The Origins of Life on Earth, Part 1

We still have many questions about the origin of life on Earth (and elsewhere).

How did the transition from “chemicals” to “life” occur?

What conditions were necessary for that transition to occur?

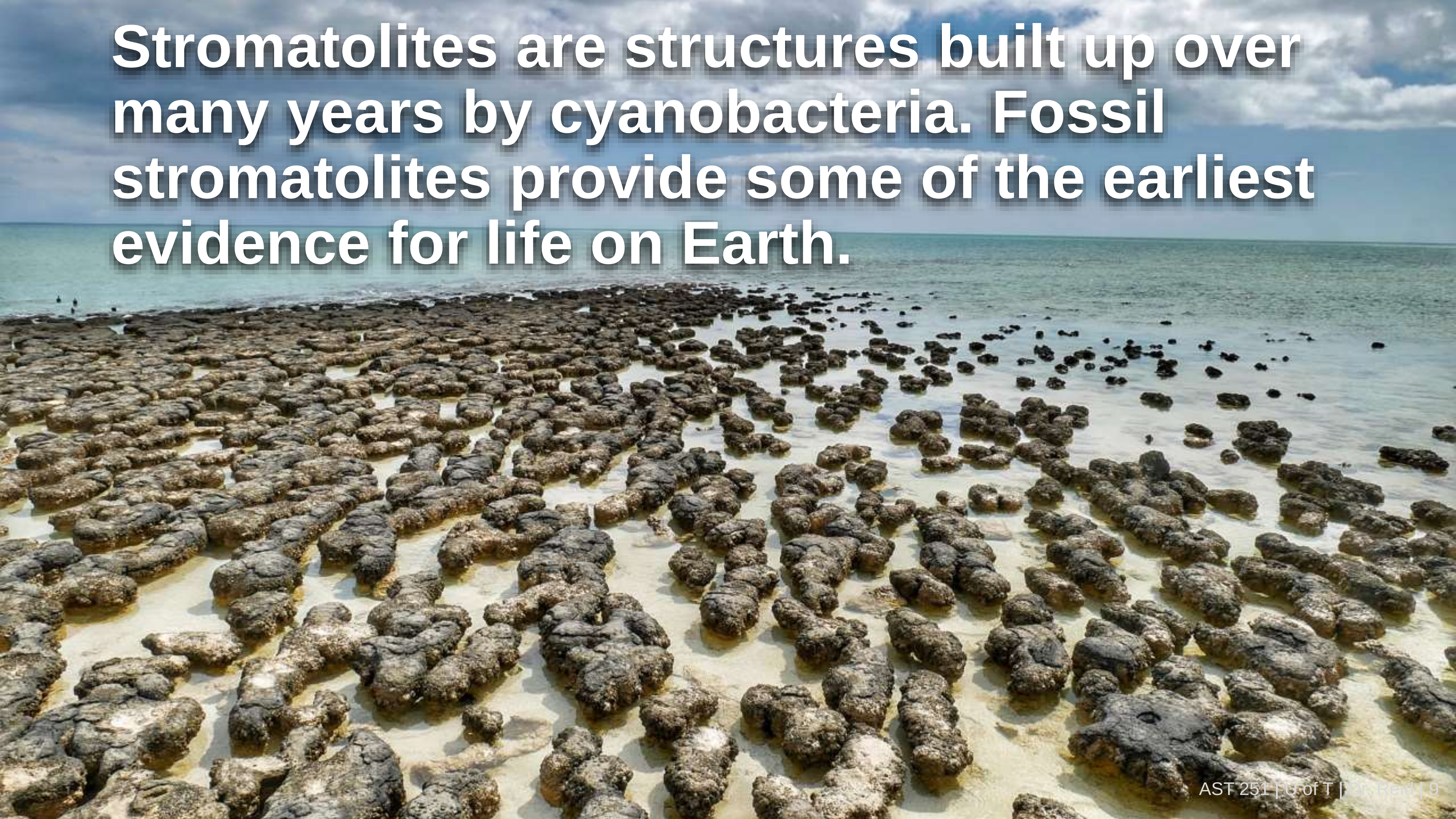
Is Earth somehow special?

Where could we find similar conditions elsewhere in the universe?

Abiogenesis is the transition from non-living matter to life.

Abiogenesis happened so long ago that billions of years of weathering have largely erased the record of how it happened.

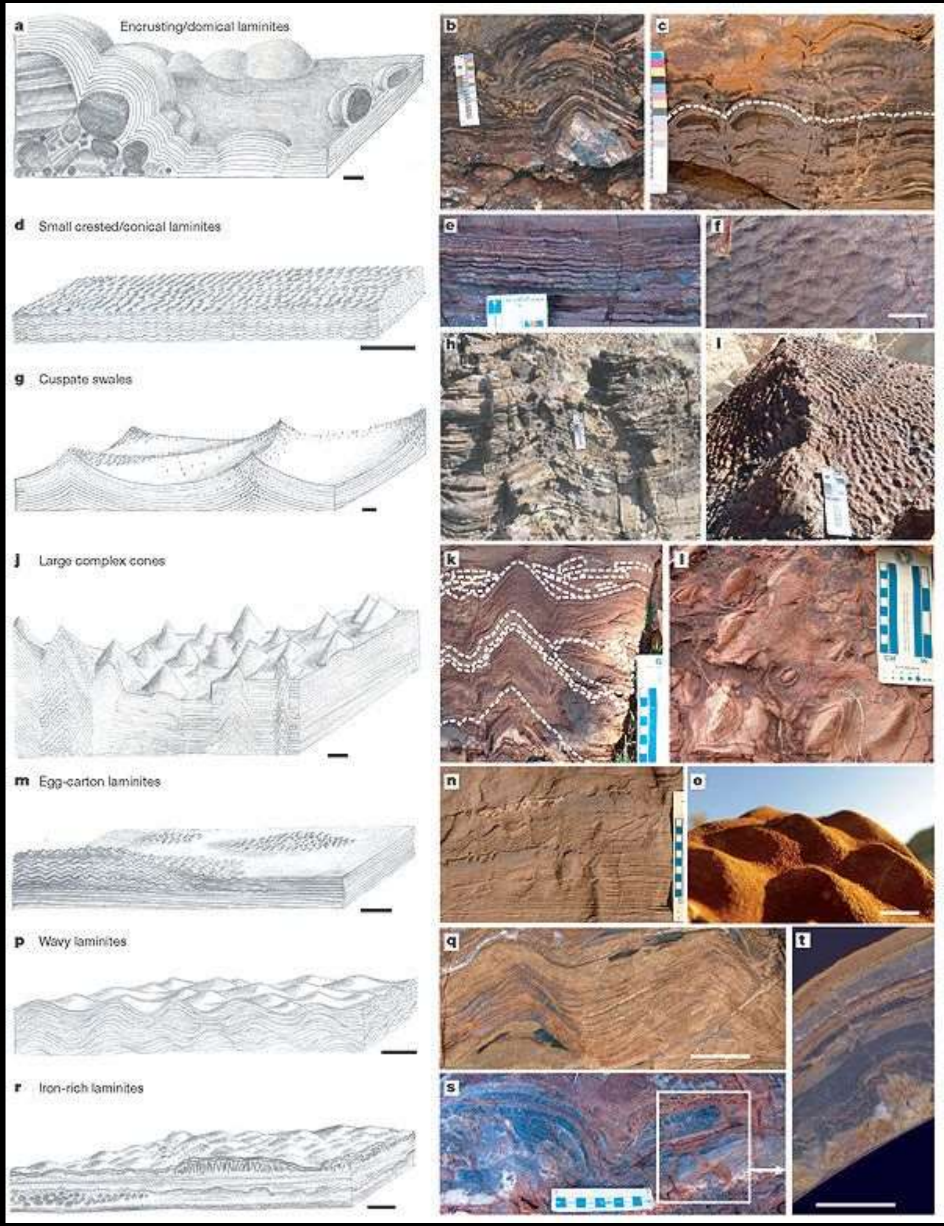
Can we at least establish *when* life began on Earth?



Stromatolites are structures built up over many years by cyanobacteria. Fossil stromatolites provide some of the earliest evidence for life on Earth.

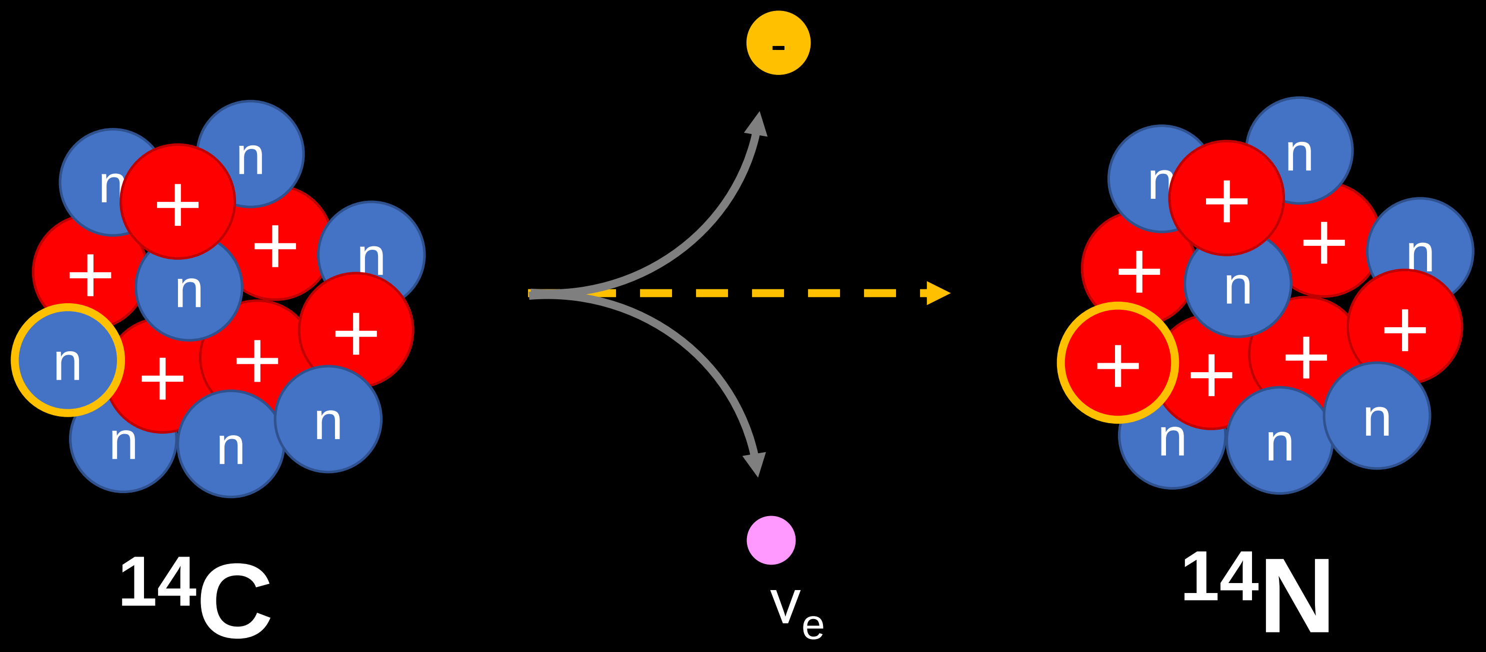
There is **direct fossil evidence** of stromatolites as far back as 3.4 Gya

(Allwood et al., Nature, 2006)

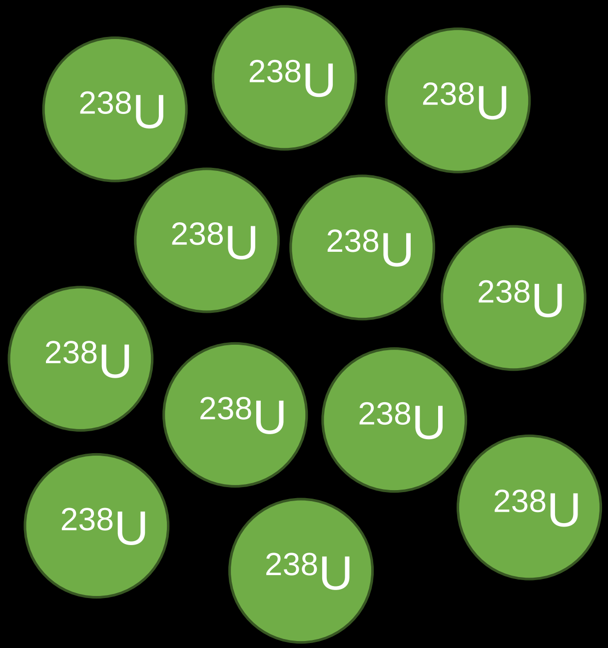


How can we know what happened billions of years ago?

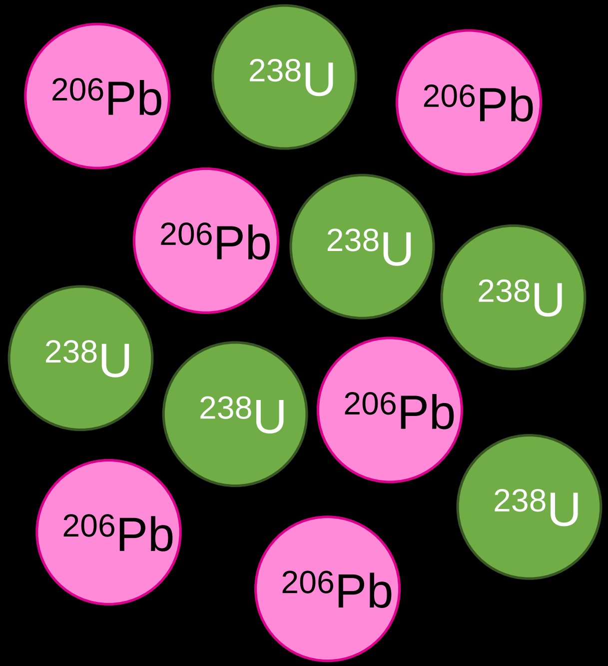
Unstable isotopes decay spontaneously at random times.



The **half-life** of an isotope is the time it takes for half of the atoms in a large sample of that isotope to decay radioactively.



A sample of ^{238}U



The same sample one half-life later.

number of
parent nuclei
at time t

$$\mathbf{N(t)} = \mathbf{N_{orig}} \left(\frac{1}{2}\right)^{\frac{t}{t_{half}}}$$

number of parent nuclei at time t

original number of parent nuclei

$$N(t) = N_{orig}\left(\frac{1}{2}\right)^{\frac{t}{t_{half}}}$$

number of parent nuclei at time t

original number of parent nuclei

current time

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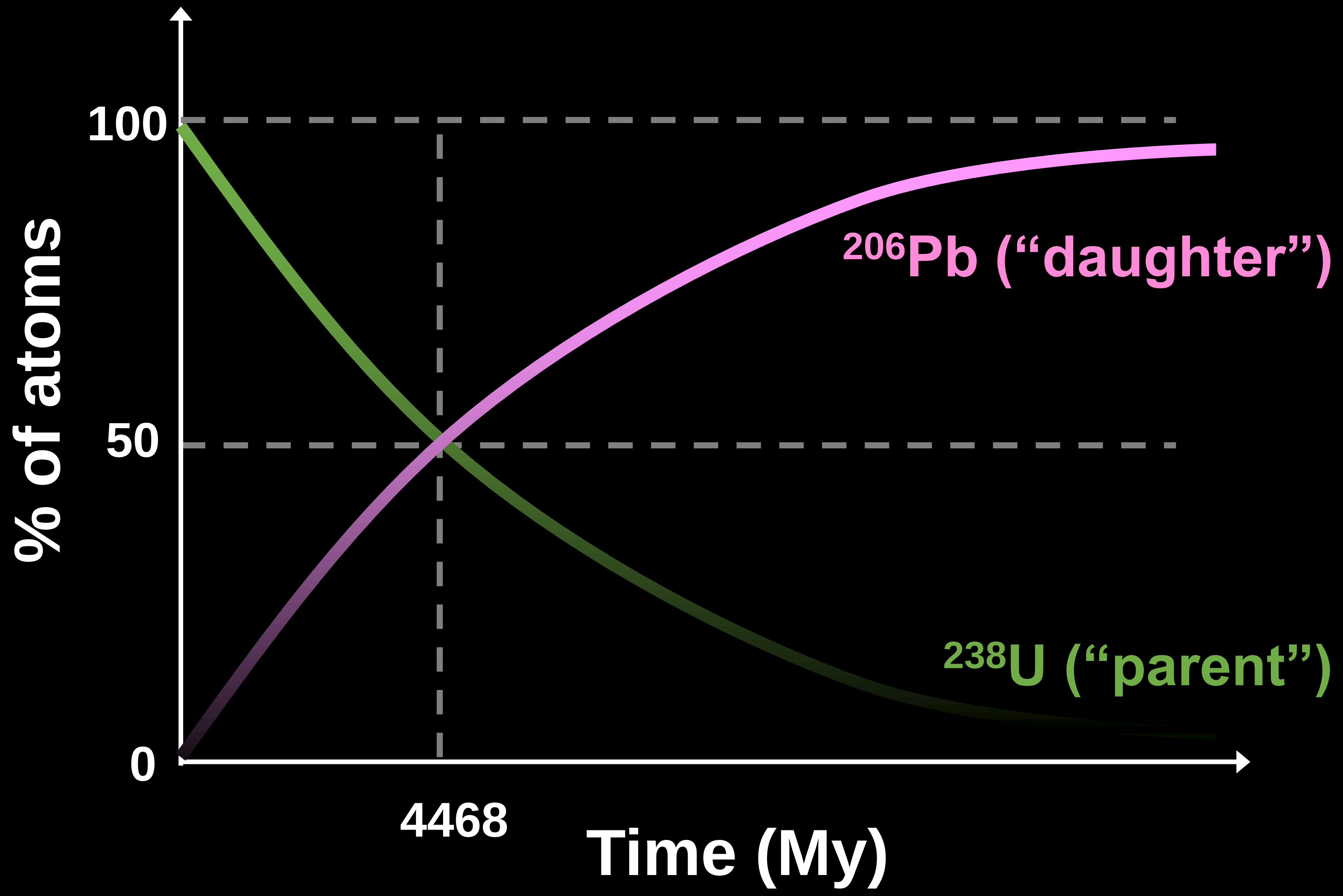
$$N(t) = N_{orig}\left(\frac{1}{2}\right)^{\frac{t}{t_{half}}}$$

half-life


% of atoms
100
50
0
^{206}Pb (“daughter”)
^{238}U (“parent”)
4468
Time (My)

Concept Check

If a sample of radioactive atoms contain 0 daughter isotopes at a given moment, what fraction of the parent isotopes will remain two half-lives later?

A. 1/2
B. 1/4
C. 1/8
D. 1/16

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Imagine we have a mineral in which 14.0% of the ^{238}U atoms have decayed to ^{206}Pb atoms. How old is the mineral?

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$$0.860 = \left(\frac{1}{2}\right)^{\frac{t}{4468\ My}}$$

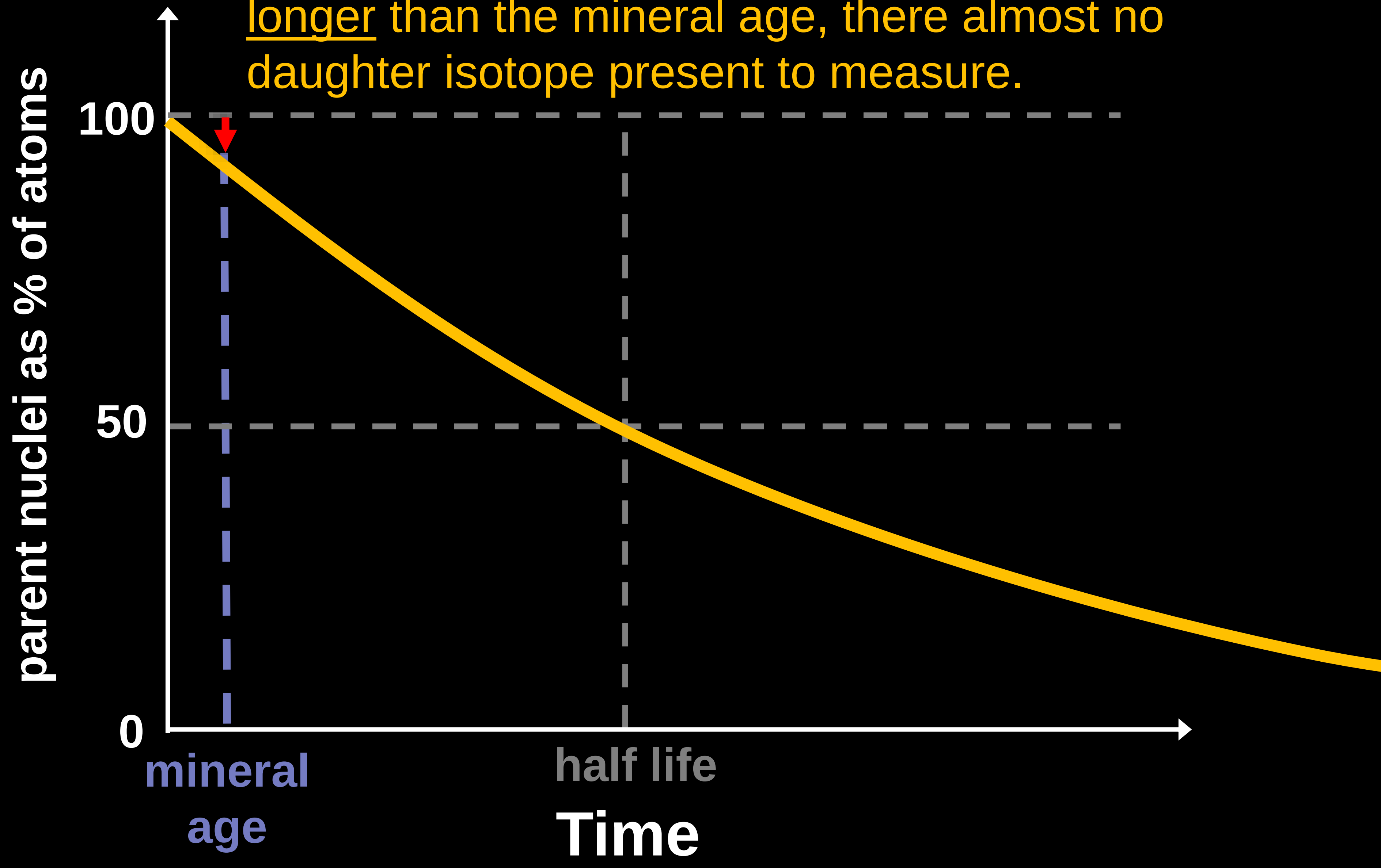
$$\log(0.860) = \frac{t}{4468\ My}\log(0.5)$$

$$t = (4468\ My)\frac{\log(0.86)}{\log(0.5)}$$

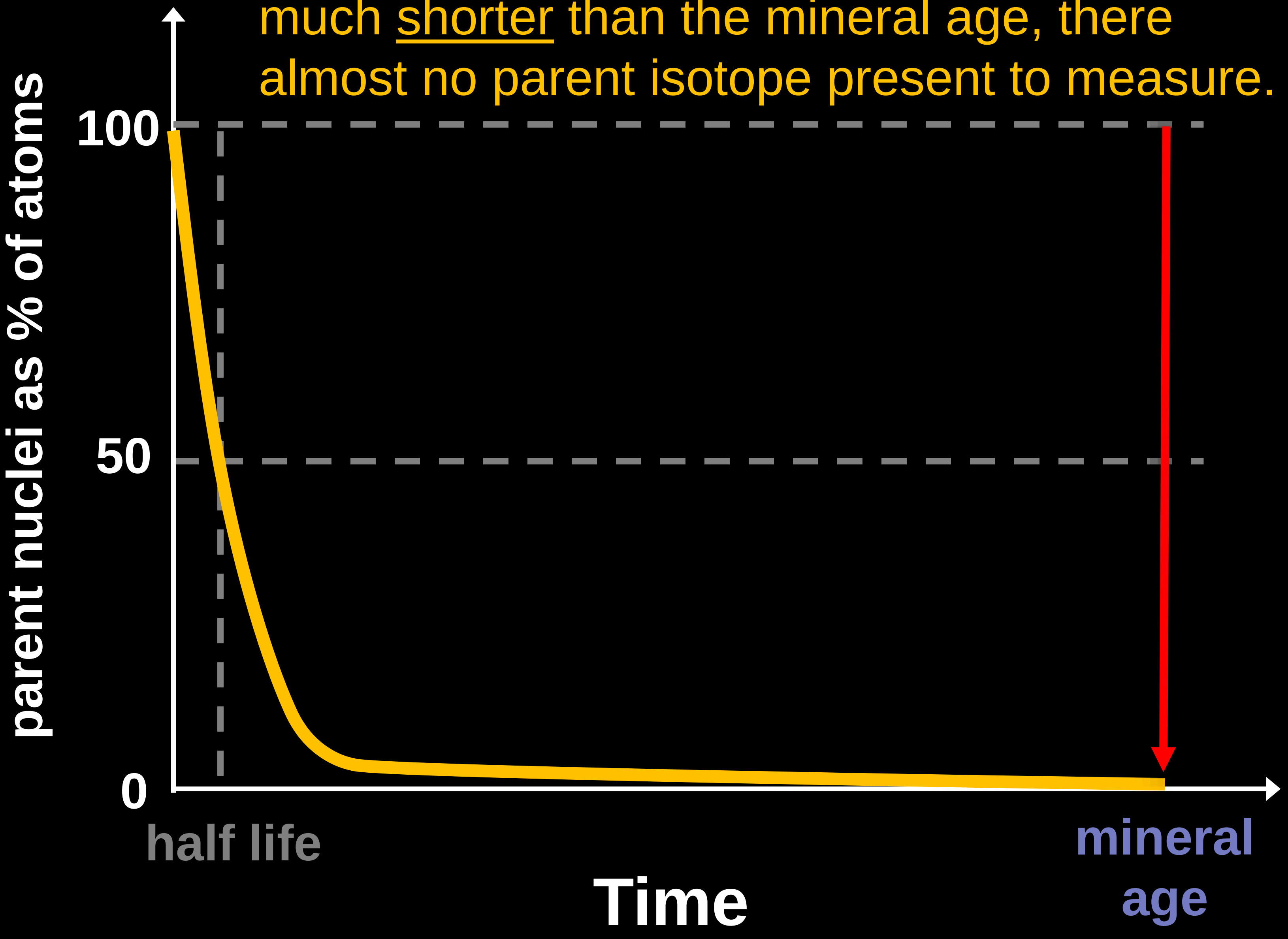
$$t = 972\ My$$

For radioisotope dating to work well, we need to choose an isotope with a half-life that is similar in magnitude to the age we are trying to measure.

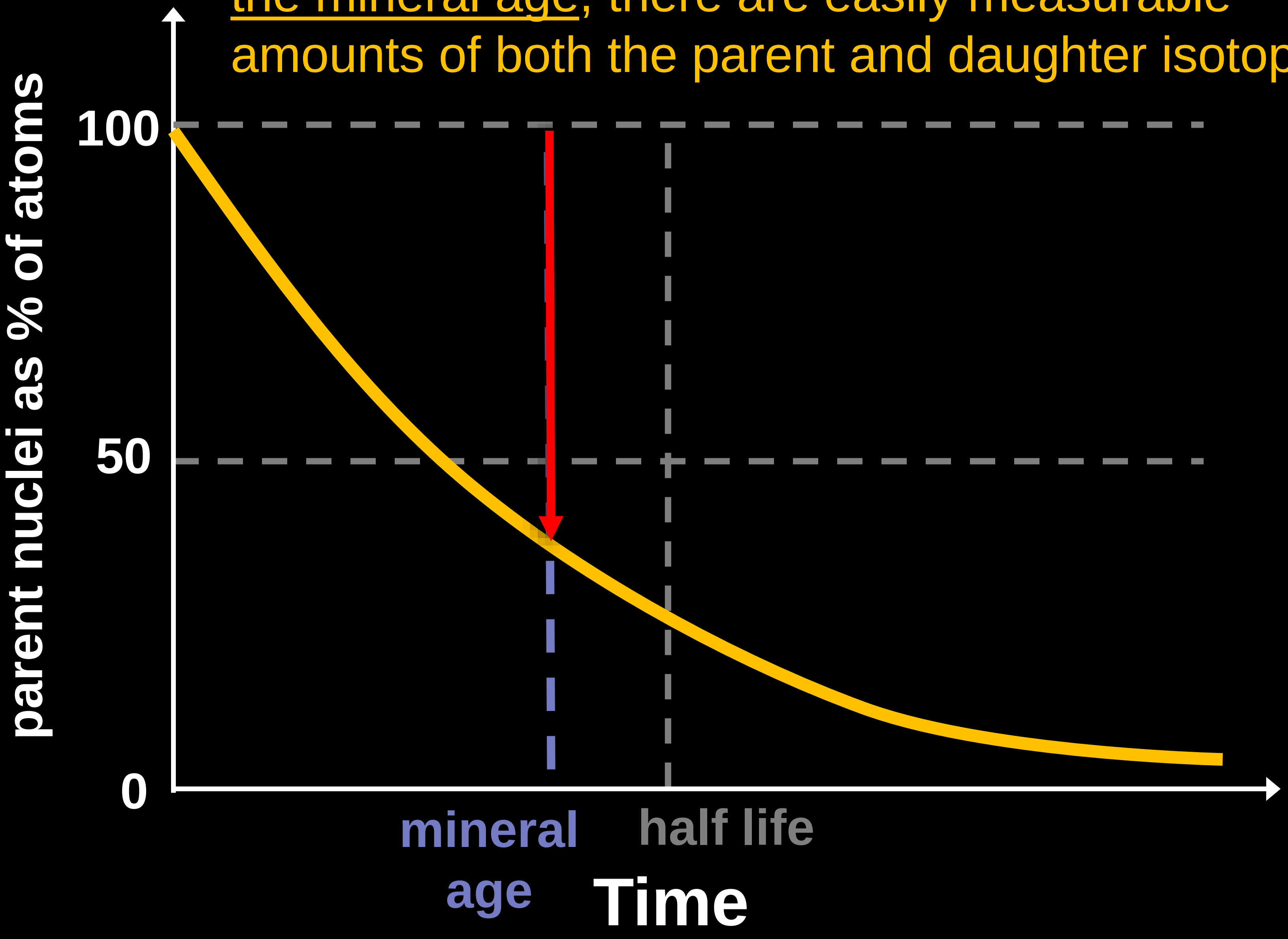
When the half life of the parent isotope is much <u>longer</u> than the mineral age, there almost no daughter isotope present to measure.



When the half life of the parent isotope is much shorter than the mineral age, there almost no parent isotope present to measure.



When the half life of the parent isotope is similar to the mineral age, there are easily measurable amounts of both the parent and daughter isotope.



The half-life of ^{238}U is known very precisely to be 4.468 Gy, so this method allows us to date rocks billions of years old to less than 1% uncertainty.

Conveniently, there is a second isotope, ^{235}U, with a half-life of 703.8 My, so we can usually cross-verify ages going back several Gy.

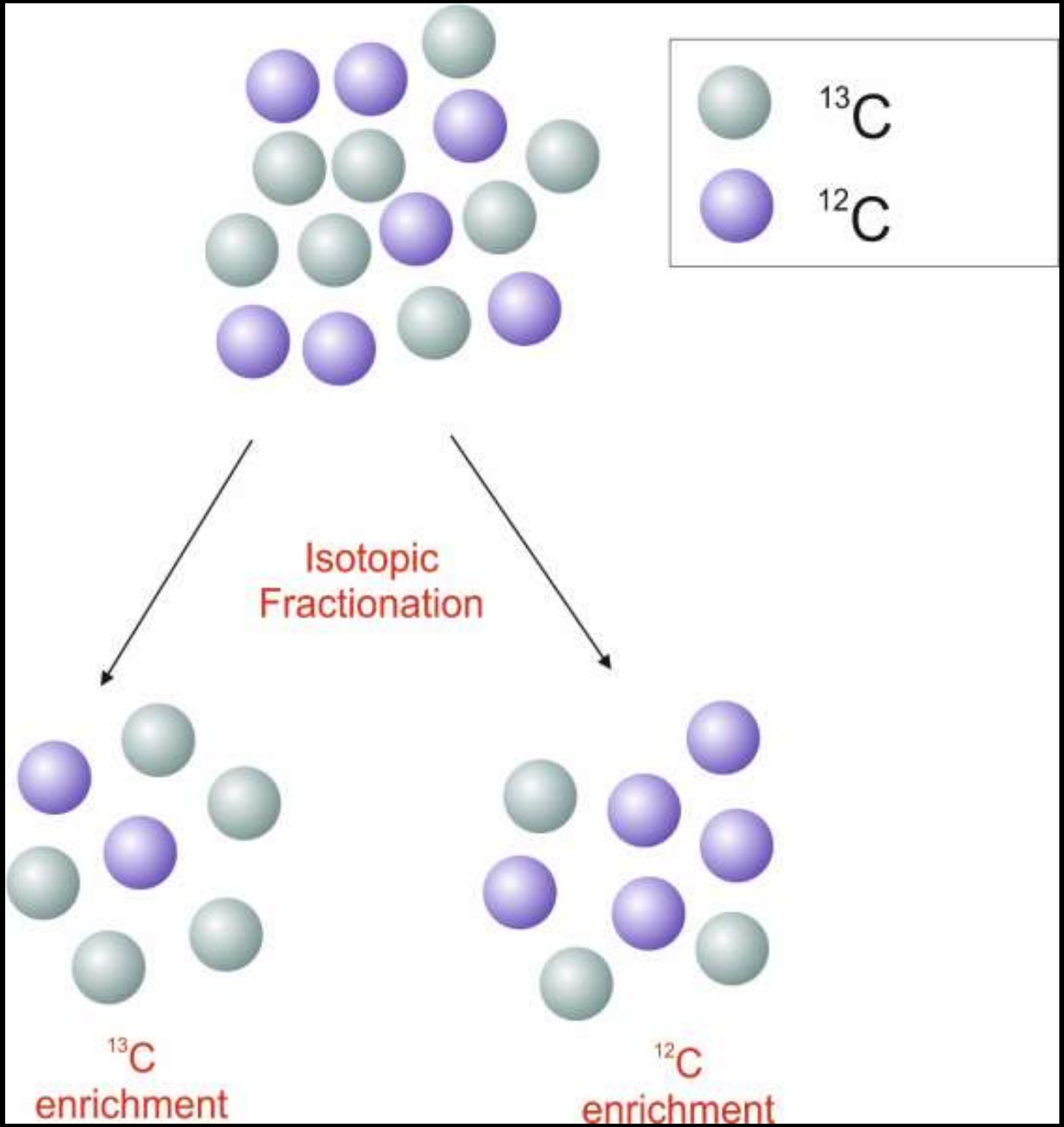
Using U-Pb dating, we can date minerals billions of years old.

But in the absence of identifiable fossils, how can we know whether life was actually present when those minerals formed?

The Origins of Life on Earth, Pt. 2

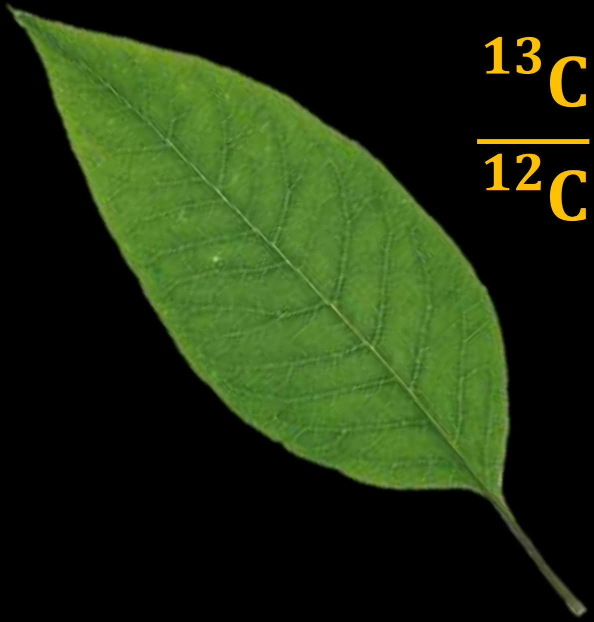
How can we determine whether a mineral billions of years old might be the fossil of a living organism?

Many biological processes have a preference for one carbon isotope over another, a phenomenon called **isotopic fractionation.**



Credit: Charles Cockell

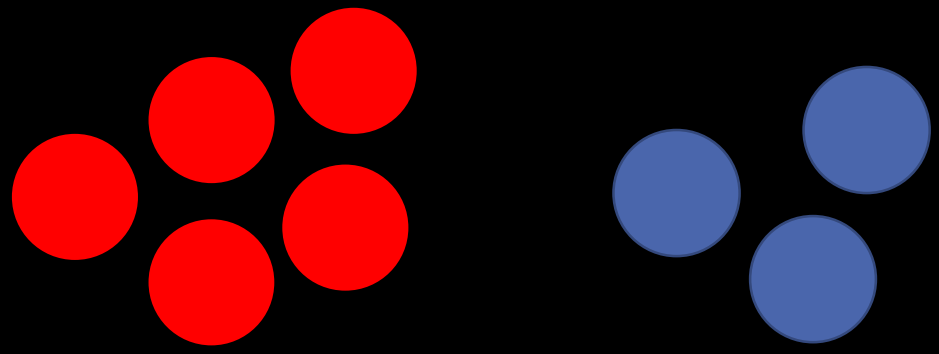
In particular, many biological reactions prefer the lighter isotope ^{12}C, over the heavier ^{13}C.



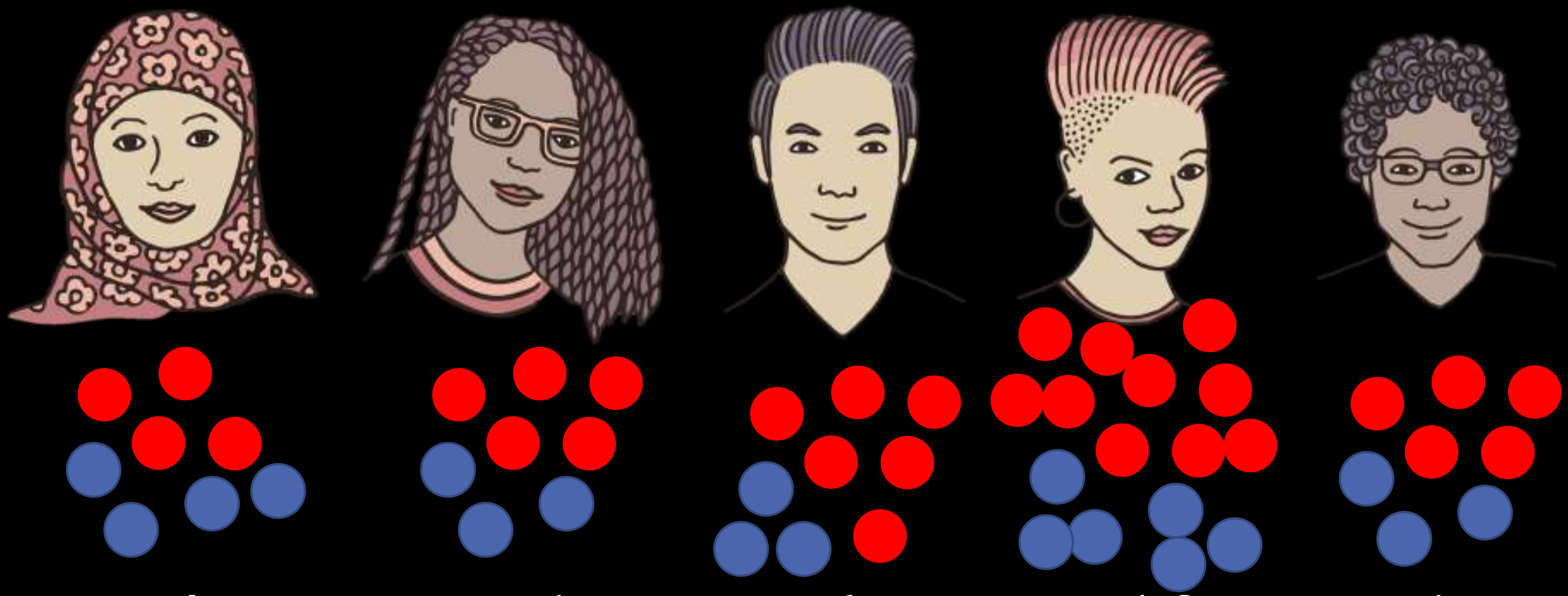
$\frac{^{13}C}{^{12}C}$ is lower because plants prefer ^{12}C to ^{13}C

$\frac{^{13}C}{^{12}C}$ is higher because non-living processes have less preference for ^{12}C vs ^{13}C

Let’s say we’re playing a party game where everyone should have five red tokens for every three blue tokens.

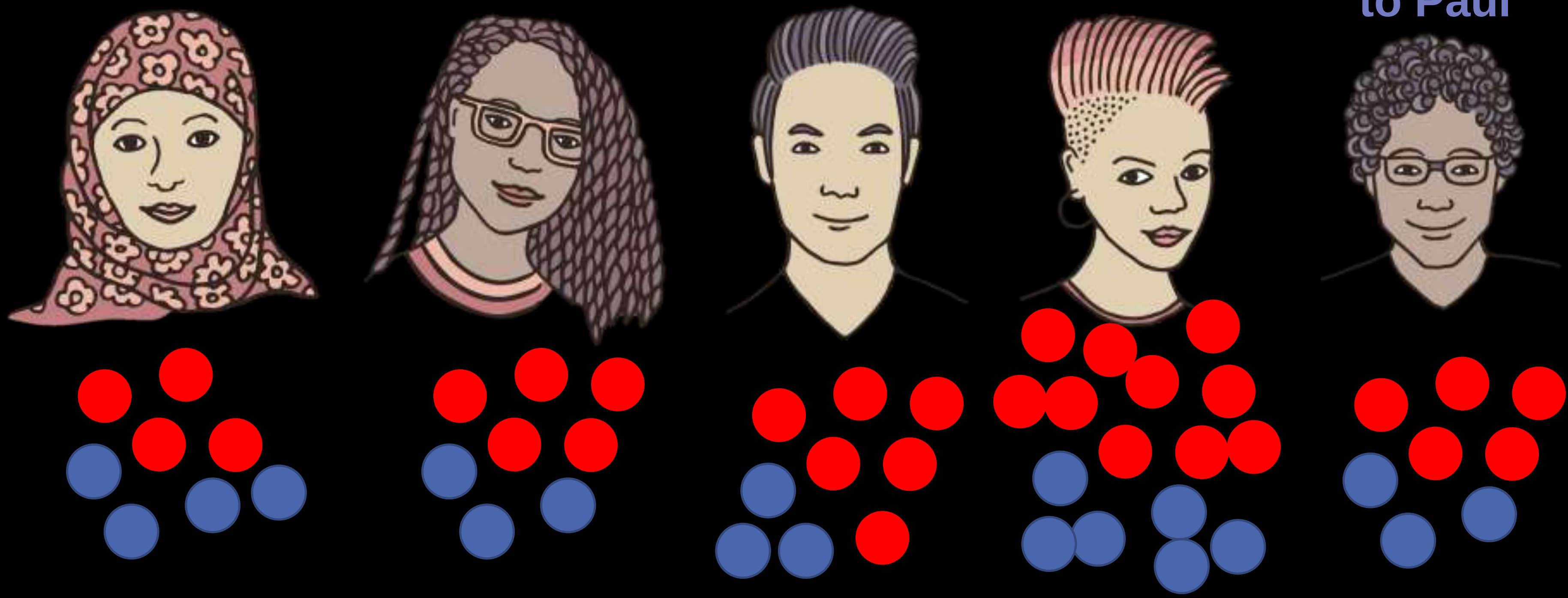


But we're worried that we may have miscounted when handing out tokens, so we want to develop a statistic to check for token balance.



$$\frac{4}{4} \qquad \frac{5}{3} \qquad \frac{6}{3} \qquad \frac{10}{6} \qquad \frac{5}{3}$$

Compare everyone to Paul



$$\frac{\left(\frac{4}{4}-\frac{5}{3}\right)}{\frac{5}{3}} = \mathbf{-0.4} \qquad \frac{\left(\frac{5}{3}-\frac{5}{3}\right)}{\frac{5}{3}} = \mathbf{0} \qquad \frac{\left(\frac{6}{3}-\frac{5}{3}\right)}{\frac{5}{3}} = \mathbf{0.2} \qquad \frac{\left(\frac{10}{6}-\frac{5}{3}\right)}{\frac{5}{3}} = \mathbf{0} \qquad \frac{\left(\frac{5}{3}-\frac{5}{3}\right)}{\frac{5}{3}} = 0$$

We can do the same thing with carbon isotope ratios: compare the ratio for a given sample to a well-established standard.

Carbon fractionation is measured via $\delta^{13}C$:

$$\delta^{13}C = \left(\frac{\left(\frac{^{13}C}{^{12}C}\right) - \left(\frac{^{13}C}{^{12}C}\right)}{\left(\frac{^{13}C}{^{12}C}\right)} \right) \times 1000‰$$

Carbon isotope ratios are usually expressed in parts-per-thousand, relative to a standardized sample called the Pee Dee Belemenite (PDB), after a rock from the Peedee Formation in South Carolina.

Carbon fractionation relative to the PDB standard:

$$\delta^{13}\mathrm{C}_{\mathrm{PDB}} = \left(\frac{\left(\frac{^{13}\mathrm{C}}{^{12}\mathrm{C}}\right)_{\mathrm{sample}} - \left(\frac{^{13}\mathrm{C}}{^{12}\mathrm{C}}\right)_{\mathrm{PDB}}}{\left(\frac{^{13}\mathrm{C}}{^{12}\mathrm{C}}\right)_{\mathrm{PDB}}} \right) \times 1000‰$$

$$\text{where } \left(\frac{^{13}\mathrm{C}}{^{12}\mathrm{C}}\right)_{\mathrm{PDB}} = 0.01123722 \text{ by definition.}$$

Concept Check

A measurement of $\delta^{13}C_{PDB}$ tells us:

A. The ratio of ^{13}C to ^{12}C in a sample
B. The amount of ^{12}C and ^{13}C in a sample
C. The ratio of ^{13}C to ^{12}C in a sample relative to a standard sample

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If we have a mineral with a $^{13}C/^{12}C$ ratio of 0.0109563, what is its $\delta^{13}C_{PDB}$?

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$$\delta^{13}C = \left(\frac{0.0109563 - 0.01123722}{0.01123722} \right) \times 1000‰$$

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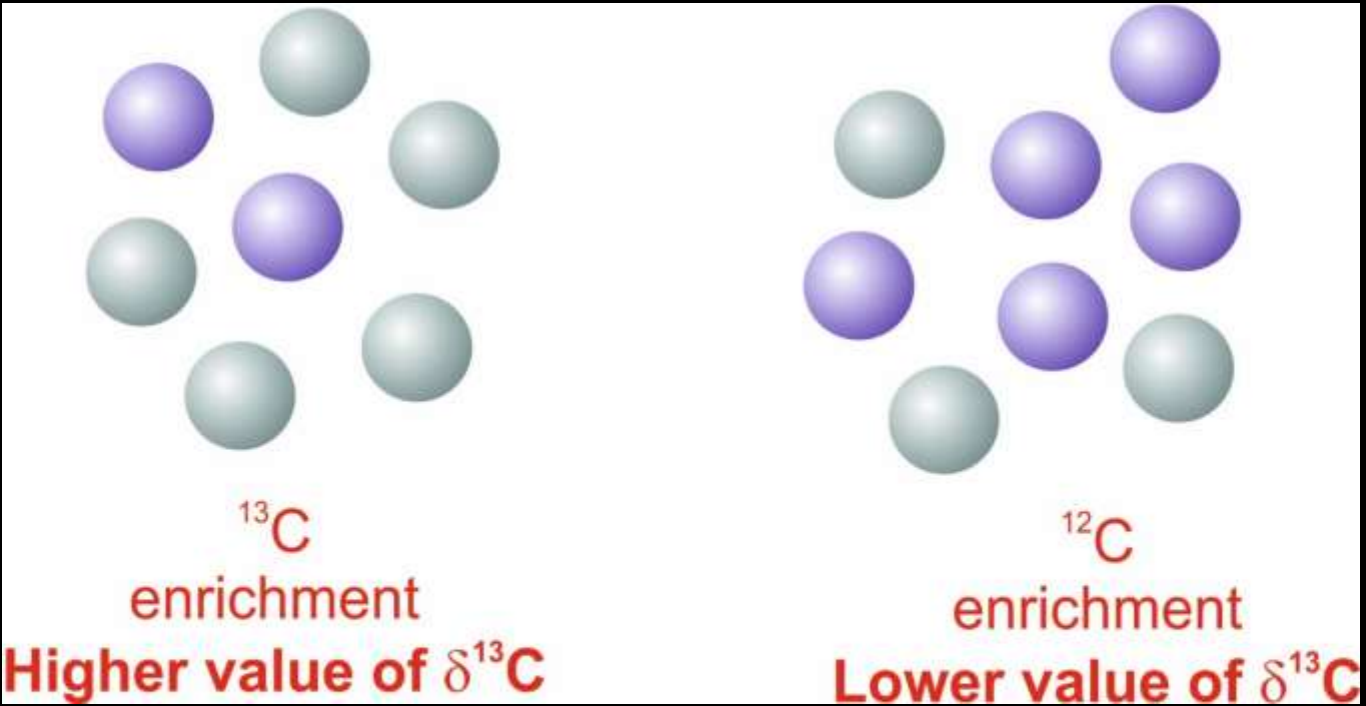
$$\delta^{13}C = \left(\frac{0.0109563 - 0.01123722}{0.01123722} \right) \times 1000‰$$

$$\delta^{13}C = -25‰$$

Confusingly, because the ratio is defined as $^{13}C/^{12}C$, adding more ^{12}C relative to the standard lowers $\delta^{13}C_{PDB}$



Credit: Charles Cockell

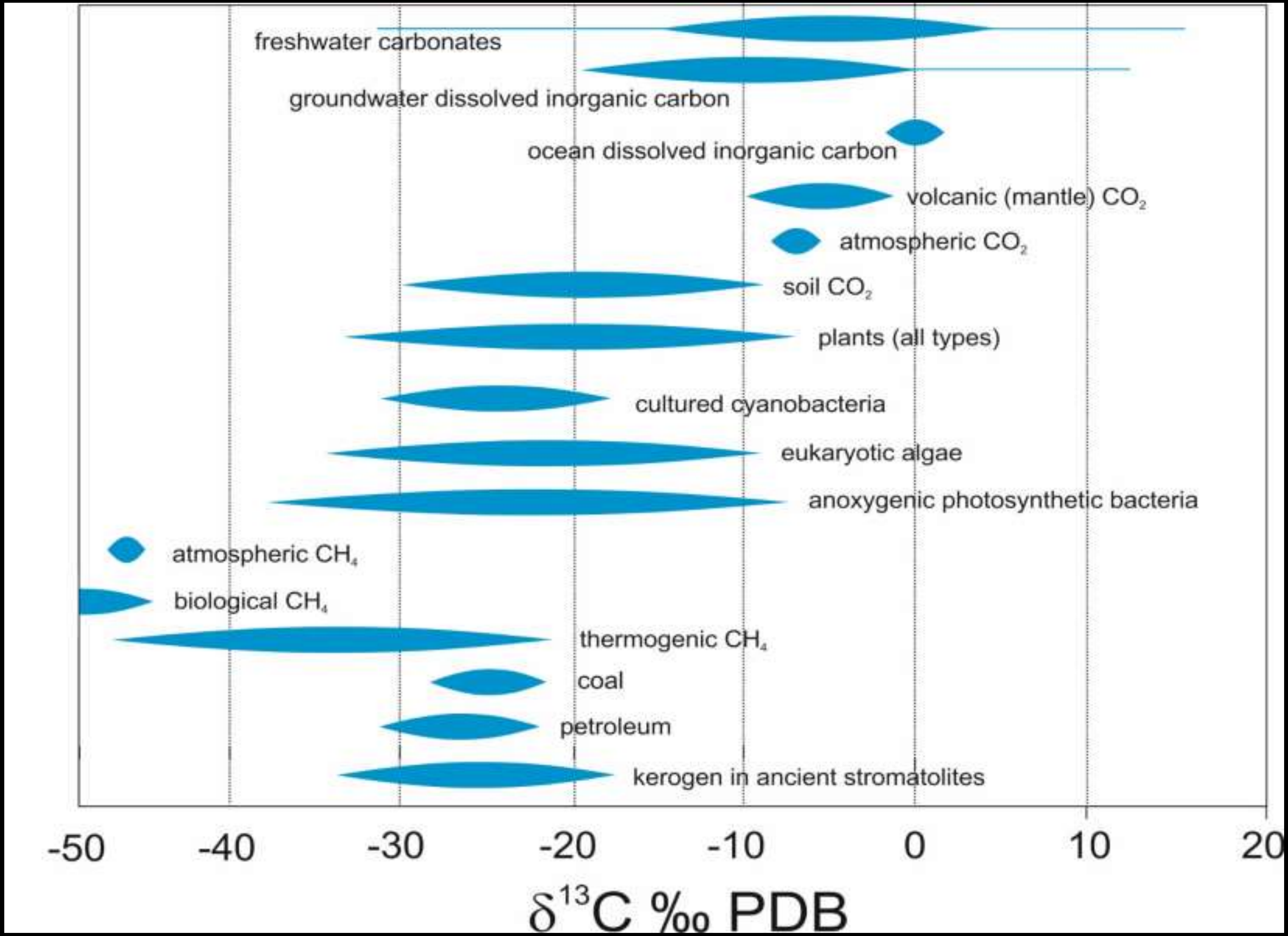
groundwater
(less ^{12}C)

PDB
mineral
standard

leaf
(more ^{12}C)

-50 $\delta^{13}C_{PDB}$ ‰ = 0 10

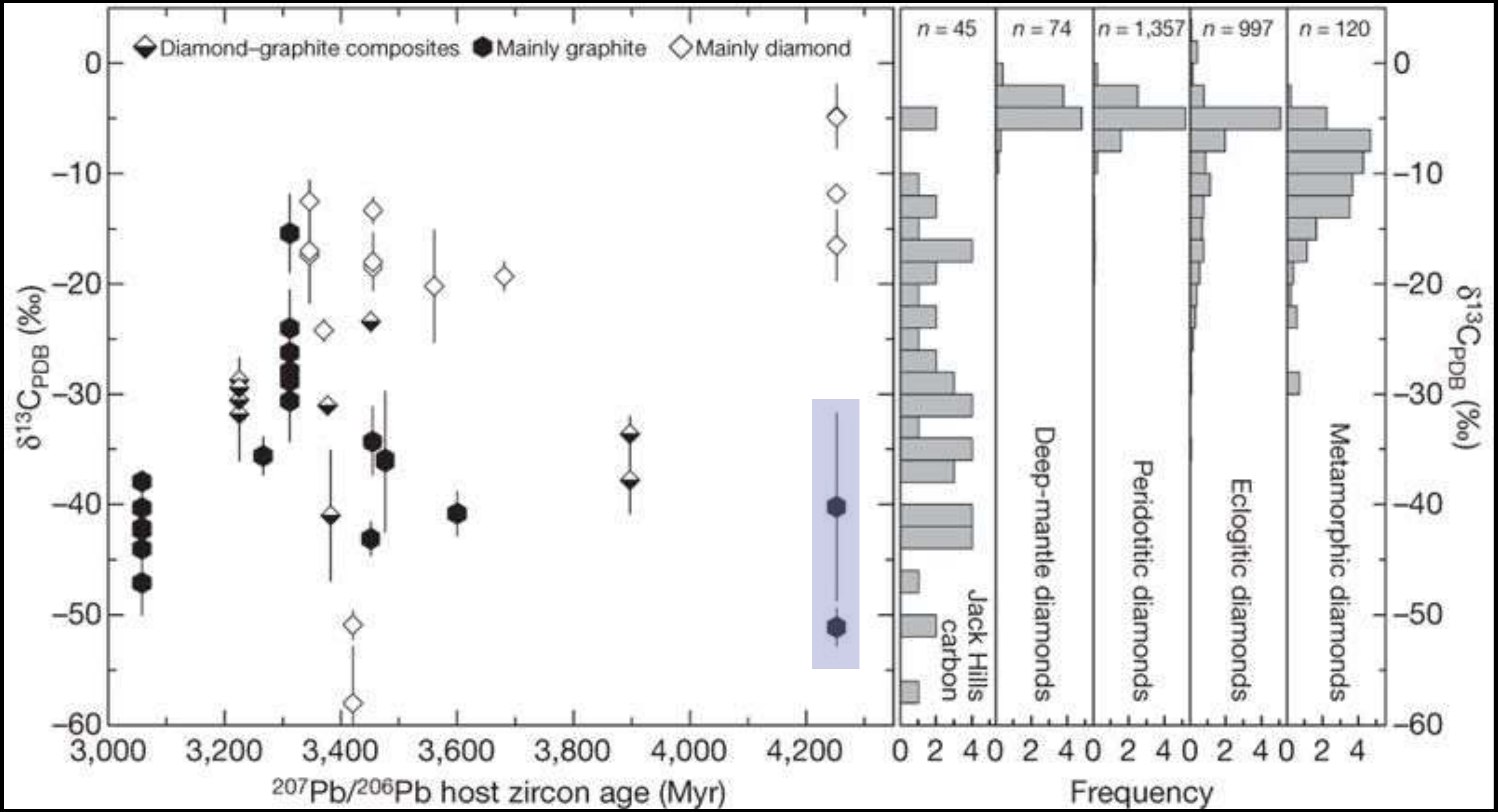
The $\delta^{13}C_{PDB}$ values of real materials span a range. But materials of biological origin tend to have lower values.



Credit: Charles Cockell

Minerals as old as 4.25 Gy show $\delta^{13}C$ values below -50, suggesting they might represent formerly biological material.

(Nemchin et al., Nature, 2008)



Credit: Nemchin et al., Nature, 2008

This is strongly suggestive of biological activity on the young Earth.

There are a few possible non-biological explanations that are also being tested.

In Summary

$\delta^{13}C$ measurements suggest that life may have begun well back into the Hadean Eon, very shortly after the formation of the oceans on Earth.

The Origins of Life on Earth, Pt. 3

Recap: measurements of carbon fractionation suggest that life may have begun only a few hundred million years after Earth formed, shortly after the oceans formed.

But what happened exactly?

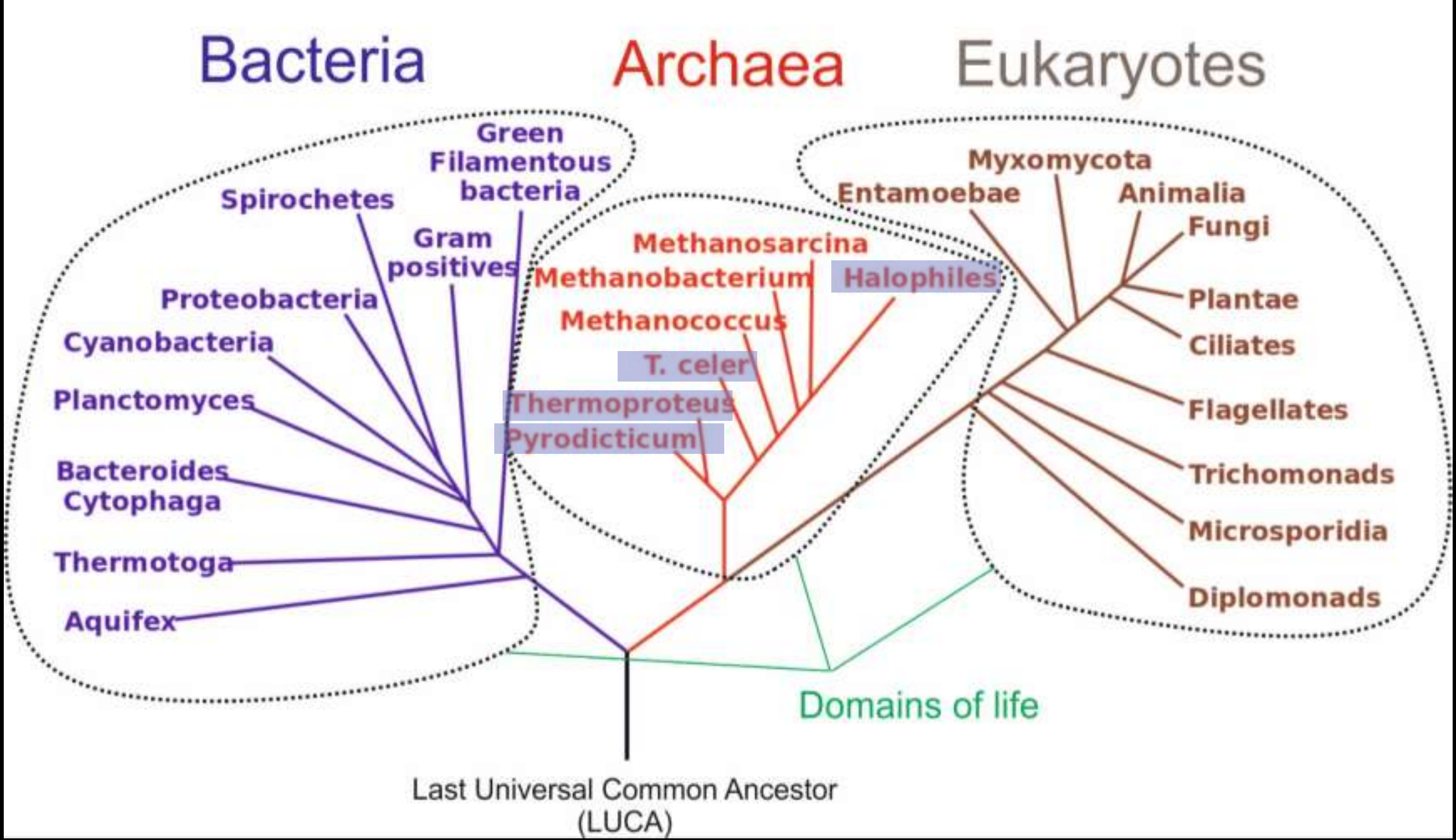
What was the mechanism of abiogenesis?

Because most of the evidence is gone, we may never know the exact mechanism of abiogenesis.

However, there are many promising theories.

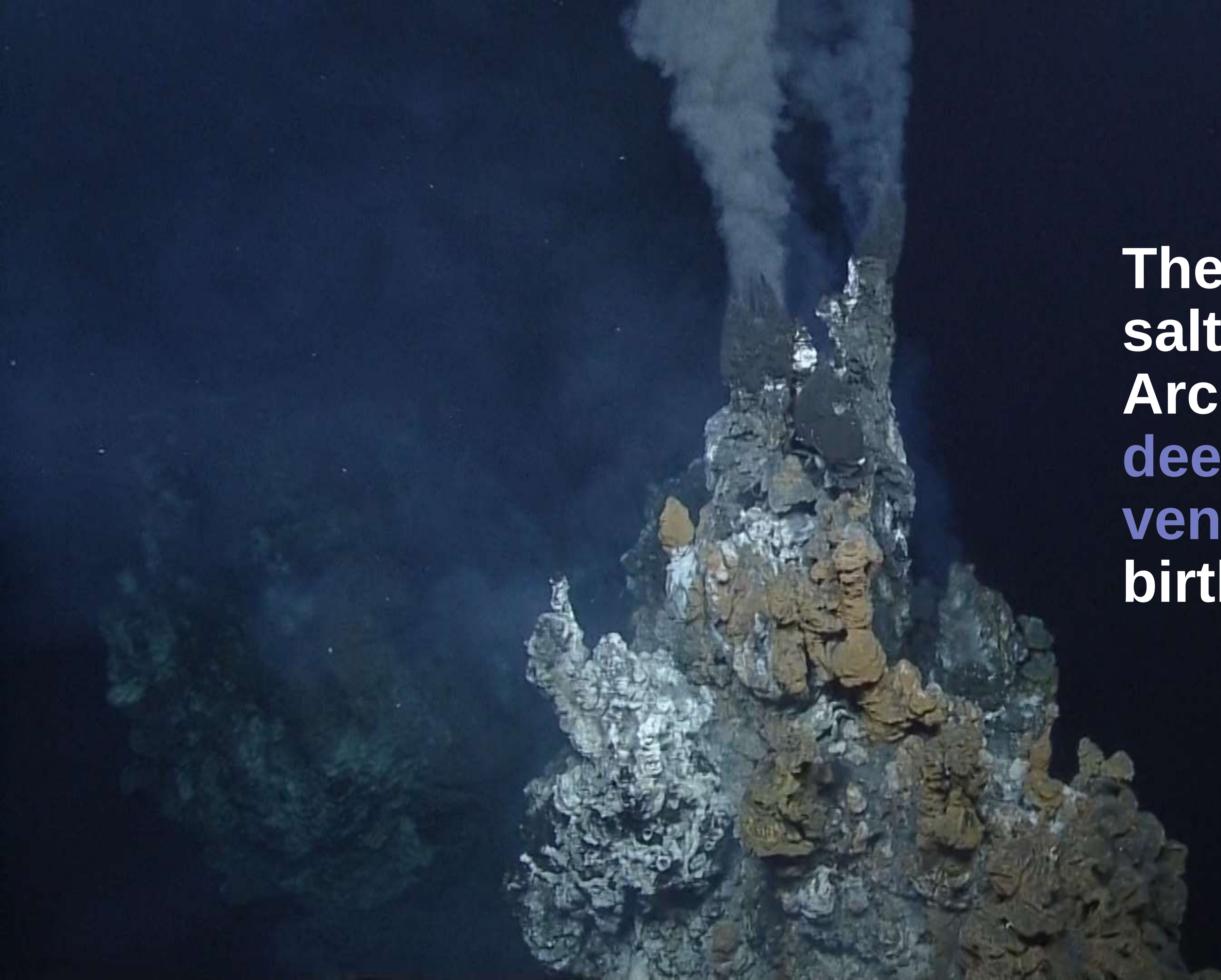

Charles Darwin famously hypothesized that life began in a "warm little pond"
Credit: Ben Pearce/cbc.ca

However, more recent evidence suggests a different origin.



The Archaea, which constitute one of the most ancient branches of the tree of life, contain many thermophiles and halophiles.

Credit: Charles Cockell



The heat-loving, salt-loving nature of Archaea points to deep hydrothermal vents as the birthplace of life.

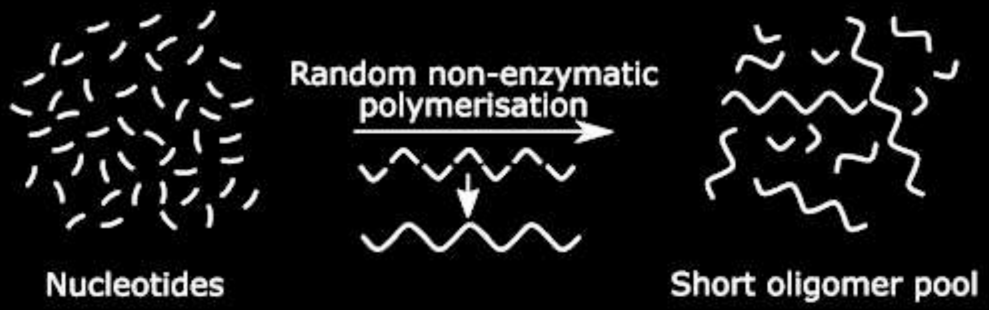
Credit: Ocean Exploration Trust

One of the major challenges in positing a successful theory for the origin of life is deciding what the first step was.

Self-replication? Metabolism? The development of a cell wall?

Perhaps the leading theory is the RNA World, which posits that short strands of RNA catalyzed their own replication, kick-starting life on Earth.

Credit: Le Vay & Mutschler 2019



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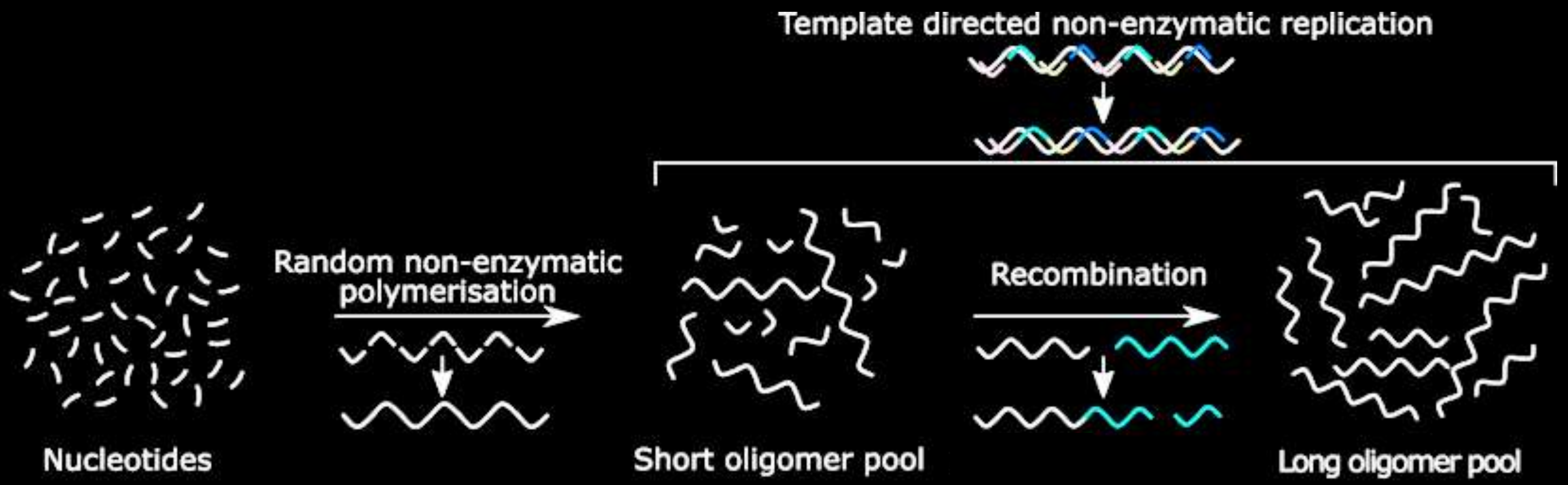

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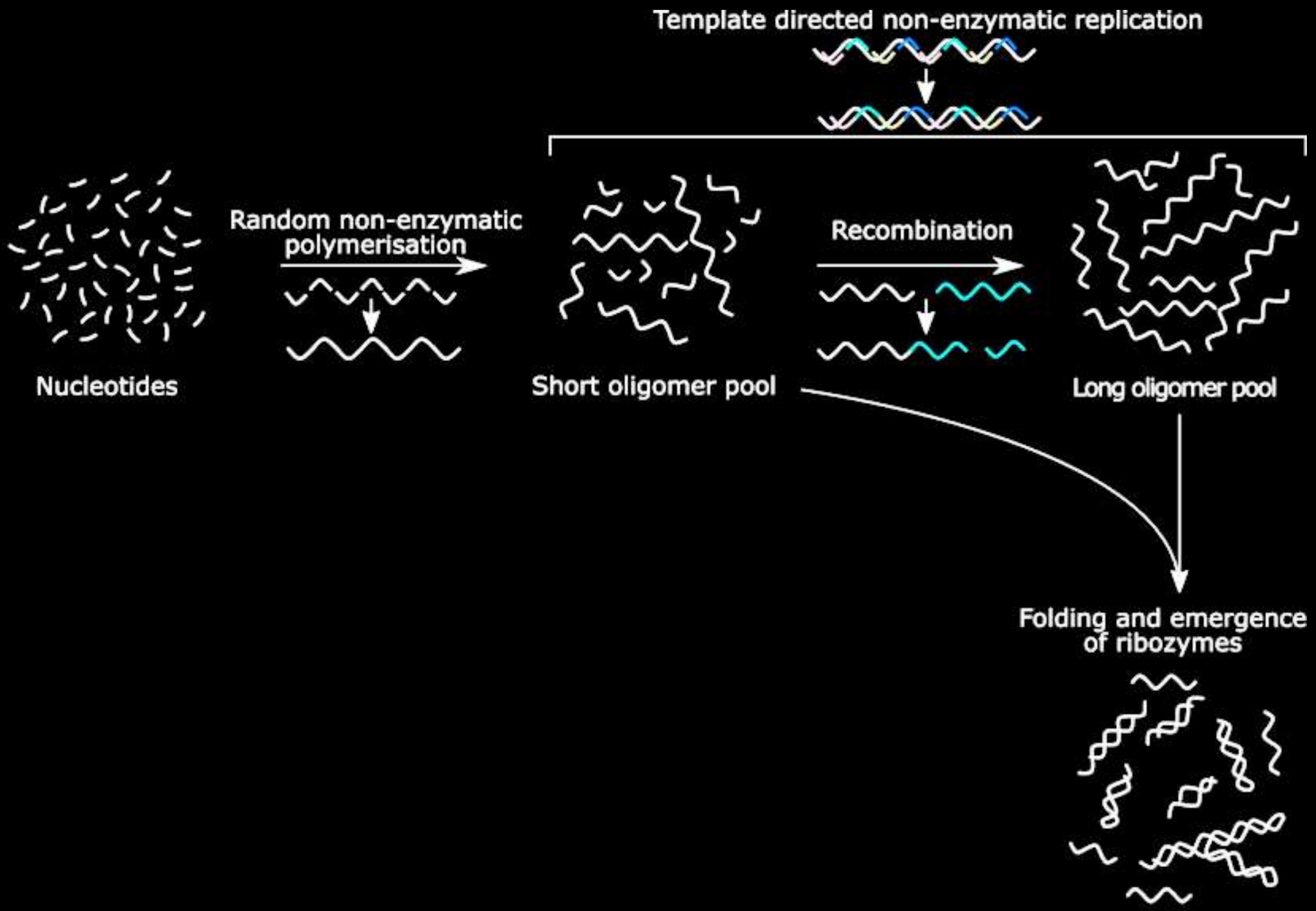

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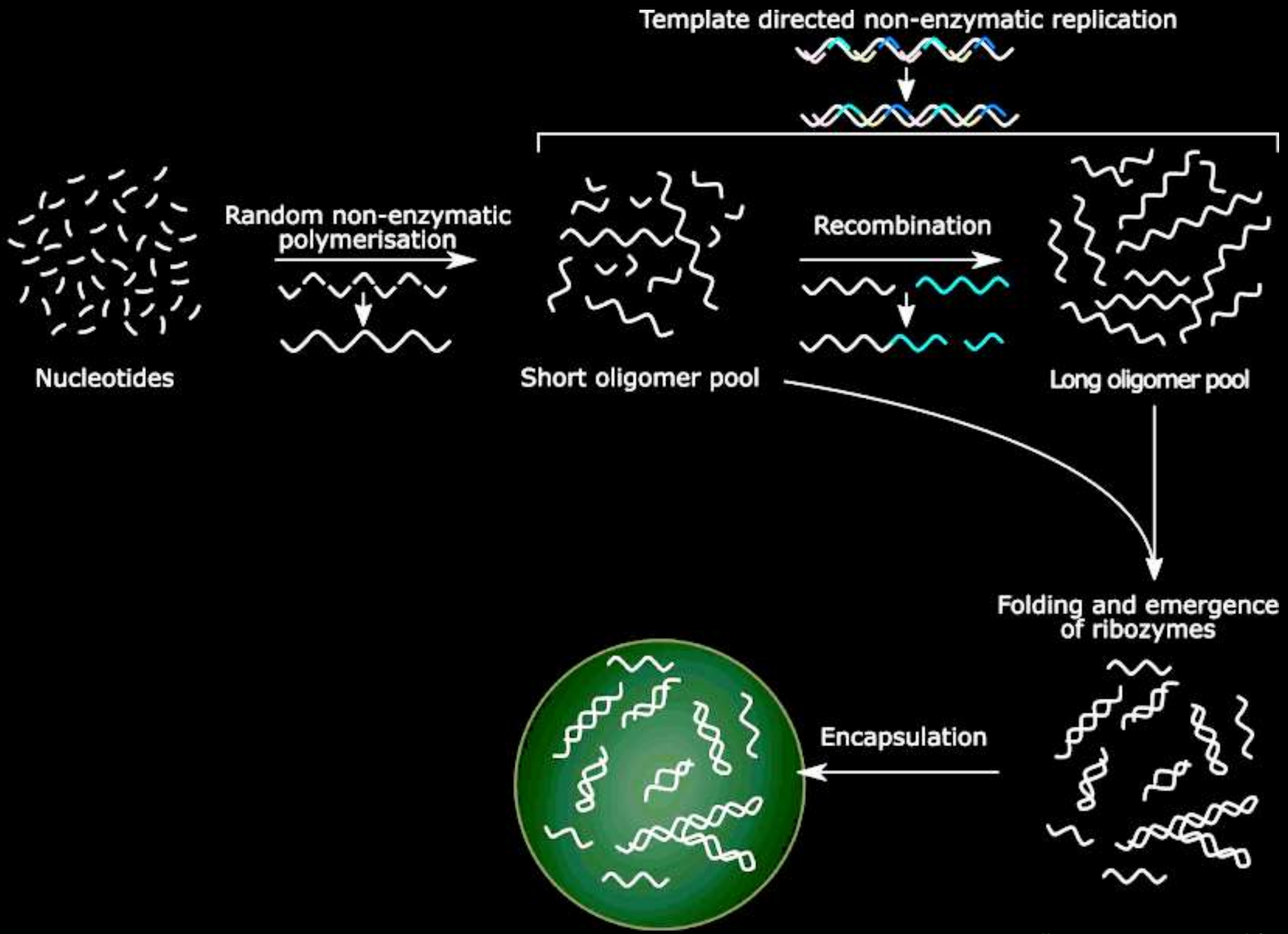

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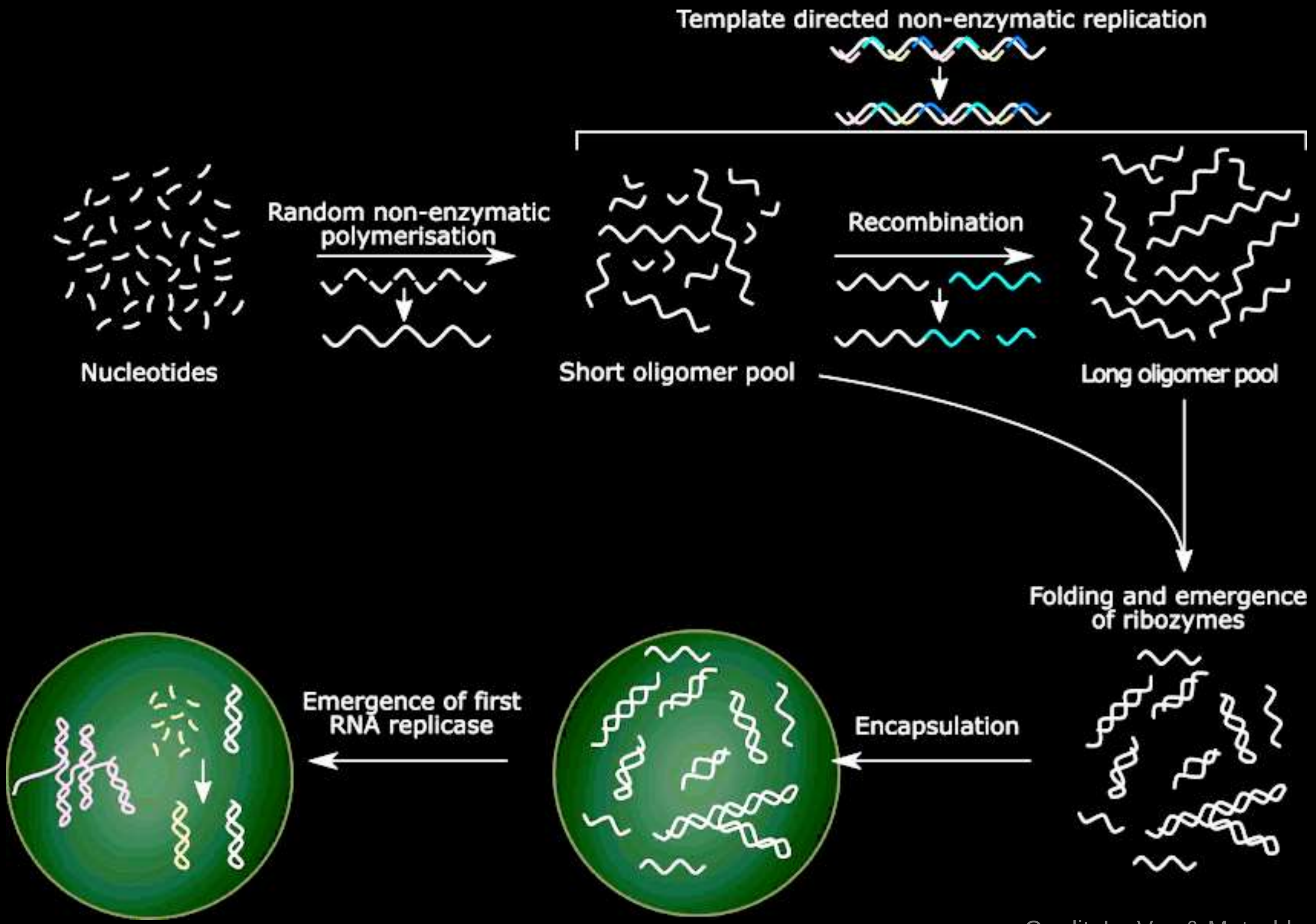
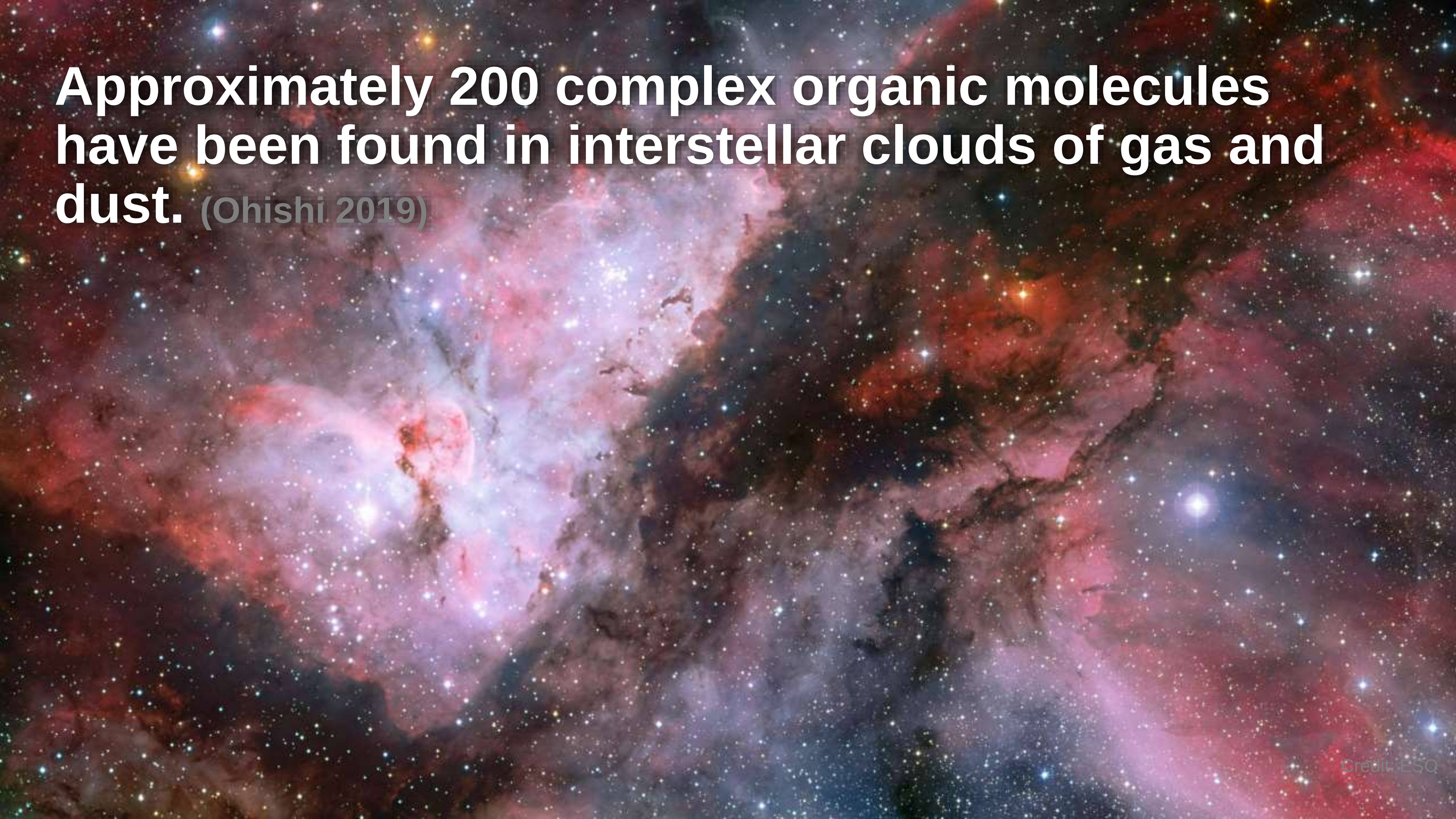


Credit: Le Vay & Mutschler 2019

Where would the raw materials to make RNA have come from?

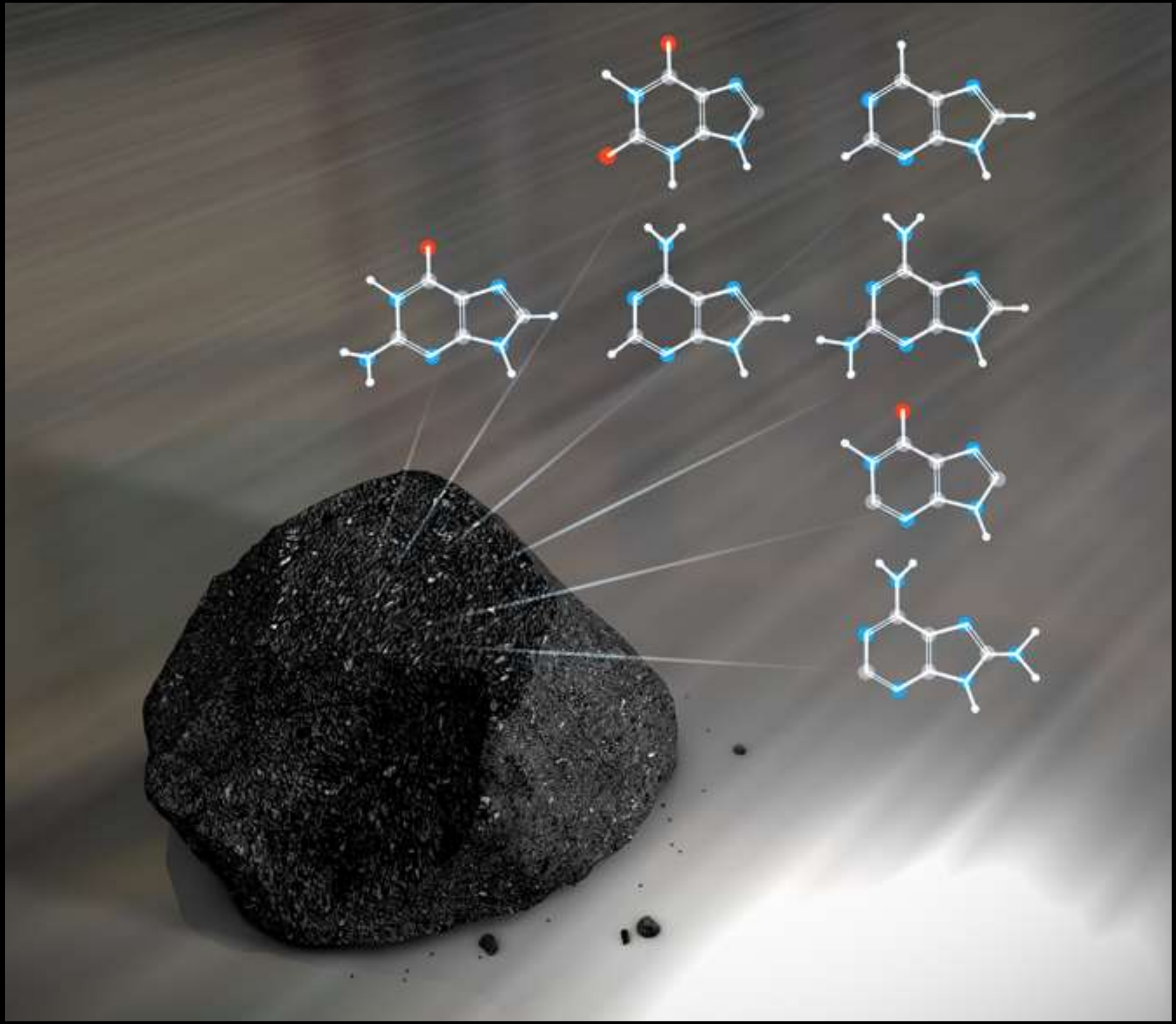
Approximately 200 complex organic molecules have been found in interstellar clouds of gas and dust. (Ohishi 2019)



Credit: ESO

Carbonaceous chondrite meteorites have been found to contain nucleobases, including adenine, guanine, and uracil.

(Callahan et al., PNAS, 2011)



Credit: NASA's Goddard Space Flight Center/Chris Smith

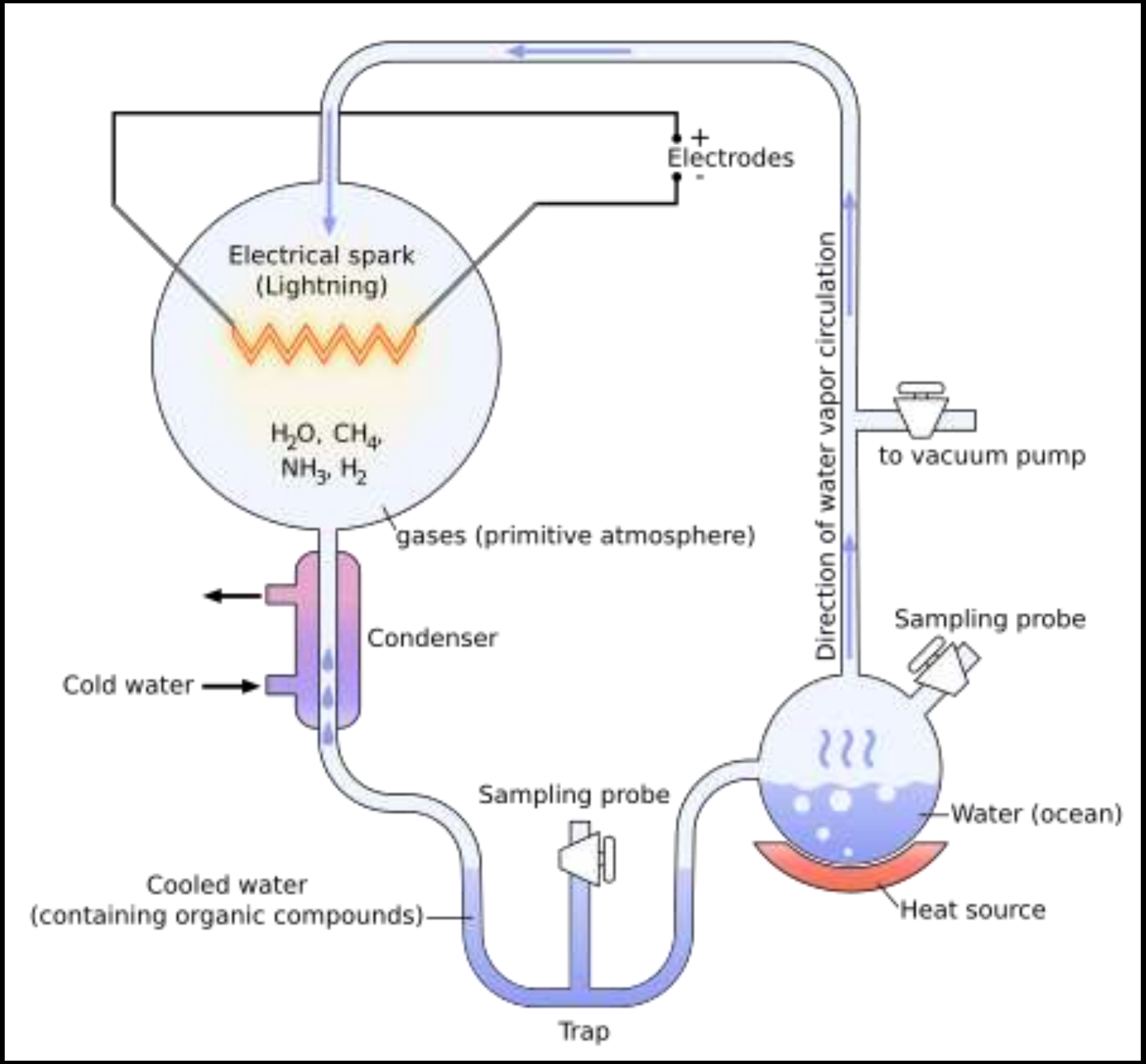
In 1952, Stanley Miller, working under Harold Urey, tried to replicate the synthesis of biological molecules from strictly nonbiological ones in the lab.

Credit: University of Chicago

The **Miller-Urey experiment** electrically shocked a chemical mix of gases thought to represent Earth's early atmosphere and oceans.

Credit: Gordon Dymowski

The Miller-Urey apparatus.



Credit: Wikimedia Commons

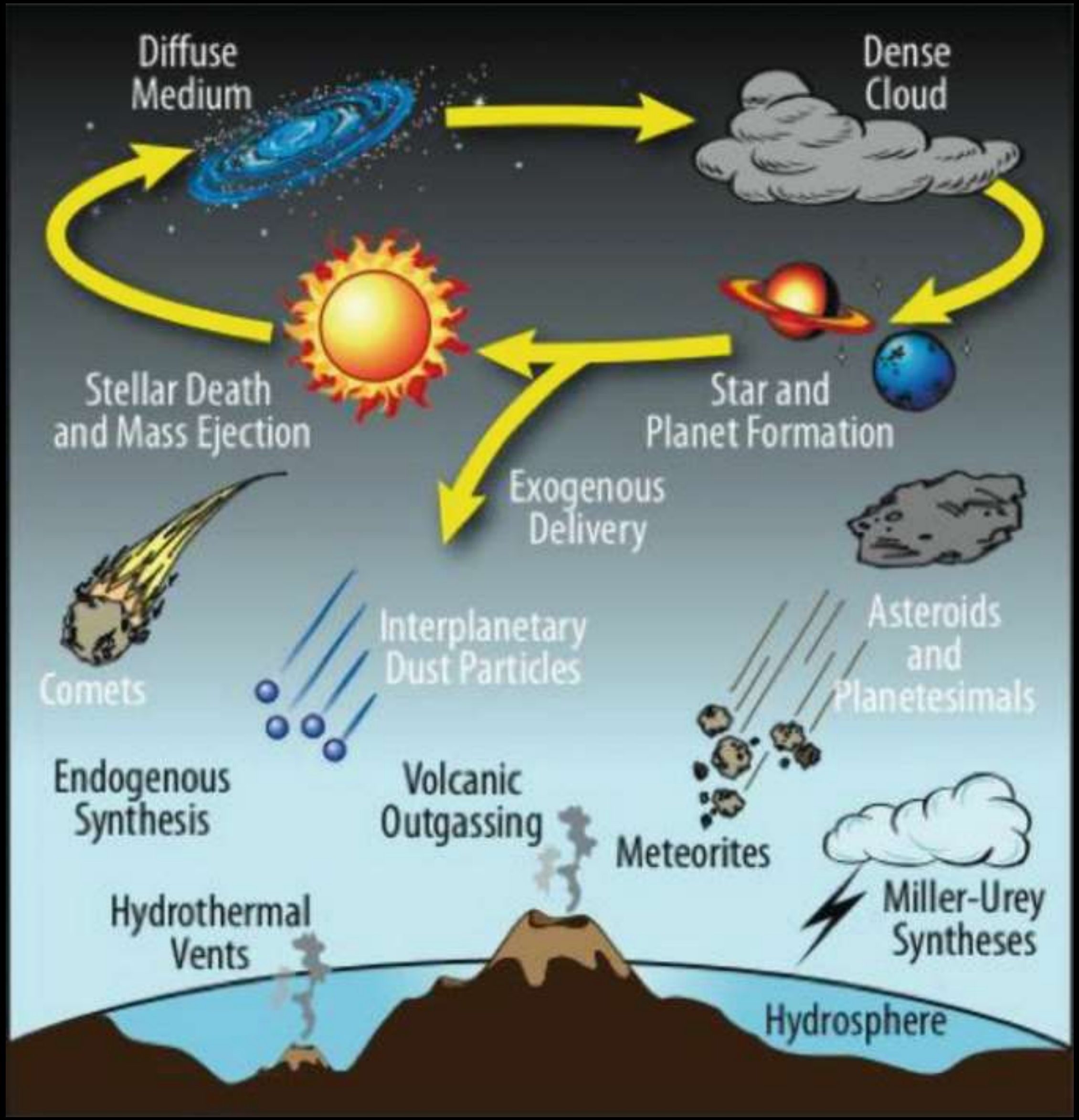
The Miller-Urey experiment (as re-analysed in 2007) generated 22 amino acids.
(Johnson et al., Science, 2008)

Later versions of the experiment have produced nucleobases—the building blocks of RNA and DNA.

More recent experiments have shown that the precursors of nucleic acids can be created from just H_2S, HCN, and ultraviolet light—all of which were abundant on the young Earth.

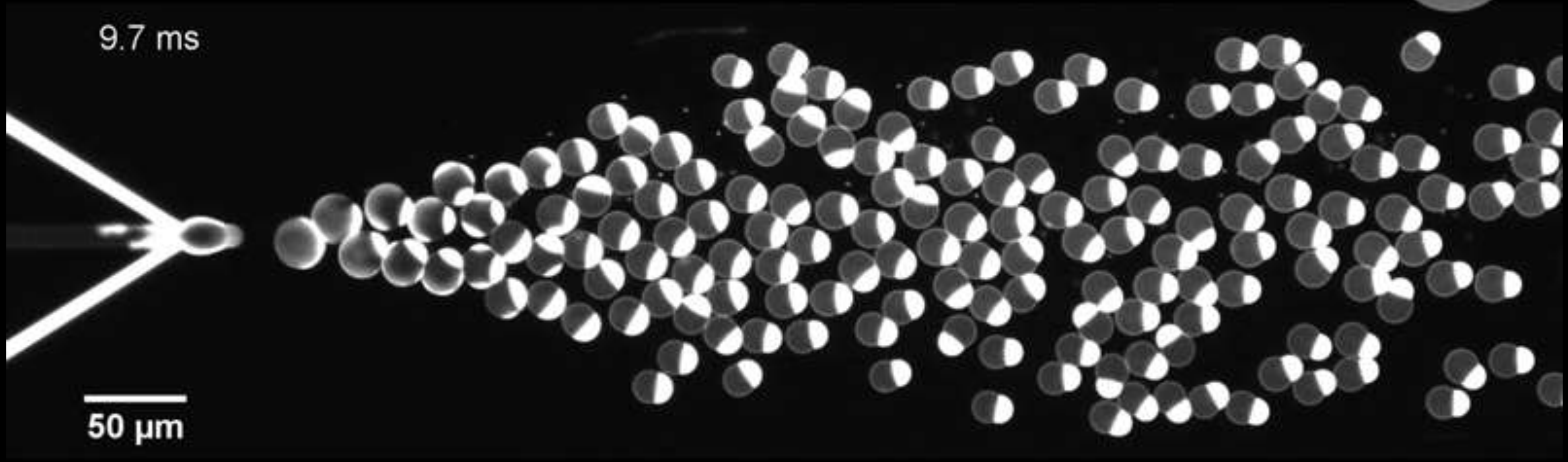
(Patel et al., Nature Chemistry, 2015)

So, it seems that there is no shortage of mechanisms to create prebiotic chemicals and deliver them to the young Earth.



Credit: by Dr. Amie Elsila (Deamer et al. 2002)

Many biologists are now attempting to create life from scratch in the lab, which provokes both excitement and ethical concerns (e.g. Powell, Nature, 2018)



Cees Dekker Lab TU Delft

In Summary

Although we have yet to prove exactly how life formed on Earth, strong evidence points toward an origin near hydrothermal vents, perhaps via RNA self-assembly and catalysis, using ingredients readily supplied from both terrestrial and astronomical sources.