The source of Earth's water

(and other important things humans seem to like)

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A *really* big moon

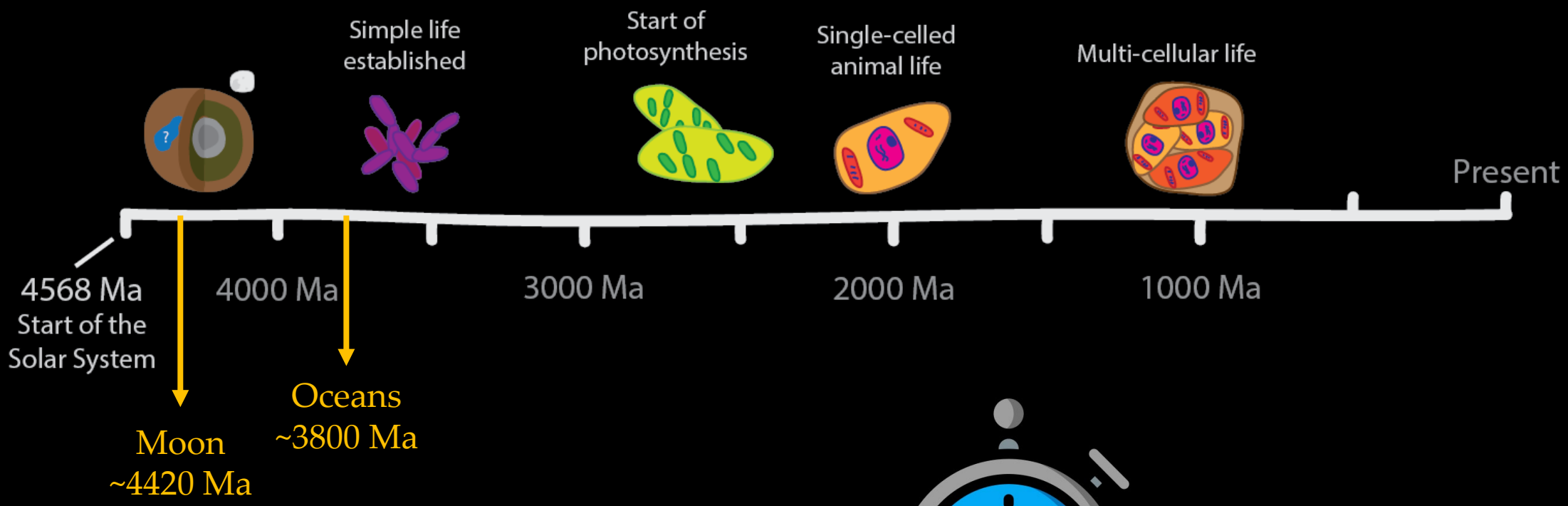
Life

What makes Earth "unique"?

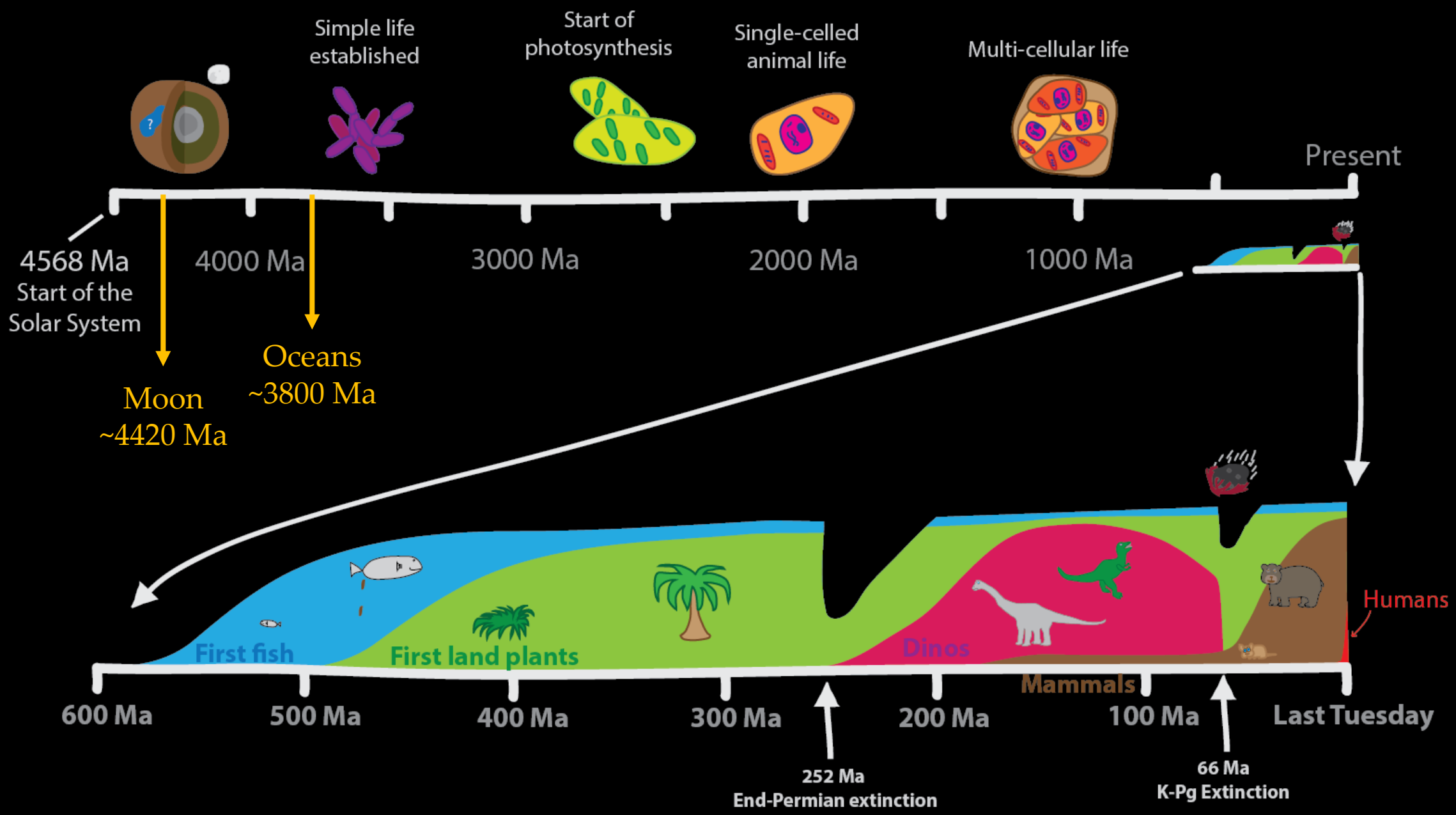
(as far as we know)

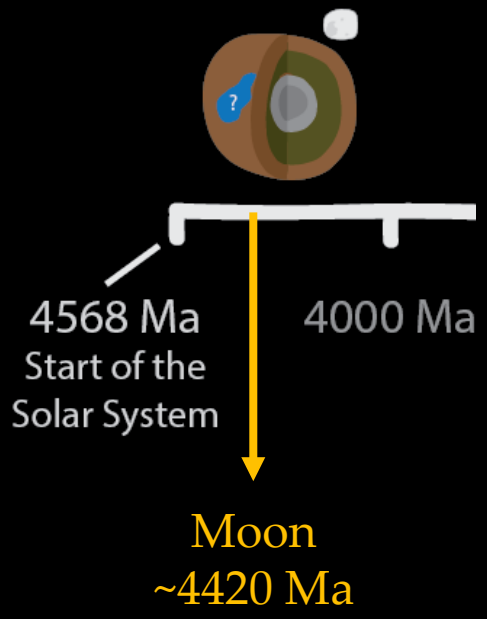
iPhones

Lots of liquid water on the surface



We know the timeline


Simple life established
Start of photosynthesis
Single-celled animal life
Multi-cellular life
Present
4568 Ma
Start of the Solar System
4000 Ma
3000 Ma
2000 Ma
1000 Ma
Moon
~4420 Ma
Oceans
~3800 Ma
First fish
First land plants
Dinos
Mammals
Humans
600 Ma
500 Ma
400 Ma
300 Ma
200 Ma
100 Ma
Last Tuesday
252 Ma
End-Permian extinction
66 Ma
K-Pg Extinction



How did we get the Moon?

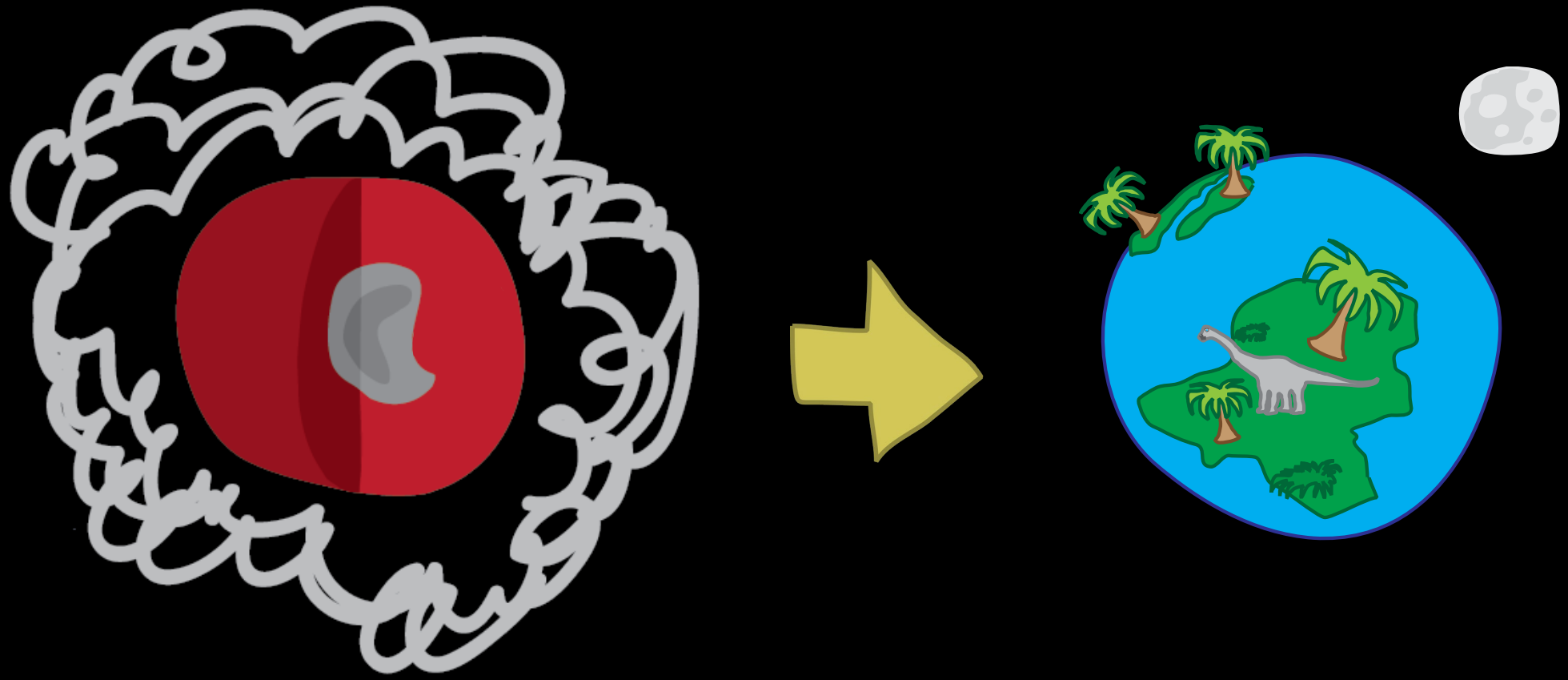
Collision

Debris disk

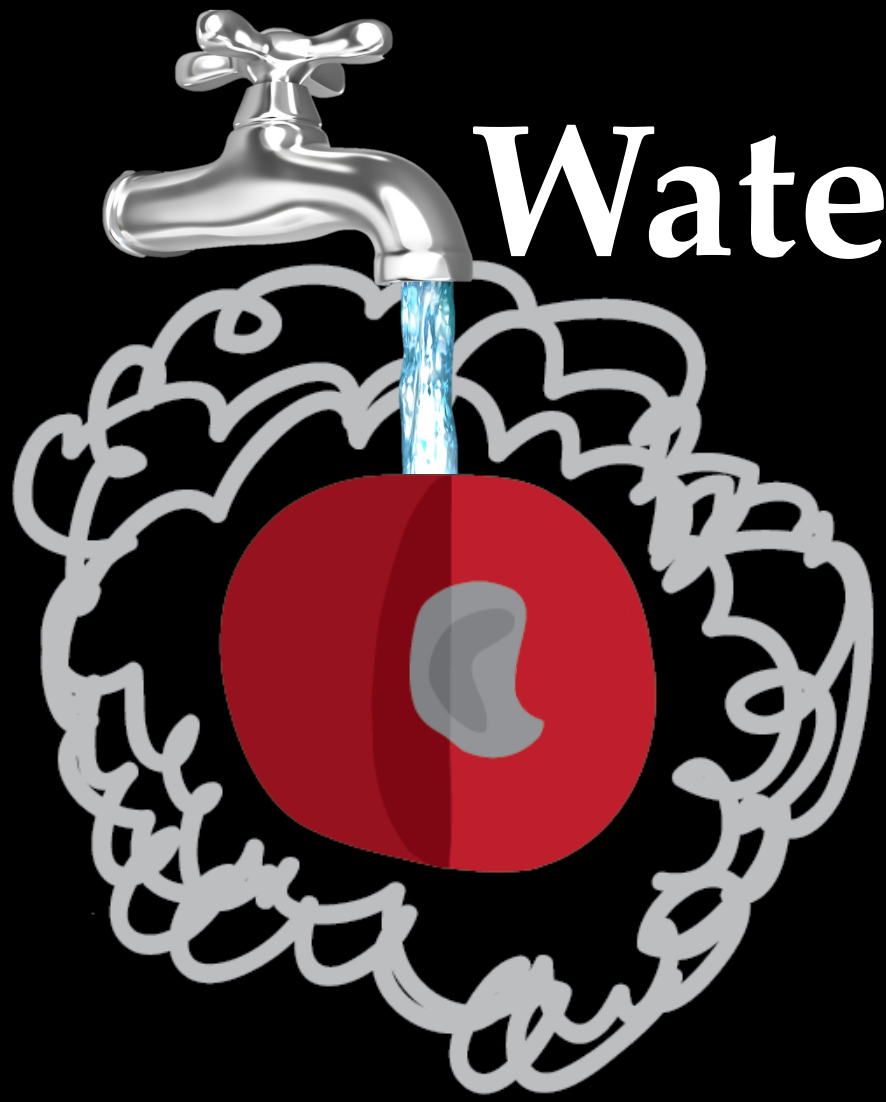
Happily
ever after

The secret ingredients are:

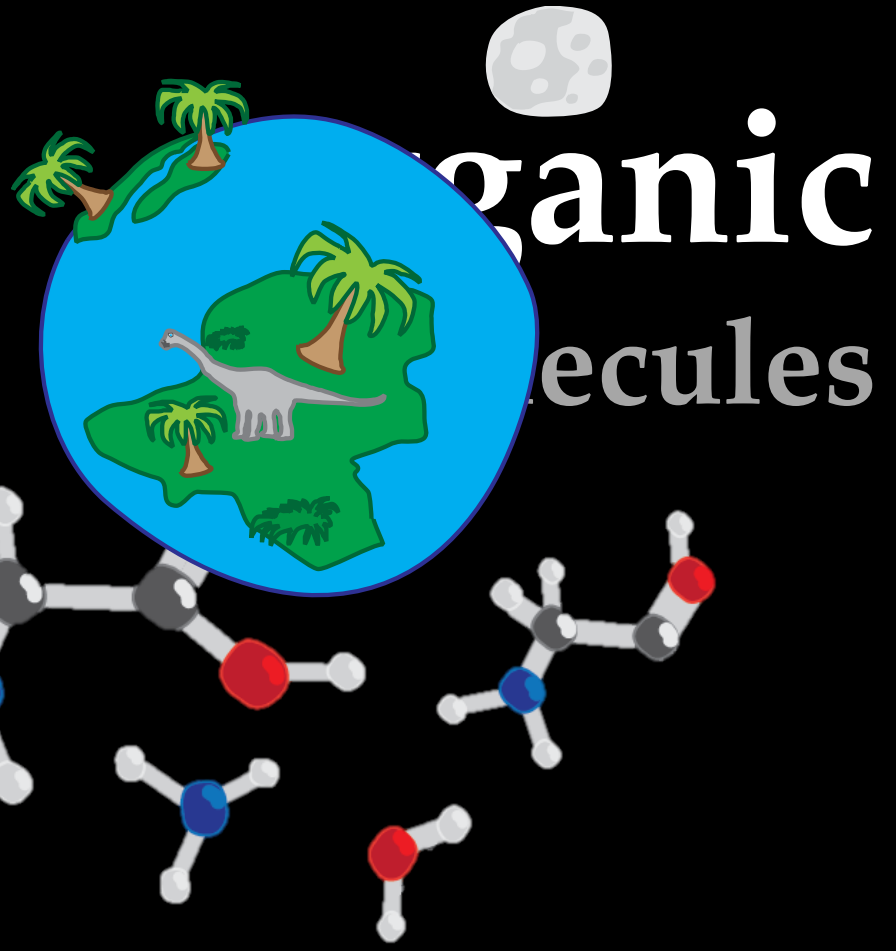
- A *really* big moon 
- **Lots of liquid water on the surface**
- **Life**
- **iPhones**



sterilized **planet**



Water (more on this later…)



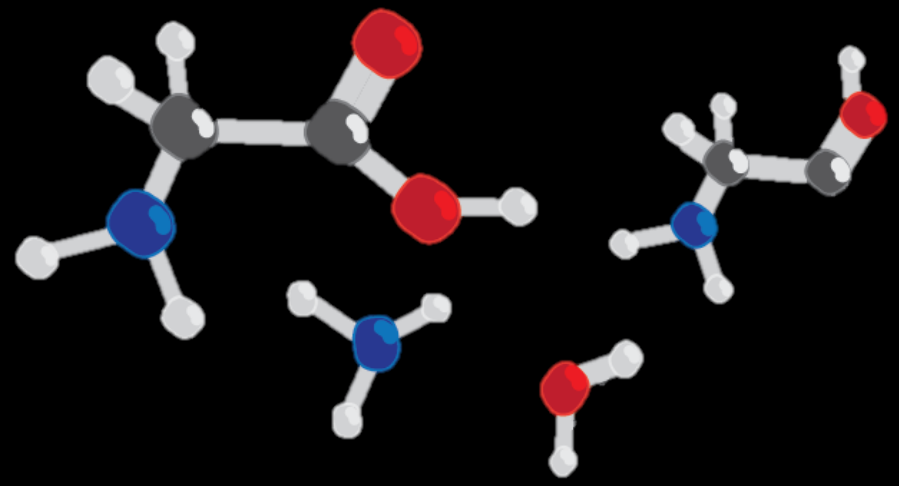
ganic

ecules

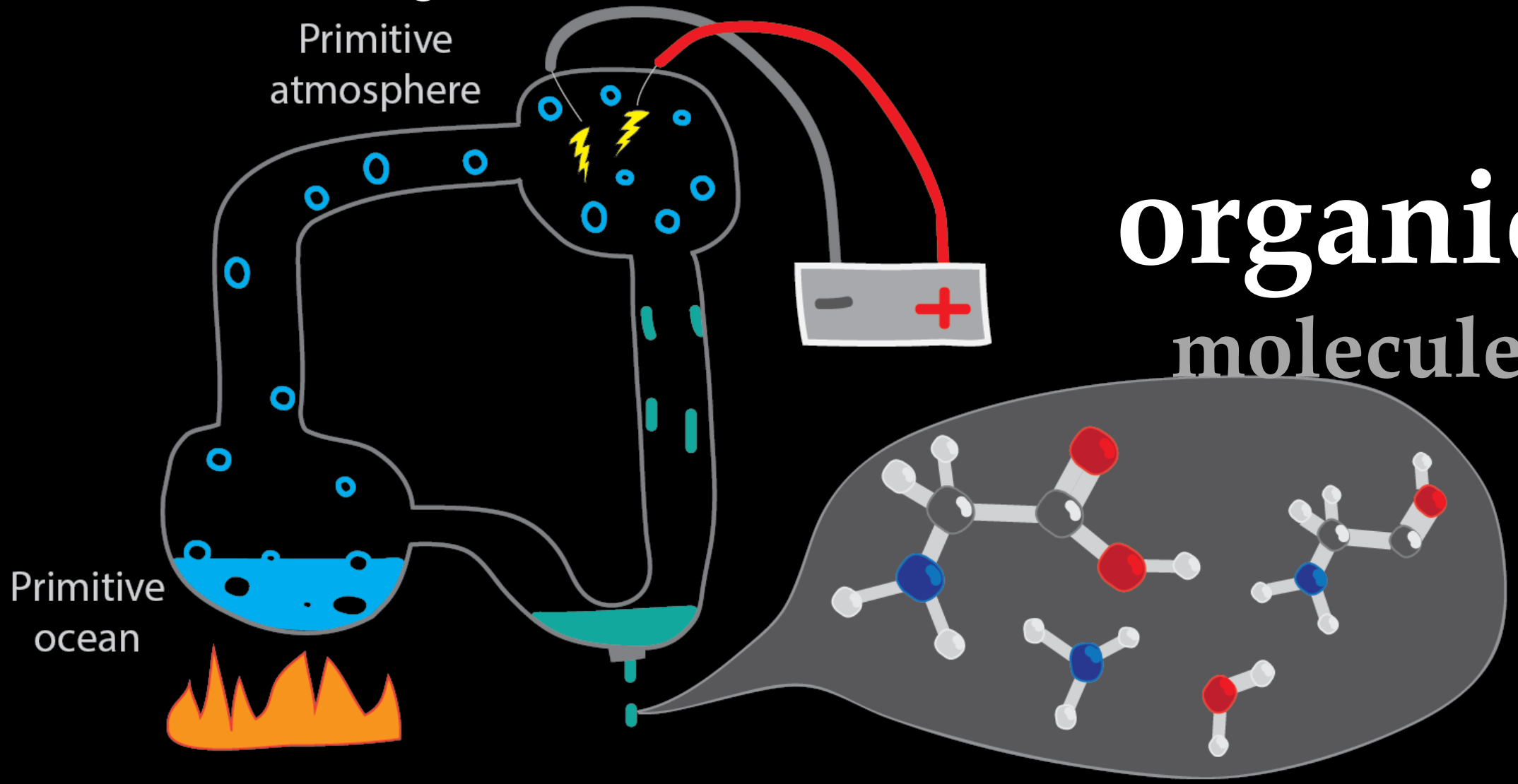
sterilized planet

Possibility 1) produced on Earth

organic molecules



Possibility 1) produced on Earth



organic molecules

Possibility 2) delivered by meteorites

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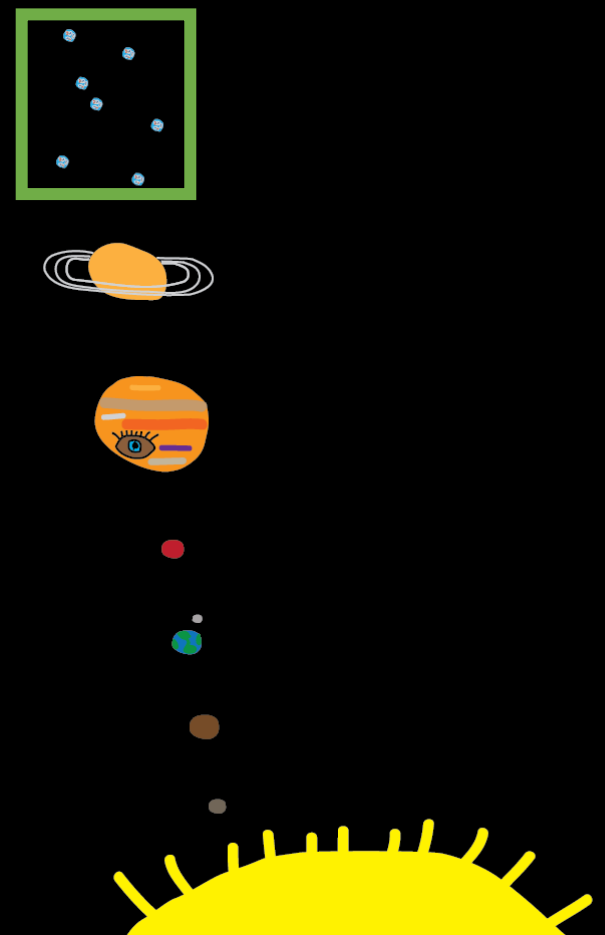
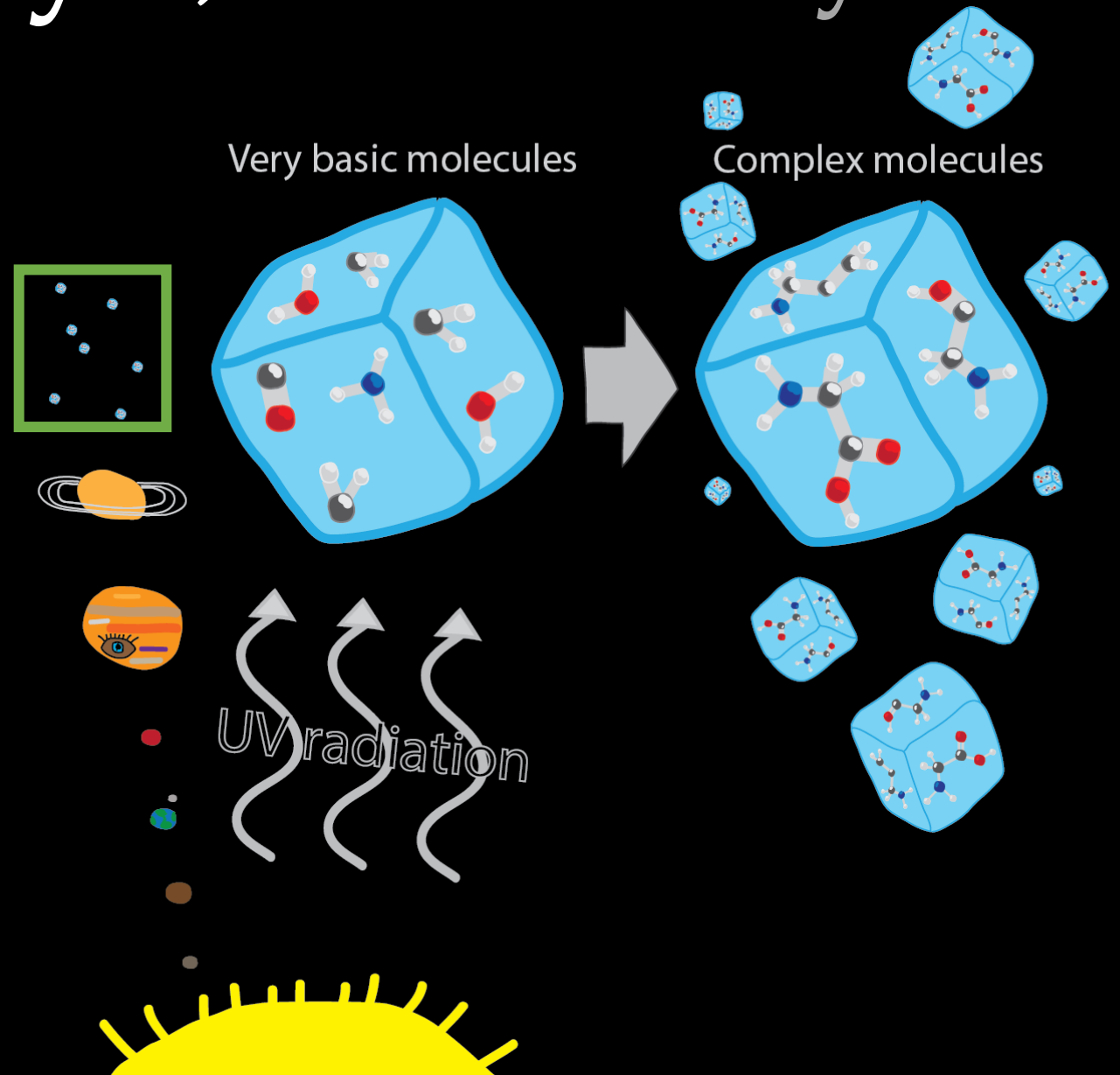


Possibility 2) delivered by meteorites



Possibility 2) delivered by meteorites

It is a numbers game…

Over 80 amino acids have been isolated

Mannose, glucose, acetone, methanol, benzene…

3 of the 4 RNA nucleotide bases

2 of the 4 DNA nucleotide bases

All in 1 meteorite

Murchison meteorite

Possibility 2) delivered by meteorites

It is a numbers game…

4+ billion years ago, Earth was receiving

~275 metric tons of carbon compounds…

PER DAY

Murchison meteorite

The secret ingredients are:

- A *really* big moon 
- **Lots of liquid water on the surface**
- Life
- **iPhones** 

accretion of raw materials

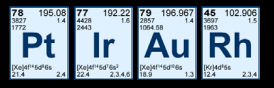
Molten Earth

78	195.08
3827	1.4
1772	
Pt	
[Xe]4f^{14}5d^{9}6s	
21.4	2,4

77	192.22
4428	1.6
2443	
Ir	
[Xe]4f^{14}5d^{7}6s^{2}	
22.4	2,3,4,6

79	196.967
2857	1.4
1064.58	
Au	
[Xe]4f^{14}5d^{10}6s	
18.9	1,3

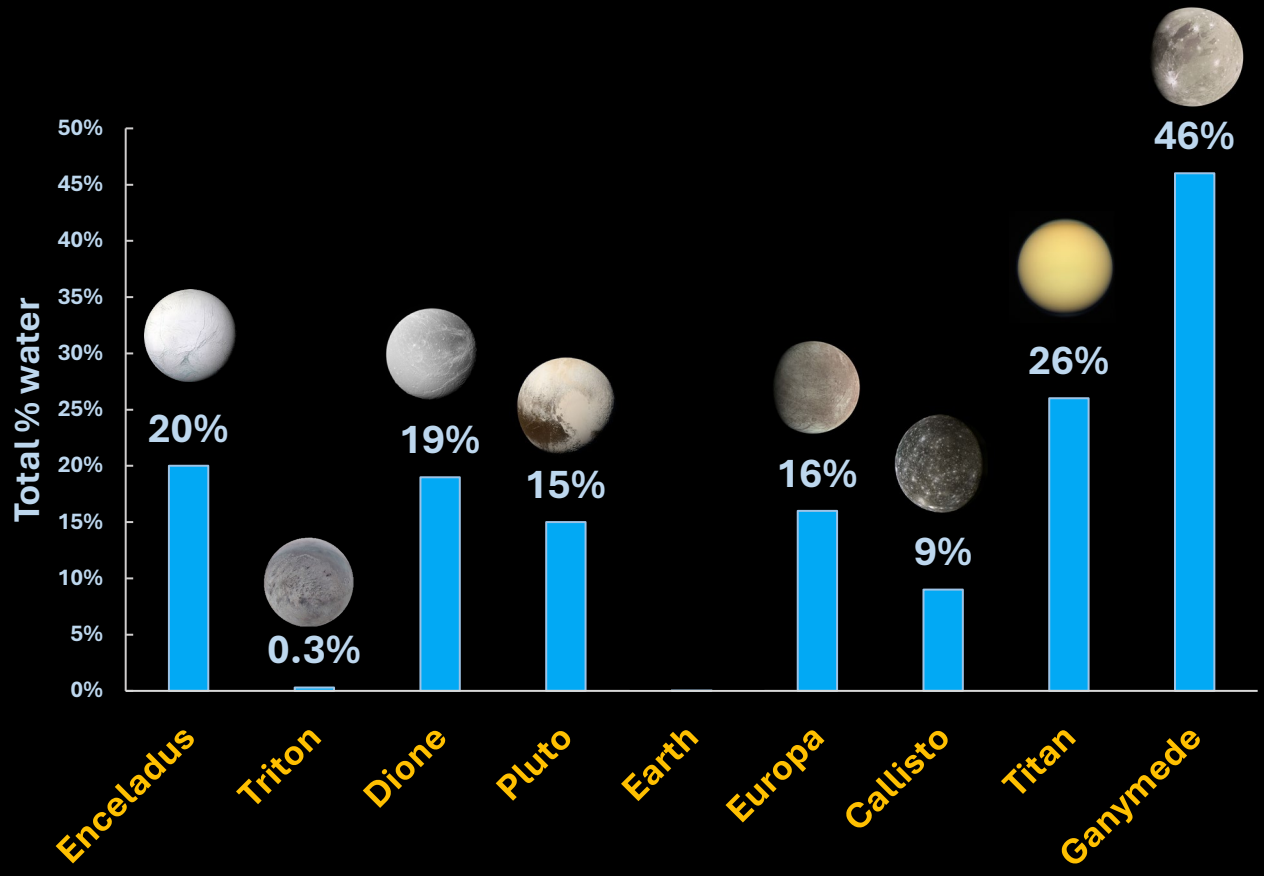
45	102.906
3697	1.5
1963	
Rh	
[Kr]4d^{8}5s	
12.4	2,3,4



The secret ingredients are:

- A *really* big moon 
- **Lots of liquid water on the surface**
- Life
- iPhones  

Does Earth really have *that* much water?



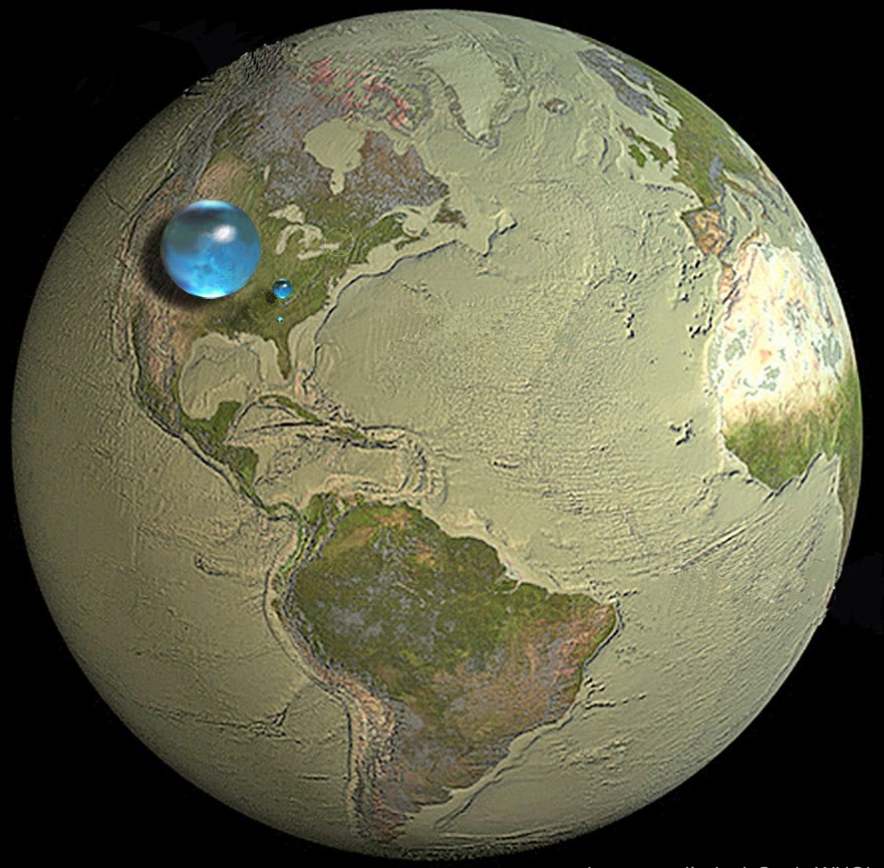


Image credit: Jack Cook, WHOI

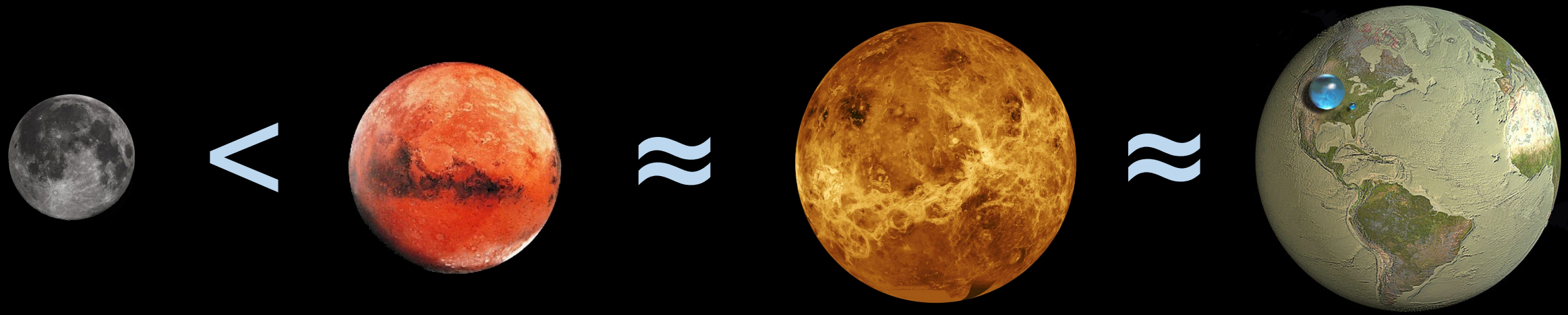
Total liquid water in various Solar System objects

(total by volume and water ice is not included)

Compared to our neighbors

Original H_2O

Lack of a magnetic field has led to major changes



But it does have water, and…

- It is on the surface
- It is liquid

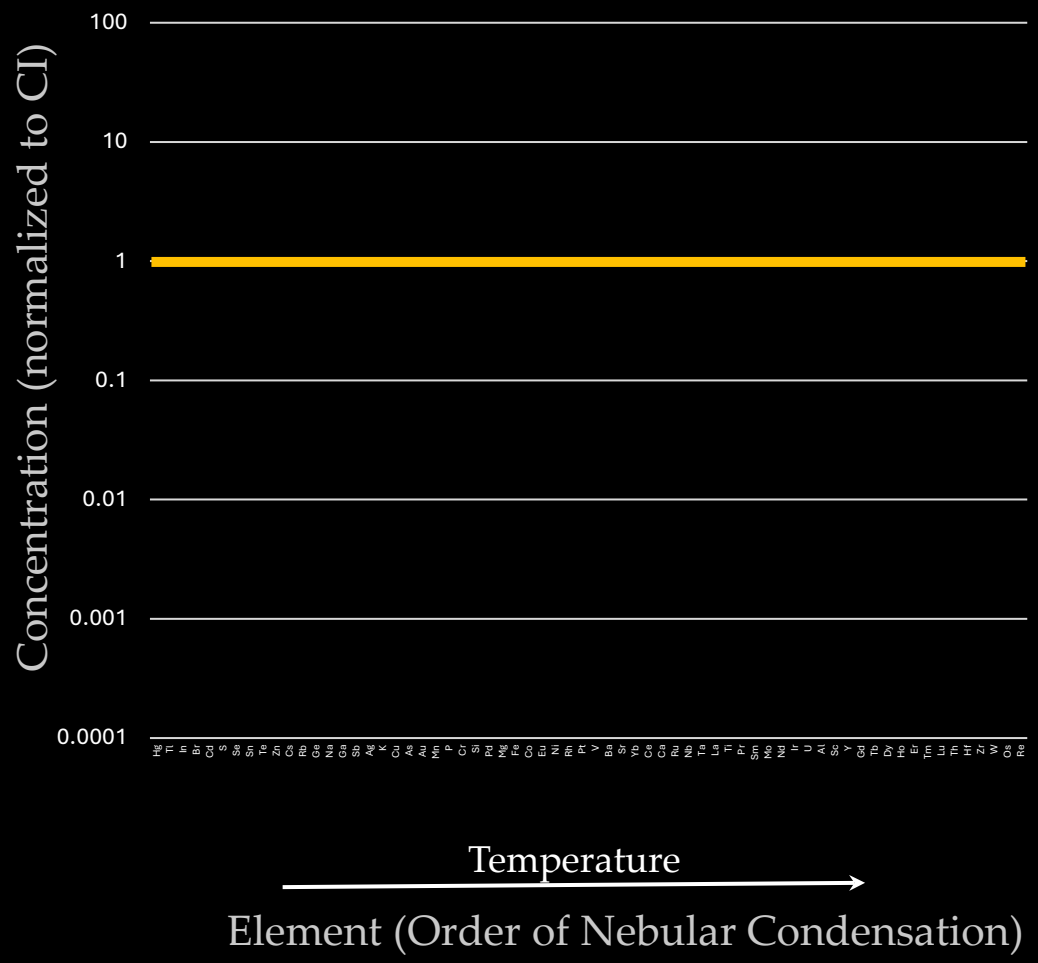
What is the *source* of Earth's water?

There aren't that many options:

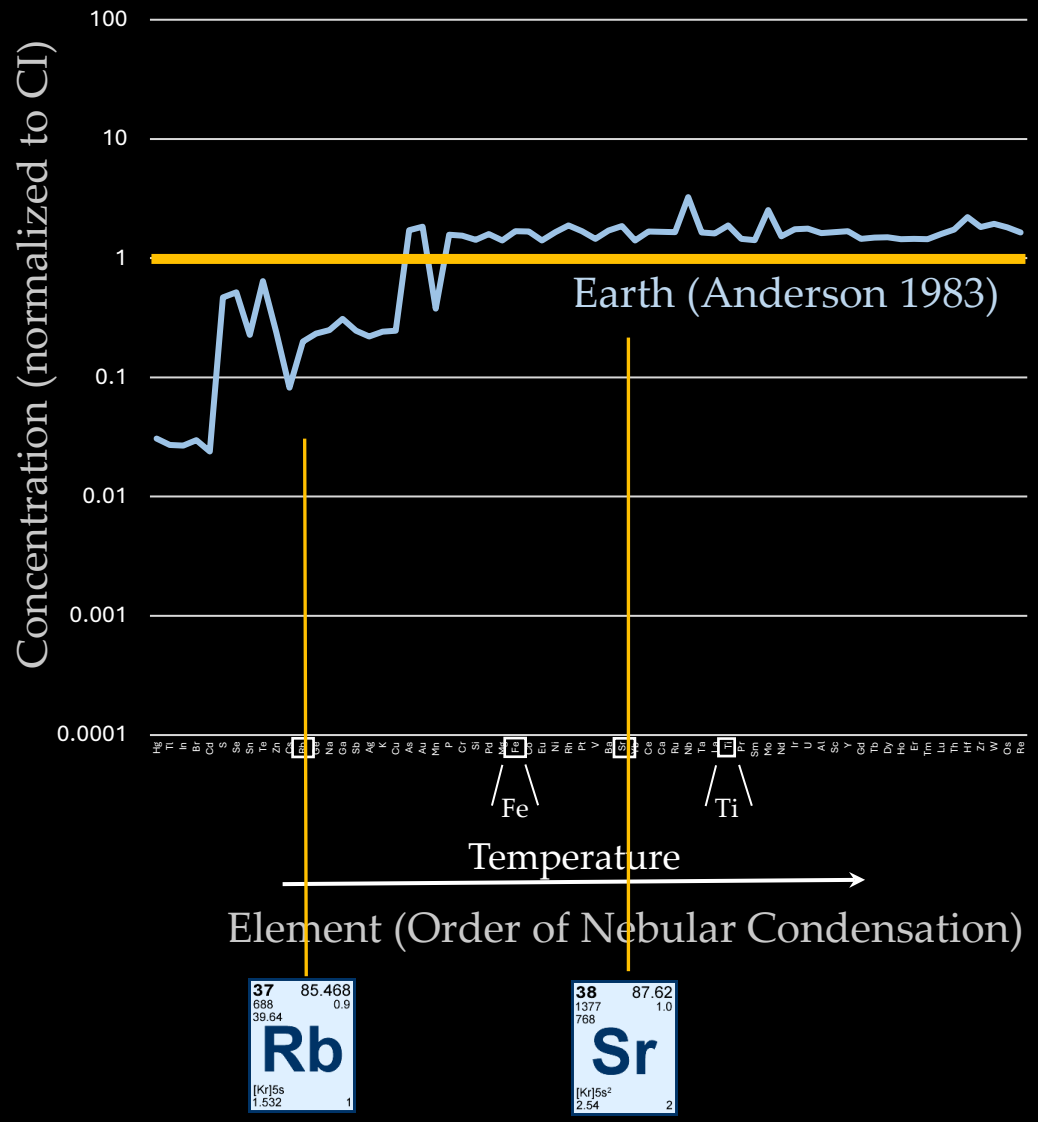
1. It was here from the start

2. It was delivered here
   - By meteorites
   - By comets

Approach – Using the Moon

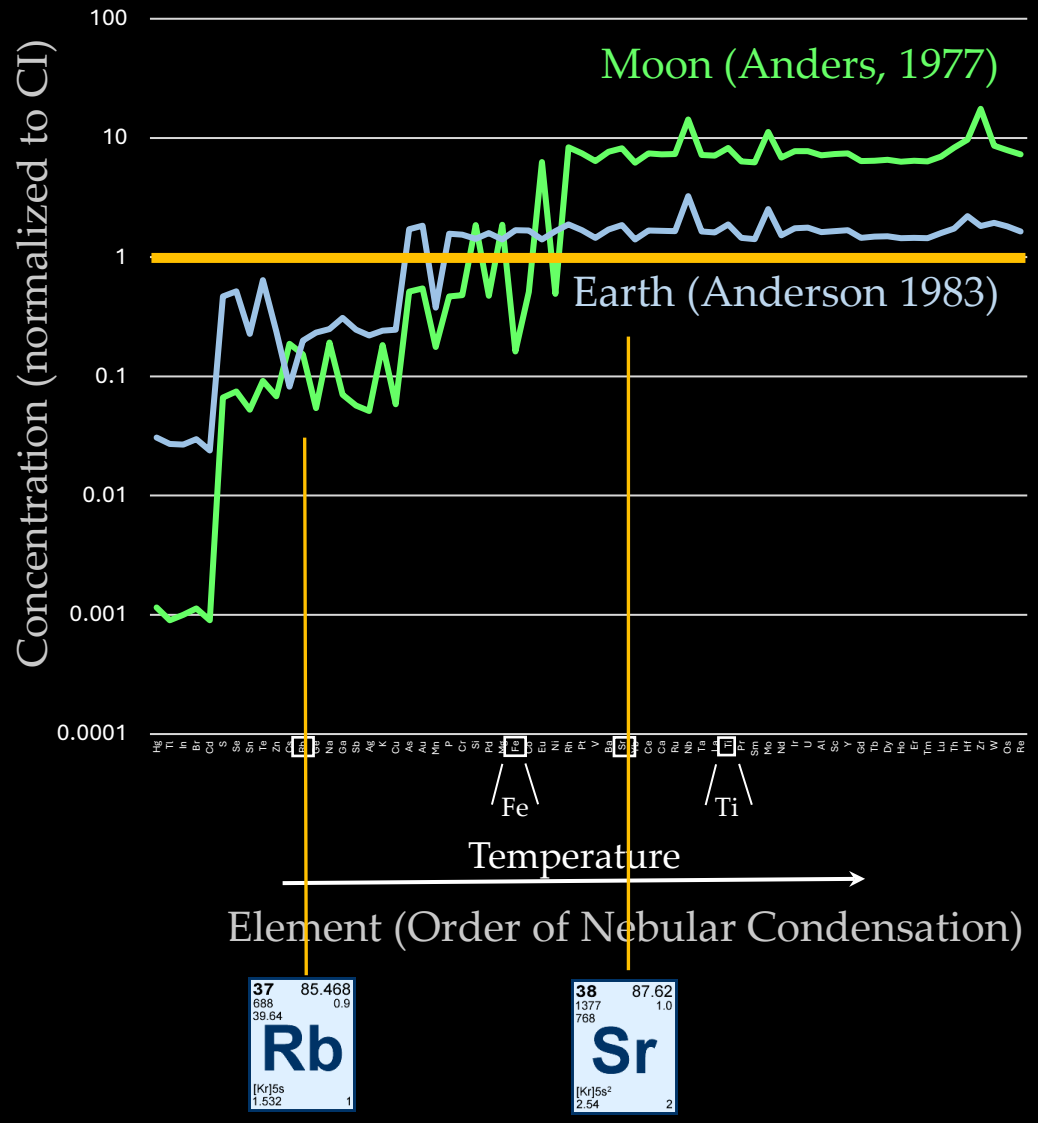


Approach – Using the Moon



The Earth is depleted in volatile elements relative to the bulk Solar System

Approach – Using the Moon



The Earth is depleted in volatile elements relative to the bulk Solar System

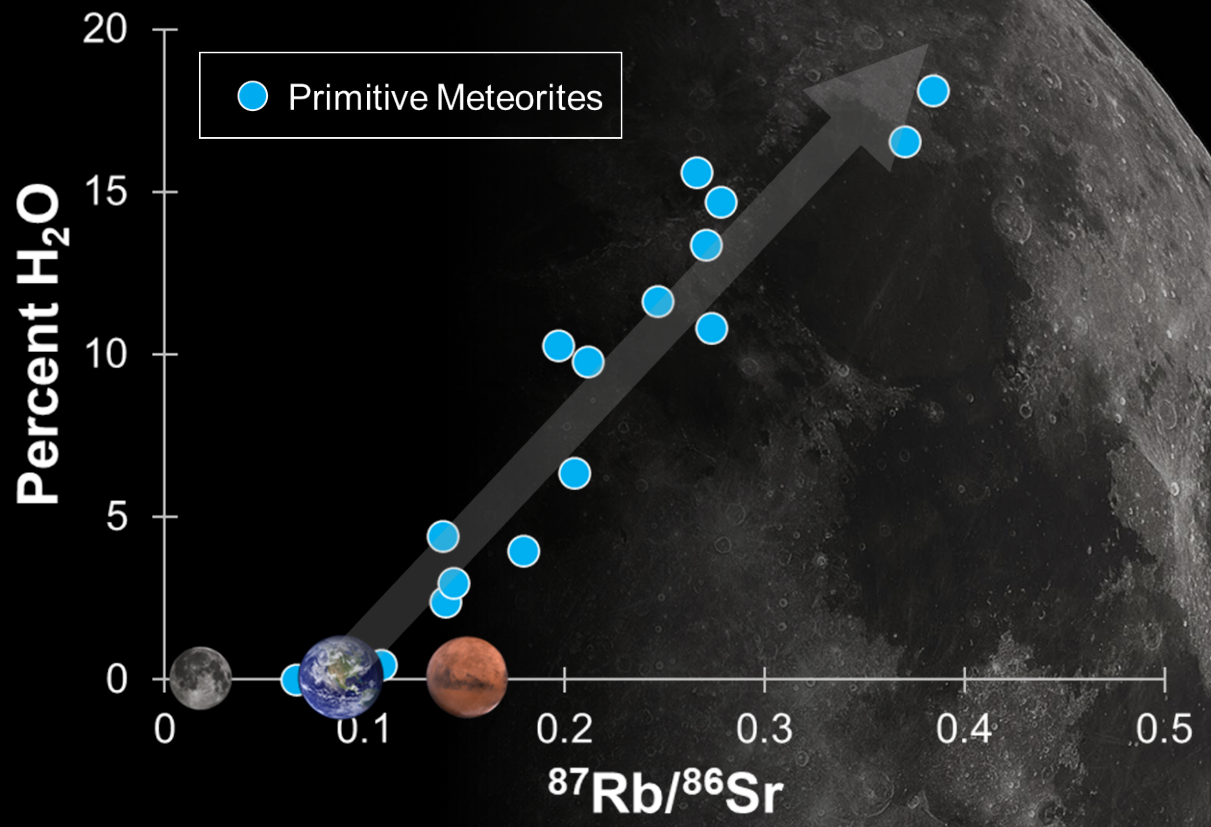
The Moon is more depleted than the Earth

Approach

$^{87}Rb \xrightarrow{(t_{1/2} = 49.6\ Ga)} {}^{87}Sr$

- Rb is a moderately volatile element
- Sr is refractory element

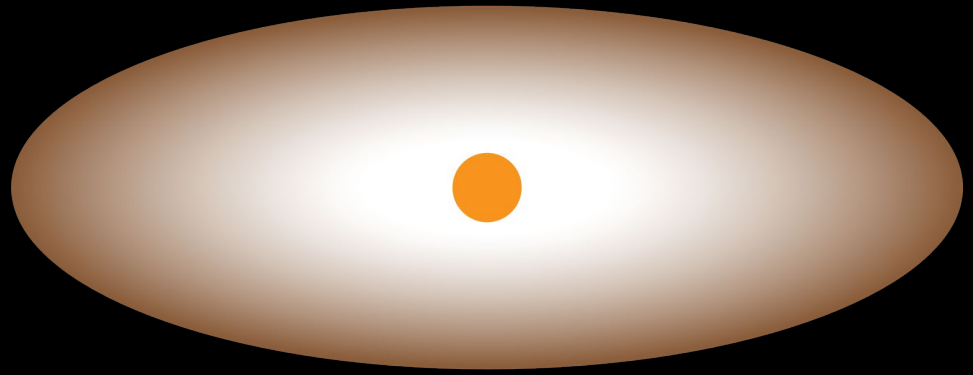
The ^{87}Sr in material records time-integrated ^{87}Rb abundance

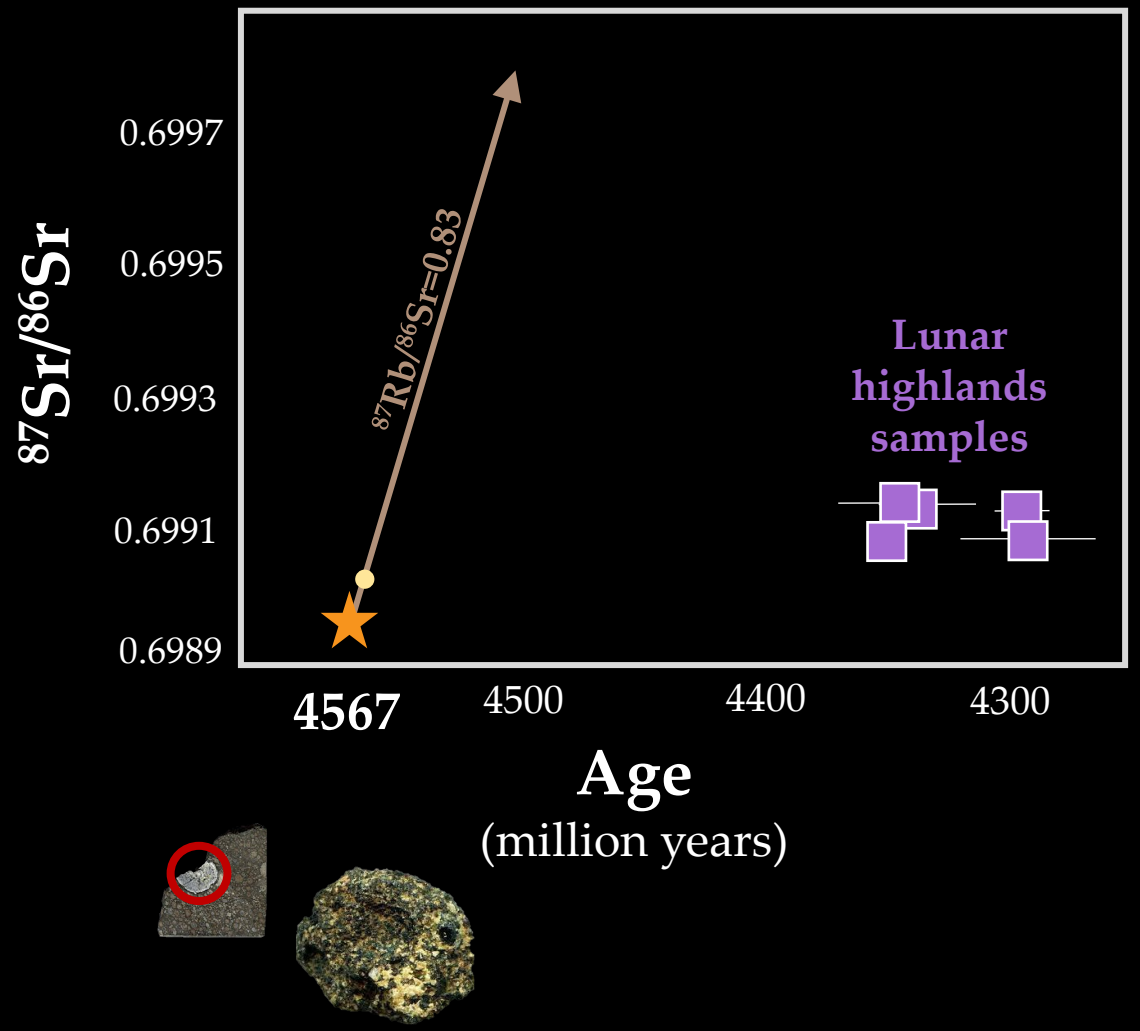


The time-integrated ^{87}Rb abundance can be calculated from the known ^{87}Sr abundance of a material today

Rb is a proxy for **H_2O**

Stage 1:
Protoplanetary Disk



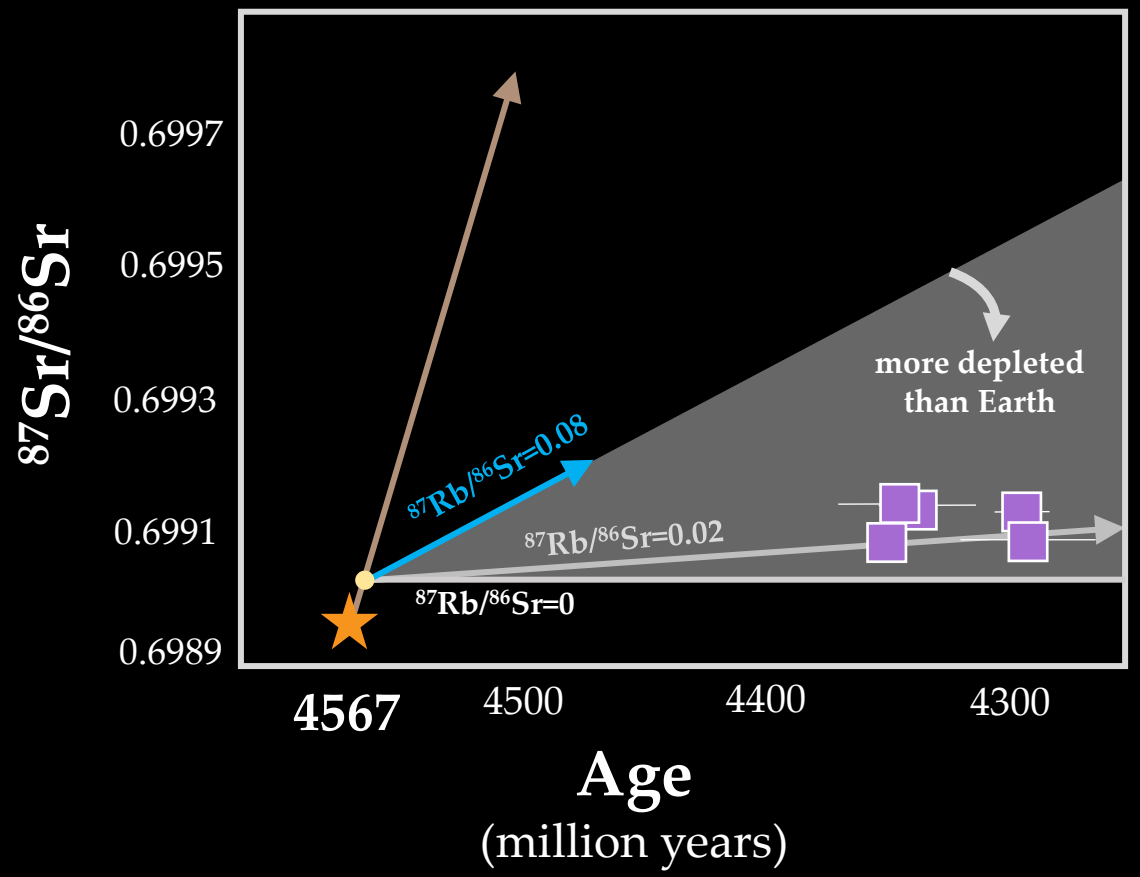


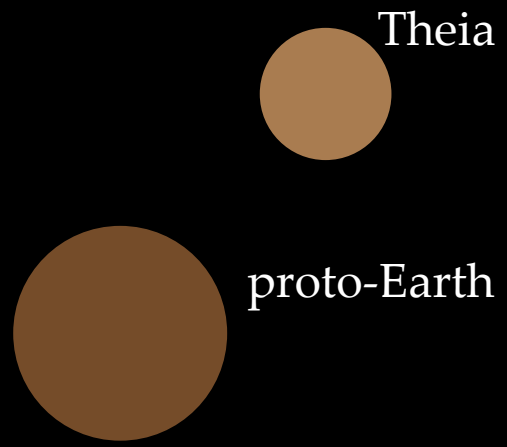
High Rb/Sr (~0.83)

Grows in a lot of ^{87}Sr

Only lasts 1-3 million years

Stage 2:
Precursor Bodies



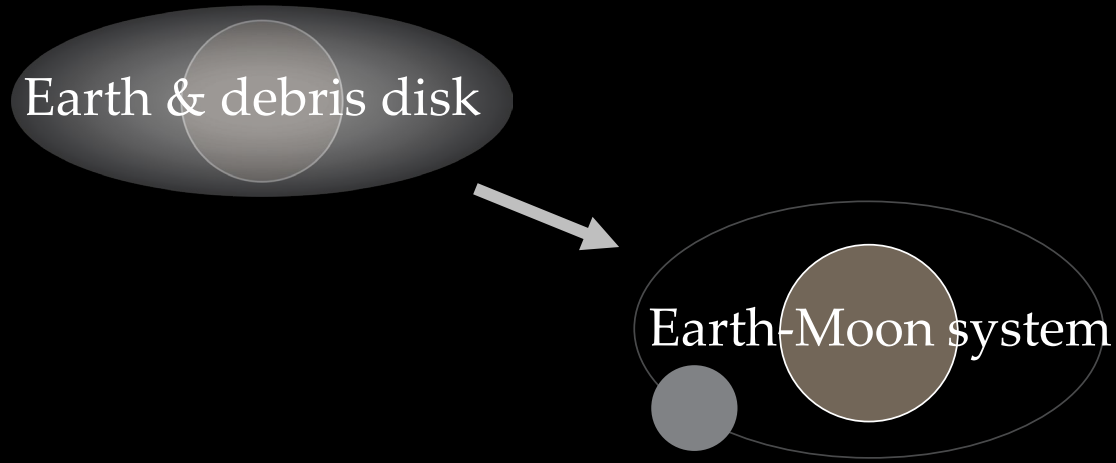


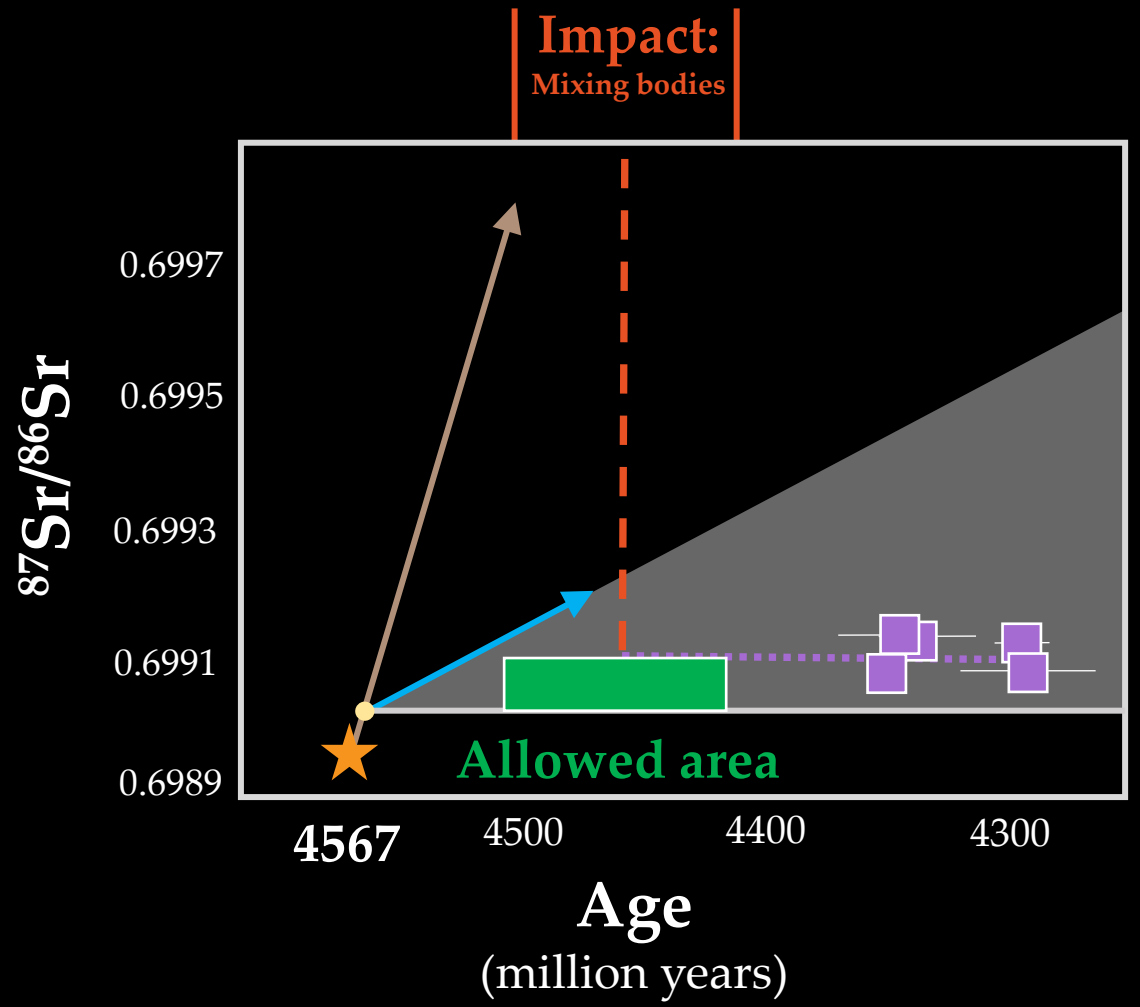
We don't know the $^{87}Rb/^{86}Sr$ (volatiles)
…but we can set constraints!

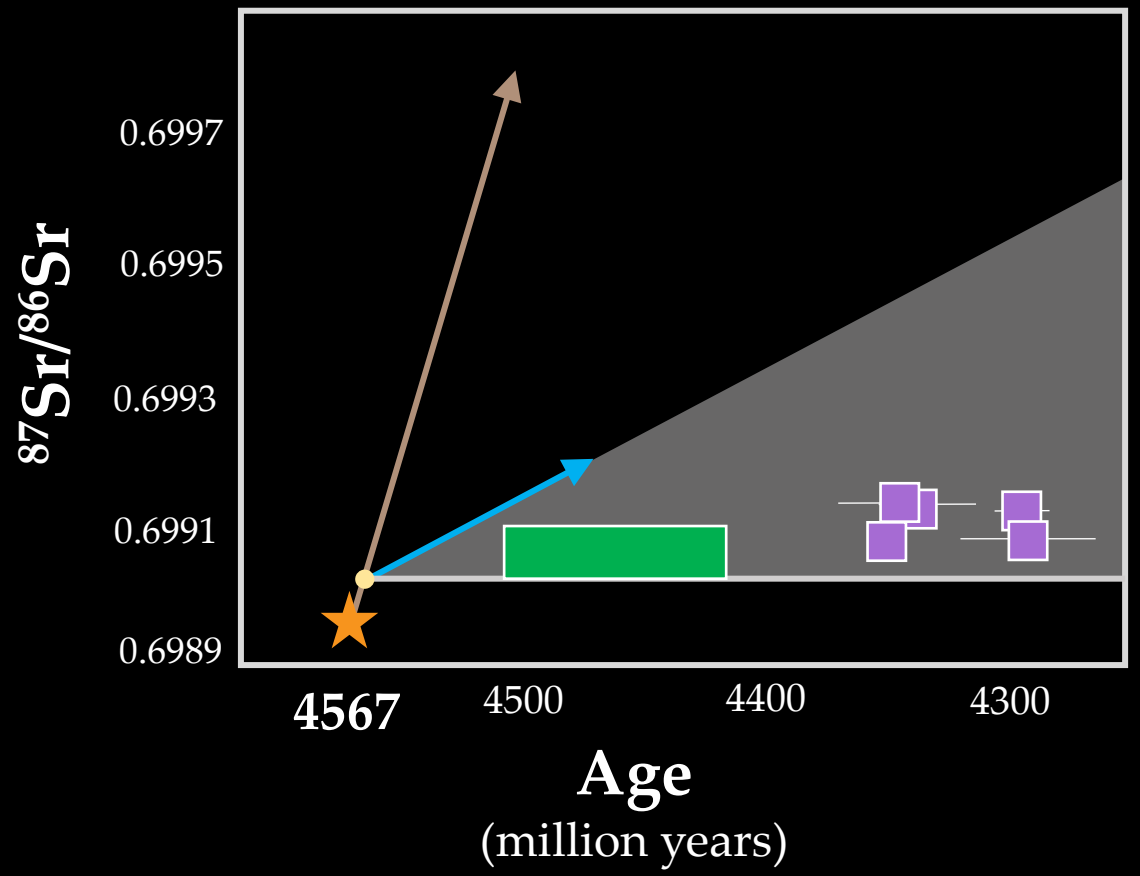
We know the $^{87}Rb/^{86}Sr$ of bulk Earth

We know the $^{87}Rb/^{86}Sr$ of bulk Moon

Stage 3:
GIANT IMPACT!
Undifferentiated Moon



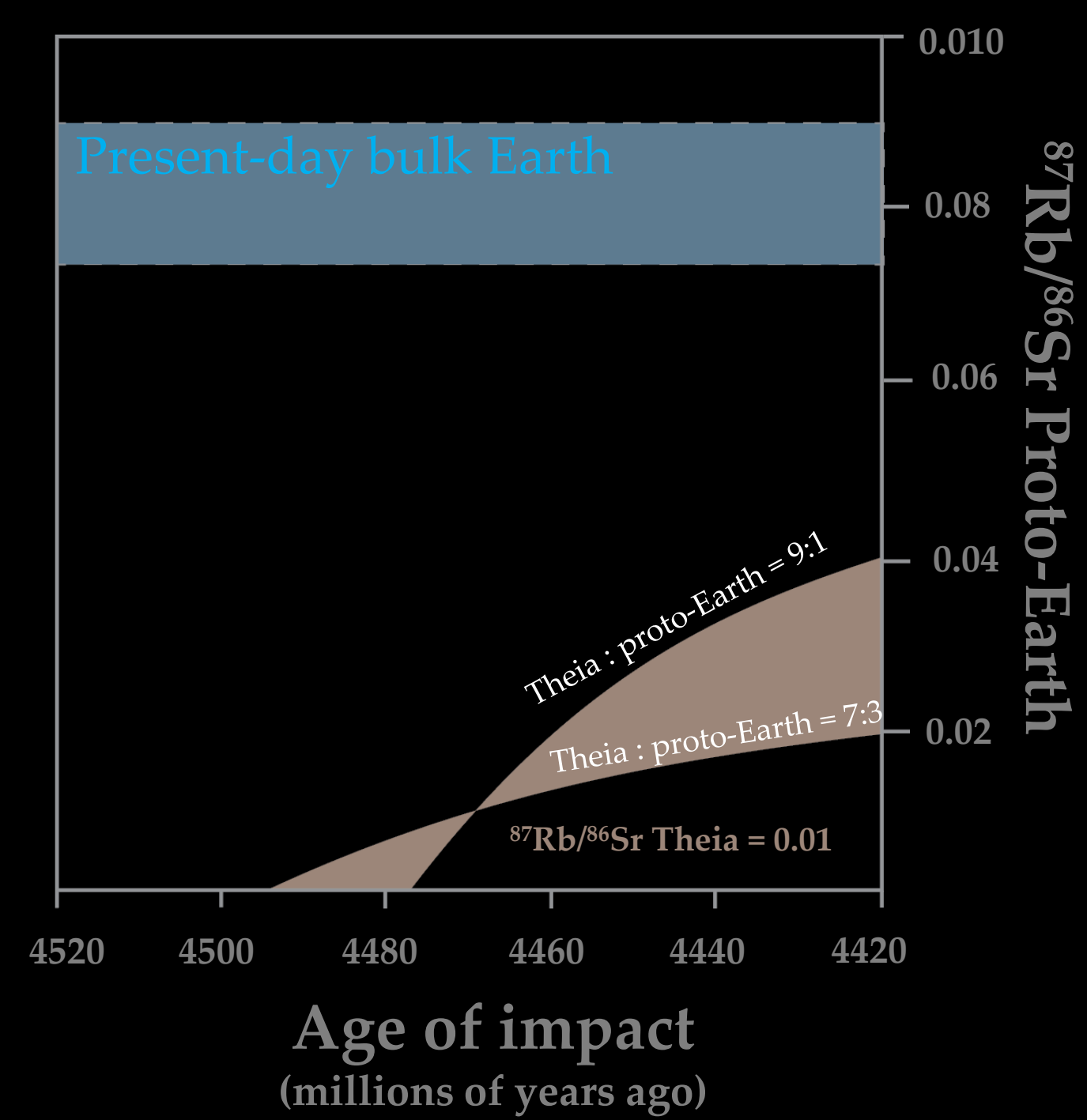




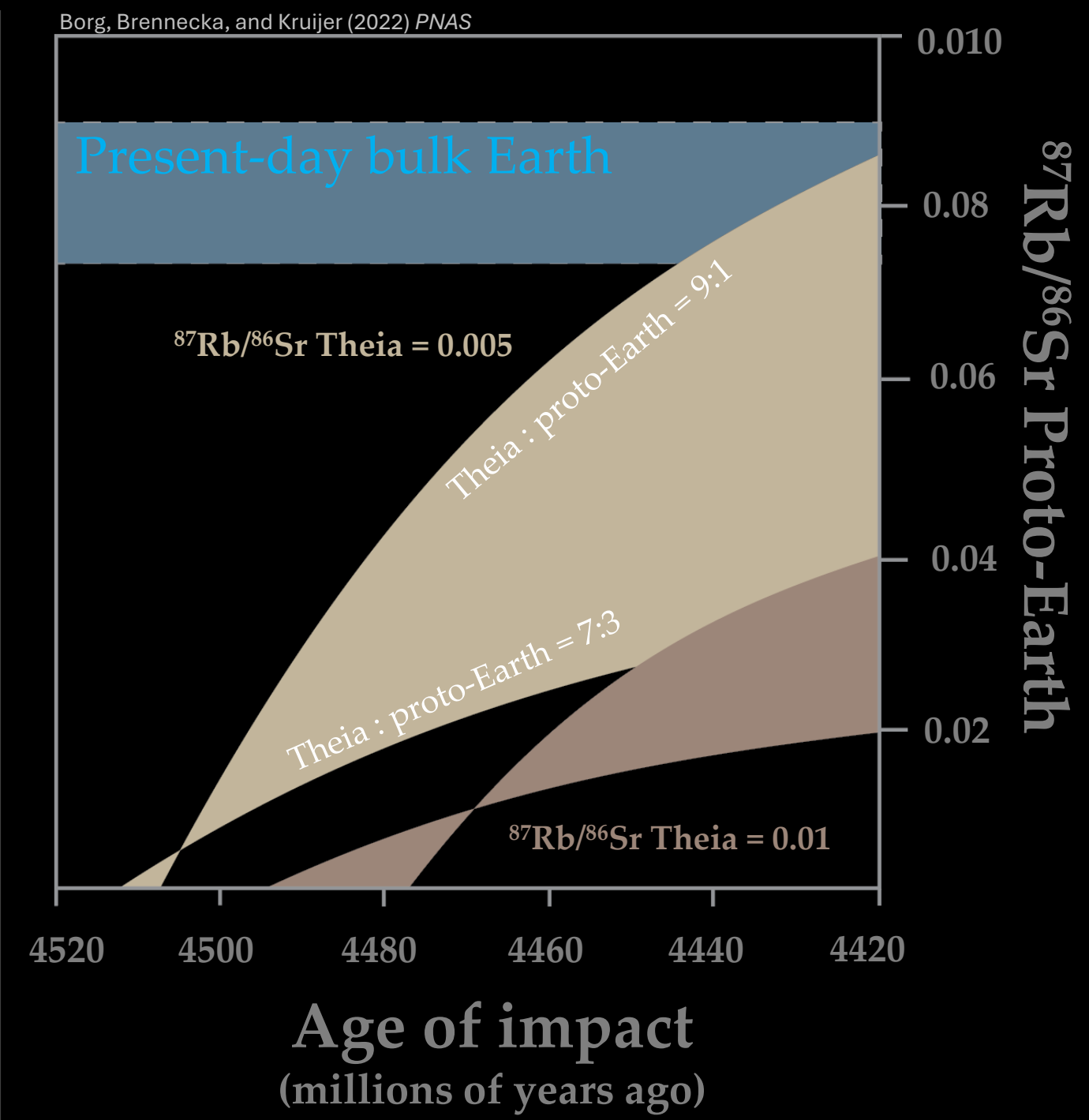
This box sets hard constrains on:

1. When the Moon-forming impact happened

2. The volatile content of both Earth and Theia



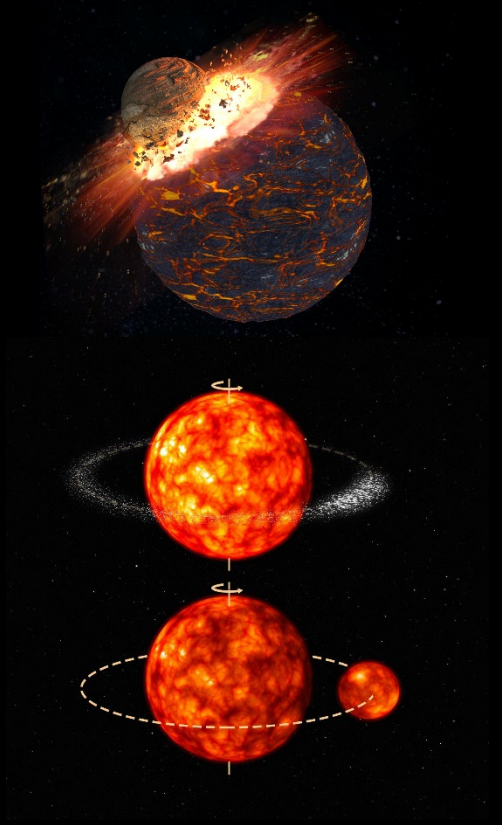
With an $^{87}Rb/^{86}Sr = 0.01$ for Theia, you cannot reproduce present-day Earth



With an $^{87}Rb/^{86}Sr = 0.005$ for Theia, you can barely reproduce present-day Earth
(0.005 is the lowest measured volatile content for any meteorite!)

With an $^{87}Rb/^{86}Sr = 0.01$ for Theia, you cannot reproduce present-day Earth

Primary outcomes from Rb-Sr research



1. The precursor materials for Earth and Theia had to be volatile-poor (not a lot of water)

2. Nothing with a significant amount of Rb—such as all known asteroids and meteorites—could have been added after the Earth/Moon system formed

There aren't that many options:

1. It was here from the start

2. It was delivered here
   - ~~By meteorites~~
   - By comets

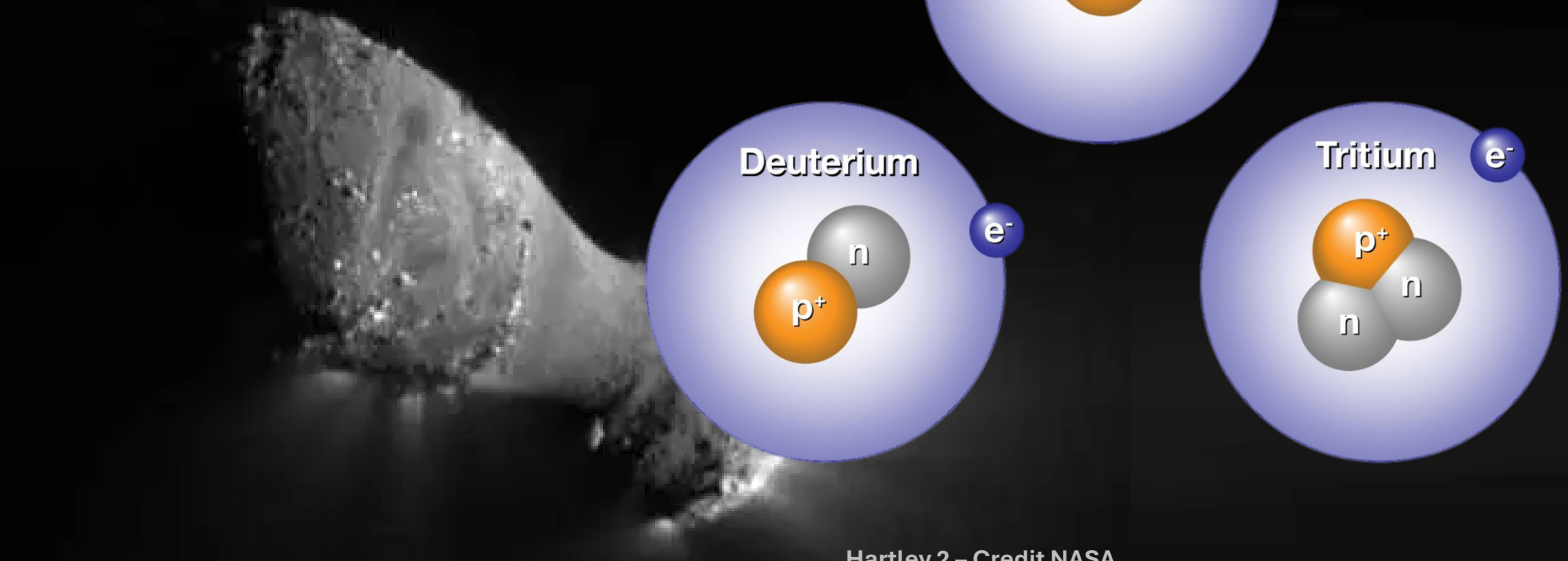
What about comets?

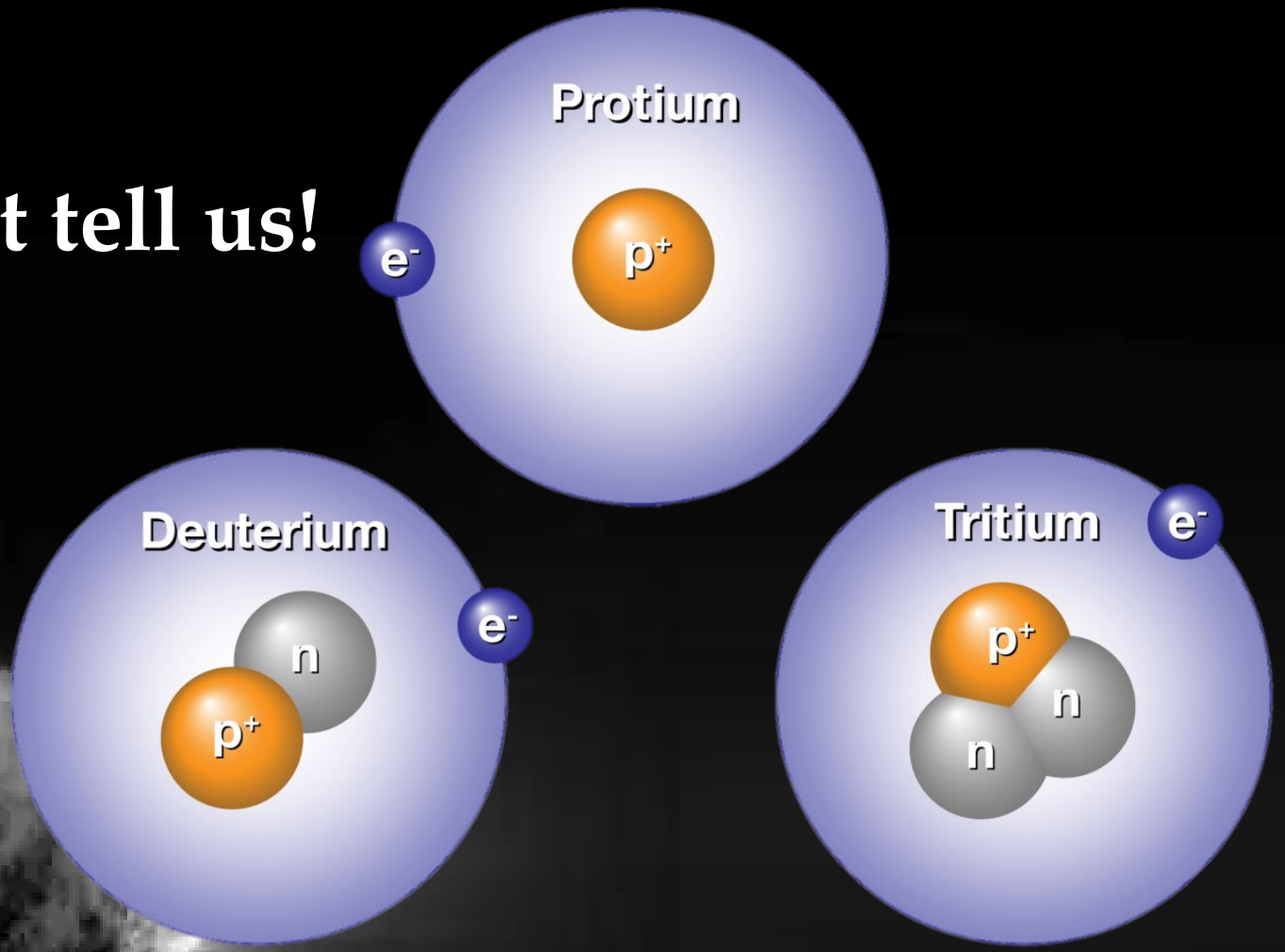
Isotopes might tell us!

Hartley 2 – Credit NASA

H_2O

Isotopes might tell us!





Hartley 2 – Credit NASA

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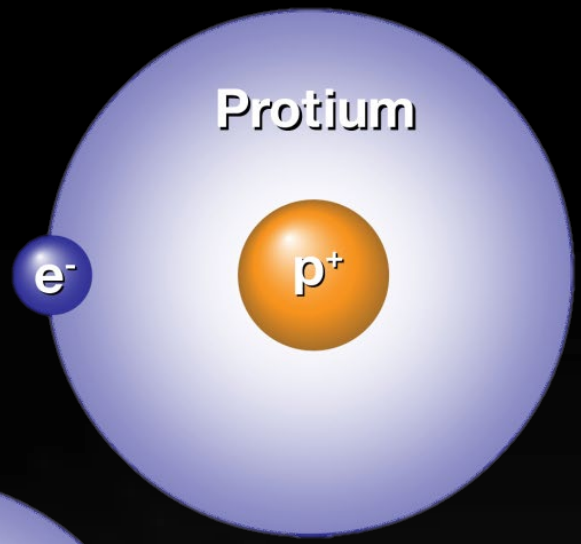
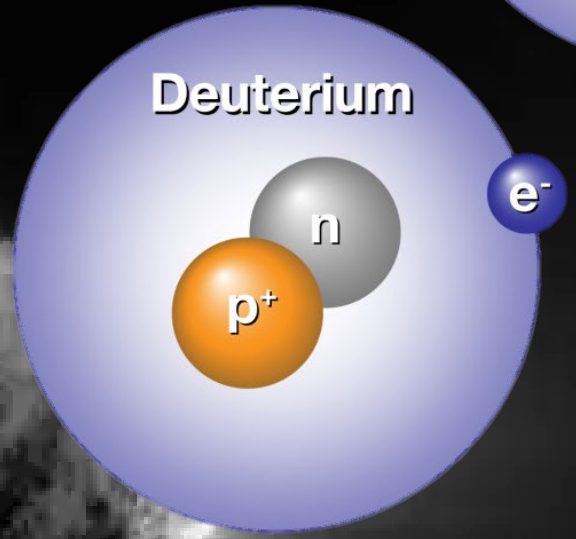
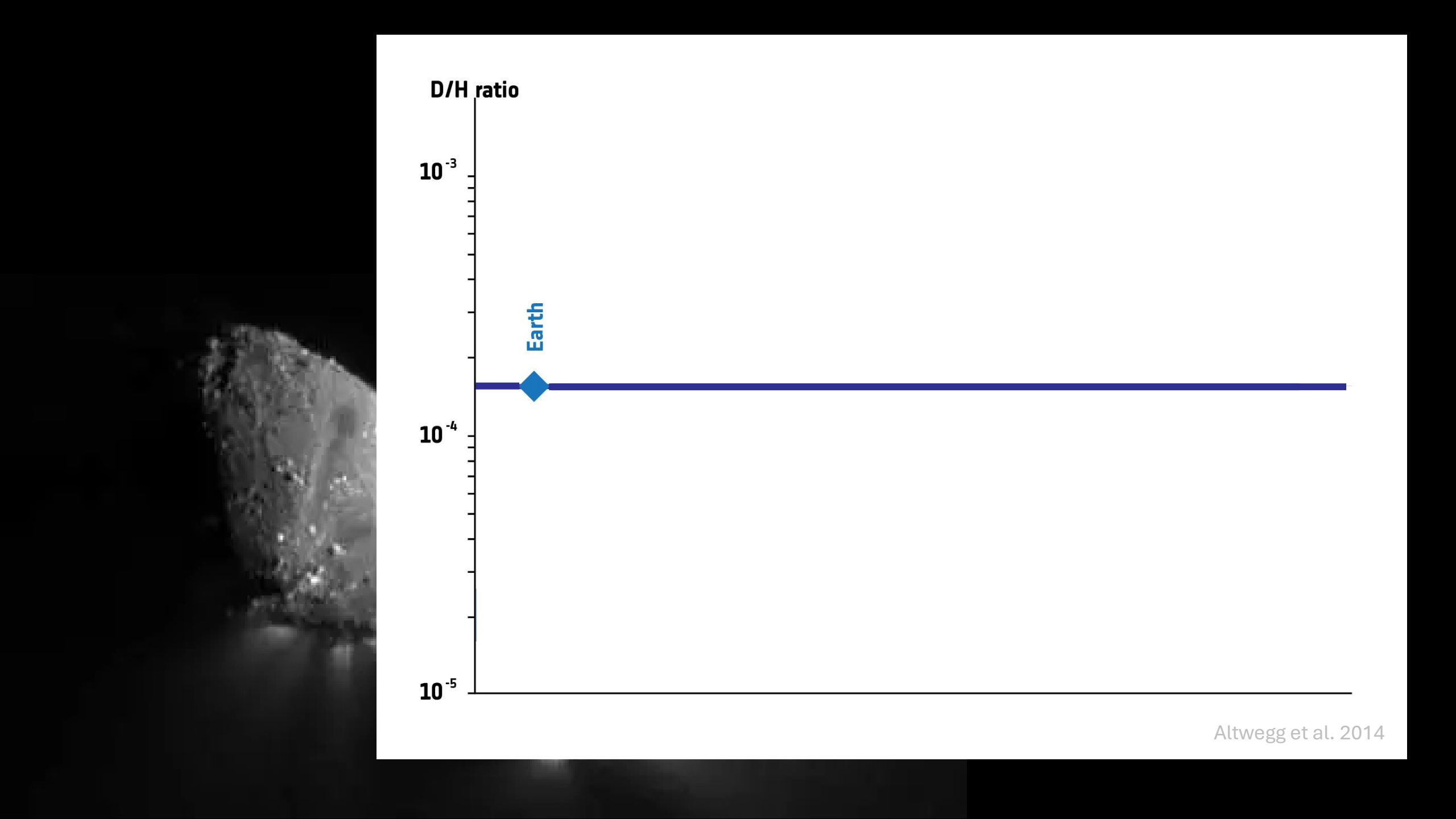


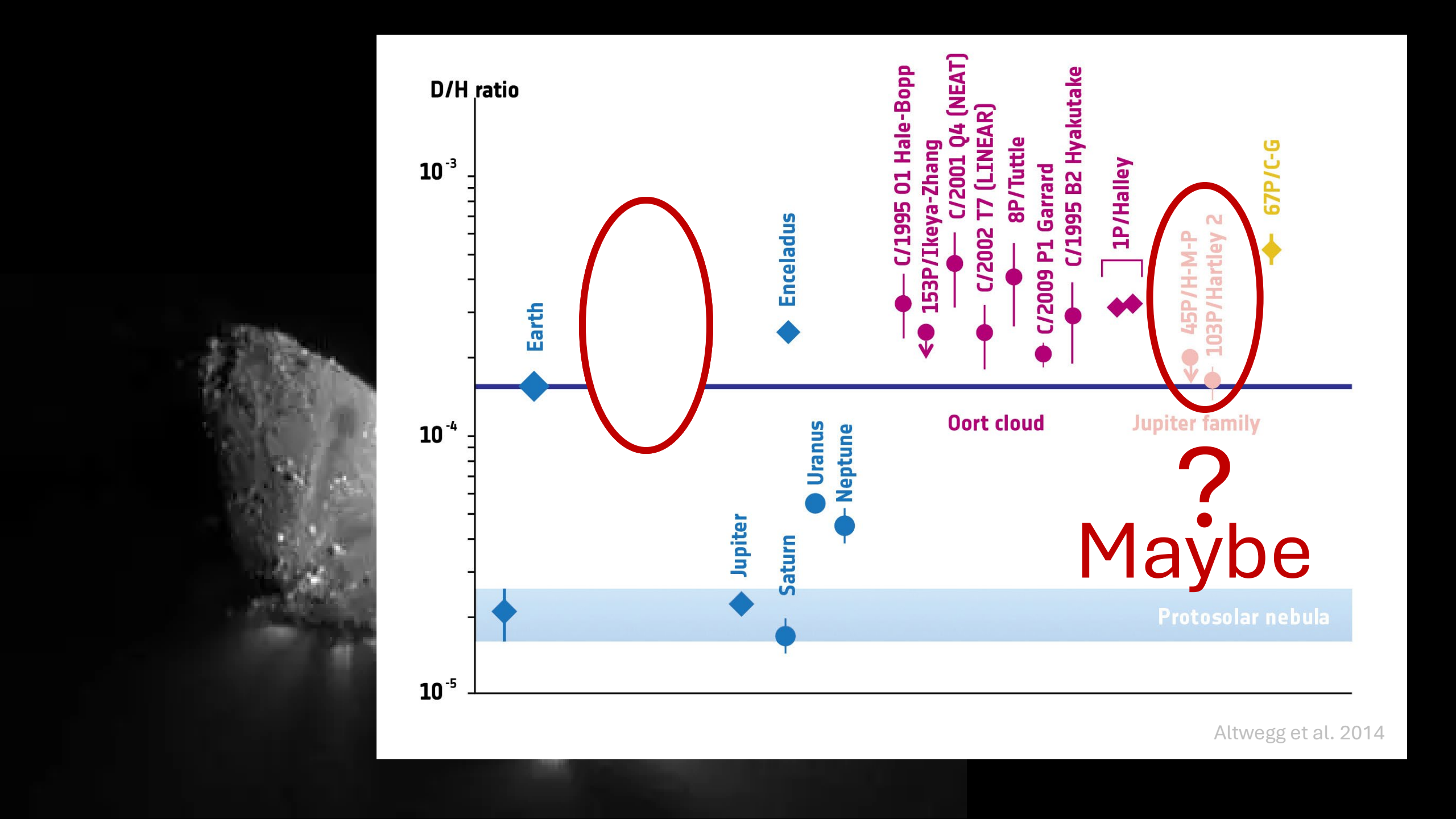


D/H

Hartley 2 – Credit NASA



Altwegg et al. 2014


D/H ratio
10^{-3}
10^{-4}
10^{-5}
Earth
Enceladus
C/1995 O1 Hale-Bopp
153P/Ikeya-Zhang
C/2001 Q4 (NEAT)
C/2002 T7 (LINEAR)
8P/Tuttle
C/2009 P1 Garrard
C/1995 B2 Hyakutake
1P/Halley
45P/H-M-P
103P/Hartley 2
67P/C-G
Oort cloud
Jupiter family
Jupiter
Saturn
Uranus
Neptune
?
Maybe
Protosolar nebula
Altwegg et al. 2014

What is the source of Earth's water?

1. It was here from the start?

2. It was delivered here
   - ~~By meteorites~~
   - By comets?

Thoughts?
Questions?