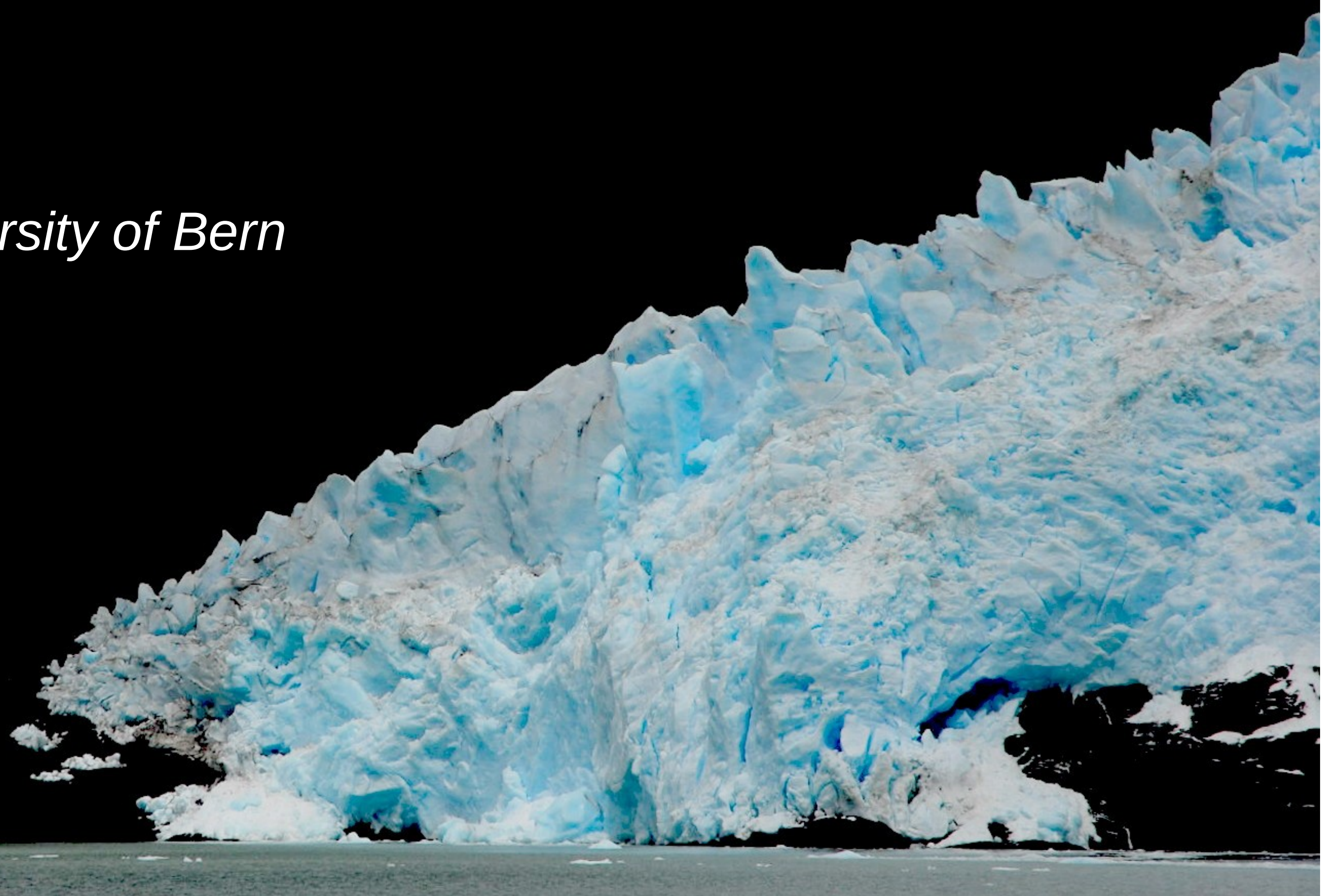
Modeling forcings and responses in the global carbon cycle-climate system: Past, present and future

Raphael Roth, University of Bern

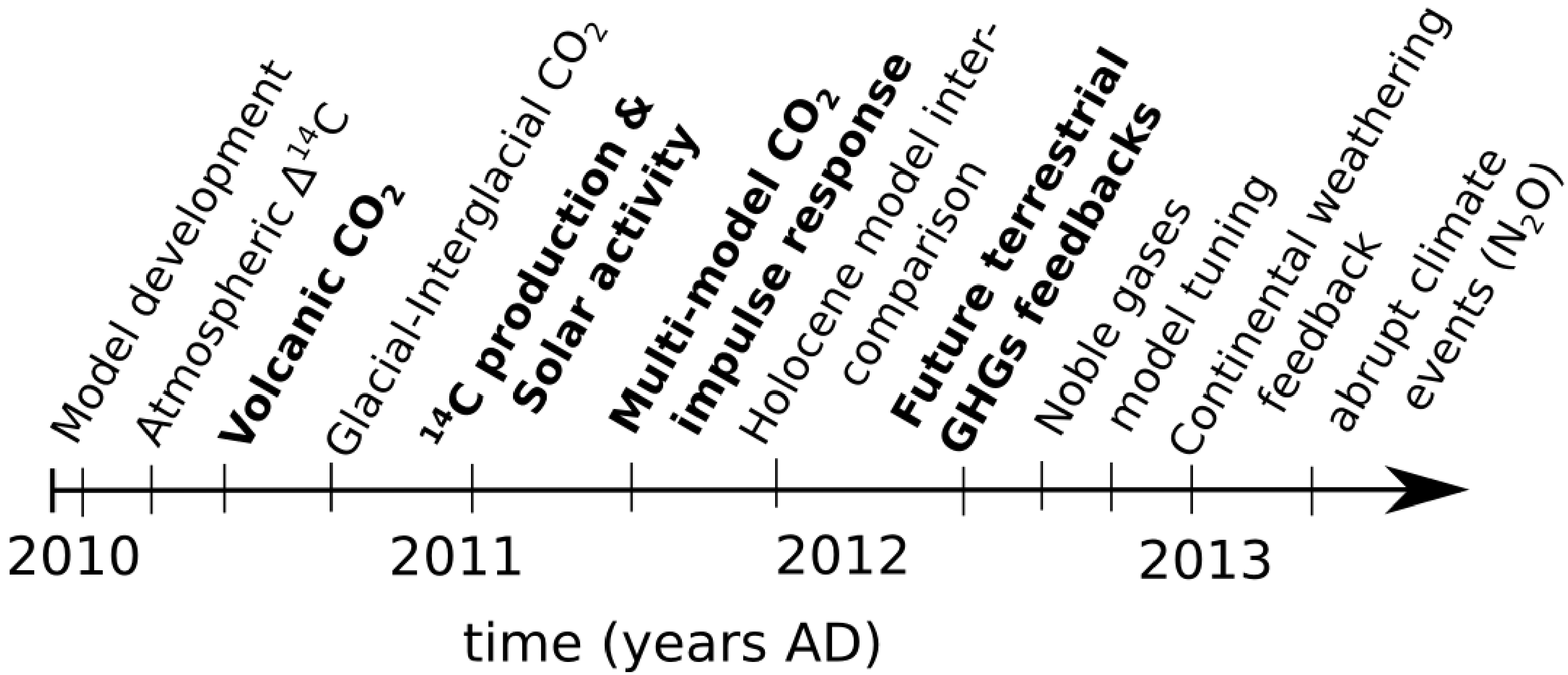
Ph.D. exam talk

12. December

2013



PhD overview



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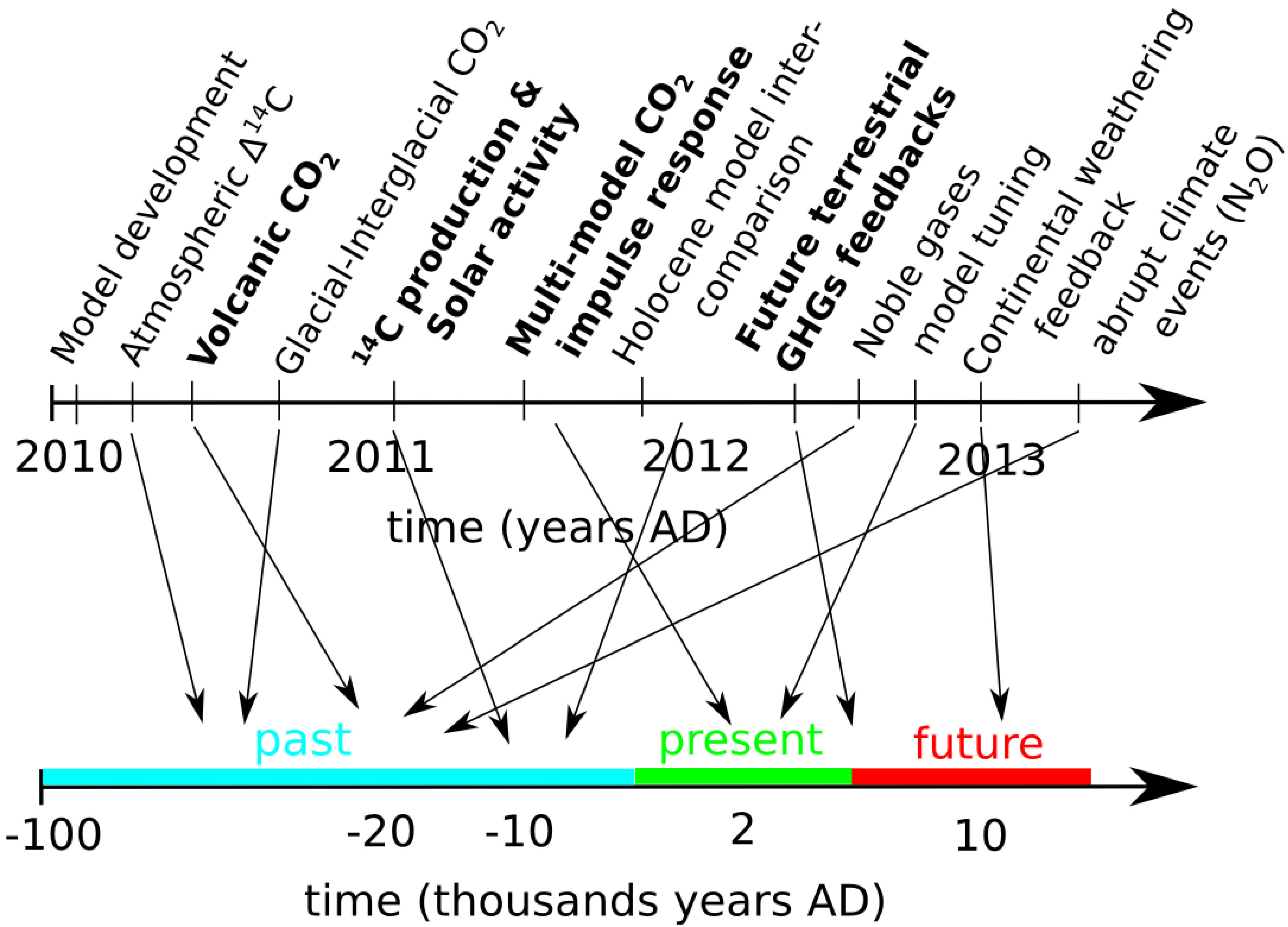

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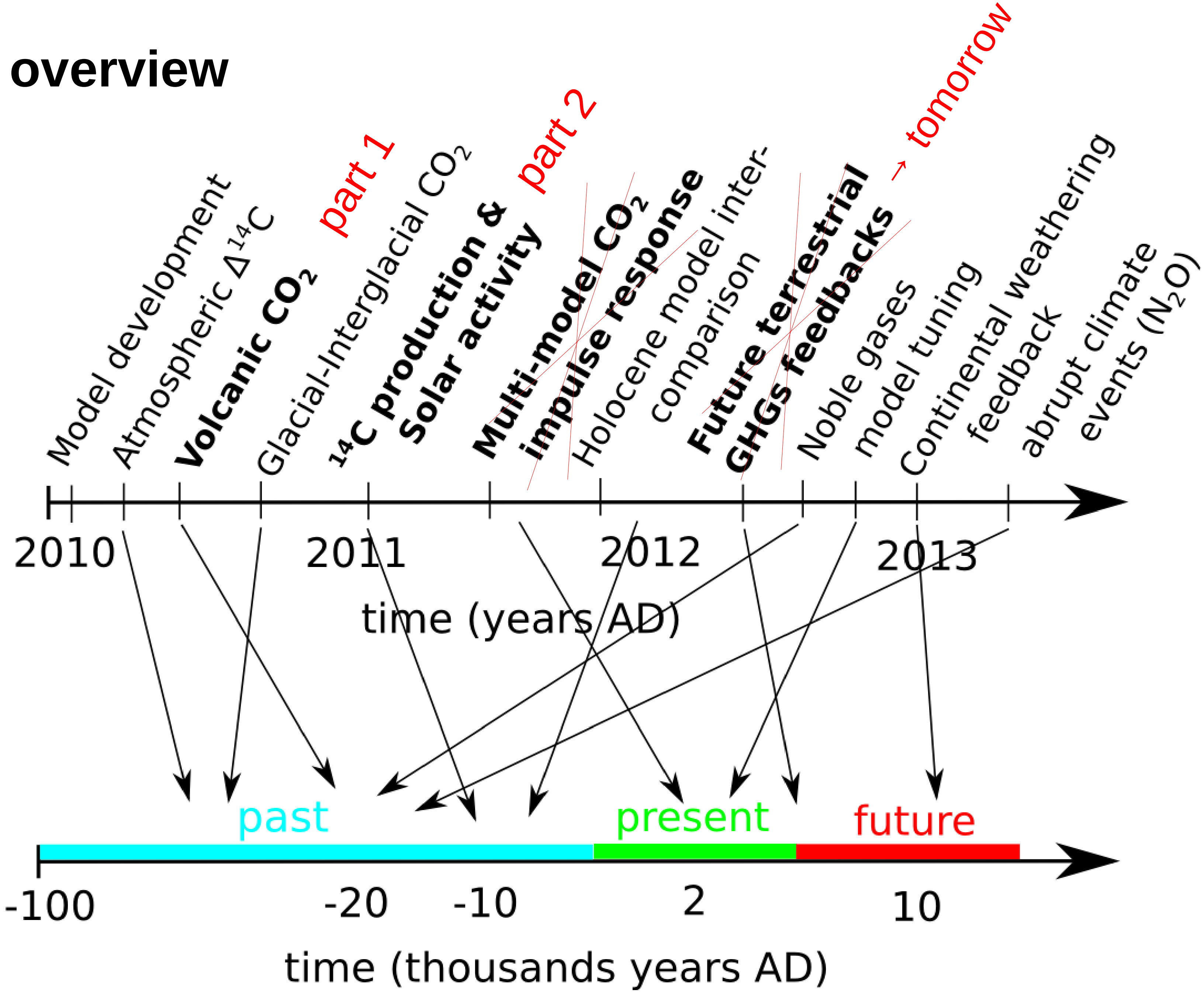
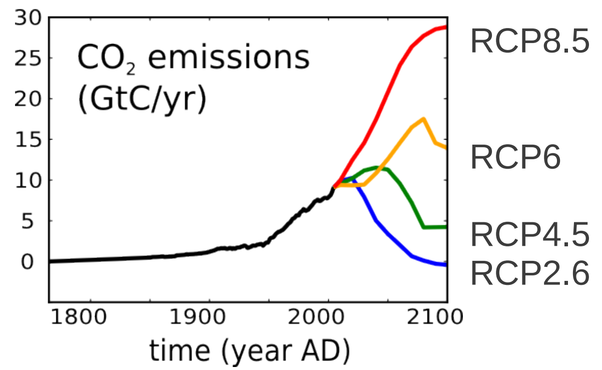
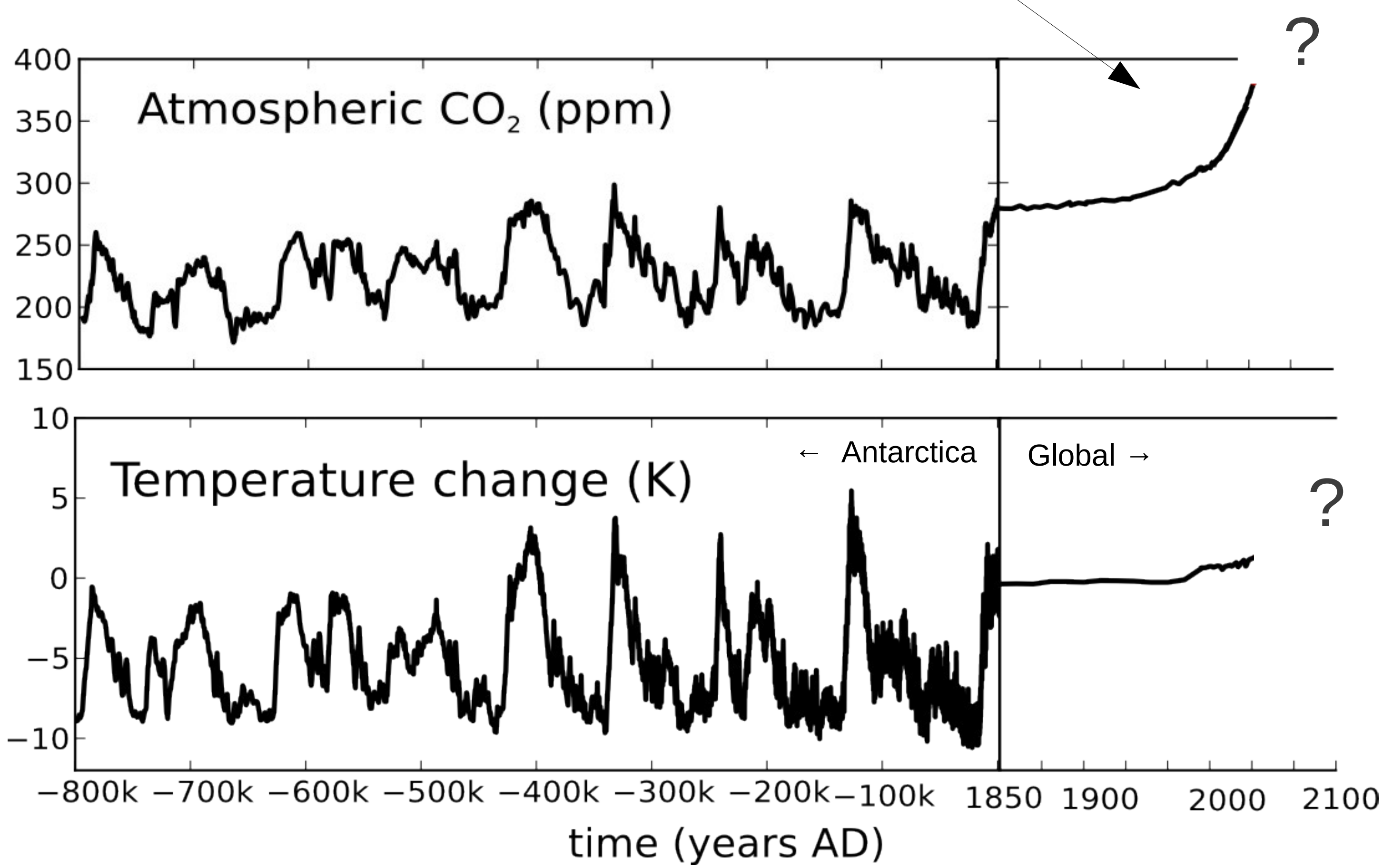


Motivation



CO_2 emissions (GtC/yr)
30
25
20
15
10
5
0
1800
1900
2000
2100
time (year AD)
RCP8.5
RCP6
RCP4.5
RCP2.6



Atmospheric CO_2 (ppm)
400
350
300
250
200
150
?
Temperature change (K)
10
5
0
−5
−10
← Antarctica
Global →
?
−800k −700k −600k −500k −400k −300k −200k −100k 1850 1900 2000 2100
time (years AD)

Motivation

Observations show:

Strong correlation between climate and atmospheric CO_2.

→ Causality? Problematic to state from observations alone.
→ Process-based understanding of the carbon cycle-climate system needed.

Identified interactions:

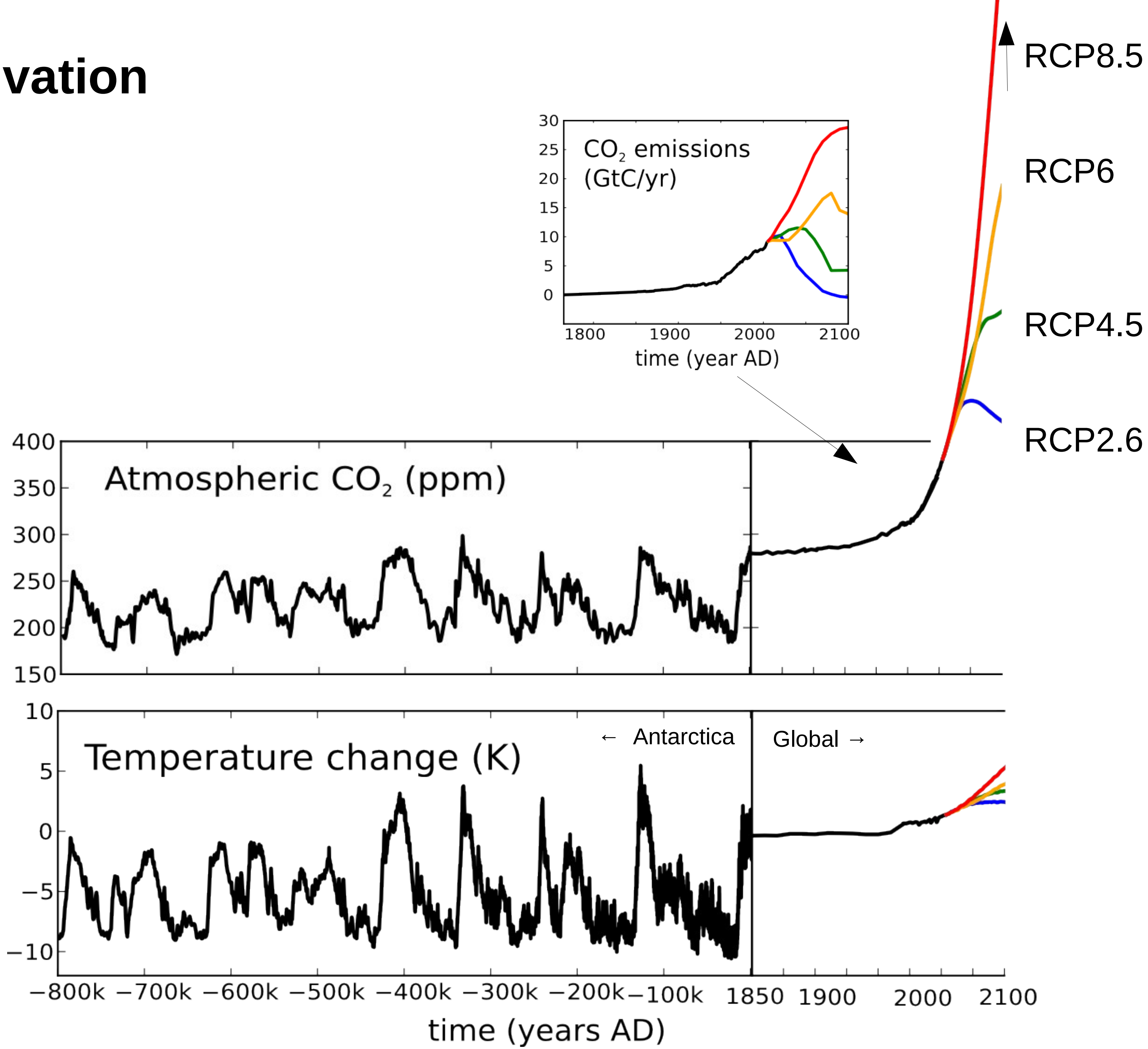
I) CO_2 influences climate through absorption of outgoing LW radiation.
→ ***carbon-climate feedback***

II) Climate influences CO_2 through interactions with the global carbon cycle.
→ ***climate-carbon feedback***

within the carbon cycle:

III) CO_2 influences carbon cycle (plant fertilization, oceanic uptake, …).
→ ***carbon-concentration feedback***

Motivation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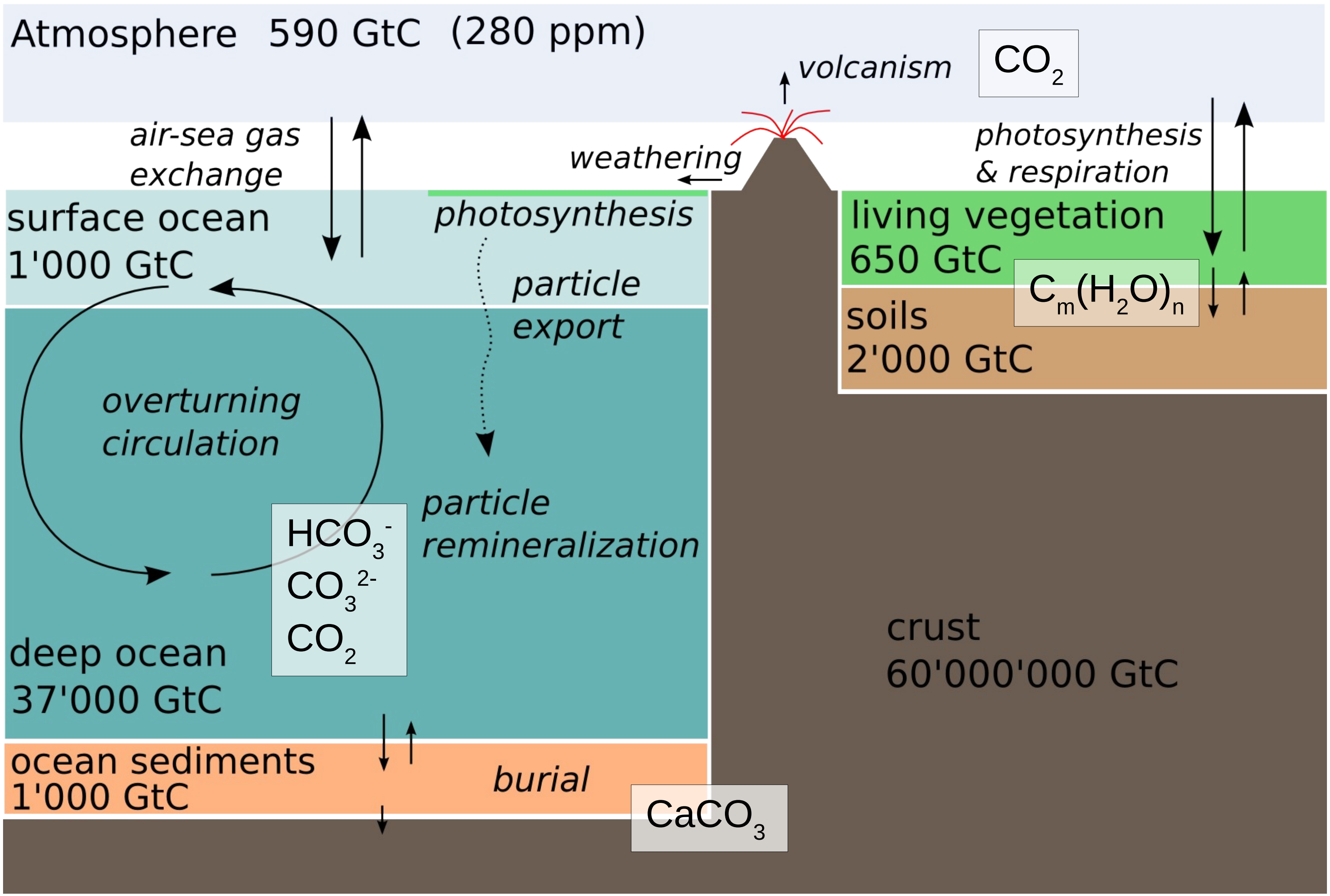
The global carbon cycle (pre-industrial)



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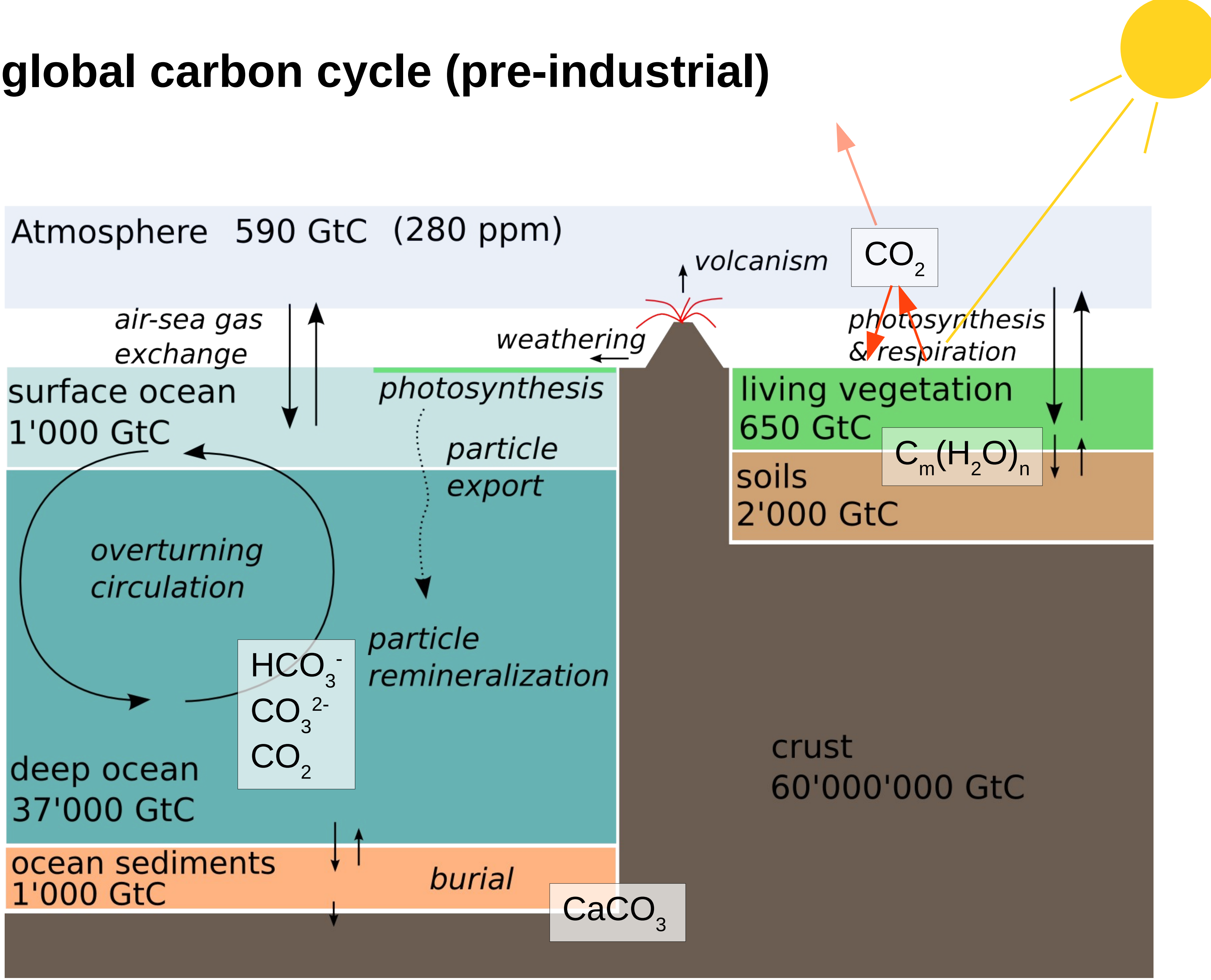


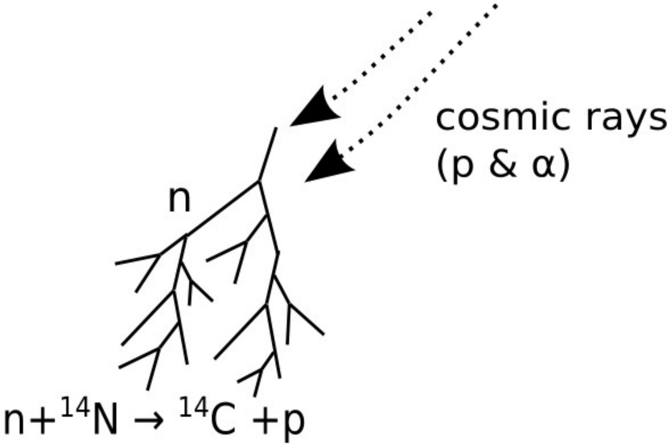
Carbon isotopes

$$[C] = [^{12}C] + [^{13}C]$$

stable
~99%

stable
~1%

Carbon isotopes



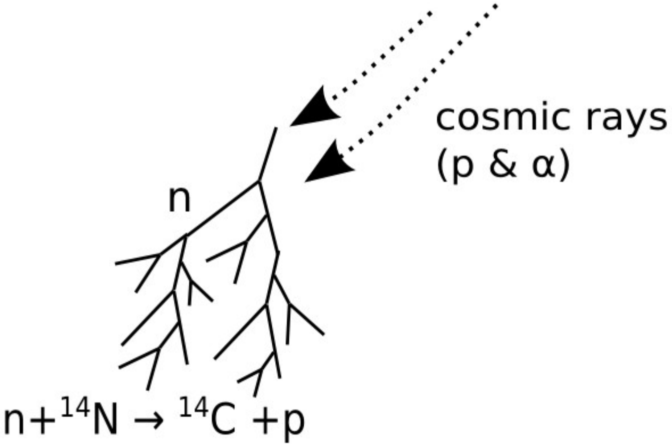
$$[C] = [^{12}C] + [^{13}C] + [^{14}C]$$

^{12}C: stable
~99%

^{13}C: stable
~1%

^{14}C: produced in upper atmosphere
unstable ($t_{1/2}$ = 5730 yr)
~10^{-10} % (“production<< rate of decay")

Carbon isotopes



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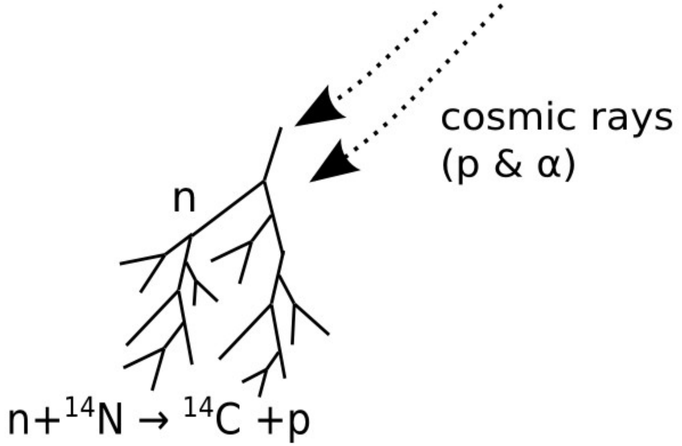
Fractionation of ^{13}C & ^{14}C:

- during air-sea gas-exchange (seawater C is “heavier” than atmospheric C)
- during photosynthesis (biomass C is “lighter” than atmospheric C)
- ...

Carbon isotopes



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- ...

$$^{13}R = \frac{^{13}\mathrm{C}}{^{12}\mathrm{C}}$$

$$\delta^{13}\mathrm{C} = \left(\frac{^{13}R}{^{13}R_{\mathrm{std}}} - 1\right) \cdot 1000‰$$

→ **sensitive to fractionation**

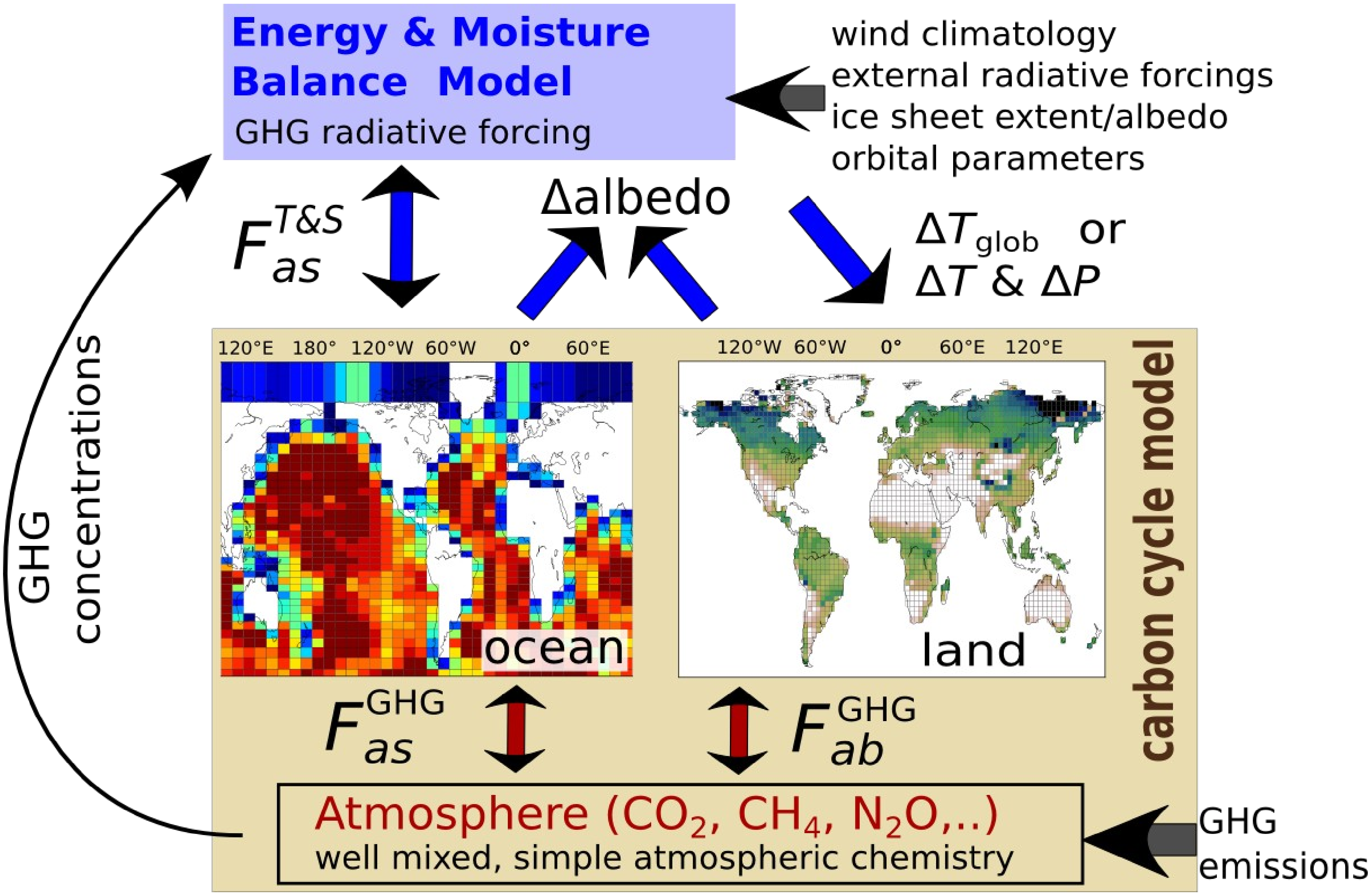
“N”: corrected for fractionation

$$\Delta^{14}\mathrm{C} = \left(\frac{^{14}R_{\mathrm{N}}}{^{14}R_{\mathrm{std}}} - 1\right) \cdot 1000‰$$

→ **sensitive to production and “age”**

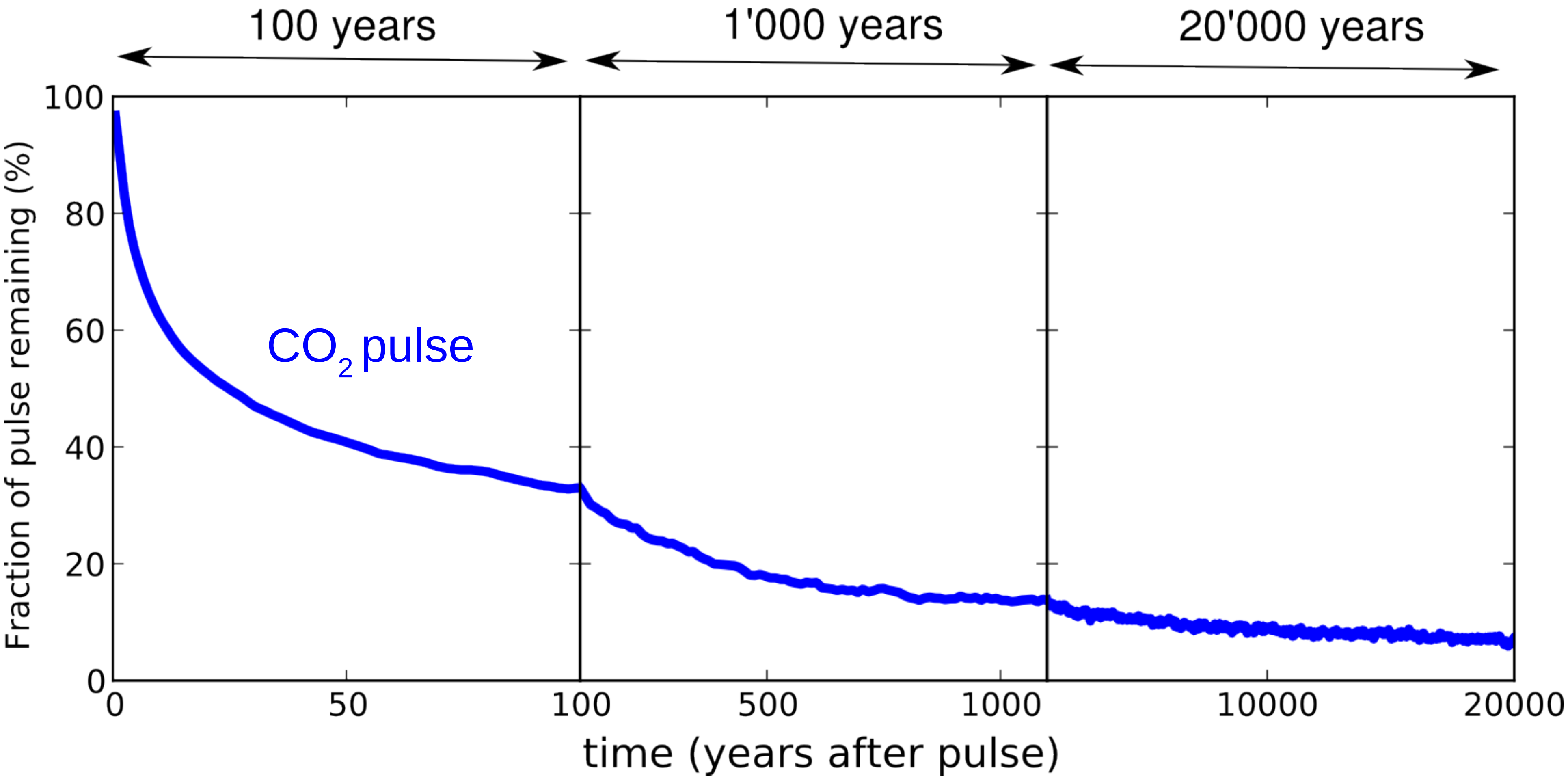
The Bern3D-LPJ model

→ "Earth System Model of Intermediate Complexity (EMIC)"



The Bern3D-LPJ model

Idealized application: carbon pulse release



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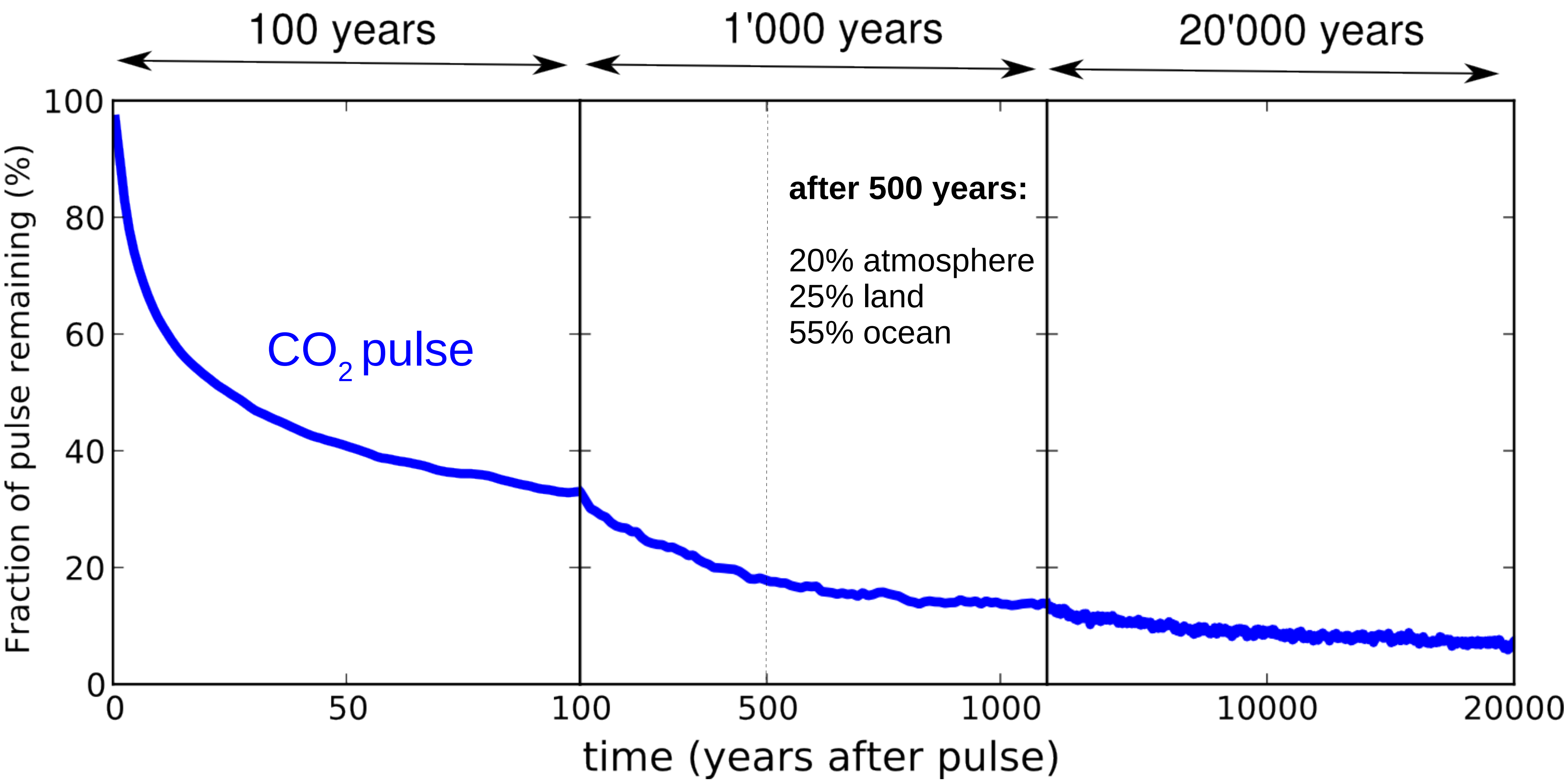

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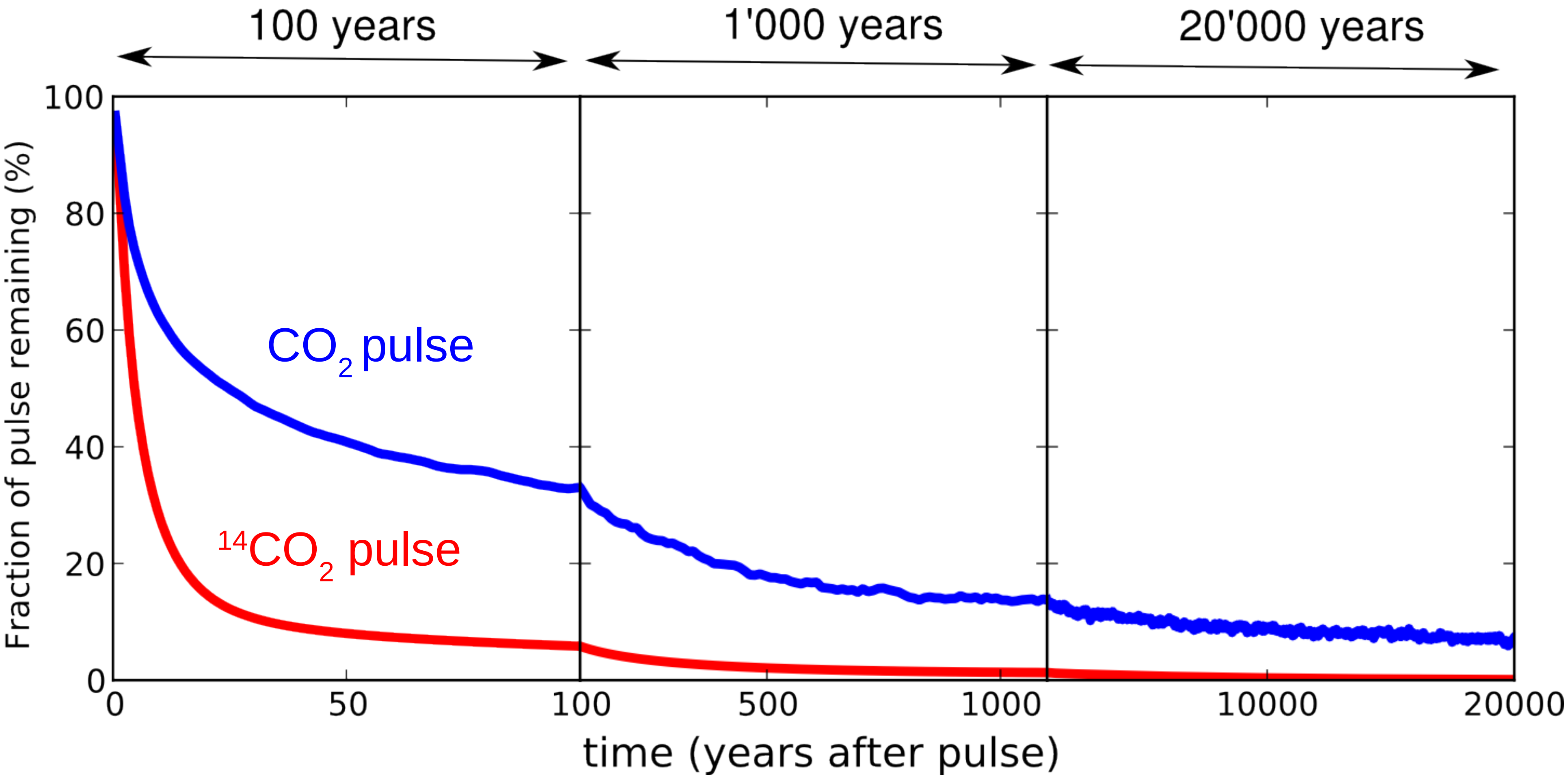


Summary (introduction & Bern3D-LPJ)

- The climate and carbon cycle are tightly coupled (positive feedback in both directions).

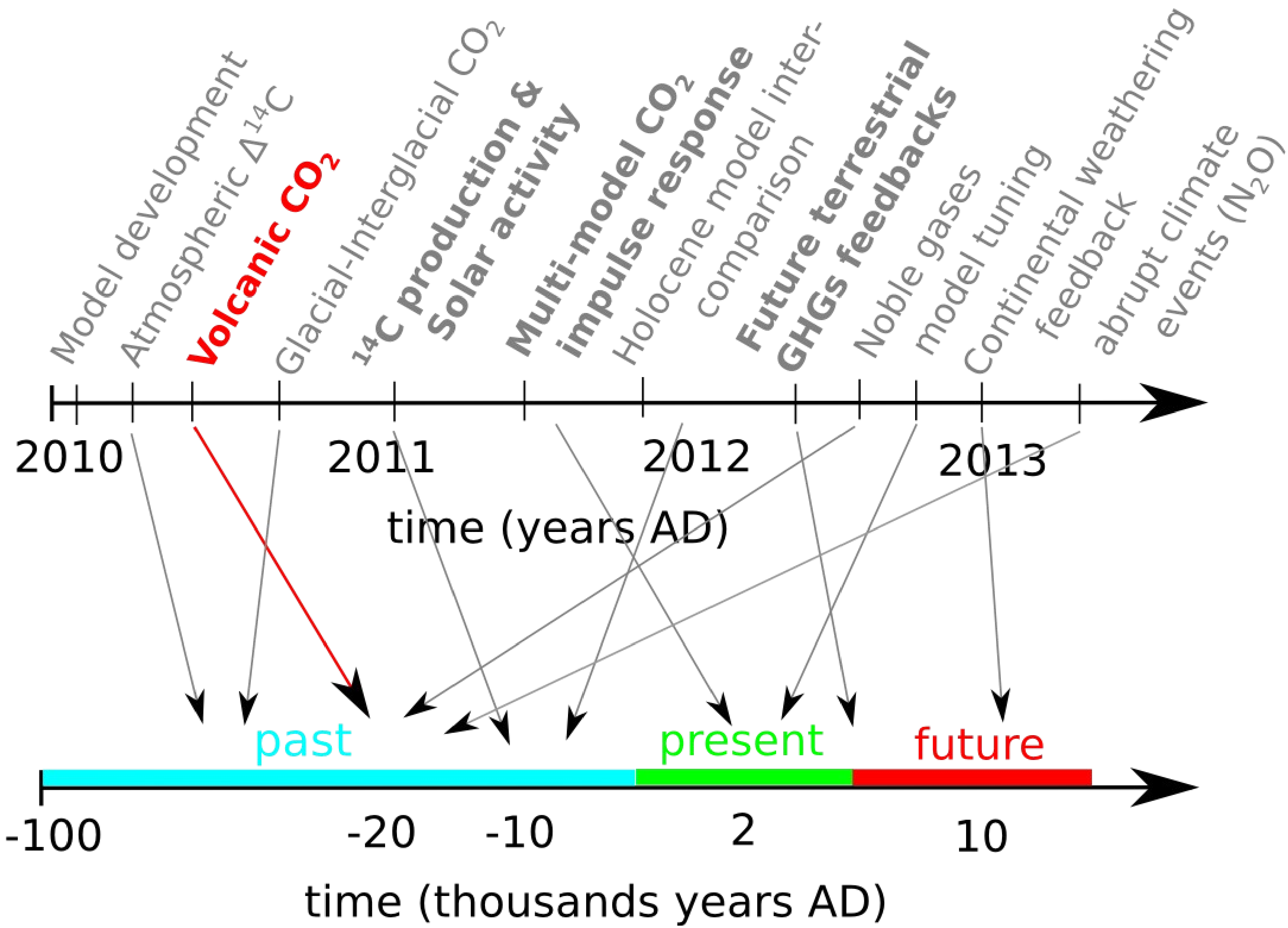
- Carbon isotopes can be measured and give additional constraints on past carbon cycle changes.

- Processes that are understood can be incorporated into models in order to predict future changes in the Earth system.

- Redistribution of carbon within the atmosphere-ocean-land system is a result of a complex interplay between physical and biogeochemical process involving many different timescales.

- Isotopic perturbation “decay” much faster than CO_2 perturbations.

Part 1: Volcanic CO_2



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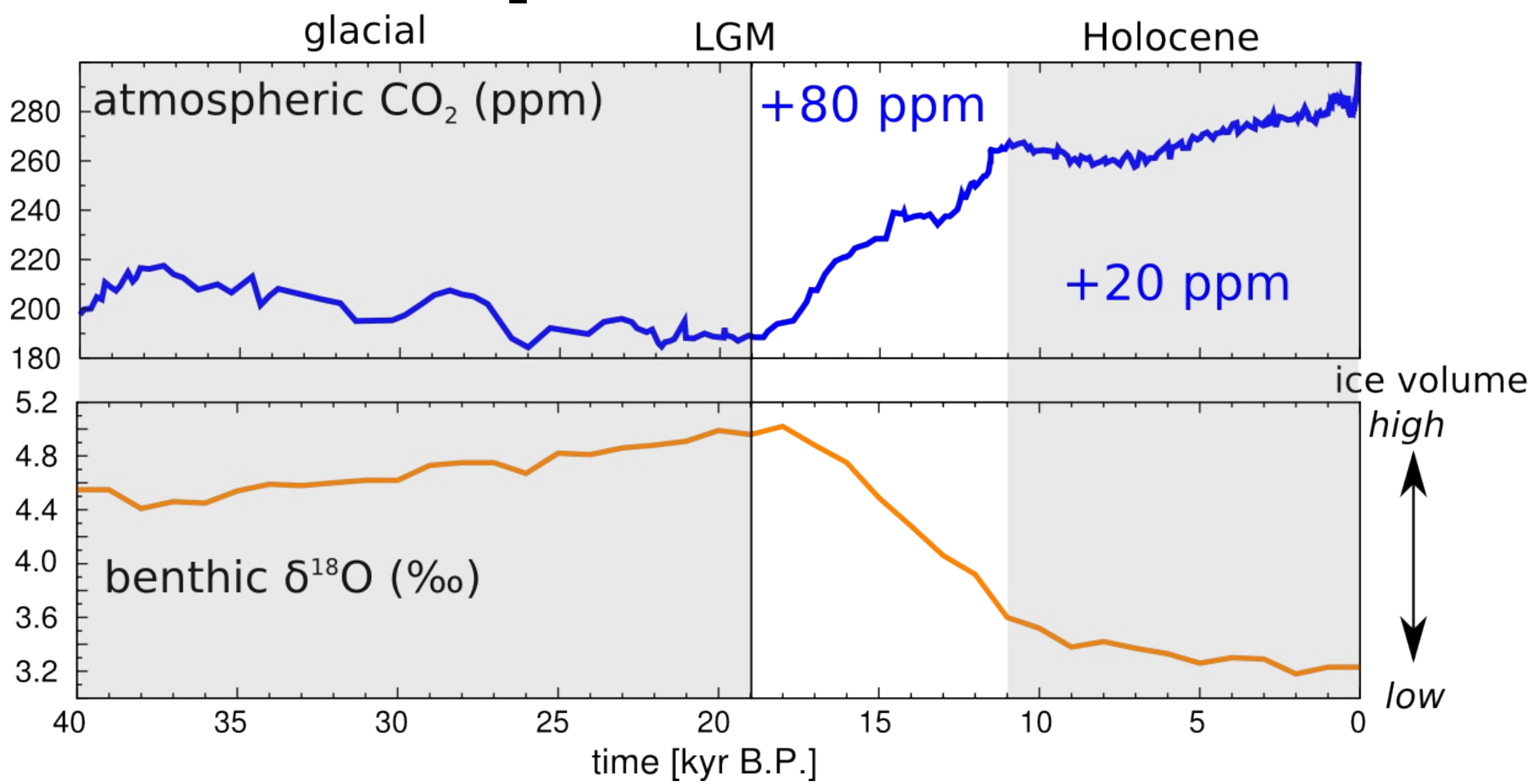

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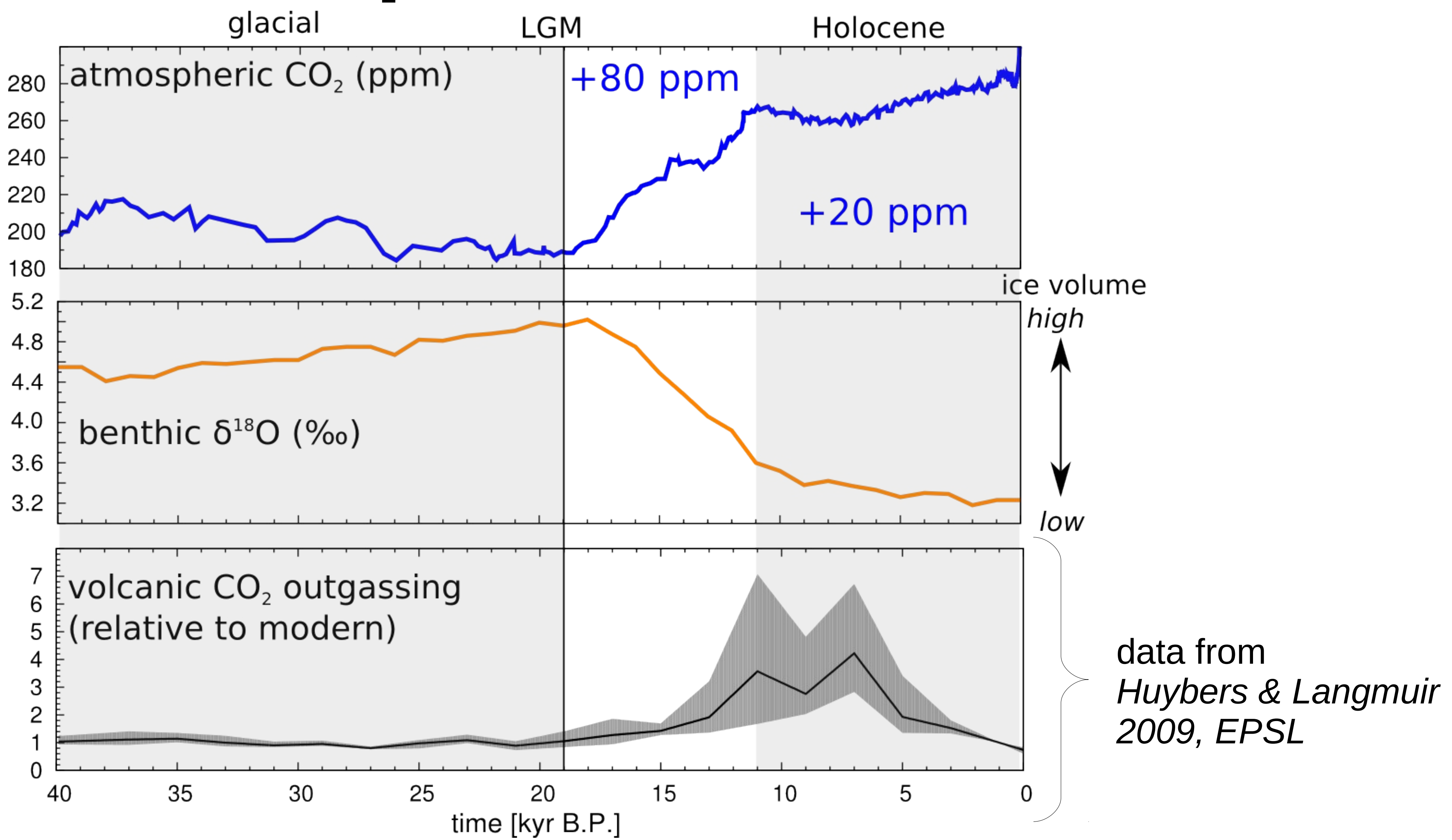
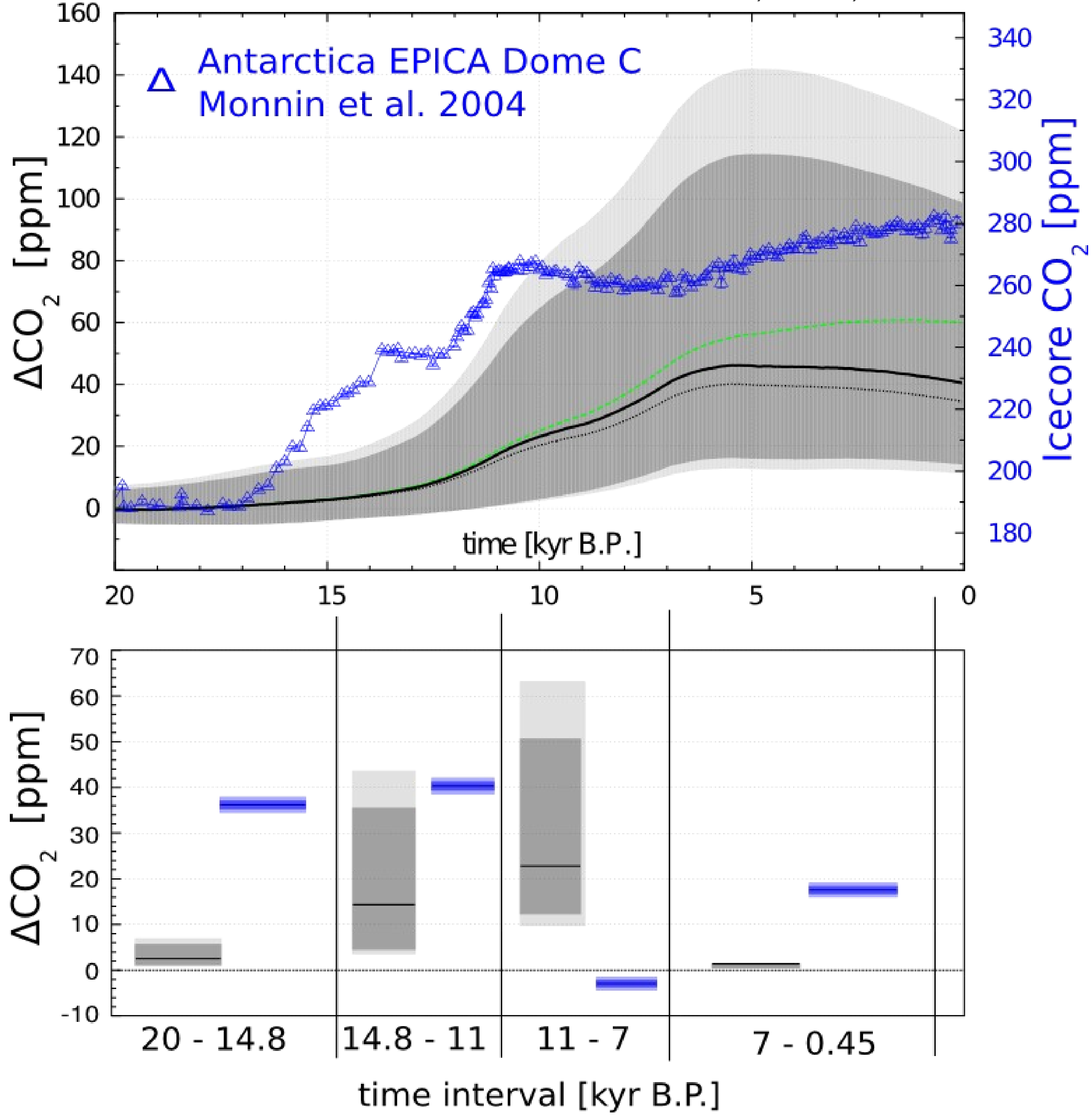


Question:
What is the impact of this hypothesized CO_2 emission on the carbon cycle? Can it be falsified?

Part 1: Volcanic CO_2

Roth and Joos, 2012, EPSL

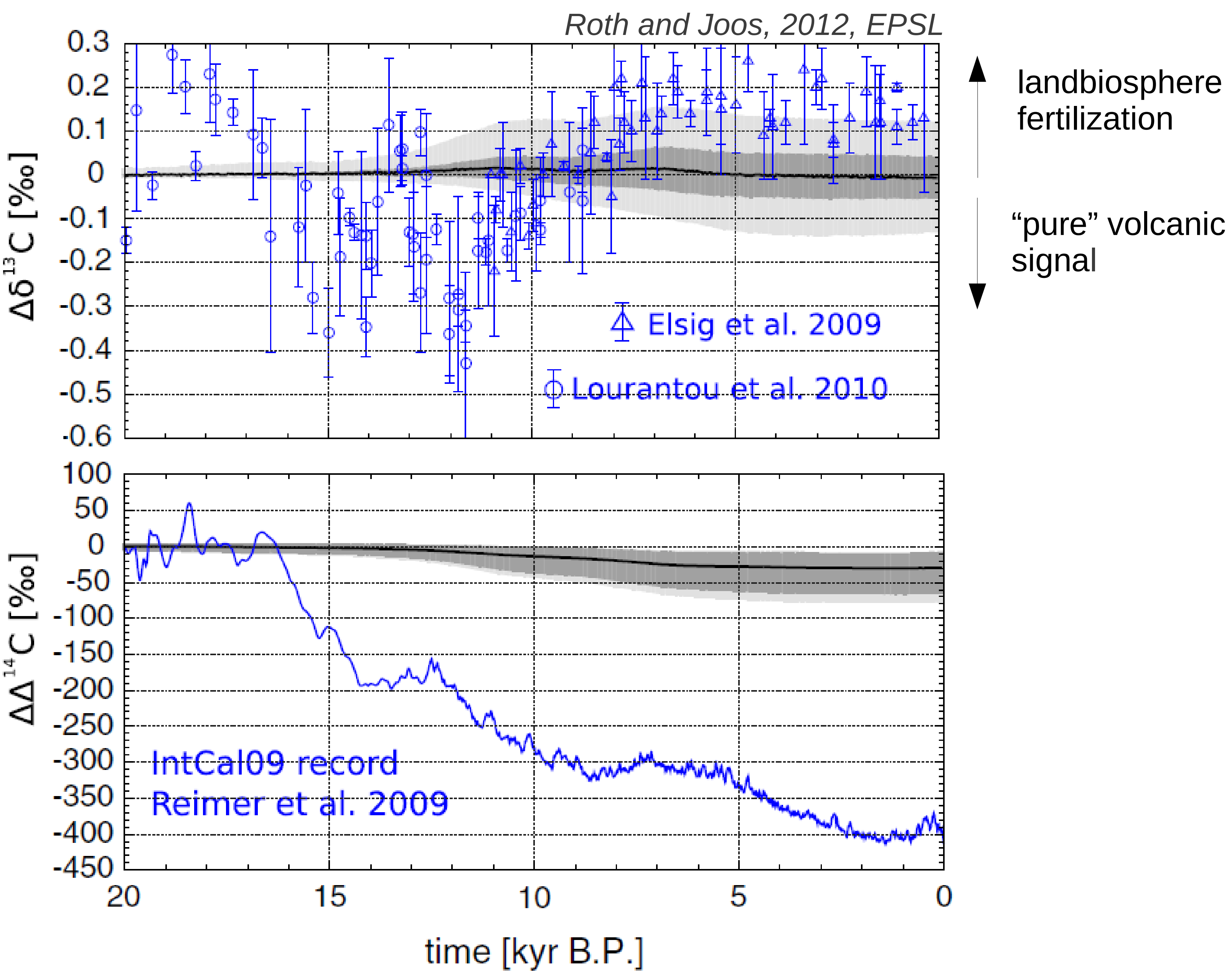


Part 1: Volcanic CO_2

Emissions

$\delta^{13}C_{volc} = -5 \pm 3‰$

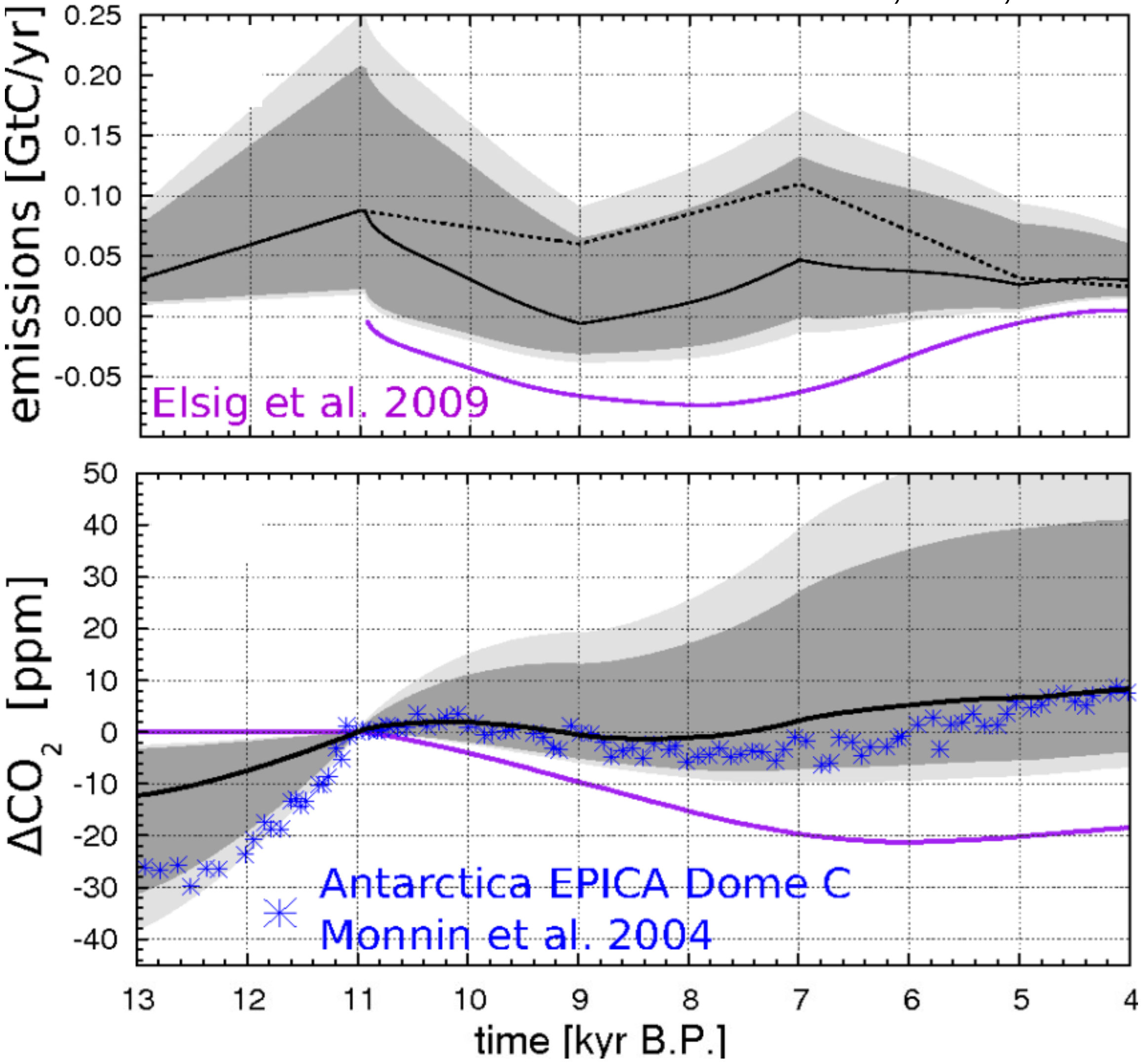
$\Delta^{14}C_{volc} = -1000‰$



Part 1: Volcanic CO_2

Other major driver for early-to-mid Holocene carbon cycle dynamics?
→ landbiosphere growth

Roth and Joos, 2012, EPSL



Summary (part 1)

- Causes on glacial – interglacial changes of CO_2 is not yet resolved.

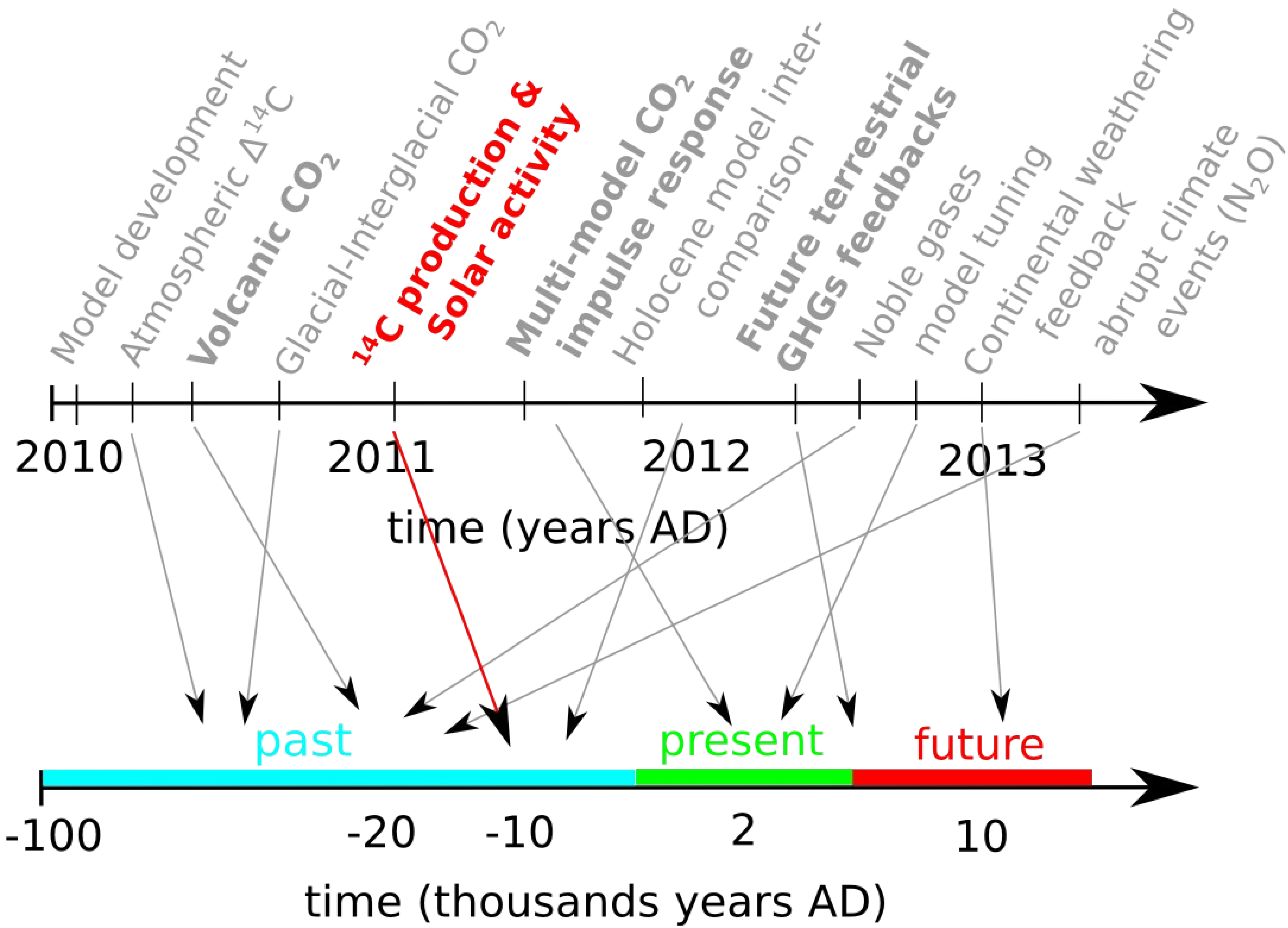
- Huybers & Langmuir (2009) proposed a volcanic feedback due to NH icesheet retreat.

- Applied to the Bern3D, the hypothesized emission scenarios result in a ~46 (13 to 142) ppm increase in CO_2 peaking in the early Holocene.

- Comparison with multiple oceanic and atmospheric proxy records points to a possible small to intermediate role for the proposed feedback.

- Uncertainties remain as carbon isotope proxies do not serve as a strong constraint in this case (volcanic signal is weak).

Part 2: ^{14}C production and solar activity



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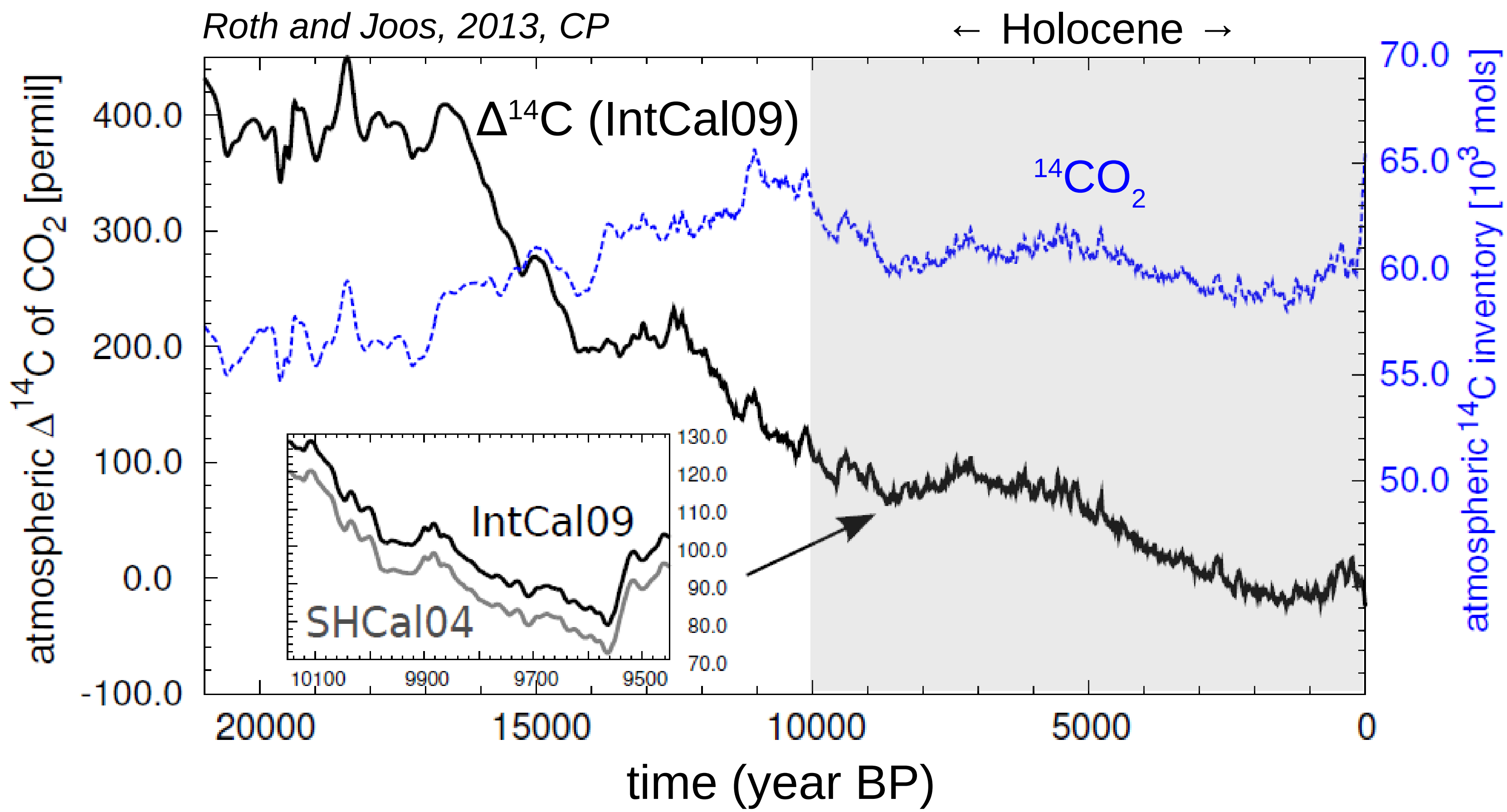

possible drivers for atmospheric $\Delta^{14}C$:

I) change in exchange fluxes (climate and/or carbon cycle changes)

II) change in atmospheric production

Part 2: ^{14}C production and solar activity

Experimental setup:

- **LGM-to-present simulations**
  → first 10 kyr to get initial conditions ("spin up").

- **Use a broad set of proxy data to constrain the model**
  → CO_2, hemispheric $\Delta^{14}C$, radiative forcing, sealevel,
  icesheets, orbital parameters, landuse area, fossil fuel emission, ...

- Monte-Carlo setup to estimate error caused by uncertainty in $\Delta^{14}C$ data.

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Atmospheric budget equation for ^{14}C:

$$Q(t) = \frac{I_{\text{atm,data}}(t)}{\tau} + \frac{\mathrm{d}I_{\text{atm,data}}(t)}{\mathrm{d}t} + {}^{14}F_{\text{budget}}(t)$$

→ atmospheric change

$$+ \frac{I_{\text{ocn,model}}(t)}{\tau} + \frac{\mathrm{d}I_{\text{ocn,model}}(t)}{\mathrm{d}t} + \frac{\Delta I_{\text{ocn,data-model}}(t=t_0)}{\tau}$$
$$+ \frac{I_{\text{sed,model}}(t)}{\tau} + \frac{\mathrm{d}I_{\text{sed,model}}(t)}{\mathrm{d}t} + {}^{14}F_{\text{burial}}(t)$$

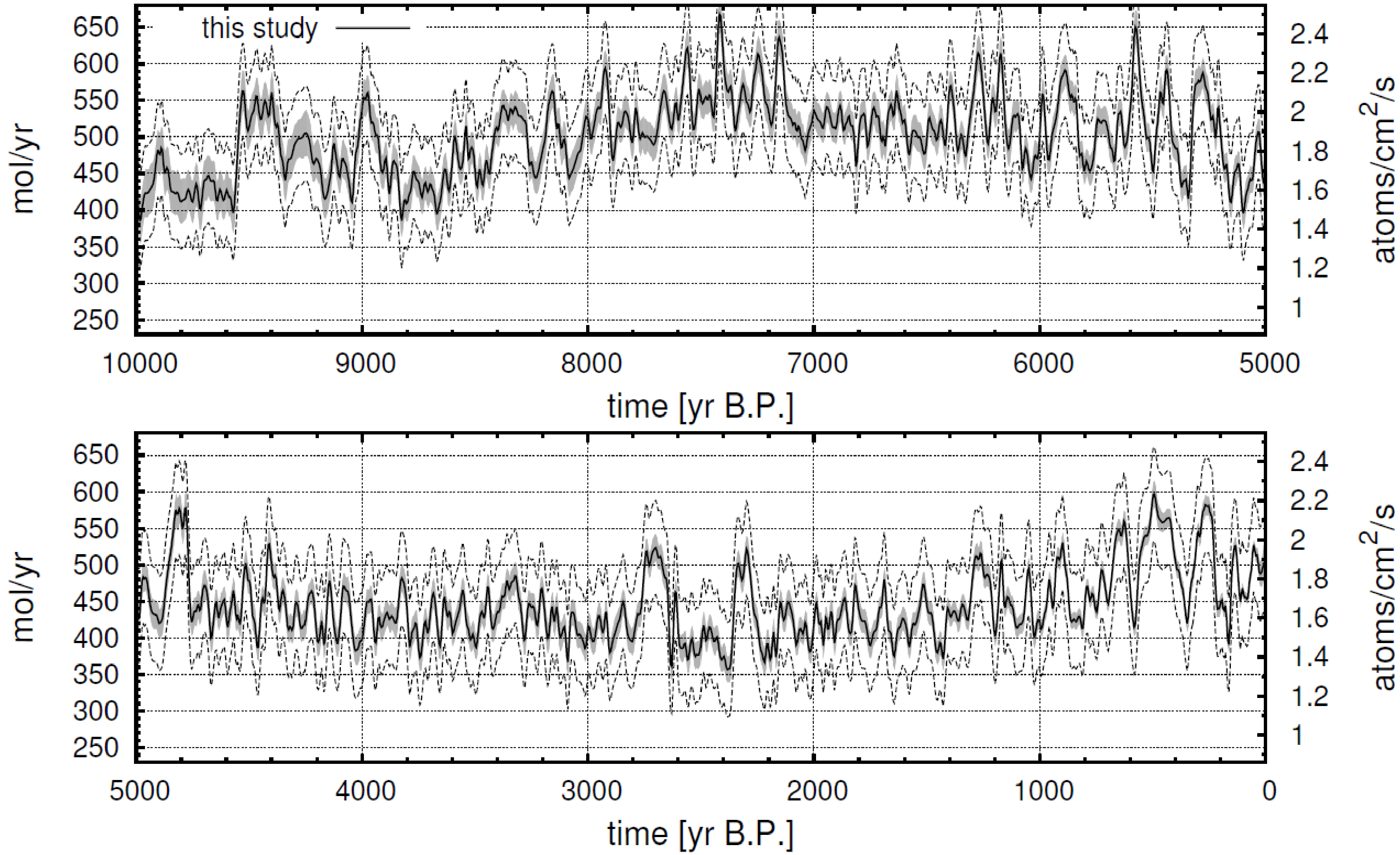
→ air-sea flux

$$+ \frac{I_{\text{lnd,model}}(t)}{\tau} + \frac{\mathrm{d}I_{\text{lnd,model}}(t)}{\mathrm{d}t} + \frac{\Delta I_{\text{lnd,data-model}}(t=t_0)}{\tau}$$

→ air-biosphere flux

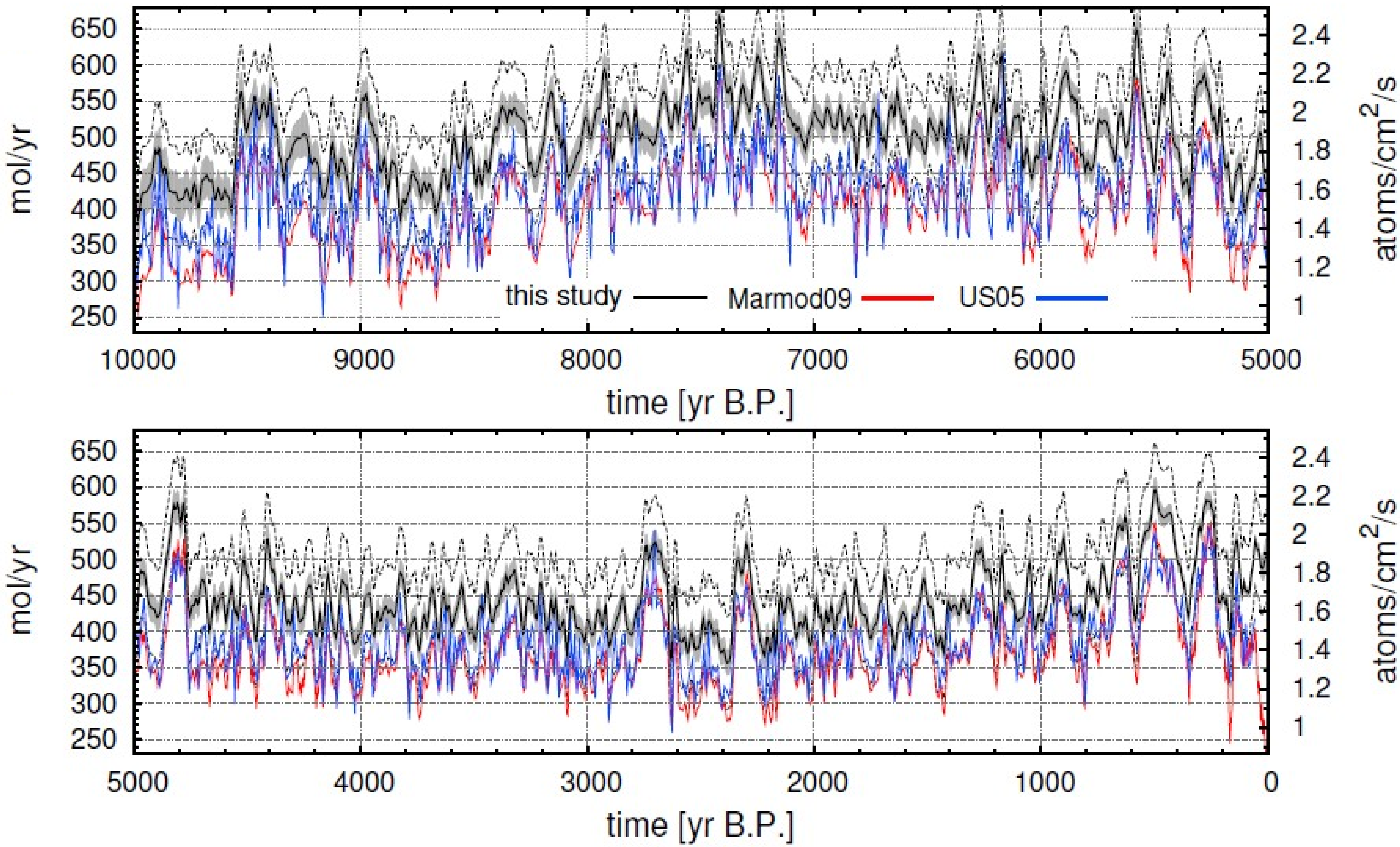
Part 2: ^{14}C production and solar activity

modified from Roth and Joos, 2013, CP



Part 2: ^{14}C production and solar activity

Roth and Joos, 2013, CP



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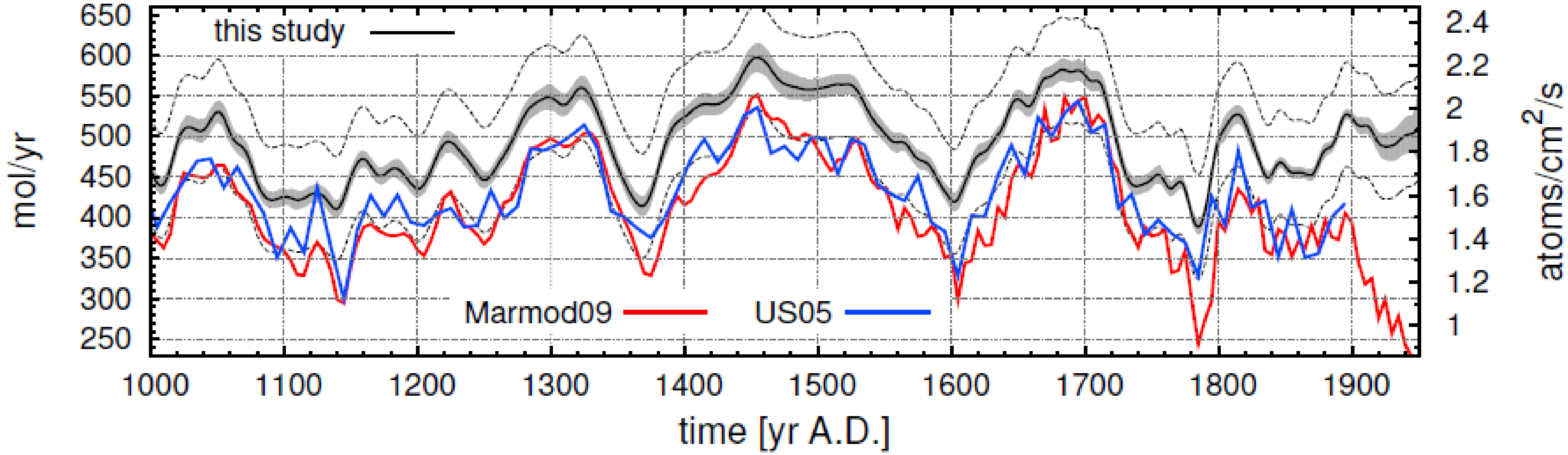
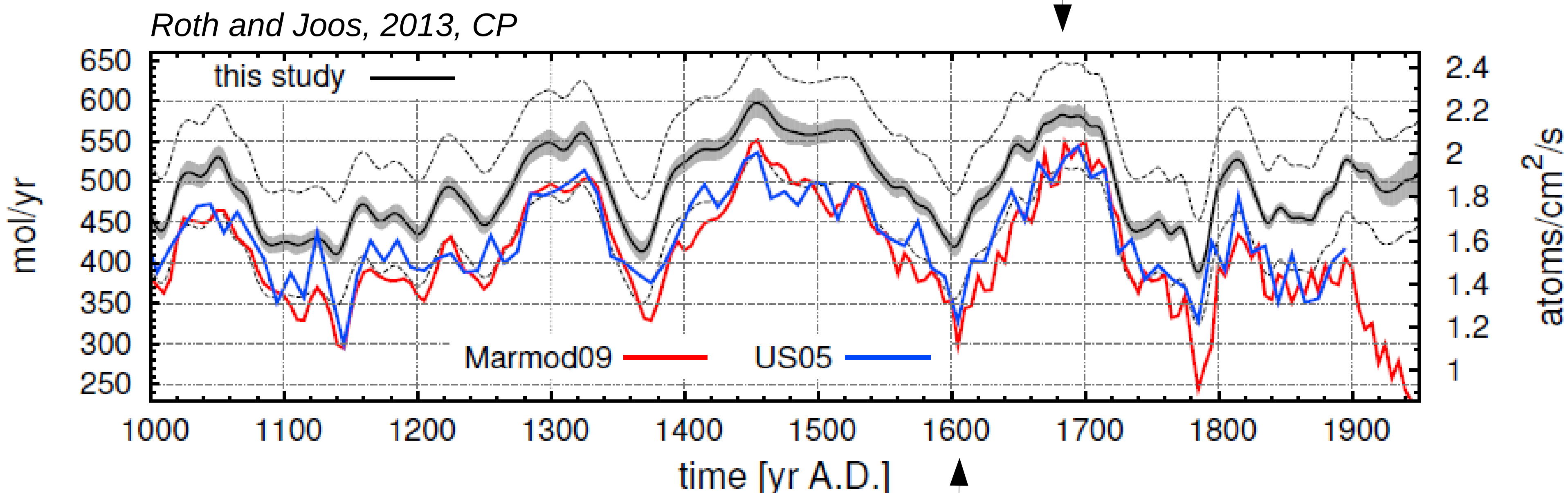


Part 2: ^{14}C production and solar activity

high production rate ↔ more cosmic rays



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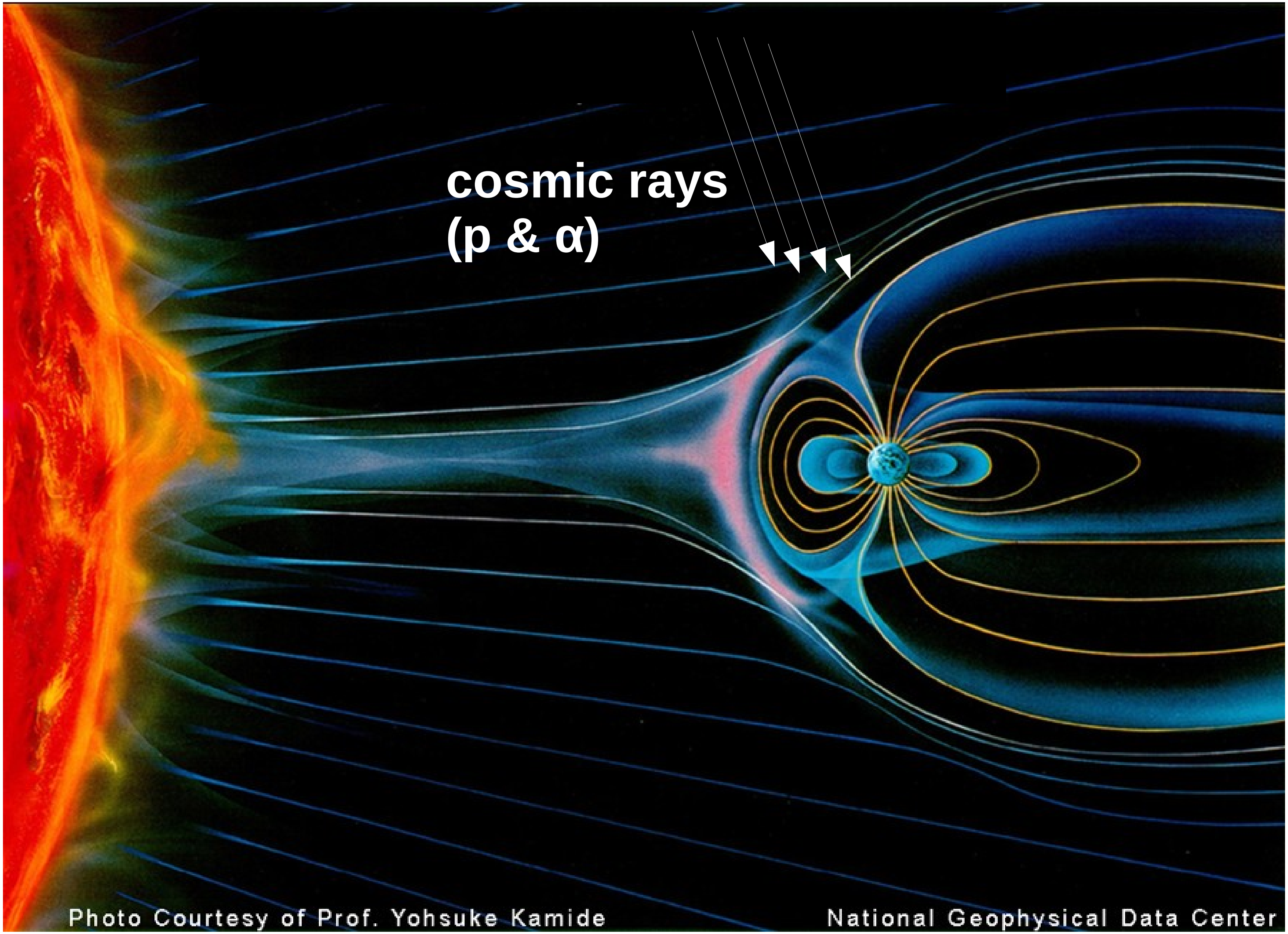
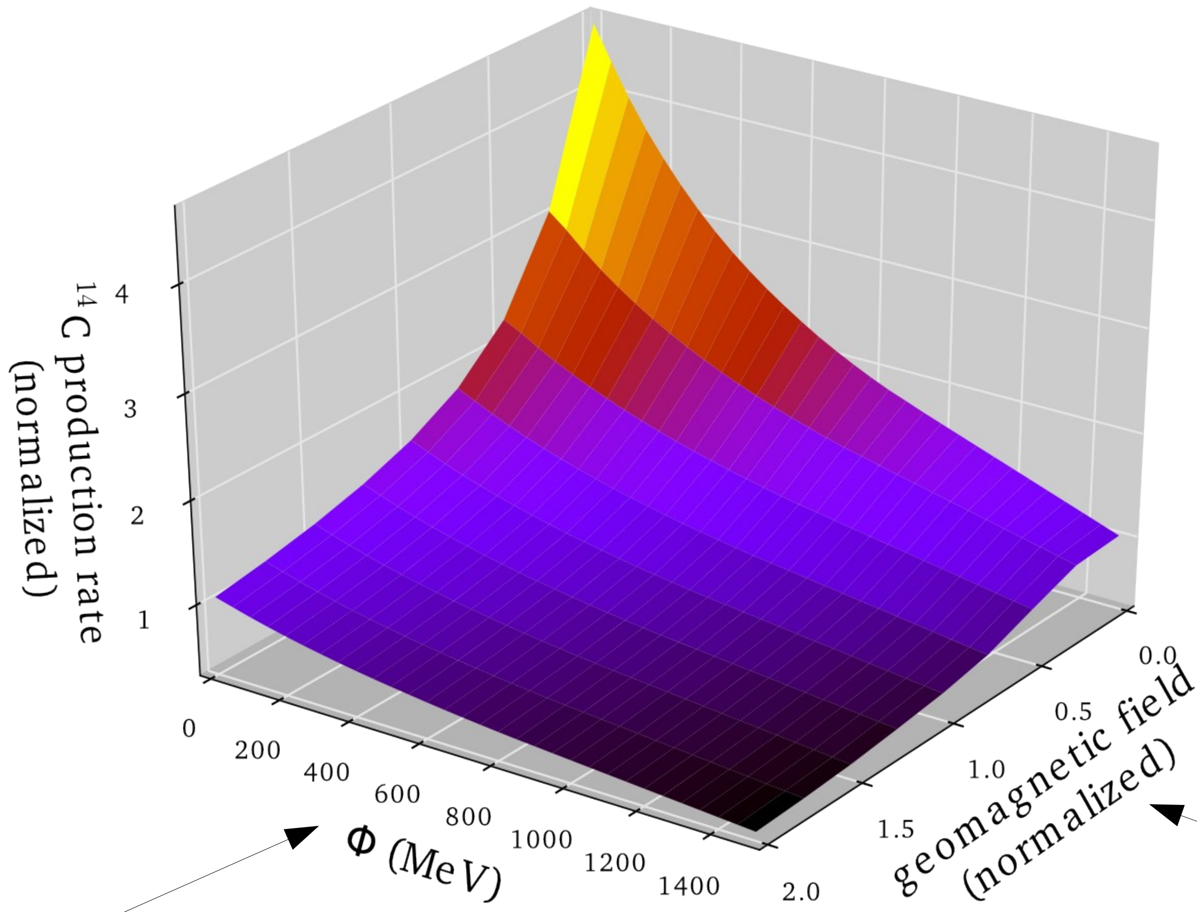


Part 2: ^{14}C production and solar activity

Results of particle simulations (e.g., *Masarik and Beer, 1999, 2009*) show:



geomagnetic modulation
(can be removed)

solar modulation Φ

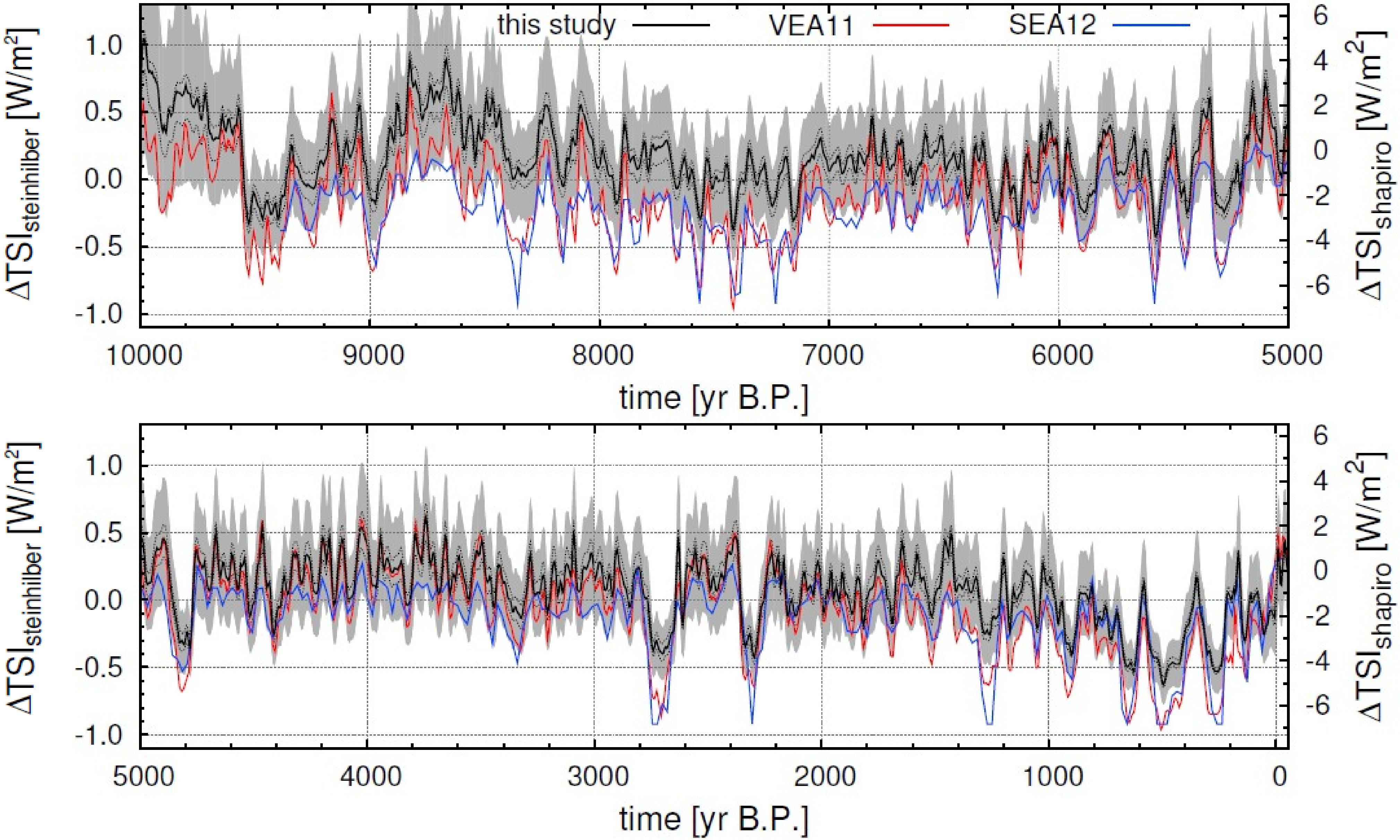
→ **Total Solar Irradiance**
(“solar constant”)

$$\mathrm{TSI}(t) \sim \mathrm{TSI}_0 + \mathrm{const} \cdot \left(\frac{\Phi(t)}{\Phi_0}\right)^{1/\alpha} \; \mathrm{W\,m^{-2}}$$

Part 2: ^{14}C production and solar activity

ΔTSI := deviation from 1365.57 W m⁻²

Roth and Joos, 2013, CP



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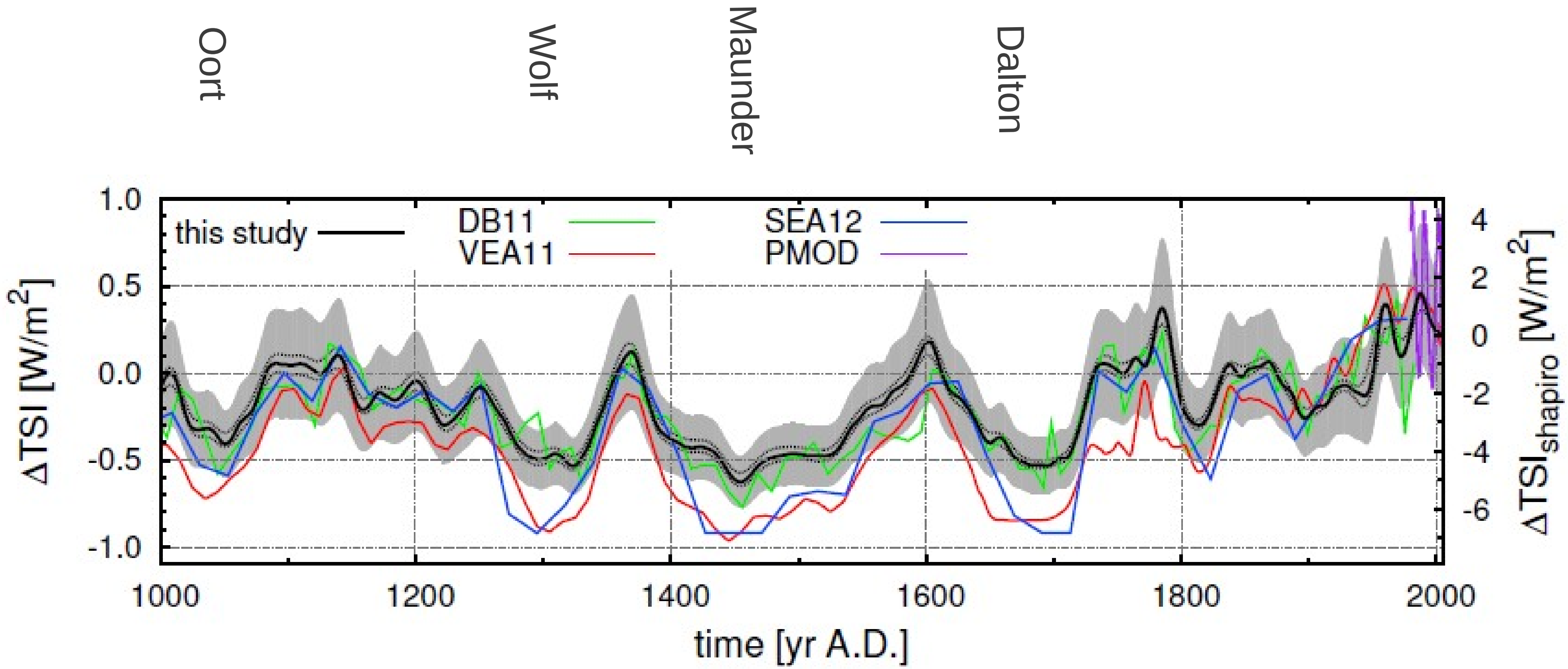


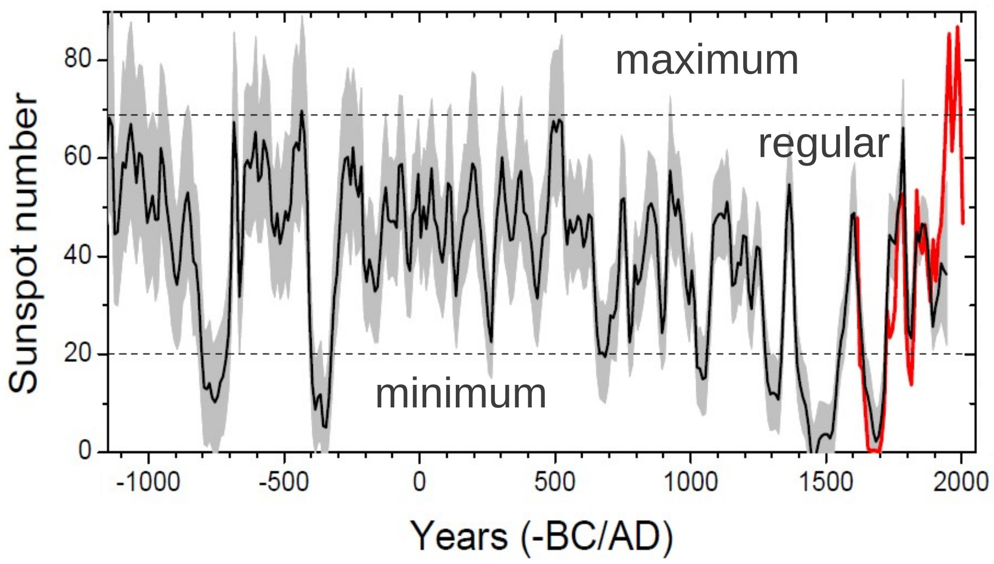
Part 2: ^{14}C production and solar activity

Ongoing collaborative effort (Switzerland, France, Finland)

State-of-the-art 3000 yr solar activity (sunspot number) reconstruction with

- consistent error treatment through the entire chain of models
- no ad-hoc normalizations

Usoskin et al., under review for Science



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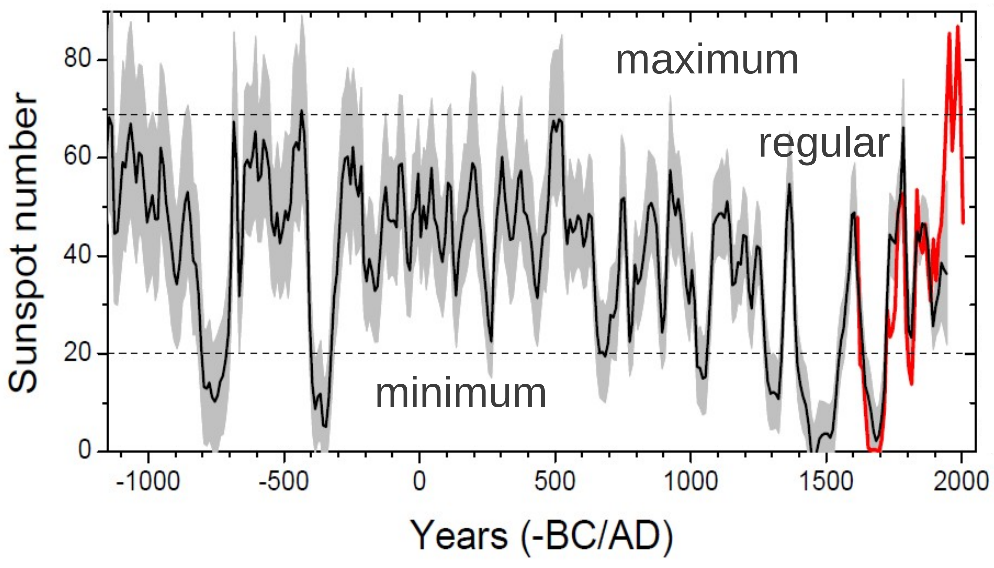

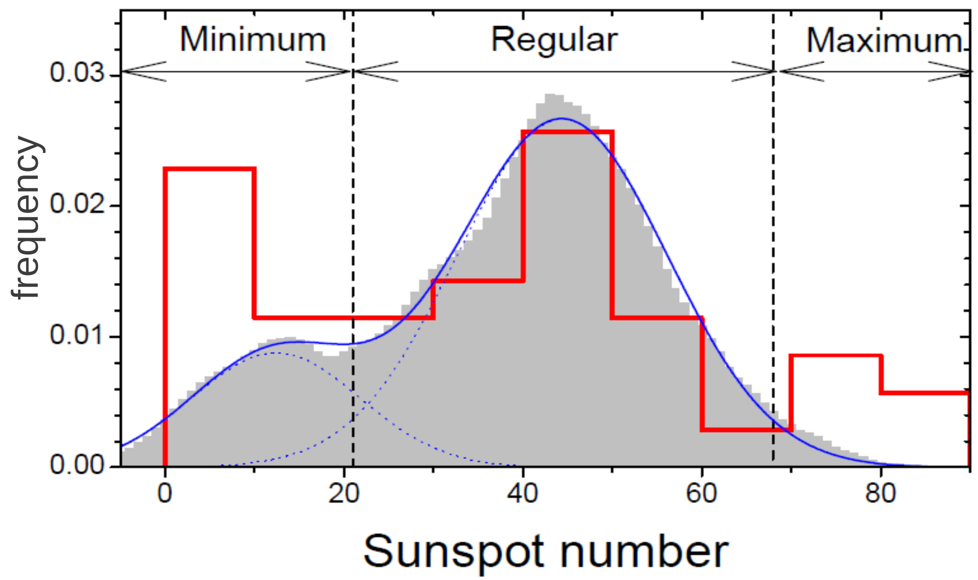

→ **Results suggest bi-modality in the state of the solar dynamo**

Summary (part 2)

- Past $\Delta^{14}C$ of atmospheric CO_2 is a valuable proxy for ^{14}C production and changes in the carbon cycle-climate system.

- Using a carbon cycle-climate model, the production signal can be separated from the climate signal.

- Our inferred modern ^{14}C production rate (~1.7 atoms/cm^2/s) links nicely to estimates from new models of cosmogenic particle simulations.

- Contemporary solar activity seems high compared to the past 3000 years, but higher states of solar activity existed earlier in the Holocene.

- A combination of new state-of-the art reconstructions reveals a bi-modality in the distribution of solar activity.

Thank you for
your attention!