The astronomical theory of palæoclimates

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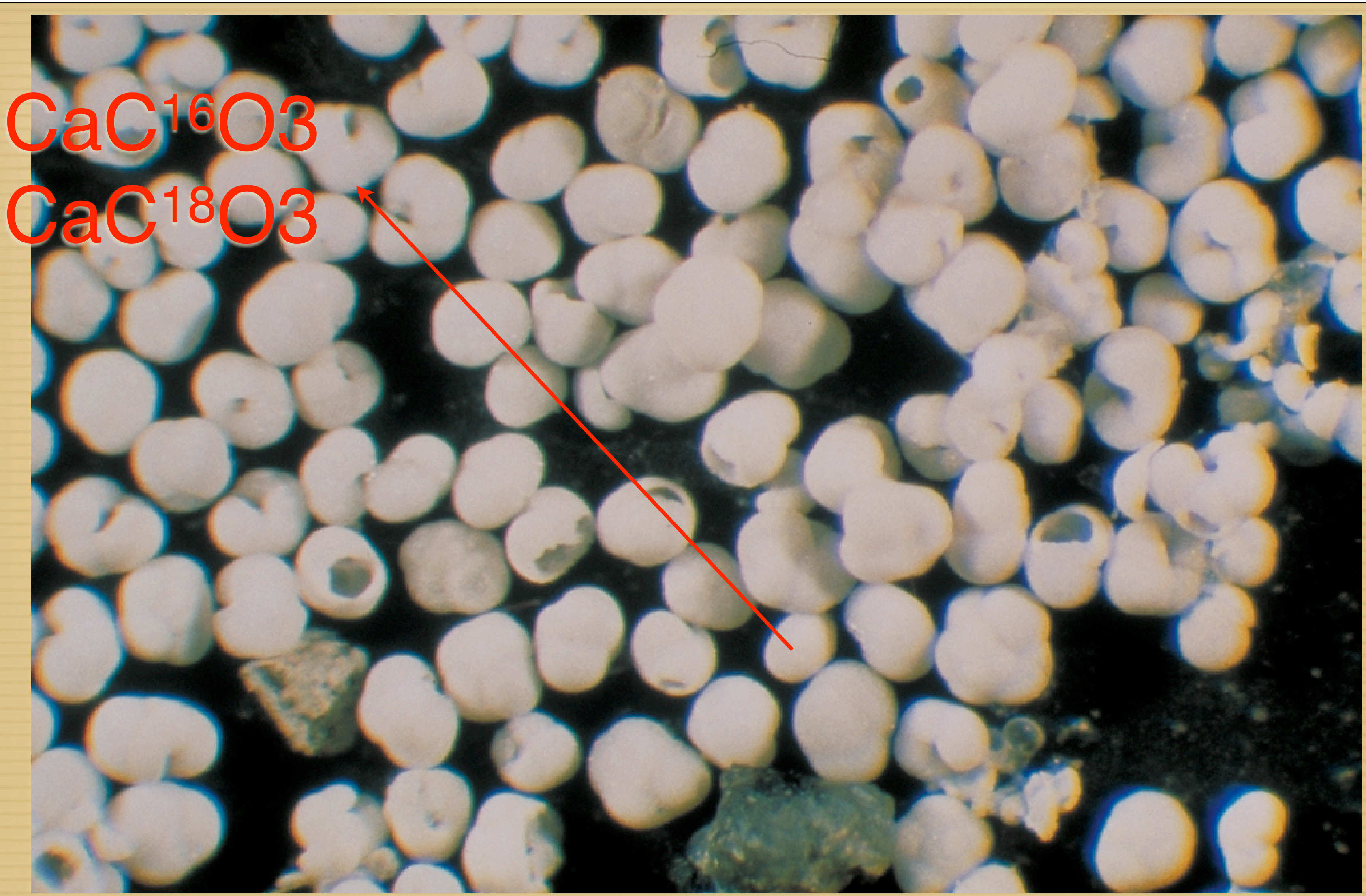
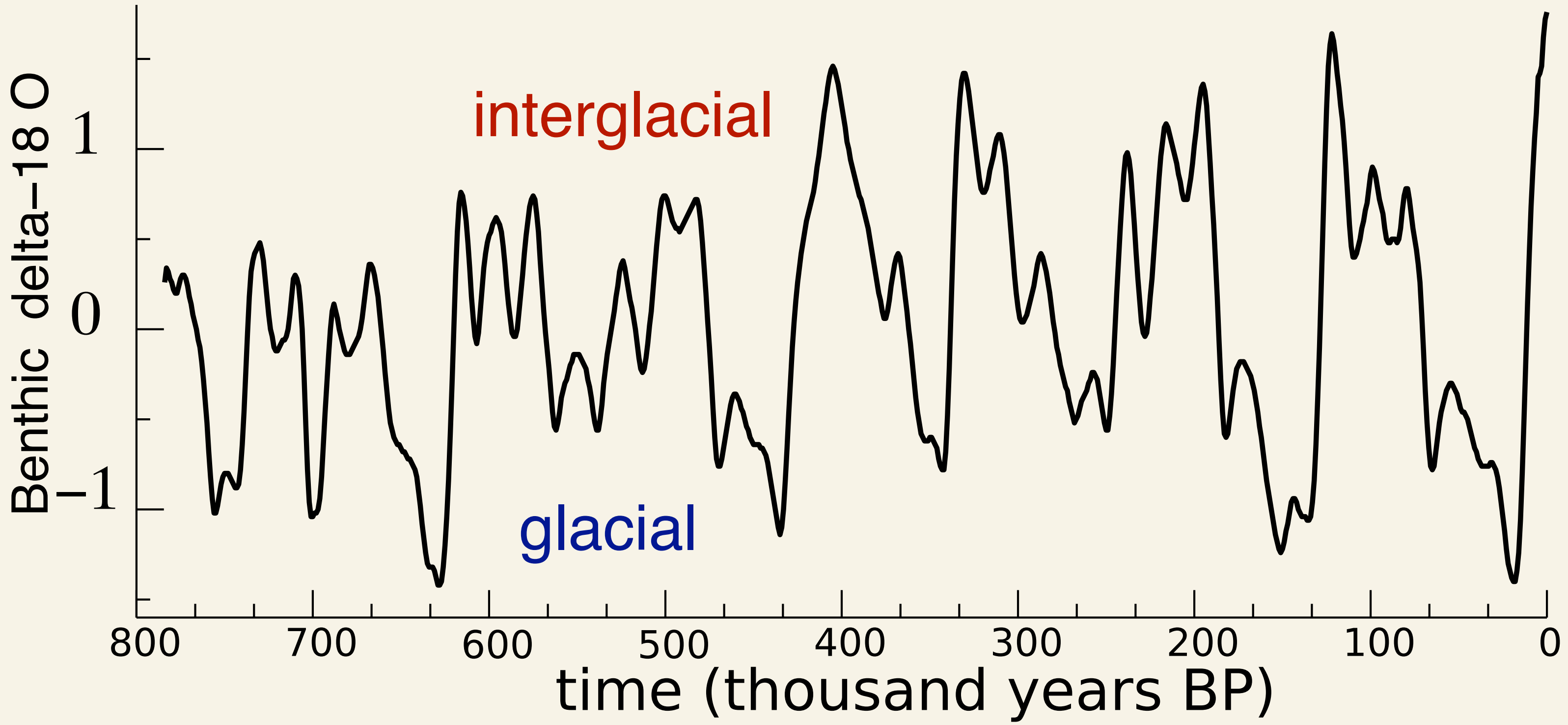
Loess-soil sequences over the last 2.6 Myr
(Shaanxi, Details in Liu et al.,1985; An et al., 1990; photo by An Z S)



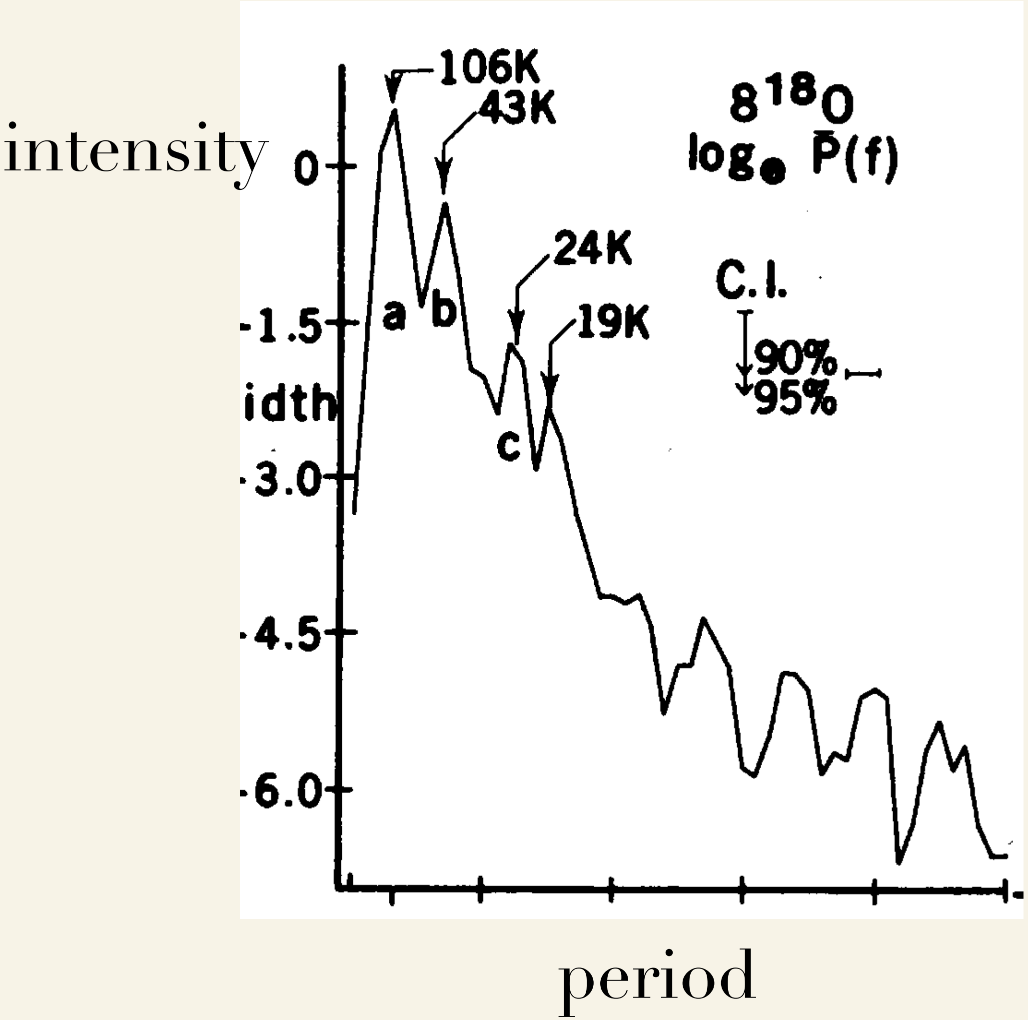
Foraminifera

Stack of 7 benthic oxygen isotopic records

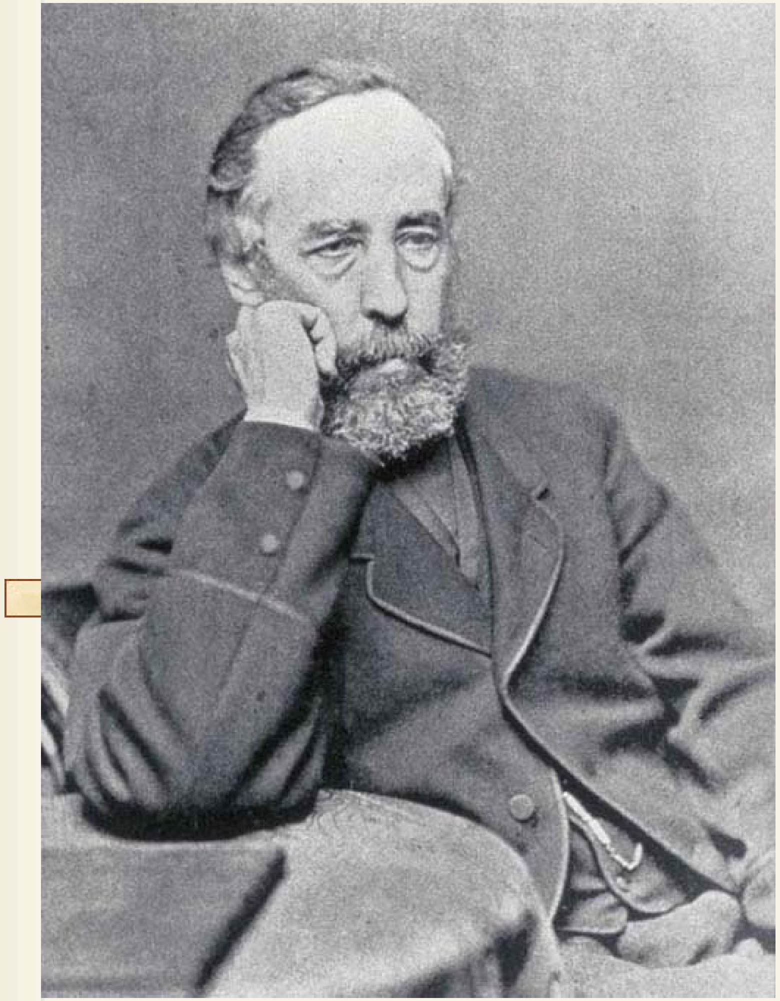


J. J. Imbrie, et al. The orbital theory of Pleistocene climate: Support from a revised chronology of the marine δO18 record. In A. Berger et al., ed., *Milankovitch and Climate, Part I*, pages 269–305, Norwell, Mass., 1984. D. Reidel.

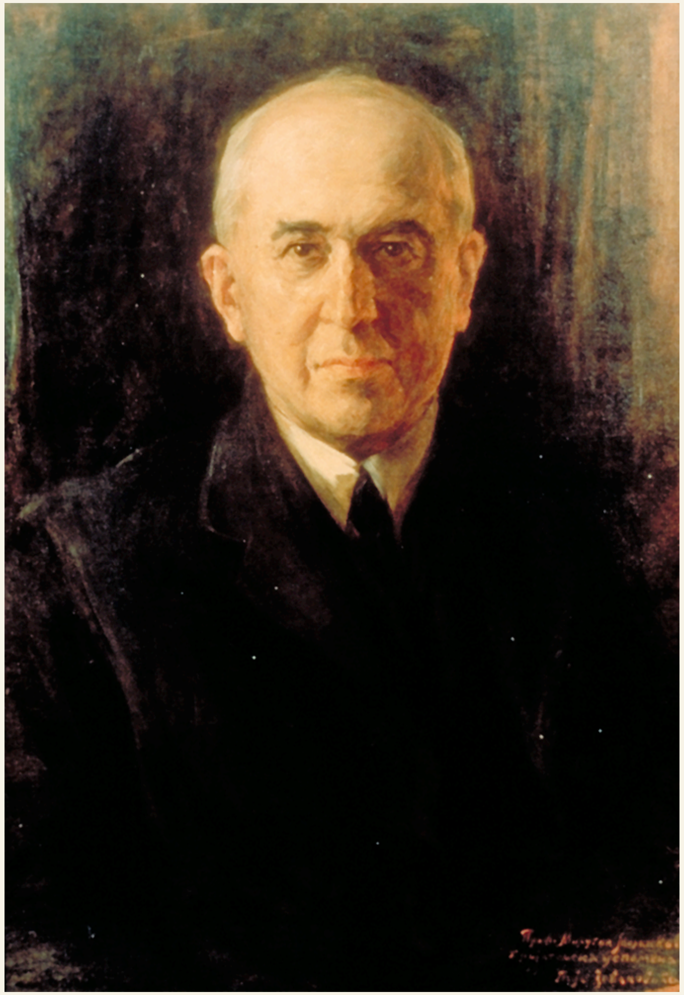
Evidence for ~ 41, 23 and 19 kyr periods



J. Hays, J. Imbrie, and N. Shackleton. Variations in the earth's orbit : Pacemaker of ice ages. *Science*, 194:1121–1132, 1976.

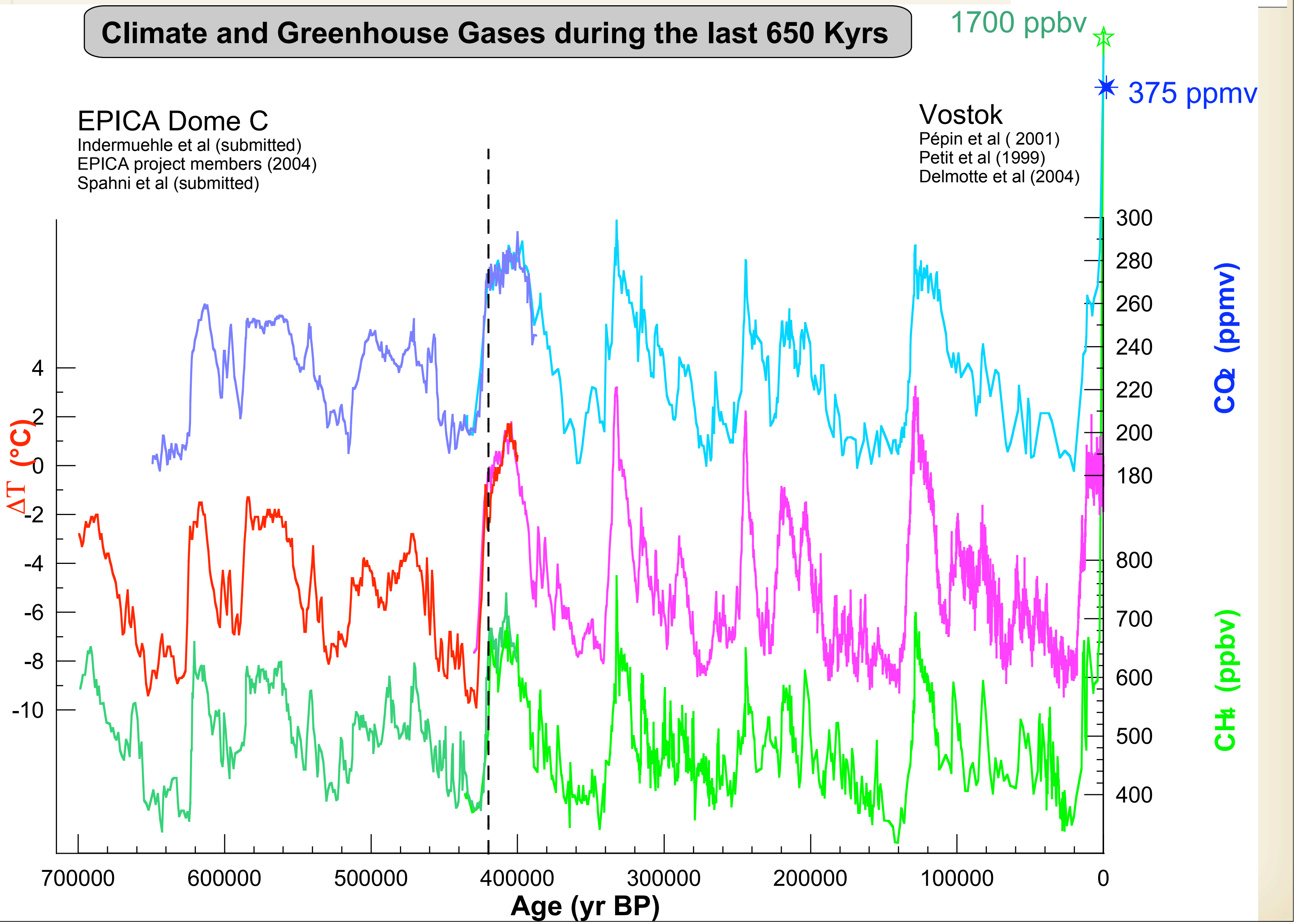


James Croll (1875)



Milutin Milankovitch (1930)

Greenhouse gases exhibit GI cycles

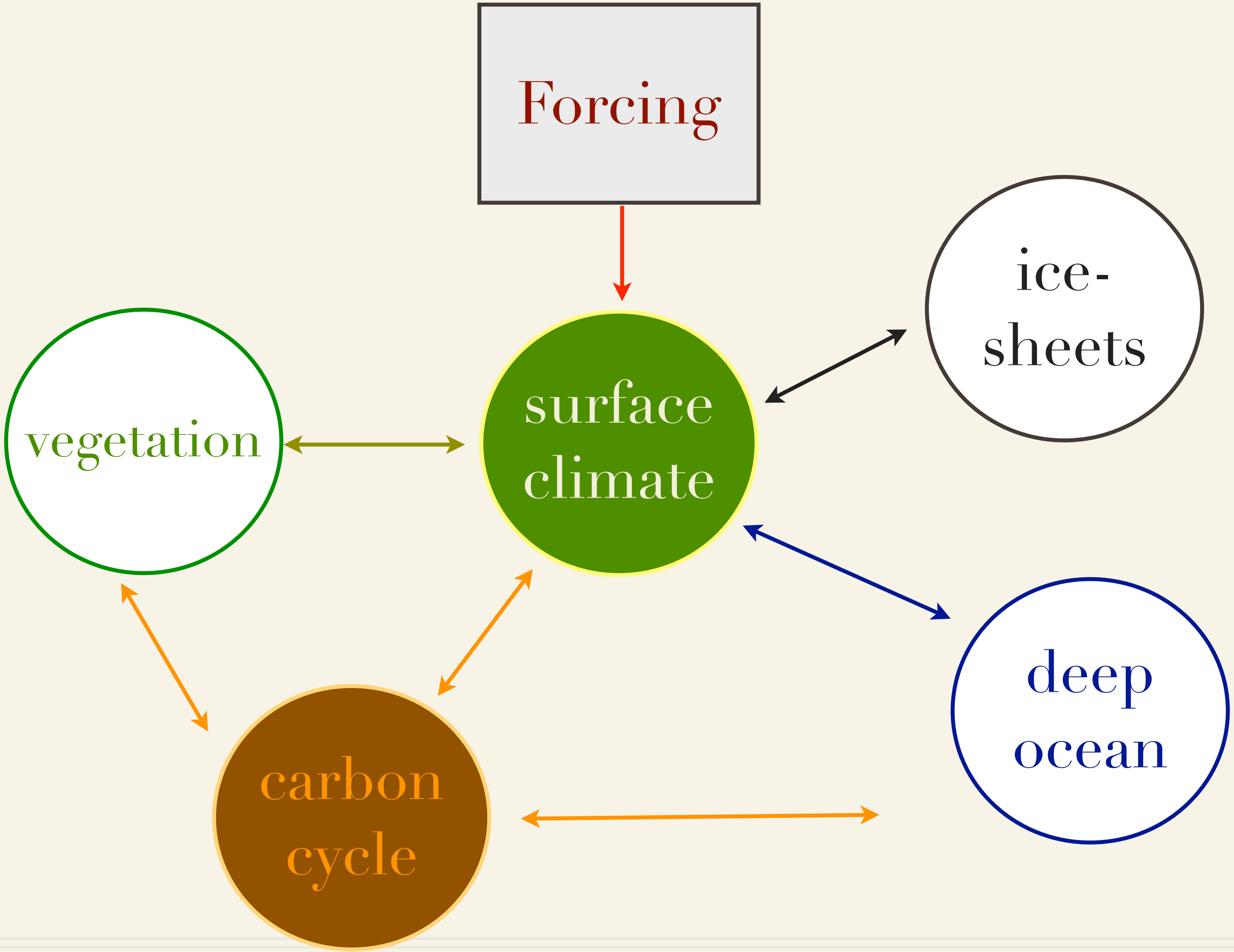


Outline

- What is climate ?
- Calculation of orbital parameters and insolation
- Deductive and inductive models of climate
- Current challenges

The climate system

Climate is the "statistical description of weather"


Forcing

ice-sheets

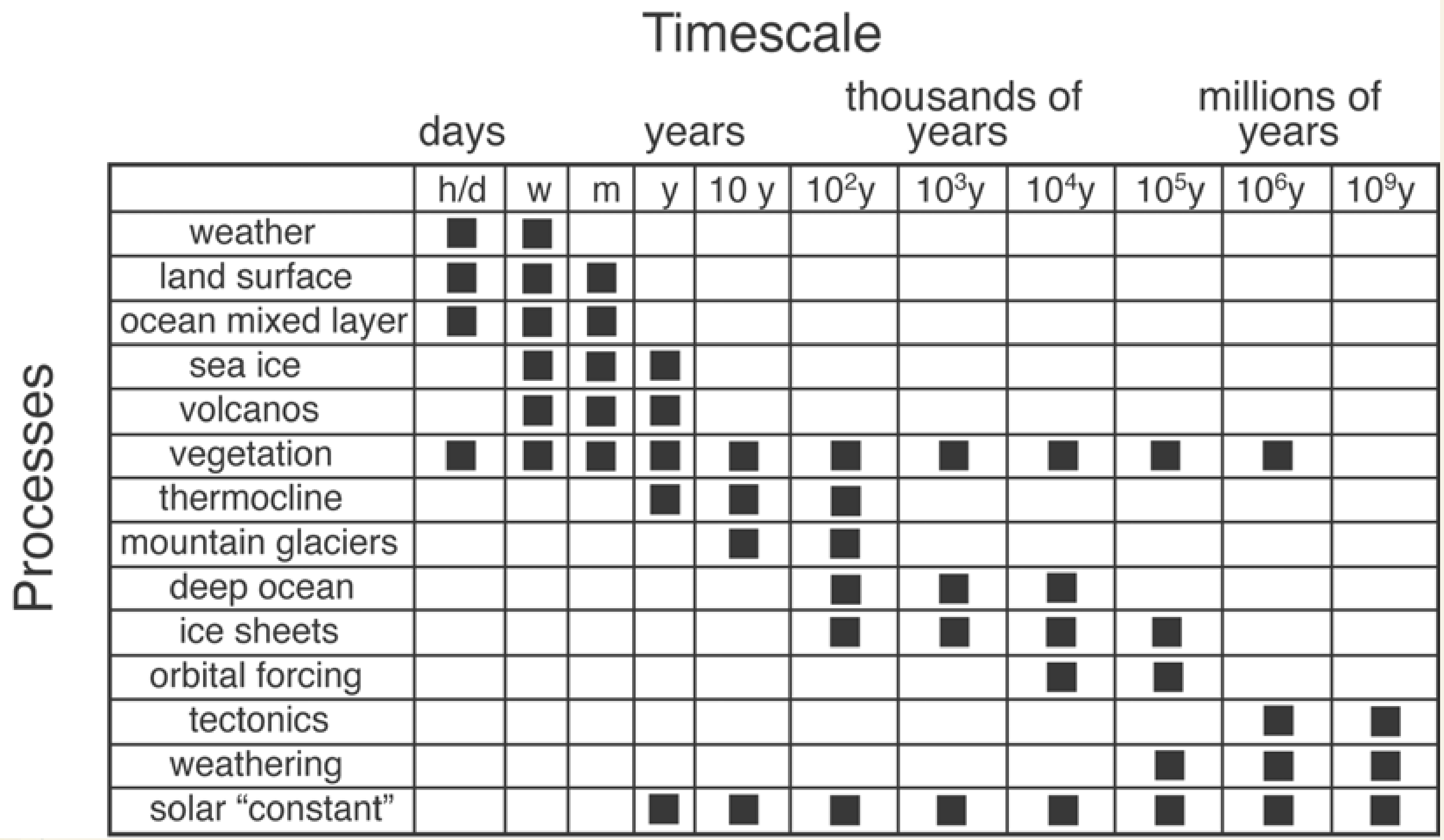
vegetation

surface climate

deep ocean

carbon cycle

Timescales



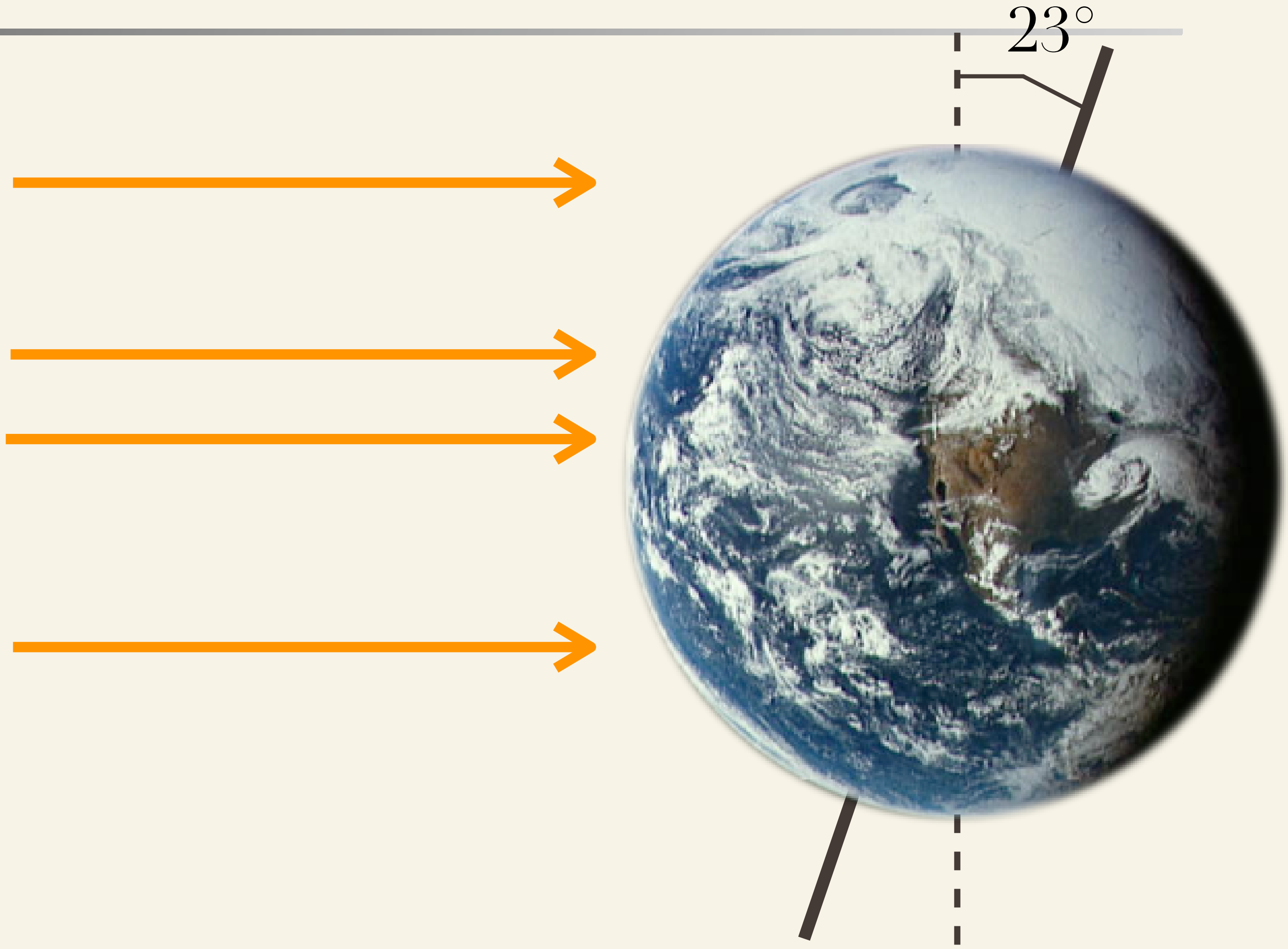
Timescale

Processes	days			years			thousands of years			millions of years	
	h/d	w	m	y	10 y	10^2y	10^3y	10^4y	10^5y	10^6y	10^9y
weather	■	■									
land surface	■	■	■								
ocean mixed layer	■	■	■								
sea ice		■	■	■							
volcanos		■	■	■							
vegetation	■	■	■	■	■	■	■	■	■	■	
thermocline				■	■	■					
mountain glaciers					■	■					
deep ocean						■	■	■			
ice sheets						■	■	■	■		
orbital forcing								■	■		
tectonics										■	■
weathering									■	■	■
solar “constant”				■	■	■	■	■	■	■	■

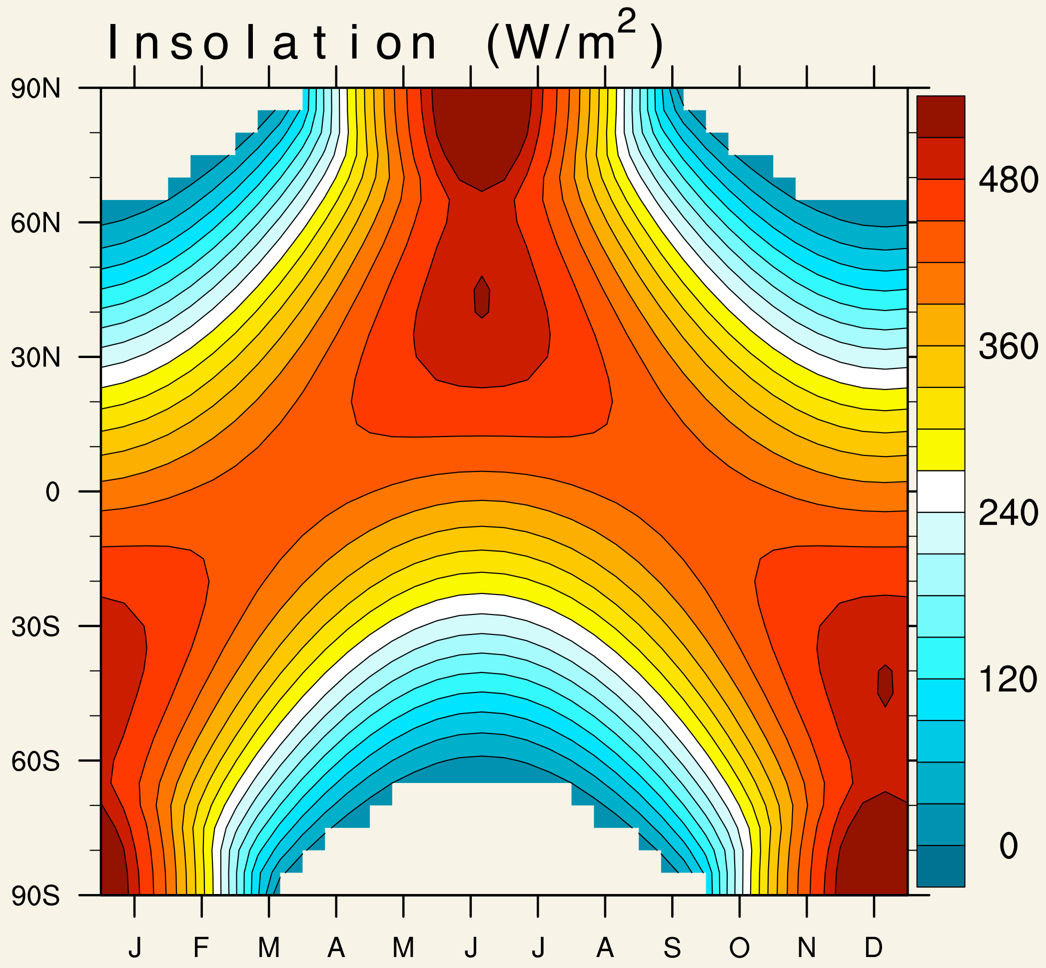
from : J. Marshall and A. Plumb, lecture notes, MIT

An astronomical explanation to the quaternary glaciations

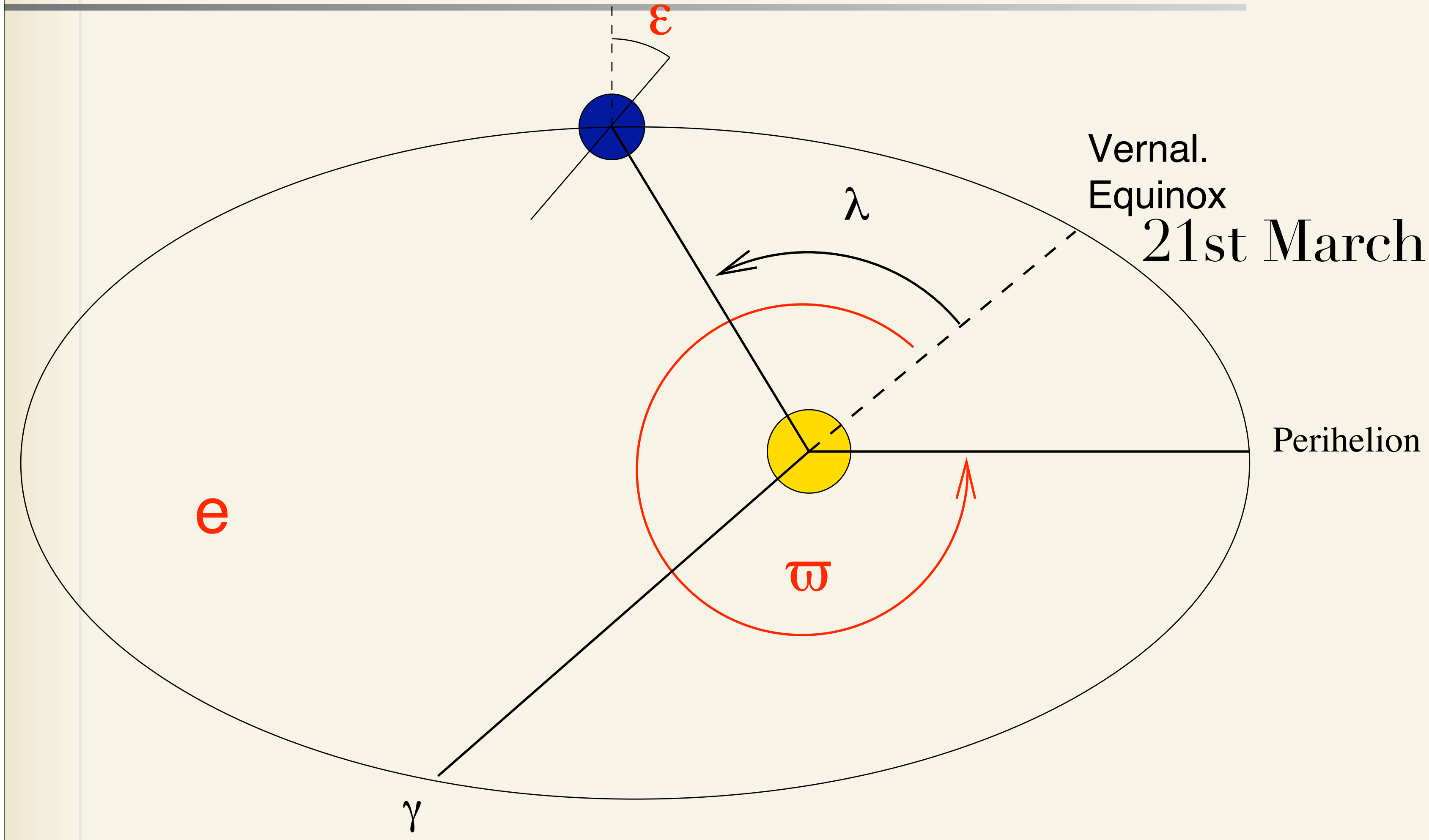
Climate dynamics driven by solar input



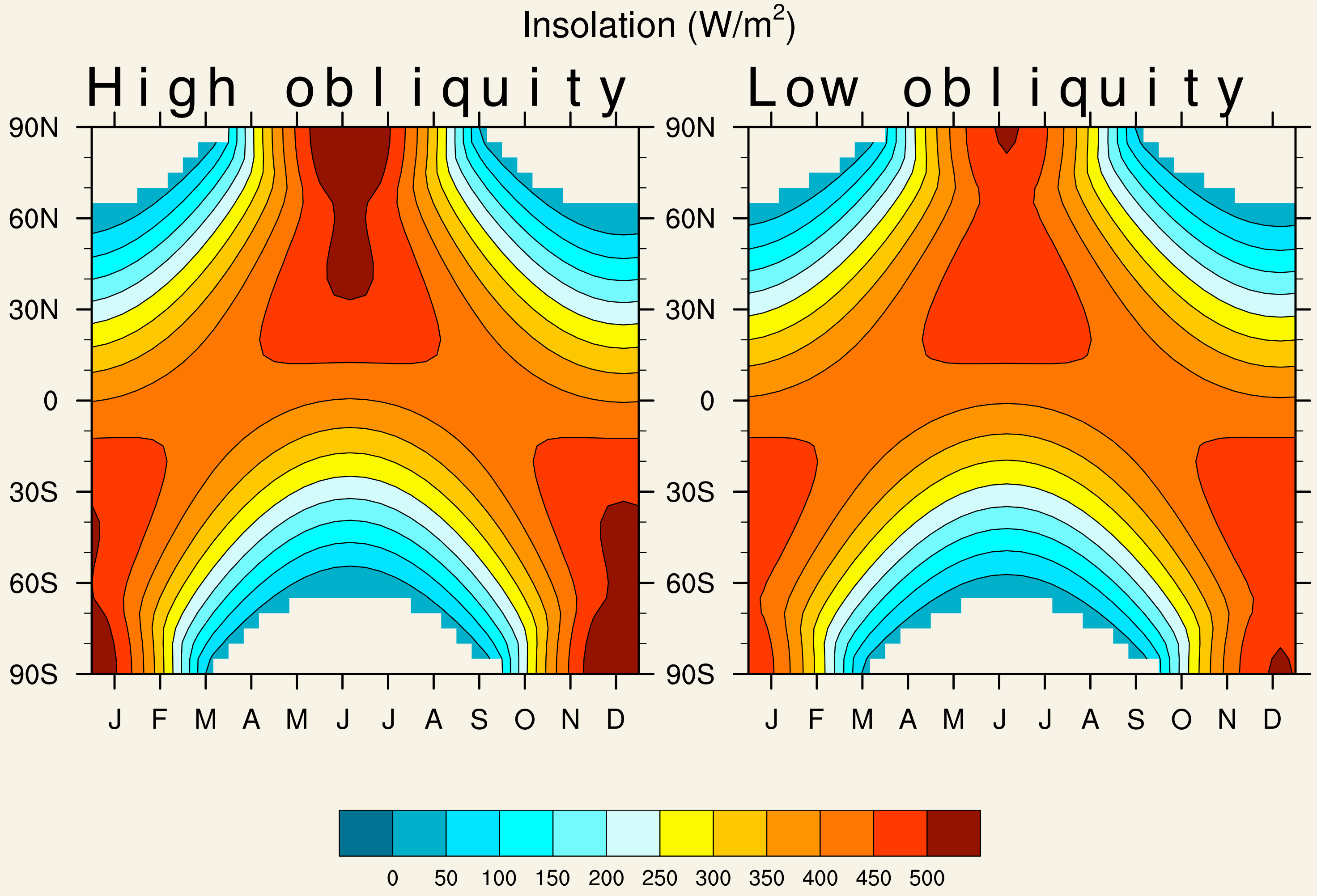
The Milankovitch graph : Insolation



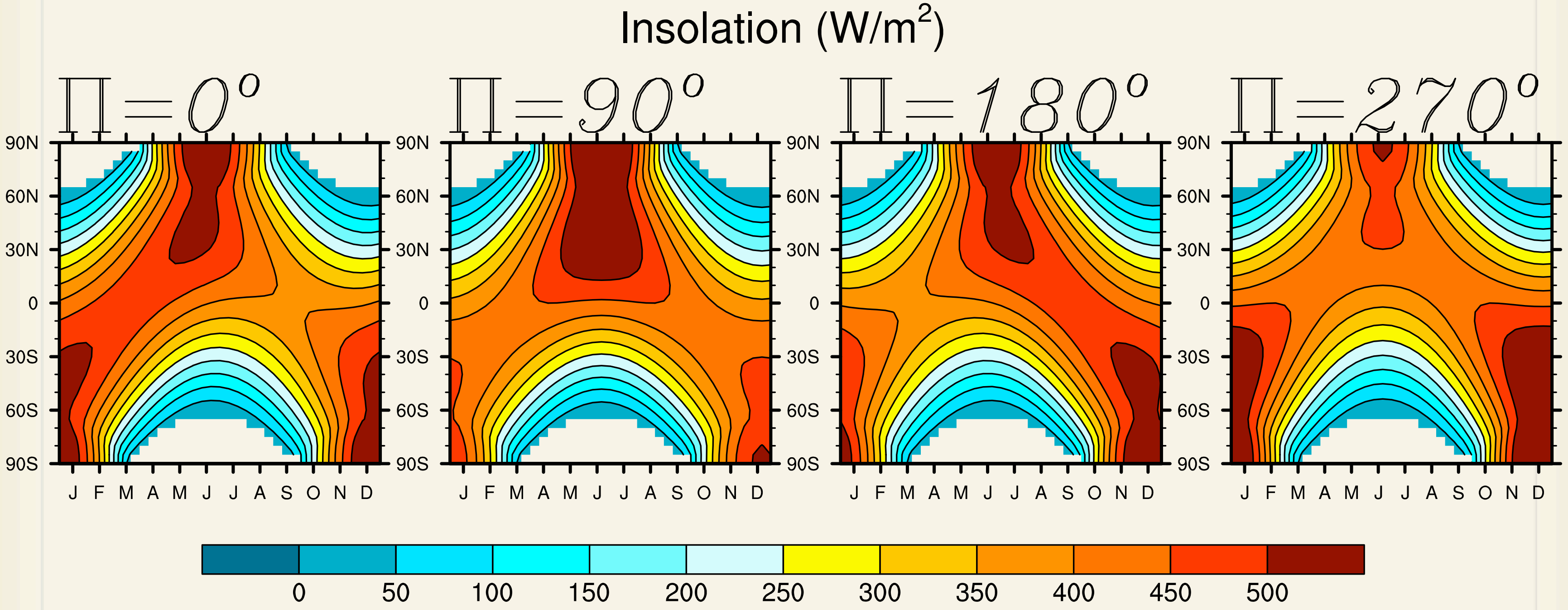
Three orbital elements determine insolation



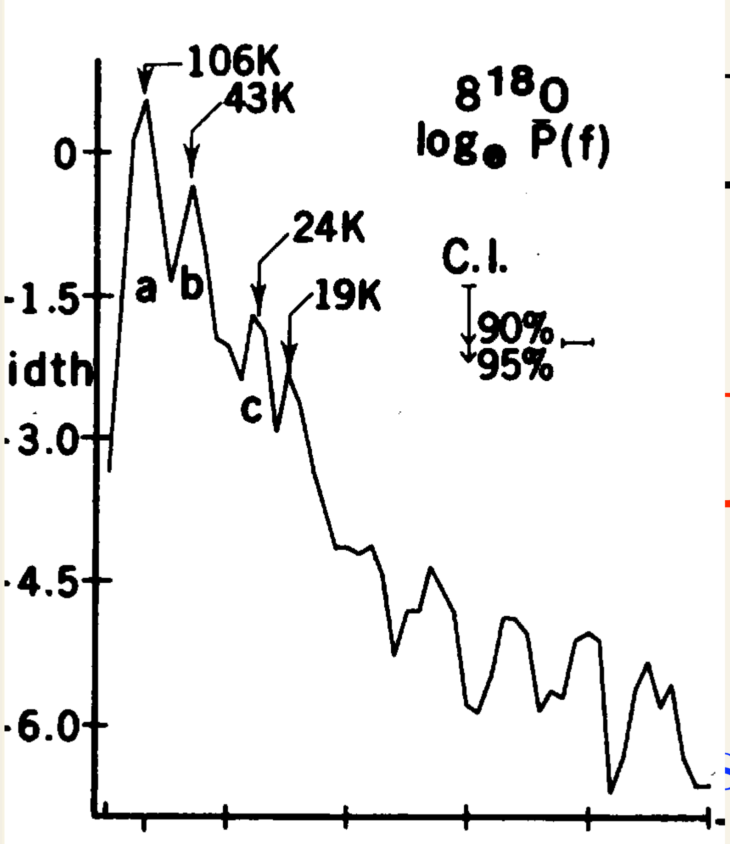
High obliquity = higher summer insolation



Precession modulates the seasonal distribution of insolation



Long-term evolution : trigonomical expansion by Berger (1978)



$$A_i \cos(f_i t + \delta_i)$$

41 000 years

$$E_i \cos(\lambda_i + \phi_i)$$

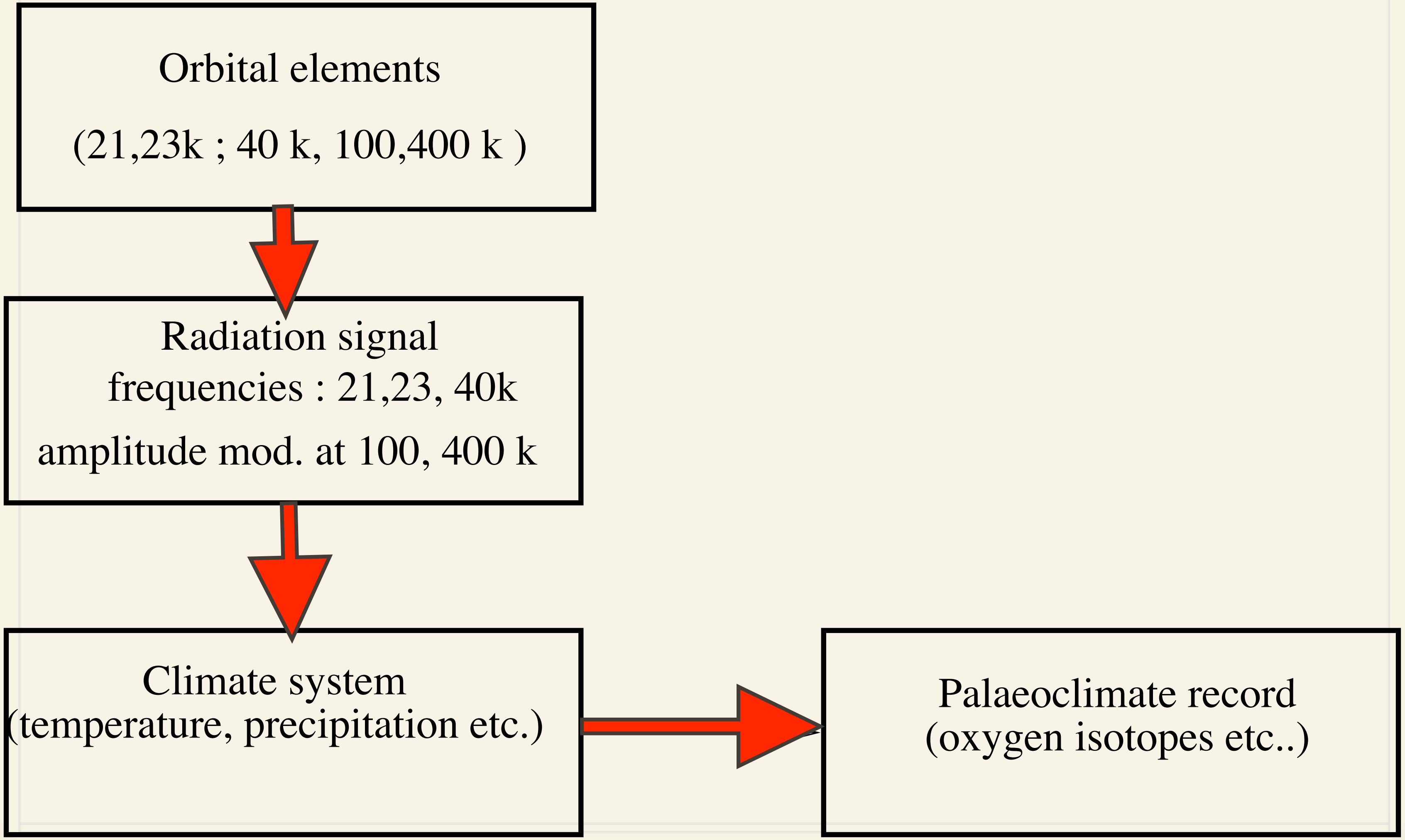
400 000 and 100 000 years

$$\sin(\alpha_i t + \zeta_i)$$

19 000 and 23 000 years

Hays et al., (1976)

Towards an astronomical theory



Orbital elements

(21,23k ; 40 k, 100,400 k)

Radiation signal
frequencies : 21,23, 40k
amplitude mod. at 100, 400 k

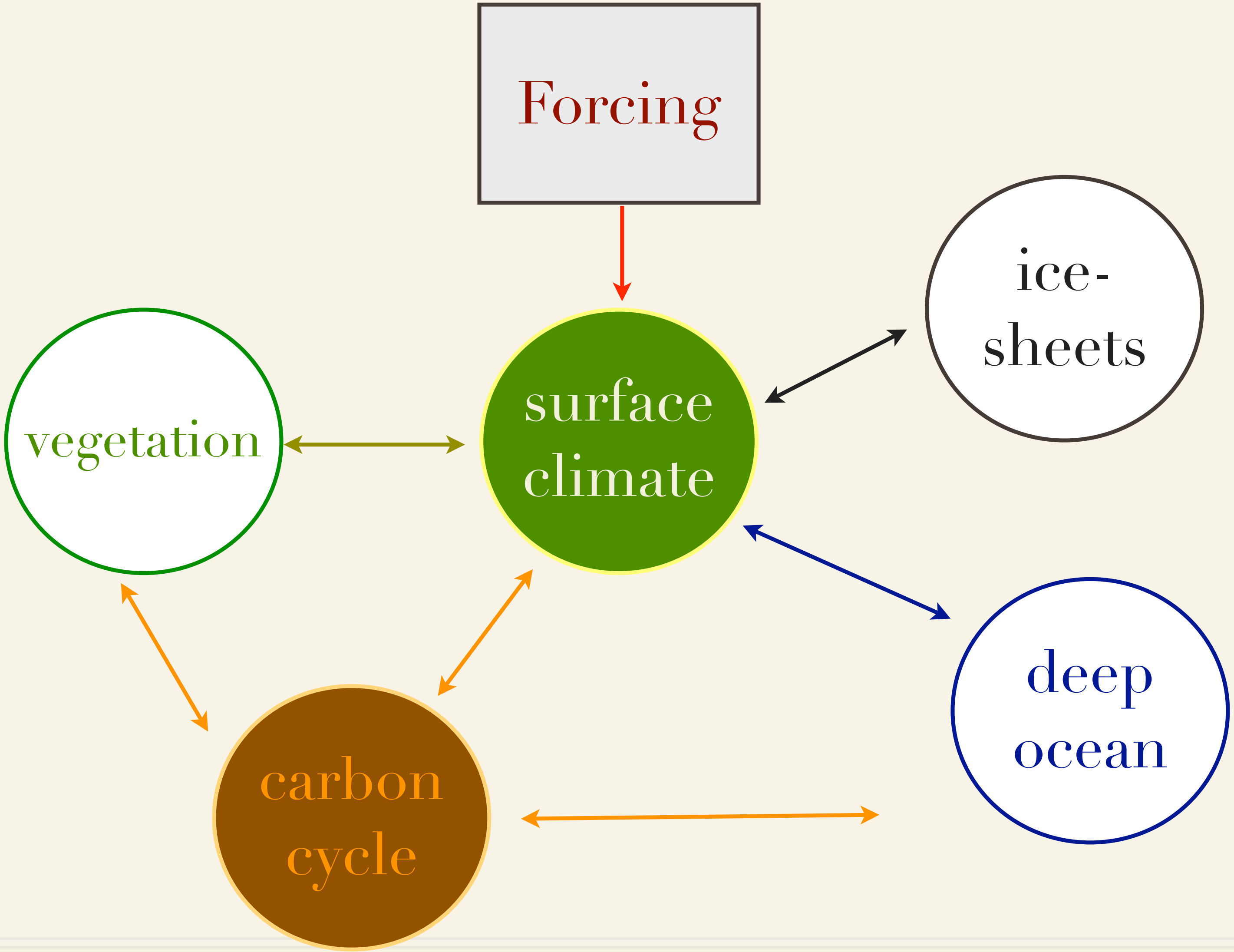
Climate system
(temperature, precipitation etc.)

Palaeoclimate record
(oxygen isotopes etc..)

Modelling climate :

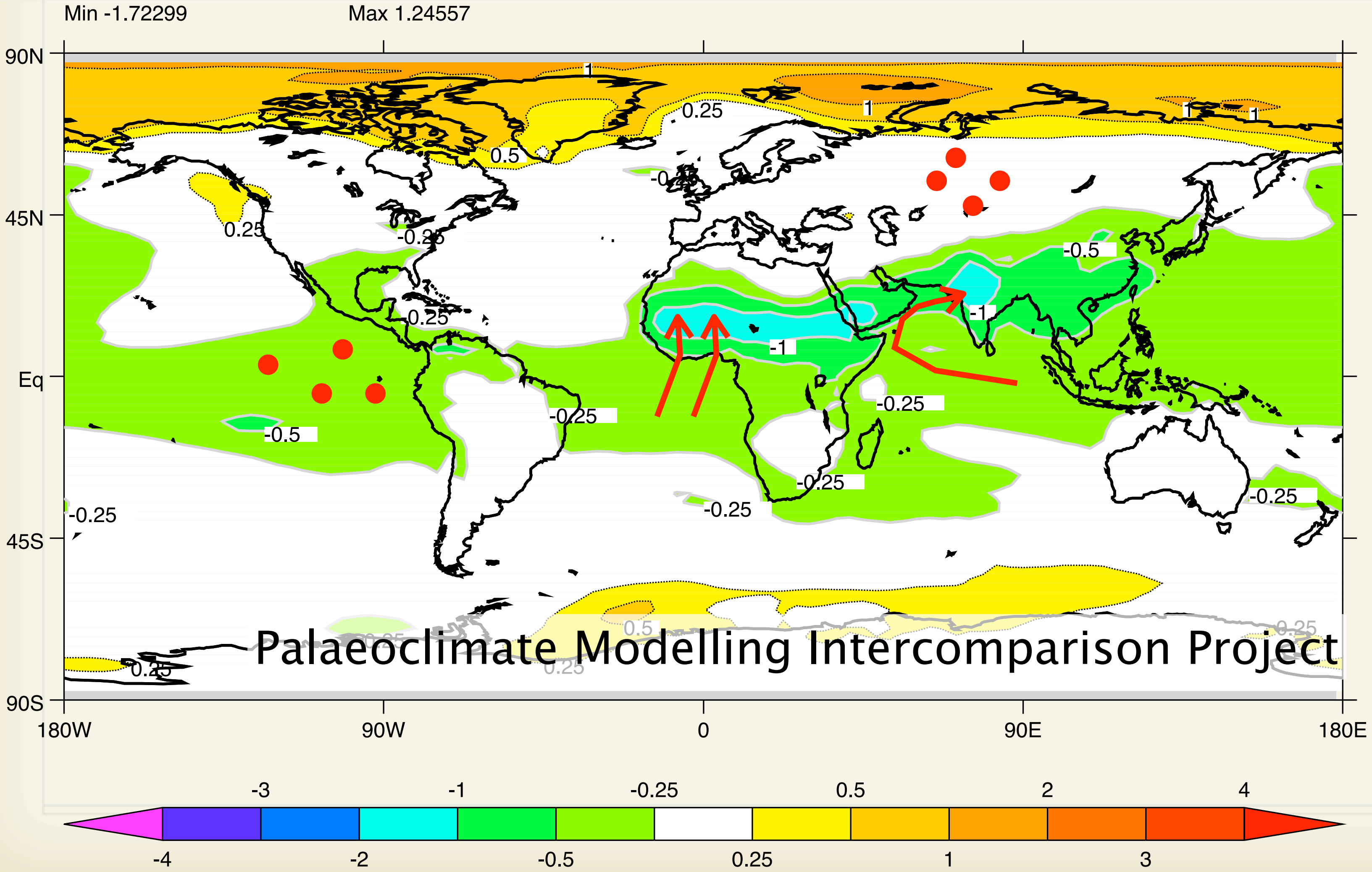
deductive and inductive climate models

Does the orbital forcing matter ?



General circulation models (deductive) allow to quantify the surface response

Temperature change when insolation of 6,000 years ago

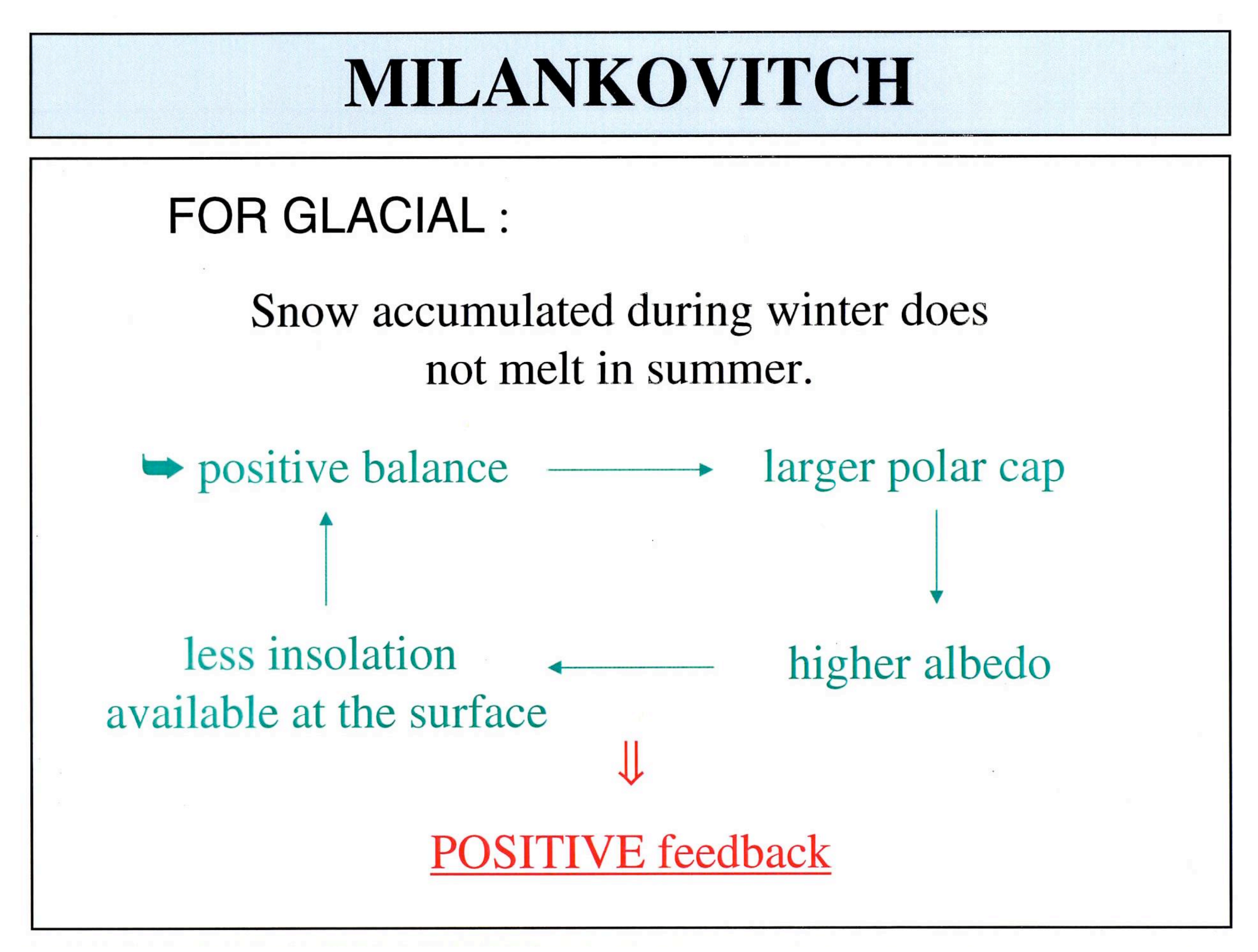


Palaeoclimate Modelling Intercomparison Project

Conclusions from GCMs

- Confirm that the impact of the astronomical forcing on the surface climate is significant
- Simple thermodynamical responses (snow melt, sea-ice reduction, ocean warming) but radiative feedbacks
- More complex dynamical responses
  - monsoon
  - variability modes (ENSO)
- Ingredients for
  - interactions between time-scales and between components
- Achille heel : GCM cannot be integrated over long time scales

Inductive models allow to formulate ideas



MILANKOVITCH

FOR GLACIAL :

Snow accumulated during winter does not melt in summer.

➥ positive balance → larger polar cap

larger polar cap ↓ higher albedo

higher albedo → less insolation available at the surface

less insolation available at the surface ↑ positive balance

⇓

<u>POSITIVE feedback</u>

The Imbrie and Imbrie (1980) conceptual model

I_{65} : Top-of-the-atmosphere insolation at 65°N at the summer solstice

V : Ice Volume

$$\boxed{\frac{dV}{dt} = \begin{cases} \frac{1+b}{T_m}(-I_{65} - V) & \text{if } x \geq y \\ \frac{1-b}{T_m}(-I_{65} - V) & \text{if } x < y \end{cases}}$$

Ice volume driven by summer insolation but different characteristic times for glacial inception and deglaciation

Imbrie captures important timings, but not the 100k signal

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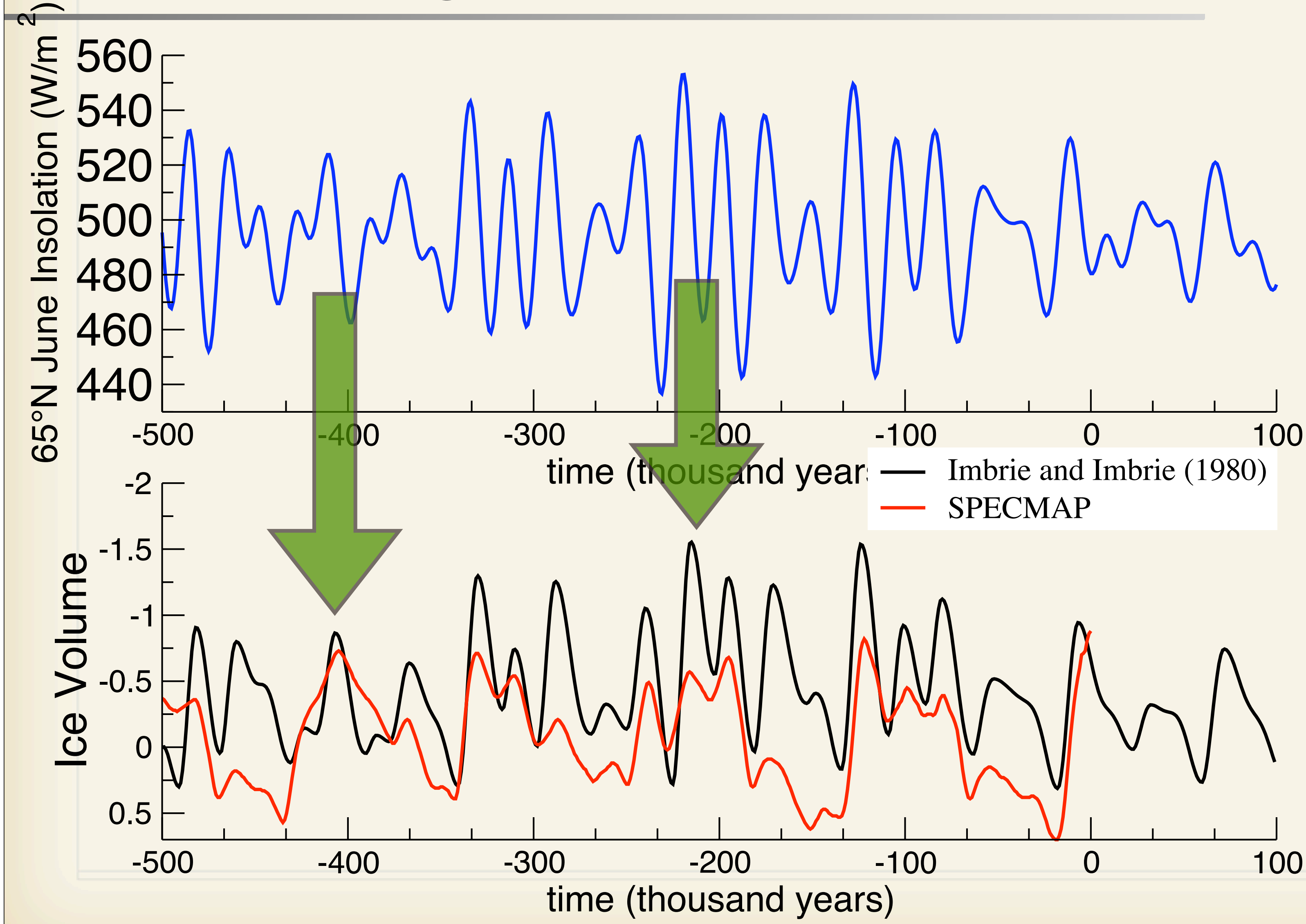


The Saltzman and Maash model (SM90)

V : Ice Volume

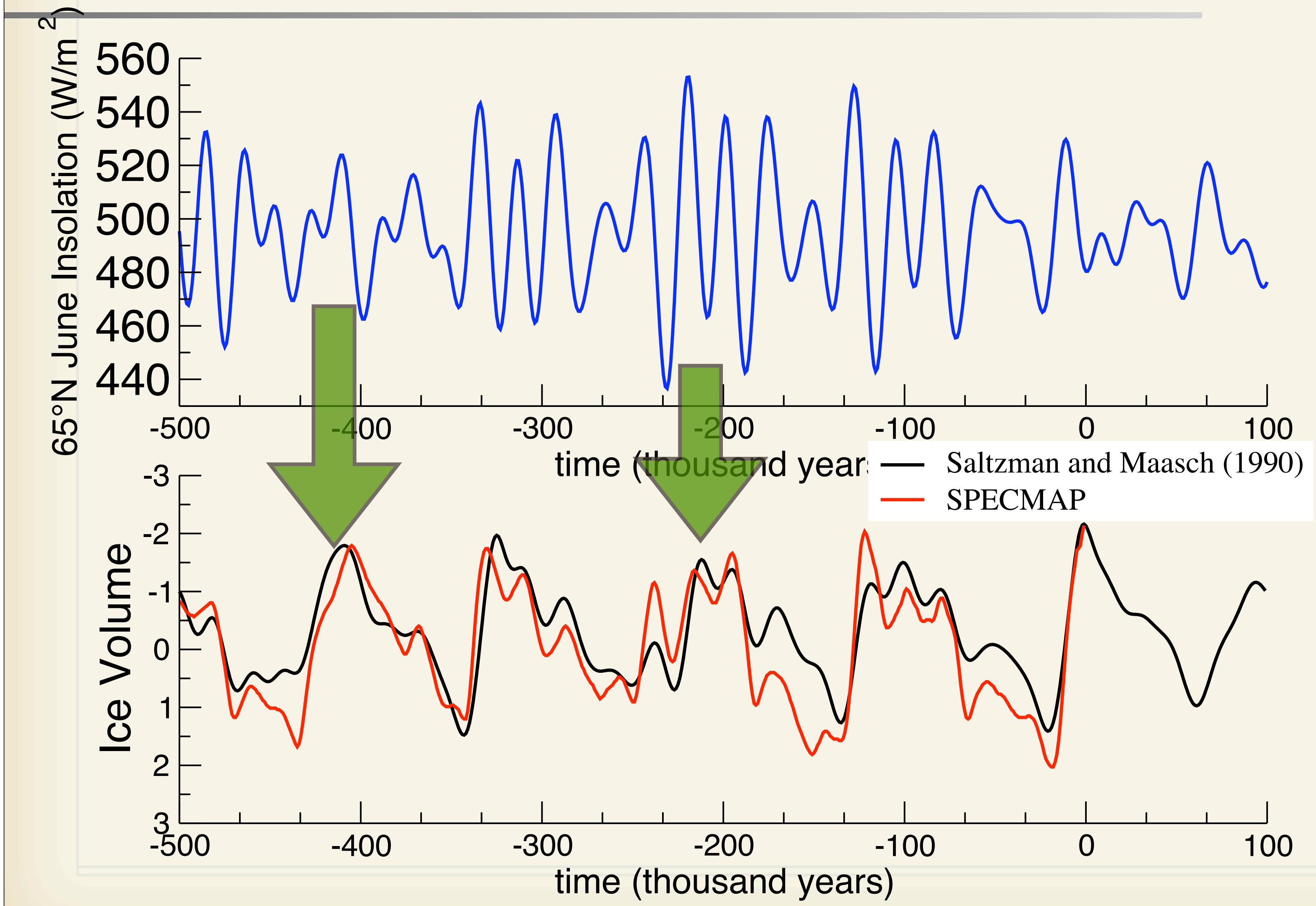
μ : CO_2 concentration

θ : Deep-ocean temperature

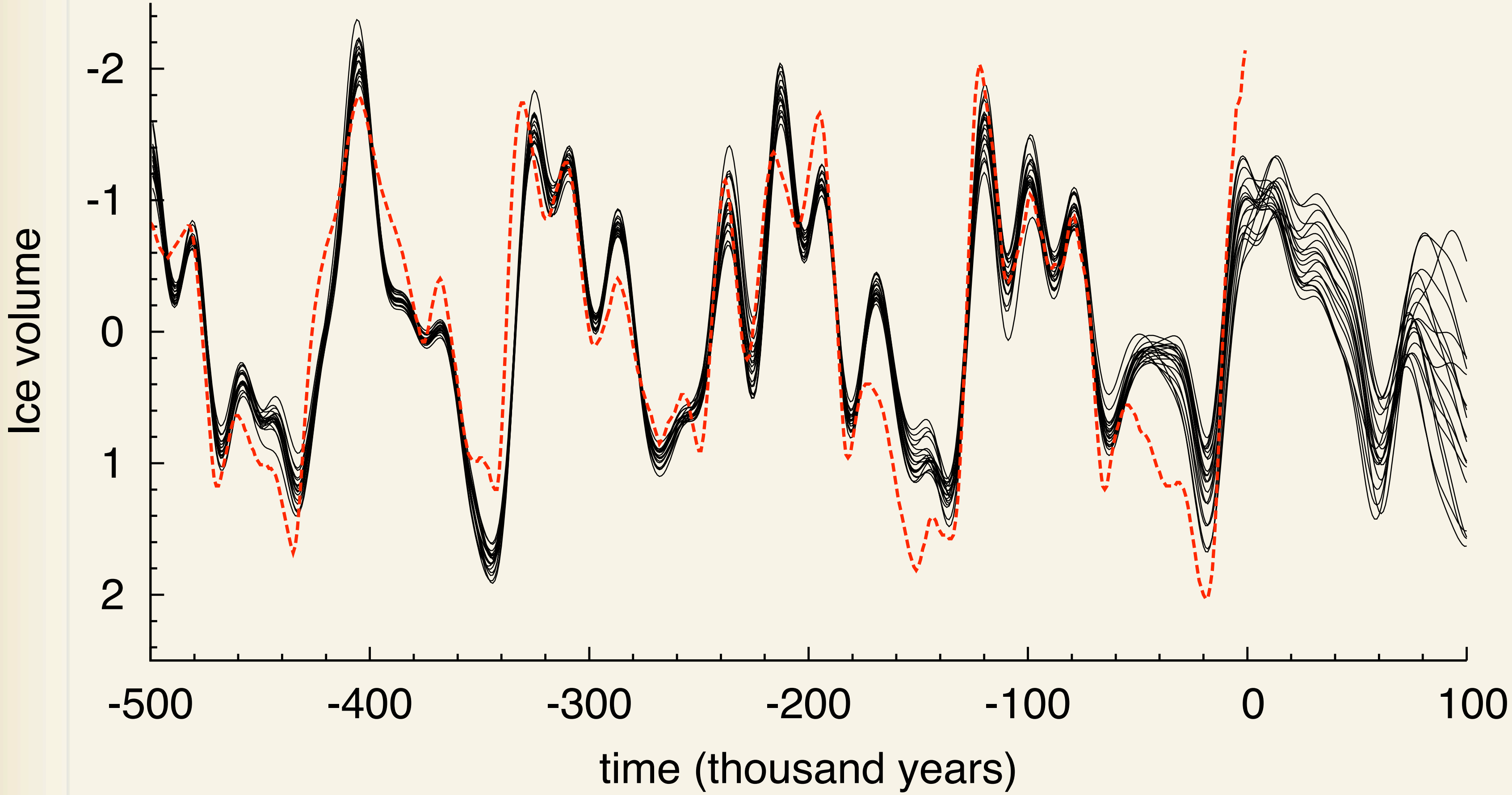
$$\boxed{\begin{aligned} \dot{V} &= -V - \mu - v\theta - uI_{65} \\ \dot{\mu} &= -p\theta + r\mu + s\theta^2 - w\mu\theta - \theta^2\mu \\ \dot{\theta} &= -q(V + \mu) \end{aligned}}$$

B. Saltzman and K. A. Maasch. A first-order global model of late Cenozoic climate. *Trans. R. Soc. Edinburgh Earth Sci*, 81:315–325, 1990.

SM90 does a amazingly good job...



Calibration and prediction with the SM90 model : unpredictablity on long time scales



Crucifix, unpublished

The SM90 theory : conclusions

- Insolation at 65°N in summer bears a great deal of the external forcing information needed to reproduce glacial – interglacial cycles
- At least three components interplay : Ice, Ocean and Carbon Cycle
- The system becomes unstable near the extremes (high ice volume, low ocean temperature, low CO_2 concentration)
- The system may spontaneously oscillate (periodic or strange attractor)
- Astronomical forcing is a pacemaker : it determines the timing of glacial inception and deglaciation.
- The Achille heel : justify the structure of the equations

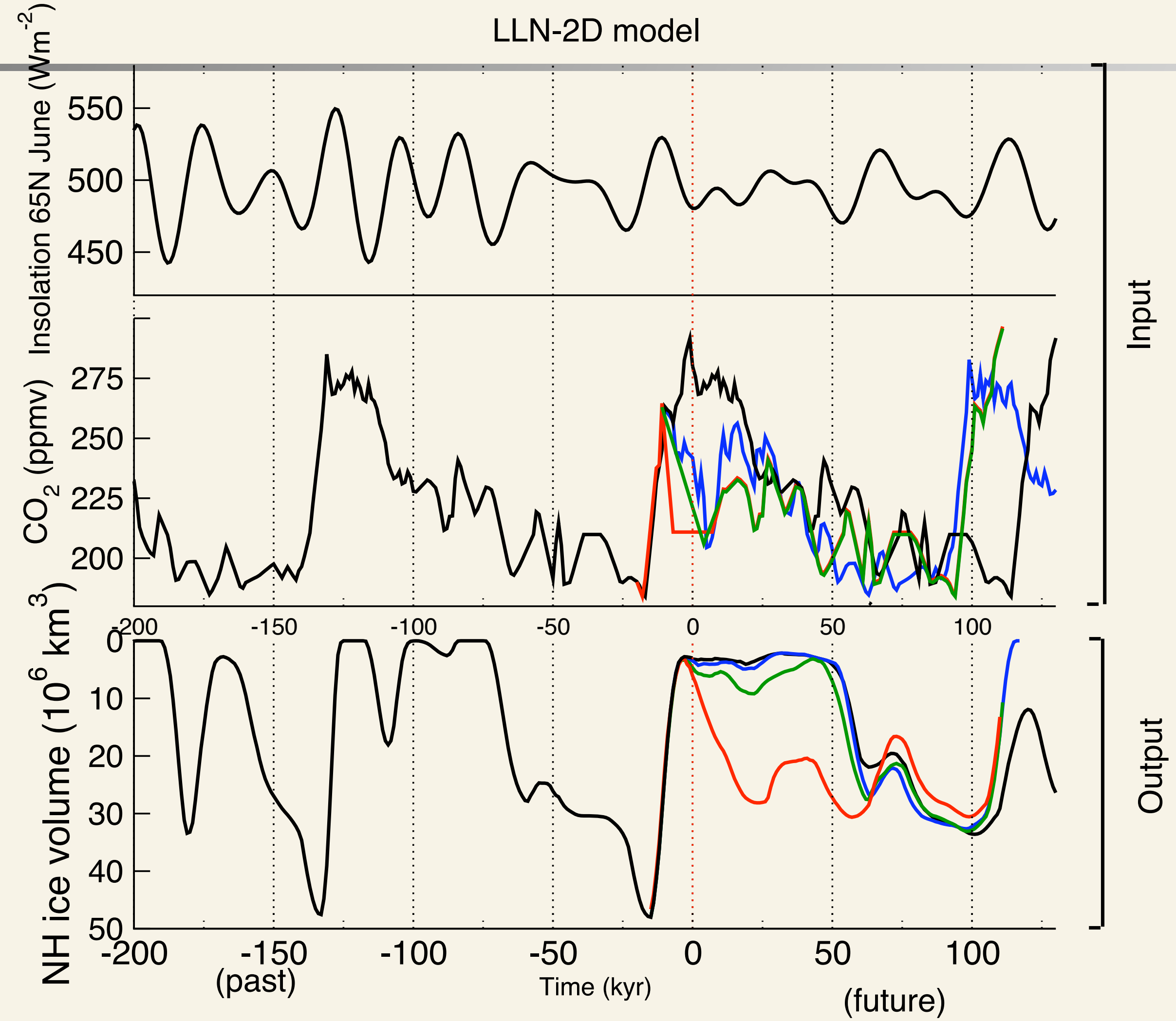
Earth models of intermediate complexity

- Deductive models
- Simplified, but explicit calculations of
  - atmosphere dynamics
  - ocean heat transport
  - radiative transfer
  - mass balance

"2.5-D formalism"

- Example : The LLN 2-D model (Gallée et al., 1991 et 1992)
  - atmosphere, ocean and ice sheet dynamics
  - no carbon cycle

The LLN-2D model



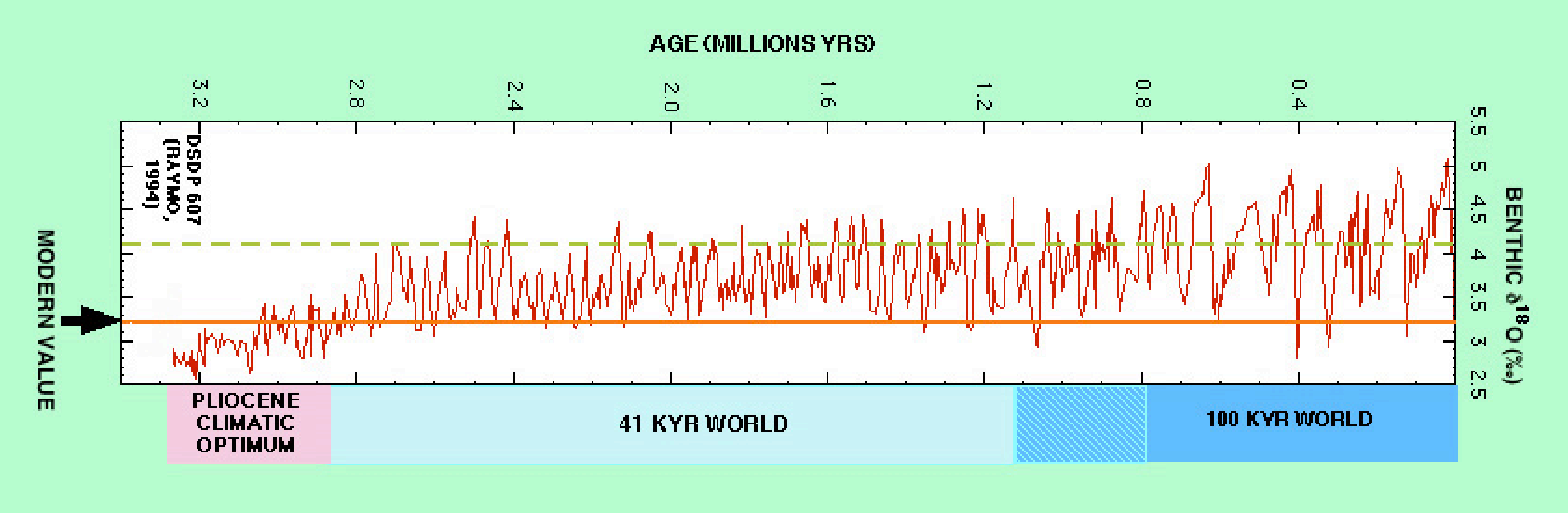
M. F. Loutre, A. Berger, M. Crucifix, S. Desprat, and M. F. Sánchez-Goñi. Interglacials as simulated by the LLN-2D NH and MoBidiC climate models. In *The climate of past interglacials*, pages 547–582.

Conclusion from the LLN-2D model

- LLN-2D models (confirmed by others) :
  - Pre-industrial levels of CO2 prevent a glacial inception before 50,000 years.
  - [CO2] concentration needed for glacial inception around 220 ppmv (or equivalent combination CO2 and CH4)
  - Next glacial maximum in around 60 ka

Current challenges

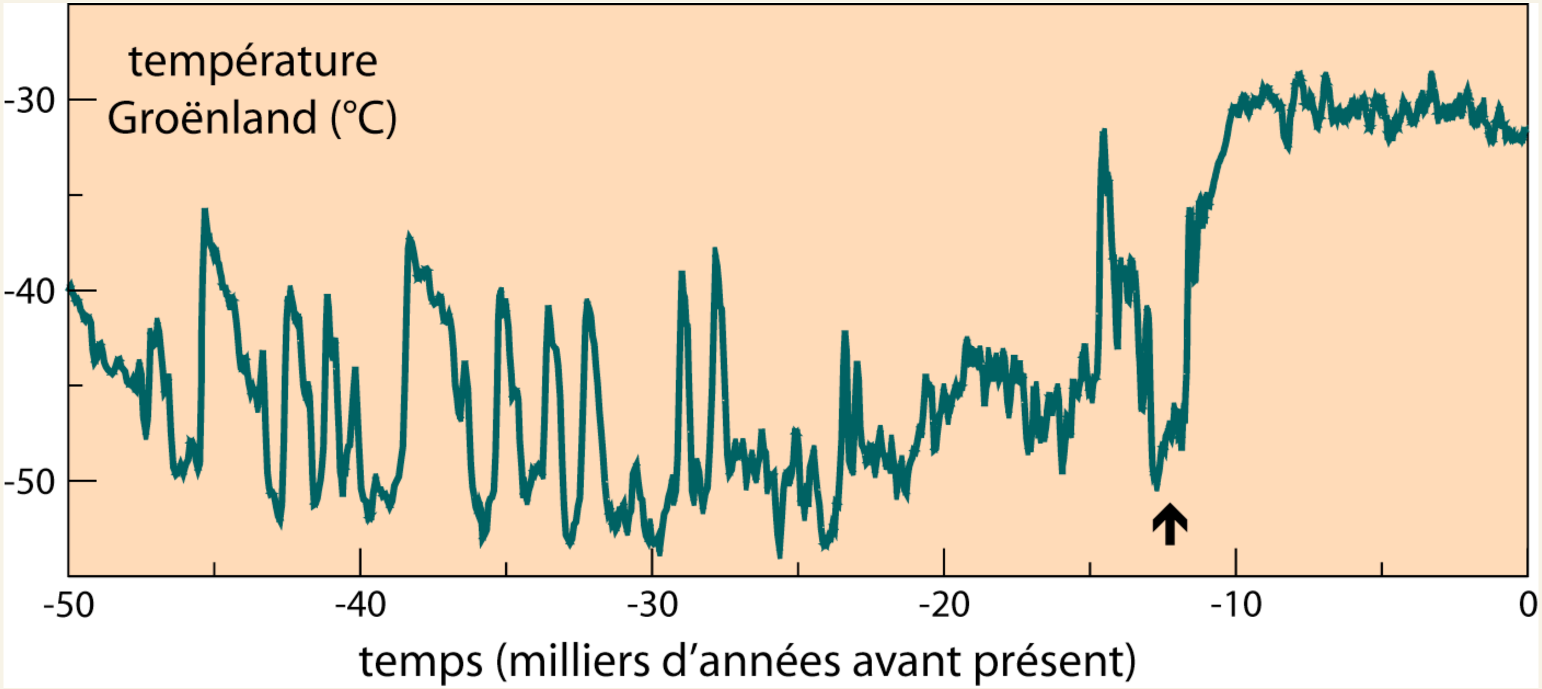
The “41k” and “100k” worlds



Raymo, M.E., W.F. Ruddiman, J. Backman, B.M. Clement, and D.G. Martinson, 1989, Late Pliocene variation in Northern Hemisphere ice sheets and North Atlantic deep circulation. Paleoceanography, v. 4, p. 413-446.

Figure taken from www.maureenraymo.com

The Dansgaard-Œshger events



Alley, R.B. 2000.
The Younger Dryas cold interval as viewed from central Greenland.
Quaternary Science Reviews 19:213-226.

The contributions to CO2 changes still need to be quantified.

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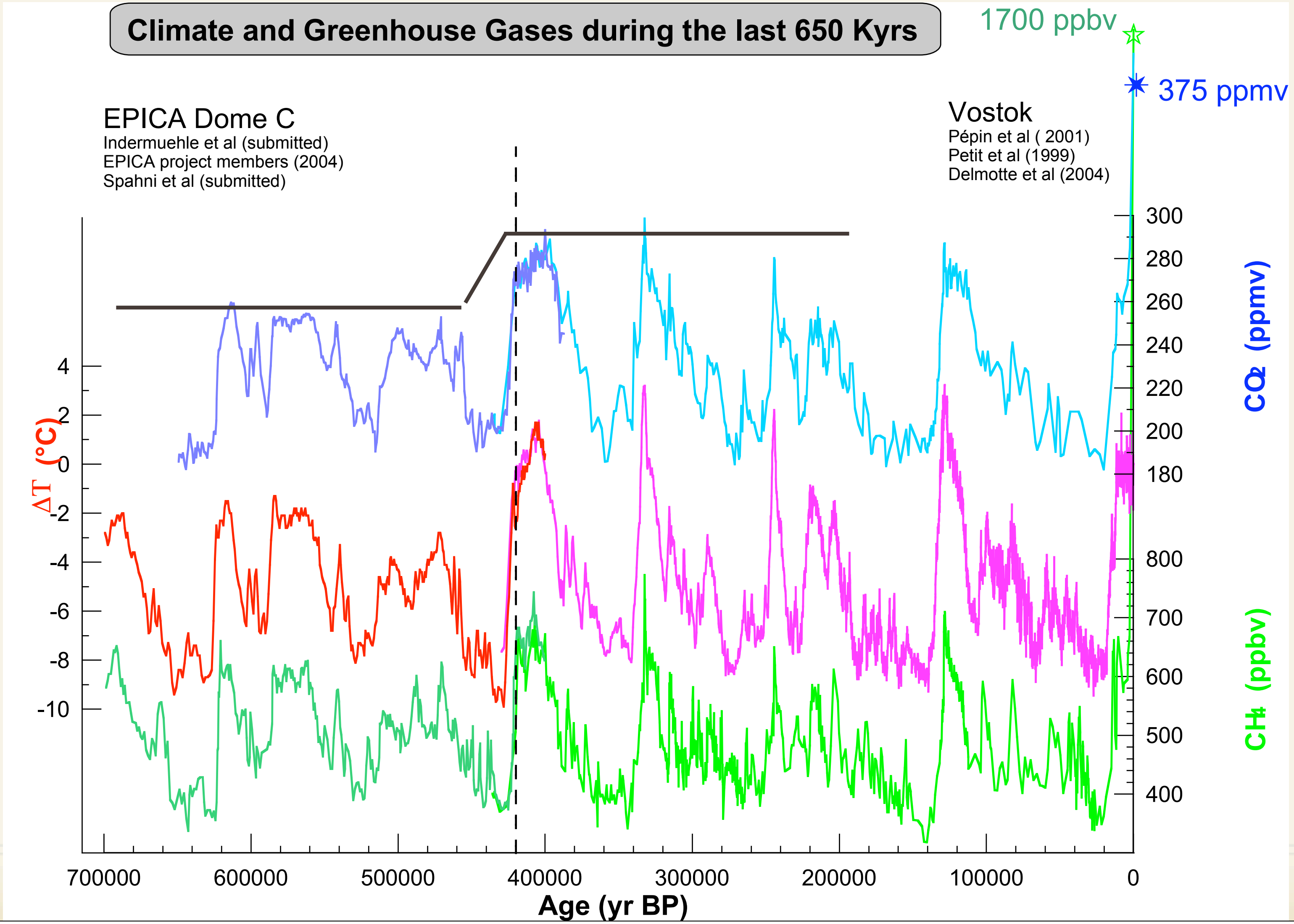

Current challenges

- Quantify climate-carbon cycle interactions
- Mechanisms of instability.
  - What causes the system to “dislike” having a high ice volume ?
- Mechanisms of stability
  - Identify mechanisms that stabilise its evolution to produce long and stable interglacials (like 400 000 years ago)
- Interactions of the orbital forcing with the longer time scales
  - apparition of glacial cycles around ~ 3 Ma
  - transition from 41k-oscillations to 100k-oscillations around 1 Ma ago
  - no full interglacial between – 800 k and – 400 k, but méga-monsoons
- Interactions of the orbital forcing with the shorter time-scales