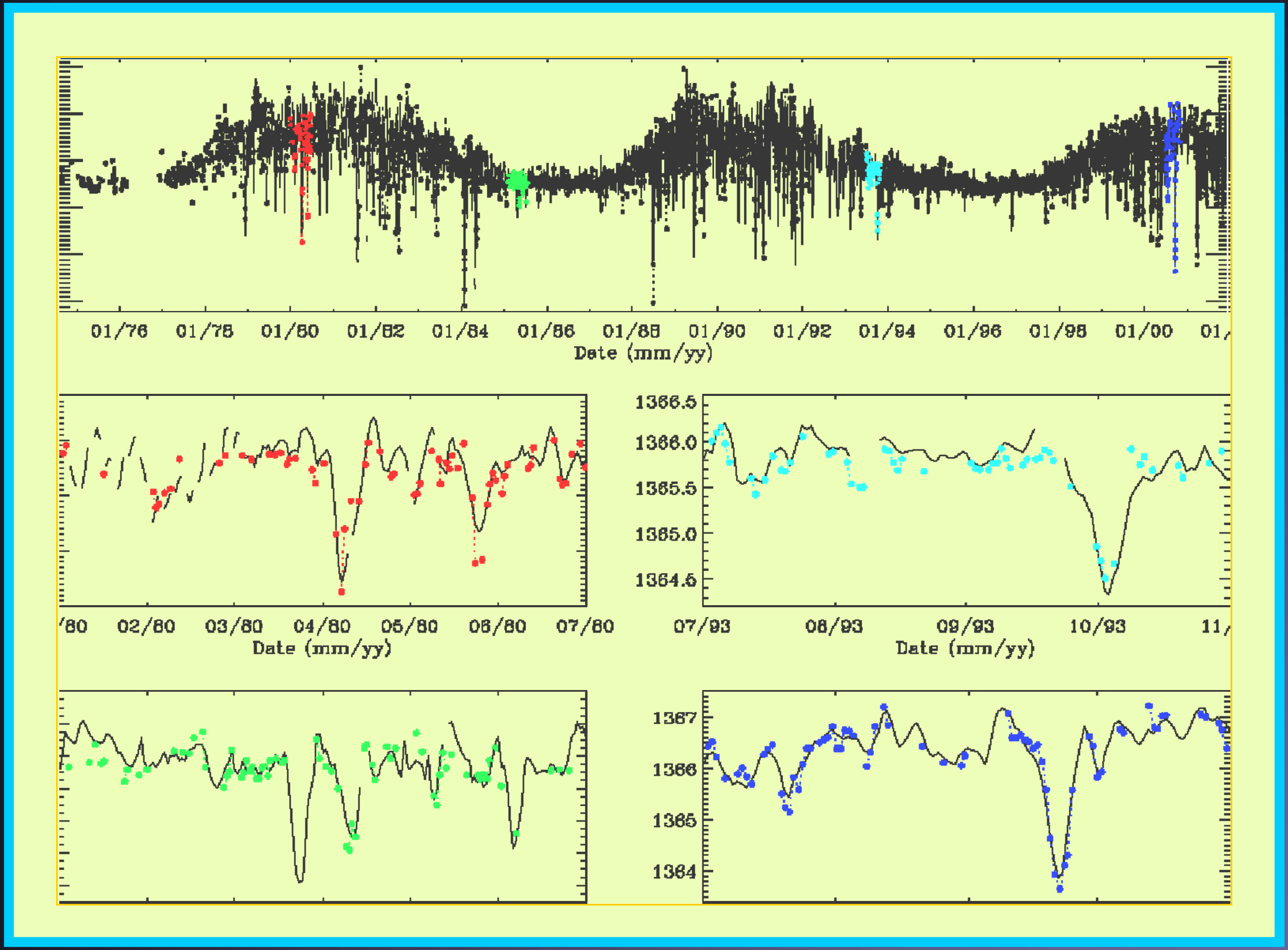
$F(\lambda)$ sunspot flux; separate umbra/penumbra
(cool Kurucz models)

$\alpha_s(t)$ filling factor of sunspots
(MDI continuum)

$F(\lambda)$ facular flux
(modified model-F; Fontenla et al. 1993; Unruh et al. 2000)

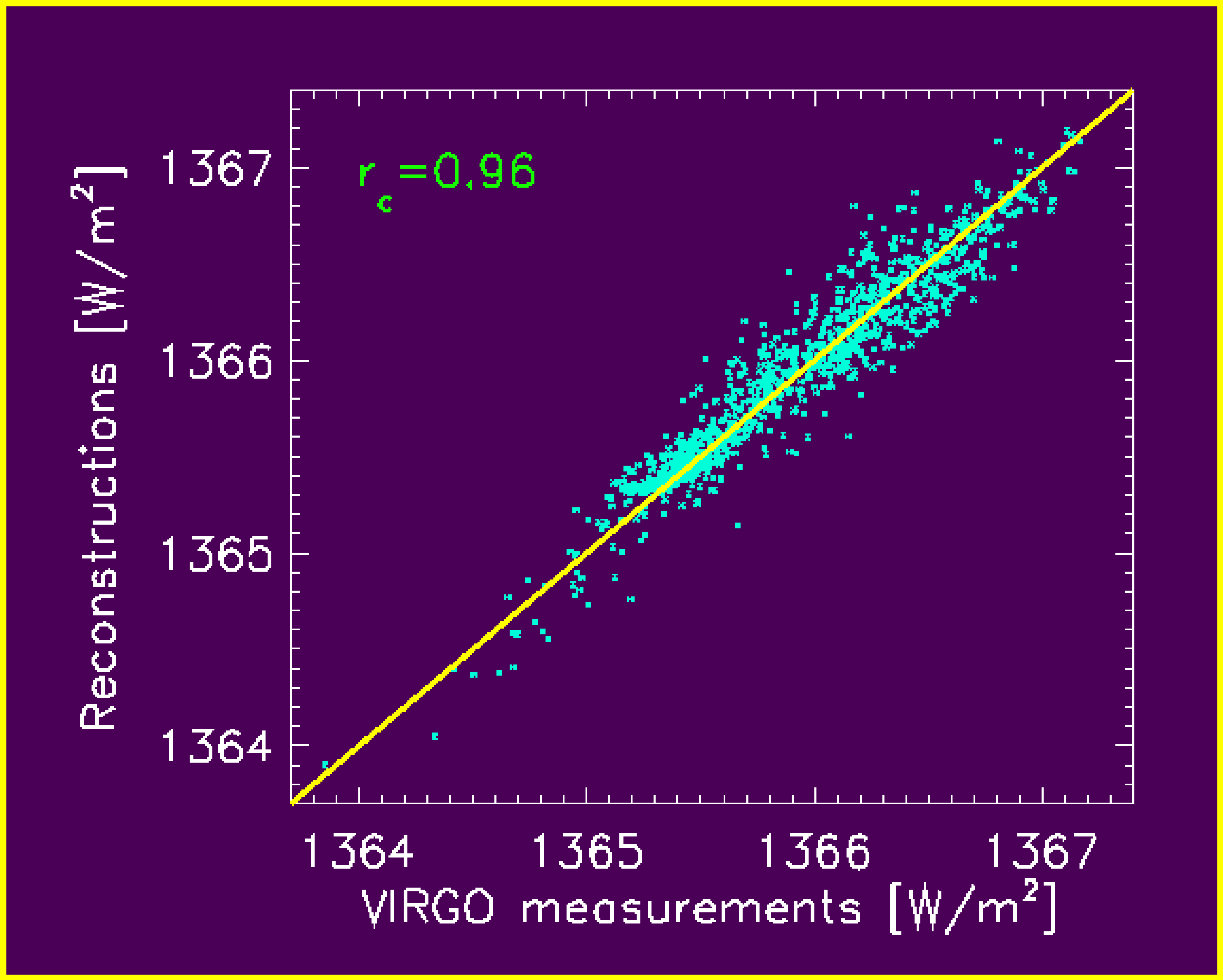
$\alpha_f(t)$ filling factor of faculae
(MDI magnetograms)

B as source of irradiance changes

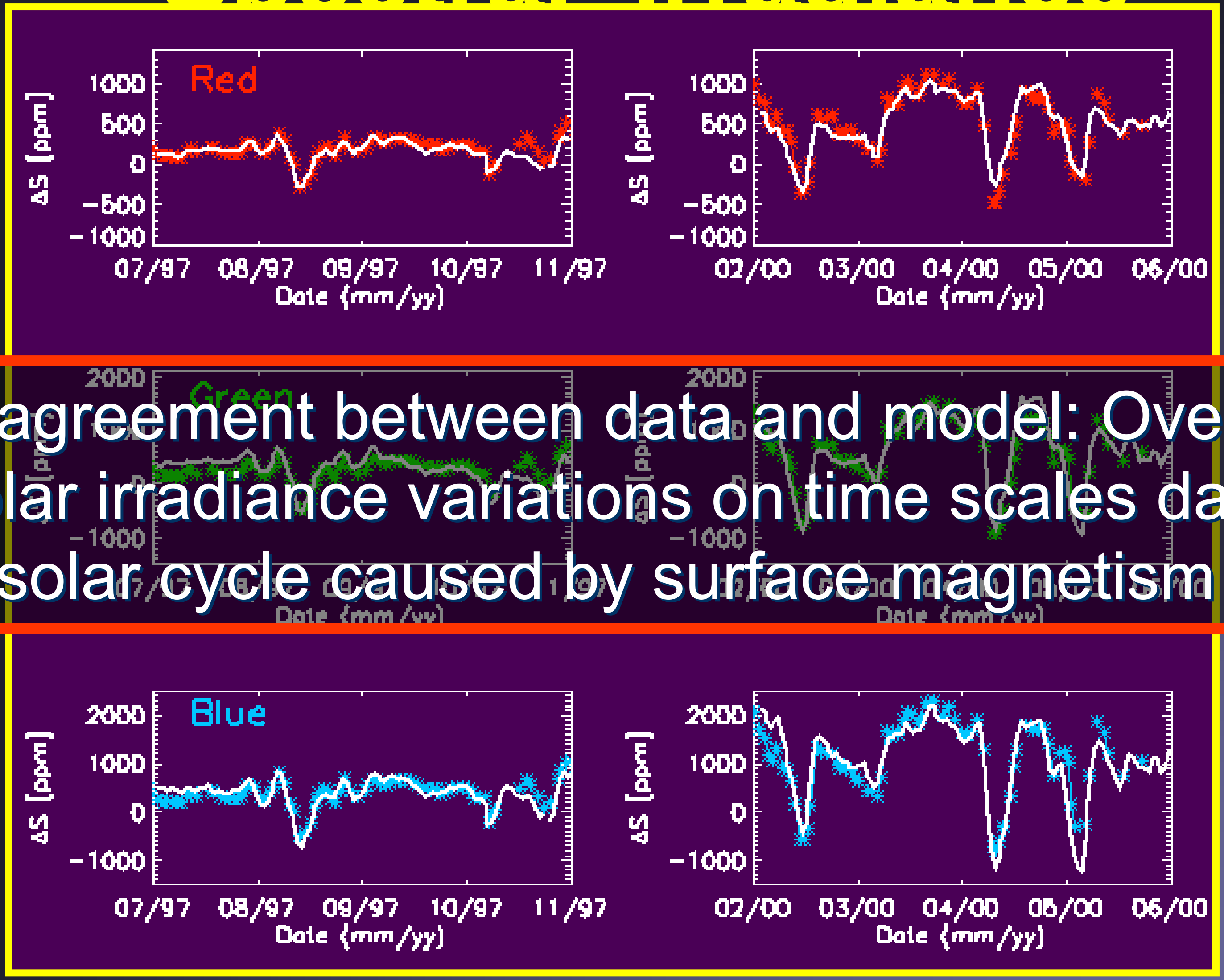


Wenzler, Solanki, Krivova 2005

Model vs. Observations



Spectral Irradiance

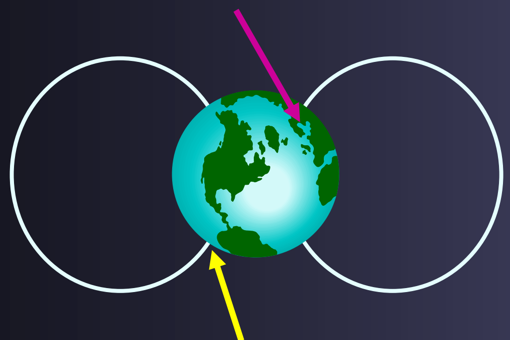


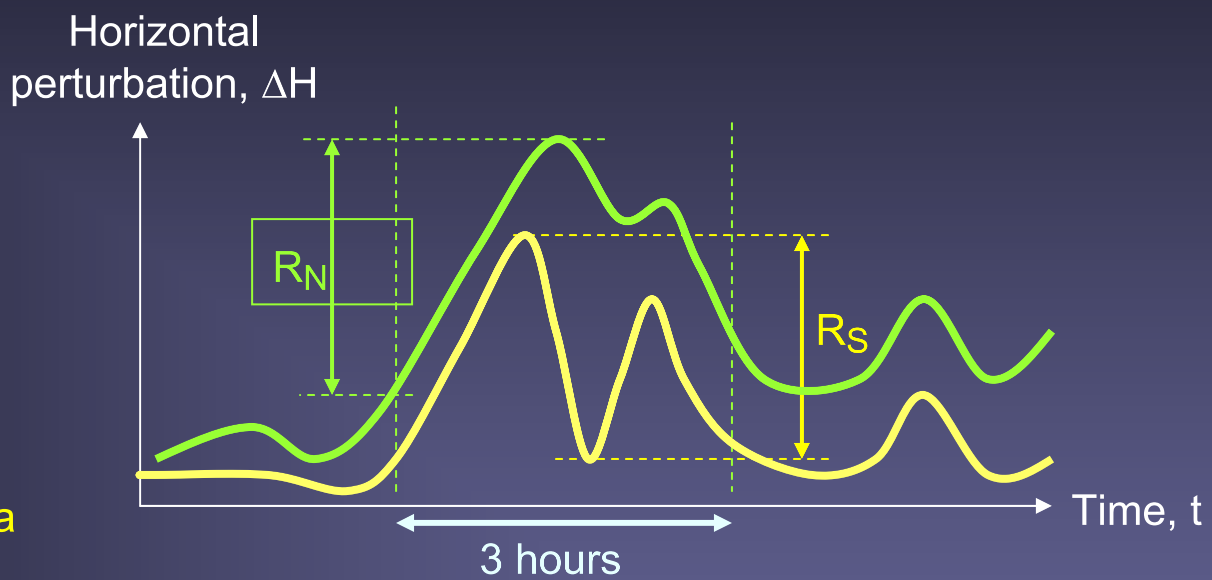
Good agreement between data and model: Over 90% of solar irradiance variations on time scales days – solar cycle caused by surface magnetism

Are there longer term variations of solar irradiance?

- No direct records of irradiance variations on longer time scales. Need to use models.
- Need to distinguish different periods
  - Since ~ 1800: good direct sunspot number measurements
  - Since 1611: telescopic sunspot number measurements
  - On longer time scales: first a proxy of the solar magnetic field must be reconstructed.

The aa geomagnetic index



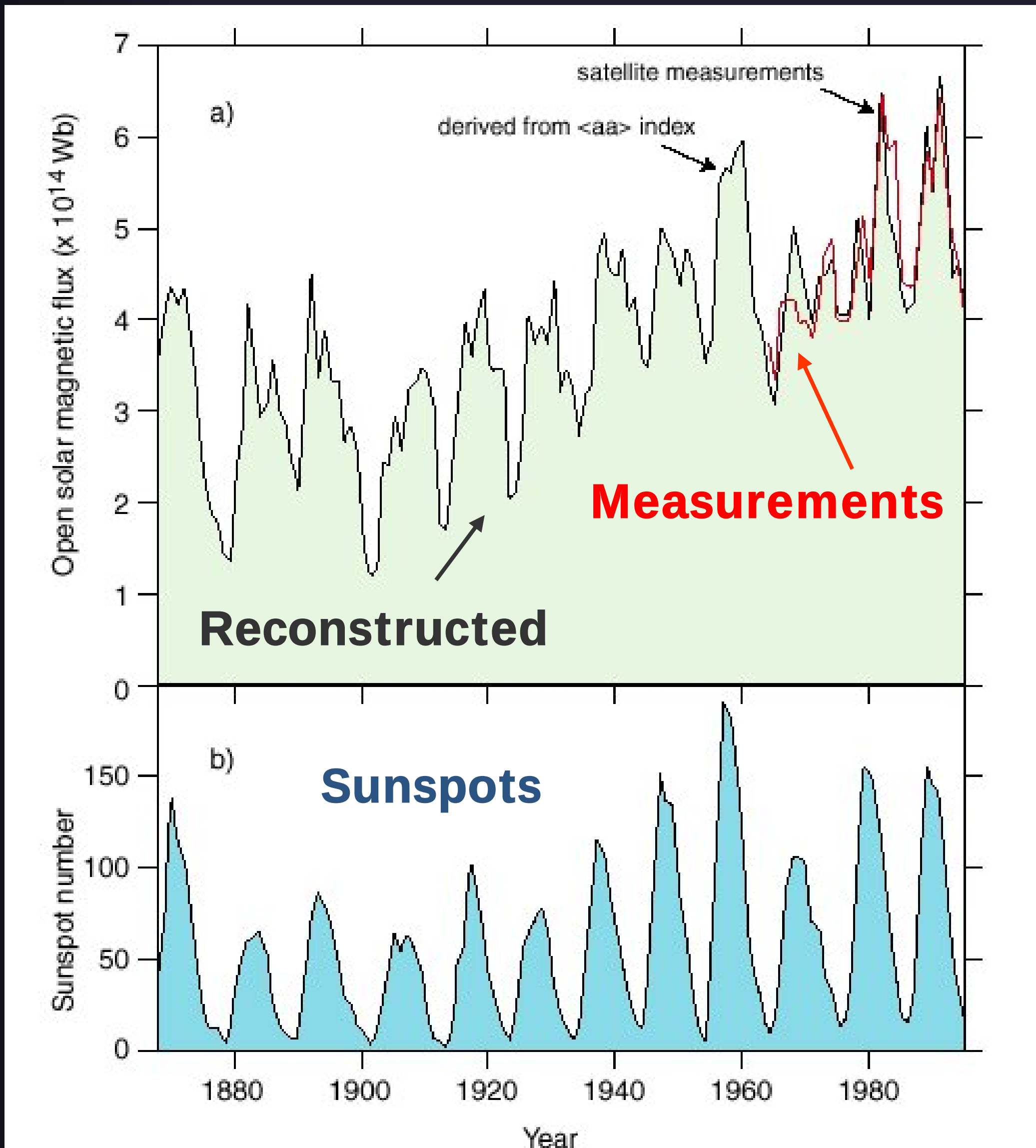


For each 3 hour interval the ranges of ΔH, R_N and R_S are scaled to give "K-values", K_N and K_S which are converted to aa_N and aa_S using an algorithm that allows for location of magnetometer

$$aa = (aa_N + aa_S)/2$$

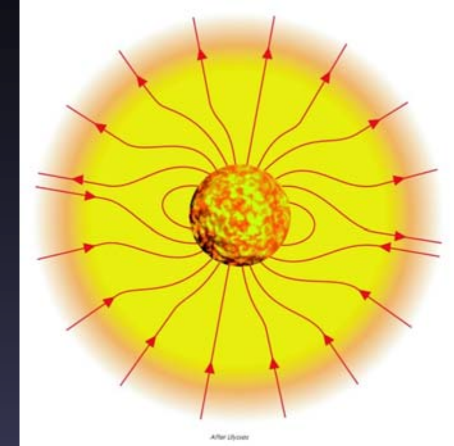
Mayaud, 1976

Interplanetary Magnetic Field



Lockwood et al. 1999 Nature

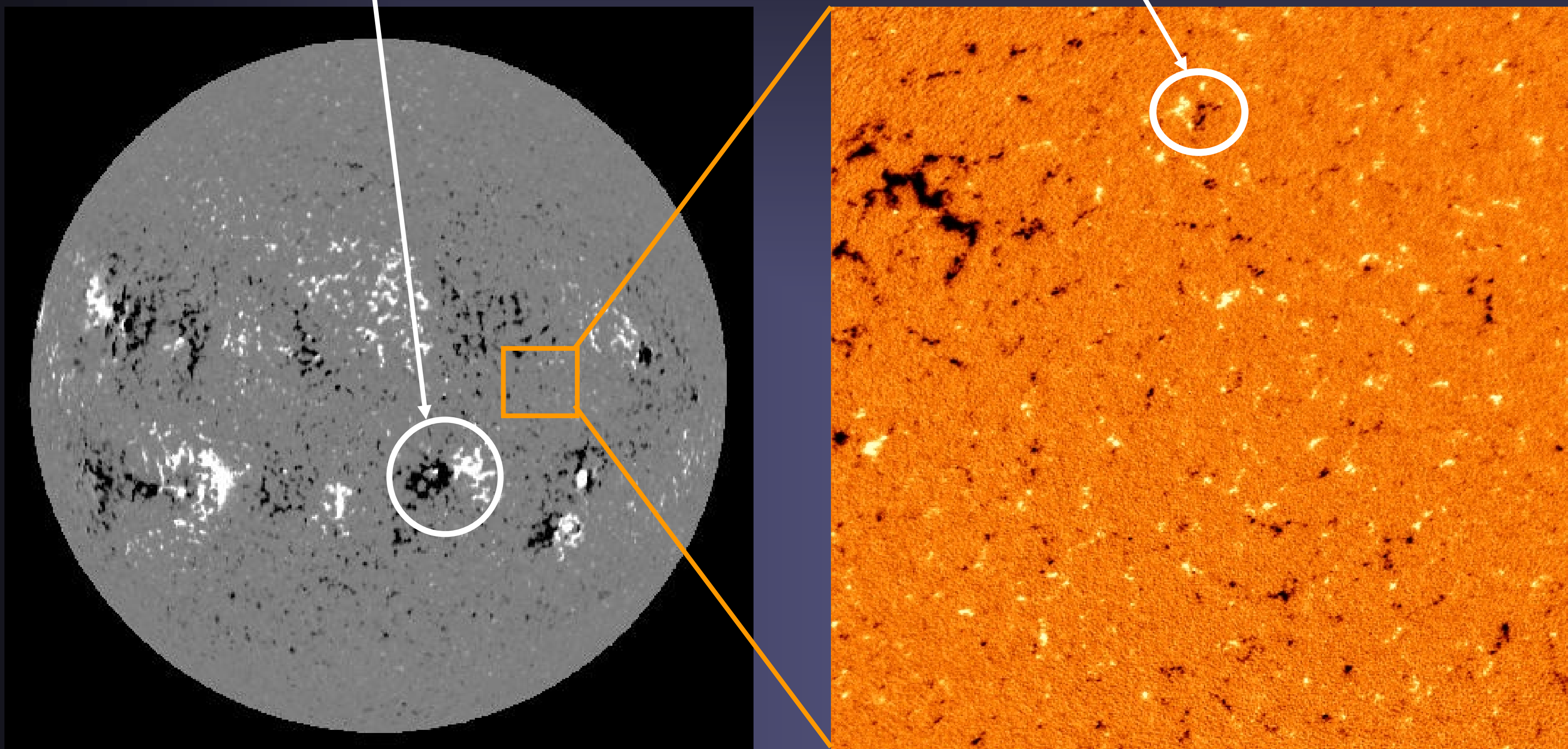
- Reconstructed from geomagnetic aa
- Open heliospheric flux doubled during the last century
- Solar origin of the secular trend?
- Does total magnetic flux show similar trend?



Active regions and ephemeral regions

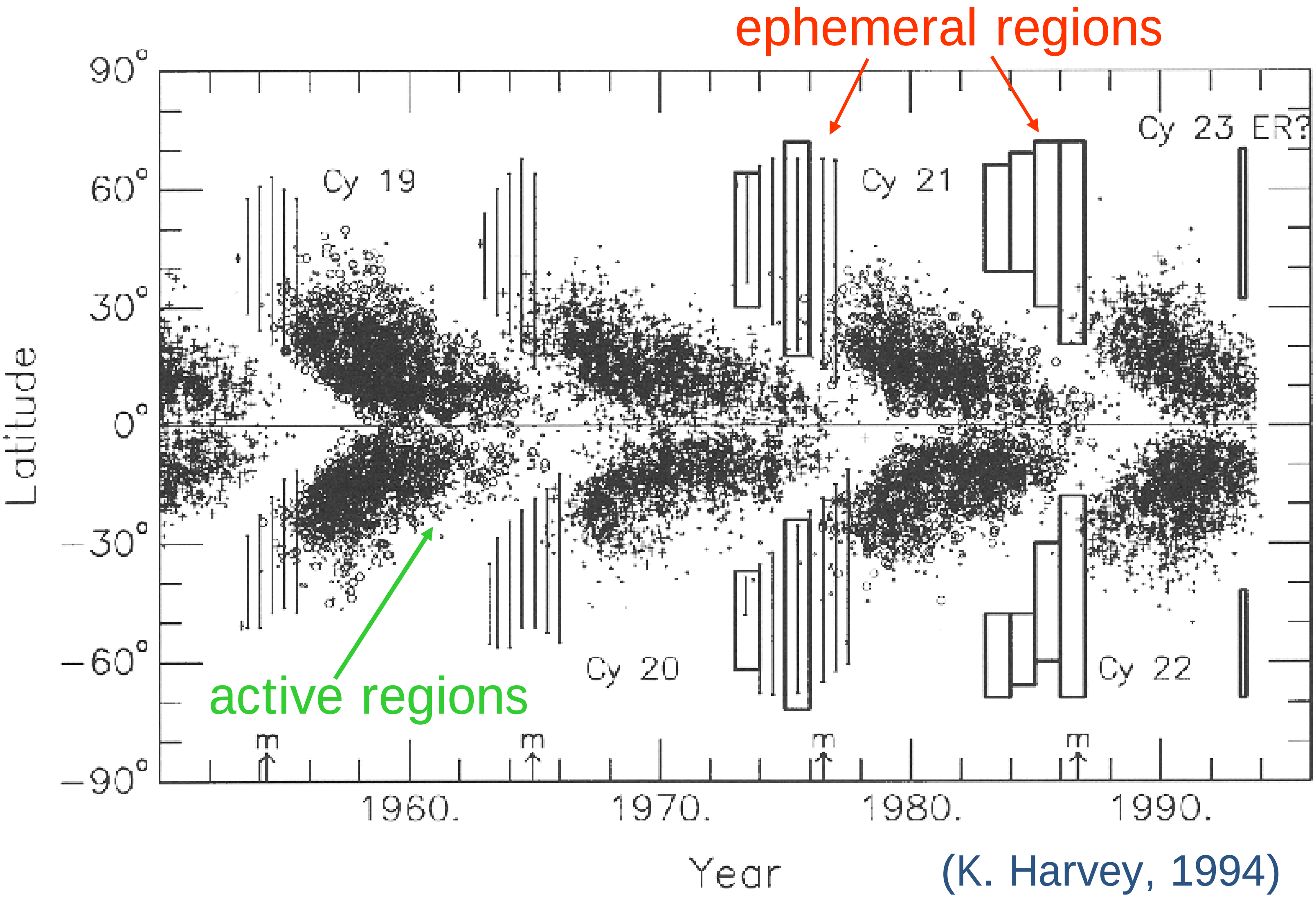
$\dot{\Phi} \approx 3 \cdot 10^{23} ... 3 \cdot 10^{24}$ Mx/yr

$\dot{\Phi} \approx 2 ... 4 \cdot 10^{26}$ Mx/yr



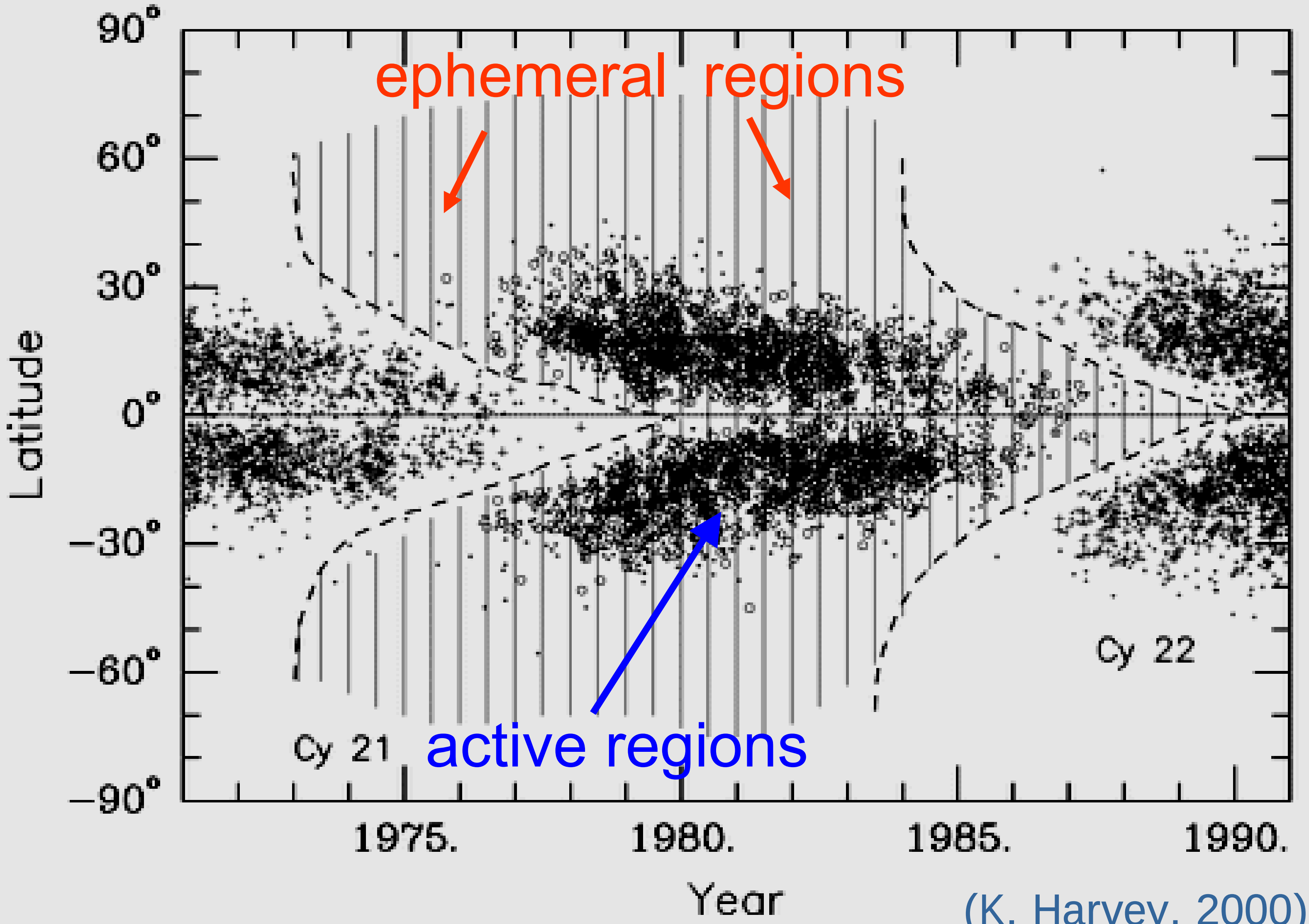
SOHO/MDI magnetograms

Solar cycle & ephemeral regions



(K. Harvey, 1994)

Ephemeral Regions: Overlapping Cycles



(K. Harvey, 2000)

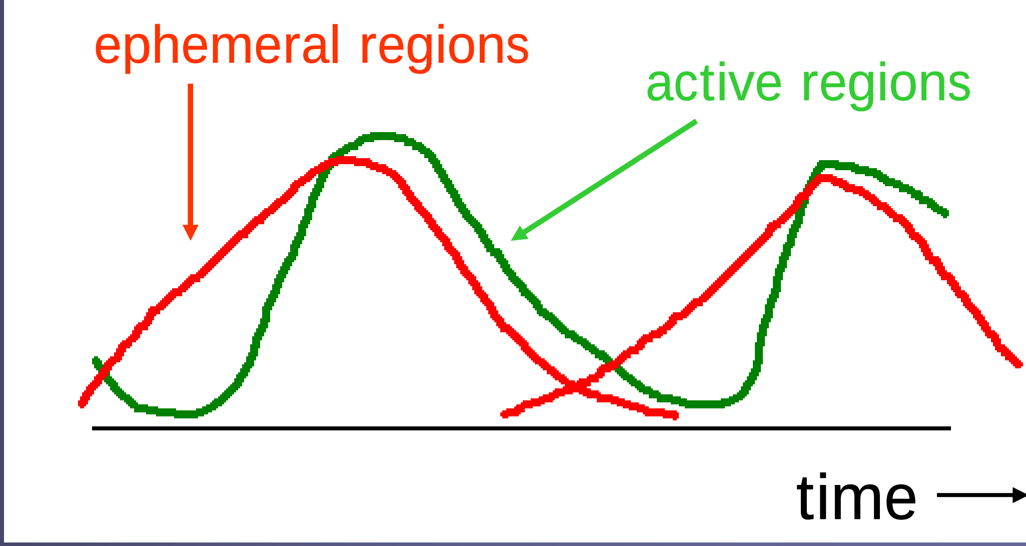
A Coarse Model for the Secular Variation of the Sun´s Magnetic Flux

- Cyclic flux emergence in (large) *active regions* and (small) *ephemeral regions*

➔ take sunspot number *(R)* as a `proxy´

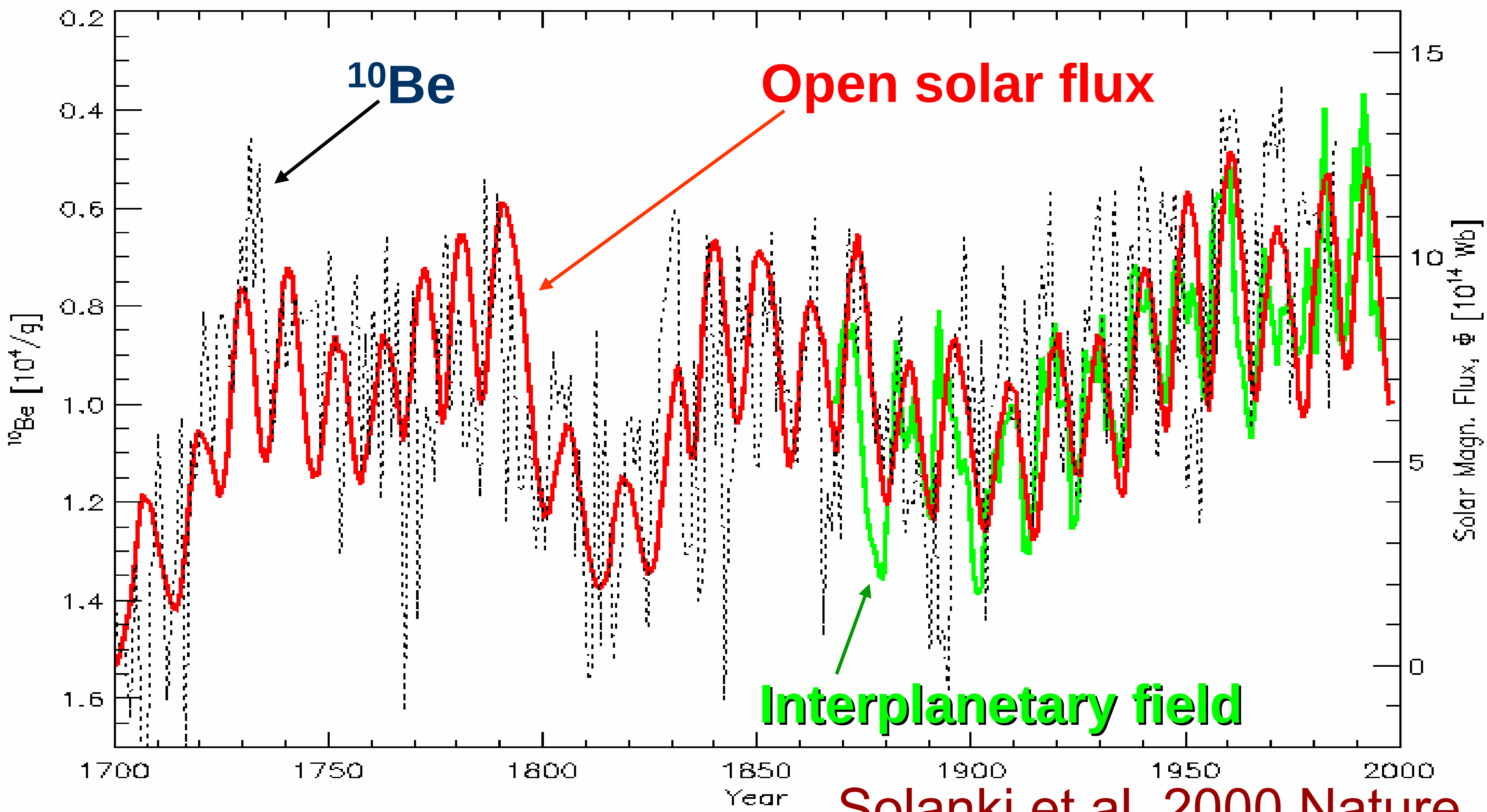
➔ extended cycle for ephemeral regions

- ER start earlier
- more extended, overlapping cycles



Solanki, Schüssler & Fligge 2000, 2002

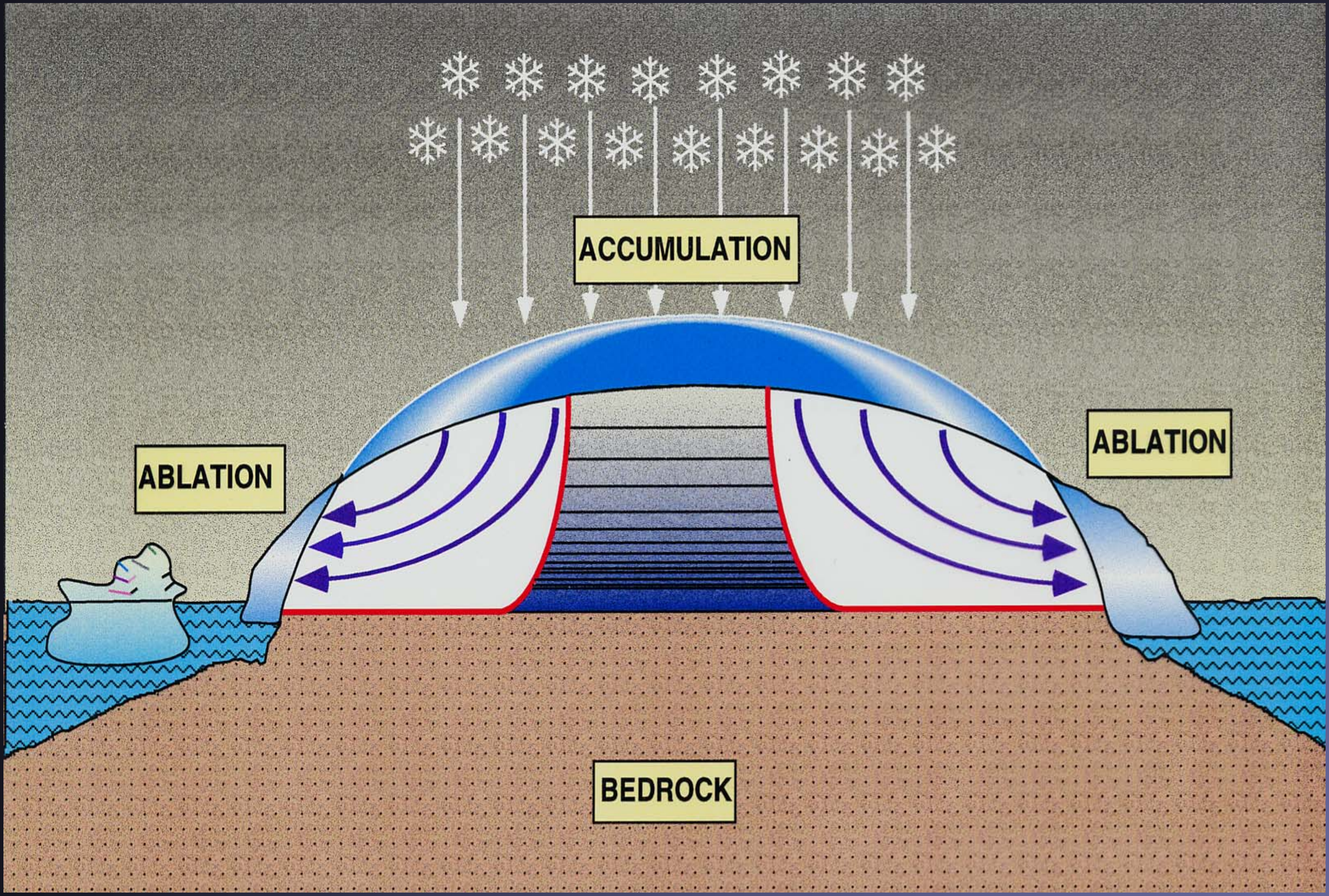
Reconstruction of Open Flux back to 1700



Solanki et al. 2000 Nature

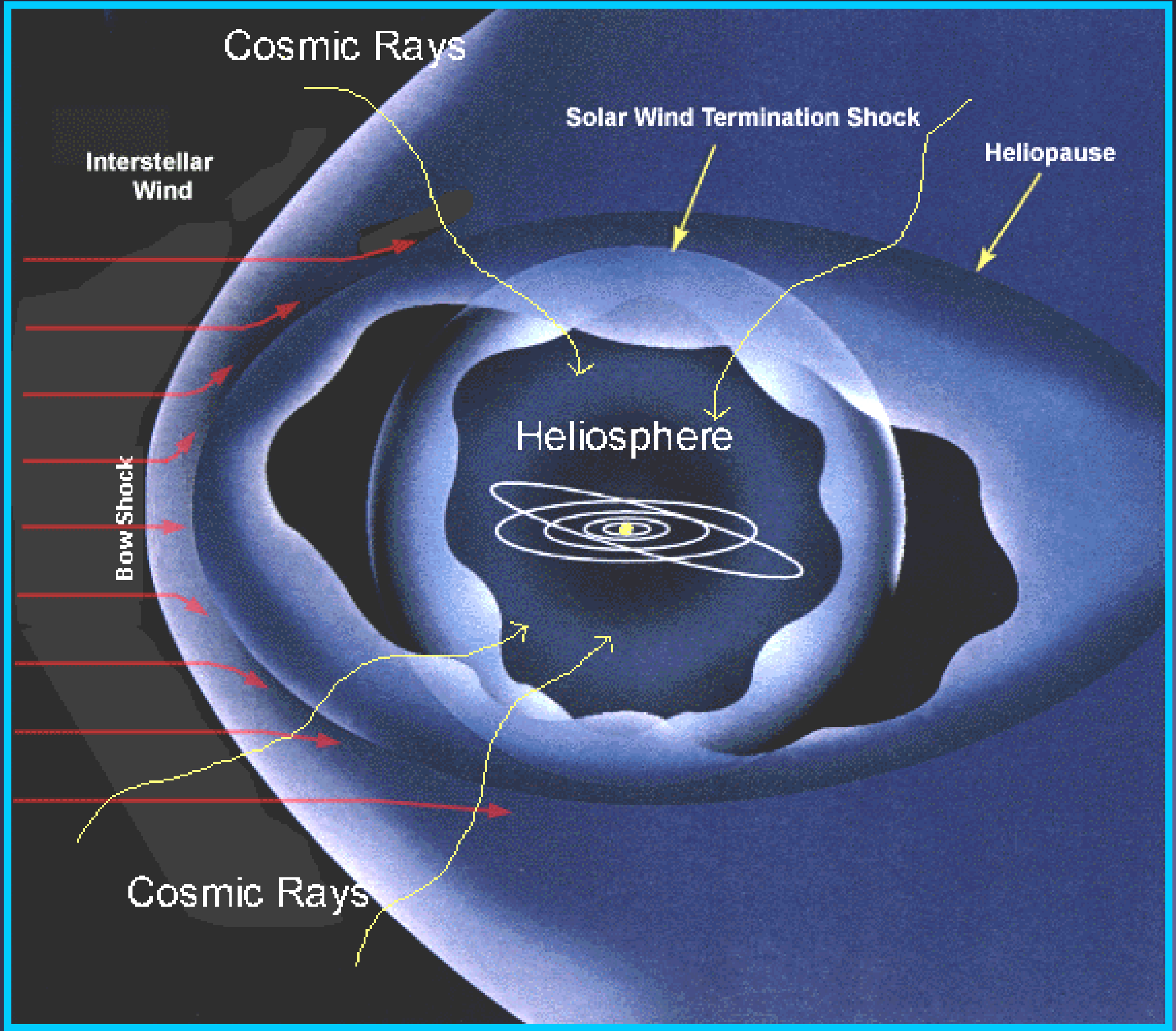
Model also predicts very similar trend for solar total magnetic flux ➔ solar irradiance should also show secular trend

Accumulation of ^{10}Be in Greenland ice

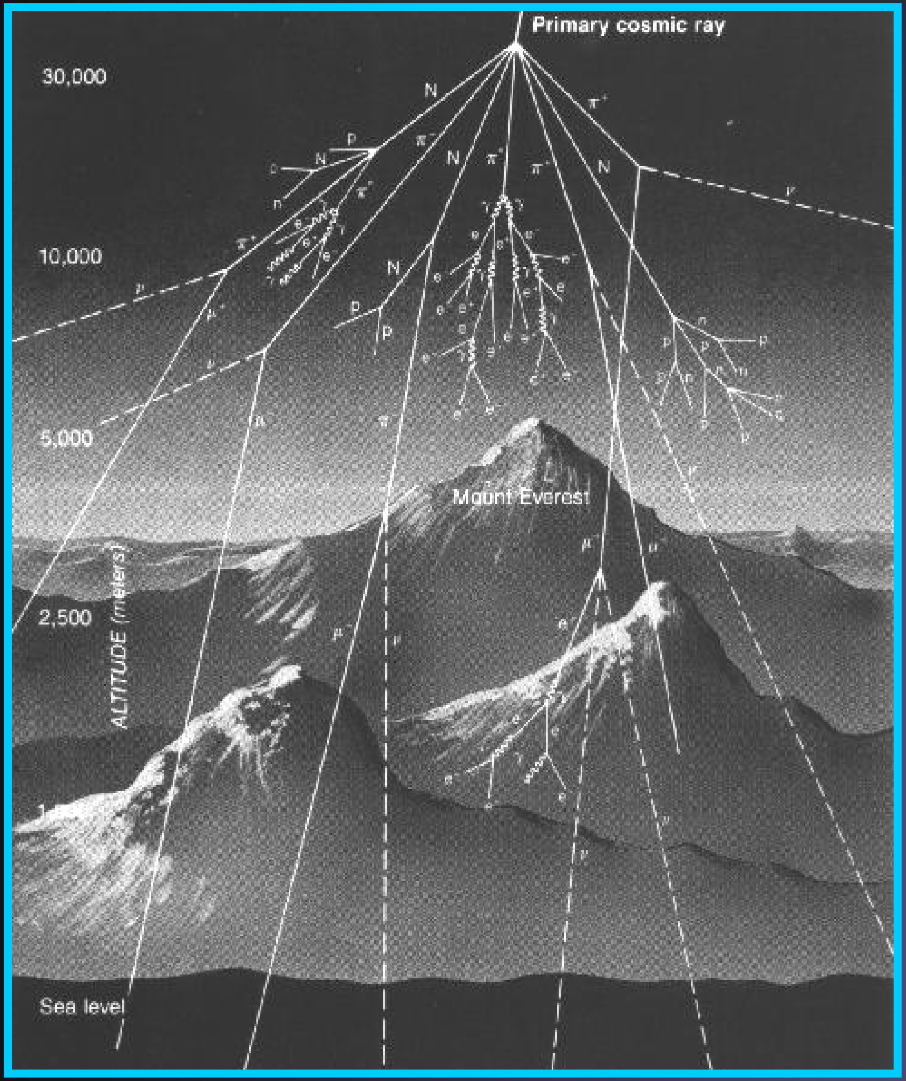


Modulation of cosmic rays

Cosmic rays = energetic particles from galactic sources. Solar magnetic field reduces number of particles reaching Earth. More active Sun ➔ less particles reach Earth

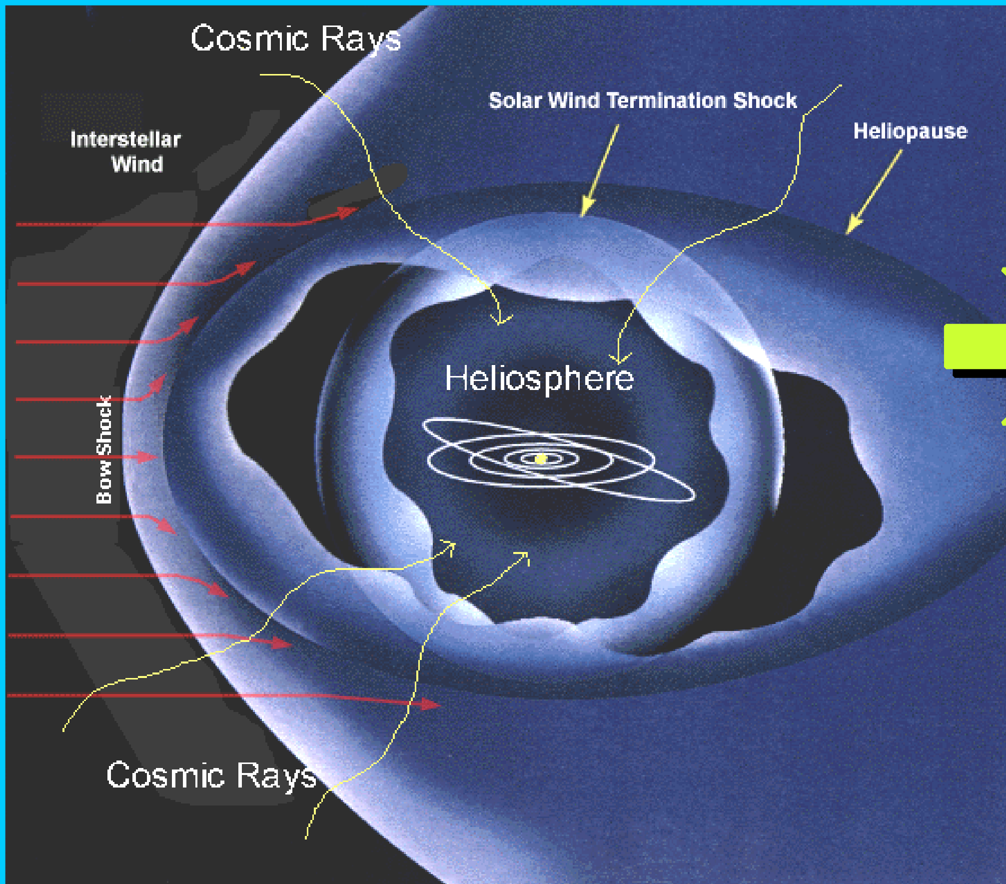


Effect of cosmic rays in atmosphere

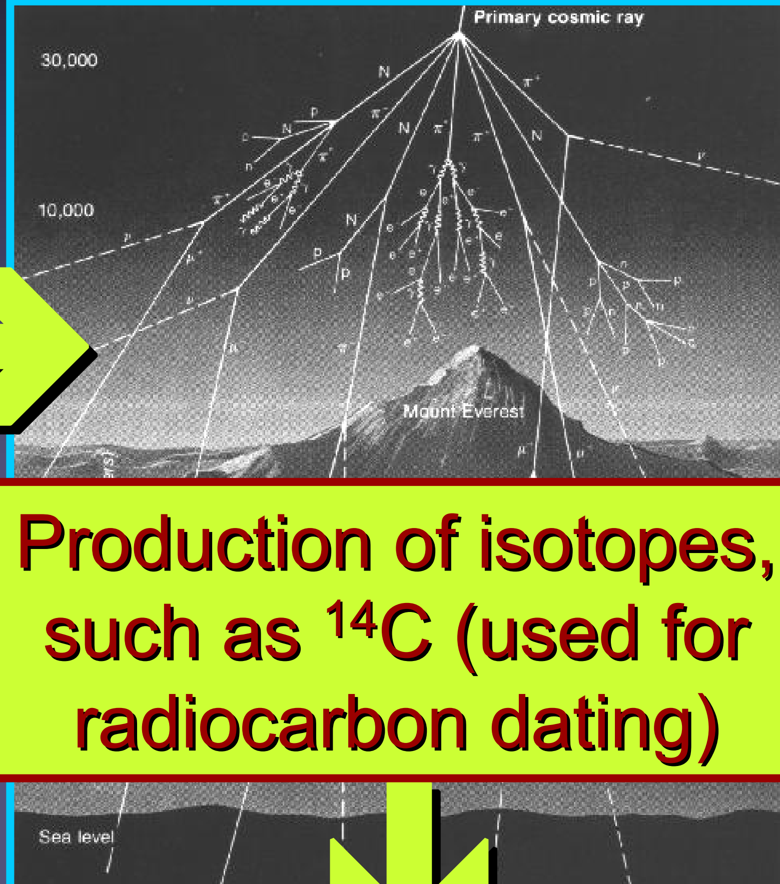


- Charged energetic CR particles interact with molecules in atmosphere
- ➔ particle showers: of interest to particle physicists
- ➔ Ionisation of many atoms
- ➔ Formation of neutrons, detected with neutron monitors
- ➔ Formation of cosmogenic isotopes: 10Be and 14C, etc.

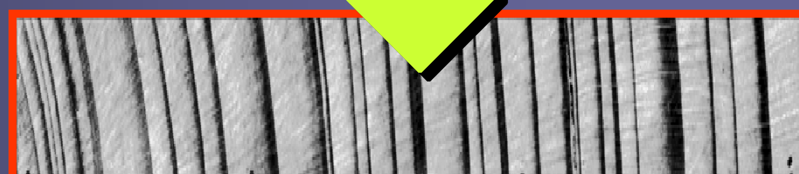
Cosmic Rays, the Sun & Tree Rings



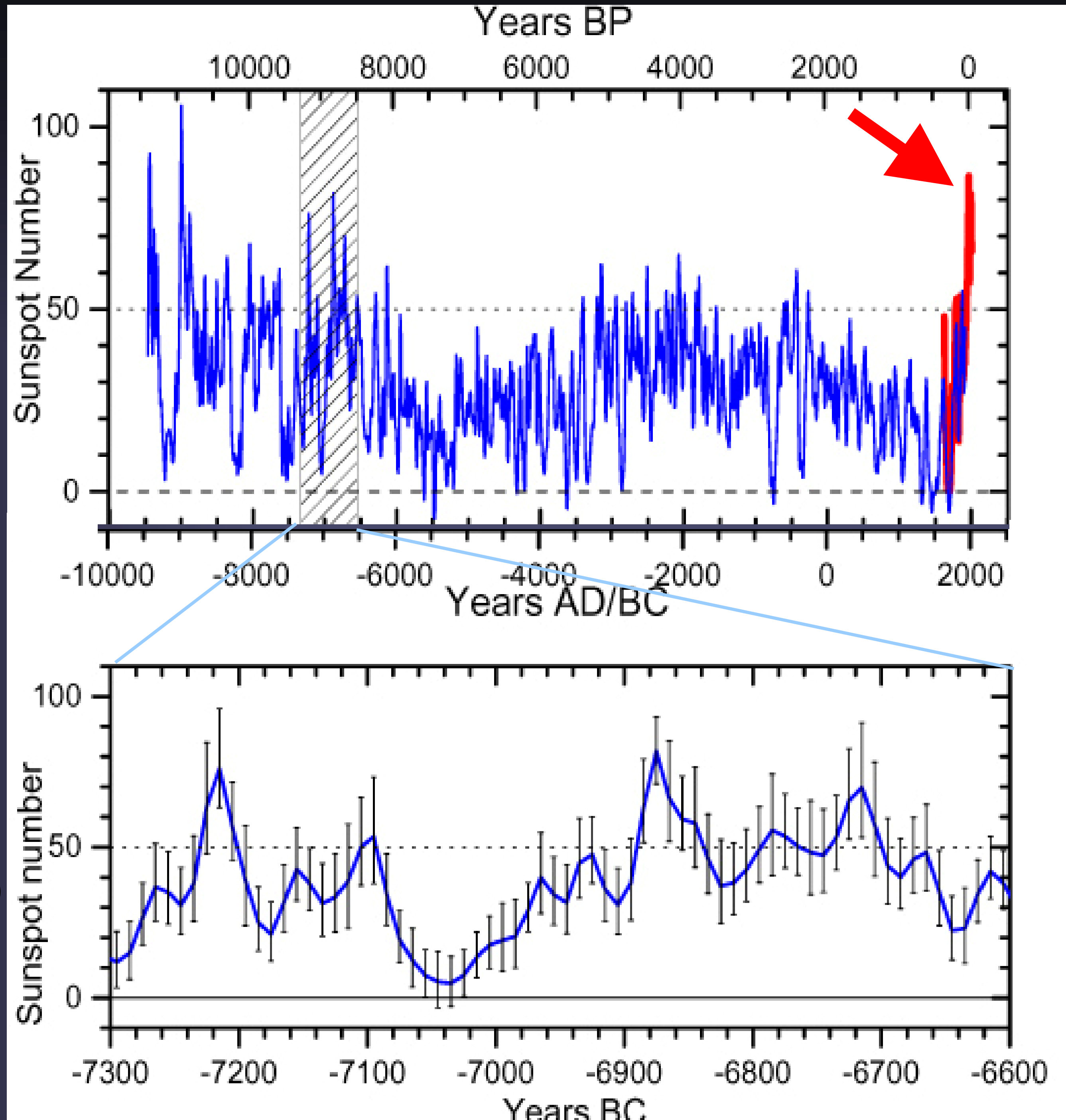
Flux of cosmic rays is changed by solar activity



Production of isotopes, such as ^{14}C (used for radiocarbon dating)

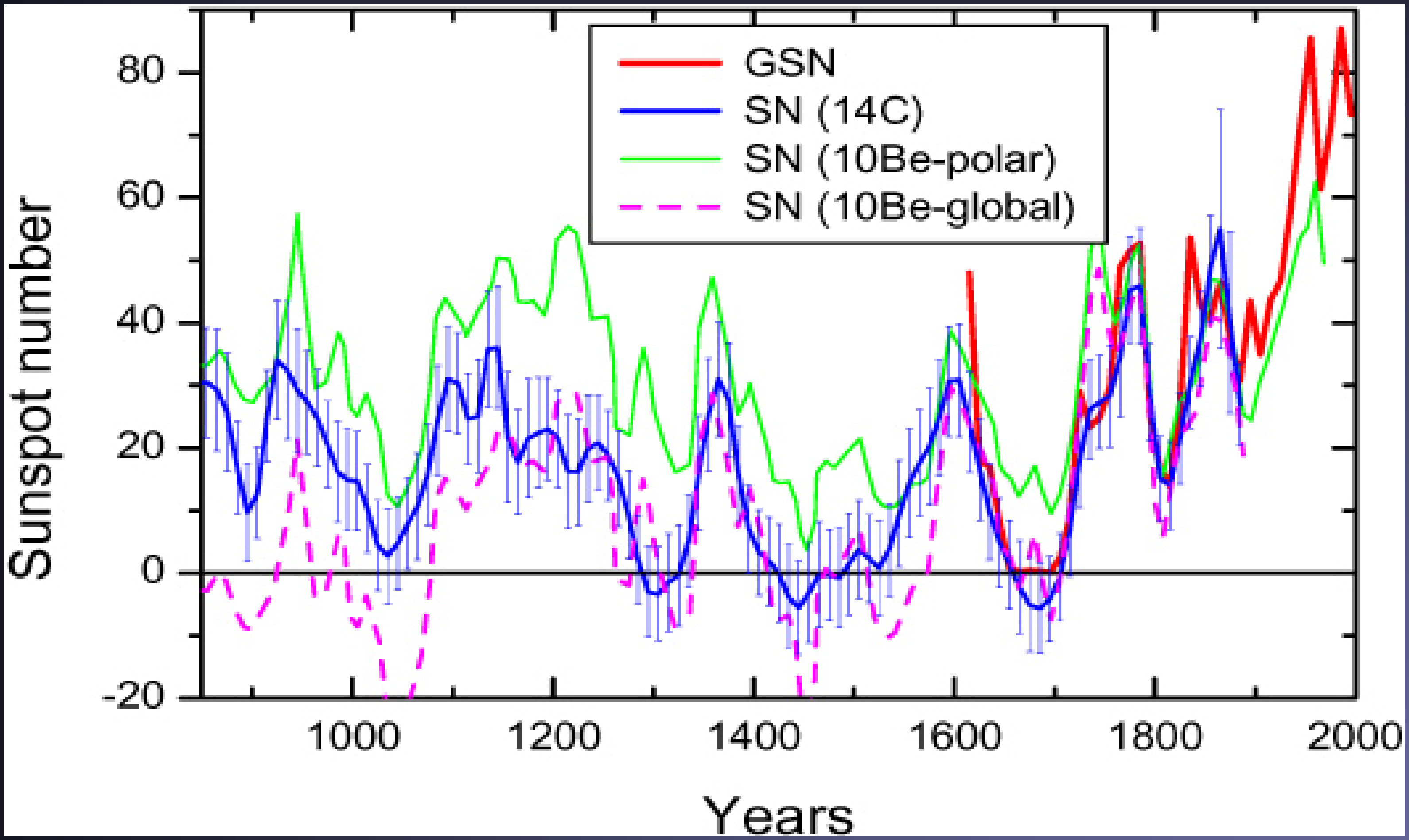


How did the Sun Behave since last Ice Age?



Number of Sunspots over last 11400 years reconstructed from ^{14}C in tree rings → Sun is very active **today** compared to last **11000 years**

Solanki et al. 2004 Nature



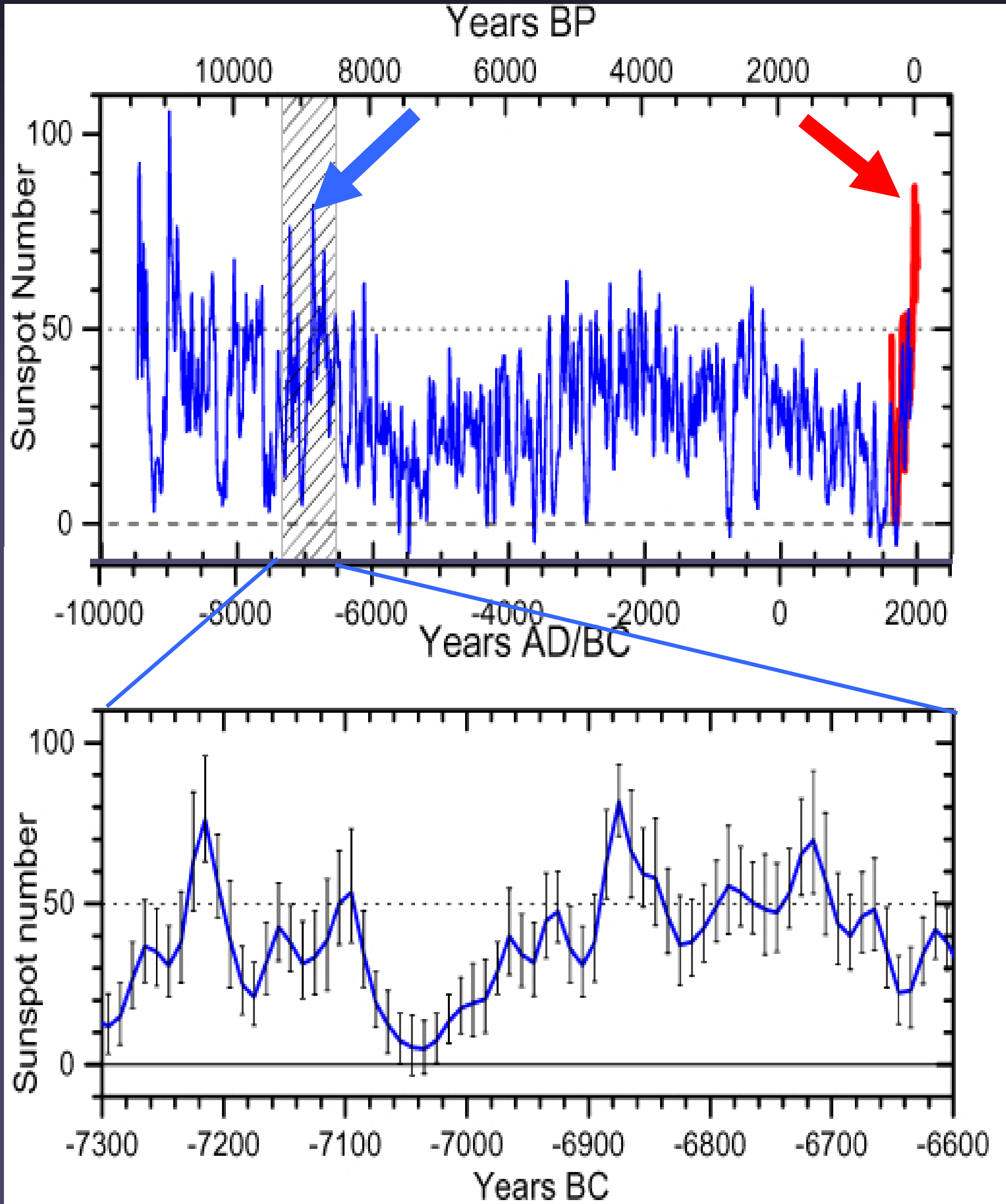
GSN
SN (14C)
SN (10Be-polar)
SN (10Be-global)
Sunspot number
80
60
40
20
0
-20
1000
1200
1400
1600
1800
2000
Years

Sunspot Number for Last 11400 Years

- ^{14}C from tree rings carries information on sunspots.
- Using physical models of all the steps connecting $\Delta^{14}C$ with sunspot number, it was possible to obtain sunspot number over 11400 years.

➔ Order of magnitude longer series than before

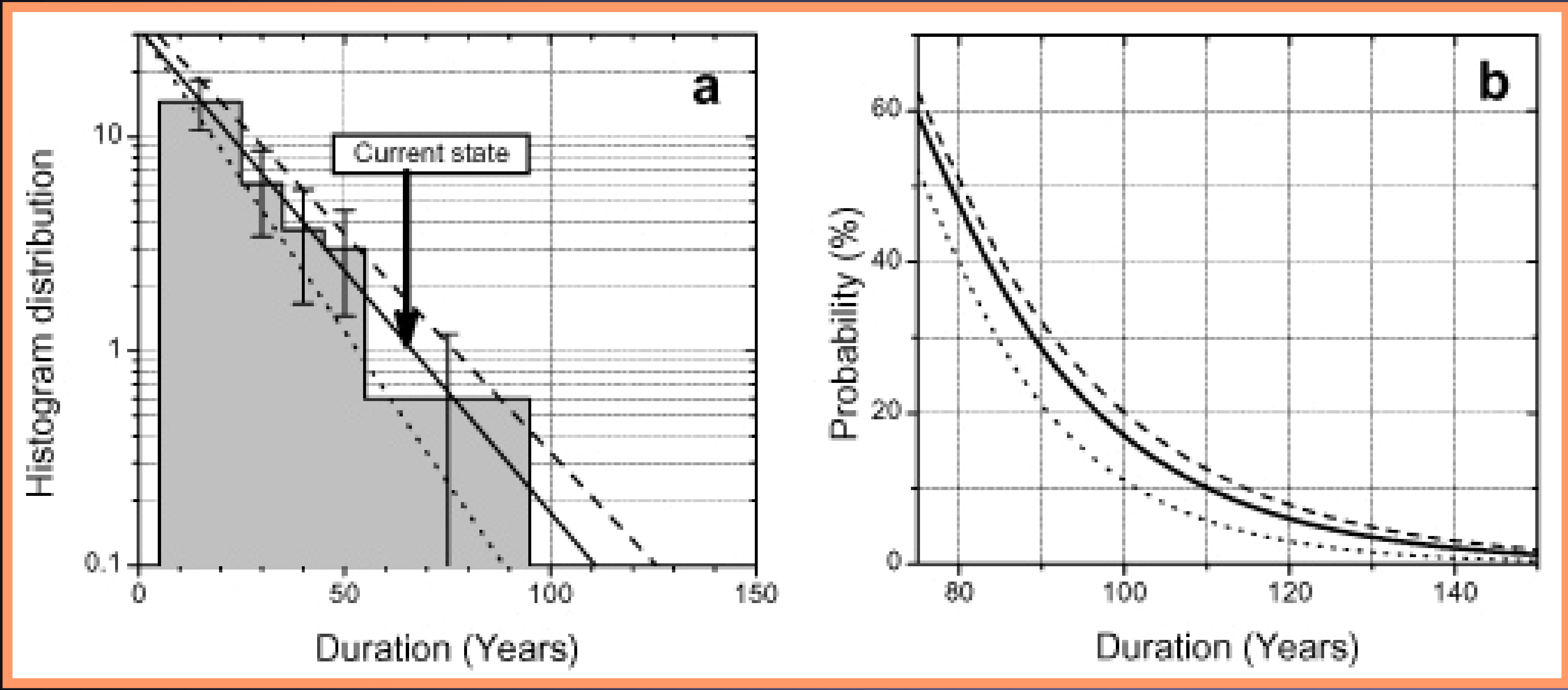
➔ Current episode of high solar activity is unique for the last 8000 years!



Solanki et al. 2004, Nature

How long will the current episode of high activity last?

- Current high activity episode is one of the longest known
- Probability that it continues until 22nd century: below 1%



Solanki et al. 2004, Nature

Solar Irradiance and Climate