Radiocarbon in Ecology and Earth System Science

2017

Goals of the class

- Learn about the Earth's carbon cycle from a ^{14}C perspective

  Lectures *– uses of ^{14}C to learn about C cycling in Ocean, Atmosphere, Land, and how they have varied in the past*

- Introduce you to the details of interpreting radiocarbon data obtained from AMS laboratories

  Exercises *– how to interpret and understand radiocarbon data*

- Important considerations when preparing samples for radiocarbon dating

  Laboratory methods *- a brief introduction to methods, especially considerations needed to be sure you evaluate all sources of uncertainty*

Outline

I. Carbon cycle

II. Fundamentals of radiocarbon

III. Three ways we use radiocarbon in the study of the Carbon cycle

- age determination for closed systems
- source partitioning
- constraining models in open systems

IIII. What goes into a good radiocarbon measurement

Global C cycle

Carbon takes different forms in different parts of the Earth System so transfers from one sphere to another involve change of chemical form or change of phase

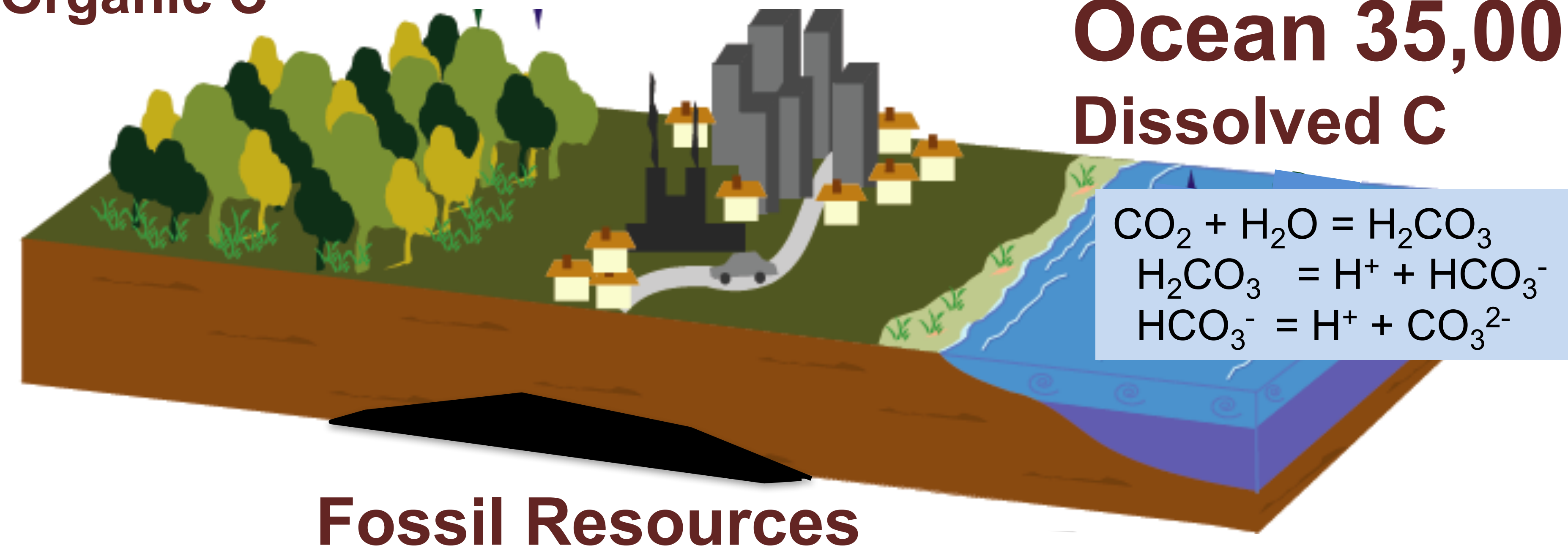
Atmosphere	Hydrosphere	Biosphere	Lithosphere
CO_2 CH_4 volatile organics	H_2CO_3 HCO_3^- CO_3^{2-} DOC	organic C (~CH_2O)	$CaCO_3$ organic C graphite
gas | liquid	liquid | dissolved ion	solid | liquid | dissolved ion	solid

We count carbon in units of Petagrams – 1 PgC = 1 billion tons or 10^{15} grams C

Atmosphere
~800
CO_2

Plants: ~600
Soils: ~2000-3000
Organic C

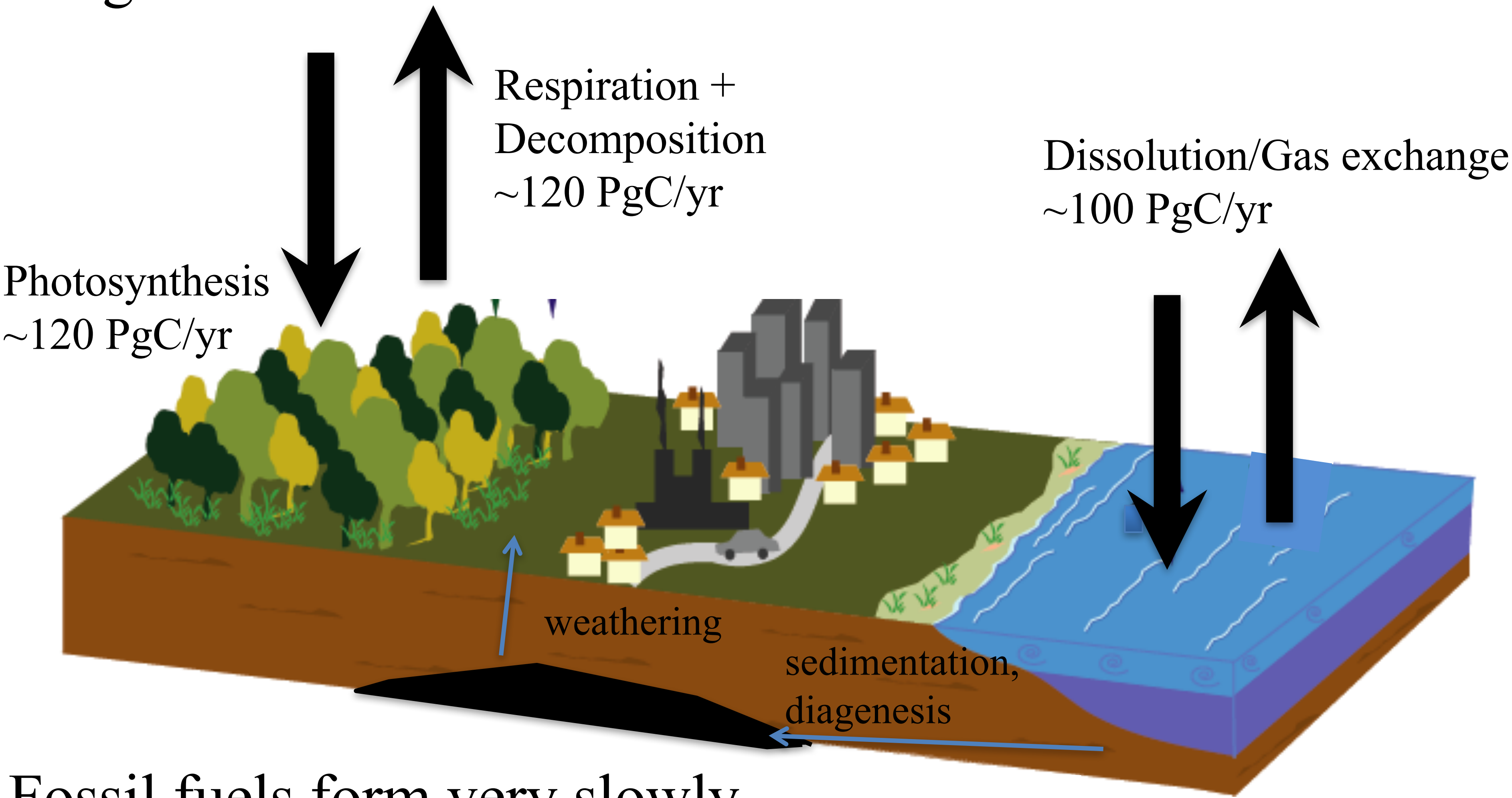
Ocean 35,000
Dissolved C



$CO_2 + H_2O = H_2CO_3$
$H_2CO_3 = H^+ + HCO_3^-$
$HCO_3^- = H^+ + CO_3^{2-}$

Fossil Resources
4300
Organic C

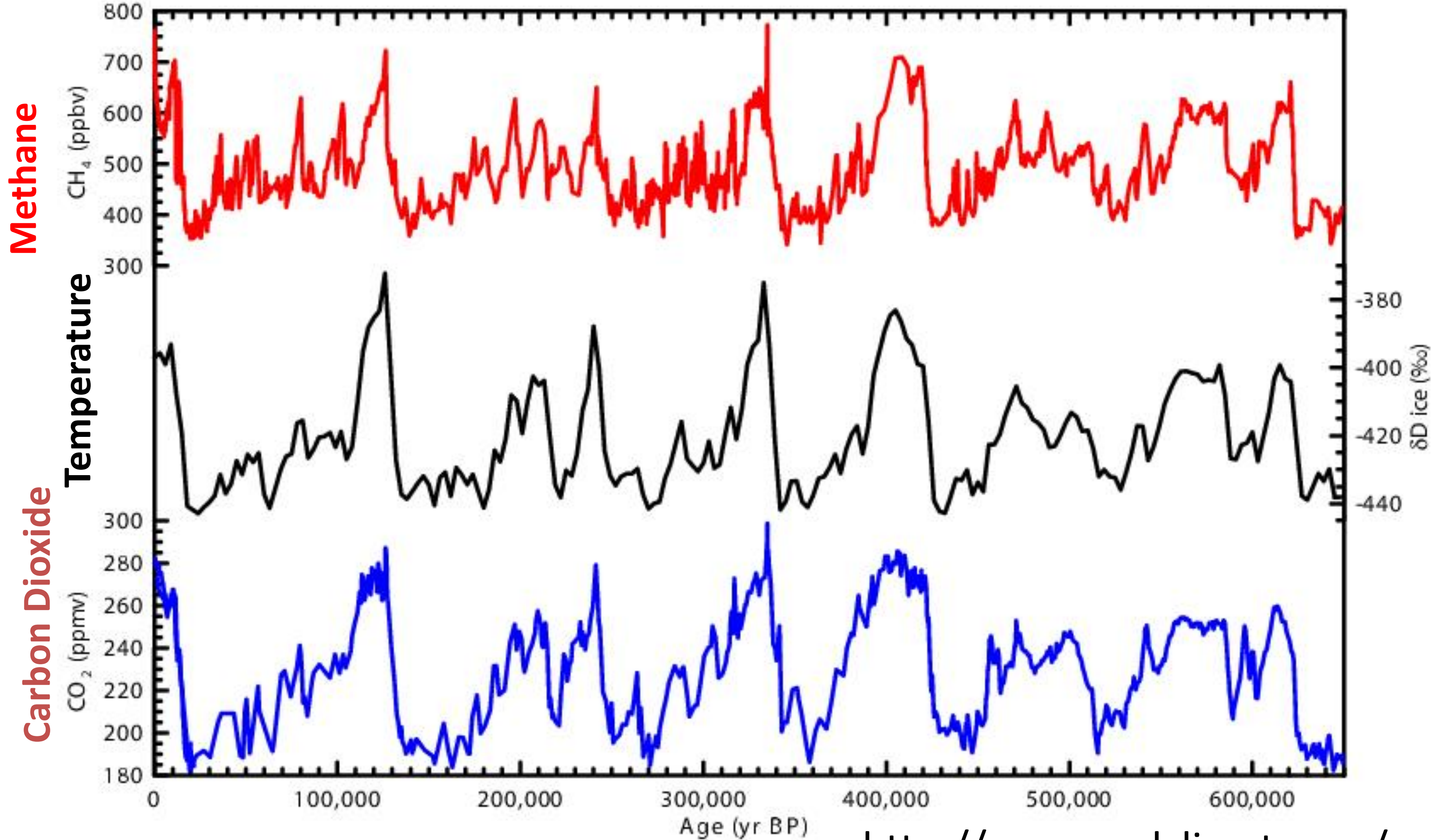
The natural Carbon cycle involves exchanges between land, air, ocean and transformations between organic and inorganic forms



Fossil fuels form very slowly
(<0.01% of C fixed every year)

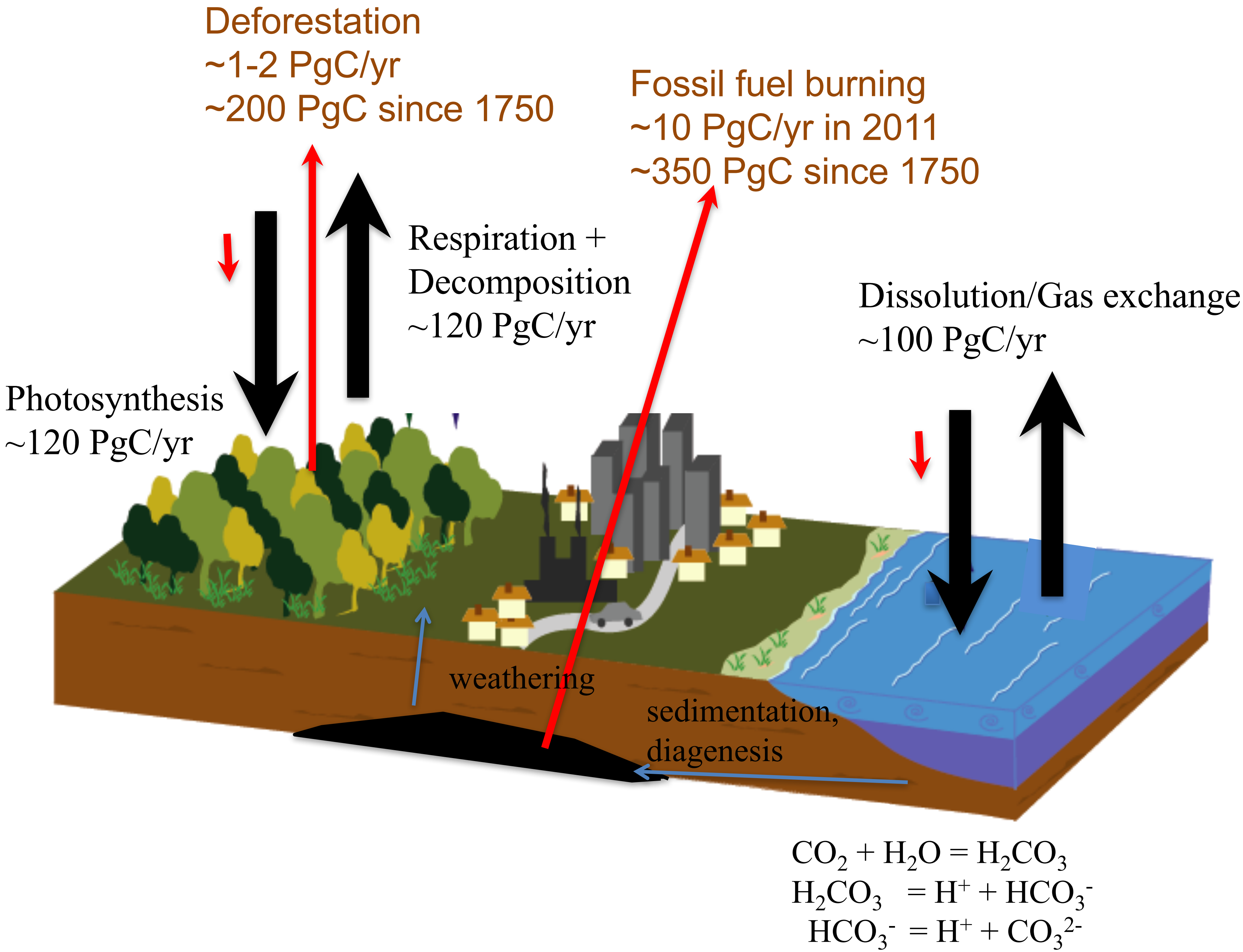
$$CO_2 + H_2O = H_2CO_3$$
$$H_2CO_3 = H^+ + HCO_3^-$$
$$HCO_3^- = H^+ + CO_3^{2-}$$

Changes in CO_2 on thousand year timescales tracks changes in climate – glacial to interglacial change
These changes reflect movement of C between reservoirs – in glacial times more is stored in the ocean



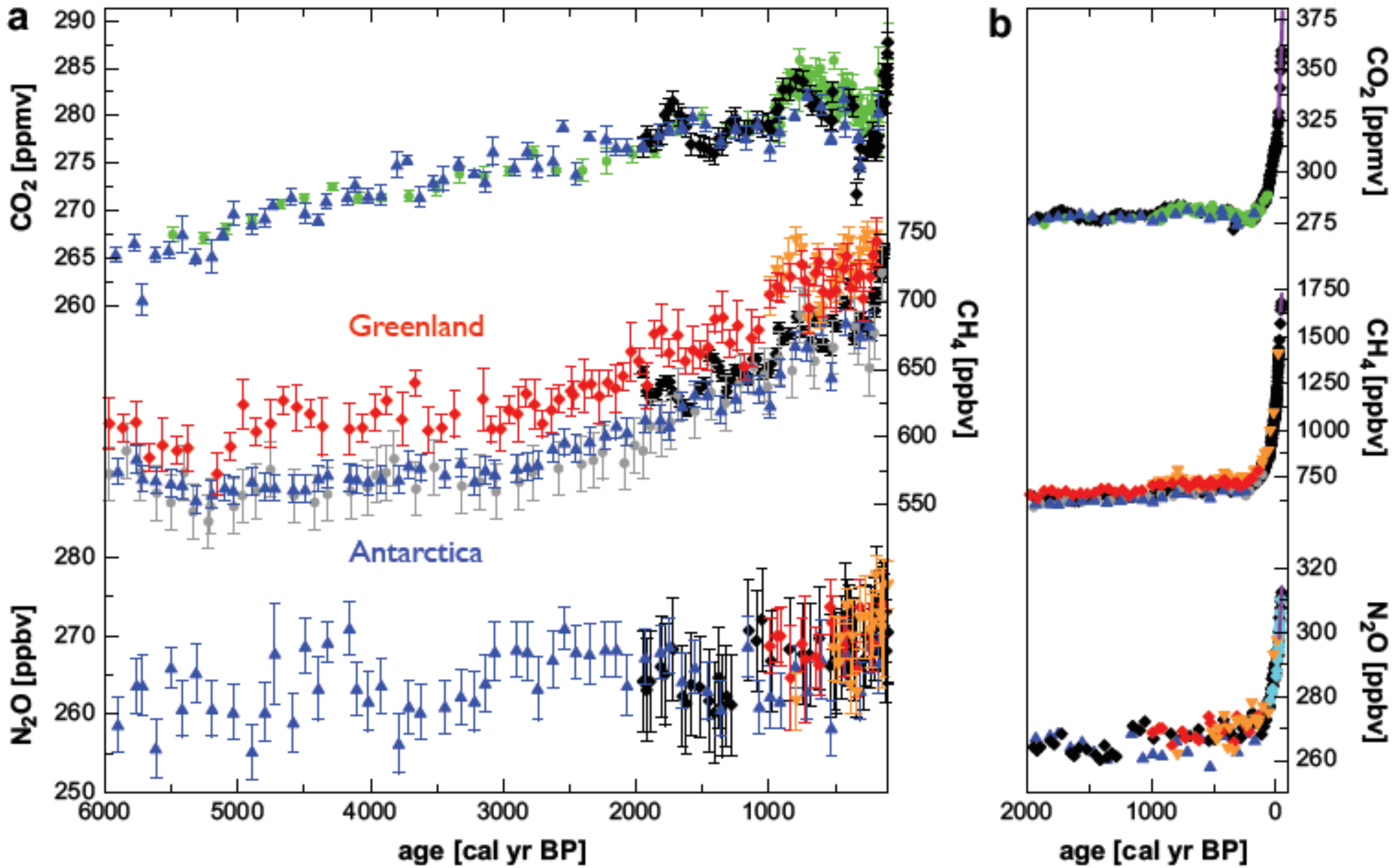
http://www.realclimate.org/epica.jpg

Brook, Nature, 2008, based on data by Lüthi et al., Nature, 2008

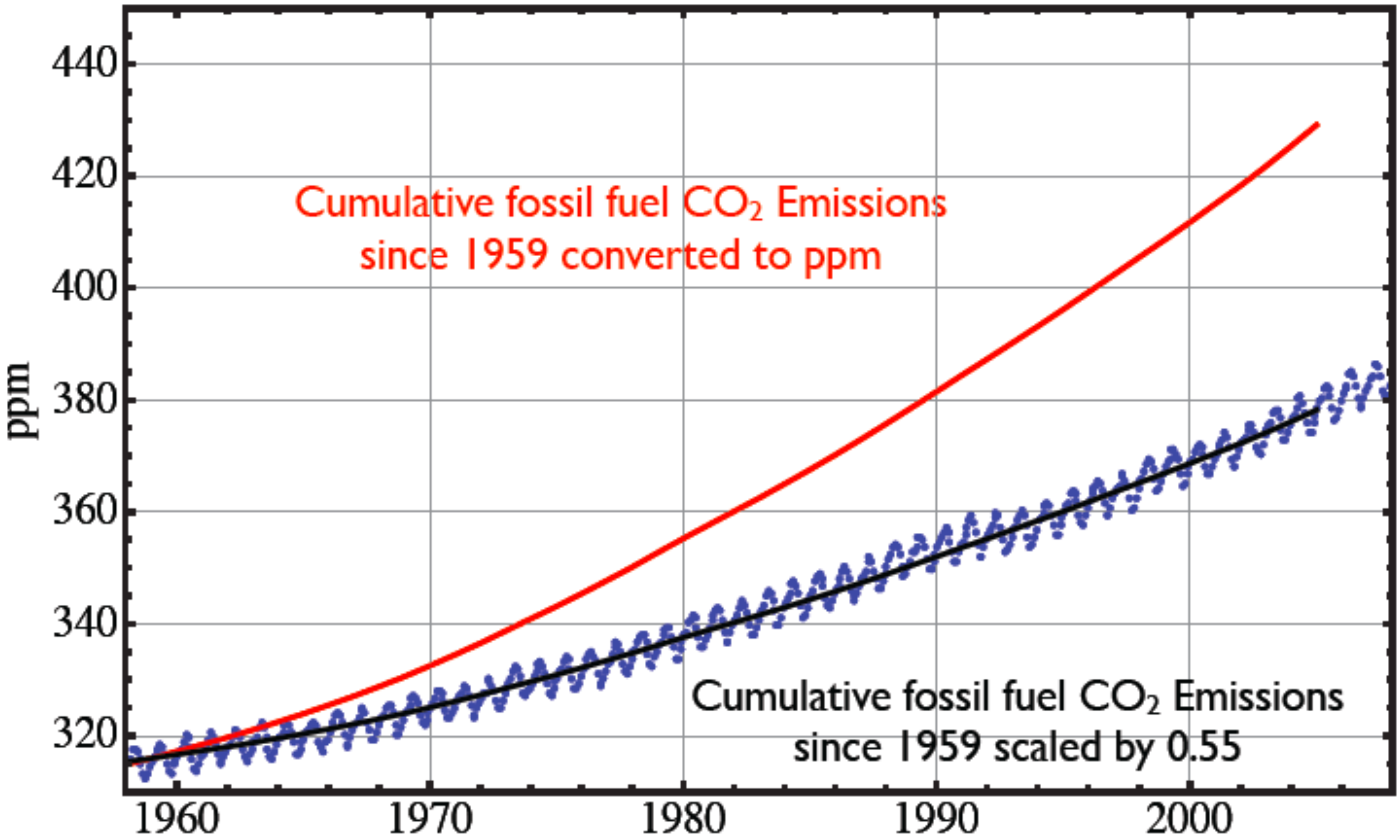

Deforestation
~1-2 PgC/yr
~200 PgC since 1750
Fossil fuel burning
~10 PgC/yr in 2011
~350 PgC since 1750
Respiration +
Decomposition
~120 PgC/yr
Photosynthesis
~120 PgC/yr
Dissolution/Gas exchange
~100 PgC/yr
weathering
sedimentation,
diagenesis
$CO_2 + H_2O = H_2CO_3$
$H_2CO_3 = H^+ + HCO_3^-$
$HCO_3^- = H^+ + CO_3^{2-}$

Holocene and Anthropocene

current carbon cycle is changing fast compared to the past



Only about ~55% of fossil fuel emitted to the atmosphere each year accumulates there



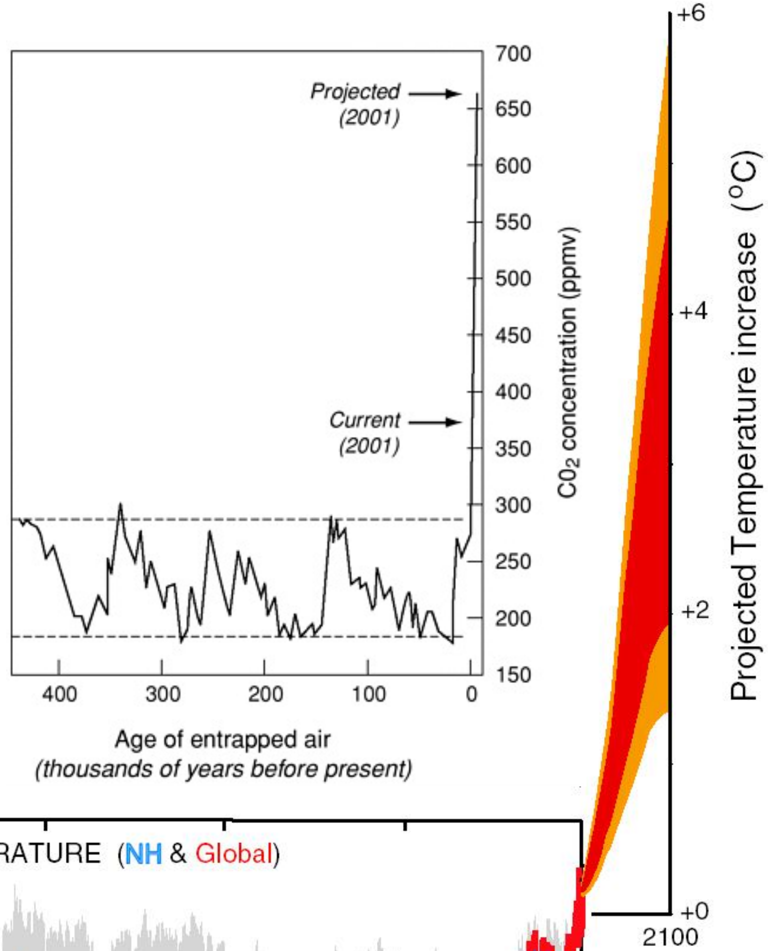
Projections of global average surface temperature show we are heading for a climatic state far outside the range of variation of the last 1000 years.

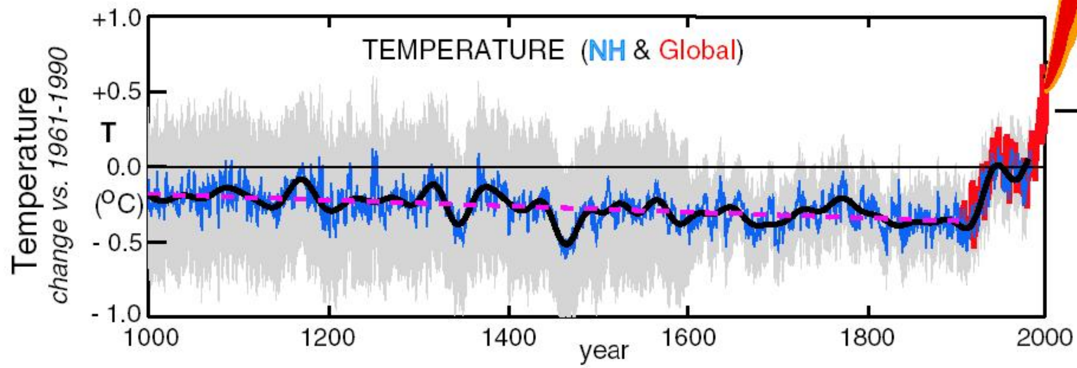
We are already out of the range of CO_2 for the last 800,000 years

CO_2 also has direct effects on ecosystems (fertilization, acidification)

Projections of global average surface temperature and CO_2

(IPCC)





Questions driving contemporary C cycle research

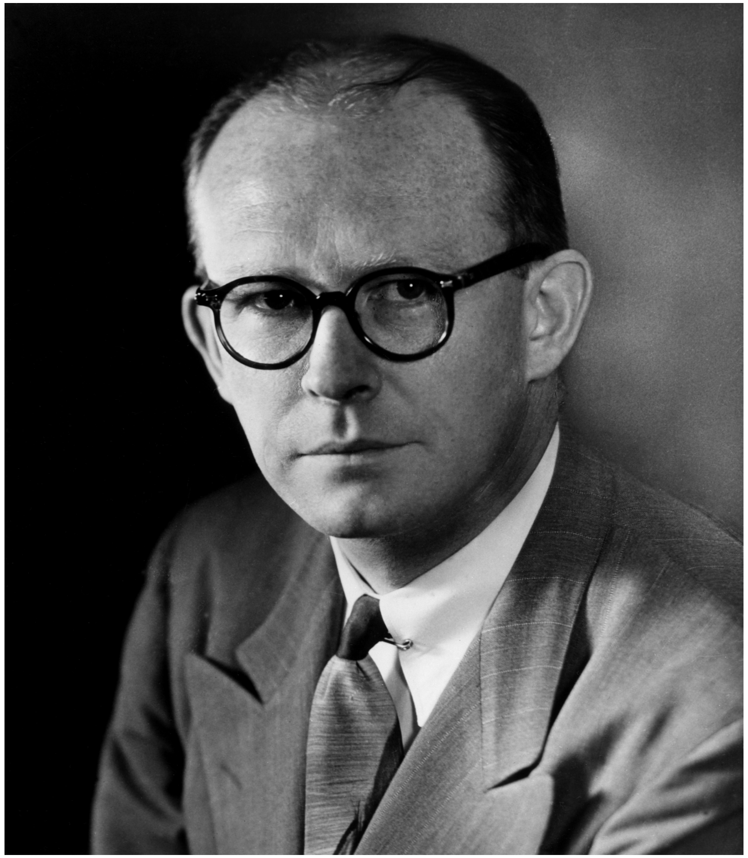
Where does the excess CO_2 go?

How will climate change affect the fate of excess CO_2?

Can we manage ecosystems to take up C and how much/how fast/how expensive?

Can we measure regional C balance well enough to verify C storage?

Fundamentals of radiocarbon



Willard Frank Libby (1908-1980)
1960 Nobel Prize in Chemistry
for development of radiocarbon dating

"Seldom has a single discovery in chemistry had such an impact on the thinking of so many fields of human endeavor. Seldom has a single discovery generated such wide public interest"

Nobel Foundation 1960

More history to come from Erv Taylor's lecture

Isotopes of an element have the same number of protons (therefore chemistry) but different numbers of neutrons (mass)

^{12}C	98.9%	(6 protons, 6 neutrons)
^{13}C	1.1 %	(6 protons, 7 neutrons)
^{14}C	$\sim 1.1 \times 10^{-10}$ %	(6 protons, 8 neutrons)

Isotopes that are unstable decay radioactively –

^{14}C decays to ^{14}N with a half-life of 5730 years

Isotopes of carbon contain different information:

^{13}C variations – patterns in the environment reflect mass-dependent fractionation (partitioning among phases at equilibrium and differences in reaction rates), mixing of sources

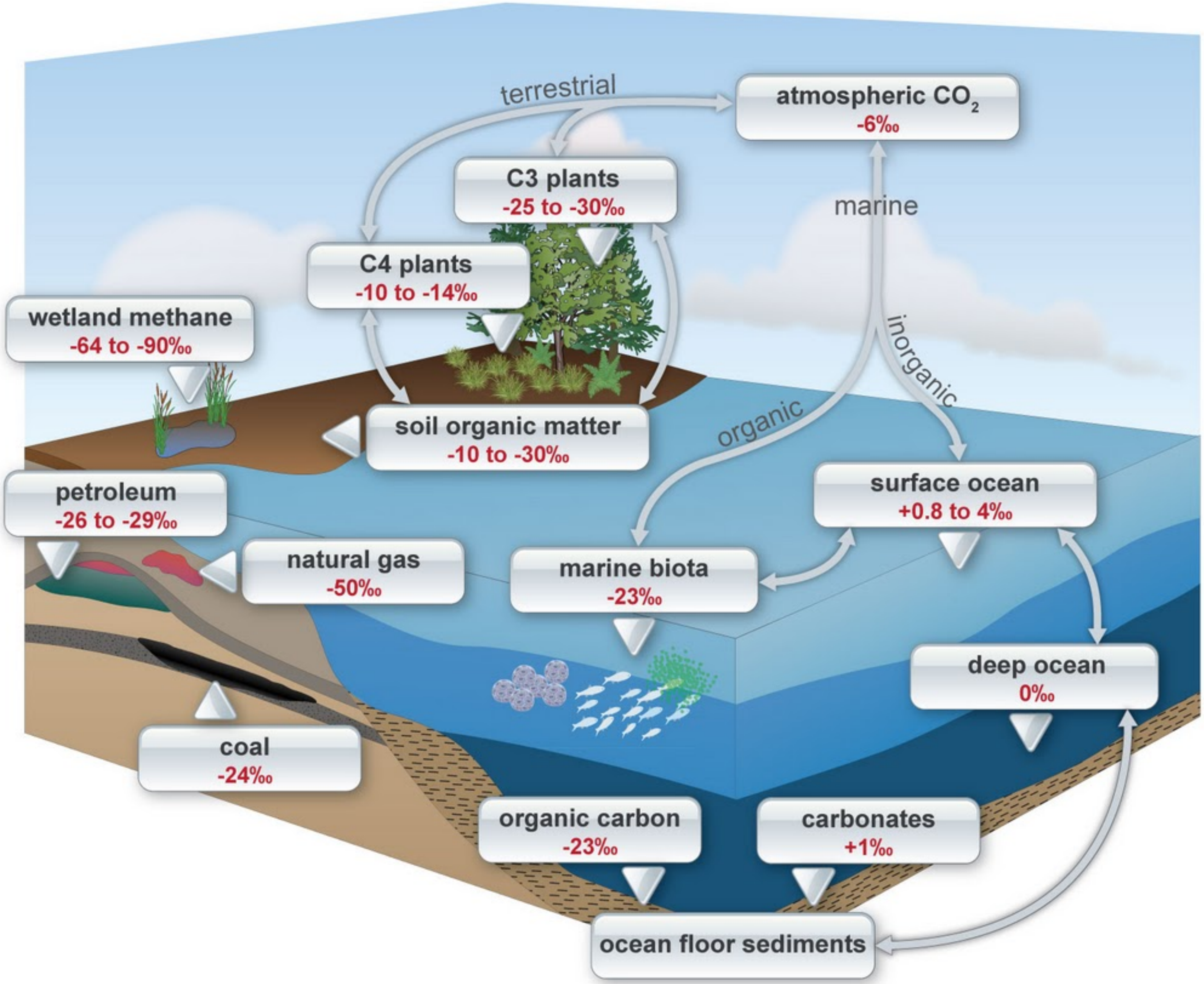
^{14}C variations – Reflects time since isolation from exchange with atmosphere; corrected for other variations using ^{13}C

Absolute isotope ratios are very difficult to measure … mostly we rely on relative measures and compare to a standard

$^{13}C/^{12}C$
sample

$^{13}C/^{12}C$
Standard material

$$\delta^{13}C = \left[\frac{\left(\frac{^{13}C}{^{12}C}\right)_{\text{sample}}}{\left(\frac{^{13}C}{^{12}C}\right)_{\text{standard}}} - 1 \right] \times 1000$$



terrestrial
atmospheric CO_2
-6‰
C3 plants
-25 to -30‰
marine
C4 plants
-10 to -14‰
wetland methane
-64 to -90‰
inorganic
organic
soil organic matter
-10 to -30‰
petroleum
-26 to -29‰
surface ocean
+0.8 to 4‰
natural gas
-50‰
marine biota
-23‰
deep ocean
0‰
coal
-24‰
organic carbon
-23‰
carbonates
+1‰
ocean floor sediments

Unlike stable isotopes, which can be moved around between C reservoirs but are always conserved, radiocarbon is constantly created and destroyed

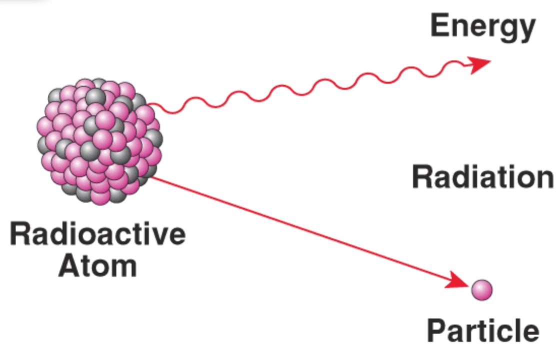
Production in the atmosphere

Total number of ^{14}C atoms (N) in the Earth System

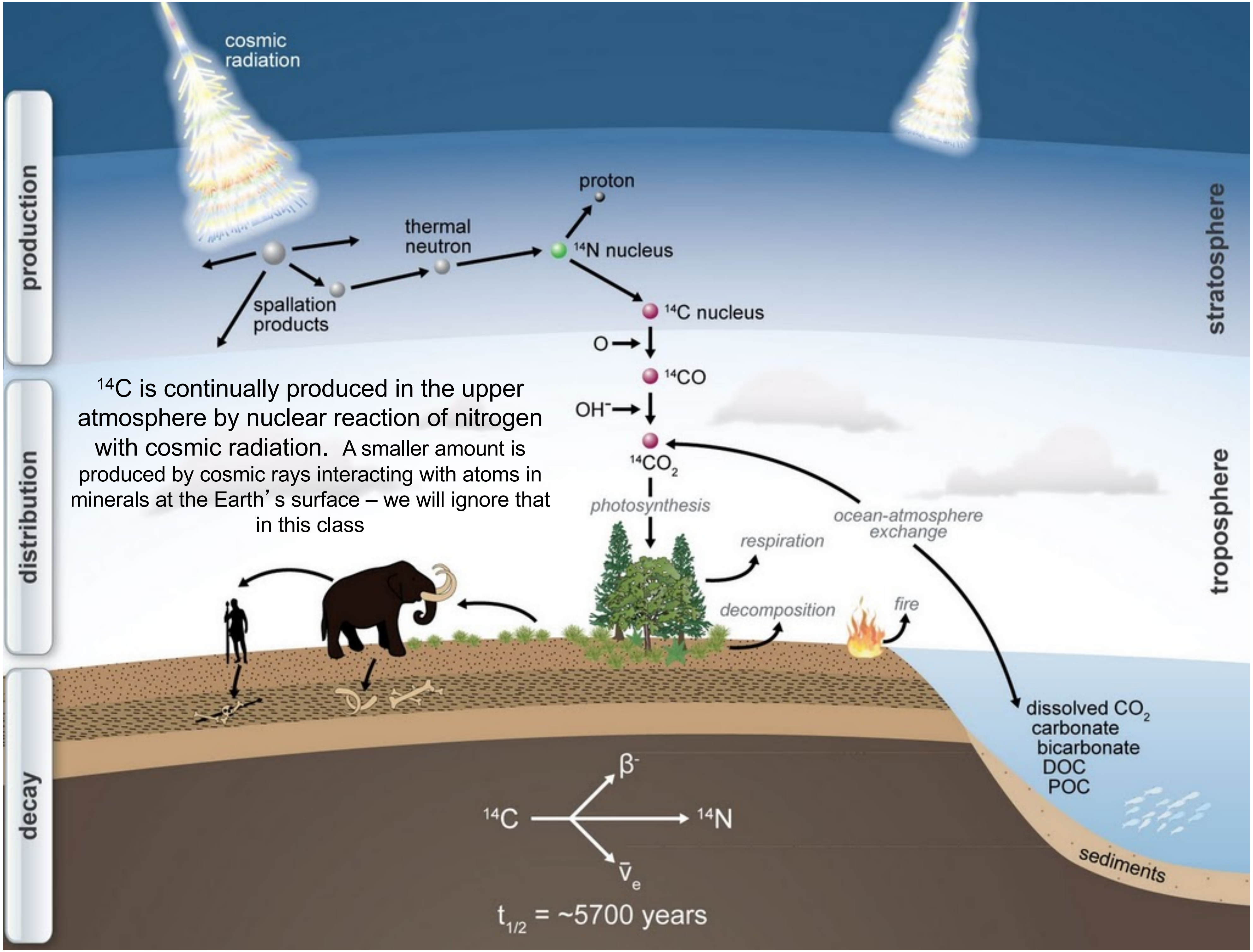
Loss by radioactive decay

$-\lambda N$

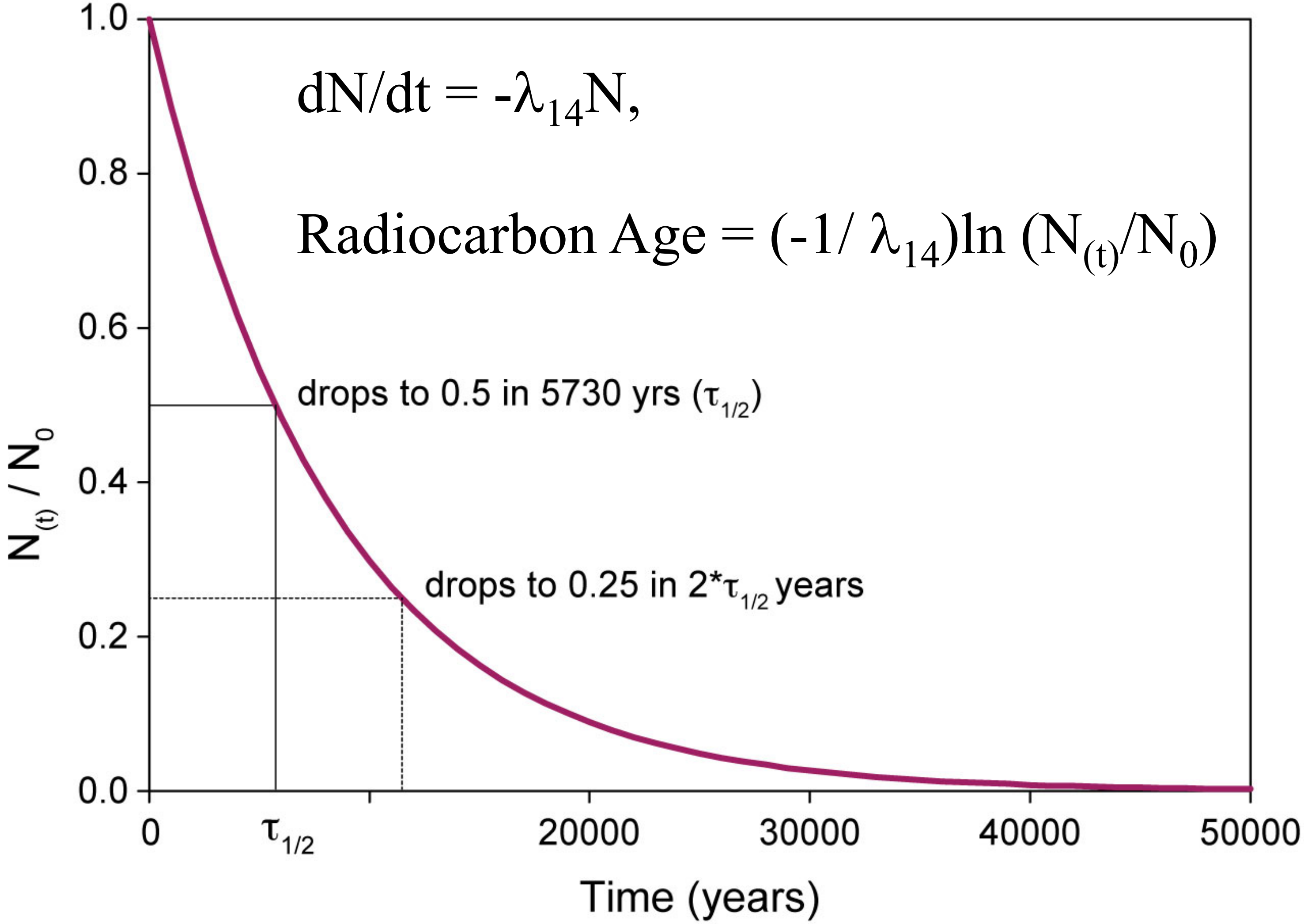
λ Is the decay constant, the probability that a ^{14}C atom with undergo radio-decay in a given time interval. Mean life $= 1/\lambda$



^{14}C is continually produced in the upper atmosphere by nuclear reaction of nitrogen with cosmic radiation. A smaller amount is produced by cosmic rays interacting with atoms in minerals at the Earth's surface – we will ignore that in this class



Basis of ^{14}C dating



Assumes

- Atmosphere $^{14}C = N_0$ = constant everywhere (pre-1900)
- What is measured is a closed system for C
- ^{14}C half-life accurately known

How do we know the half-life of radiocarbon?

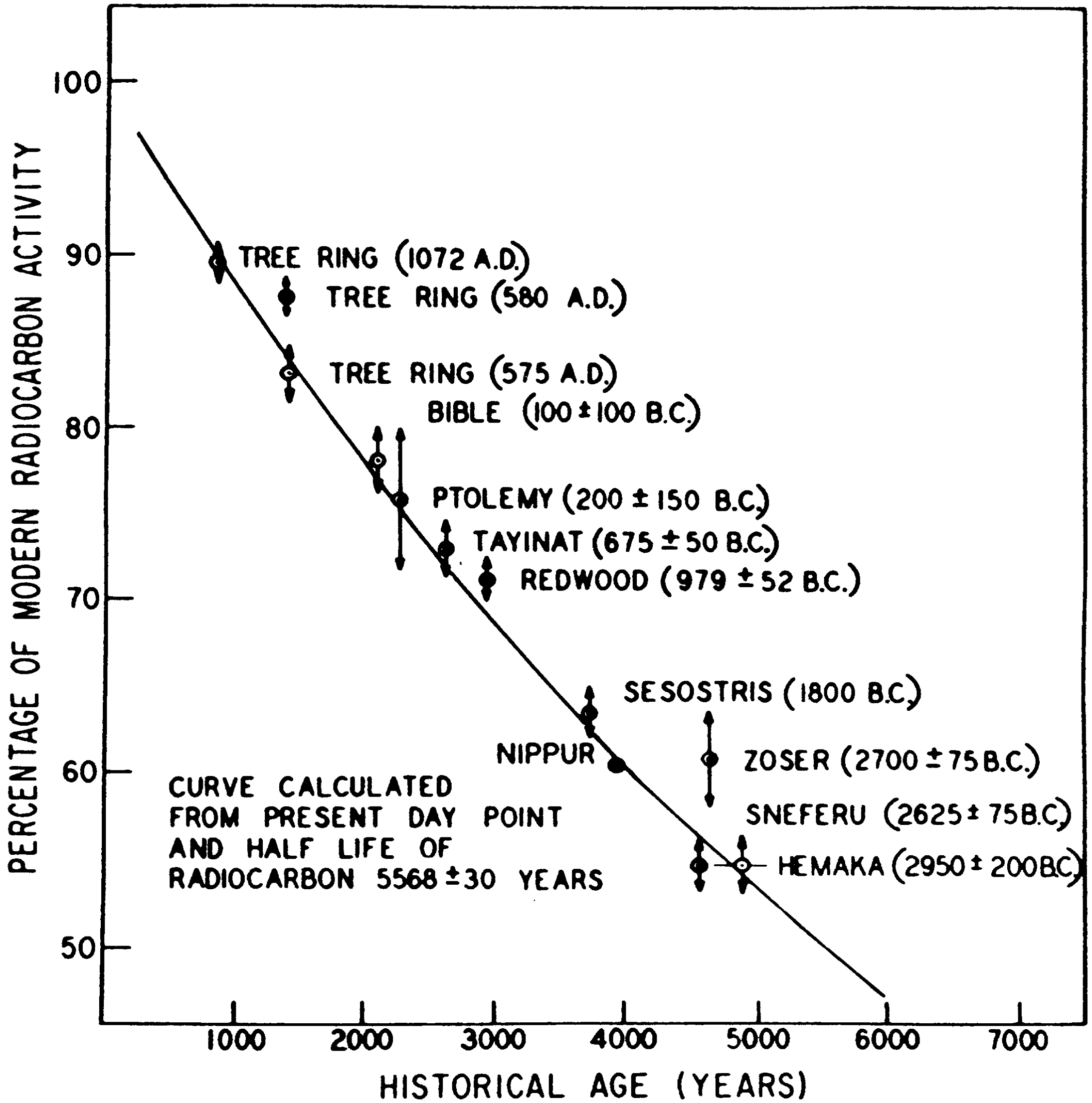
- the currently accepted half-life of radiocarbon is 5700 ± 30 yr (National Nuclear Data Center, Brookhaven National Laboratory, www.nndc.bnl.gov)
- You commonly see 5730 ± 40 yr
- (Godwin 1962)

- The value used to calculate radiocarbon age is 5568 years, the so-called "Libby" half life

How can we use different half-lives?

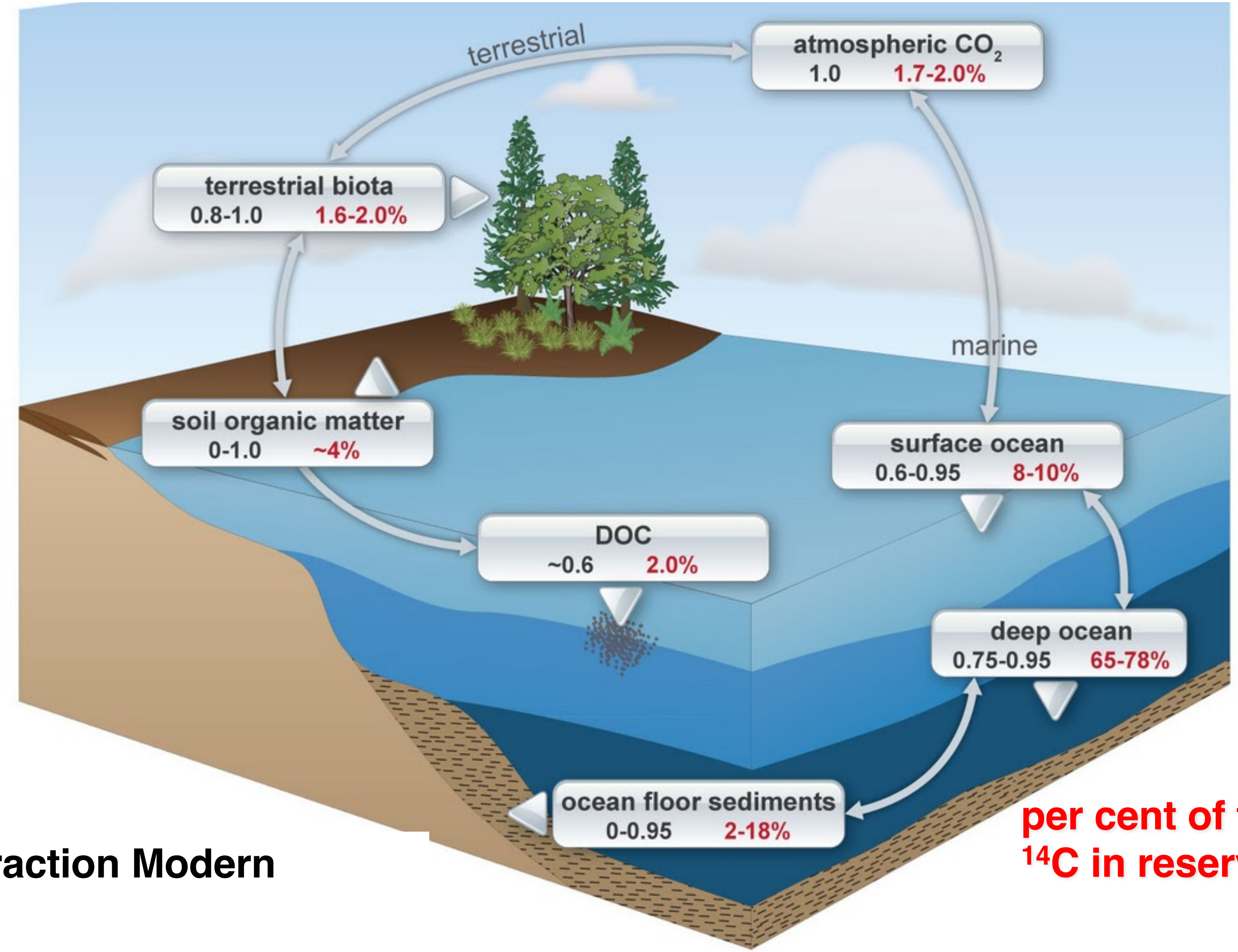
Method 1. Wait and see

Libby's second curve of 'knowns' (1950) 12 points….
Responsible for the "Libby" half-life of 5568 years



- For ^{14}C you have to wait a long time, so get something from a known time in the past….
- Because you also do not know N_0, you have two unknowns, so you need more than one sample

Differences between the distribution of ^{14}C and total C depend on (1) how much C is there (2) how fast it exchanges with the atmosphere



Fraction Modern

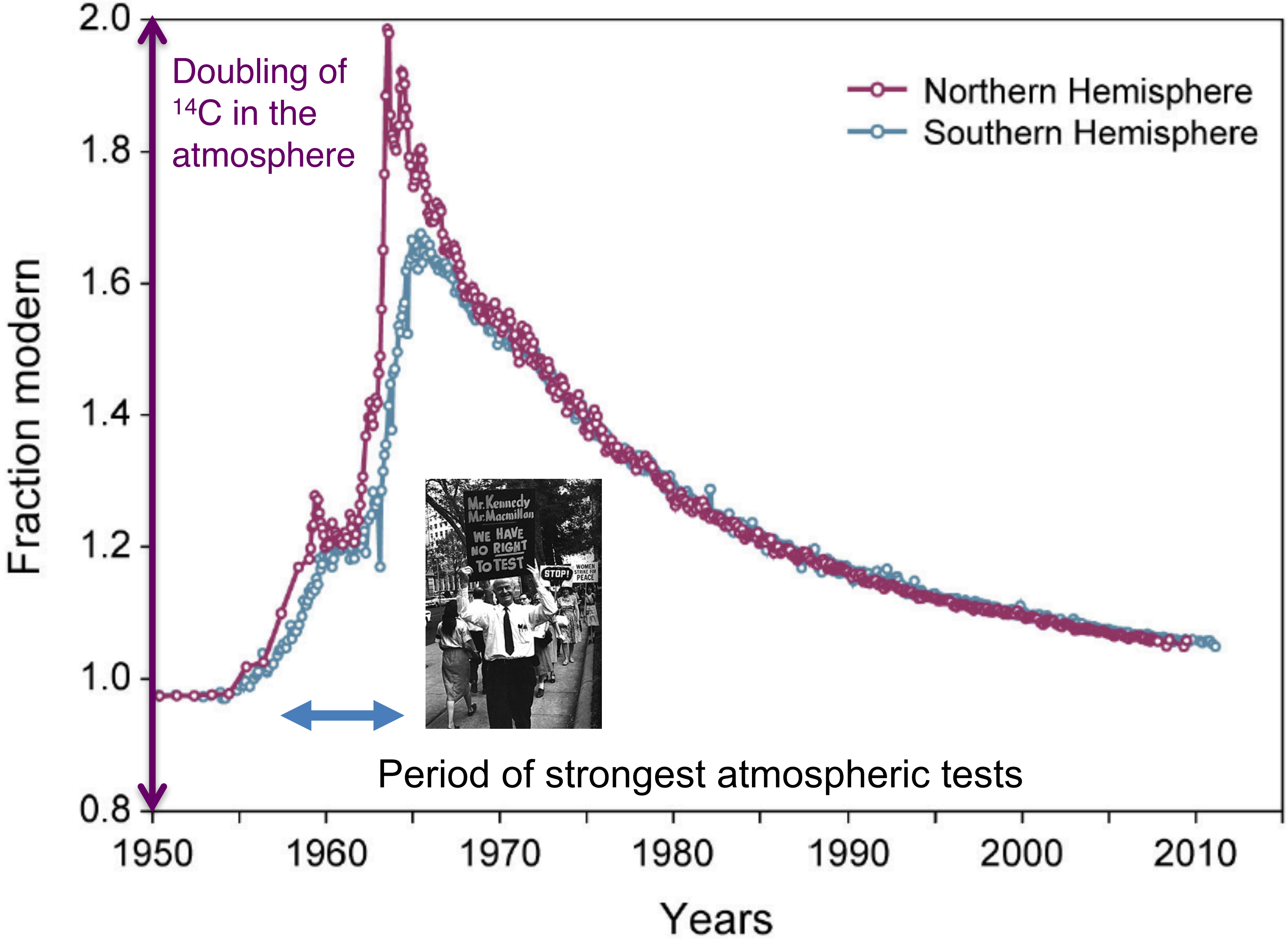
per cent of total ^{14}C in reservoir

Timescales of use for radiocarbon

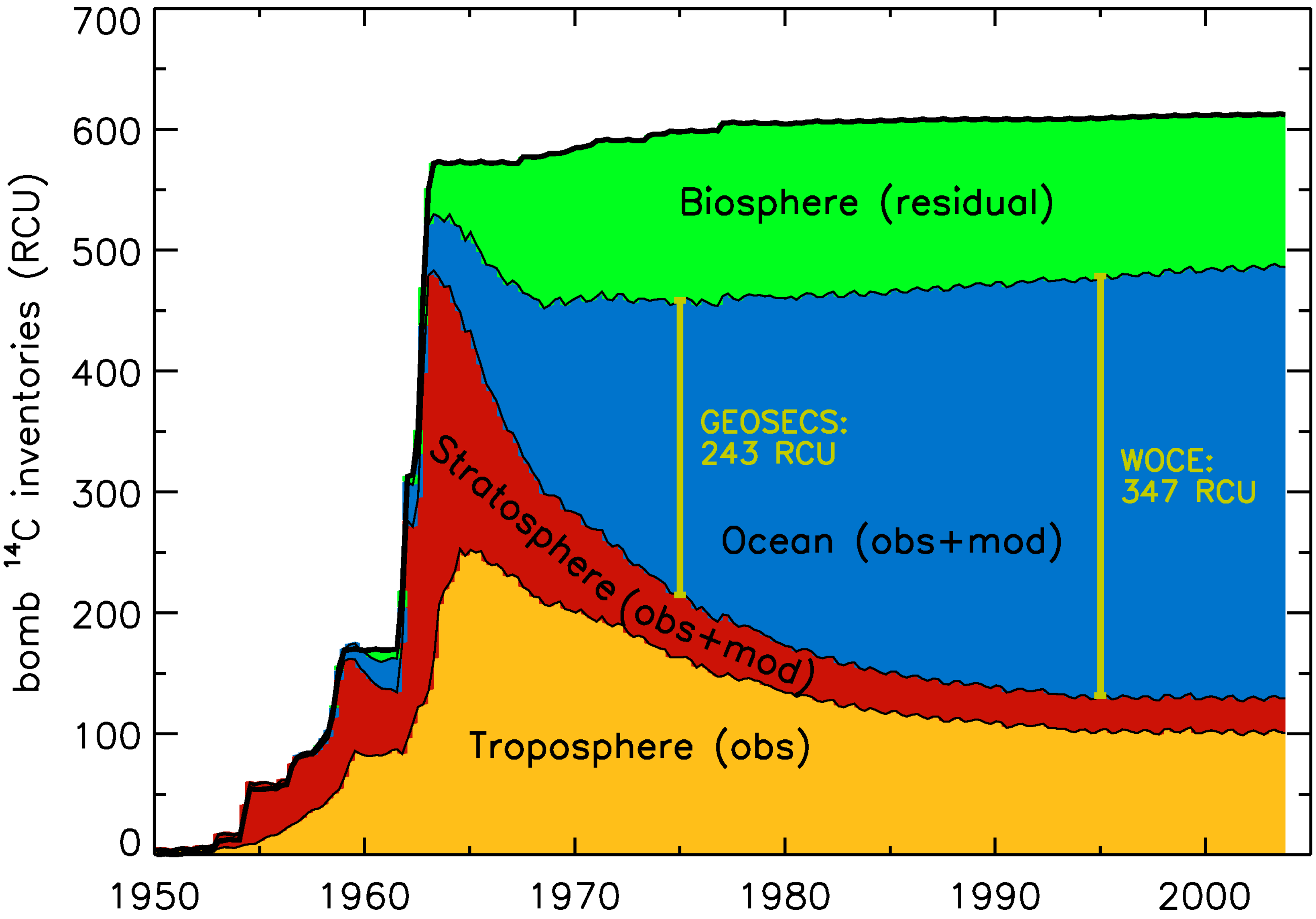
Source of ^{14}C	cosmogenic ^{14}C (radiocarbon dating)
Timescale of interest	**>300 years to ~50,000 years (± 20–100 years)**
Method of analysis	model residence time based on comparison of ^{14}C with Modern C

Radiocarbon is also made by humans – “bomb” 14C

Differences between the hemispheres (Turnbull lecture)



Tracing the bomb ^{14}C allows us information on how the global C cycle operates on decadal timescales (T. Naegler/I. Levin)



Timescales of use for radiocarbon

Source of ^{14}C	cosmogenic ^{14}C (radiocarbon dating)	"bomb" ^{14}C produced by atmospheric thermo-nuclear weapons testing
Timescale of interest	**>300 years to ~50,000 years (± 20–100 years)**	**~1950 to present (± 1–2 years)**
Method of analysis	model residence time based on comparison of ^{14}C with Modern C	compare ^{14}C to known redord of change in atmosphere

Timescales of use for radiocarbon

Source of ^{14}C	cosmogenic ^{14}C (radiocarbon dating)	“bomb” ^{14}C produced by atmospheric thermo-nuclear weapons testing	purposeful tracer ^{14}C follow added radiocarbon
Timescale of interest	**>300 years to ~50,000 years (± 20–100 years)**	**~1950 to present (± 1–2 years)**	**minutes to years, depending on activity of tracer**
Method of analysis	model residence time based on comparison of ^{14}C with Modern C	compare ^{14}C to known redord of change in atmosphere	allows tracing of specific pathways of allocation and resource use

The ways we use radiocarbon to study the carbon cycle:

- ***Determining the age*** of C in a **closed system**

- ***As a source tracer:*** mixing of sources with different ^{14}C signatures

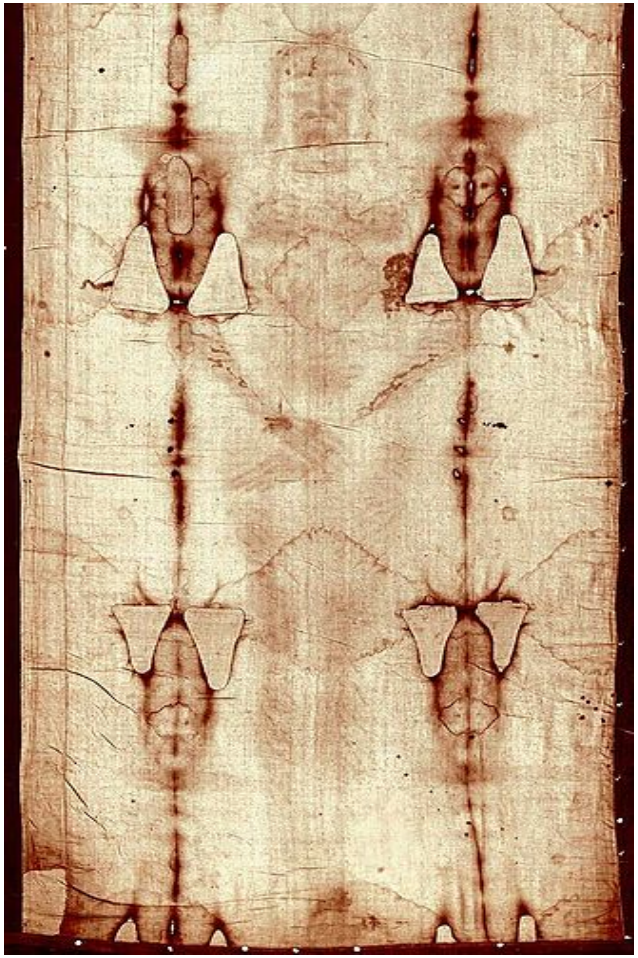
- For **open systems**, ***the rate of exchange of C*** with other reservoirs (requires models)

- ***As a purposeful tracer***

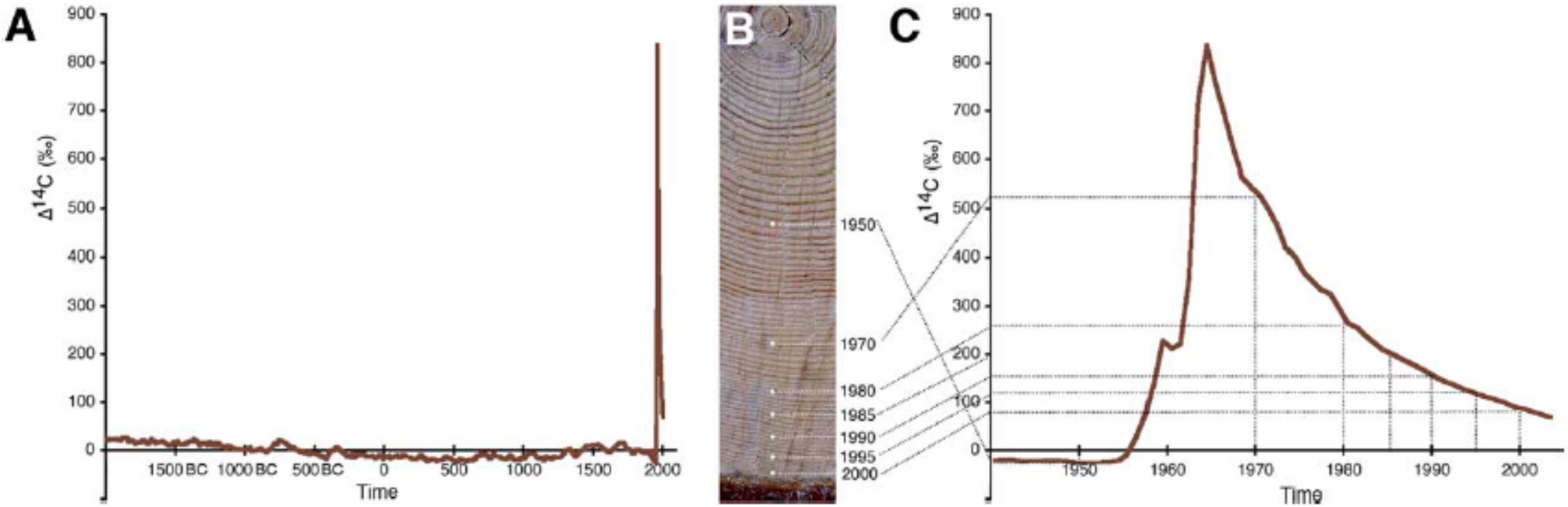
Examples – closed system homogeneous, pre-bomb

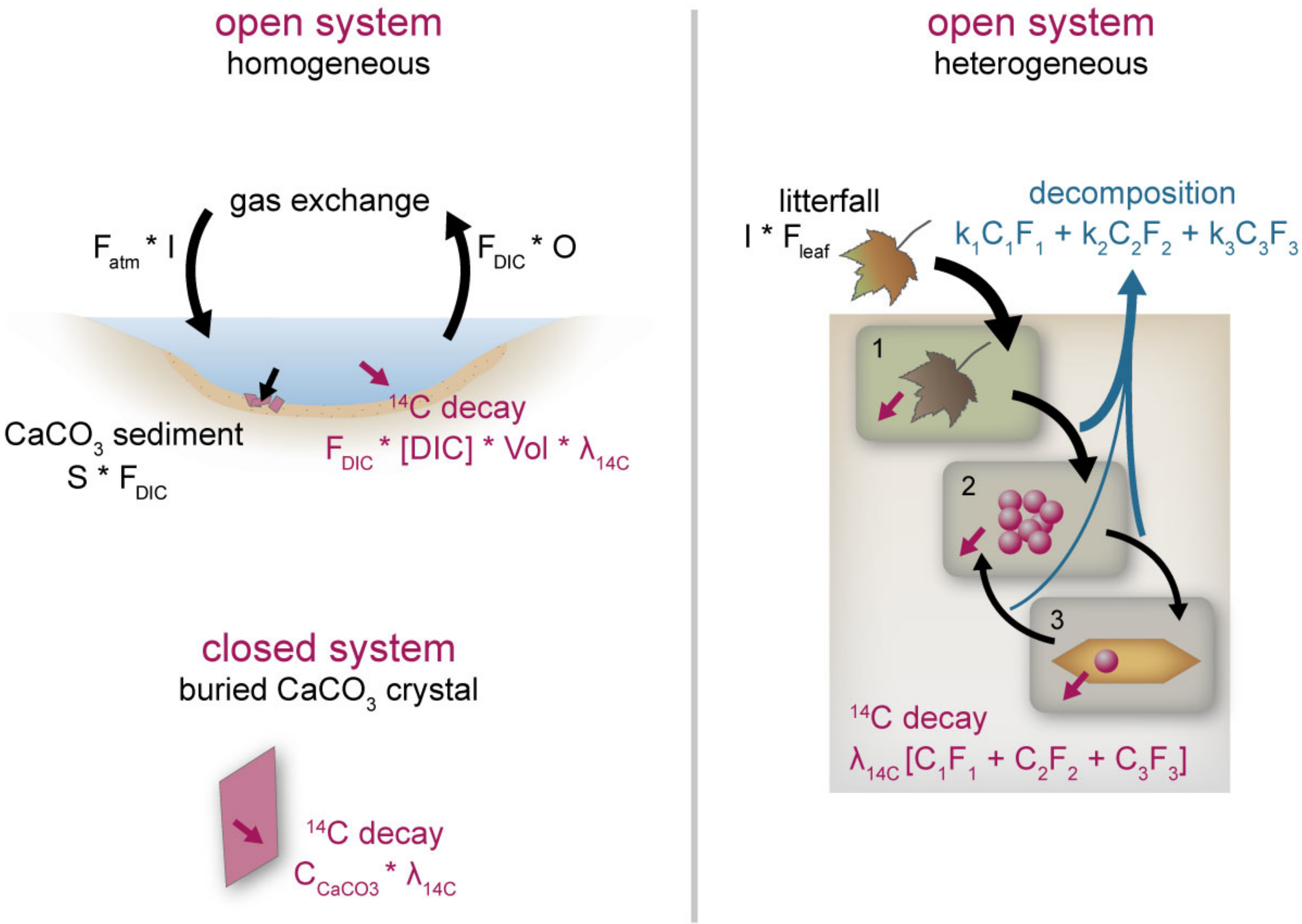
Convert **radiocarbon age** to **calendar age** using calibration curves

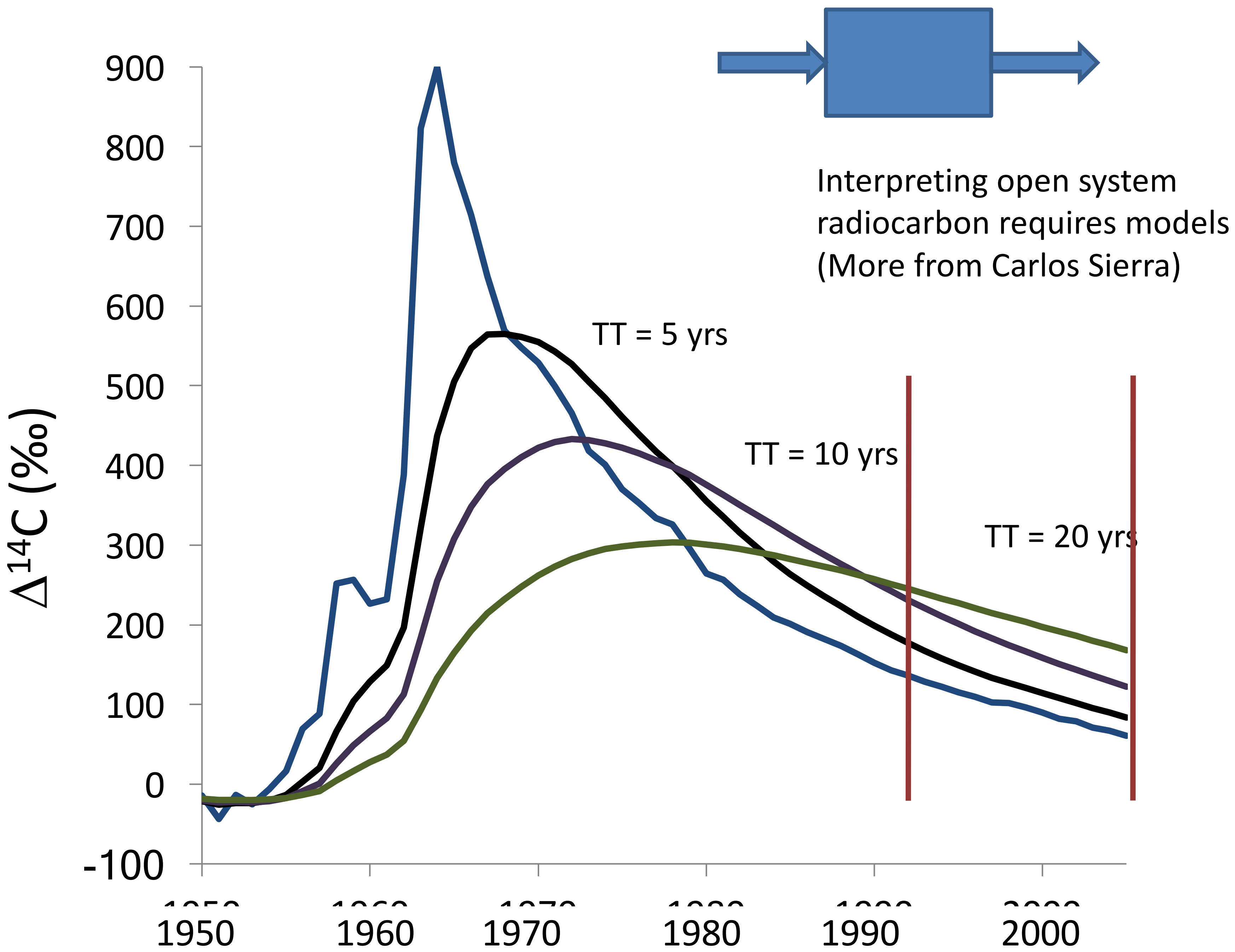
Shroud of Turin
(CE 1262-1384)



Determining age – post-bomb
Homogeneous (cellulose), closed system




open system
homogeneous
gas exchange
$F_{atm} * I$
$F_{DIC} * O$
$CaCO_3$ sediment
$S * F_{DIC}$
^{14}C decay
$F_{DIC} * [DIC] * Vol * \lambda_{14C}$
closed system
buried $CaCO_3$ crystal
^{14}C decay
$C_{CaCO3} * \lambda_{14C}$
open system
heterogeneous
litterfall
$I * F_{leaf}$
decomposition
$k_1C_1F_1 + k_2C_2F_2 + k_3C_3F_3$
1
2
3
^{14}C decay
$\lambda_{14C} [C_1F_1 + C_2F_2 + C_3F_3]$


Interpreting open system radiocarbon requires models (More from Carlos Sierra)
TT = 5 yrs
TT = 10 yrs
TT = 20 yrs
$\Delta^{14}C$ (‰)
900
800
700
600
500
400
300
200
100
0
-100
1950
1960
1970
1980
1990
2000

In the coming week you will hear examples of many of the uses of ^{14}C

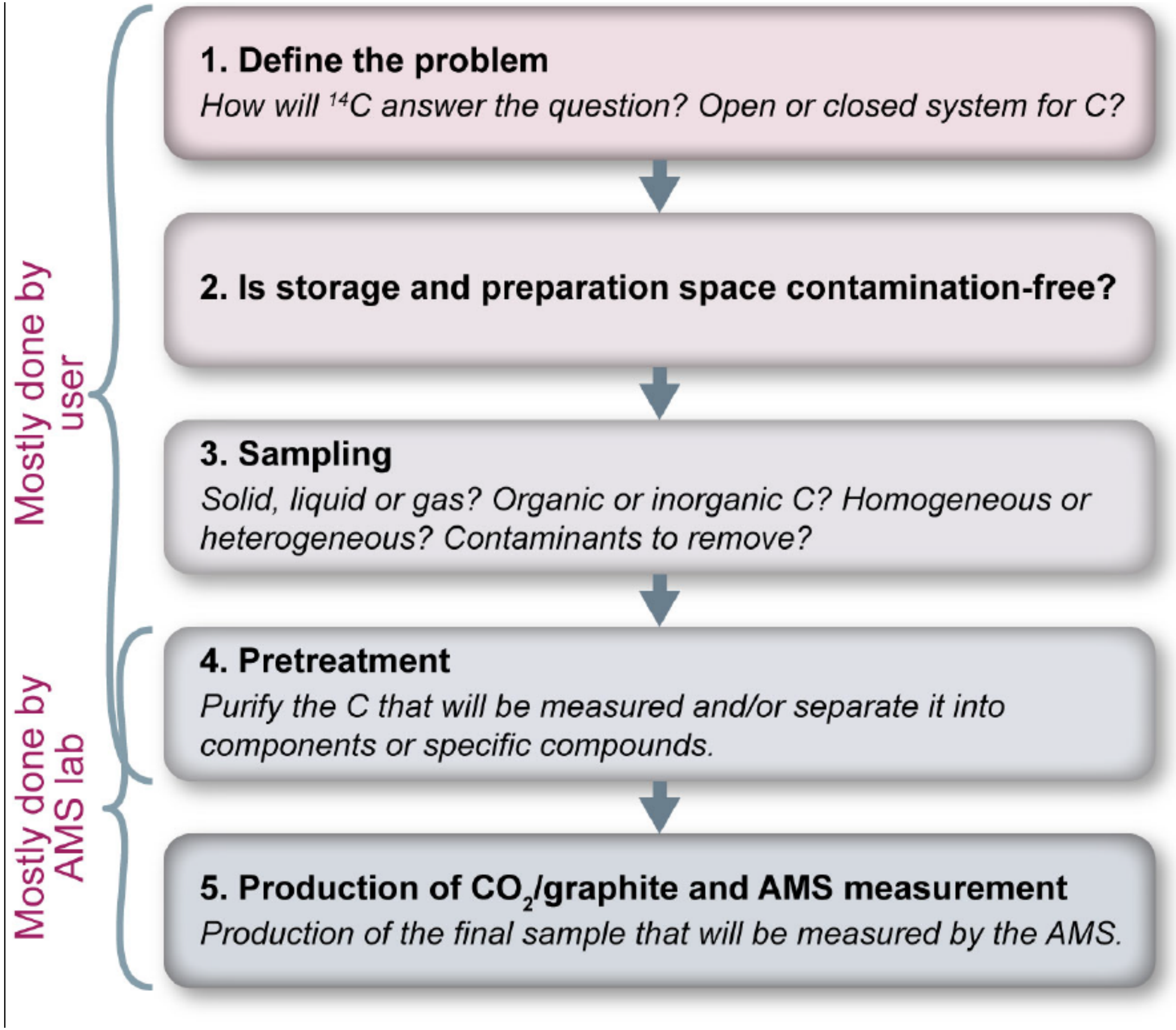
- Today --- Closed systems/Dating
- Applications in Land/Atmosphere/Ocean
- Modeling radiocarbon in open systems, Focus on organic matter (DOM, sediments, soils, aersols, plants)

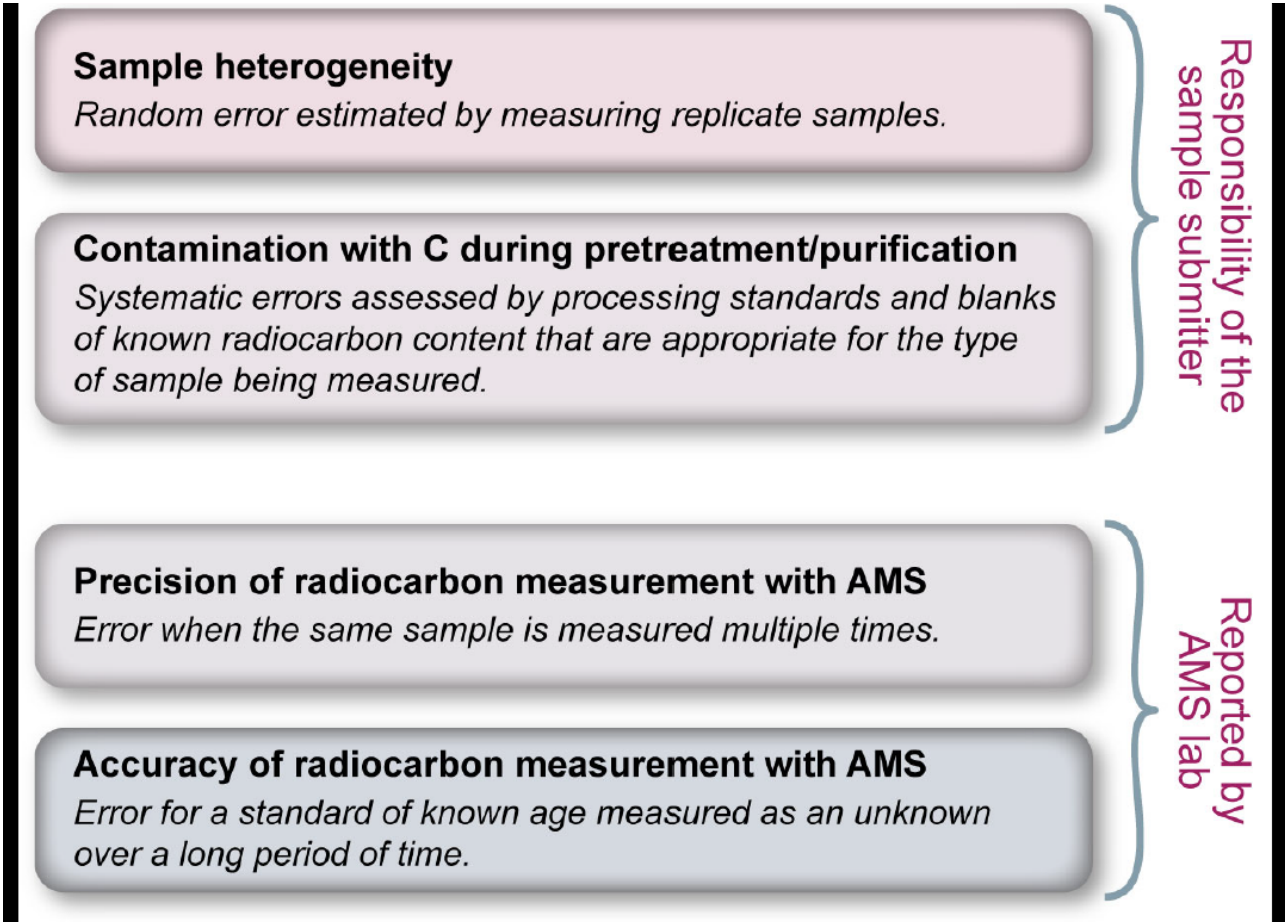
Lots of creative uses of ^{14}C still remain

A few words on the lab

- We assume you are sending your sample to an AMS lab and need to be able to understand
  - How to select the best sample to answer your question
  - How to make sure the C you are measuring is appropriate for answering your question
  - How to interpret the data when you get them

Steps in using radiocarbon





Sample heterogeneity
Random error estimated by measuring replicate samples.
Contamination with C during pretreatment/purification
Systematic errors assessed by processing standards and blanks of known radiocarbon content that are appropriate for the type of sample being measured.
Precision of radiocarbon measurement with AMS
Error when the same sample is measured multiple times.
Accuracy of radiocarbon measurement with AMS
Error for a standard of known age measured as an unknown over a long period of time.
Responsibility of the sample submitter
Reported by AMS lab

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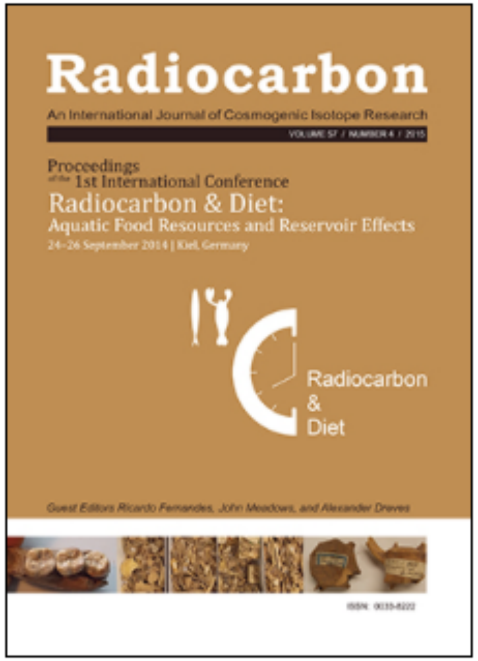

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Radiocarbon and Archaeology submission deadline was **September 30**

NEW! The 23rd International Radiocarbon Conference will be held in Trondheim, Norway, on June 17–22, 2018, at the hotel Scandic Lerkendal. More details to follow.

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IntCal13 Supplemental Information

SIRI update; VIRI Consensus values

Announcements