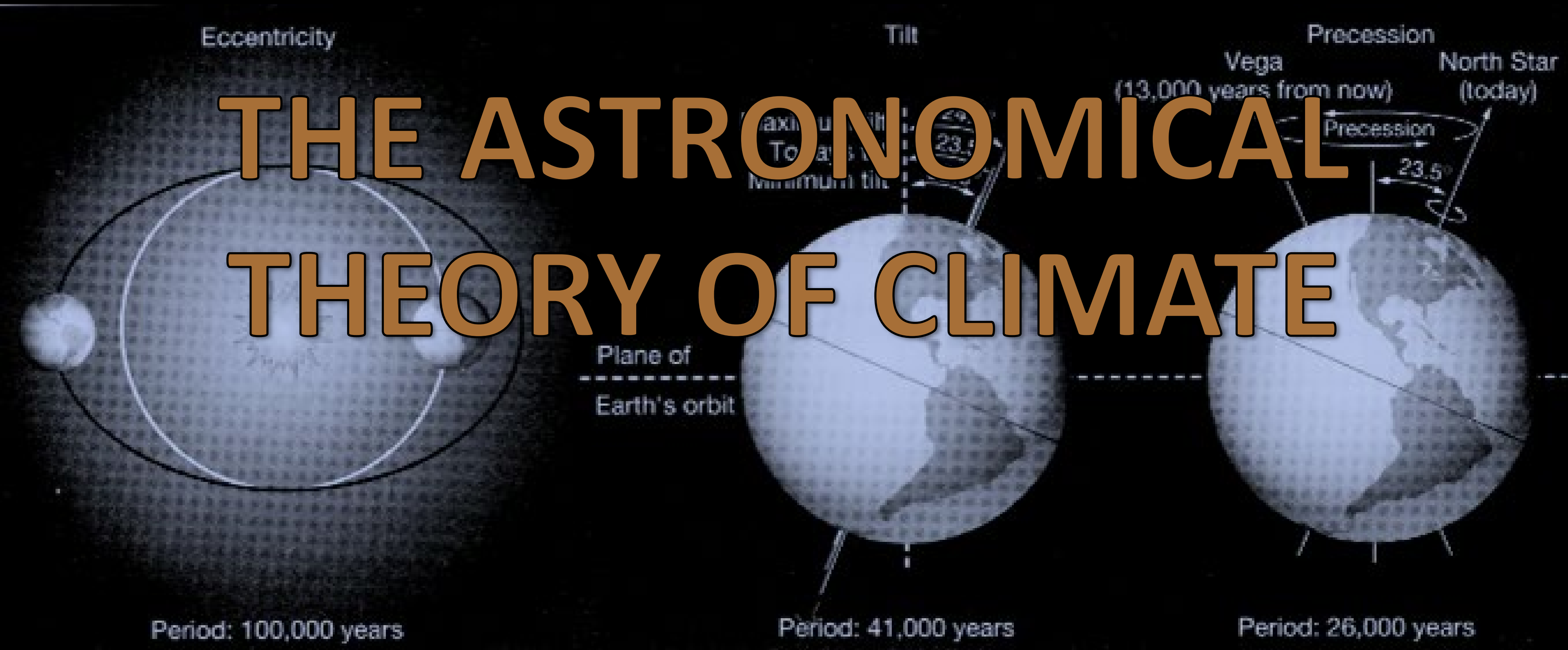
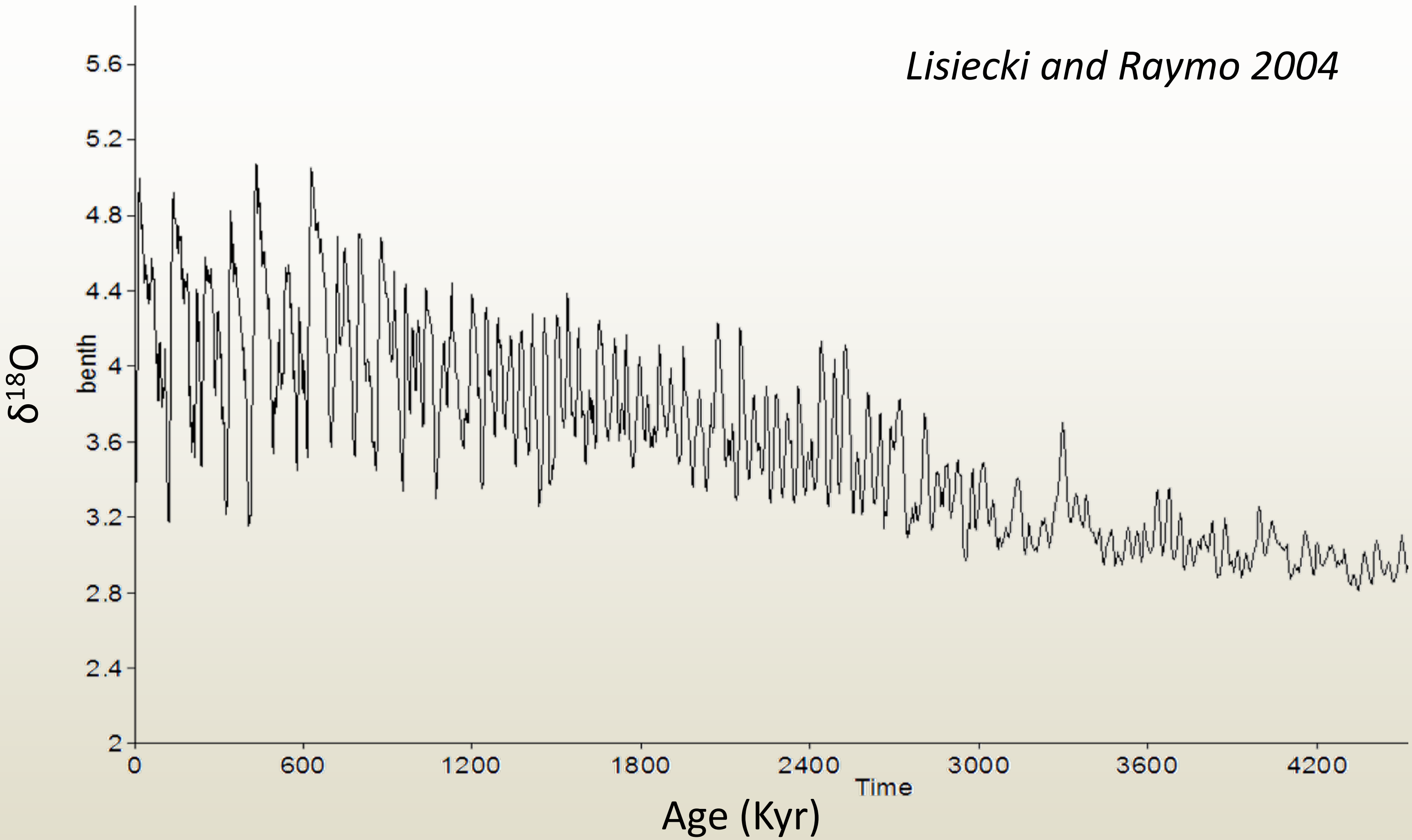
THE ASTRONOMICAL THEORY OF CLIMATE



Basics, limits and applications

LR04 $\delta^{18}O$ Benthic Stack



The isotopic signal shows a pervasive cyclicity, the origin of which is largely climatic and linked to the glacial-interglacial cycles.

ISOTOPE AND CLIMATE

Since the 1970s, efforts have been made to:

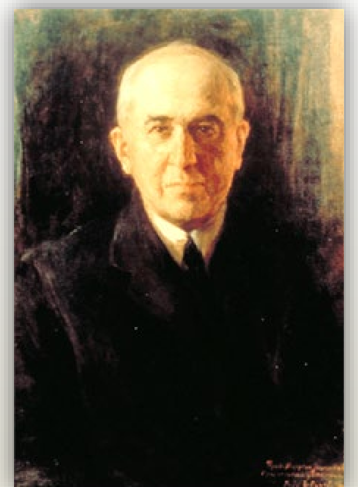
- **define a chronology for the curves of δ^{18}O;**
- **explain the cyclicality of the δ^{18}O curves.**

The isotopic curves show cyclicities attributable to glacial-interglacial cycles. The δ^{18}O curves show more of the 4 glaciations (Günz, Mindel, Riss and Würm) that are documented in continental sediments.

TERRESTRIAL DATA

North American:	**European:**
Wisconsin	Wurm
Illinoian	Riss
Kansan	Mindel
Nebraskan	Gunz

THE MILANKOVITCH THEORY



Milutin Milankovich

Milutin Milankovitch's idea:
If the simple day/night contrast is so pronounced, how can the **orbital variations**, which cause enormously higher **variations in average insolation**, not affect the global climate?

This theory was only validated in the 1970s, when ...

THE ASTRONOMICAL THEORY OF CLIMATE VARIATION

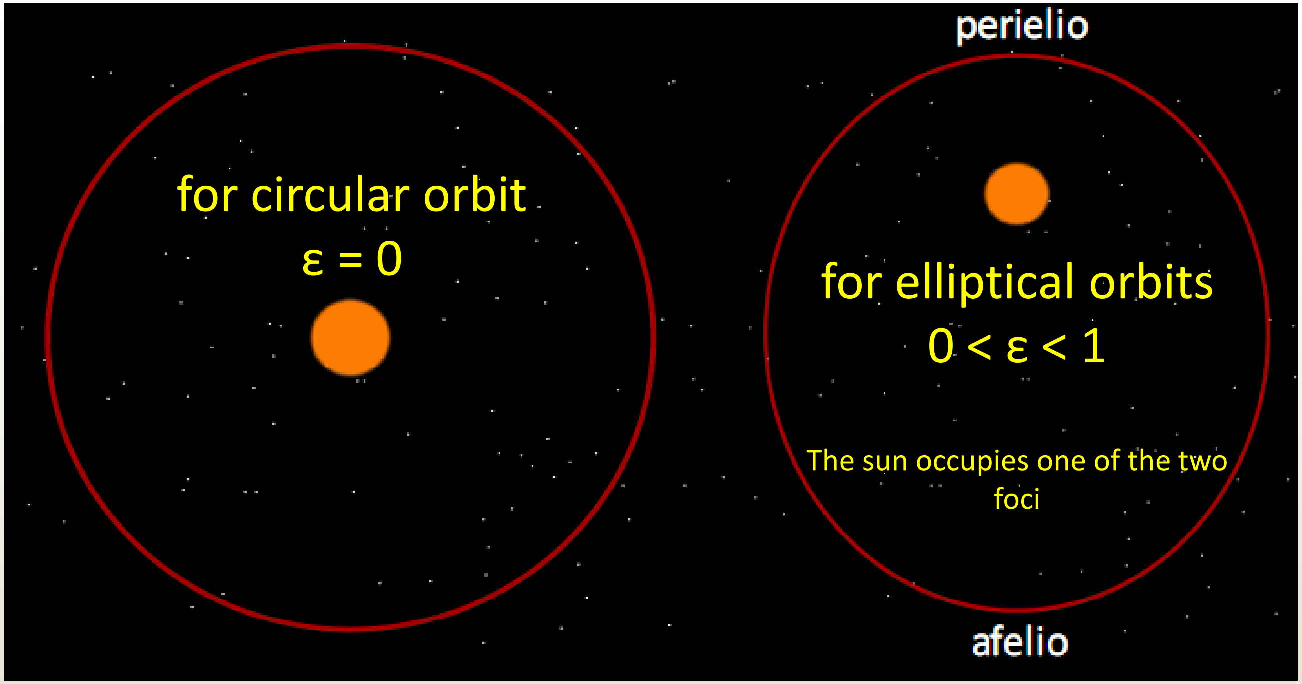
in 1976: Hays, Imbrie & Shackleton published a work in which they re-evaluate the hypotheses of Milutin Milankovitch and hypothesized that:

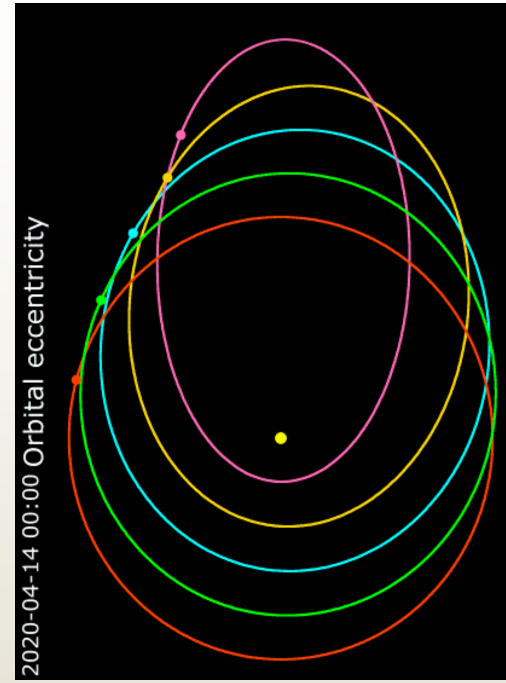
"**The terrestrial climatic variations, recorded in the isotopic curves, would be attributable to variations in the orbital parameters over geological time**"

This hypothesis is known as

ASTRONOMICAL THEORY OF CLIMATE

ECCENTRICITY (e)





Periodicity:

95 kyr *"short eccentricity"*

125 kyr

413 kyr → *"long eccentricity"*

Eccentricity is defined as **the deviation of an orbit with respect to a circle.**

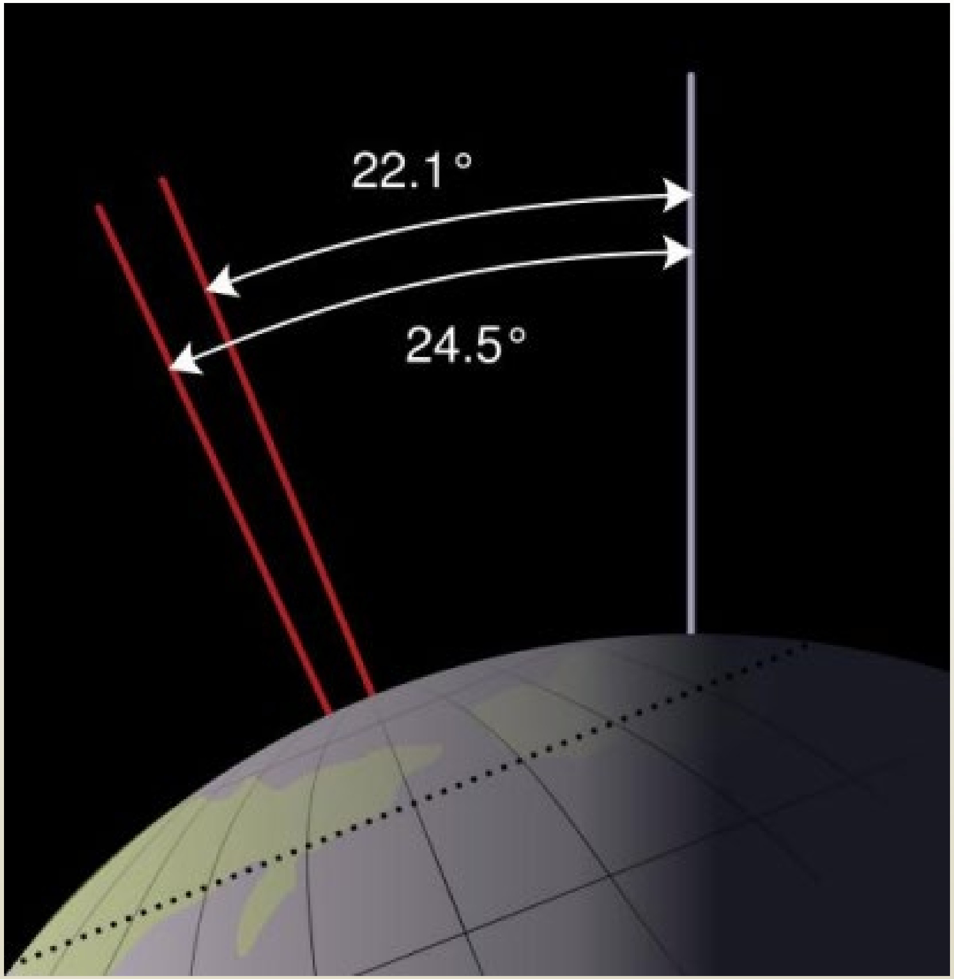
Earth's orbit relative to the Sun

ε_{TERRA} = from 0.005 to 0.0607

Today's value ε_{TERRA} = 0.0167

https://www.youtube.com/watch?v=_tkZZVB3_VQ

OBLIQUITY (T)



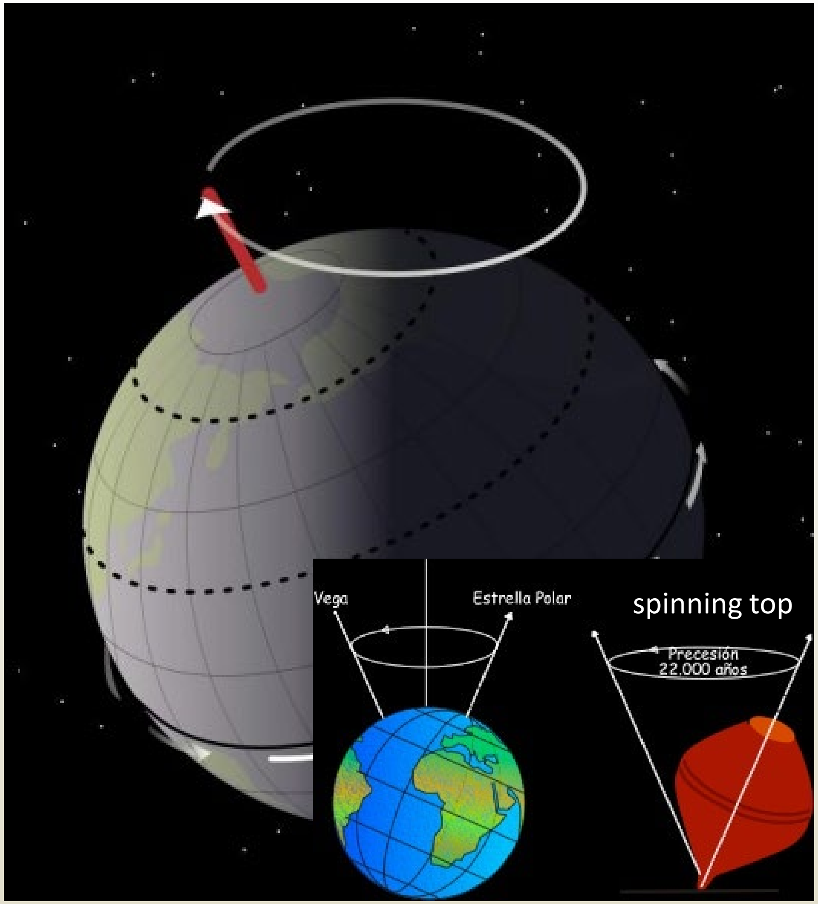
Periodicity: 41 kyr

The **obliquity**, also referred to as TILTING (hence abbreviated as T**), is the angle of the Earth's axis in relation to the ecliptic plane.**
This angle periodically varies between 21 and 24.5 degrees and completes a full cycle every 41,000 years.

Important: T is a value determinant to HIGH LATITUDES (HL).
As T increases, the insolation at HL increases but decreases at LOW LATITUDES.

→ Control on the albedo also in terms of angle of incidence.

PRECESSION (p)



Periodicity:
PRECESSION (p)
19 kyr → *"short precession"*
22,24 kyr →"long precession"

Precession is the **change in the direction of the Earth's rotation axis with respect to background stars.** It constitutes a gyroscopic motion influenced by gravitational interactions with both the Moon and the Sun (in a comparable manner). Owing to interactions with other celestial bodies, the "standard" precession period (26,000 years) is "compressed" into shorter cycles, ranging from 24 to 19 thousand years.

Important: p is a value determinant to LOW LATITUDES(LL), but practically insignificant at HL.

When the axis is oriented toward the Sun at perihelion, one hemisphere will experience a more pronounced climatic difference between seasons, while the other will have relatively milder seasons.

OTHER ORBITAL FORCING

SOLAR CYCLES, aperiodic or periodic (11 yr);

MOON ORBIT PERIODICITY (precession=8 yr, ecliptic interference =18 yr);

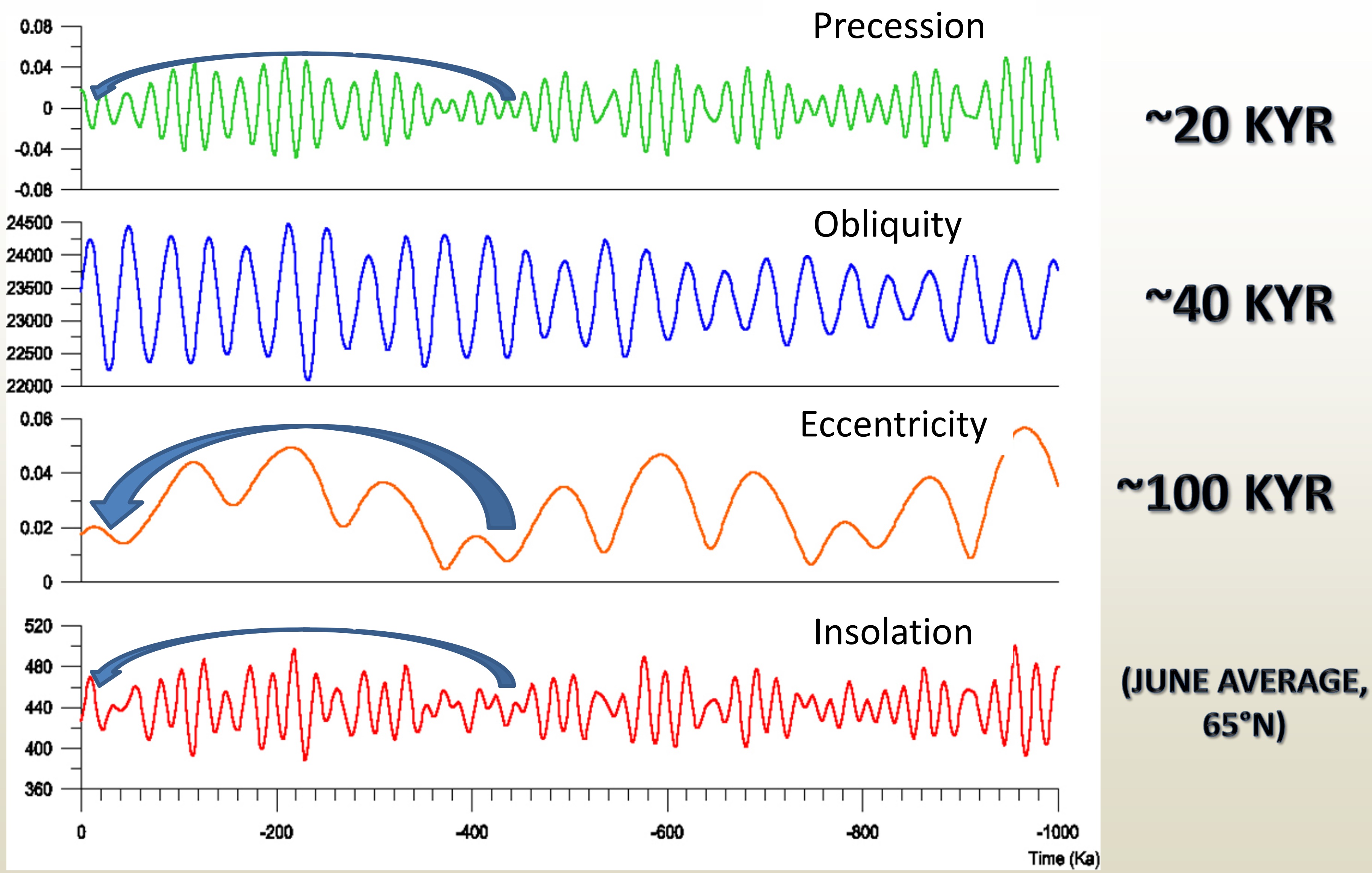
TILTING OF THE PLANE OF THE EARTH ECLIPTIC, ca. 70 kyr;

INTERACTION WITH THE ASTEROID BAND, > 400 kyr;

"LONG" VARIATIONS OF THE EARTH ORBIT, up to 2.5 Myr...

But… how to recognize all these periodicities in data series apparently "mute" (e.g., isotope curves)?

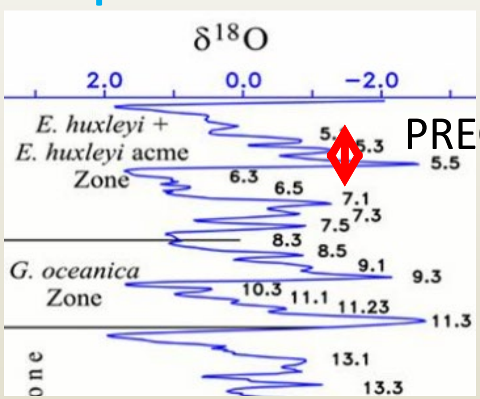
→ **SPECTRAL ANALYSIS**

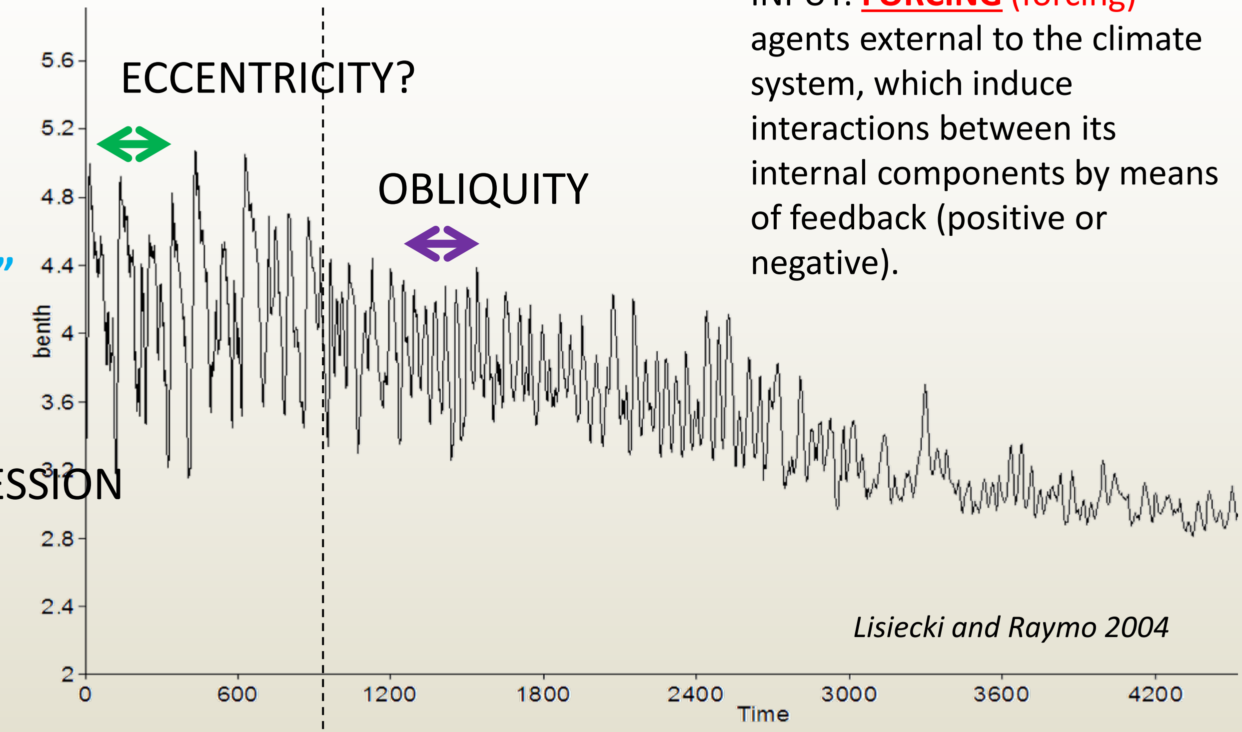


Modulated parametric solutions (Laskar, 2004) and insolation for the last million years. The insolation highlights the "nested" hierarchy (like a Matryoshka) of the orbital parameters.

INSOLATION AND CLIMATE CYCLES - 1

In recent decades it has been hypothesized that **there was a direct correlation between forcing and cyclicality characterized by "similar" frequencies.**





Lisiecki and Raymo 2004

INPUT: <u>**FORCING**</u> (forcing) - agents external to the climate system, which induce interactions between its internal components by means of feedback (positive or negative).

For this reason, the climatic cycles of the Pliocene and the lower Pleistocene (duration 40 kyr) were interpreted as a response to the control of the obliquity, while the cycles of the "glacial" Pleistocene (~ 100 kyr) were related to the eccentricity of the orbit terrestrial. Secondly, in the isotope curves of oxygen, a higher frequency joint is observed, interpreted as a response to the precessional signal (20 kyr).

INSOLATION AND CLIMATE CYCLES - 2

At this point we verify the validity of Milankovitch's theory,

by punctually comparing the relationship between insolation (and its variability over time) and quantitative paleoclimatic data (i.e., stable oxygen isotopes).

We apply an effective method of statistical investigation. Which?

SPECTRAL ANALYSIS

Traditional spectral analysis on data-series:
development of a Fourier series"Adapted", which allows to identify and "weigh" (→ frequency and intensity) in recursive signals of a given series of values.

Fourier series definition: is the representation of a periodic function by means of a linear combination of fundamental sinusoidal functions.

Used for the most varied purposes (e.g., heart rhythm in heart patients, trend of titlesstocks, etc.), this method allows us to identify (or confirm) repetitive signals in a packet of geological data (e.g., isotopes, fossils, rock strata, etc.).

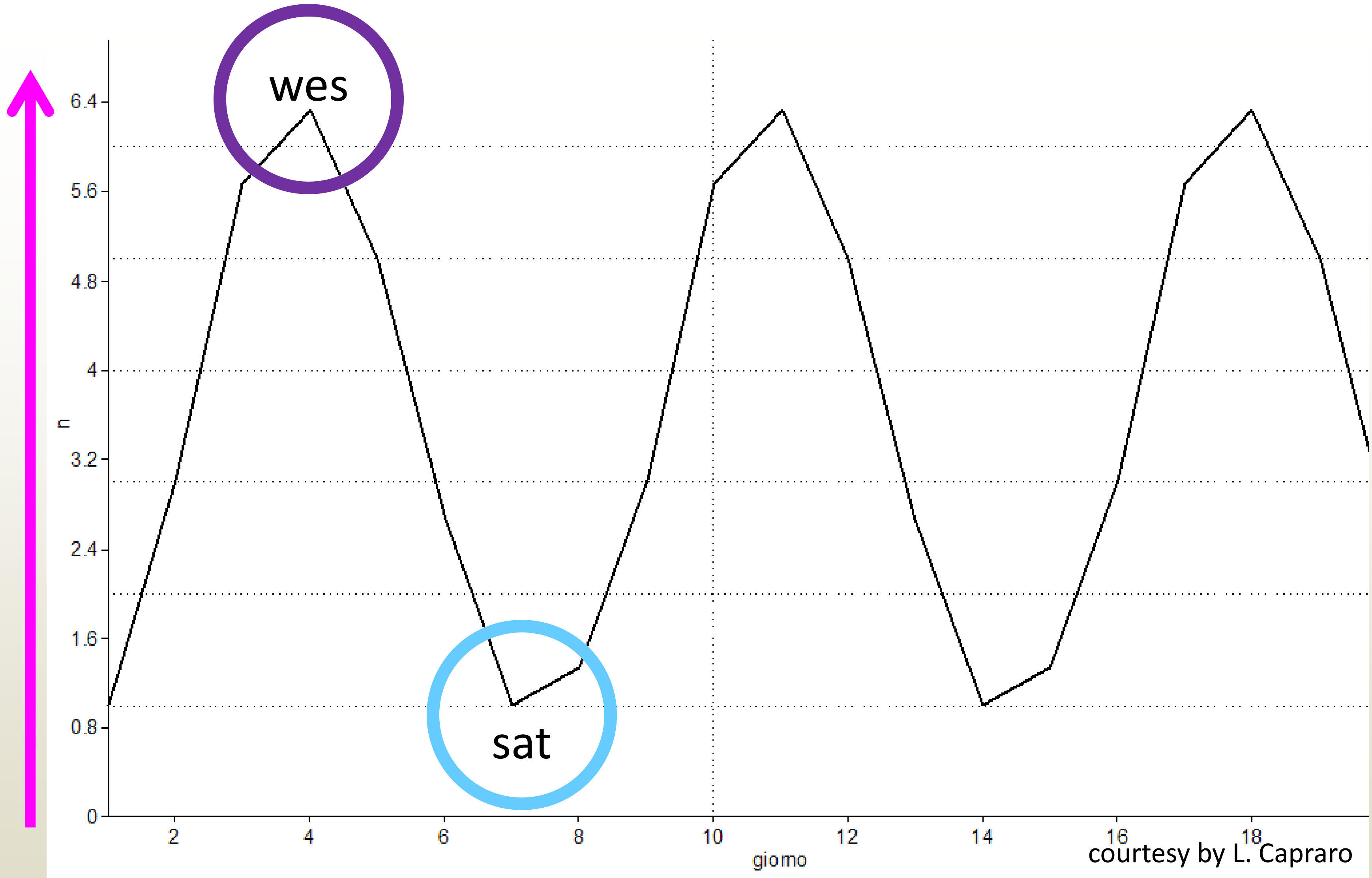
LOMB-SCARGLE PERIODOGRAM

We will begin the analysis using the **LOMB-SCARGLE PERIODOGRAM**, a method capable of returning in simple form the characteristic frequencies (x) and the relative spectral intensity (y) of equally spaced and unequaled series.

The periodogram is therefore a graph that relates the duration of the period with its relevance.

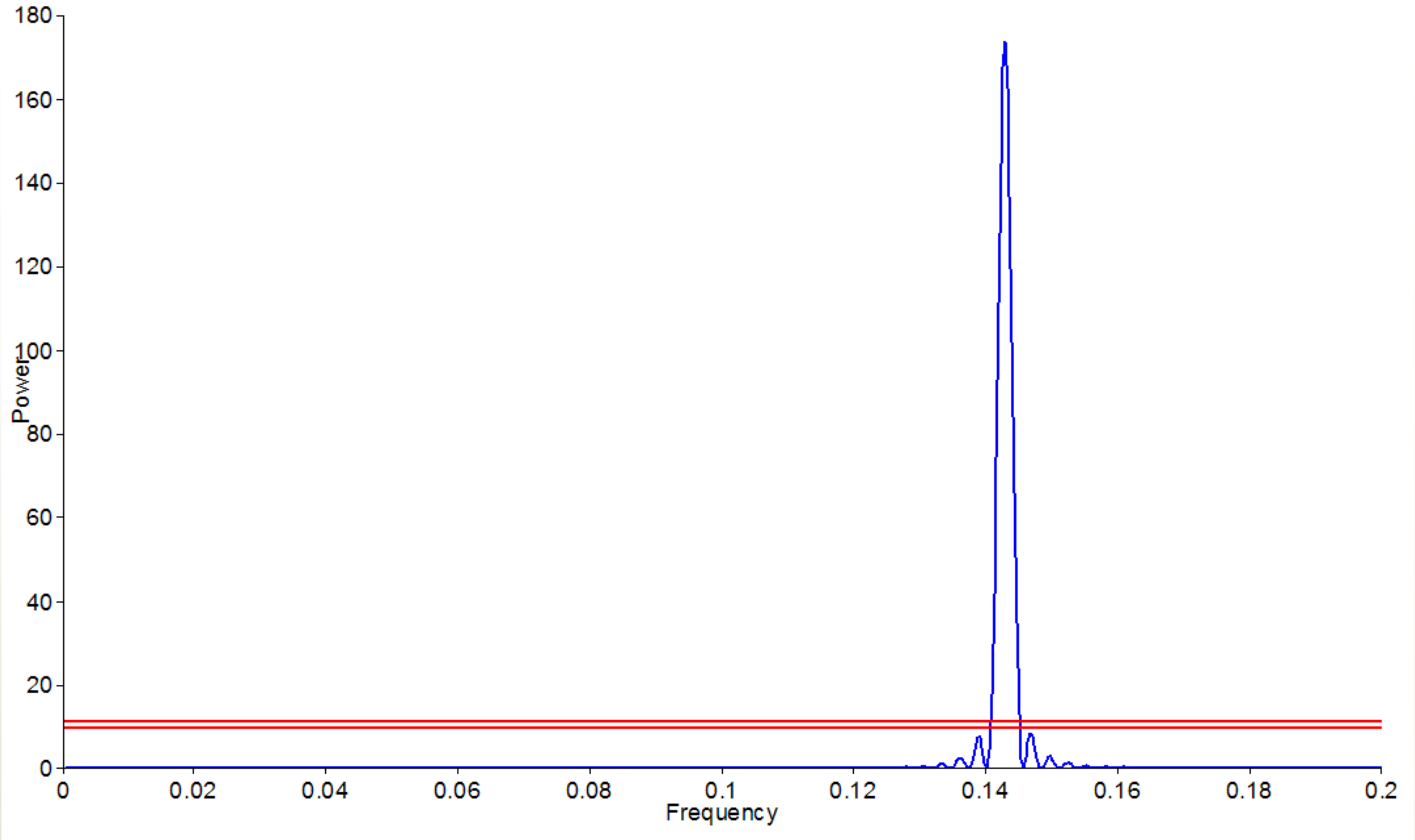
ADVANTAGES: simple method (it is fast, there are specific software available), therefore usable by anyone;
DISADVANTAGES: interpretation is not always immediate on certain types of data; the method does not take into account the variability of the signals in time / space → "flattening" of the signals in a single frequency.

let's get acquainted ...



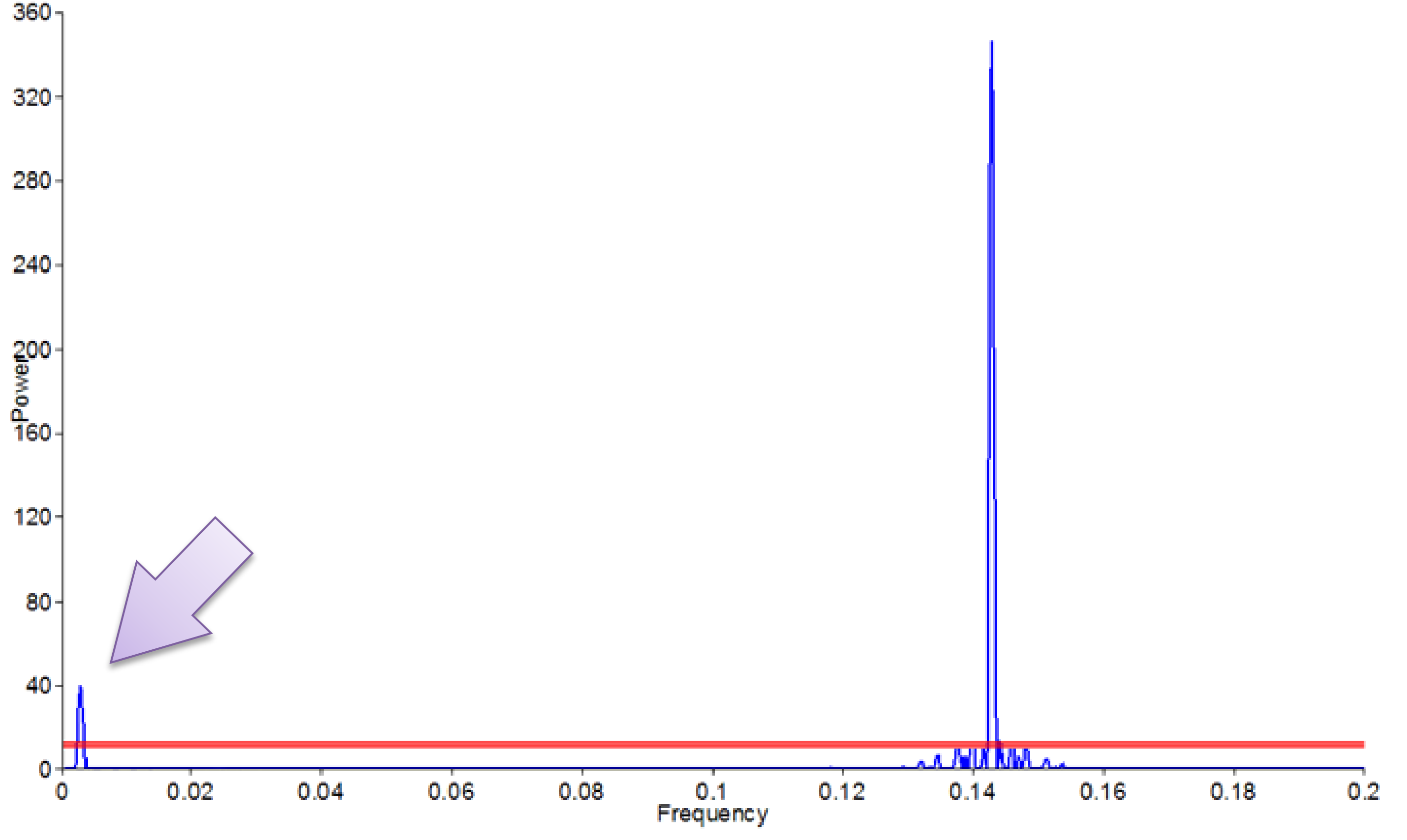
Example 1:

Let **n** be the hypothetical willing to study of a student **s**, measured daily for a year. It is observed that the (relative) maximum falls on Wednesdays, while the values drop to a minimum on weekends and during the summer (2 months).



Example 1 (1 year of observation)

A very strong peak appears in the periodogram (=> far exceeds the 95% confidence limit, red band) at frequency f = 0.143. Recall that f = 1 / p (period), so p = 7. Since the unit of measurement is the day, it is mathematically demonstrated that the willing to study **s**, measured over short periods (1 year), varies ONLY with weekly recursion; the summer break does not appear as it is NOT CYCLIC (1 event / year).



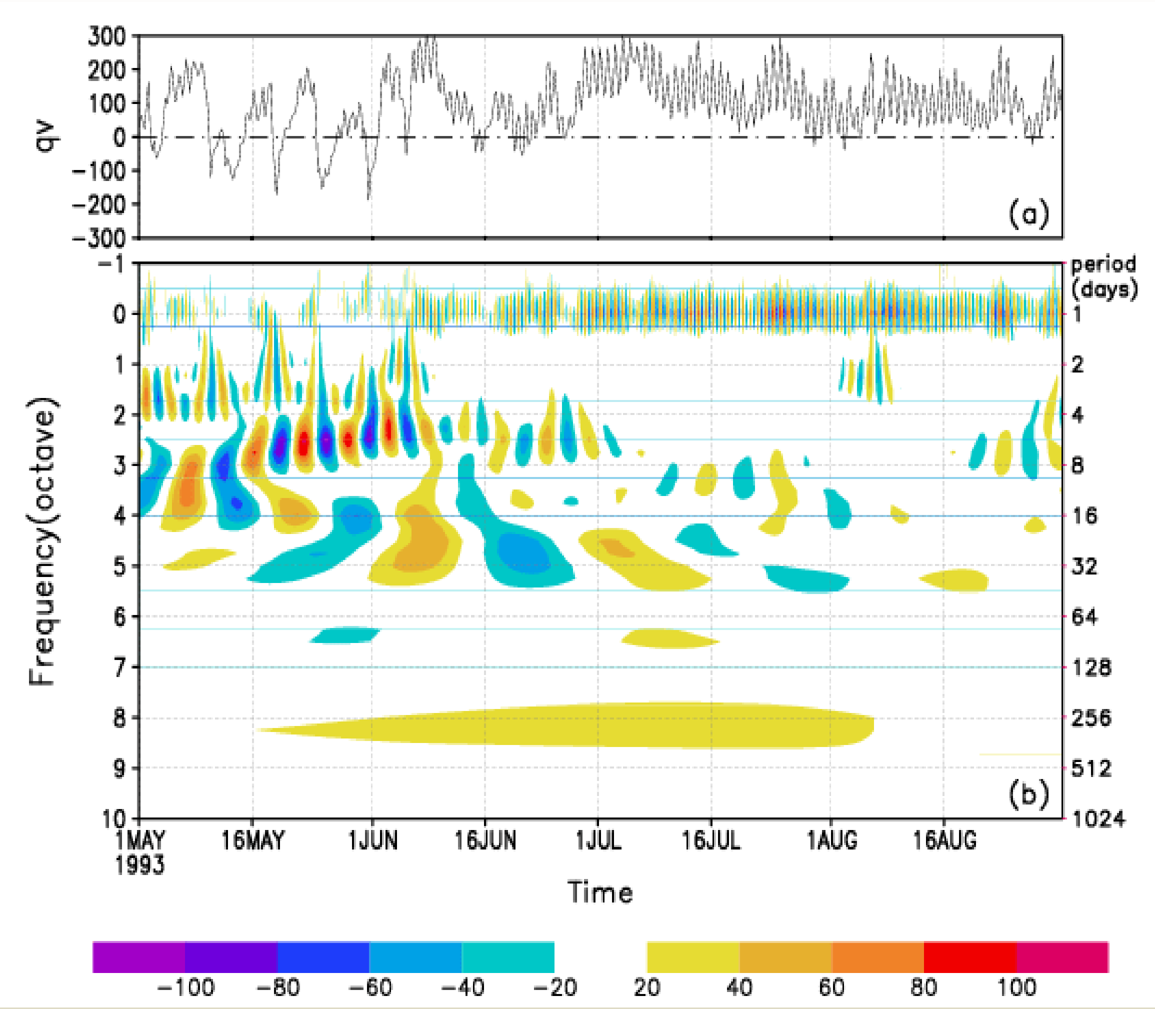
Example 2 (3 years of observation):

We measured **n** of **s** for 3 years. The summer period, when the student does not study (n = 0 for two months), thus becomes an event repeated 3 times.

A second peak appears in the periodogram (weak, but exceeds the 95% limit) at f = 0.00274. Since f = 1 / p, it turns out that p = 365. The unit of measurement is still the day, so it is shown that the willing to study **s**, measured over medium-long periods (3 years), varies with recurrence BOTH weekly and annually.

Unfortunately, in geology we do not know the meaning of the data in advance!

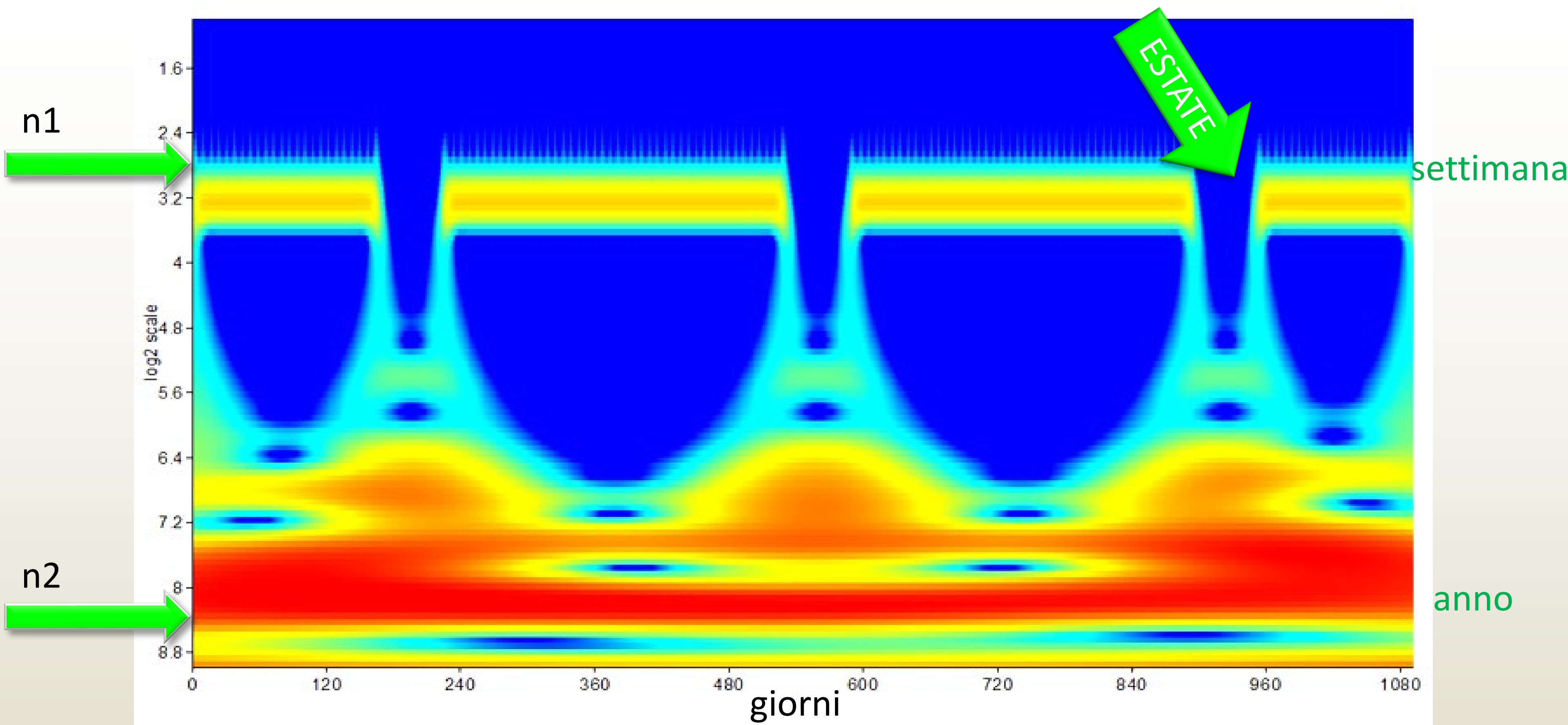
WAVELET



Wavelets are a “powerful” but also very complex instrument.

Compared to periodograms, it keeps the data in serial succession by continuously measuring the variations in intensity and frequency of the signal.

Advantages: method that allows you to evaluate the "distribution" of each periodicity in space and / or time.
Disadvantages: VERY complex interpretation; the help of super-specialists is needed on unknowns series of time.



Esempio 3:

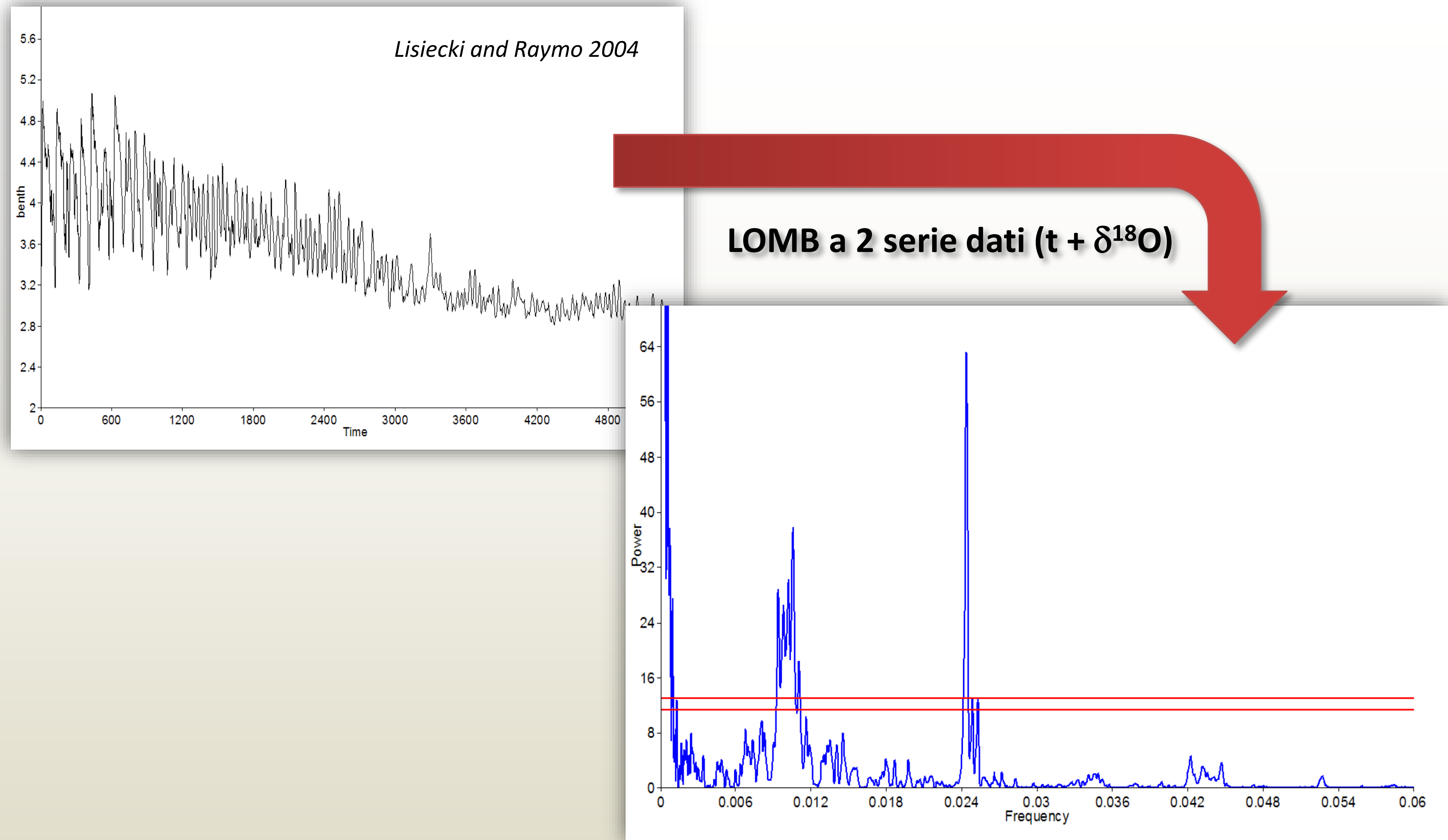
utilizziamo ancora la serie dello studente (3 anni, 1095 giorni; asse X, i). Per ricavare le periodicità, bisogna applicare la formula **$p=2^n$**, dove n=y. Quindi:

n1 = 2.8 → p = 7 → **settimana**

n2 = 8.5 → p = 365 → **anno**

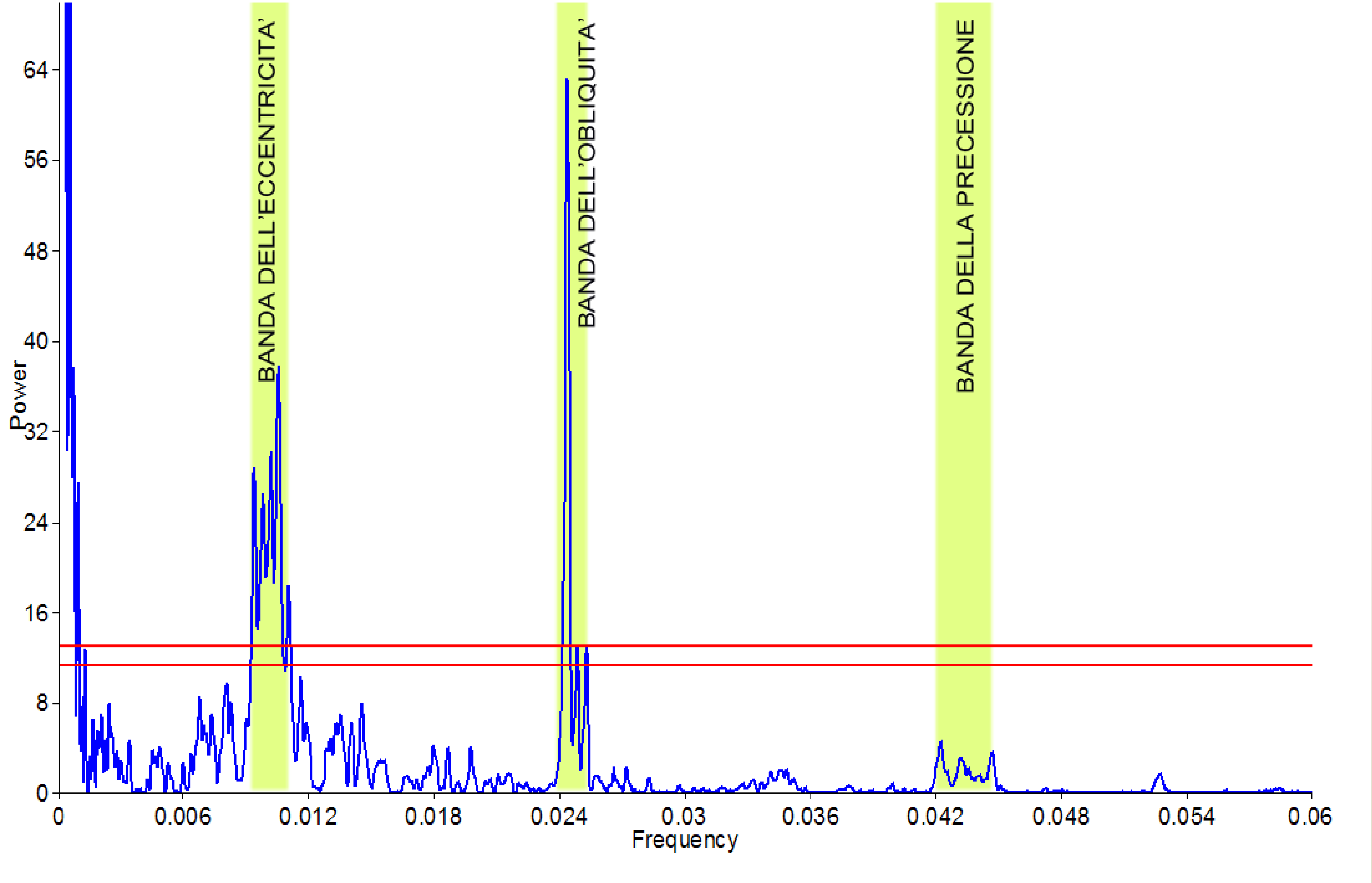
INSTRUMENTAL DATA:

STABLE OXYGEN ISOTOPES



LR04 $\delta^{18}O$ Benthic Stack: the last5.3 Myr

The spectral analysis shows some significant peaks; be aware that the first peak (at x = ~ 0) must be neglected => autocorrelation). To “translate” the values into periodicity, remember that p = 1 / f.



→ **p=1/f** (pay attention to units! In the data, t was expressed as kyr)

f (E) = ca. 0.01 → p = ca. 100 kyr → **"short" ECCENTRICITY (103 kyr)**

f (O) = ca. 0.025 → p = ca. 40 kyr → **OBLIQUITY (41 kyr)**

f (P) = ca. 0.044 → p = ca. 23 kyr → **PRECESSION (19, 21 e 23 kyr)**

VERIFYING CAUSE-AND-EFFECT RELATIONSHIPS

You can observe how straightforward it becomes, provided a set of points and specific chronological constraints, to pinpoint any cyclic patterns.

The process remains relatively simple when periodicity aligns with recognized bands, such as orbital cycles. Conversely, challenges arise when encountering harmonic or interference frequencies, exemplified by the enigmatic cycles of 11 or 35 kyr.

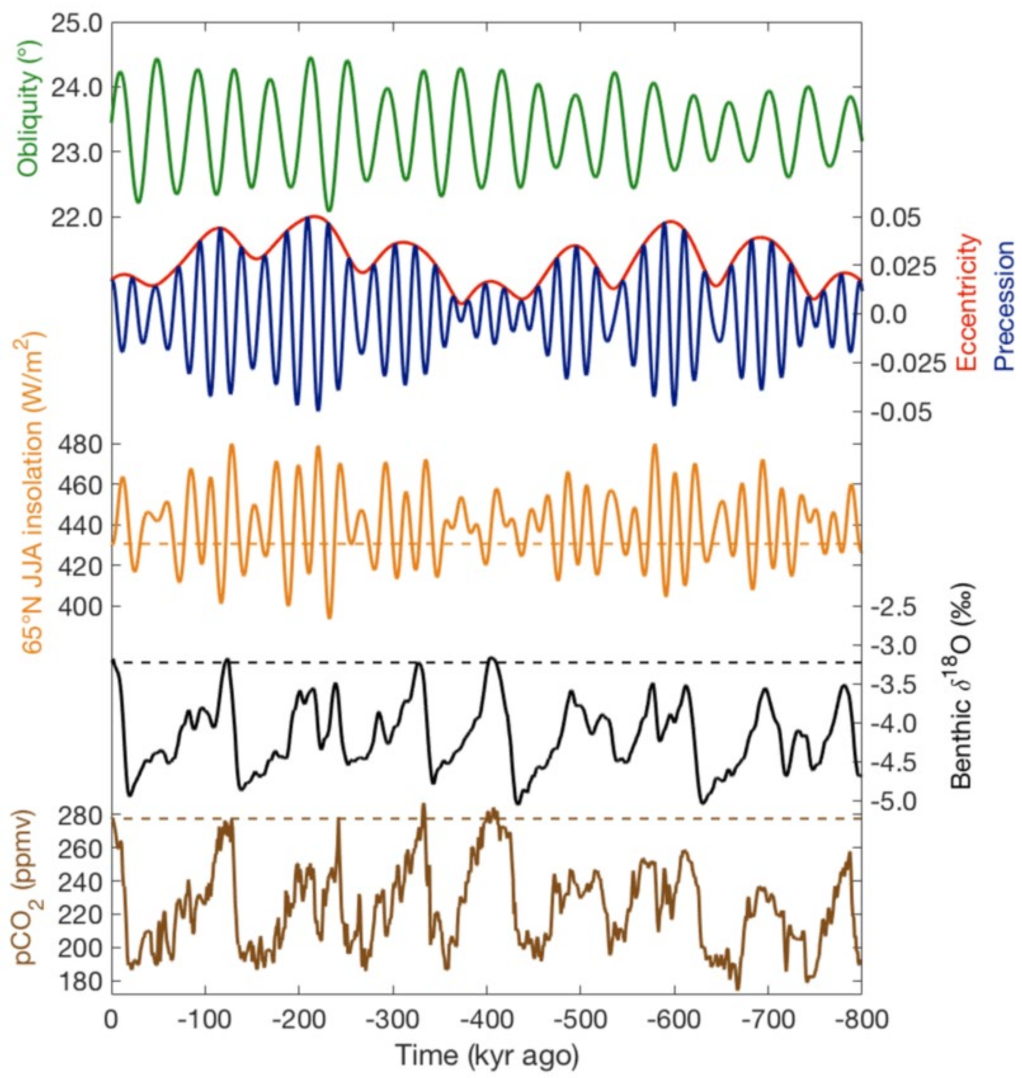
Spectral analysis proves highly valuable for assessing coherence between experimental data (e.g., isotopes) and forcing (e.g., insolation) or for verifying cause-and-effect relationships.

HOW TO CHECK THE CAUSE-EFFECT RELATIONSHIP??

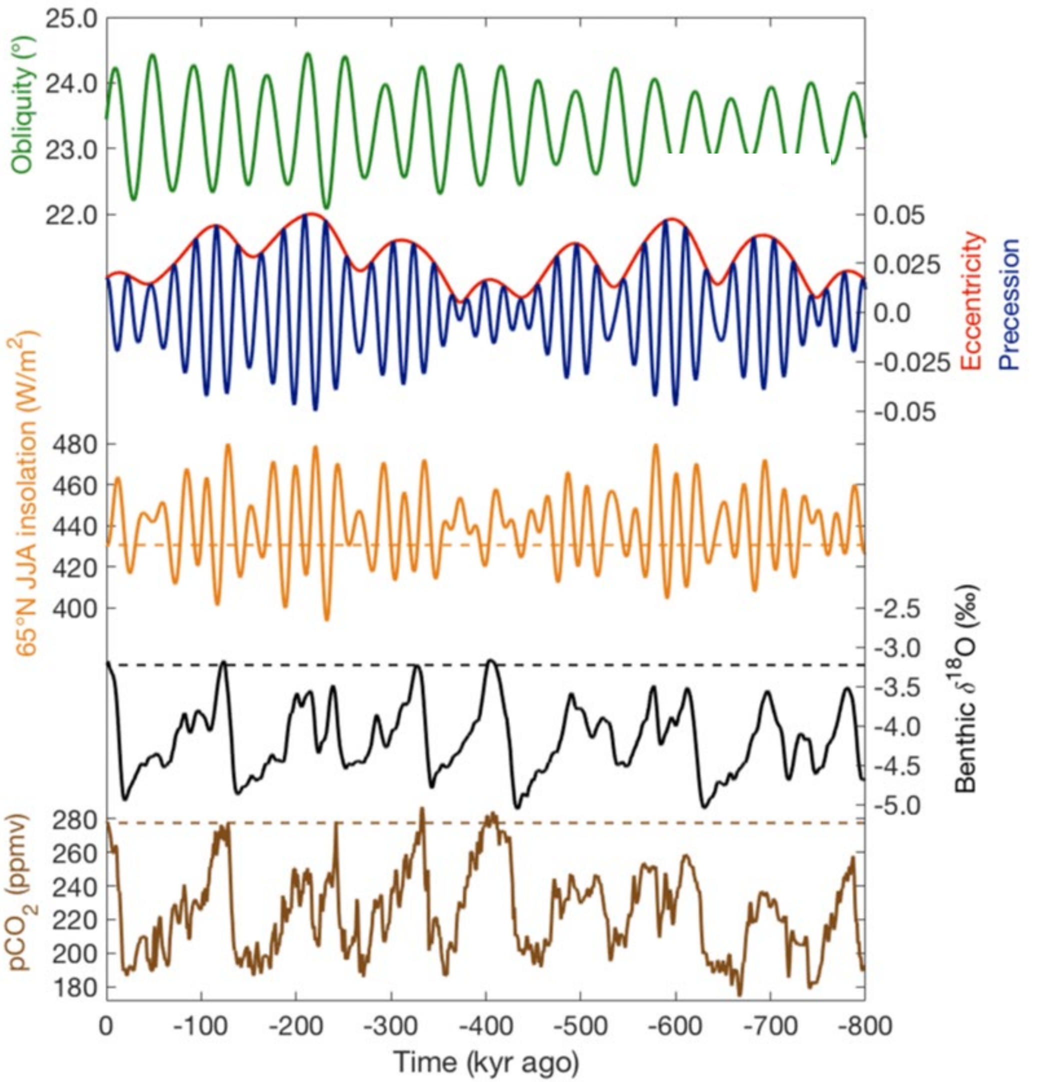
A cause-effect relationship can be hypothesized ONLY if

The same significant frequencies are recognized both in the solution of the forcing and in the instrumental data

So, let's check what happens if we first analyze the curve of the $\delta^{18}O$ isotopes and then the variability of the insolation in the last million years

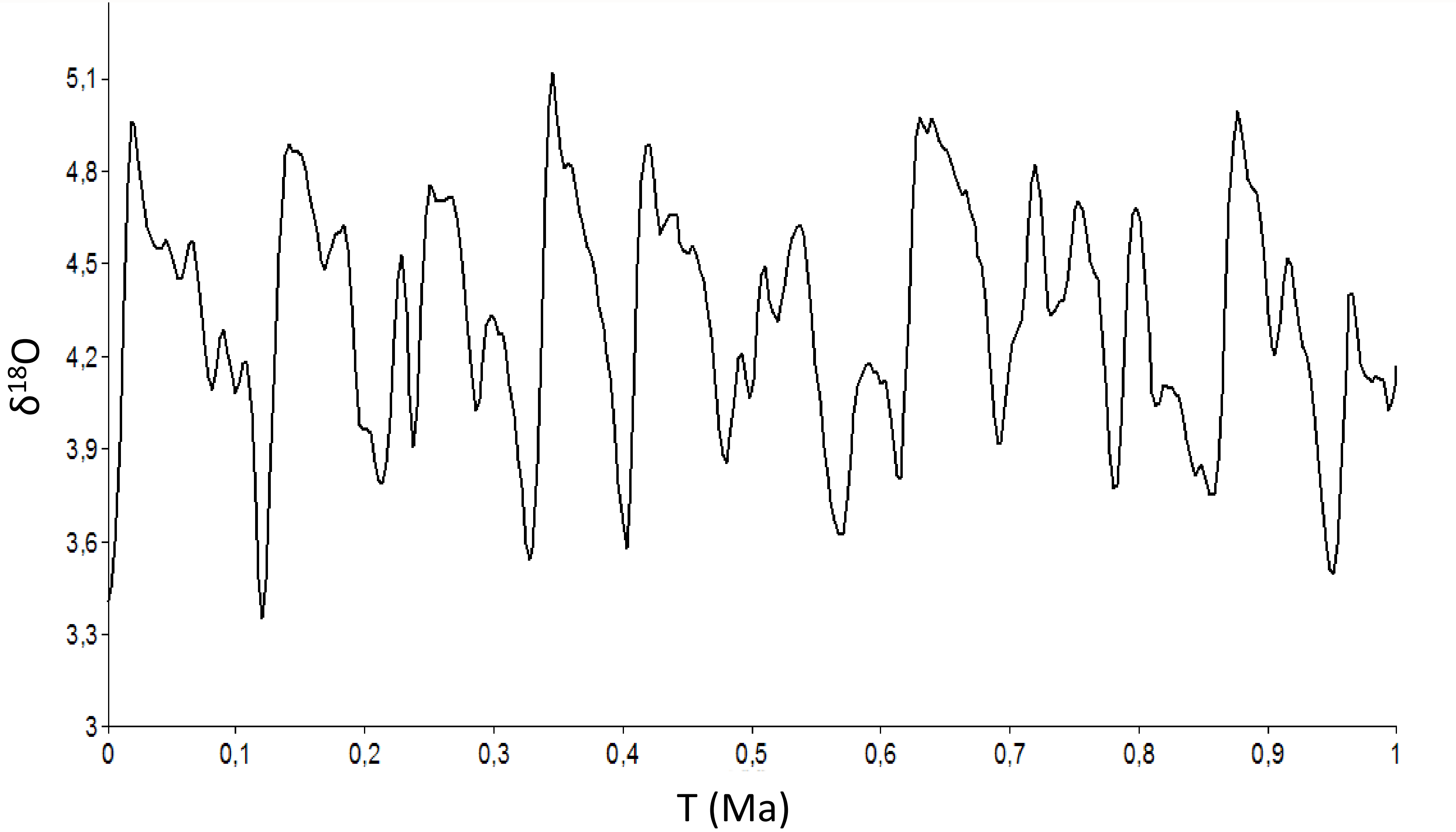


THE INSTRUMENTAL DATA: $\delta^{18}O$



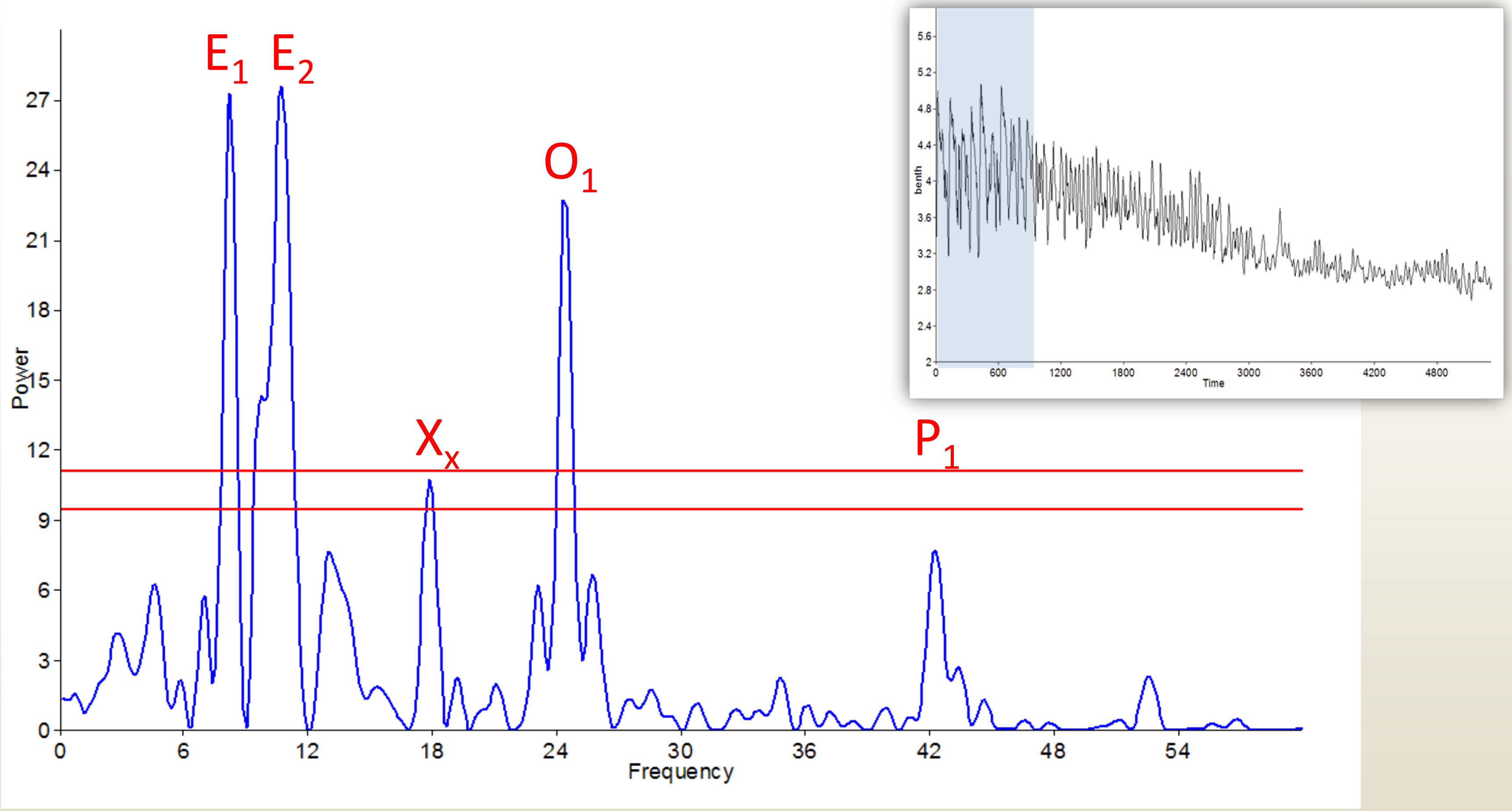
benthic $\delta^{18}O$ record

(3 POINT *running average*)



Notice that depths have been already transformed in time.

p=1/f (last milion years, complete)



$E_1 = 1/8_{\text{norm (My)}}$ = **125 kyr → ECCENTRICITY**

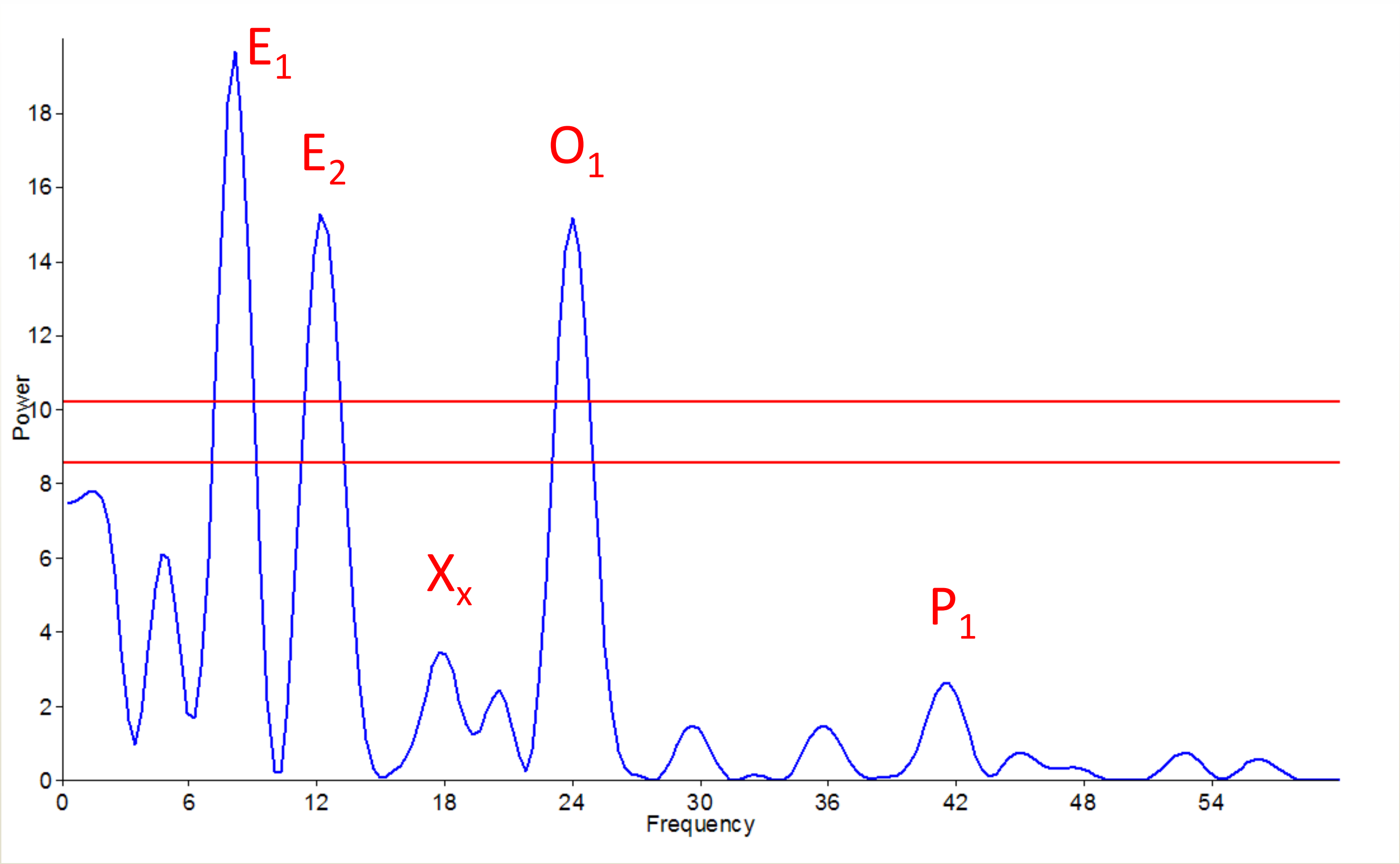
$E_2 = 1/11_{\text{norm (My)}}$ = **90 kyr → ECCENTRICITY**

$X_x = 1/18_{\text{norm (My)}}$ = **55 kyr** *< 95% confidence (harmonic)*

$O_1 = 1/25_{\text{norm (My)}}$ = **40 kyr → OBLIQUITY**

$P_1 = 1/43_{\text{norm (My)}}$ = **23 kyr → PRECESSION** *<< 95% confidence*

p=1/f : da 1.0 a 0.6 Ma



$E_1 = 1/8_{norm\ (My)}$ = **125 kyr → ECCENTRICITY**

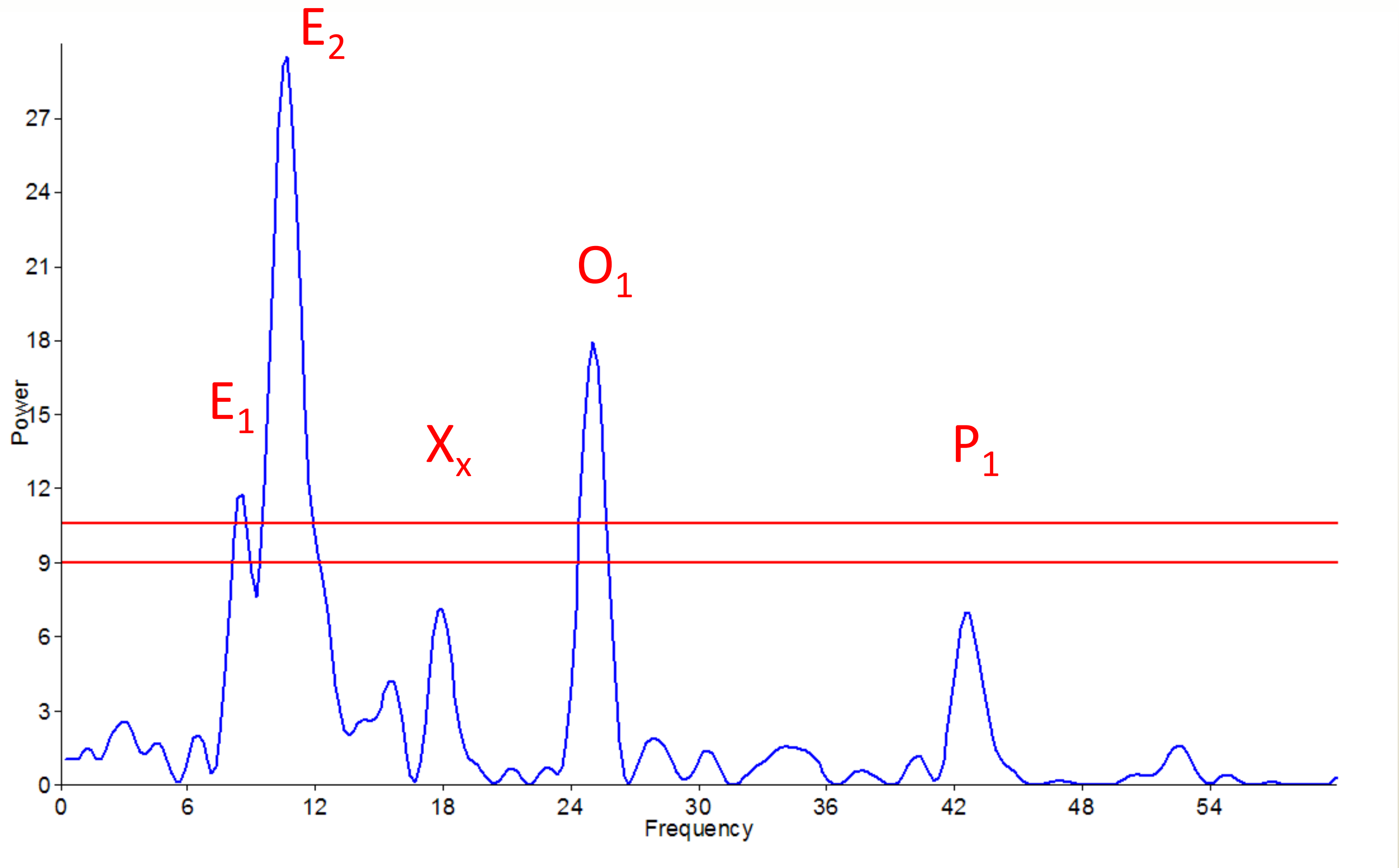
$E_2 = 1/12_{norm\ (My)}$ = **90 kyr → ECCENTRICITY**

$X_x = 1/18_{norm\ (My)}$ = **55 kyr** *< 95% confidence (harmonic)*

$O_1 = 1/24_{norm\ (My)}$ = **41 kyr → OBLIQUITY**

$P_1 = 1/41_{norm\ (My)}$ = **24 kyr → PRECESSION** *<< 95% confidence*

p=1/f : last 600 kyr



E_1 = virtually absent

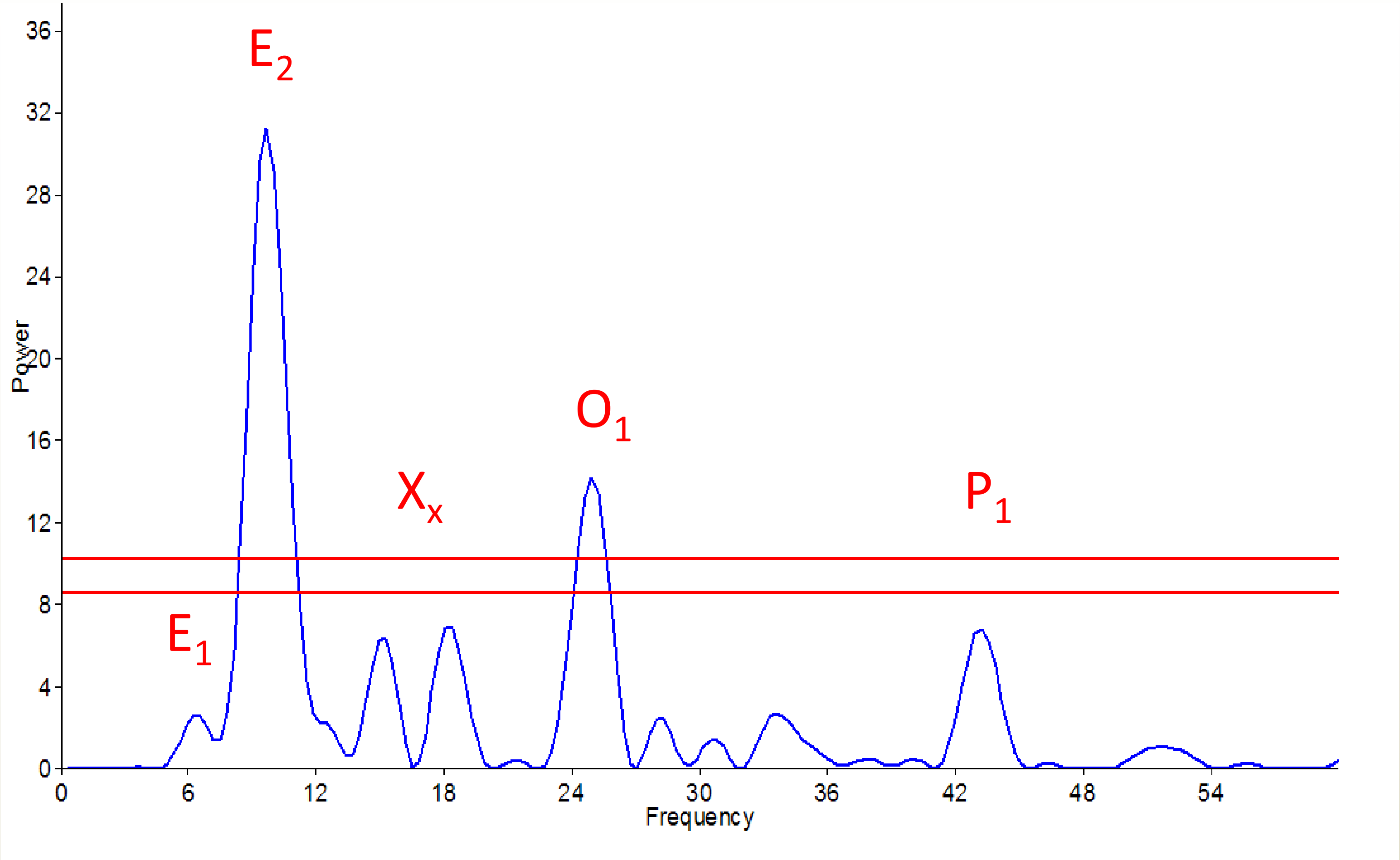
$E_2 = 1/11_{norm\ (My)}$ = **90 kyr**

$X_X = 1/18_{norm\ (My)}$ = **55 kyr** *<< 95% confidence (harmonic)*

$O_1 = 1/25_{norm\ (My)}$ = **40 kyr**

$P_1 = 1/43_{norm\ (My)}$ = **23 kyr** *<< 95% confidence*

p=1/f : ultimi 400 kyr



E_1 = absent

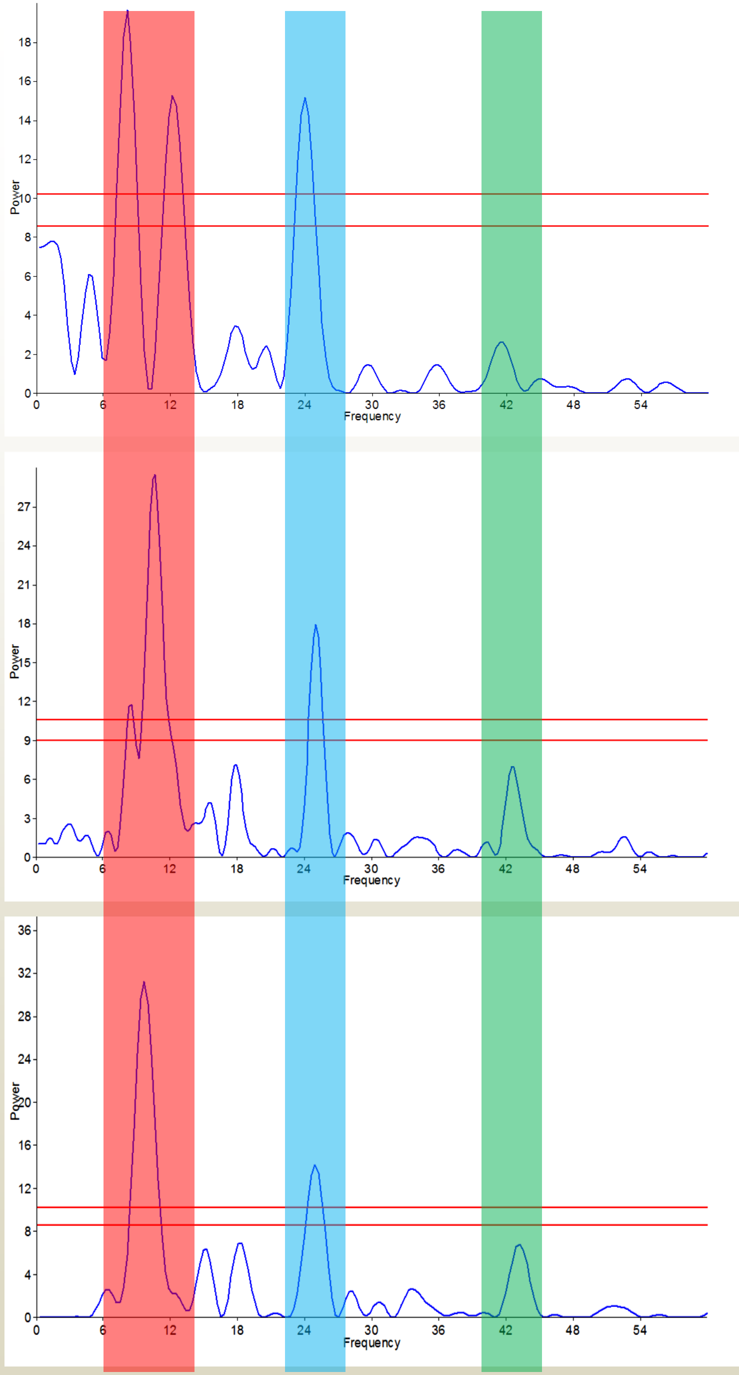
$E_2 = 1/10_{norm\ (My)}$ = **100 kyr**

X_X = doble << *95% confidence (harmonic)*

$O_1 = 1/25_{norm\ (My)}$ = **40 kyr**

$P_1 = 1/44_{norm\ (My)}$ = **23 kyr** << *95% confidence*

SUMMARY $\delta^{18}O$



During the last 1 Myr, the main cyclicities in the $\delta^{18}O$ curve relate to periods of approx. 100 and 40 kyr.
In the precession band (approx. 20 kyr), the peak is very weak, although it grows over time.

<u>Conclusion suggested by the data:</u> the changes in the ice caps volume and, therefore, of the climate are controlled by forcing with frequencies in the band of "small" eccentricity and obliquity. The effect of the precession is negligible.

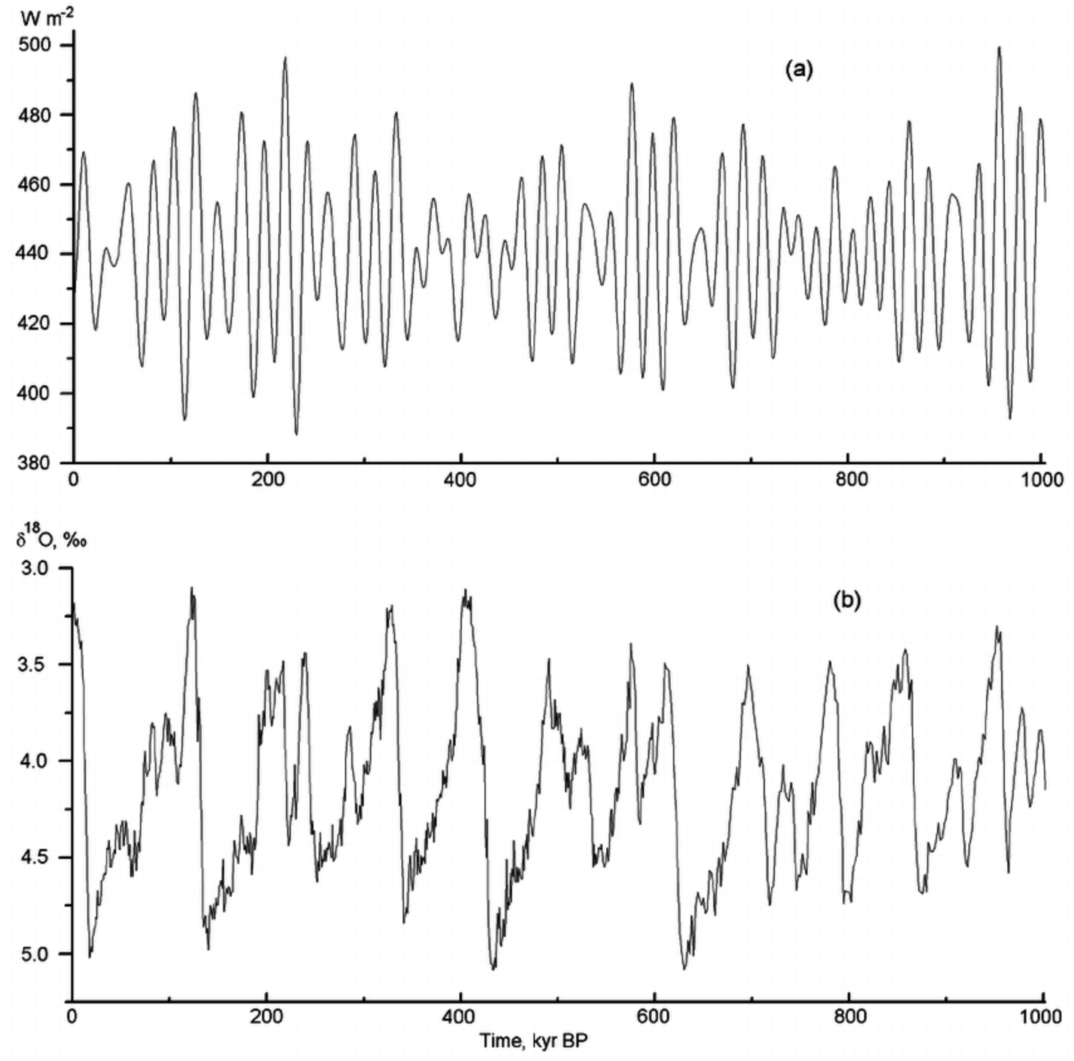
<u>Figure</u>:

α) $\delta^{18}O$ spectrum between 1 and 0.6 Ma

β) $\delta^{18}O$ spectrum between 0.6 and 0.4 Ma

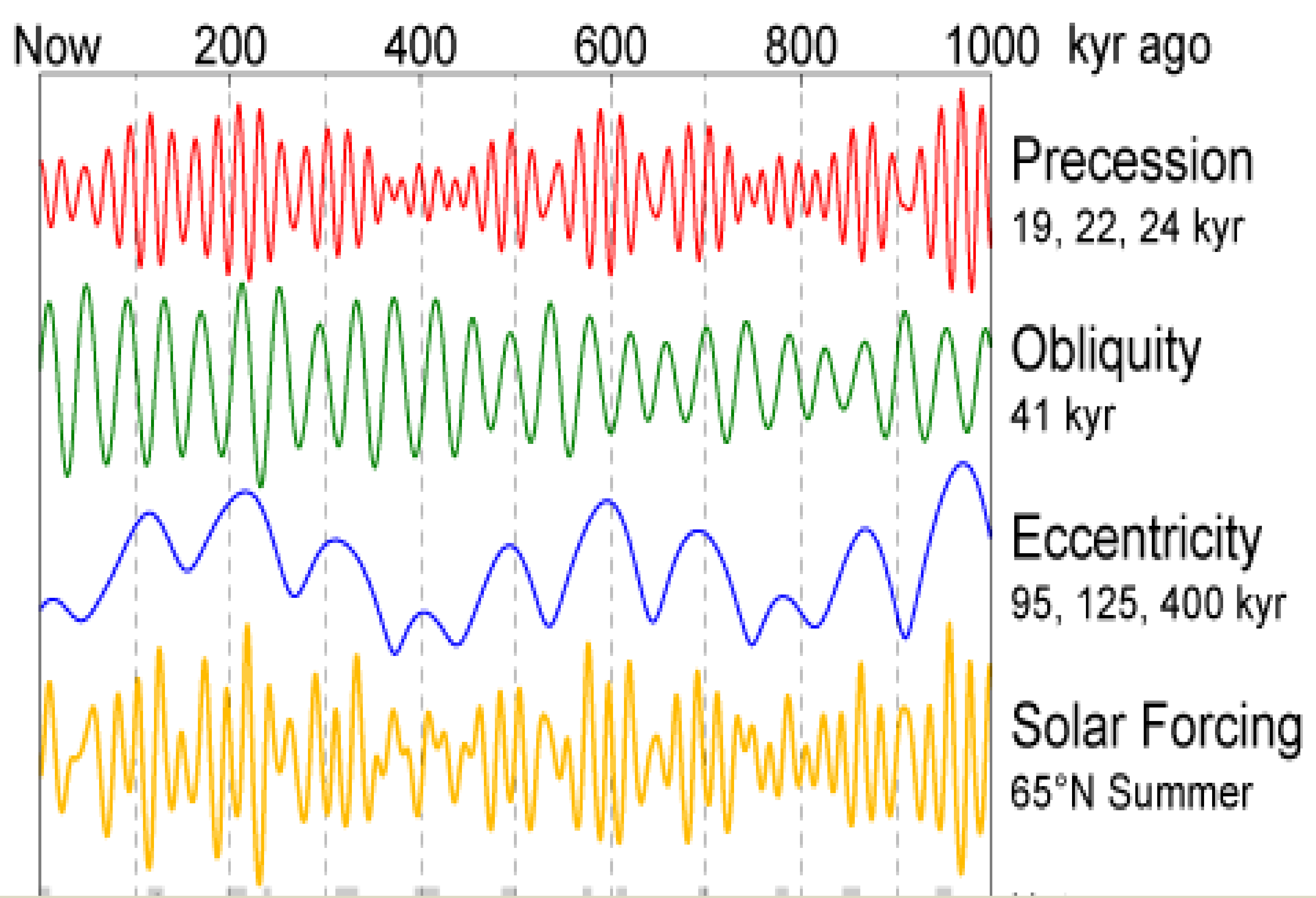
χ) $\delta^{18}O$ spectrum between 0.4 and 0 Ma

FORCING: *INSOLATION*

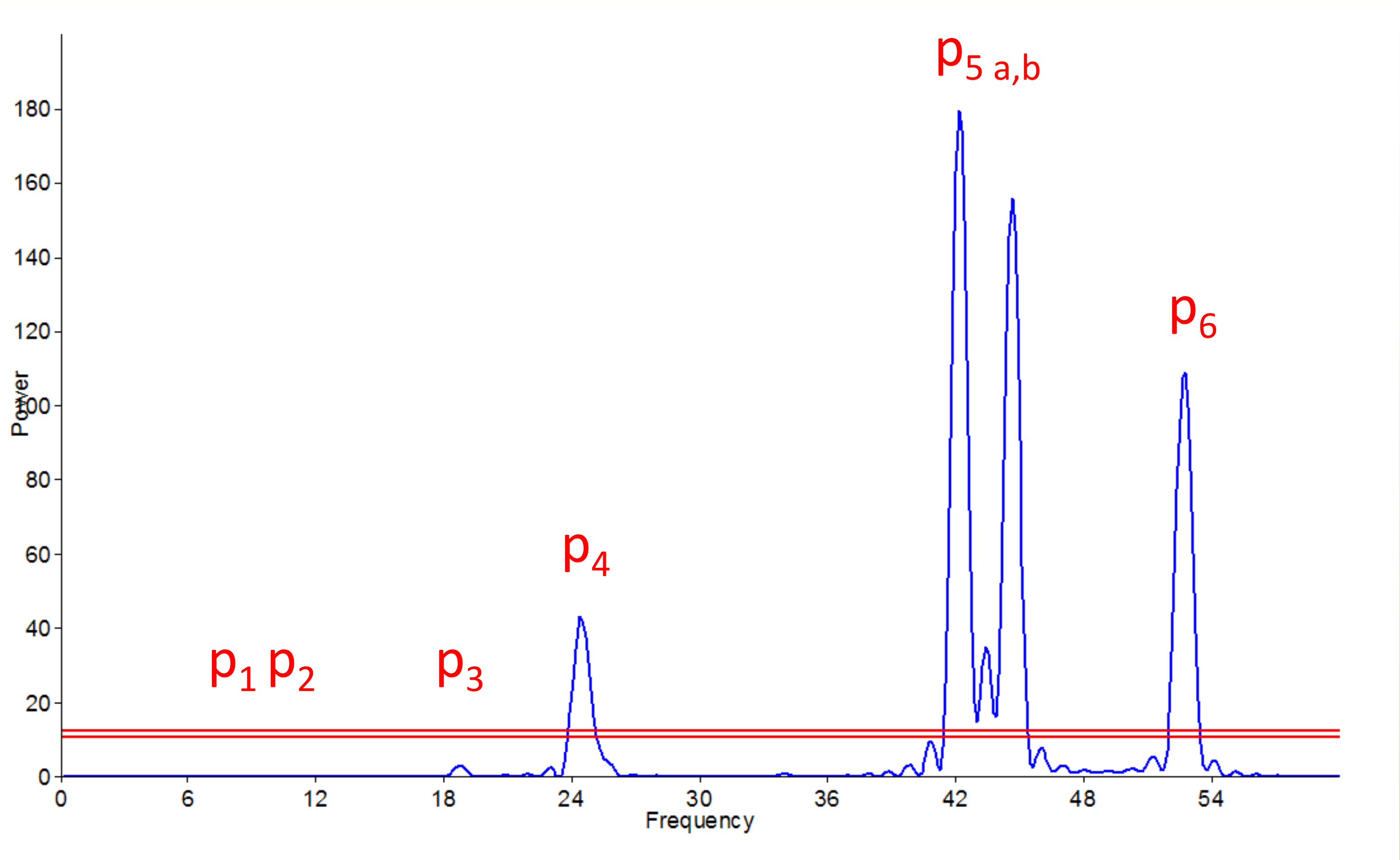


The change of July insolation at 65 ◦ N for the last million years (after [Berger and Loutre, 1991]), b – compound oxygen-isotope record LR04 for the time interval 0 to 1 million years (after [Lisiecki and Raymo, 2005].

Solution of the orbitalparameters and total insolation at 65 ° N



p=1/f: INSOLATION, last 1 Myr complete



1 Myr

p_1 , p_2 = **100kyr** absent!!!

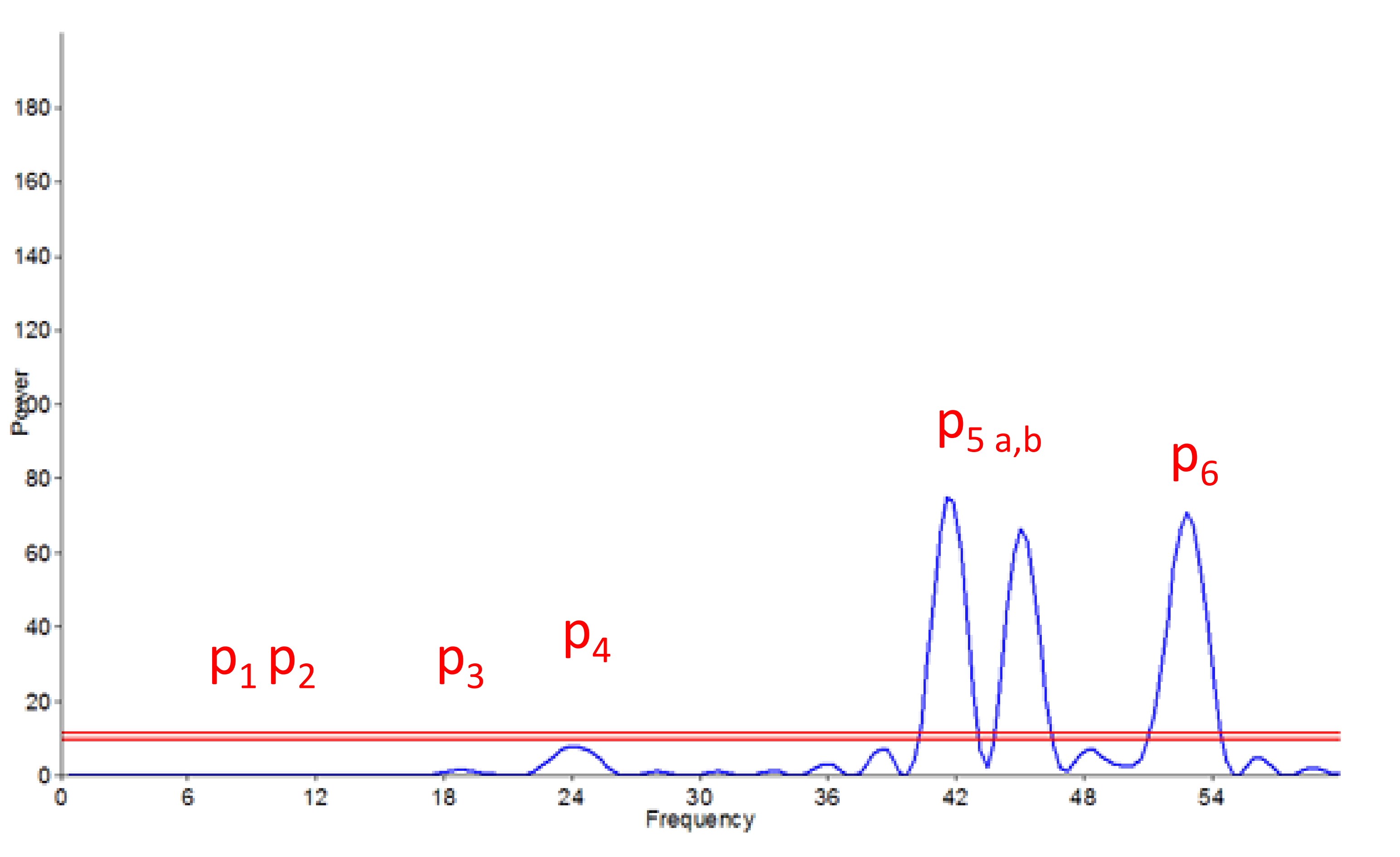
p_3 = absent

$p_4 = 1/25_{norm\ (My)}$ = **40 kyr → OBLIQUITY**

$P_{5\ a,b} = (1/43 + 1/46)_{norm\ (My)}$ = **23 + 21 kyr → "LONG" PRECESSION**

$p_6 = 1/52_{norm\ (My)}$ = **19 kyr → "SHORT"PRECESSION**

p=1/f : da 1.0 a 0.6 Ma



p_1 , p_2 = **100kyr** absent!!

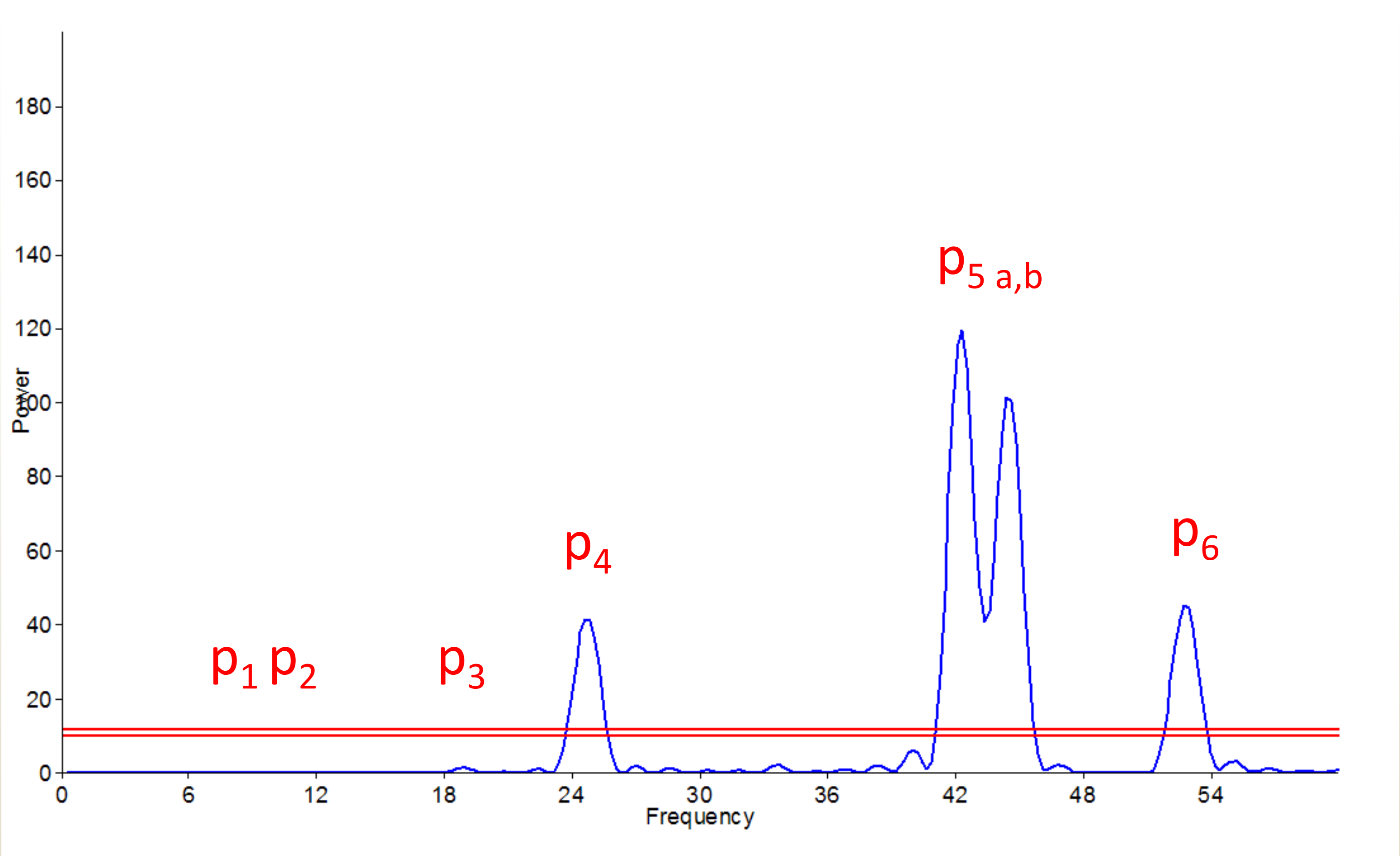
p_3 = absent

$p_4 = 1/24_{norm\ (My)}$ = **41 kyr**

$P_{5\ a,b} = (1/41 + 1/46)_{norm\ (My)}$ = **24 + 21 kyr**

$p_6 = 1/53_{norm\ (My)}$ = **19 kyr**

p=1/f : last 600 kyr



600 kyr

p_1 , p_2 = **100kyr** absent!!!

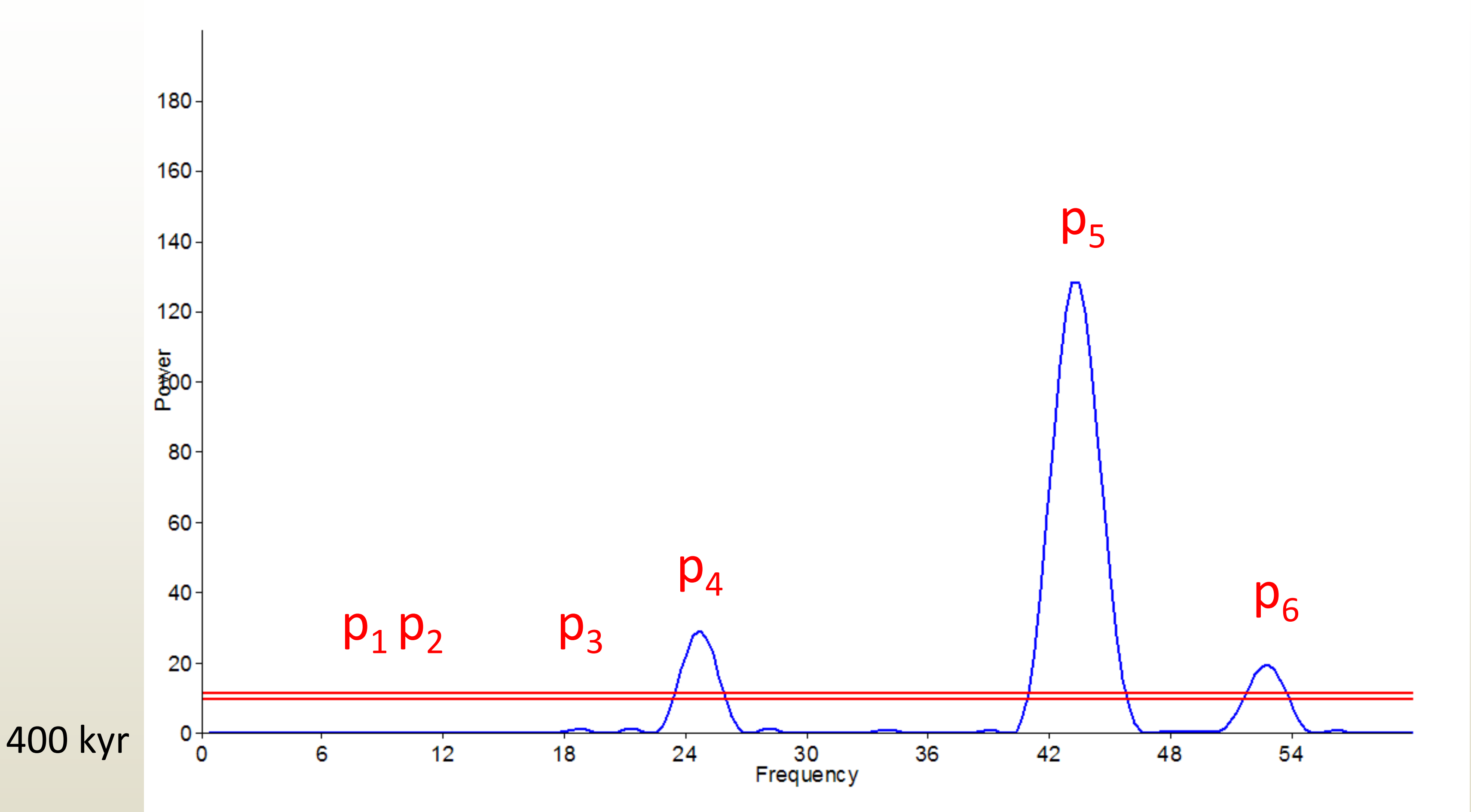
p_3 = absent

$p_4 = 1/25_{norm\ (My)}$ = **40 kyr**

$P_{5\ a,b} = (1/43 + 1/46)_{norm\ (My)}$ = **23 + 21 kyr**

$p_6 = 1/52_{norm\ (My)}$ = **19 kyr**

p=1/f : ultimi 400 kyr



p_1 , p_2 = **100kyr** assente!!!

p_3 = assente

$p_4 = 1/25_{norm\ (My)}$ = **40 kyr**

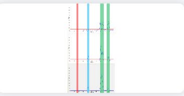
$P_5 = 1/43_{\ norm\ (My)}$ = **23 kyr**

$p_6 = 1/52_{norm\ (My)}$ = **19 kyr**

Which orbital parameters control insolation over the last million years?

Exit

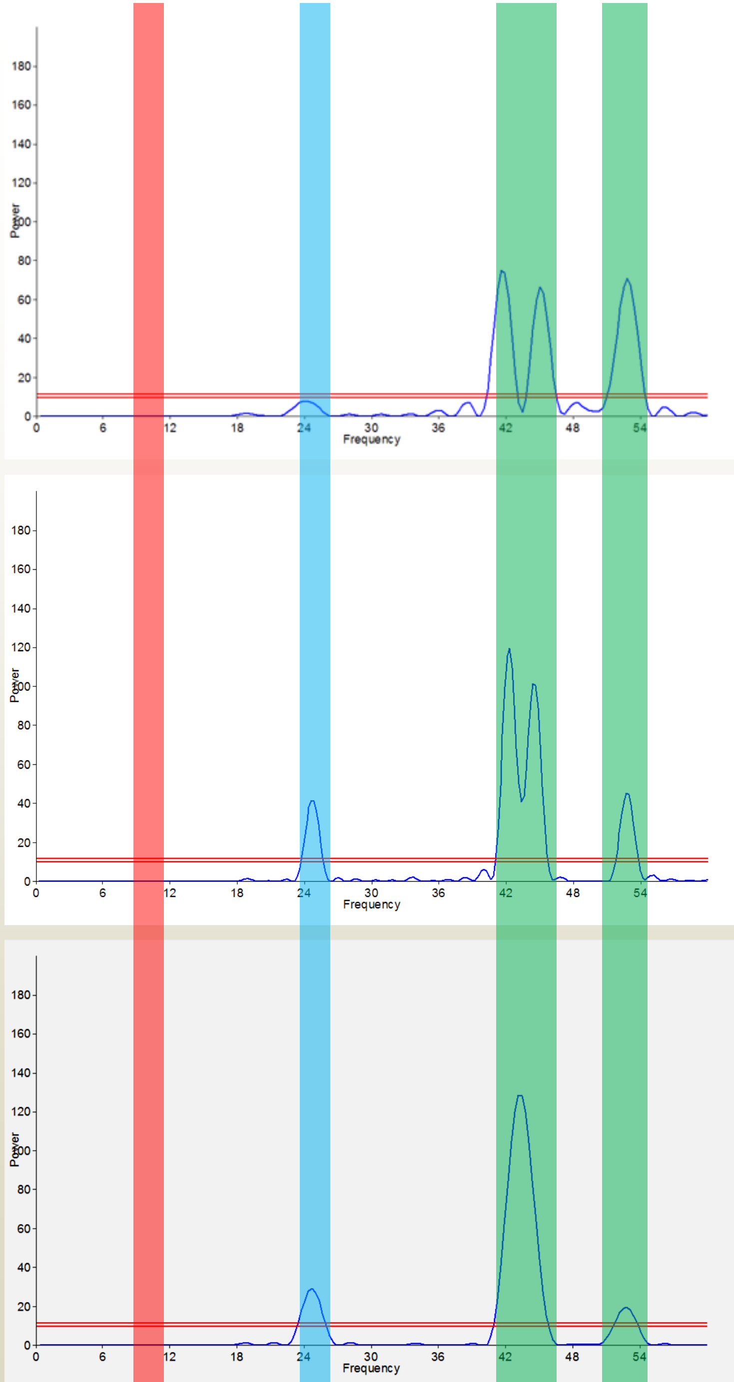
Go to **wooclap.com** and use the code **PCCC2023**



Which orbital parameters control insolation over the last million years?

1. Precession — 0% — 0
2. Obliquity — 0% — 0
3. Eccentricity — 0% — 0

https://app.wooclap.com/events/PCCC2023/0



SUMMARY: INSOLATION

During the last 1 Myr, the main cyclicities in the insolation curve relate to periods of approx. 40 and 20 kyr.
In the band of the “short" eccentricity (approx. 100 kyr) no peak is NEVER recognized.

Conclusion suggested by the data: obliquity and precession are the only orbital forcings capable of influencing the Earth's climate: eccentricity has no effect.

Figure:

α) $\delta^{18}O$ spectrum between 1 and 0.6 Ma

β) $\delta^{18}O$ spectrum between 0.6 and 0.4 Ma

χ) $\delta^{18}O$ spectrum between 0.4 and 0 Ma

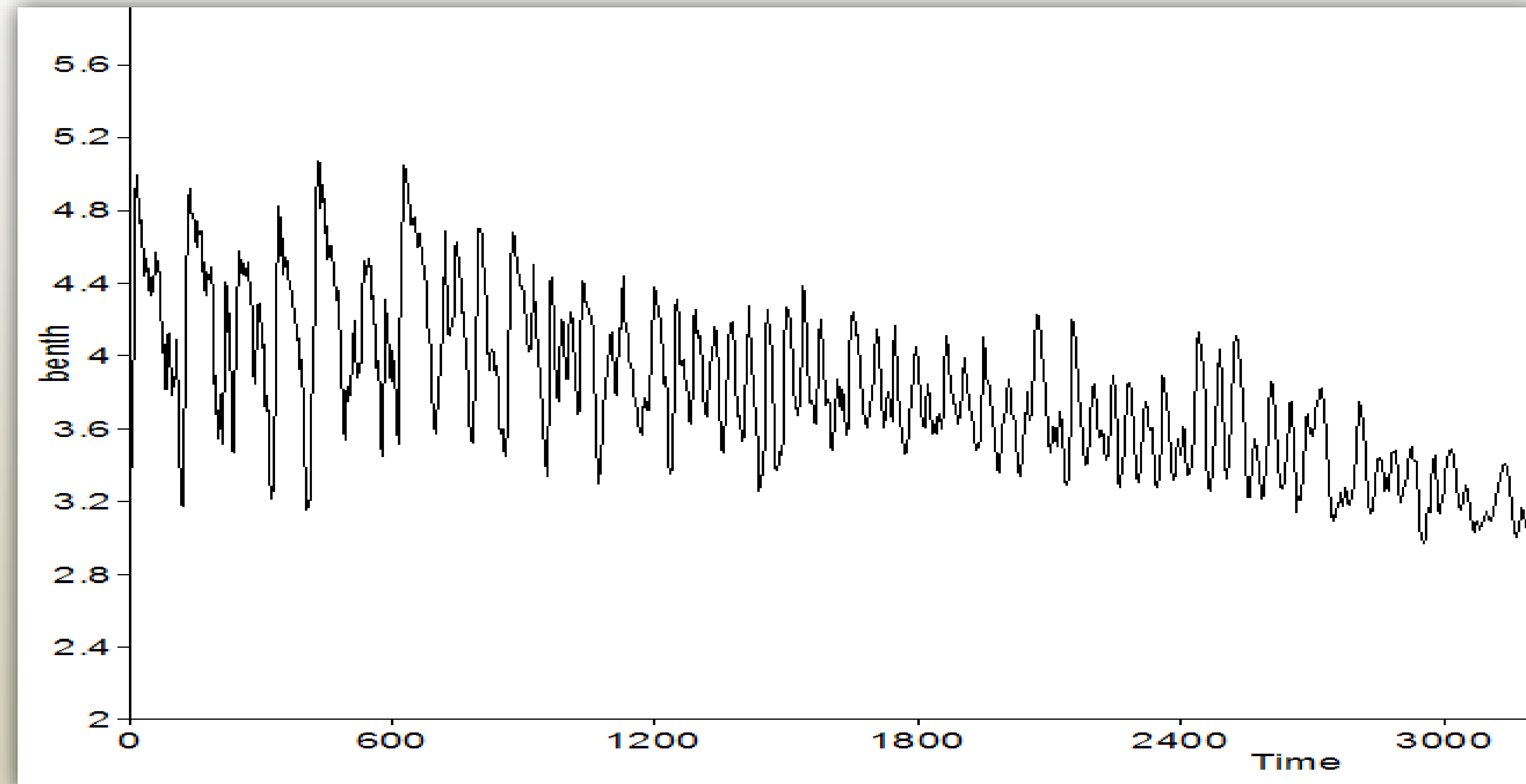
100 kyr cycle: ECCENTRICITY?

We have demonstrated that the 100 kyr climate cycles **DO NOT originate** from variations in the eccentricity of the Earth's orbit.

OTHER POINTS AGAINST THE ECCENTRICITY MODEL:

- The so-called "100 kyr cycles" actually have variable durations between 80 and 120 kyr, compatible only in a first approximation with the eccentricity band;
- Variations in eccentricity cause variations in insolation (approx. 2%) that are lower than the combined effect of obliquity and precession. The intensity of the peaks of the different orbital parameters in the periodogram confirms this hypothesis.

GLACIAL CYCLES:
FROM SIMMETRICAL TO ASIMMETRICAL



HOW TO EXPLAIN THE "ASYMMETRIC" 100 kyr CYCLES?

STARTING POINT: we cannot deny the "climatic" character of the 100 kyr cycles; but, if the climate is controlled by the Sun (insolation), even the cycles of 100 kyr are (or should be).

THEORY: 100 kyr cycles could originate from a high frequency variability (see harmonic frequencies) repeated over time (=> resonance).

HYPOTHESIS: Earth's climate is a system controlled by precession (cycles of 20 kyr) through residual feedback.

N.B.: some scientists proposed different models, invoking obliquity (it is the only force well expressed both in isotope curves and in insolation), but problems arise with this hypothesis.

CYCLES: *n* x 20 kyr?

Therefore, according to the hypothesis of residual feedback (Ridgwell and Maslin, 2005), precession would be the dominant forcing during the "glacial" Pleistocene.

RIDGWELL & MASLIN THEORY

The mechanism consists in the fact that the ice accumulated during the minimum of insolation cannot completely melt during the subsequent phase of precessional maximum.

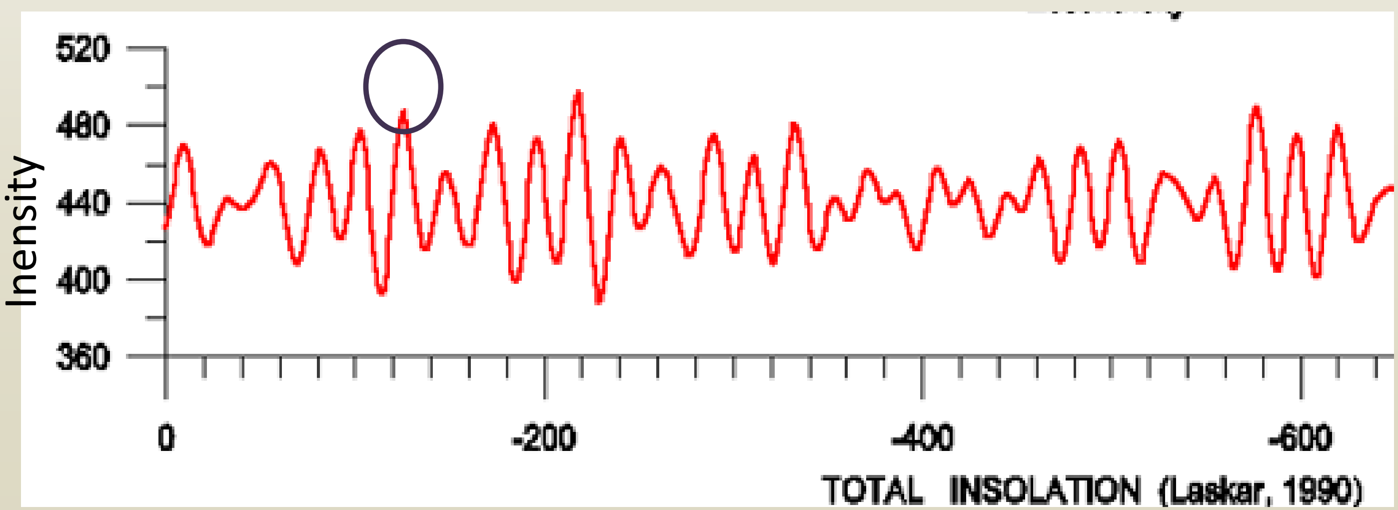
At the 4^{th}-5^{th}-6^{th} precession cycle (= 80-100-120 kyr), the fronts of the ice-caps would be in instable => rapid collapse.

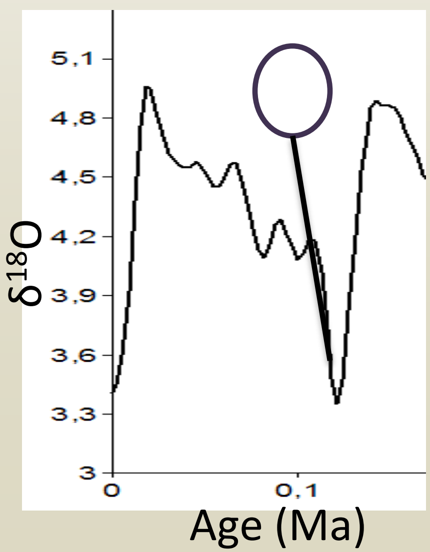
This model also explains the characteristic “sawtooth” shape of the $\delta^{18}O$ curves, characterized by a rapid transition (few kyr) to the interglacial maximum and a clear internal articulation in higher frequency cycles (approx. 20 kyr) during the glacials.

RESIDUAL FEEDBACK MODEL - 1

Initial ice cap volume (t=0)

Ice cap expansion during the insolation MAXIMUM (t=0)

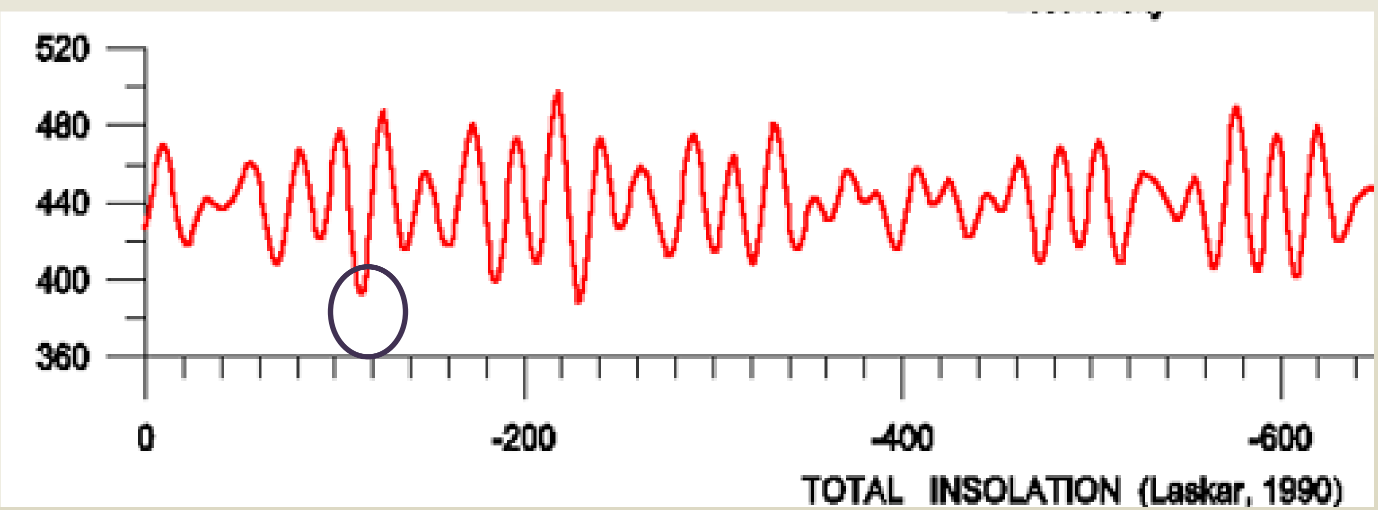


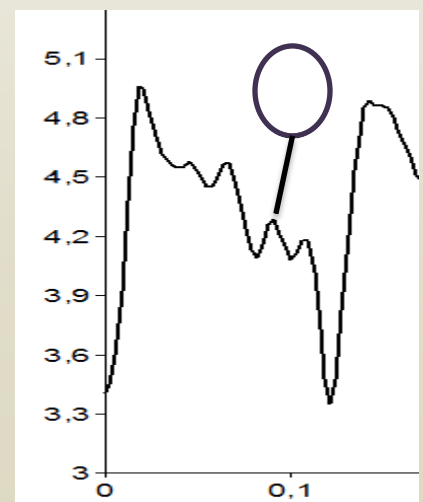


RESIDUAL FEEDBACK MODEL - 2

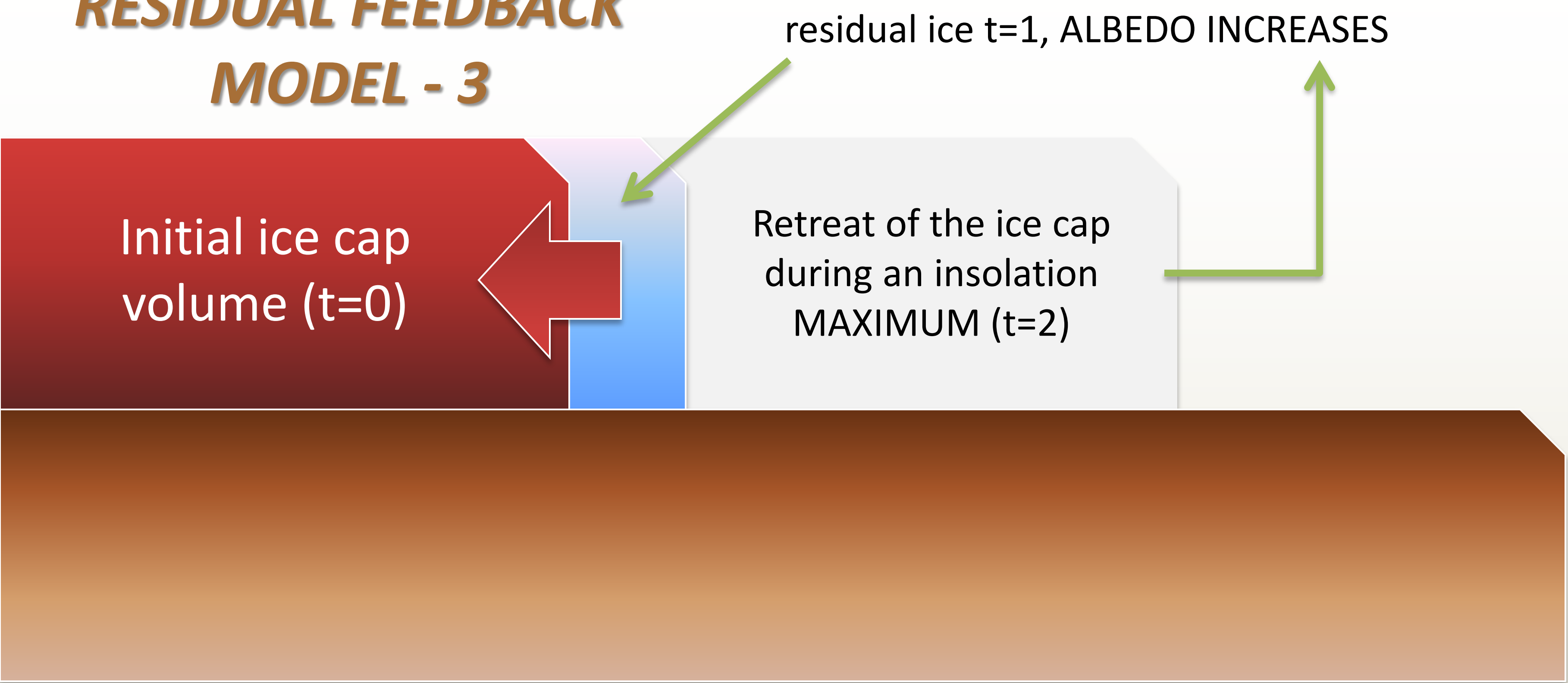
Initial ice cap volume (t=0)

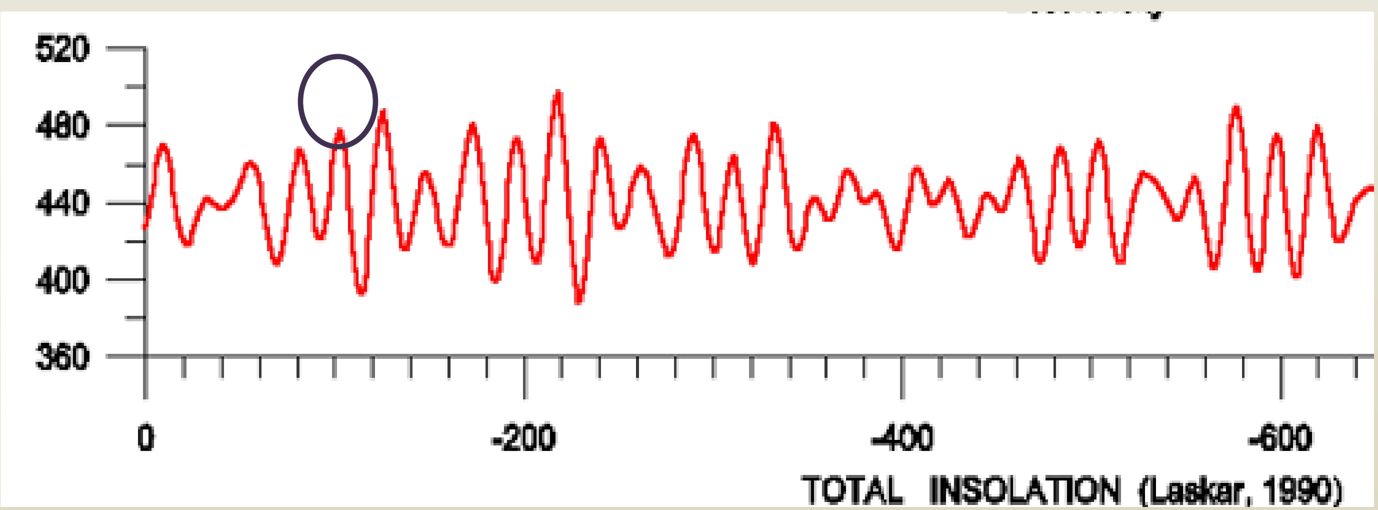
Ice cap expansion during the insolation MINIMUM (t=1)

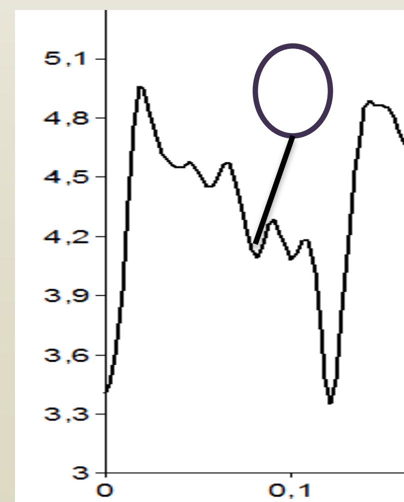




RESIDUAL FEEDBACK MODEL - 3





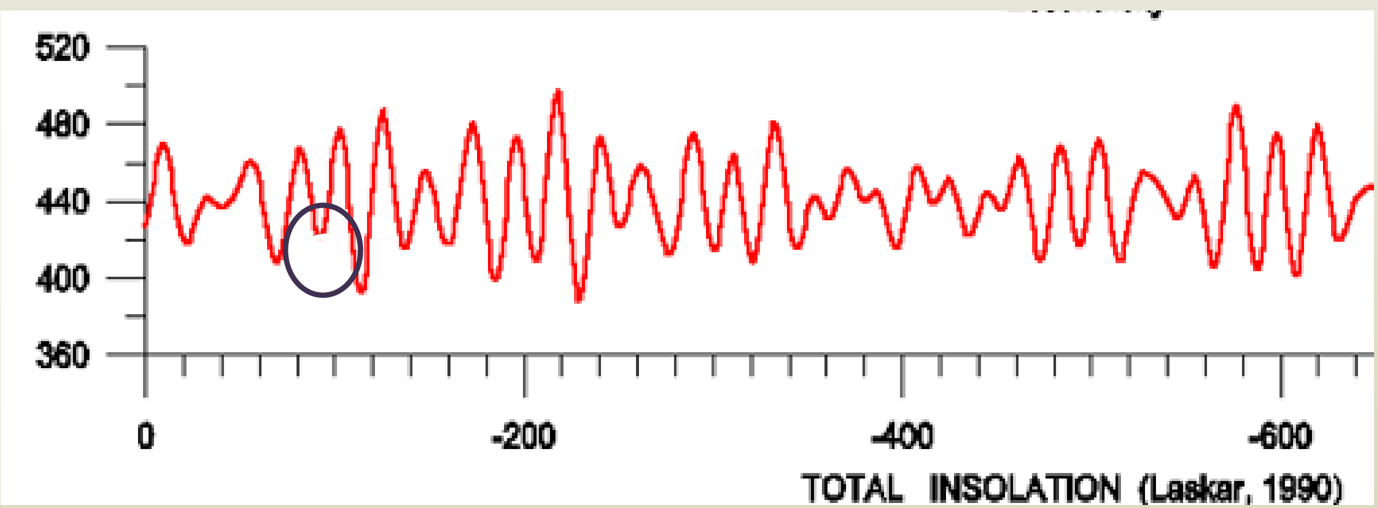


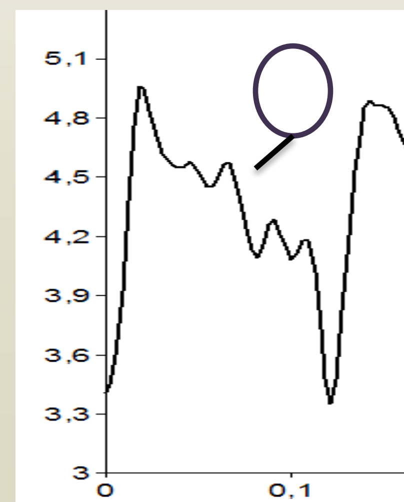
RESIDUAL FEEDBACK MODEL - 4

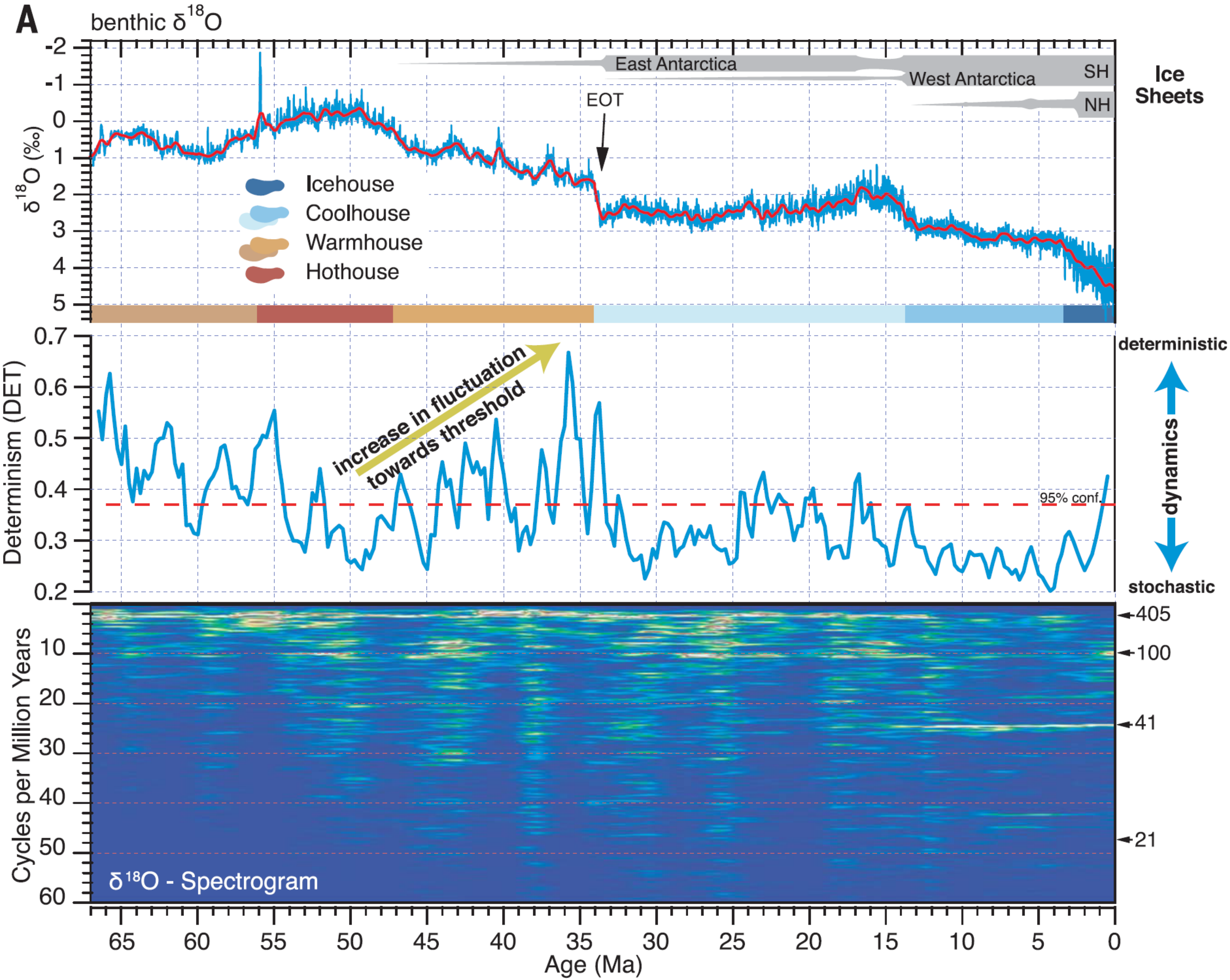
Ghiaccio residuo di t=1, ALBEDO INCREASES

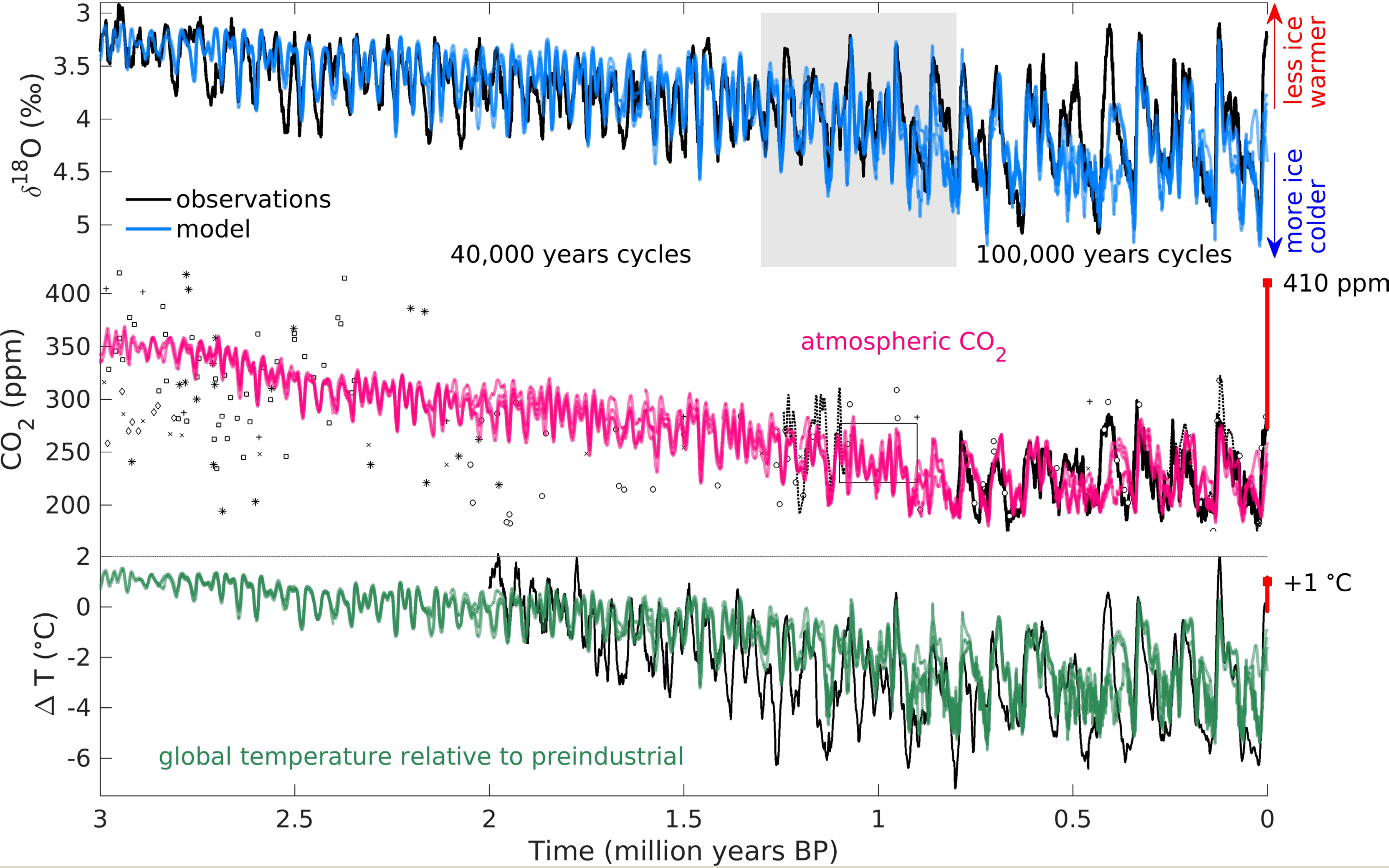
Initial ice cap volume (t=0)

Ice cap expansion during the insolation MINIMUM (t=3); **> ALBEDO**






A
benthic δ18O
East Antarctica
West Antarctica
SH
NH
Ice Sheets
EOT
δ18O (‰)
Icehouse
Coolhouse
Warmhouse
Hothouse
Determinism (DET)
increase in fluctuation towards threshold
95% conf.
deterministic
dynamics
stochastic
Cycles per Million Years
δ18O - Spectrogram
405
100
41
21
Age (Ma)



$\delta^{18}O$ (‰)
observations
model
40,000 years cycles
100,000 years cycles
less ice
warmer
more ice
colder
CO_2 (ppm)
410 ppm
atmospheric CO_2
ΔT (°C)
+1 °C
global temperature relative to preindustrial
Time (million years BP)