Ice ages and the role of carbon in past and future climate

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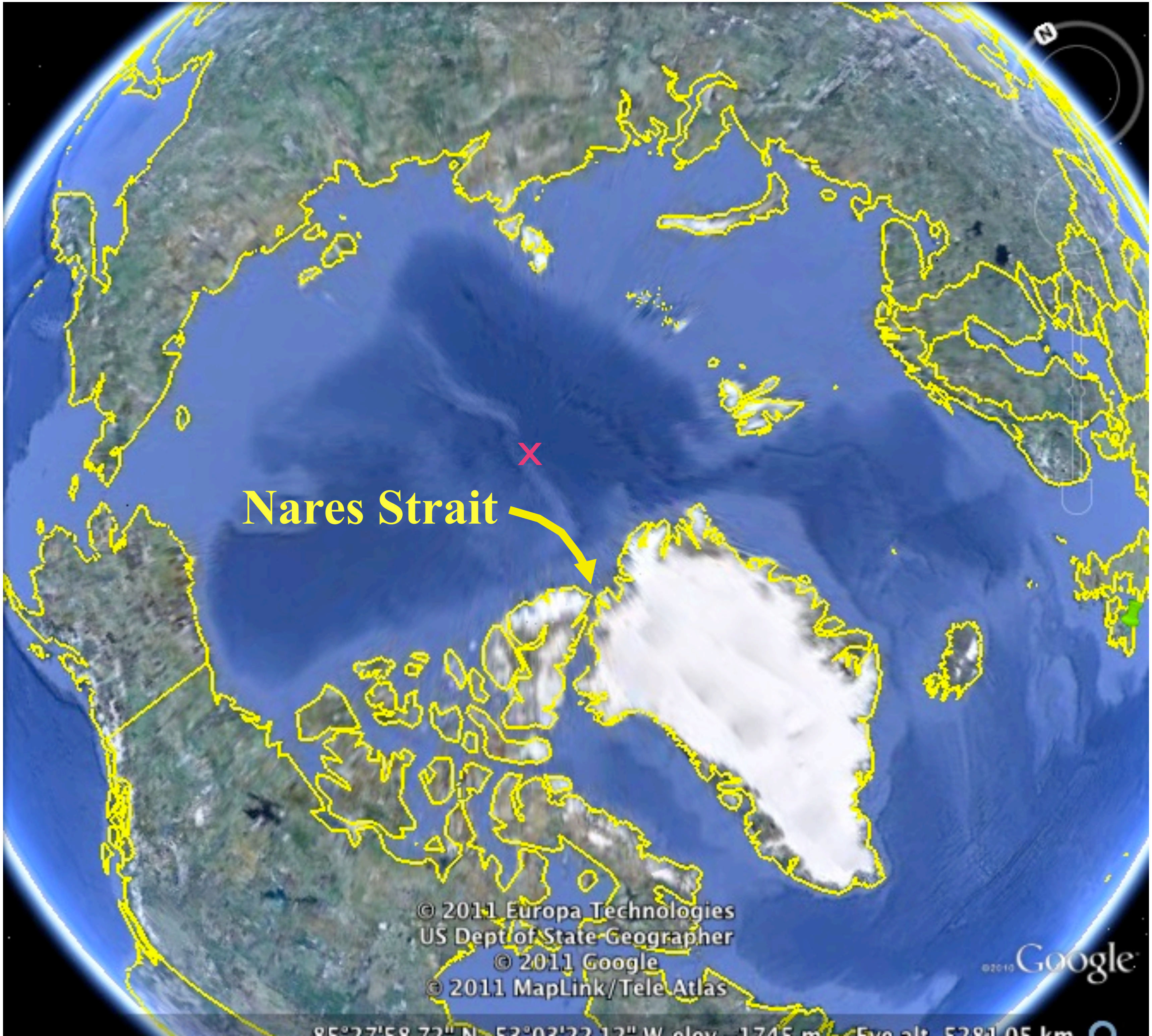

Nares Strait
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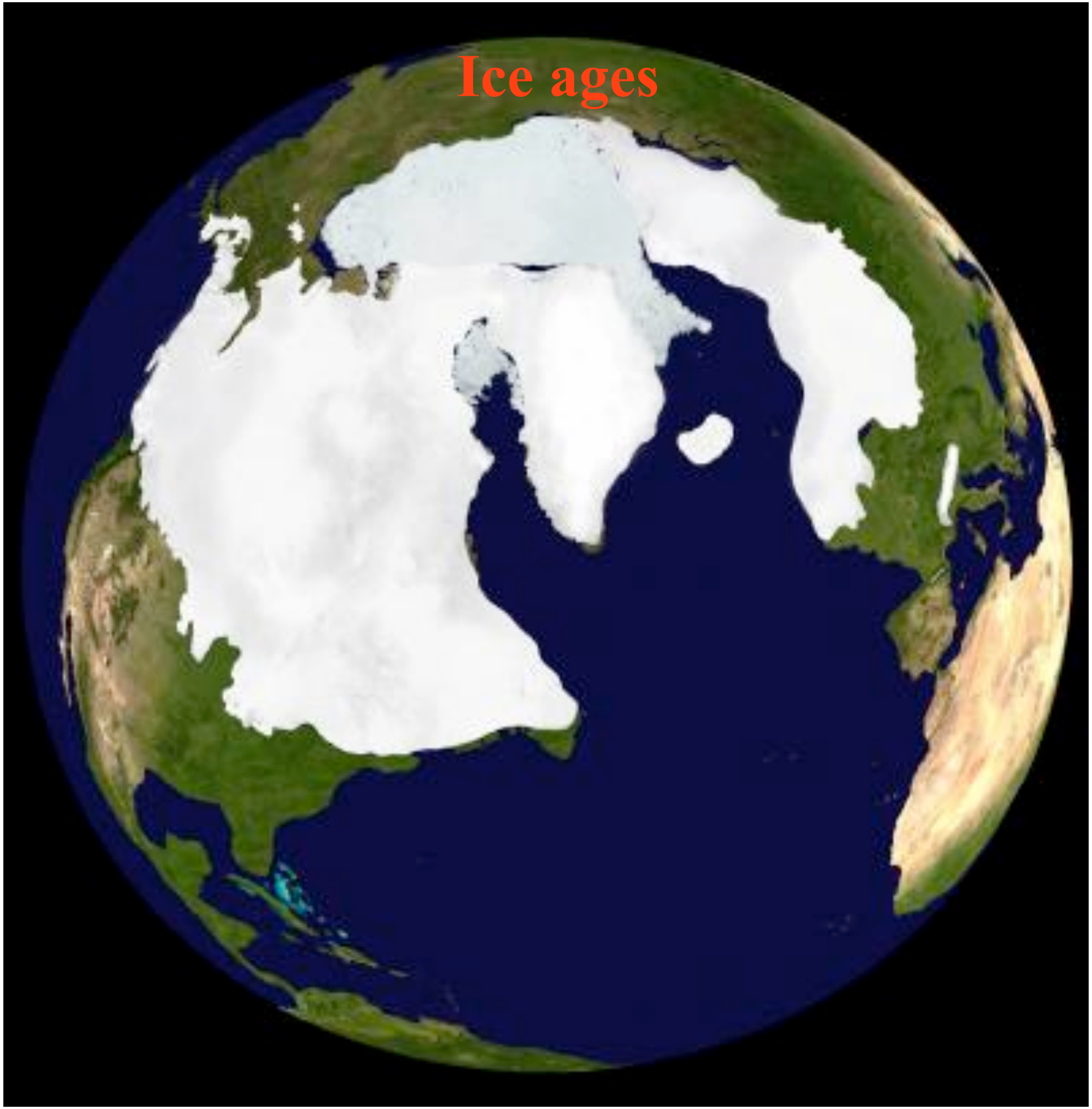
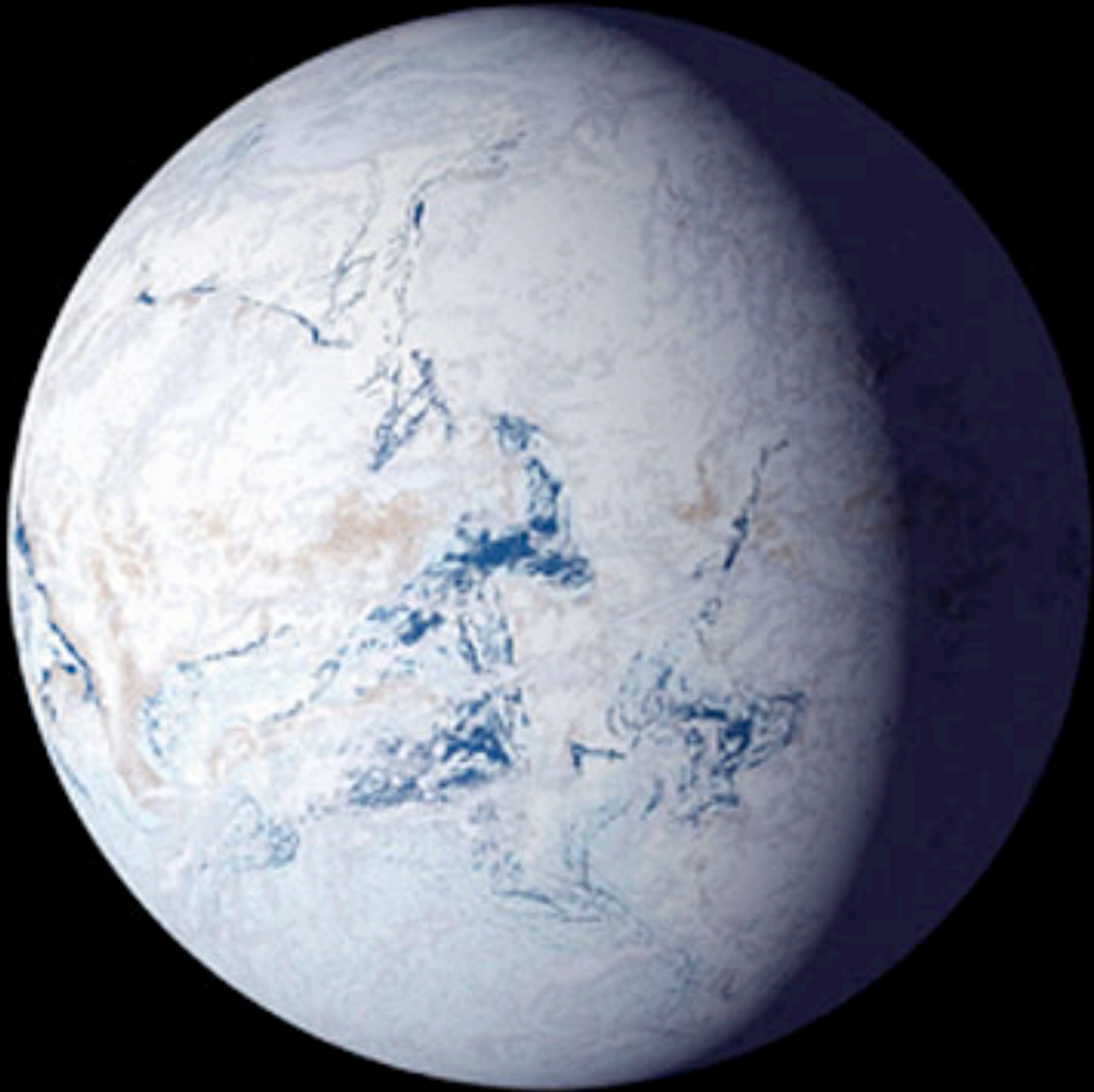
Ice ages



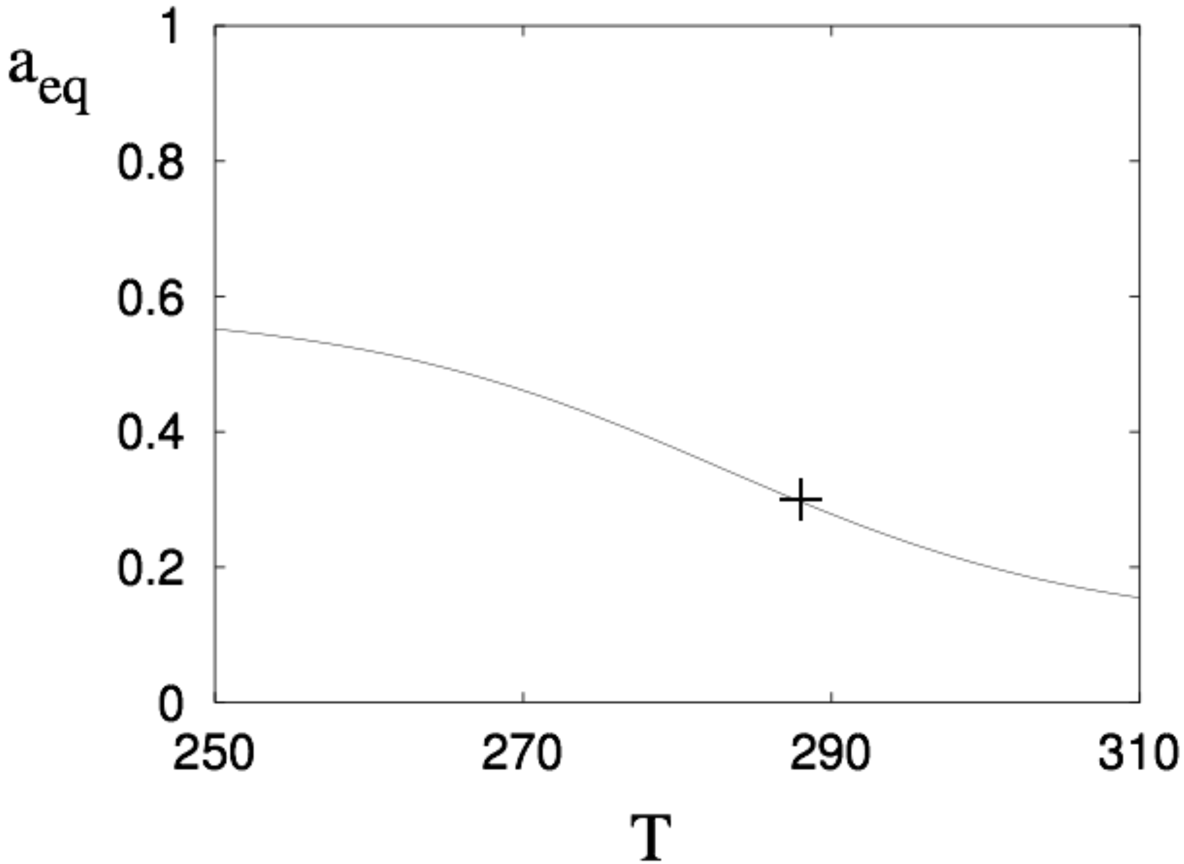
Snowball Earth



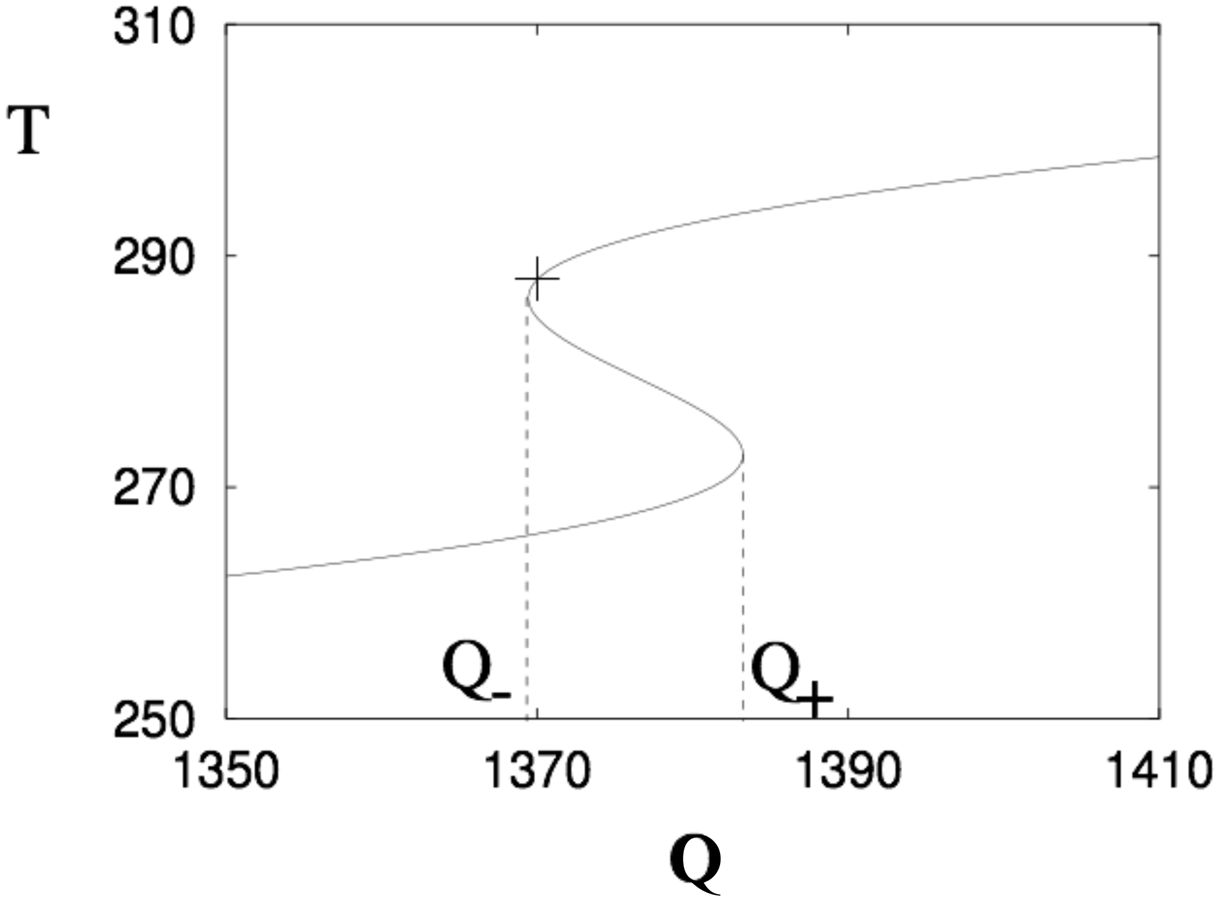
Energy balance model

$$\rho_a c_p d\frac{dT}{dt} = \tfrac{1}{4}(1-a)Q - \sigma\gamma T^4$$

Ice-albedo feedback

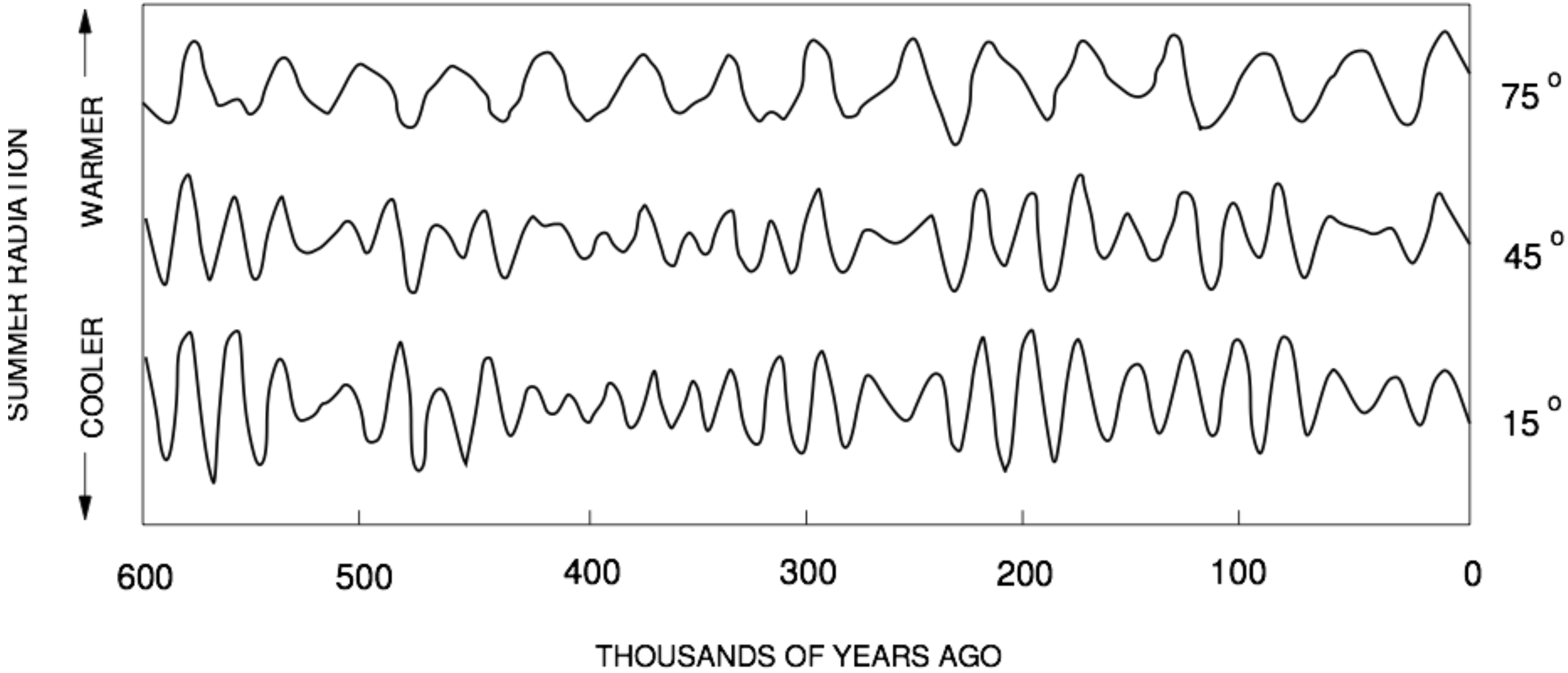


Bistability



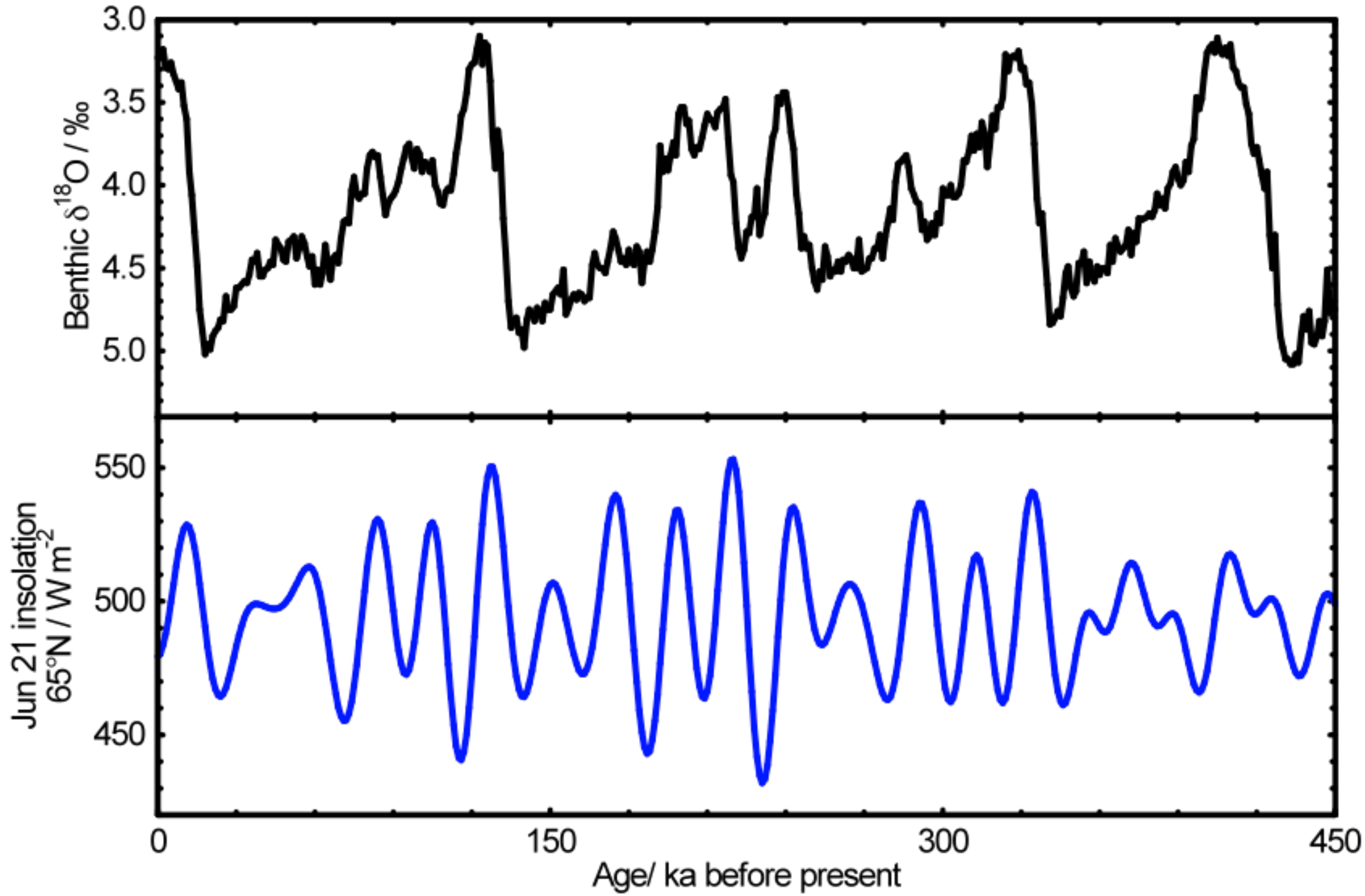
$$\rho_a c_p d\frac{dT}{dt} = \tfrac{1}{4}(1-a)Q - \sigma\gamma T^4$$

Milanković

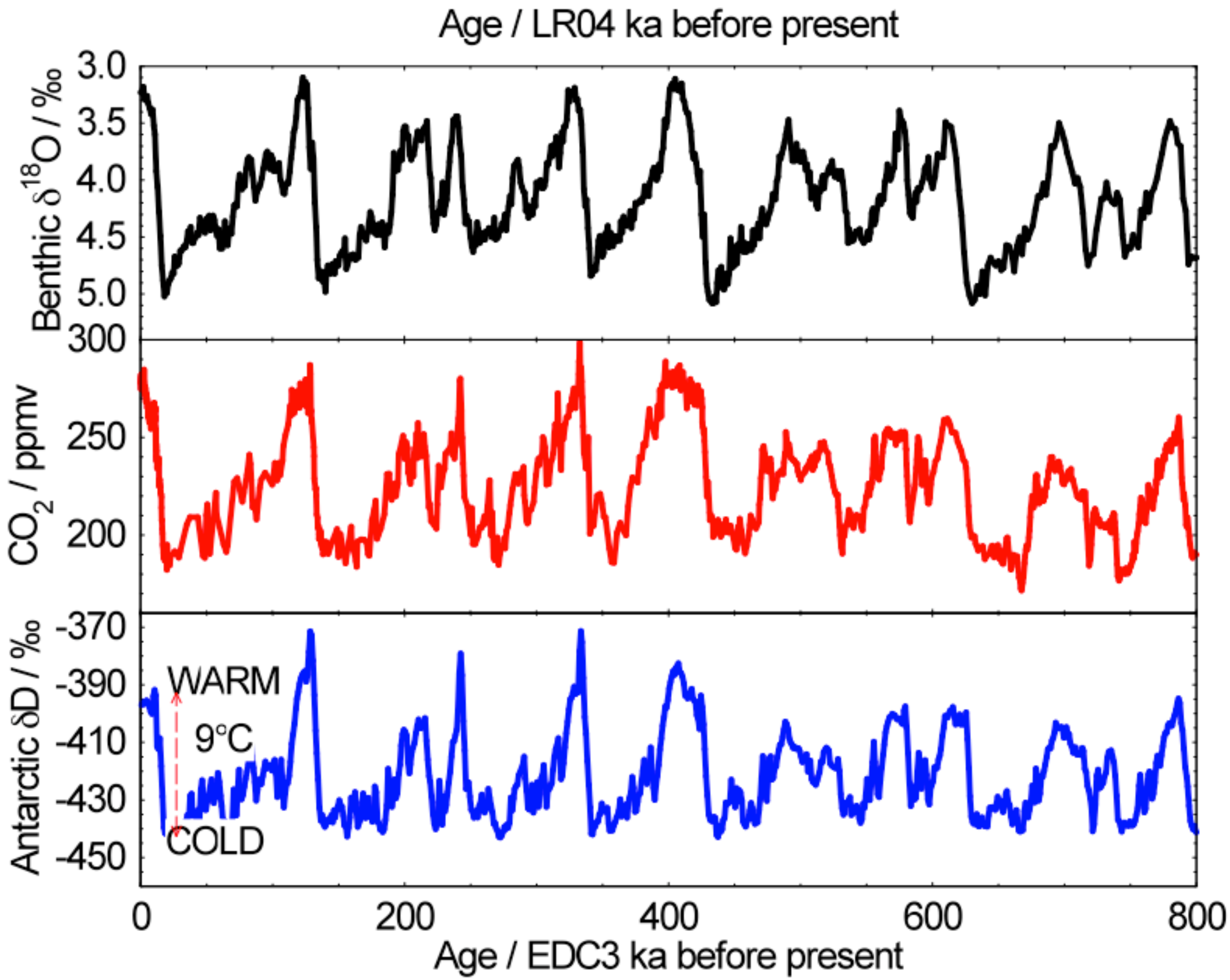


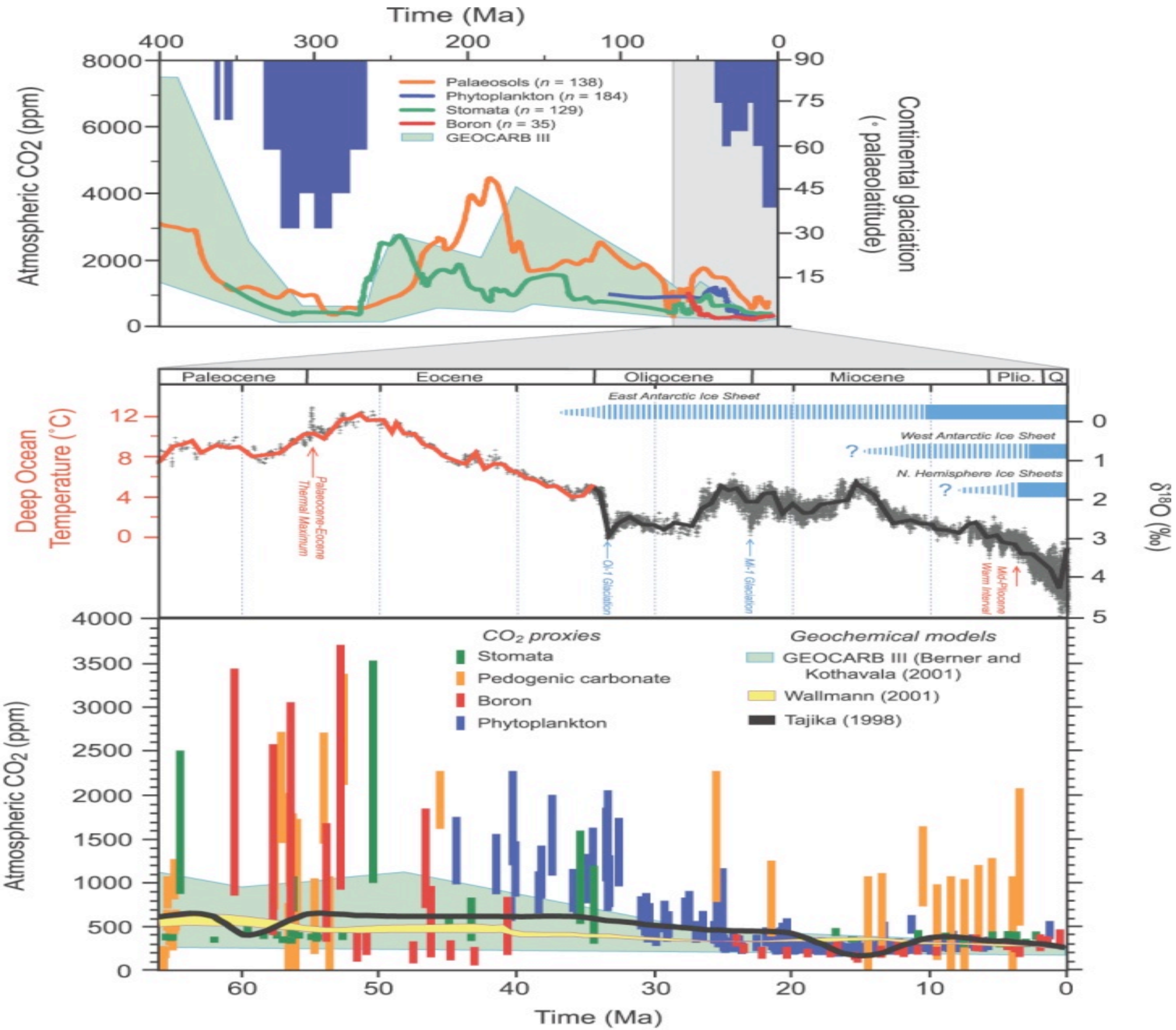
Problems: no 100 kyr cycle
no saw tooth

Sawtooth oscillations

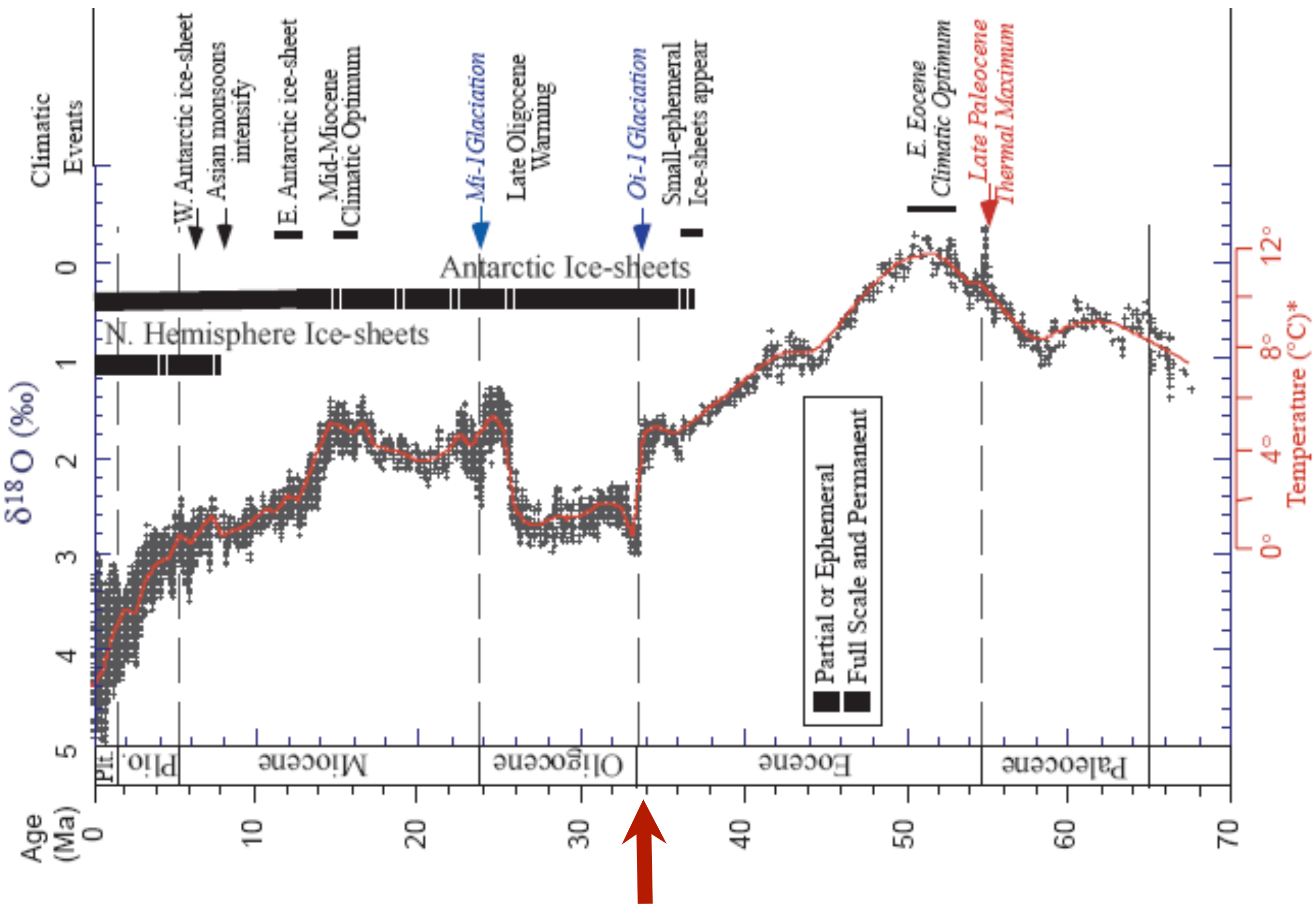


Milanković


Age / LR04 ka before present
Benthic δ18O / ‰
3.0
3.5
4.0
4.5
5.0
300
CO2 / ppmv
250
200
Antarctic δD / ‰
-370
-390
-410
-430
-450
WARM
9°C
COLD
0
200
400
600
800
Age / EDC3 ka before present

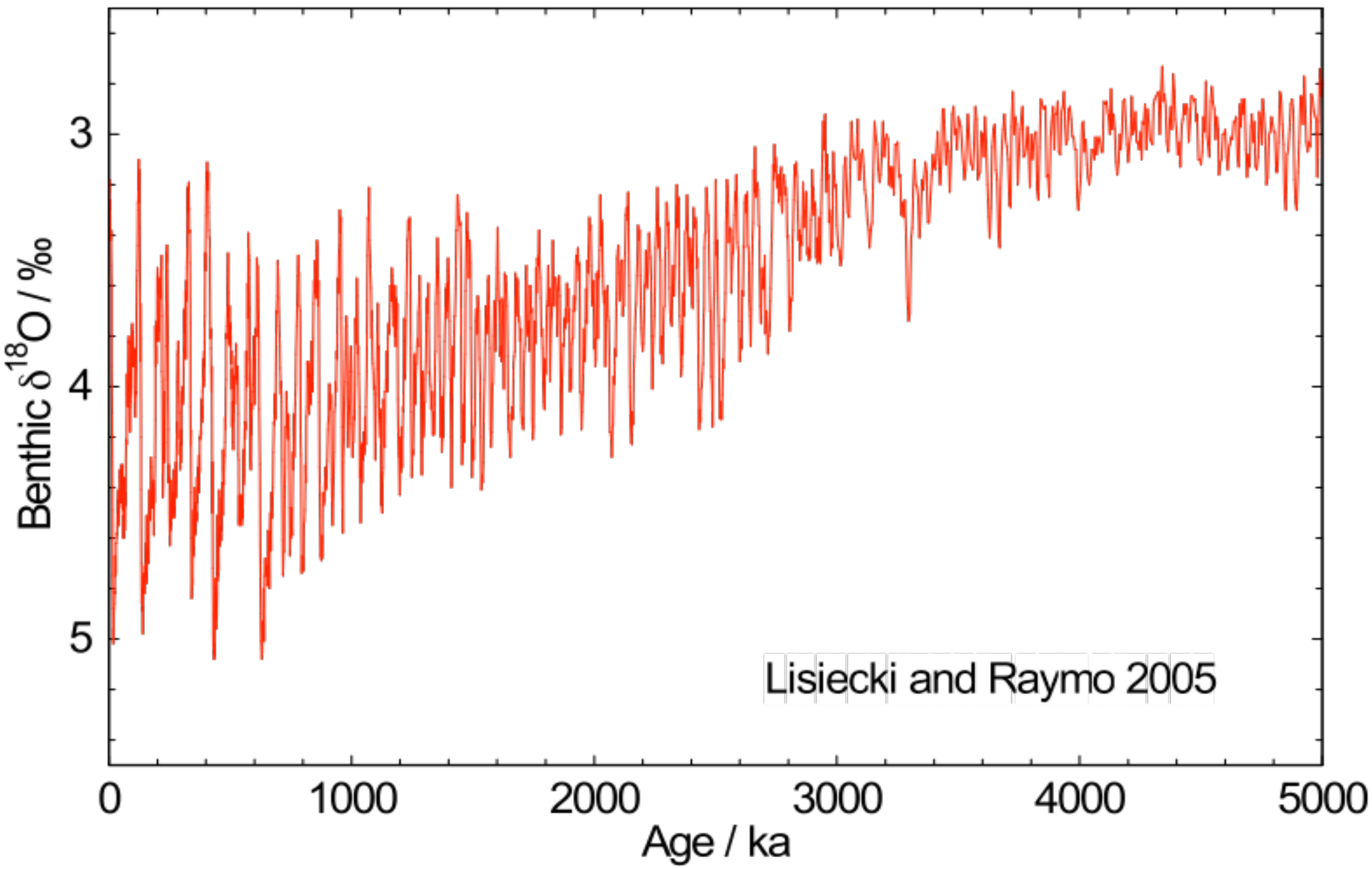


Time (Ma)
Atmospheric CO2 (ppm)
Continental glaciation (° palaeolatitude)
Palaeosols (n = 138)
Phytoplankton (n = 184)
Stomata (n = 129)
Boron (n = 35)
GEOCARB III
Paleocene
Eocene
Oligocene
Miocene
Plio.
Q
East Antarctic Ice Sheet
West Antarctic Ice Sheet
N. Hemisphere Ice Sheets
Deep Ocean Temperature (°C)
δ18O (‰)
Palaeocene-Eocene Thermal Maximum
Oi-1 Glaciation
Mi-1 Glaciation
Mid-Pliocene Warm Interval
CO2 proxies
Stomata
Pedogenic carbonate
Boron
Phytoplankton
Geochemical models
GEOCARB III (Berner and Kothavala (2001)
Wallmann (2001)
Tajika (1998)

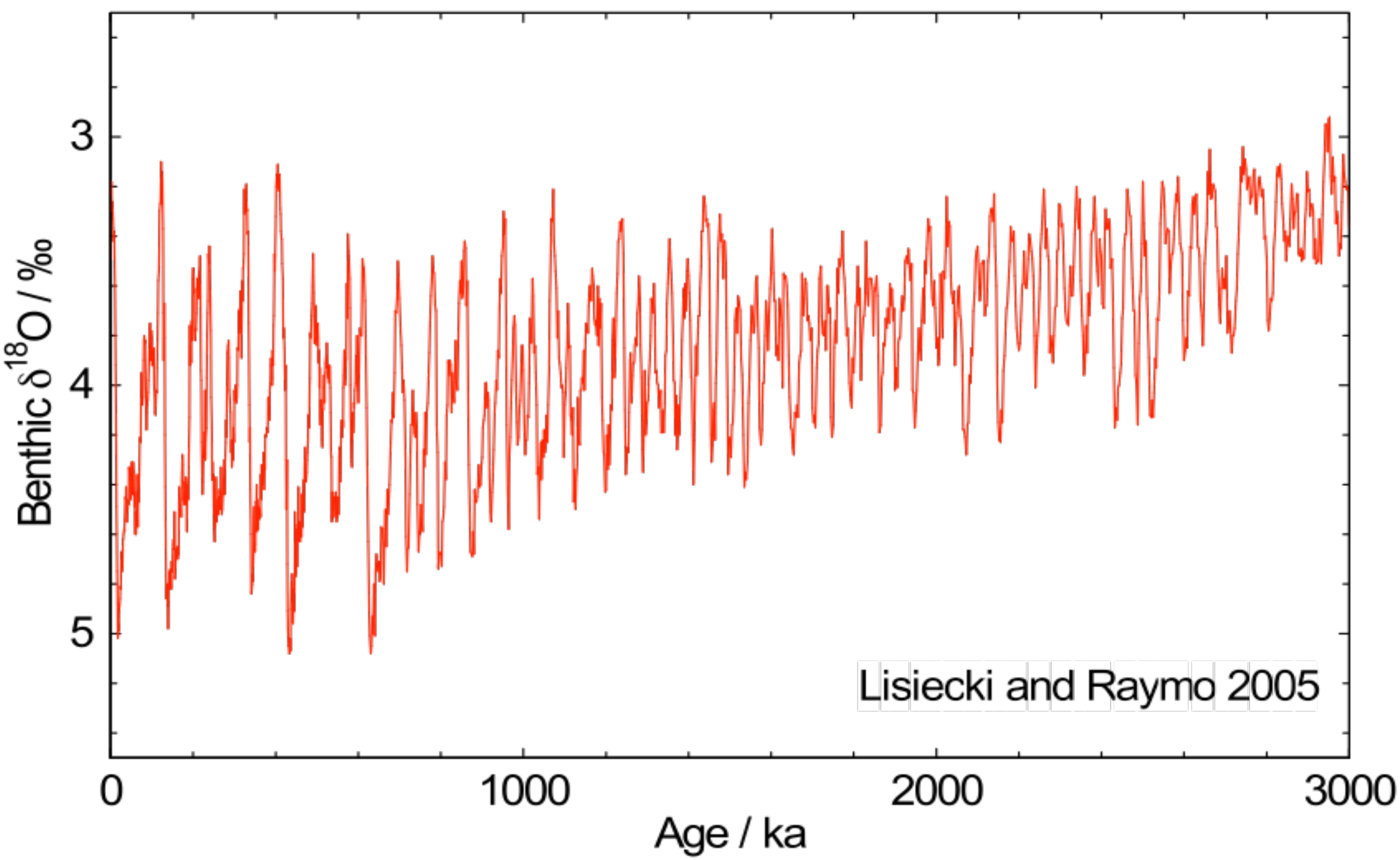


Climatic Events
W. Antarctic ice-sheet
Asian monsoons intensify
E. Antarctic ice-sheet
Mid-Miocene Climatic Optimum
Mi-1 Glaciation
Late Oligocene Warming
Oi-1 Glaciation
Small-ephemeral Ice-sheets appear
E. Eocene Climatic Optimum
Late Paleocene Thermal Maximum
Antarctic Ice-sheets
N. Hemisphere Ice-sheets
δ18 O (‰)
Temperature (°C)*
Partial or Ephemeral
Full Scale and Permanent
Pt.
Plio.
Miocene
Oligocene
Eocene
Paleocene
Age (Ma)

Antarctica



100 kyr ← **40 kyr**

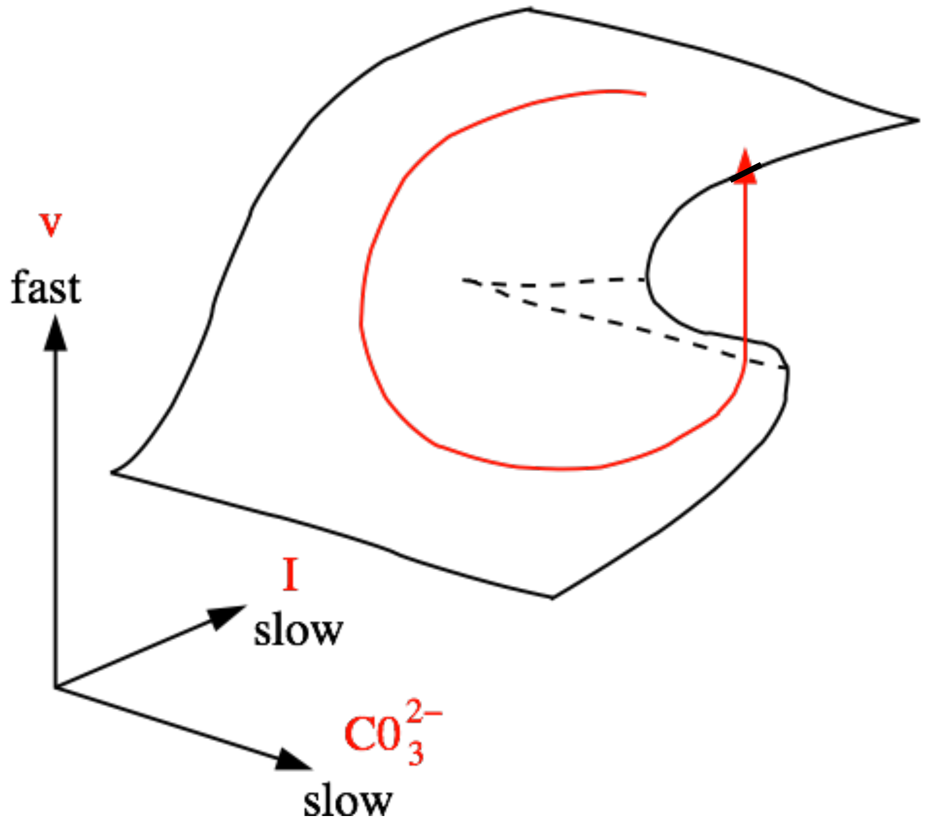

Benthic δ18O / ‰
3
4
5
0
1000
2000
3000
Age / ka
Lisiecki and Raymo 2005

Input:

- not Milanković
- CO_2 driver
- sawtooth → 3 variable

Output:

- sawtooth
- post_Eocene cooling
- anthropogenic warming
- snowball Earth
- mid-Pleistocene transition



Energy balance

$$c\dot{T} = \tfrac{1}{4}Q_s(1-a) - \sigma e^{-\Gamma}T^4$$

thus

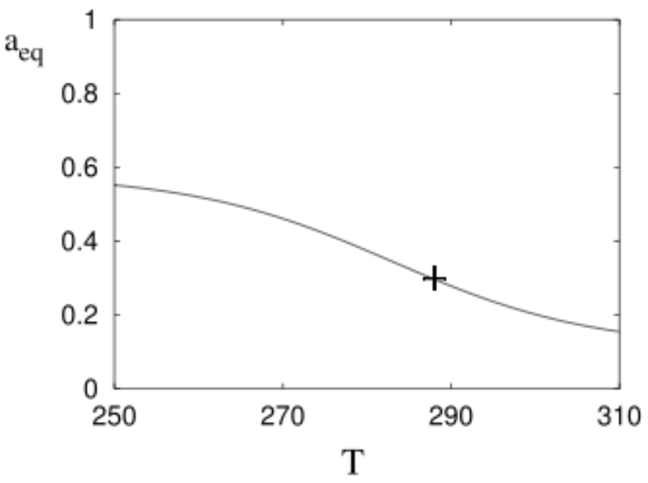
$$\Delta T \approx \frac{\frac{T}{4}\left[\Gamma_p \Delta p - \frac{a_I}{1-a}\Delta I\right]}{1 + \frac{T}{4}\left\{\frac{a_T}{1-a} - \Gamma_T\right\}}$$

A (too) simple model of ice ages

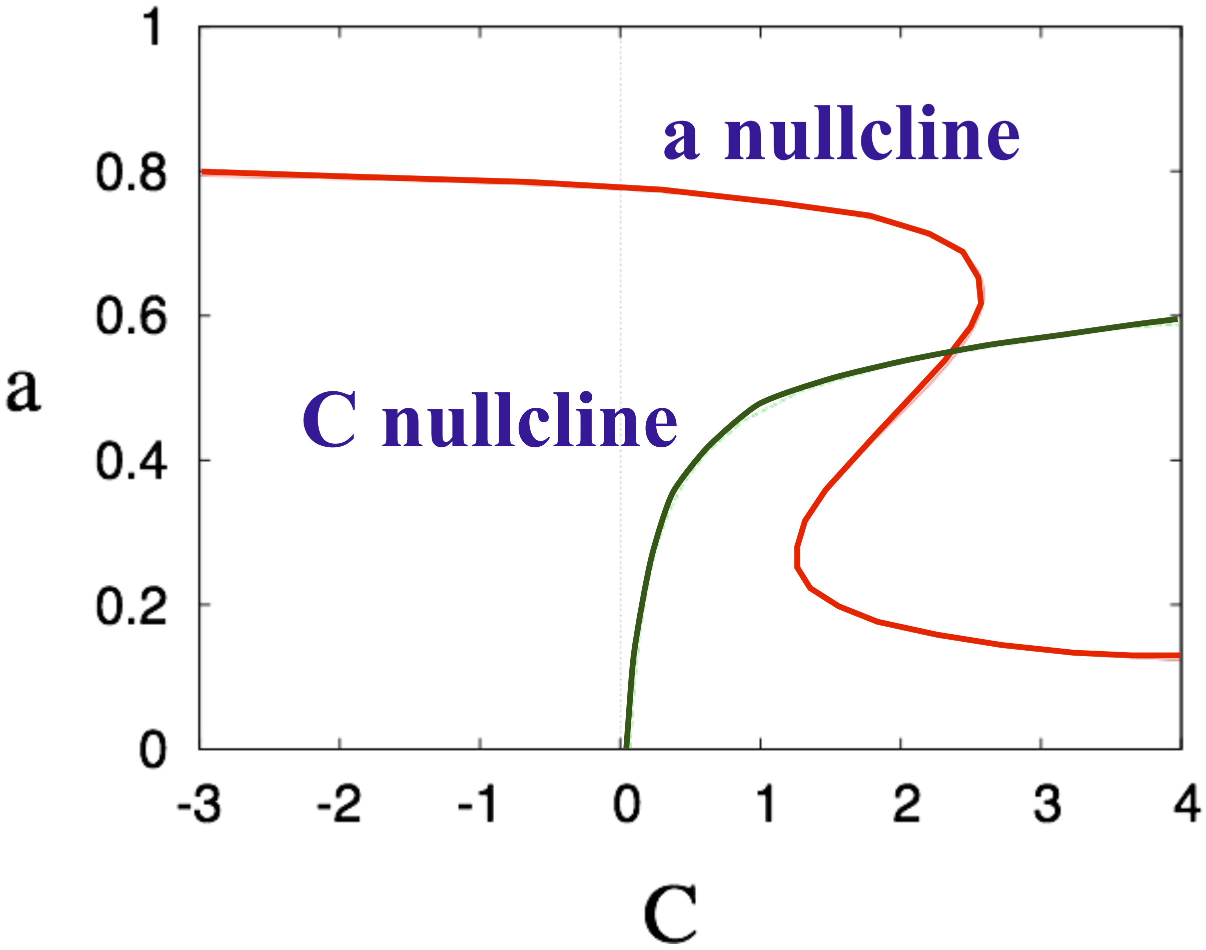
Temperature $$\theta \approx \kappa(a_0 - a) + \lambda p,$$

Ice albedo $$\dot{a} = B(\theta) - a,$$

Ocean carbon $$\dot{C} = \delta\left[C_\infty - b^*(a)C\right]$$

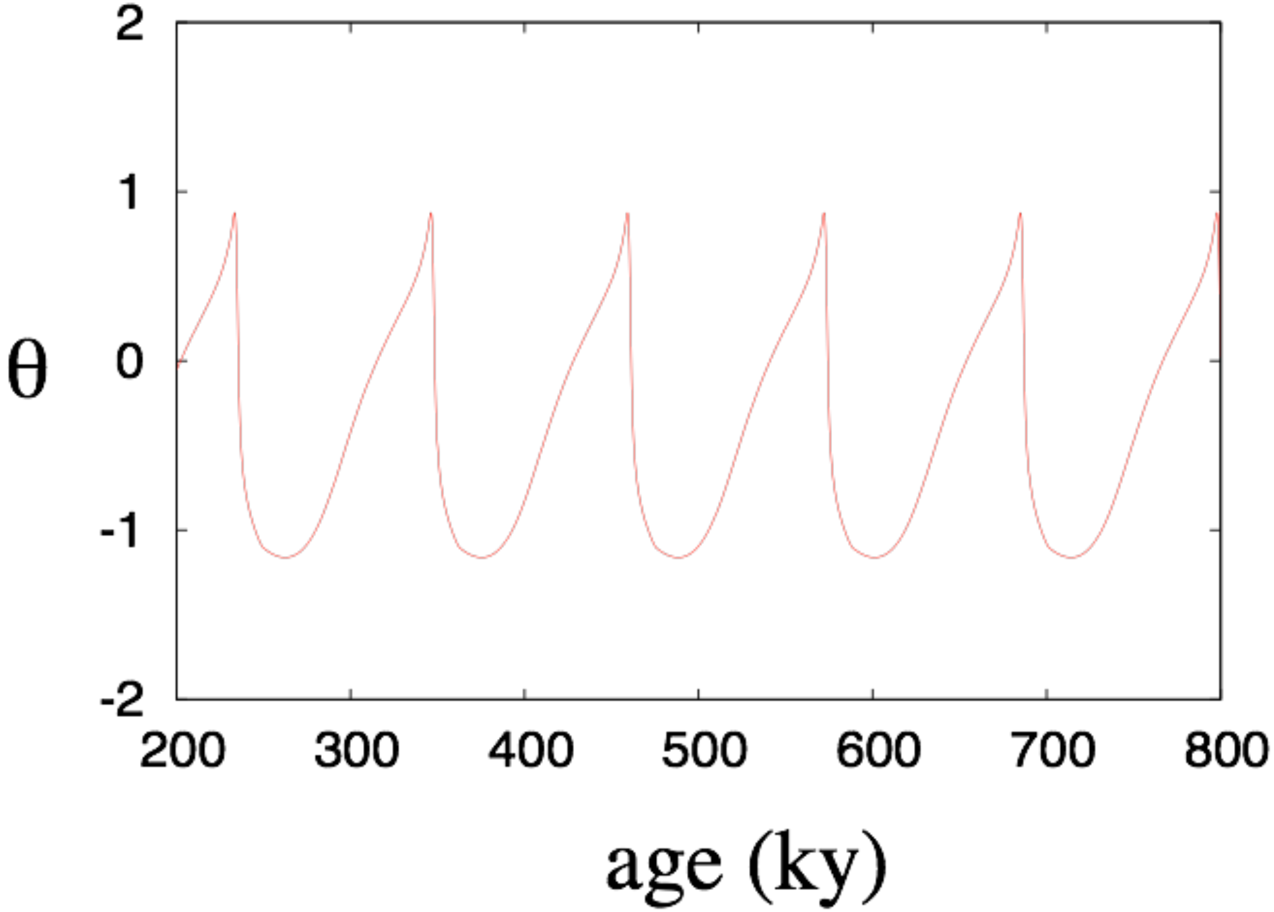


Burial



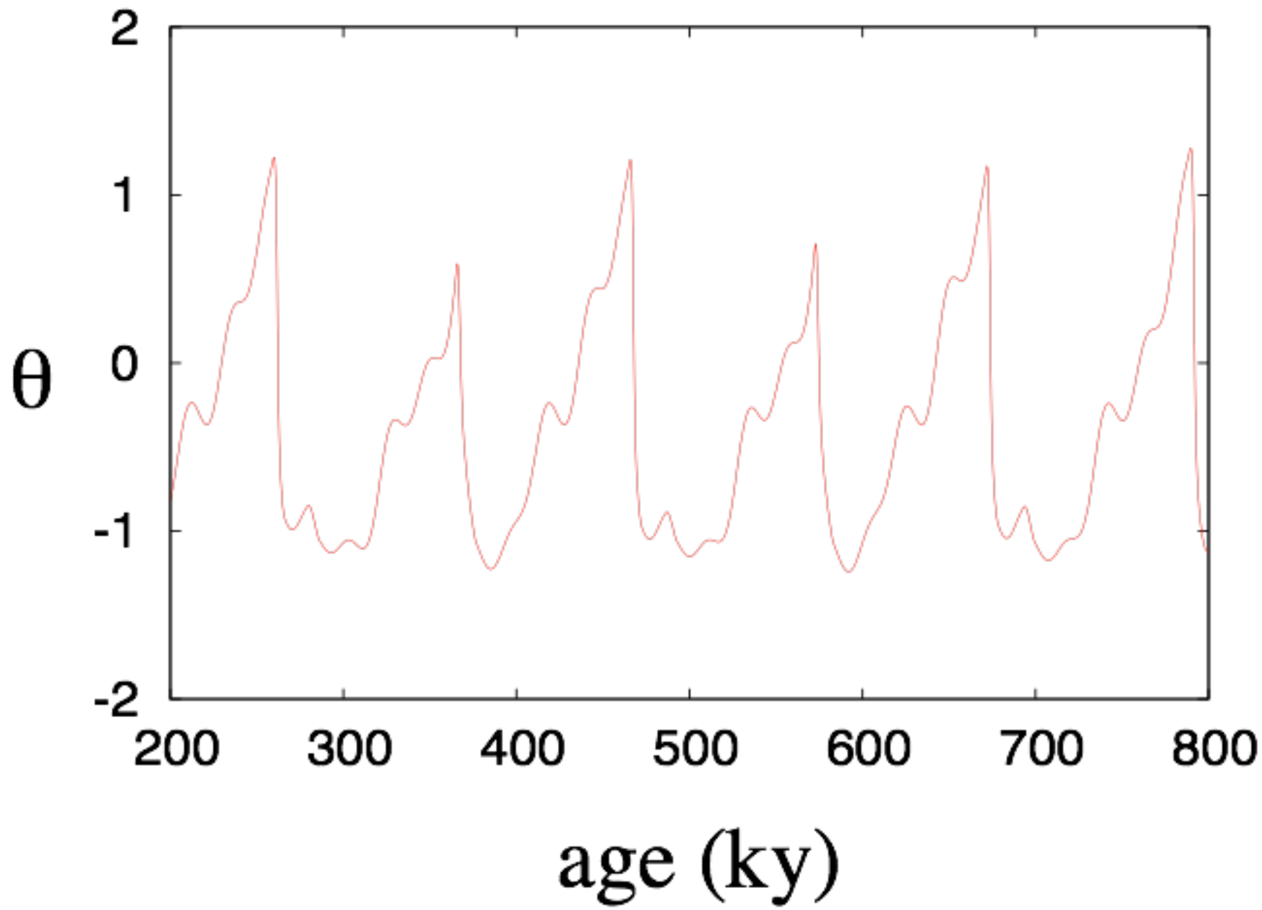
1
0.8
0.6
0.4
0.2
0
a
-3
-2
-1
0
1
2
3
4
C
a nullcline
C nullcline

oscillations

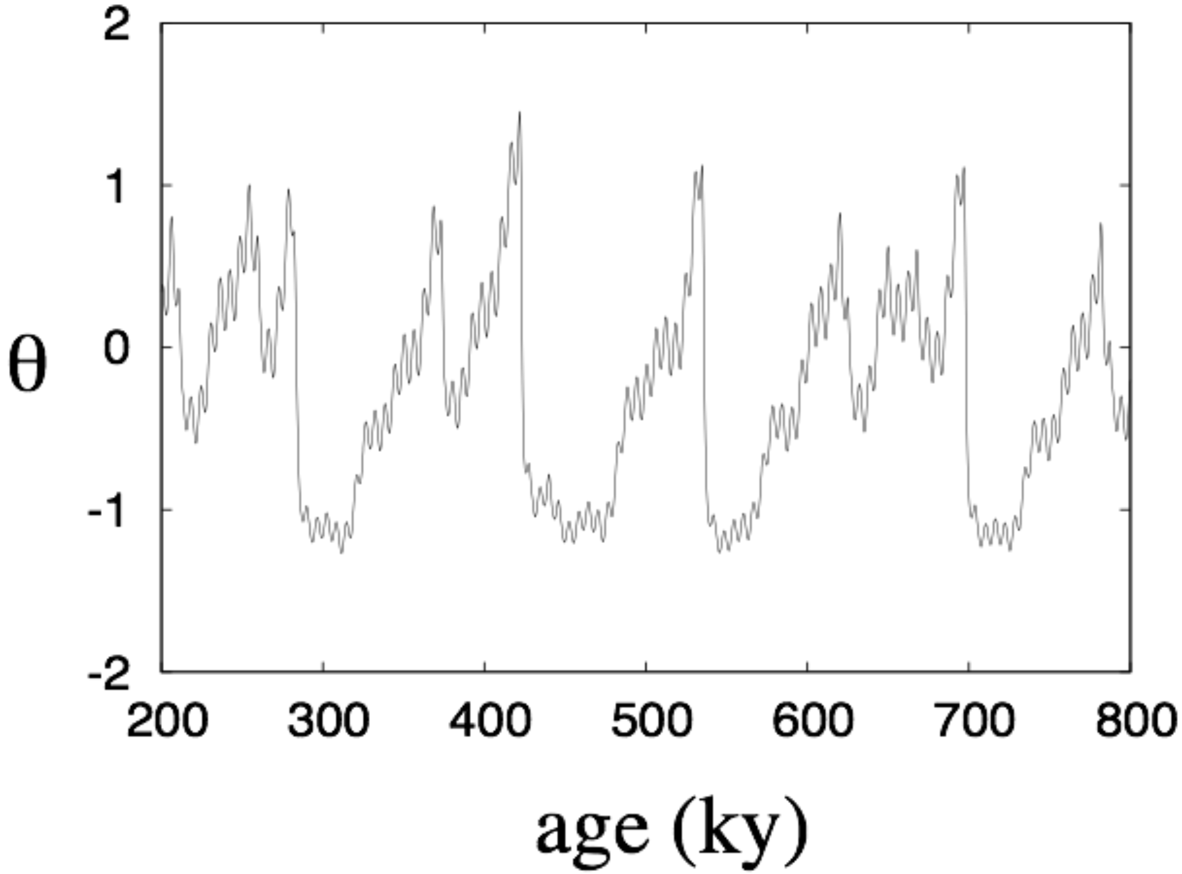


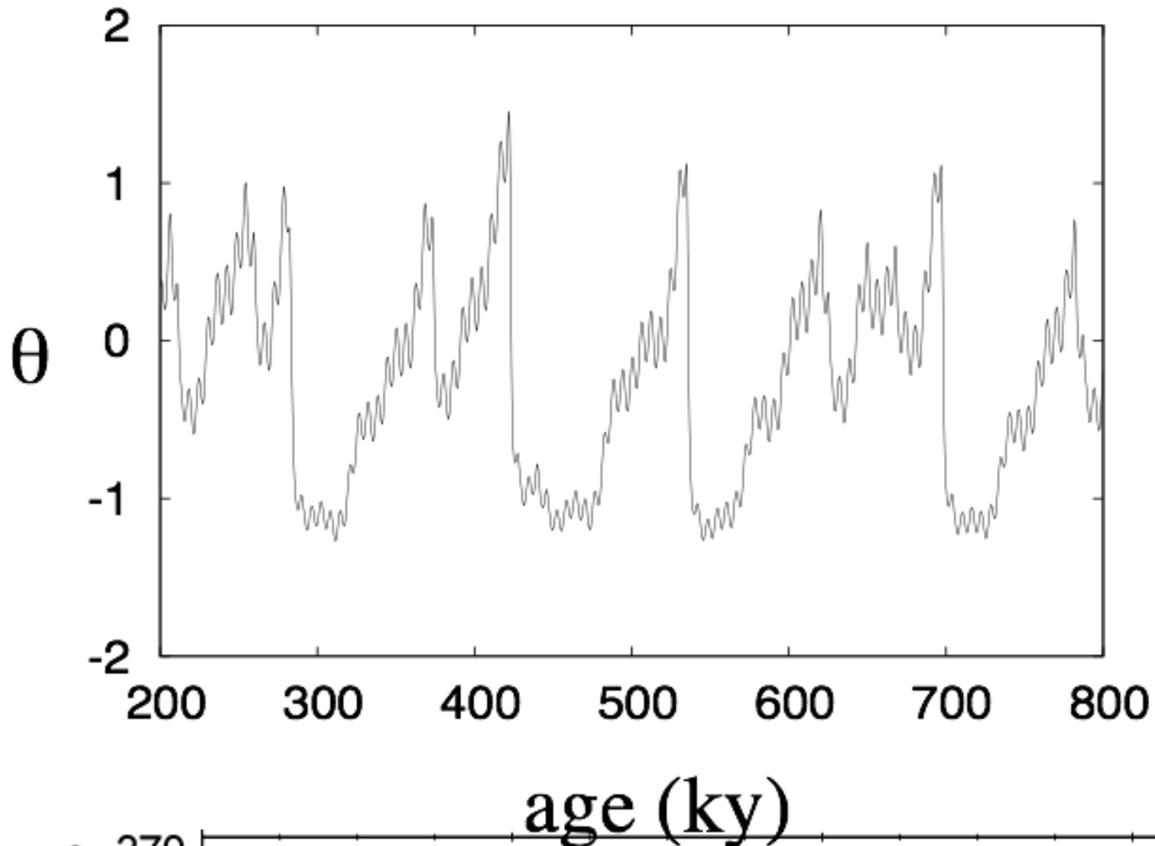
enhanced melt rate during wastage!

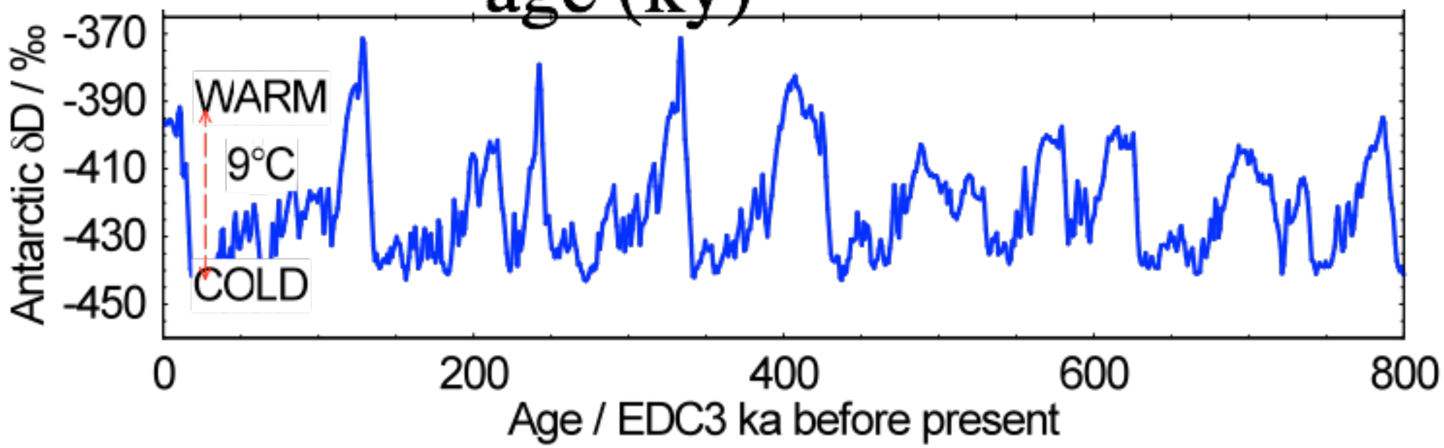
with Milanković



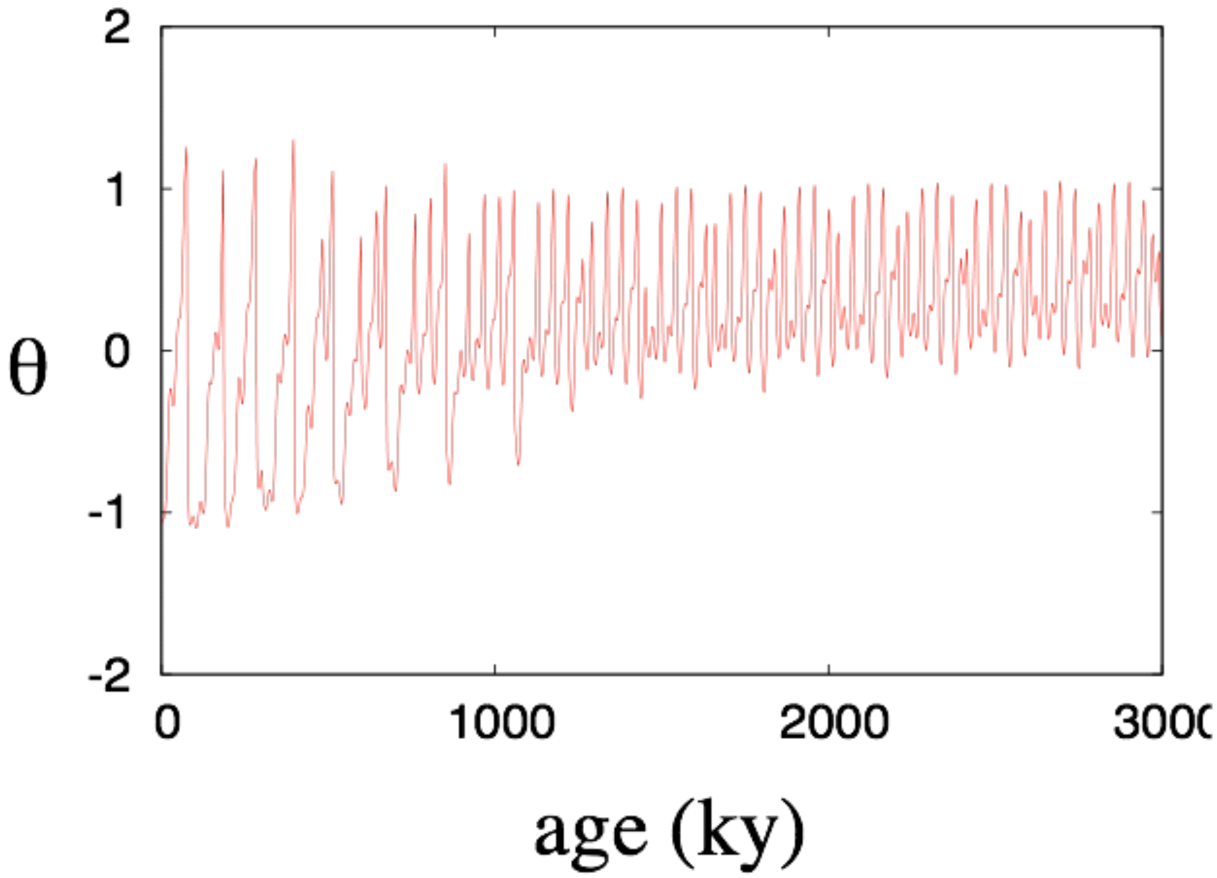
plus ‘D-O’ fluctuations



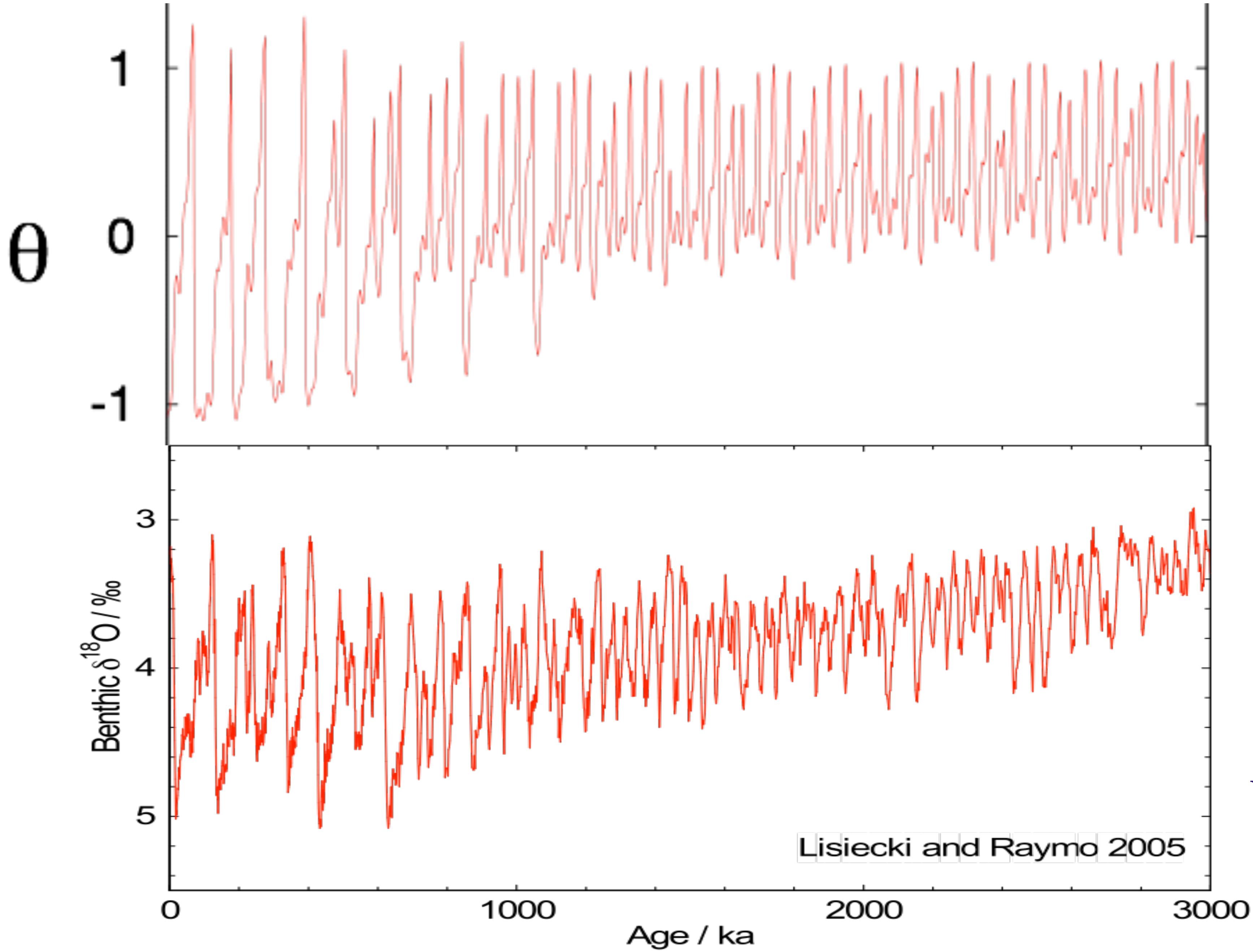

θ
2
1
0
-1
-2
200
300
400
500
600
700
800
age (ky)


Antarctic δD / ‰
-370
-390
-410
-430
-450
WARM
9°C
COLD
0
200
400
600
800
Age / EDC3 ka before present

post-Eocene cooling



via slow background decrease in C


θ
1
0
-1
3
4
5
Benthic δ18O / ‰
Lisiecki and Raymo 2005
0
1000
2000
3000
Age / ka

but...

Henry's law

sea surface $$p_s = \frac{[CO_2]}{K_H}$$

Carbon buffering

$$[H_2O] + CO_2 \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} HCO_3^- + H^+$$

$$HCO_3^- \underset{k_{-2}}{\overset{k_2}{\rightleftharpoons}} CO_3^{2-} + H^+$$

← H^+ ← Ca^{2+} ← $CaCO_3$

← biota

$$Ca^{2+} + HCO_3^- \rightleftharpoons CaCO_3 + H^+$$

rate-limited by P

thermal activation

$$P_B + P \xrightarrow{k_3} 2P_B$$

$$P_B \xrightarrow{k_{-3}} P$$ dissolution

C > P ← supersaturation, precipitation

$$Ca^{2+} + CO_3^{2-} \rightleftharpoons CaCO_3$$

Reaction rates

carbon buffering

$$R_1 = k_1[CO_2] - k_{-1}[HCO_3^-][H^+],$$
$$R_2 = k_2[HCO_3^-] - k_{-2}[CO_3^{2-}][H^+].$$

biomass

$$r_3 = k_3[P_B][P] - k_{-3}[P_B] \qquad R_3 = Rr_3.$$

precipitation

$$R_4 = k_4\left([Ca^{2+}][CO_3^{2-}] - K_{cp}\right)^n$$

Weathering

$$CaSiO_3 + 2CO_2 + H_2O \longrightarrow Ca^{2+} + 2HCO_3^- + SiO_2$$

$$Ca^{2+} + 2HCO_3^- \longrightarrow CaCO_3 + CO_2 + H_2O$$

overall ...

$$CaSiO_3 + CO_2 \longrightarrow CaCO_3 + SiO_2$$

essentially:

$$C \rightarrow HCO_3^- + \tfrac{1}{2}Ca^{2+}$$

$$Ca^{2+} + HCO_3^- \underset{k_{-3}}{\overset{k_3}{\rightleftharpoons}} CaCO_3 + H^+$$

Reactions

$$
\begin{aligned}
[\dot{\mathrm{CO}_2}] &= -R_1 + h(p - p_s), \\
[\dot{\mathrm{CO}_3^{2-}}] &= R_2 - R_4, \\
[\dot{\mathrm{HCO}_3^{-}}] &= R_1 - R_2 - R_3 + A^*W, \\
[\dot{\mathrm{H}^{+}}] &= R_1 + R_2 + R_3, \\
[\dot{\mathrm{Ca}^{2+}}] &= -R_3 - R_4 + \tfrac{1}{2}A^*W, \\
[\dot{\mathrm{CaCO}_3}] &= R_3 + R_4 - B[\mathrm{CaCO}_3], \\
[\dot{\mathrm{P}}] &= -r_3 + \rho A^*W, \\
[\dot{\mathrm{P}_\mathrm{B}}] &= r_3 - B[\mathrm{P}_\mathrm{B}],
\end{aligned}
$$

Quasi-equilibrium, $R_1 \approx R_2 \approx 0$

Atmospheric CO_2

$$\frac{A_E}{M_a g m_{oc}} \dot{p} = v - A^* W - h(p - p_s)$$

Weathering

$$W = W_0 \left(\frac{p}{p_0} \right)^{\mu} \exp \left[\frac{T - T_0}{\Delta T_c} \right]$$

Non-dimensionalisation

$$p_{CO_2} \qquad \varepsilon\dot{p} = 1 - \Omega w - \Lambda(p - p_s),$$

$$[HCO_3^-] \qquad \eta\dot{Q} = 2\Lambda(p - p_s) + \Omega w,$$

$$[CO_3^{2-}] \qquad \nu\dot{S} = -\beta u_b - u_p - \Lambda(p - p_s),$$

$$[CaCO_3] \qquad \dot{N} = \beta u_b + u_p - N,$$

$$[P]: \qquad \zeta\dot{P} = -u_b + \frac{\gamma\Omega w}{\beta},$$

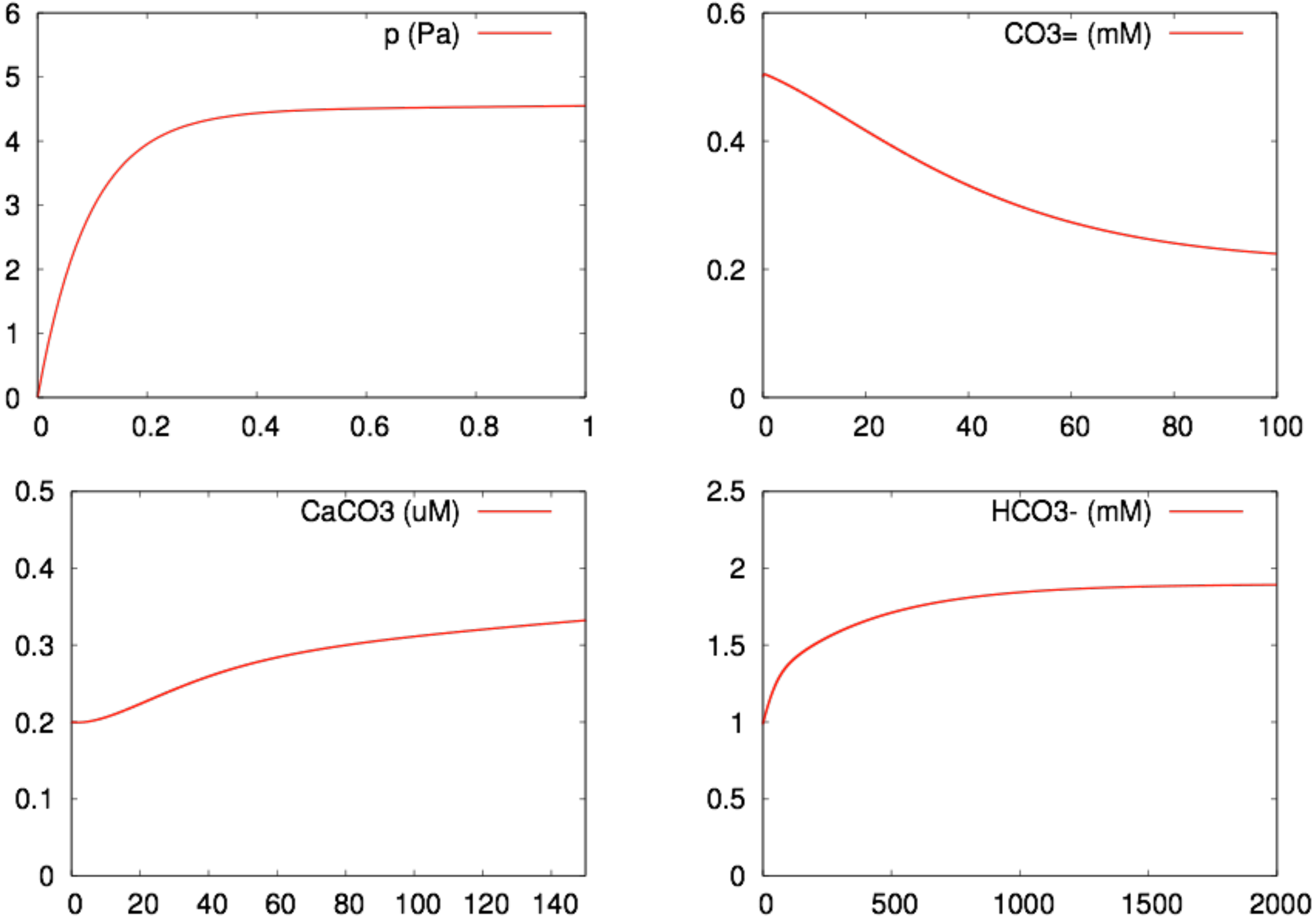
Formation of $CaCO_3$ $\quad u_b = (\kappa_3 P - 1)P_B, \quad u_p \approx S - \Sigma$

Ocean surface CO_2 $\quad p_s = \dfrac{Q^2}{\kappa_H S}$

Weathering $\quad w = p^\mu e^\theta$

Energy balance $\quad \theta = \lambda \ln p - \kappa I$

Non-dimensionalisation


p (Pa)
CO3= (mM)
CaCO3 (uM)
HCO3- (mM)
0
0.2
0.4
0.6
0.8
1
20
40
60
80
100
120
140
500
1000
1500
2000
2
3
4
5
6
0.1
0.3
0.5
1.5
2.5

t in kyr

Post-Eocene cooling

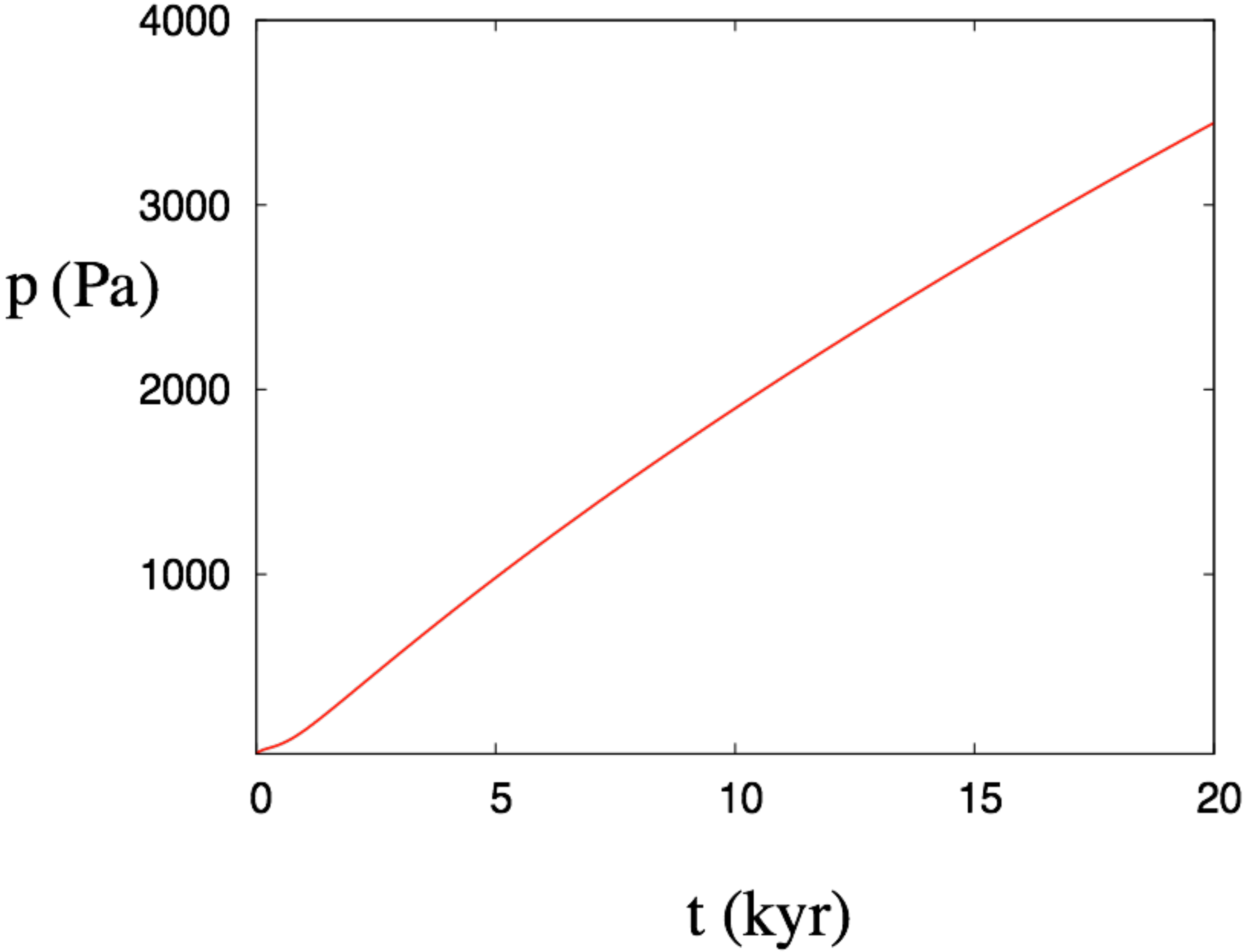
via increasing weathering [India]
or decreased CO_2 production

Global warming

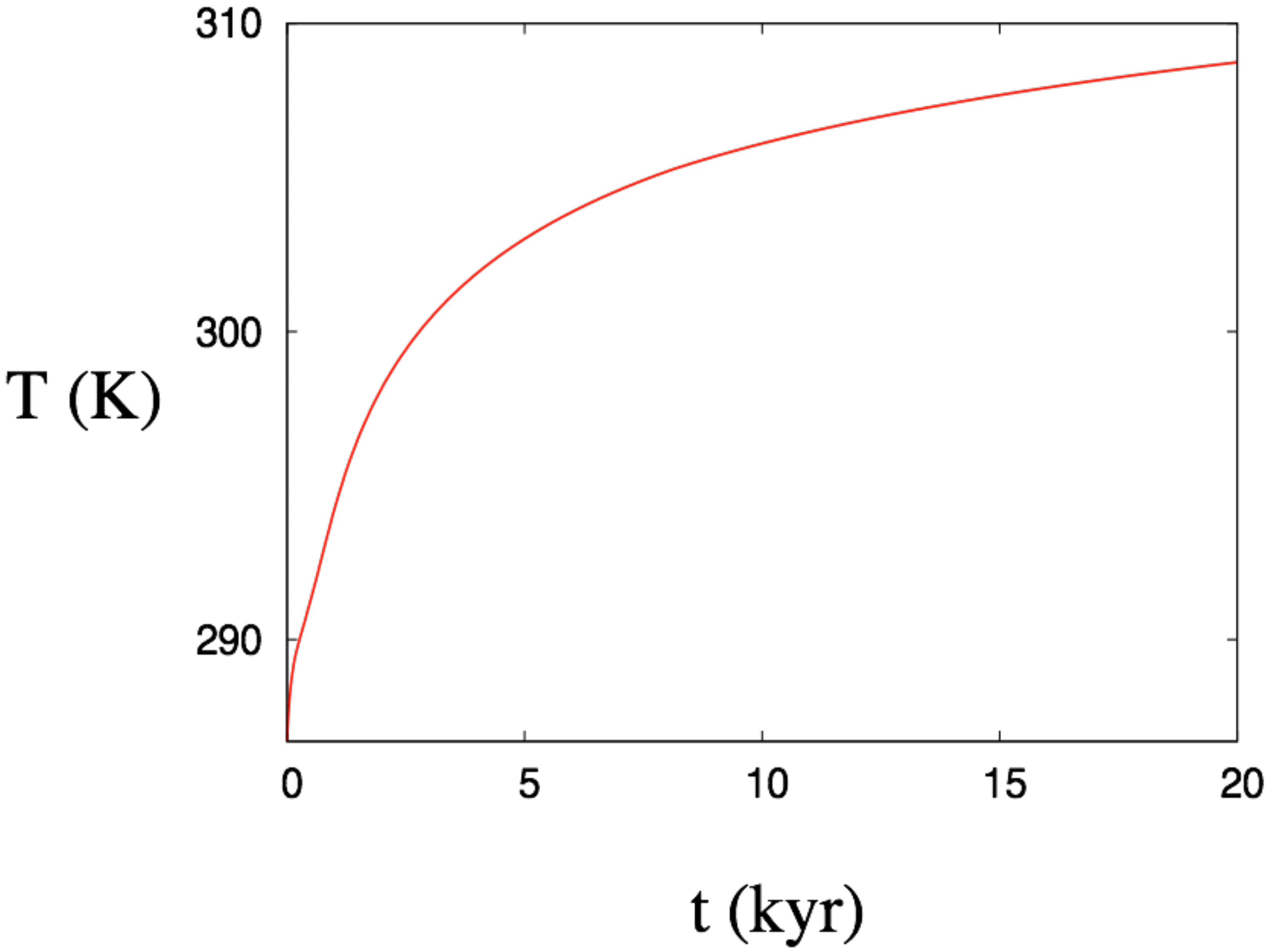
$v_A \approx 70\ v_P$

CO_2 equilibrates $p \approx 560$ Pa, $t \sim 300$ y

$CO_3^{2-} \downarrow HCO_3^- \uparrow \approx CO_2 \Uparrow$ (and H^+) $t \sim 2000$ y

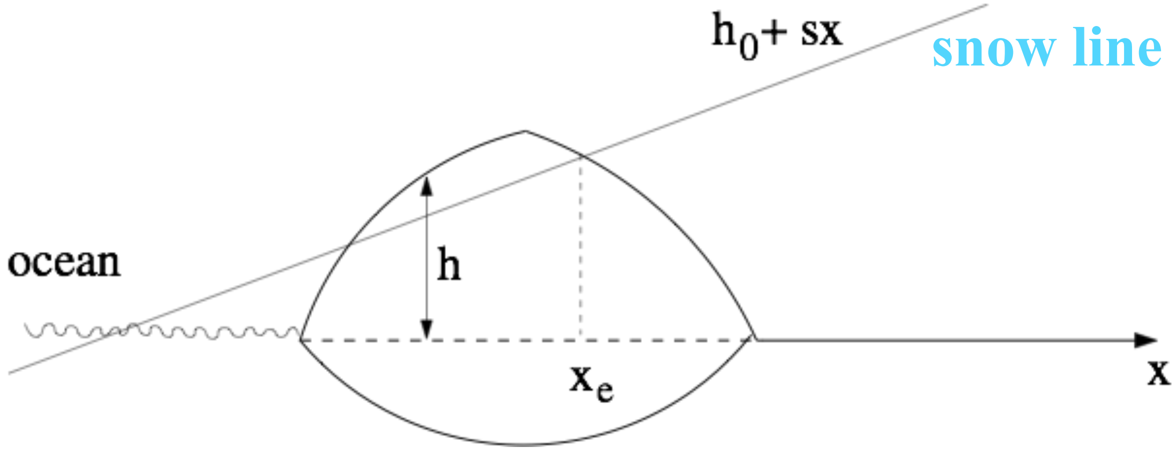


4000
3000
2000
1000
p (Pa)
0
5
10
15
20
t (kyr)

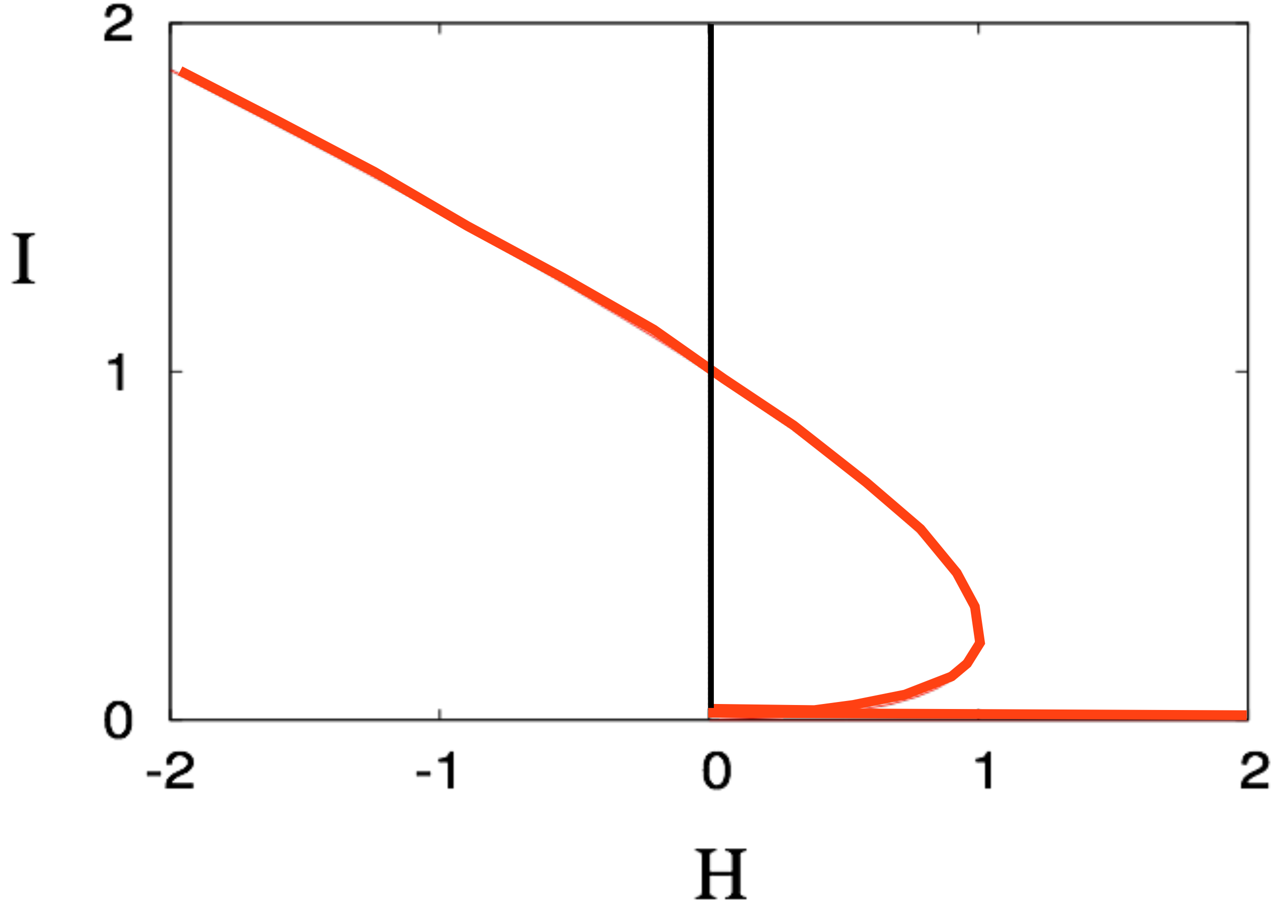


310
300
290
T (K)
0
5
10
15
20
t (kyr)

Ice sheet model



Plastic flow (Weertman, Ghil)

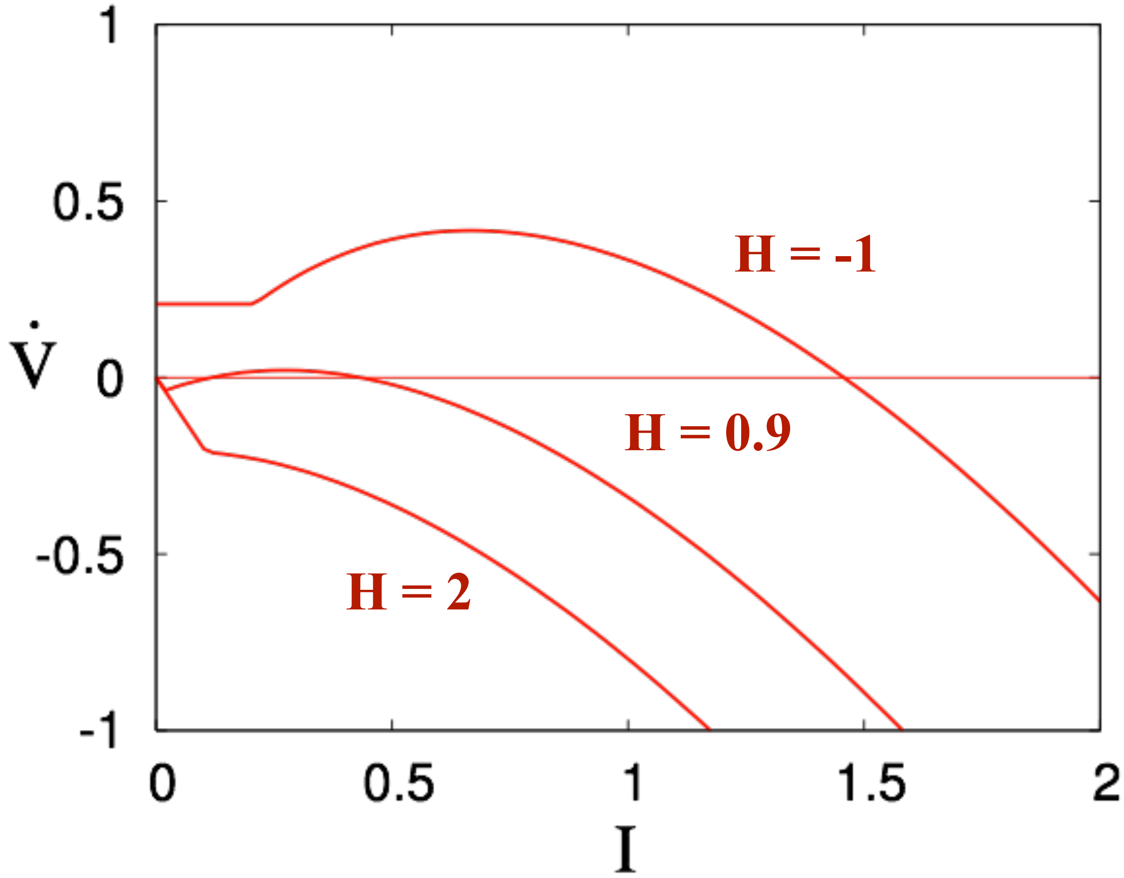


hysteresis

Simple ice sheet model

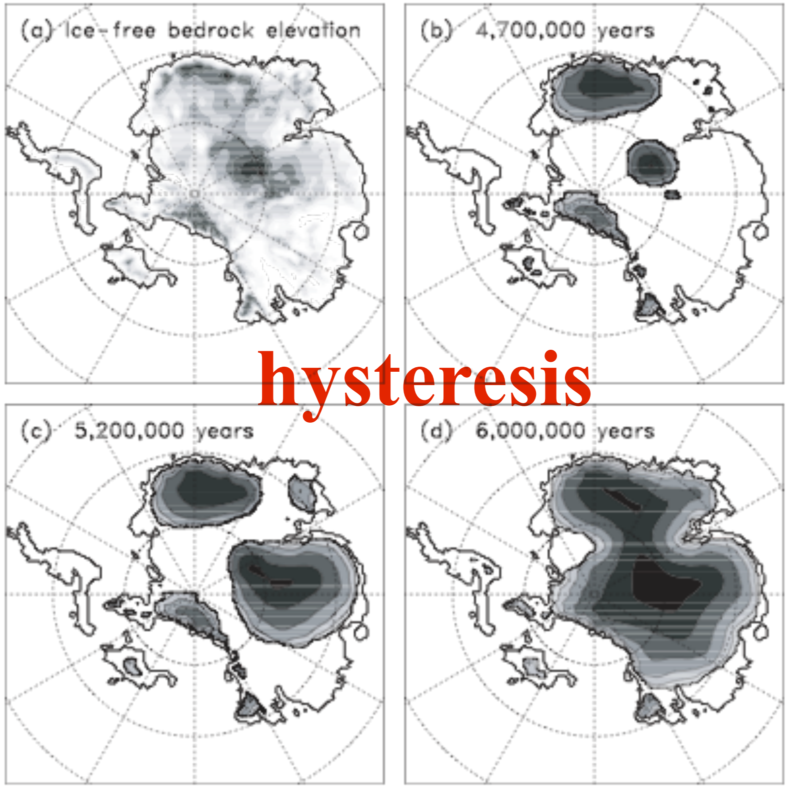
$$L^*\dot{V}_I = \max\left[\mathcal{H}(Z)\left\{(1+\alpha)\left[(1+4Z)^{1/2} - (1+2Z)\right] + Z\right\} - J^*H, -\alpha L^* I\right]$$

$$Z = J^*H + L^*I$$

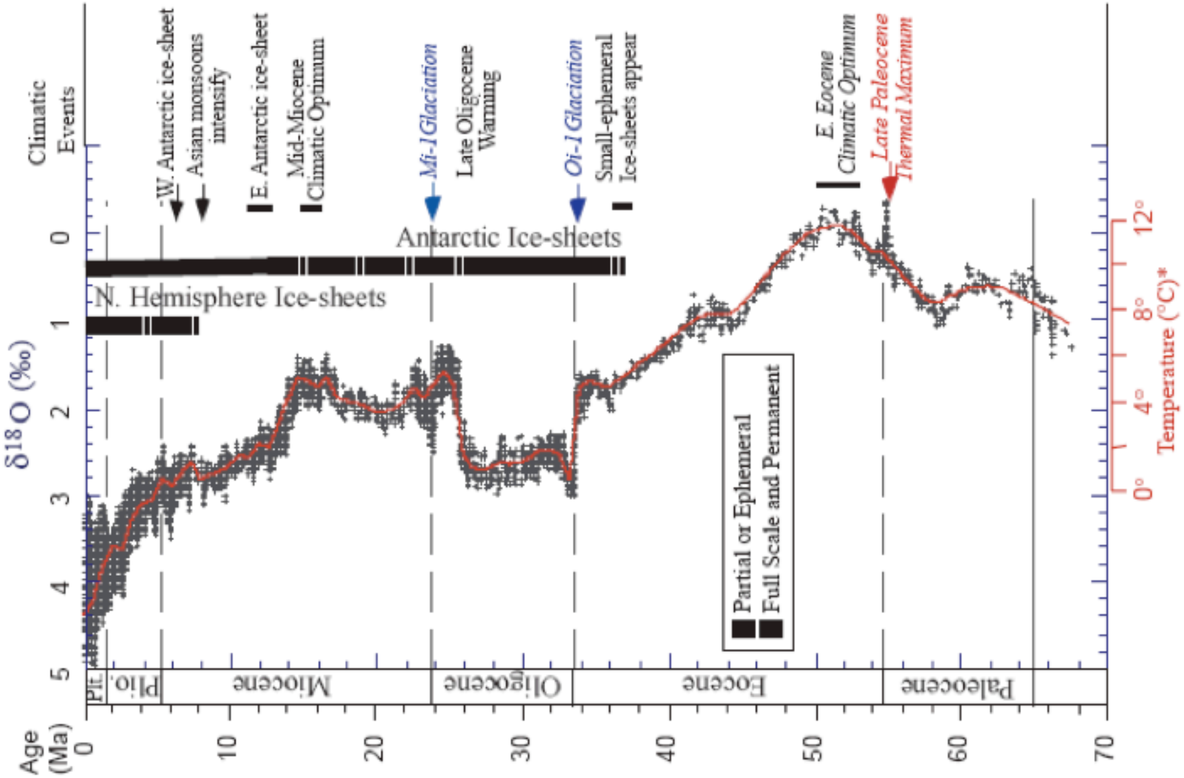


$\alpha = 2$

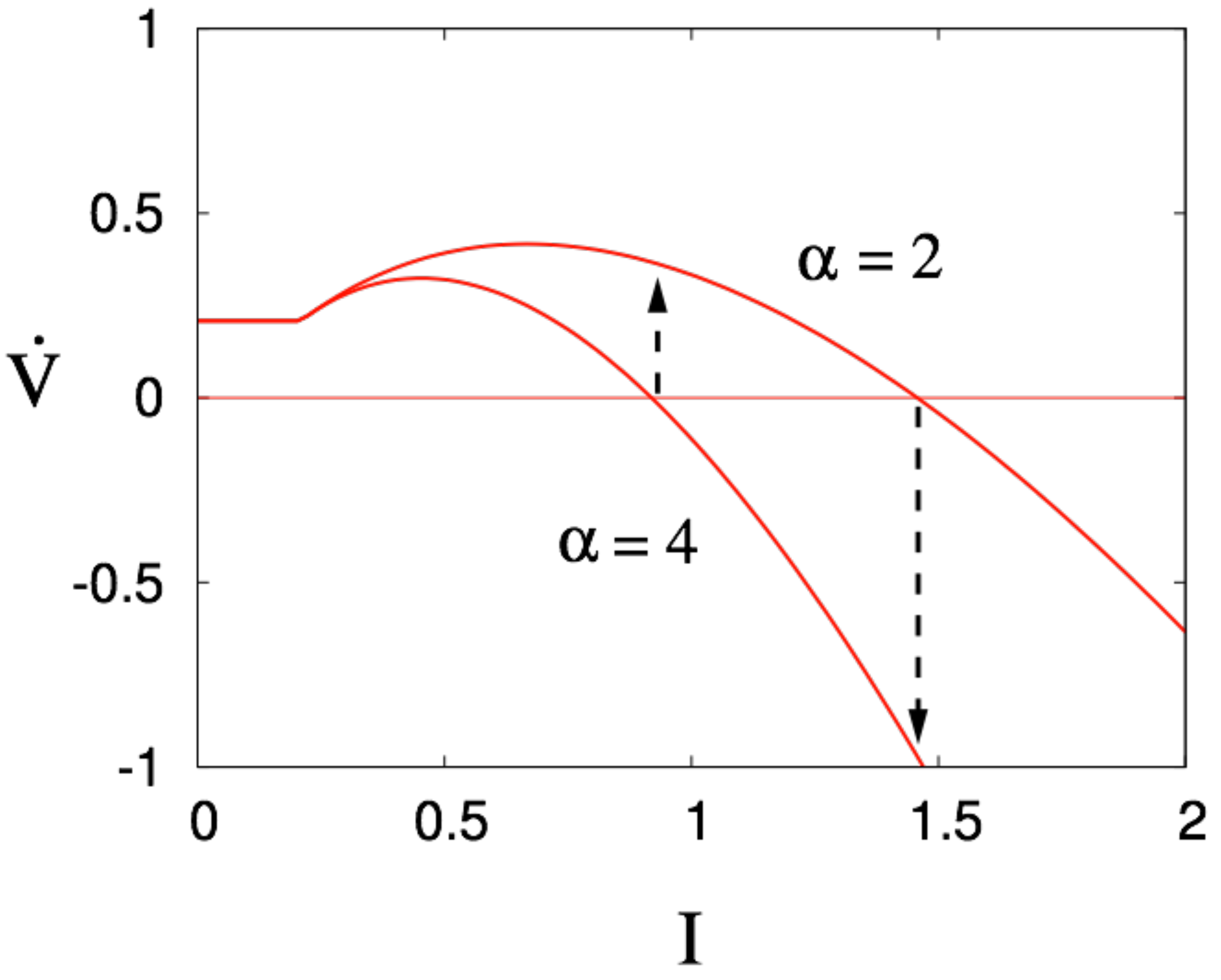
moisture



hysteresis



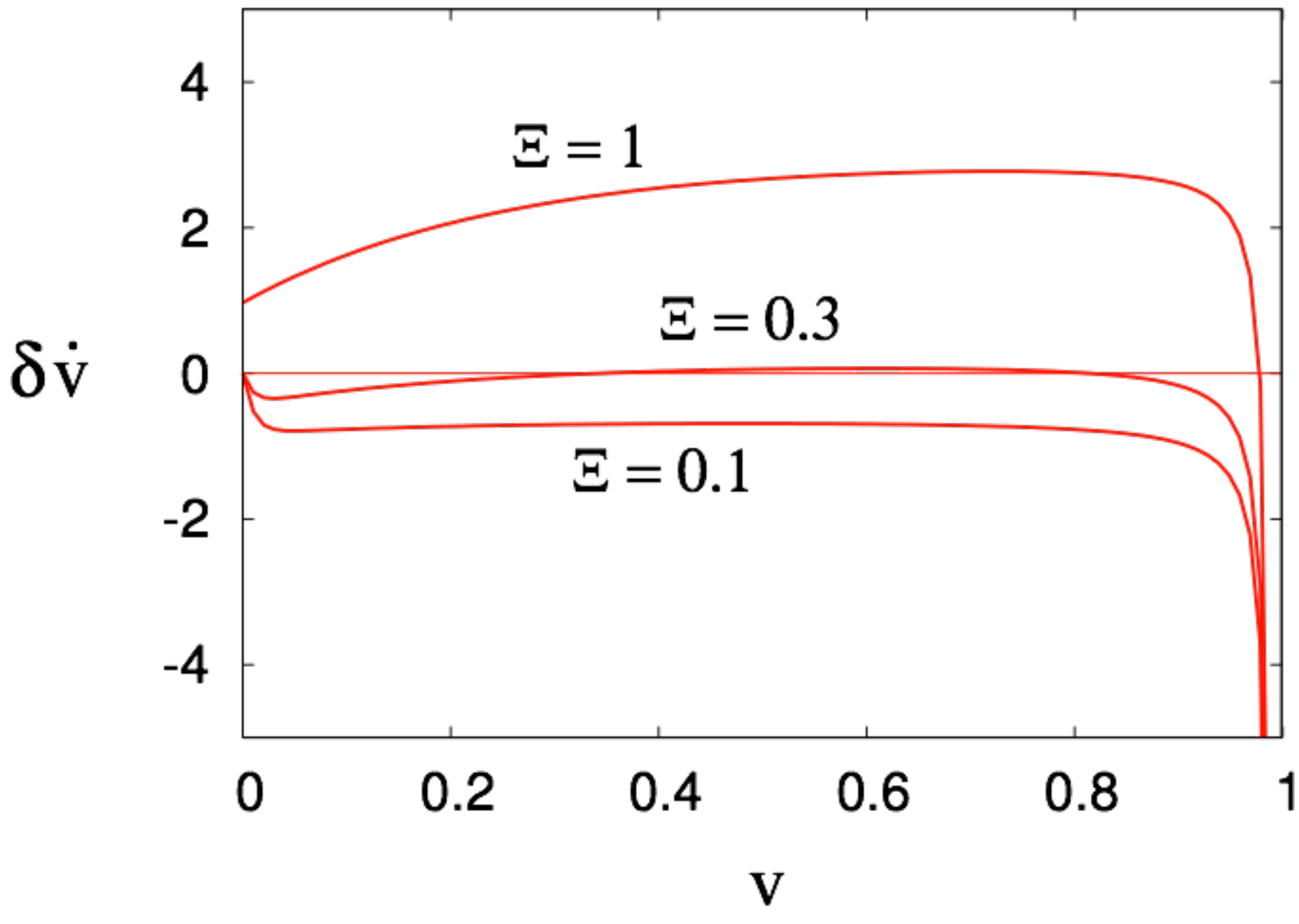
Rapid melting ⟶ lakes $\sqrt{\frac{L}{2}}\dot{L} = L[1-2\{1+\alpha(\dot{L})\}\xi]$



runoff **discharge**

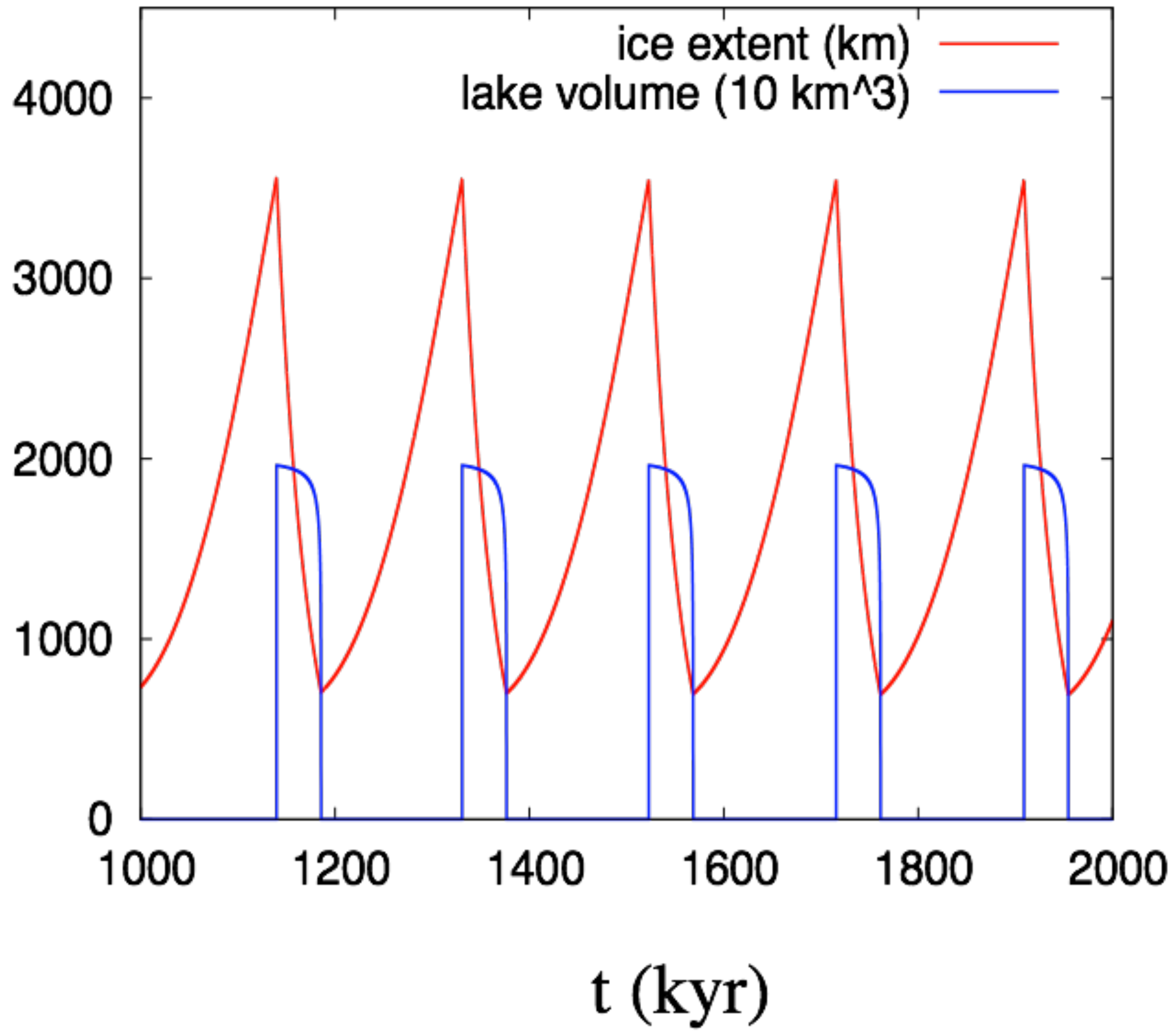
$$\delta\dot{v} = M^*\Xi(I,H)\alpha(v) - r(v)$$

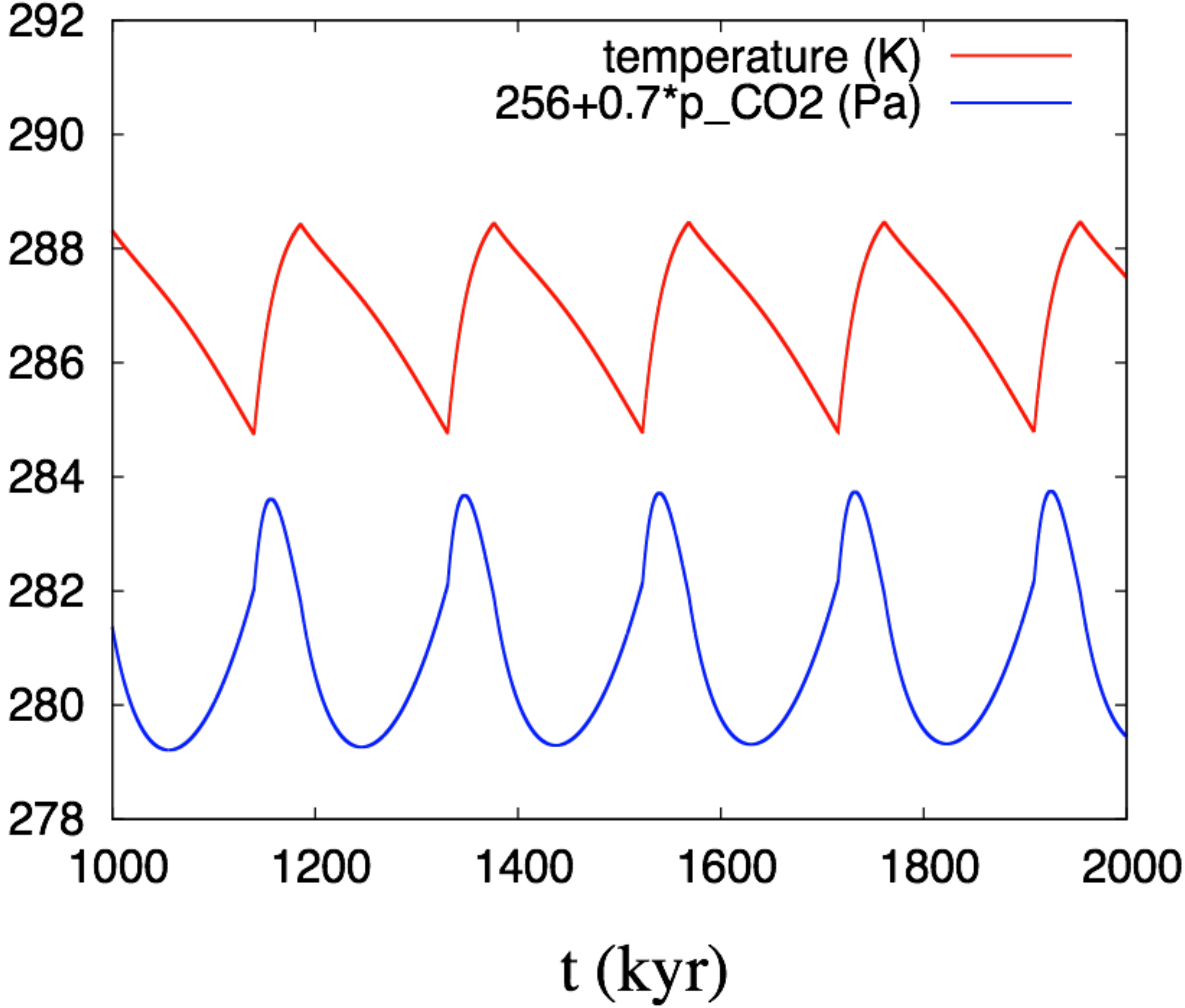
$$\Xi \approx (I + k^*H)^2$$



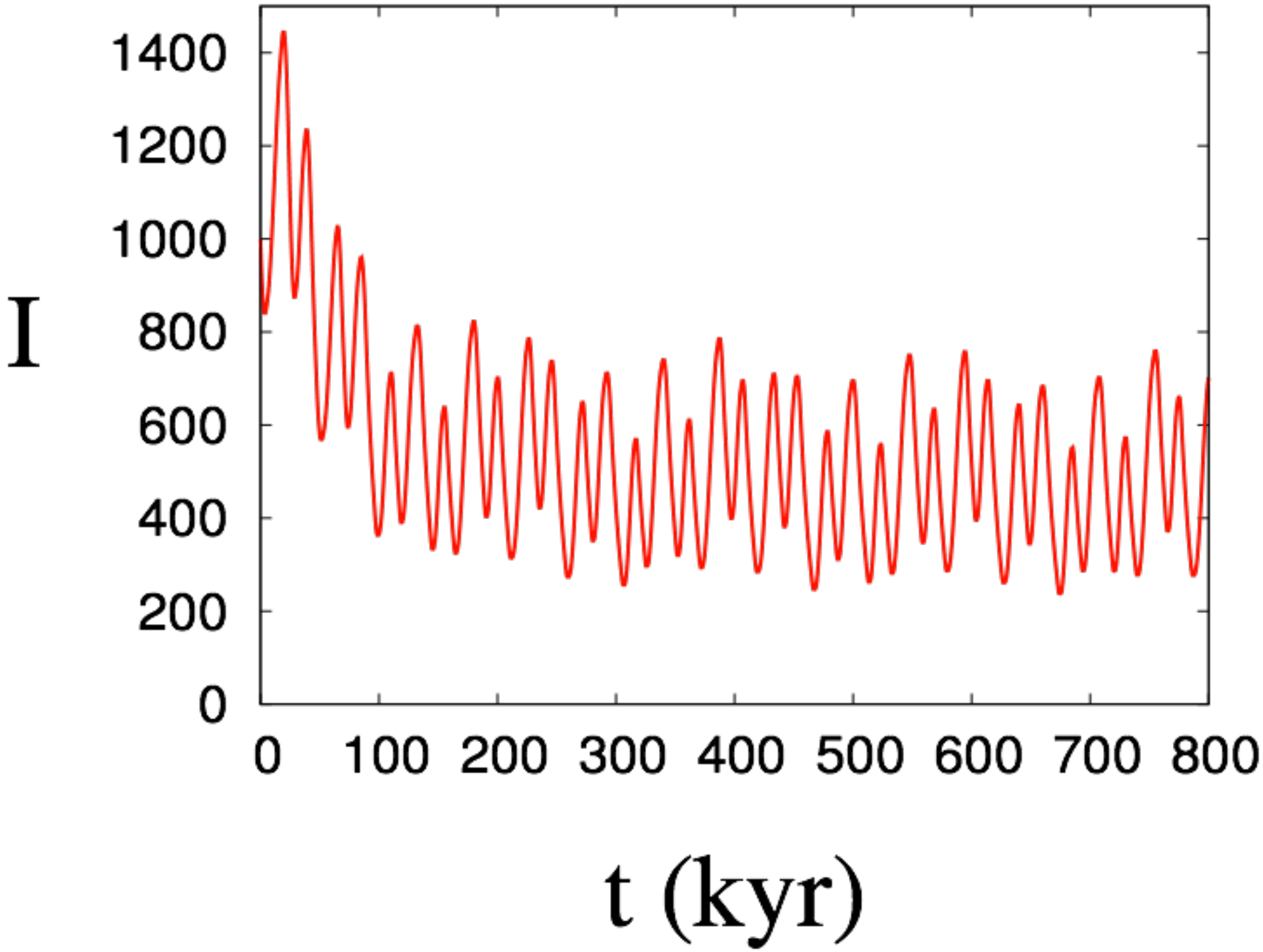
I,v model

→ oscillations⟹




temperature (K)
256+0.7*p_CO2 (Pa)
292
290
288
286
284
282
280
278
1000
1200
1400
1600
1800
2000
t (kyr)

Milanković ⟹ rapid oscillations⟹



Post-glacial rapid CO_2 rise:

Shelf exposure?

Carbonate erosion?

Ocean lowering?

Terrestrial biomass? Mixing layer?

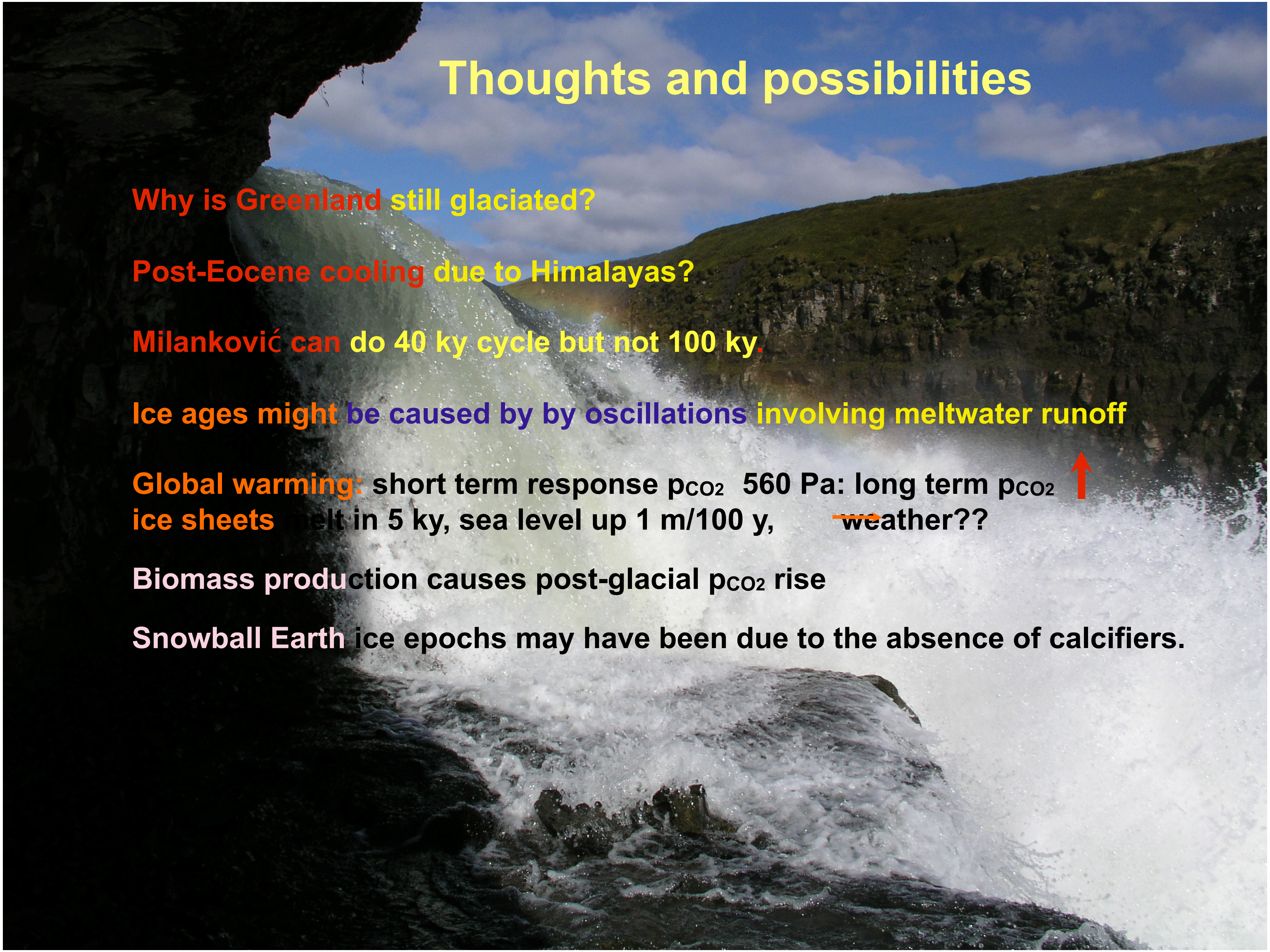
Thermally activated bioproduction:

$$\zeta \dot{P} = -\left(Pe^{b'/\theta} - 1\right) P_B + \frac{\gamma \Omega_S w}{\beta},$$

$$\dot{P}_B = \frac{\beta}{2\gamma}\left(Pe^{b'/\theta} - 1\right) P_B,$$

$$\nu \dot{S} = -\beta\left(Pe^{b'/\theta} - 1\right) P_B - (1 - \Sigma) - S + \Omega_S w.$$

$$\Delta S \approx -\frac{\beta \zeta b'}{\nu} \Delta \theta$$


Thoughts and possibilities
Why is Greenland still glaciated?
Post-Eocene cooling due to Himalayas?
Milanković can do 40 ky cycle but not 100 ky.
Ice ages might be caused by by oscillations involving meltwater runoff
Global warming: short term response p_{CO_2} 560 Pa: long term p_{CO_2} ↑
ice sheets elt in 5 ky, sea level up 1 m/100 y, → weather??
Biomass production causes post-glacial p_{CO_2} rise
Snowball Earth ice epochs may have been due to the absence of calcifiers.