AST251

LIFE ON OTHER WORLDS

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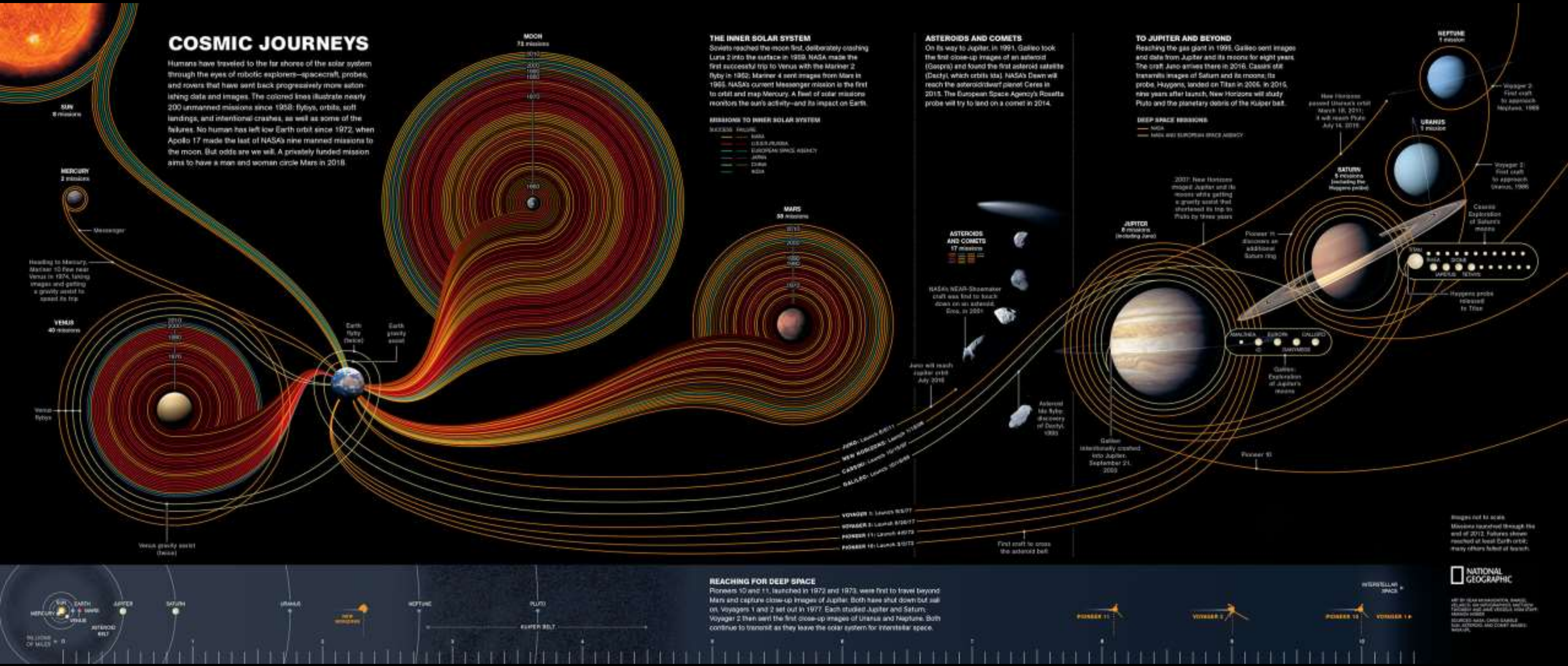
Image credit: ESO/M. KornmesserESO/M. Kornmesser

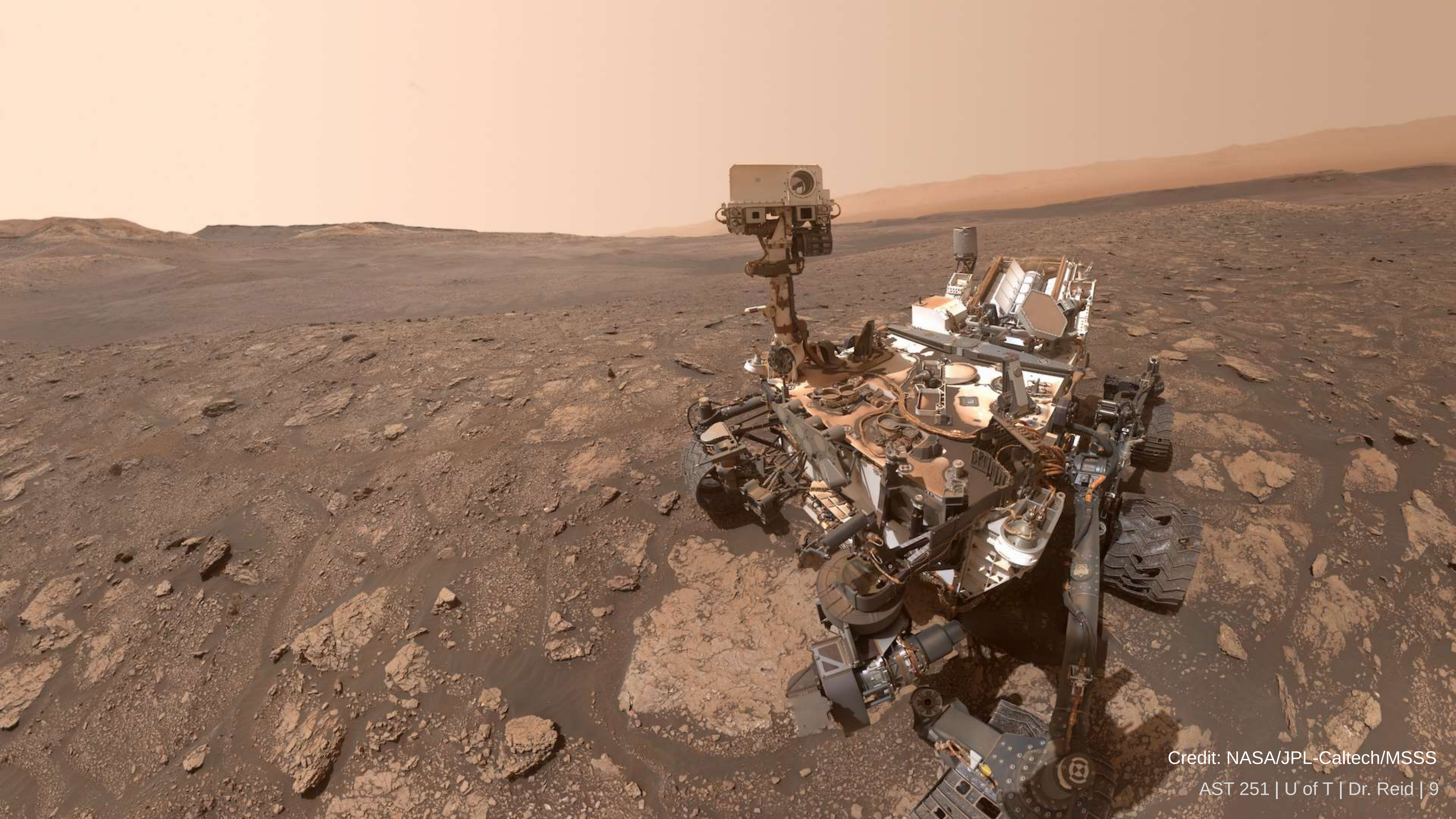
Credit: NASA Goddard Space Flight Center

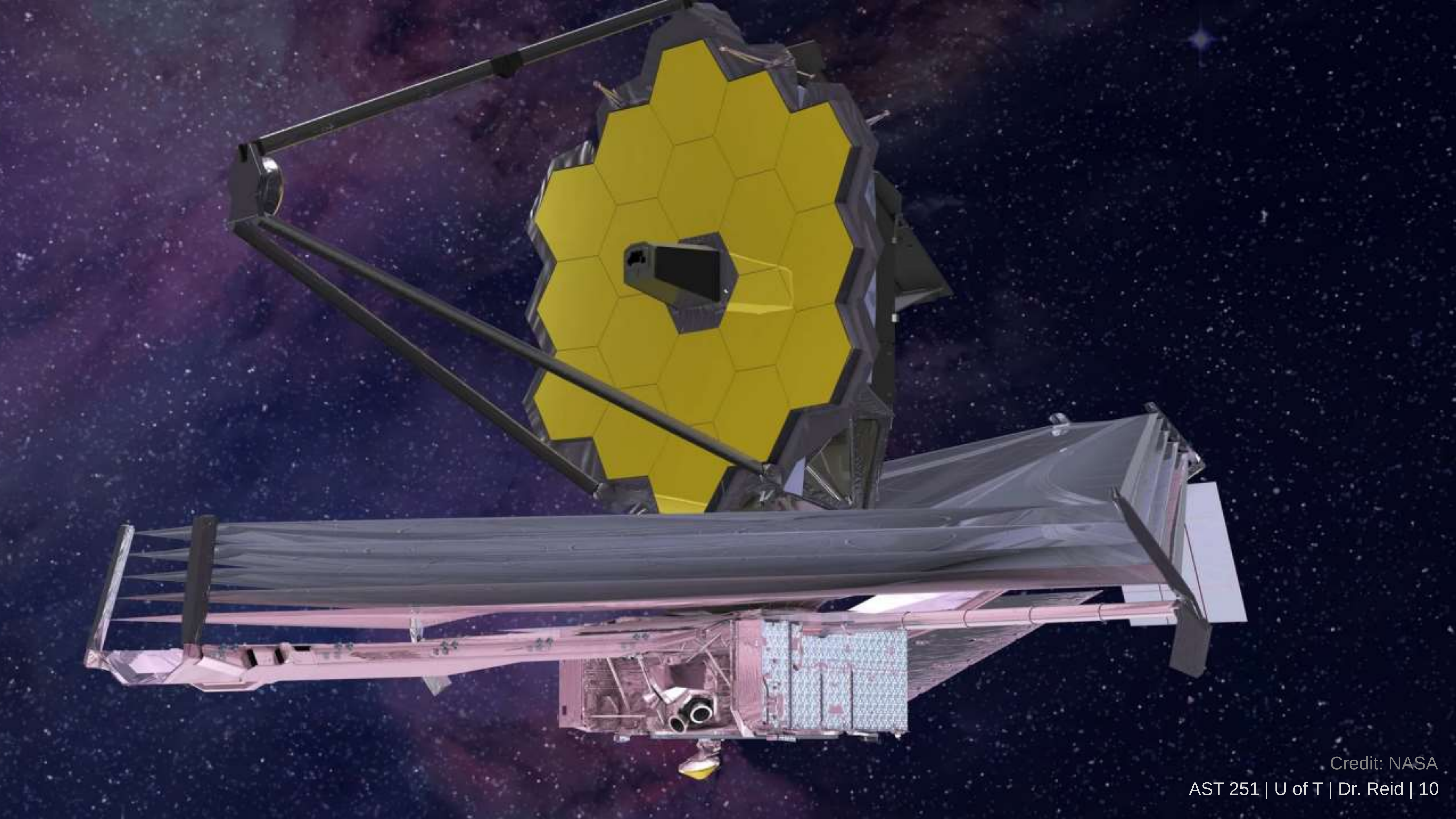
Why are we here?

Are we alone?

We've put a lot of time and resources into trying to answer these questions.


COSMIC JOURNEYS
Humans have traveled to the far shores of the solar system through the eyes of robotic explorers—spacecraft, probes, and rovers that have sent back progressively more astonishing data and images. The colored lines illustrate nearly 200 unmanned missions since 1958: flybys, orbits, soft landings, and intentional crashes, as well as some of the failures. No human has left low Earth orbit since 1972, when Apollo 17 made the last of NASA's nine manned missions to the moon. But odds are we will. A privately funded mission aims to have a man and woman circle Mars in 2018.
SUN
MERCURY
VENUS
MOON
MARS
THE INNER SOLAR SYSTEM
ASTEROIDS AND COMETS
TO JUPITER AND BEYOND
JUPITER
SATURN
URANUS
NEPTUNE
REACHING FOR DEEP SPACE
NATIONAL GEOGRAPHIC

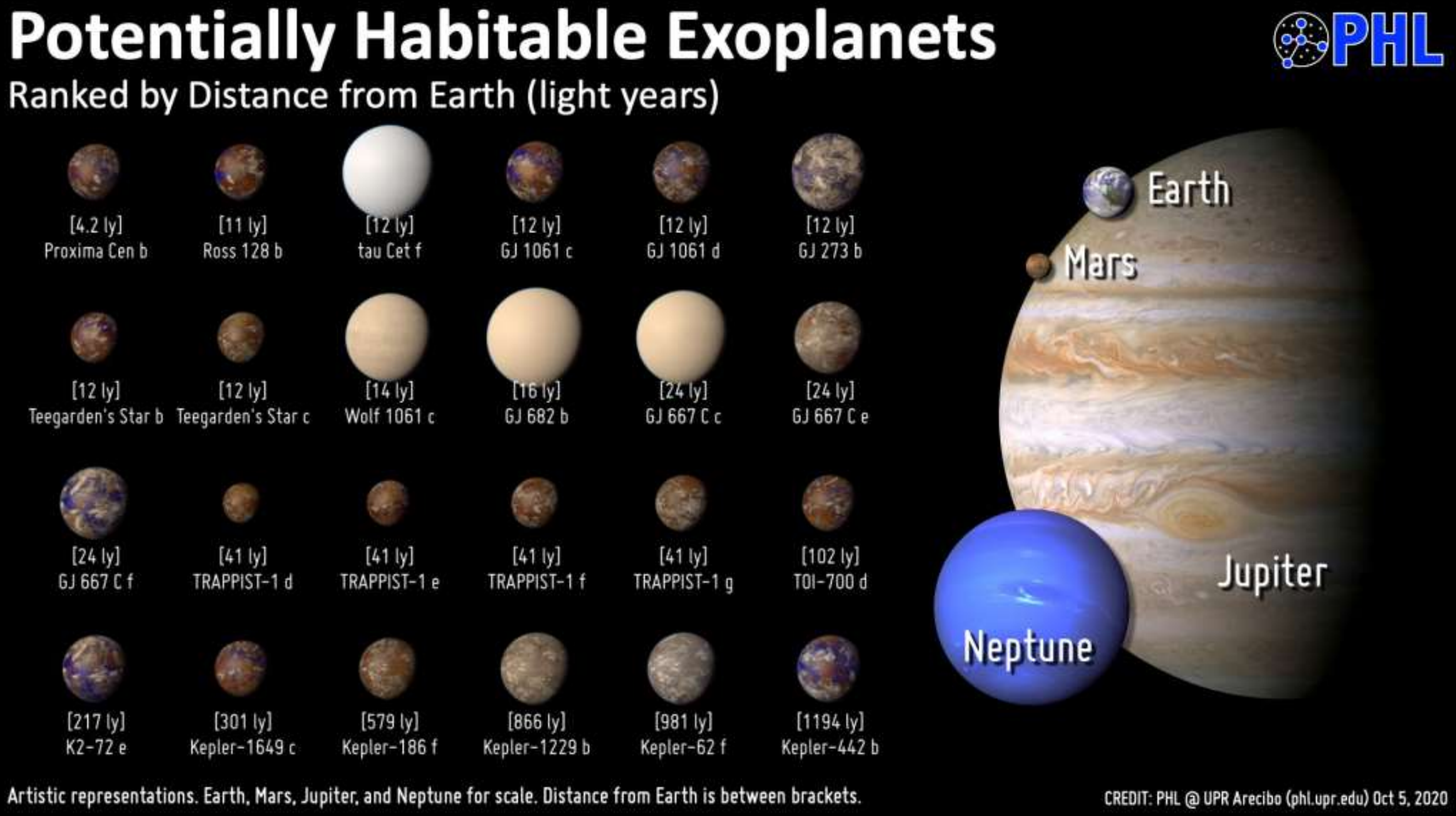

Credit: NASA/JPL-Caltech/MSSS



Credit: NASA

Credit: SETI Institute

After thousands of years, we are getting really close to finally answering these questions.


Potentially Habitable Exoplanets
Ranked by Distance from Earth (light years)
[4.2 ly] Proxima Cen b
[11 ly] Ross 128 b
[12 ly] tau Cet f
[12 ly] GJ 1061 c
[12 ly] GJ 1061 d
[12 ly] GJ 273 b
[12 ly] Teegarden's Star b
[12 ly] Teegarden's Star c
[14 ly] Wolf 1061 c
[16 ly] GJ 682 b
[24 ly] GJ 667 C c
[24 ly] GJ 667 C e
[24 ly] GJ 667 C f
[41 ly] TRAPPIST-1 d
[41 ly] TRAPPIST-1 e
[41 ly] TRAPPIST-1 f
[41 ly] TRAPPIST-1 g
[102 ly] TOI-700 d
[217 ly] K2-72 e
[301 ly] Kepler-1649 c
[579 ly] Kepler-186 f
[866 ly] Kepler-1229 b
[981 ly] Kepler-62 f
[1194 ly] Kepler-442 b
Earth
Mars
Jupiter
Neptune
Artistic representations. Earth, Mars, Jupiter, and Neptune for scale. Distance from Earth is between brackets.
CREDIT: PHL @ UPR Arecibo (phl.upr.edu) Oct 5, 2020

Japanese spacecraft Hayabusa2 collects a sample of asteroid Ryugu and returns it to Earth in December 2020

Credit: JAXA/EPA

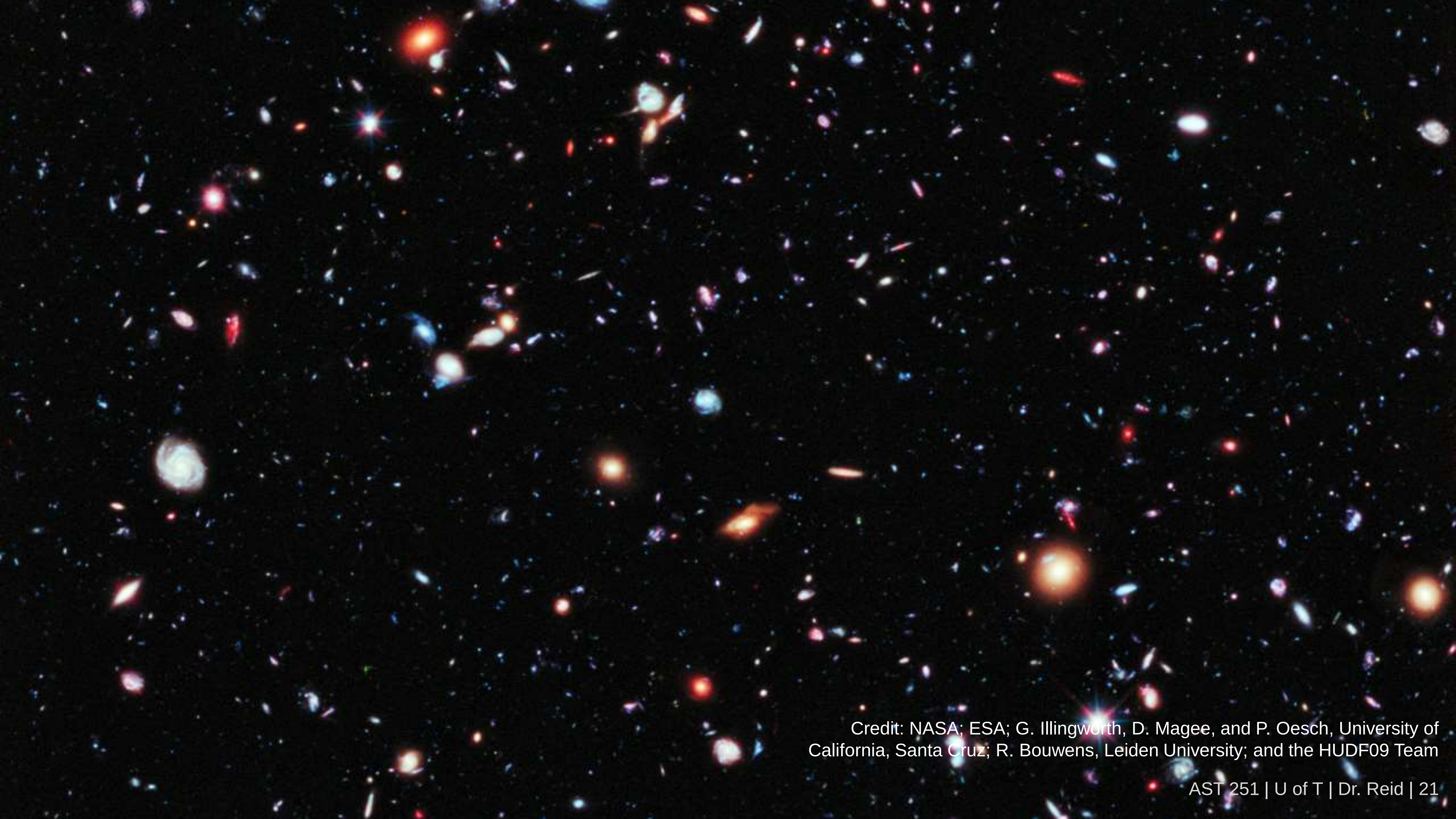
How close are we?

What are the big challenges still remaining?

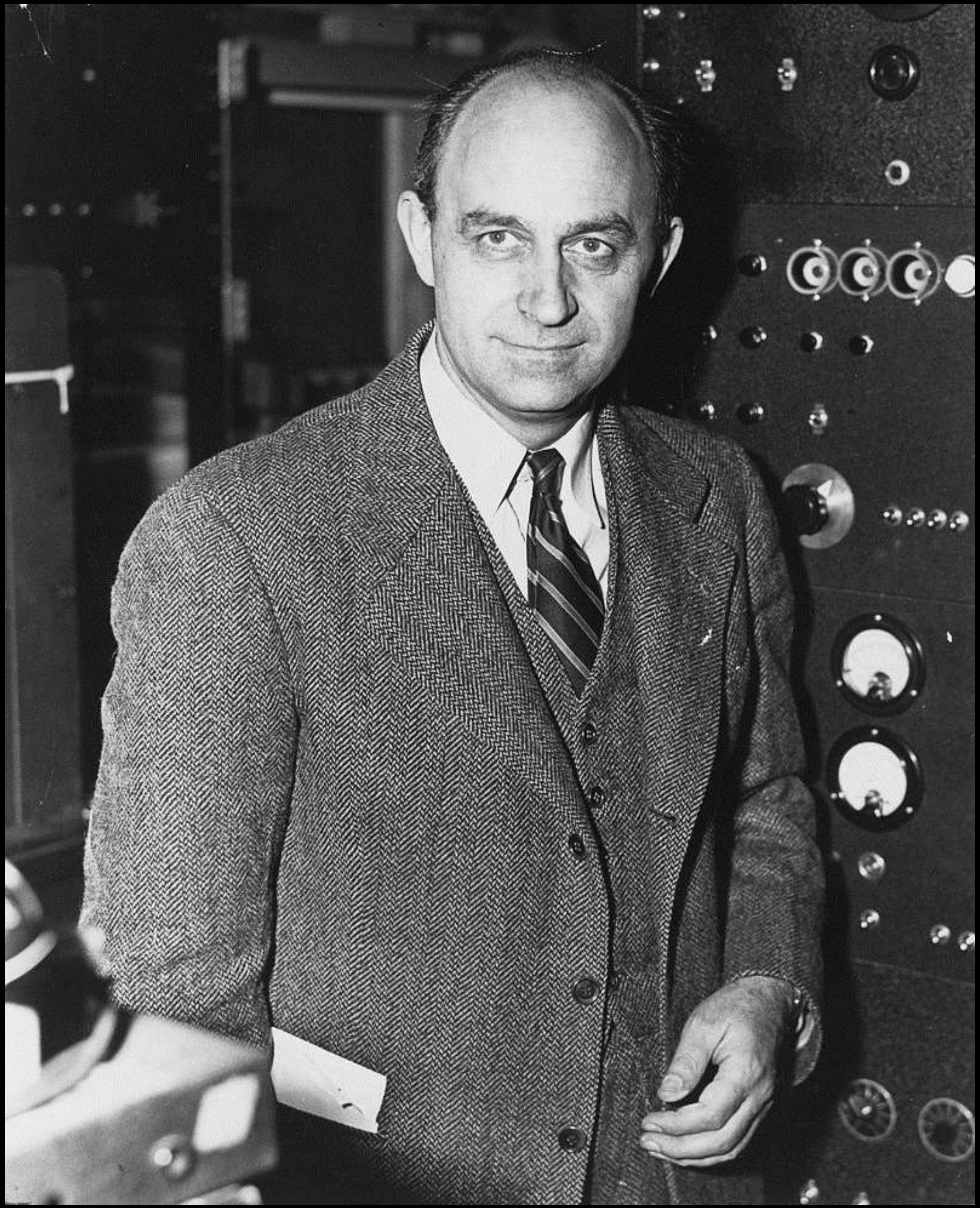
How will we know when we’ve succeeded?

What will the answer mean?

The Fermi Paradox



Credit: NASA; ESA; G. Illingworth, D. Magee, and P. Oesch, University of California, Santa Cruz; R. Bouwens, Leiden University; and the HUDF09 Team



Enrico Fermi

Nobel prize-winning nuclear physicist, 1901-1954

Our Milky Way galaxy contains approximately 400 billion stars

Credit: Babak Tafreshi

Most of these stars have one or more planets

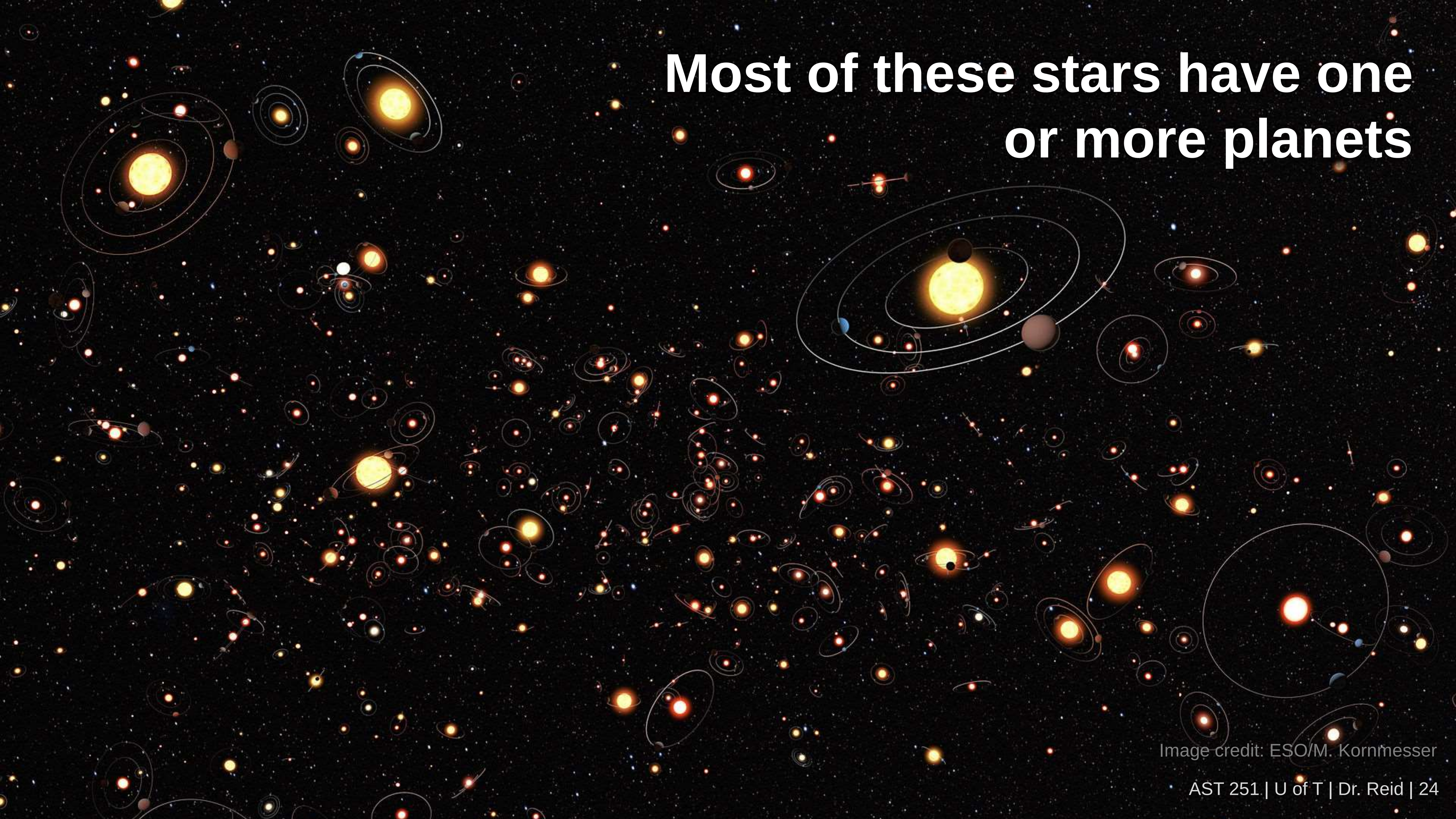
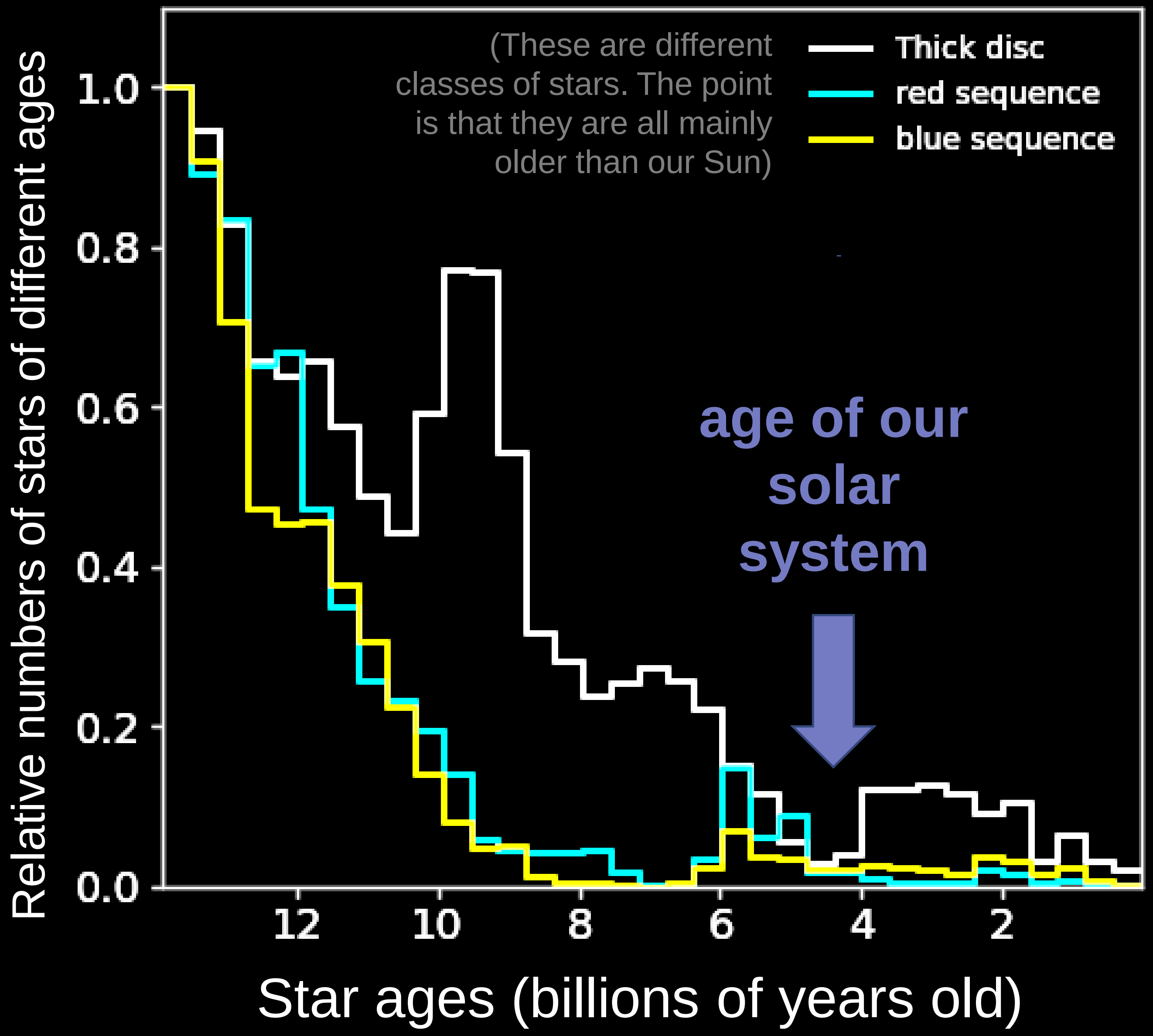


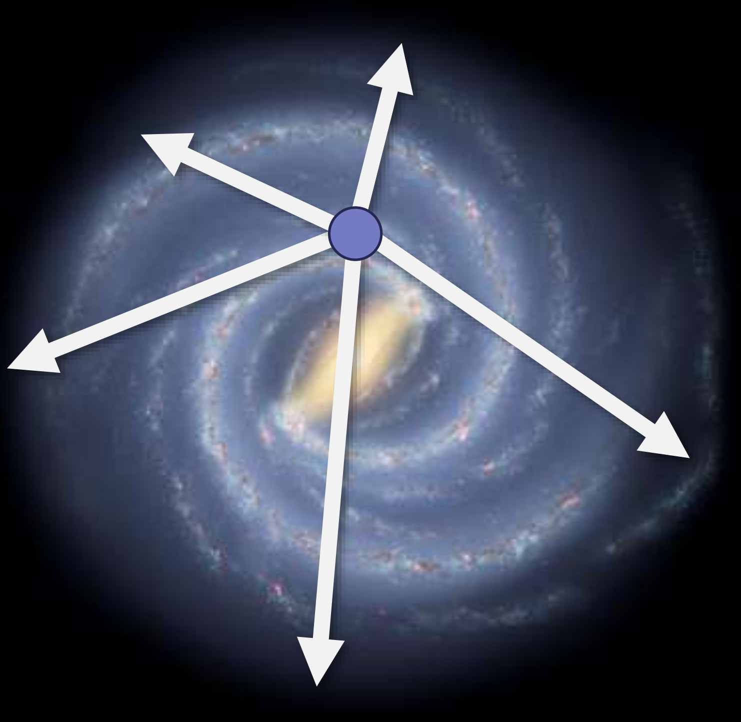
Image credit: ESO/M. Kornmesser

Most of the stars in the Milky Way are much older than our Sun (and so are their planets)



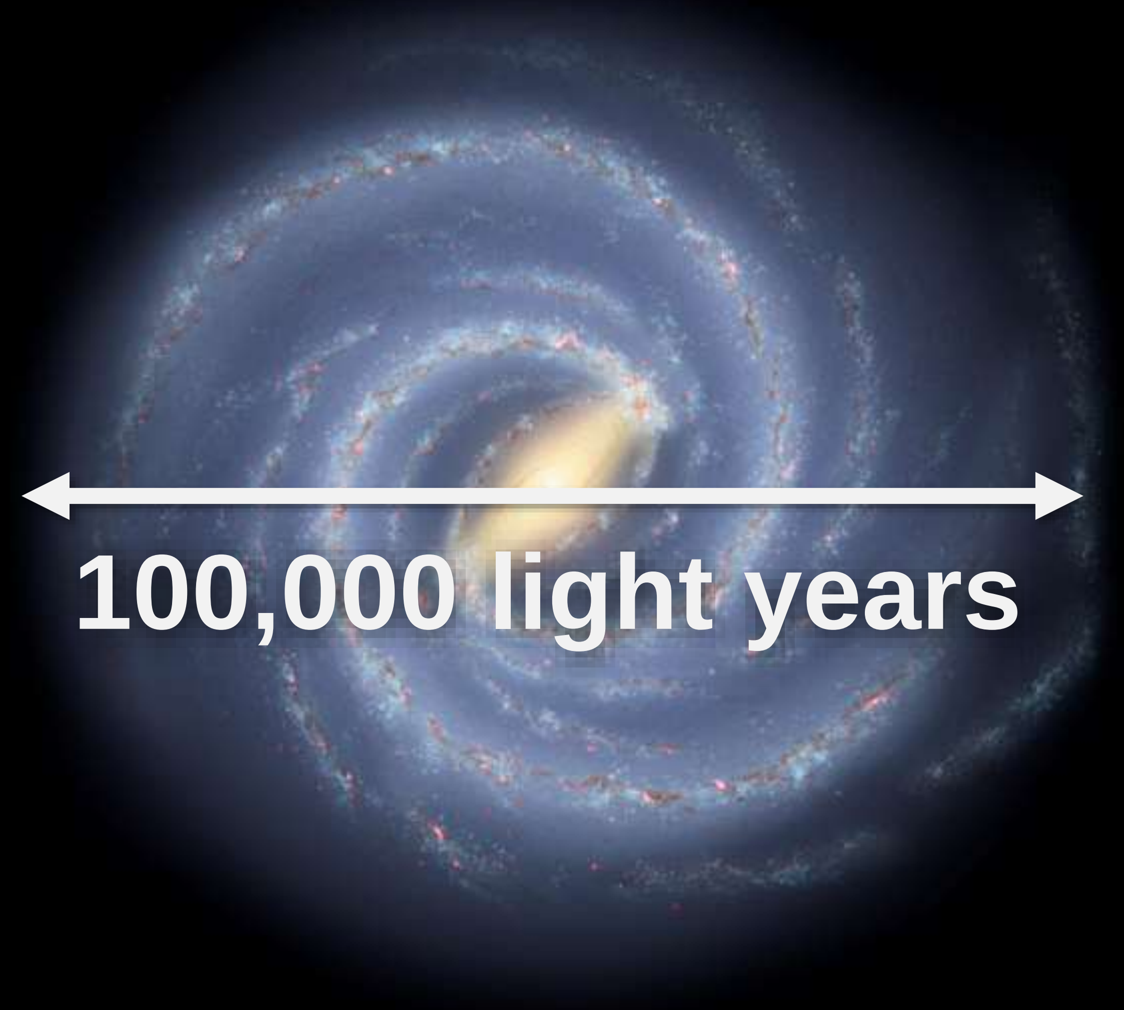
Adapted from Gallart, et al. 2019, *Nature*

Therefore, many of these planets might host civilizations much older and more advanced than ours.



If one of these civilizations wanted to spread throughout the Milky Way galaxy, how long would this take?

Image credit: NASA/JPL-Caltech/R. Hurt (SSC/Caltech)



The Milky Way

(artist's impression)

Image credit: NASA/JPL-Caltech/R. Hurt (SSC/Caltech)

Concept Check

How long would it take for light to travel 100,000 light years?

a. No time at all, because light travels incredibly quickly
b. 100,000 years
c. A few million years
d. Billions of years, because the distance is so long

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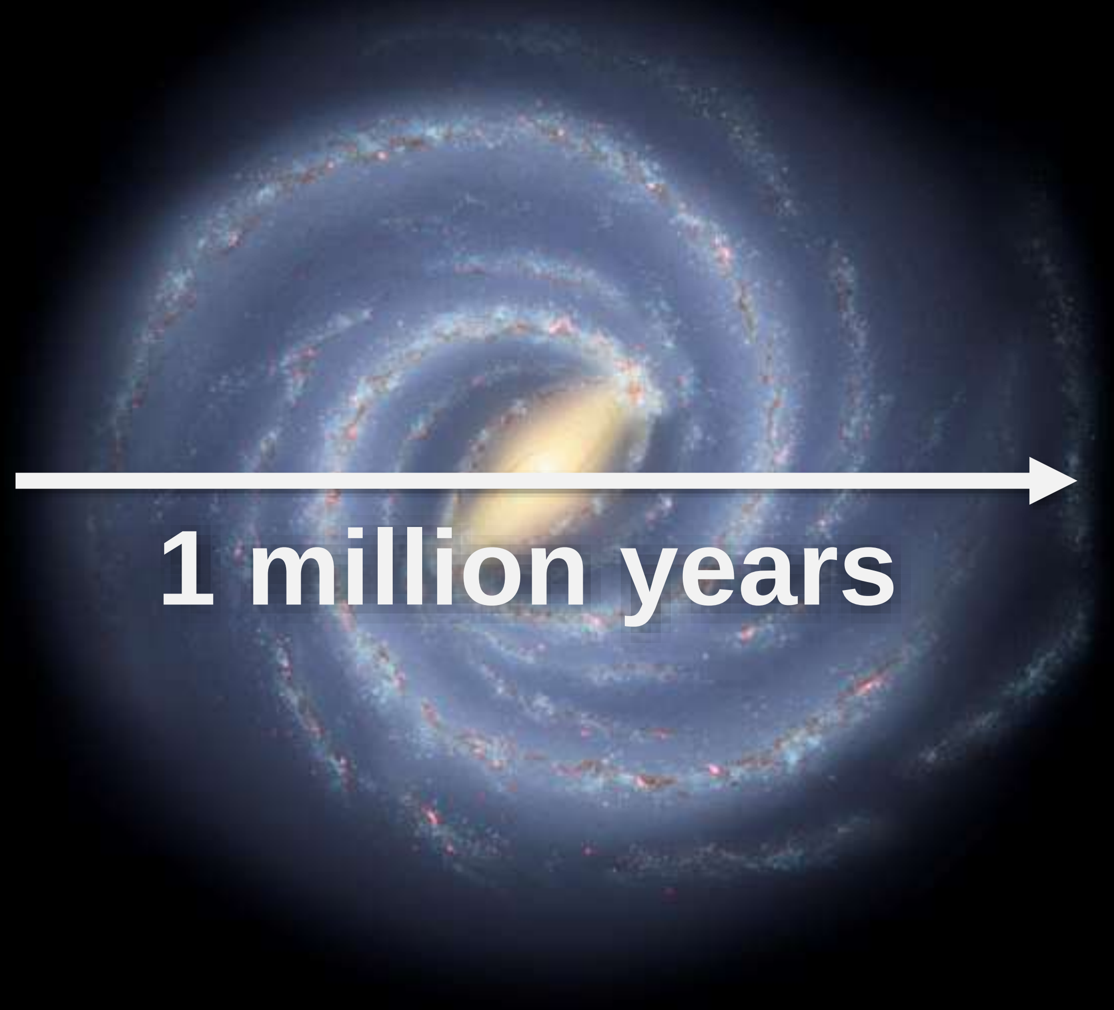
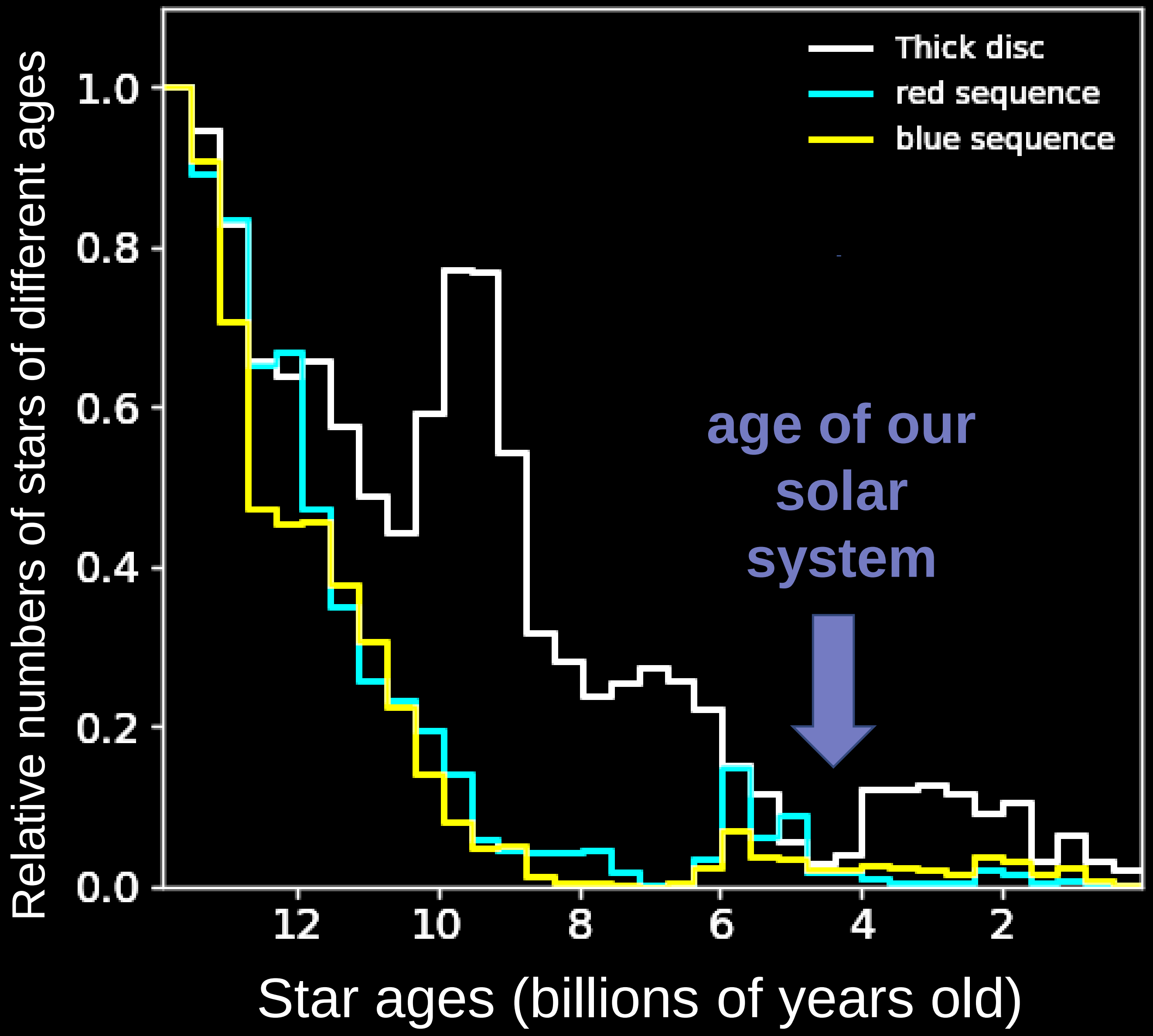
Imagine that aliens somewhat more advanced than us were capable of travelling at 10% of the speed of light



At 10% of the speed of light, it would take only 1 million years to cross the Milky Way

Image credit: NASA/JPL-Caltech/R. Hurt (SSC/Caltech)

But remember that most species could be billions of years older than us, not just *millions*.



Adapted from Gallart, et al. 2019, *Nature*

Concept Check

If a civilization developed interstellar travel (at 10% of the speed of light) 1 billion years ago, how many times could they have crossed the Milky Way by now?

a. None—it's too far to travel.
b. 1 thousand times
c. 1 million times
d. 1 billion times
e. As many as they wanted, with that level of technology

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So, if any one of potentially millions of ancient civilizations could already have colonized the entire Milky Way several times over,

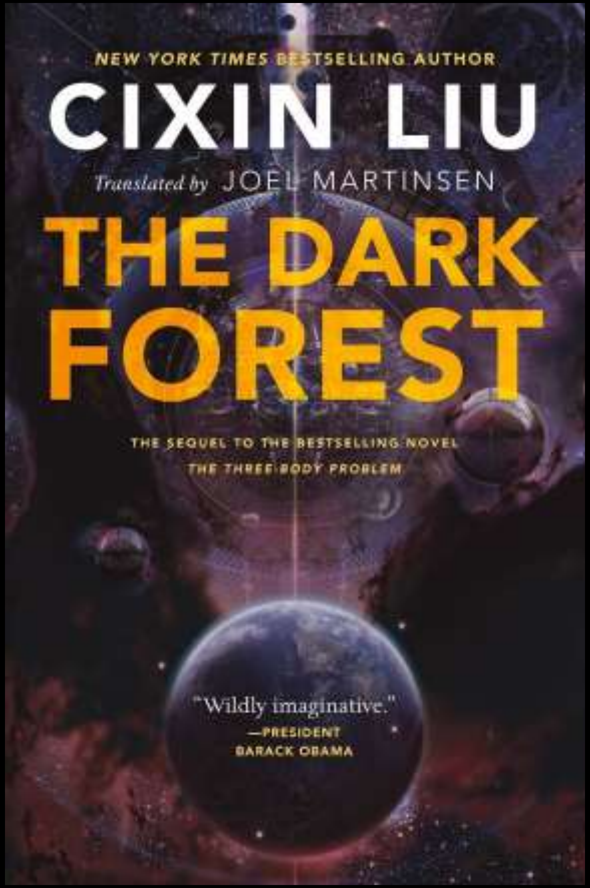
where are they?

This apparent contradiction is known as the Fermi Paradox.

There are hundreds of possible solutions to the Fermi Paradox. Can you think of one?

Zoo Earth

Credit: NASA Goddard Space Flight Center



The Dark Forest

An Astrobiological History of the Universe

Part 1: From the Big Bang to the Formation of the Solar System

“Deep Time”

“Astrobiologically significant”

An astrobiologically significant event or phenomenon is one that strongly impacts the whole story of life in the cosmos (as we know it).

Concept Check

Which of the following events in the history of Earth is *not* astrobiologically significant?

a. The formation of the oceans
b. The movement of life onto land
c. The evolution of bees
d. The development of spaceflight

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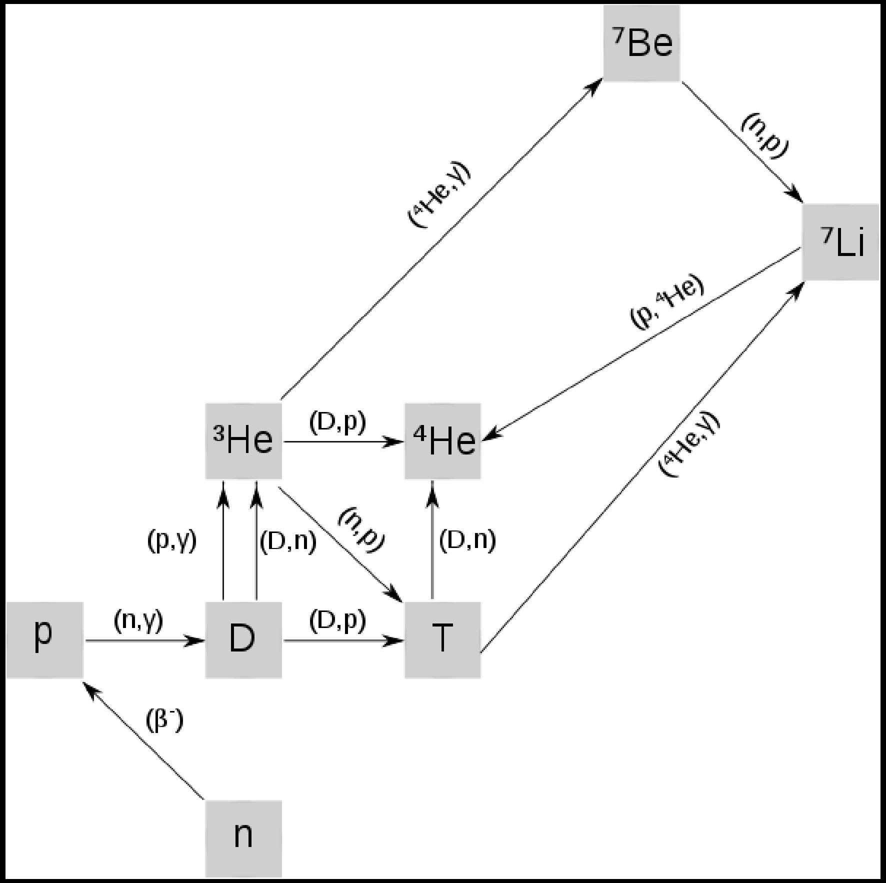
0 seconds: The Beginning

The whole universe is filled with hot, dense plasma.

Credit: Solar Dynamics Observatory, NASA

10 s — 20 min: Big Bang Nucleosynthesis



Credit: Wikimedia Commons

After Big Bang Nucleosynthesis, the composition of the universe was approximately 75% H, 25% He, and trace quantities of Li.

(e.g. Pitrou et al. 2018, PhR)

H He Li

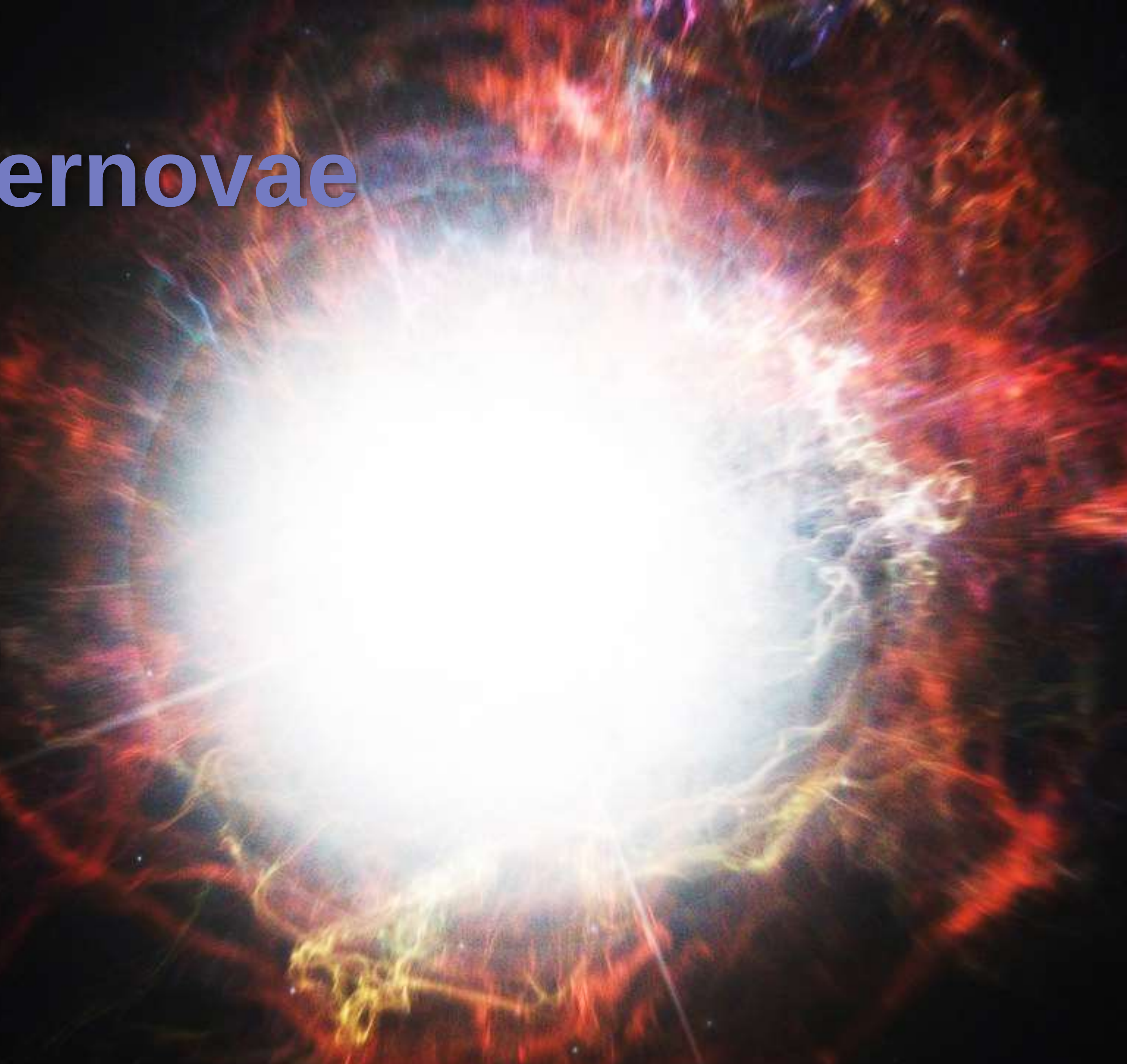
400 My: First Stars and Galaxies Form

The gas that fills space cools to the point where its own gravity can crush portions of it until it becomes dense enough to form stars and galaxies.

Credit: ESO/ M. Kornmesser

400 My: First Supernovae

The first generation of stars were extremely massive and lived only a few million years. Their supernova deaths enriched the universe with elements heavier than helium for the first time.



Credit: ESO/M. Kornmesser

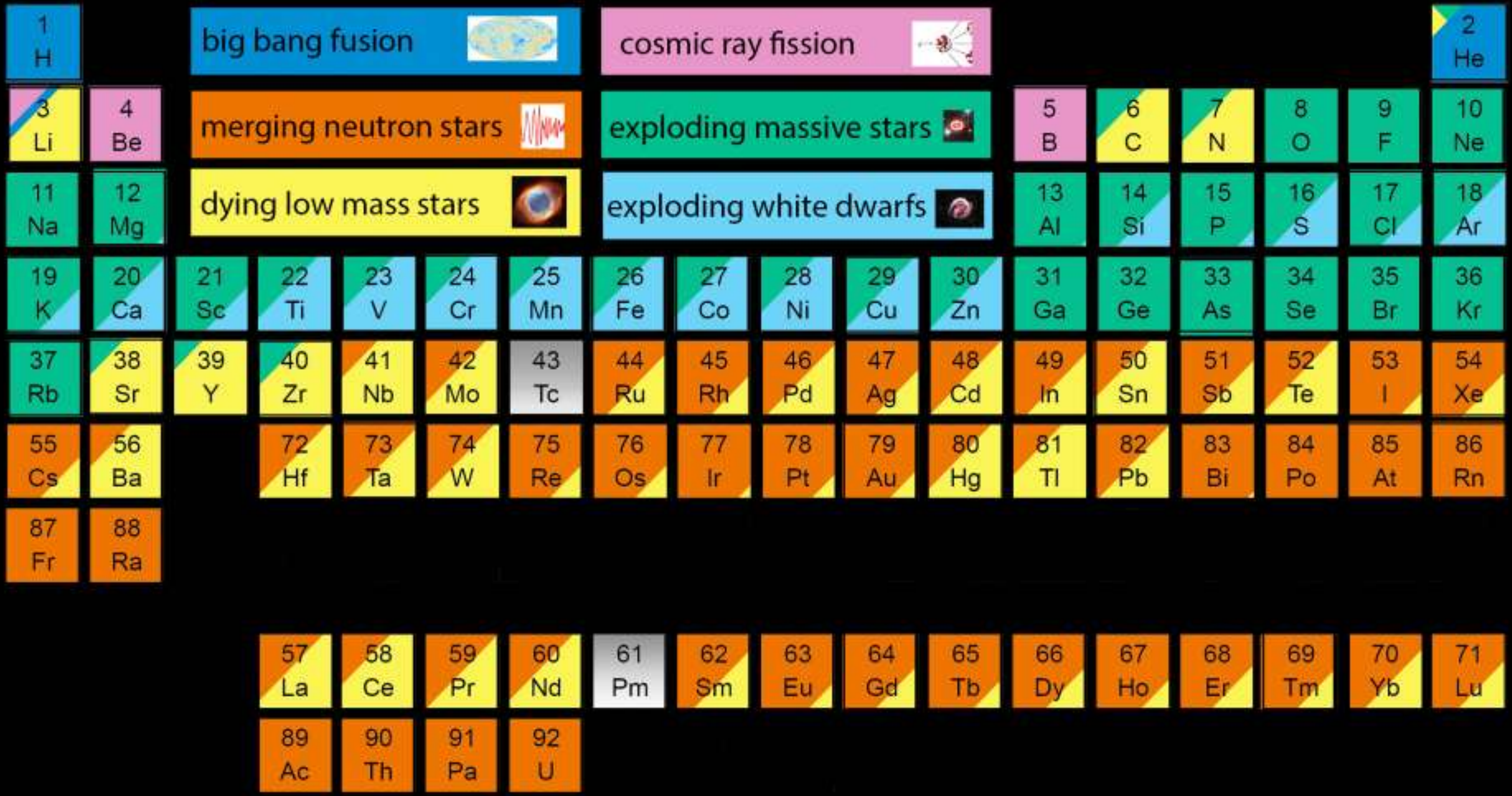
400 My: First Gamma Ray Bursts

Some of the first supernovae would have been colossally energetic Gamma Ray Bursts (GRBs), which could have sterilized any life on nearby planets. Then and now, GRBs may limit the spread and longevity of life in the universe.

(Piran & Jiminez, 2014, PhysRevLett)

Credit: ESO/A. Roquette

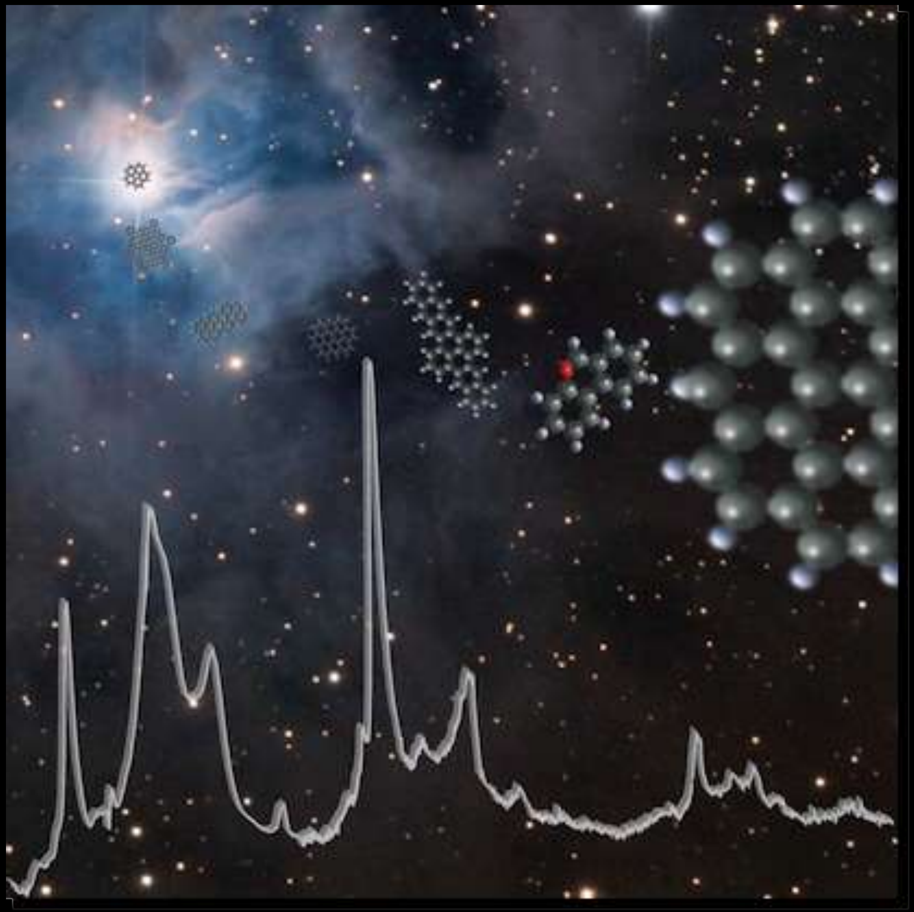
The Origin of the Solar System Elements



Graphic created by Jennifer Johnson

Astronomical Image Credits:
ESA/NASA/AASNova

? My: Organic Chemicals in Space



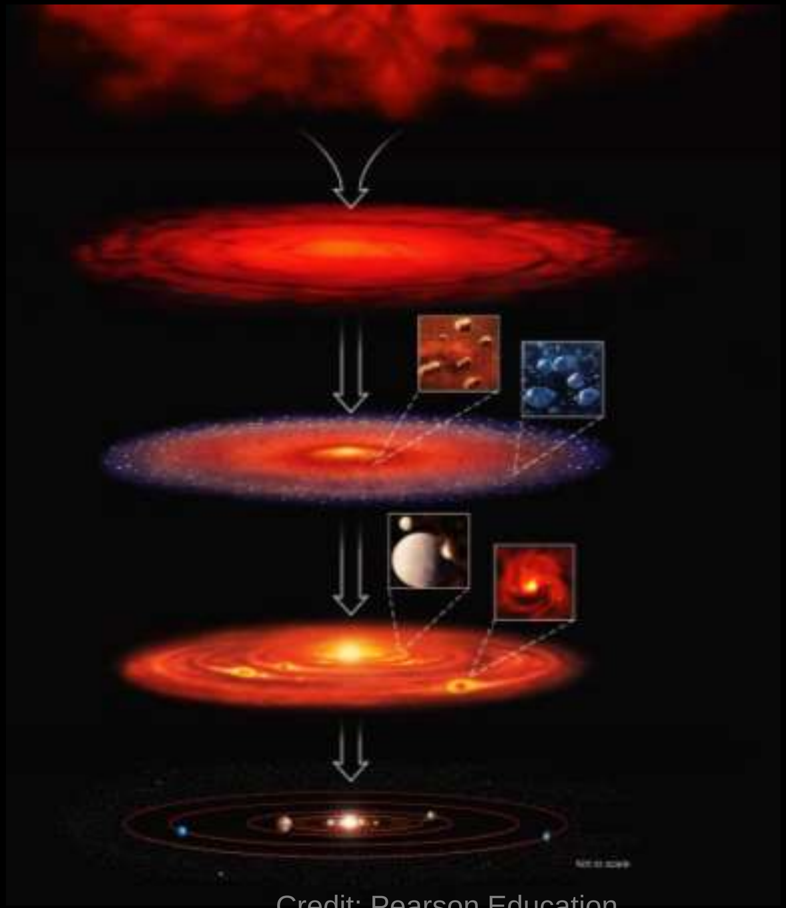
Stellar winds and supernovae enriched the gas and dust in space with elements heavier than H and He, allowing the formation of organic molecules such as polycyclic aromatic hydrocarbons (PAHs) and likely simple amino acids.

Credit: astrochem.org

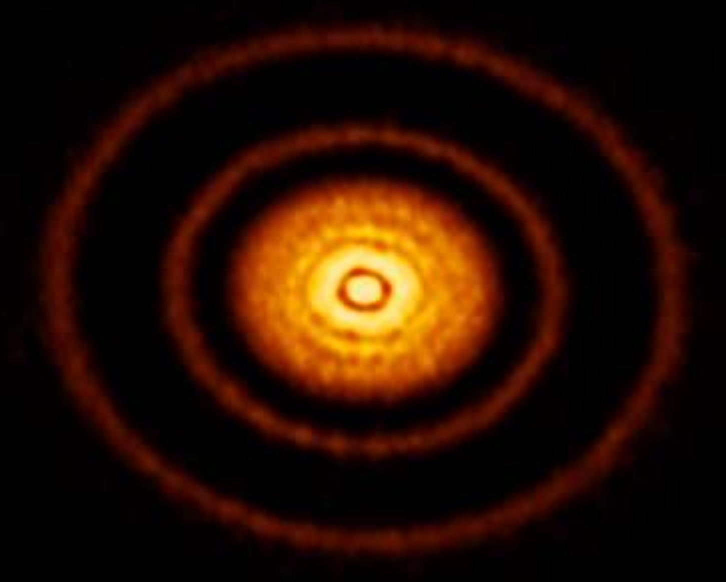
9.2 Gy (4.6 Gya): Our Solar System Forms

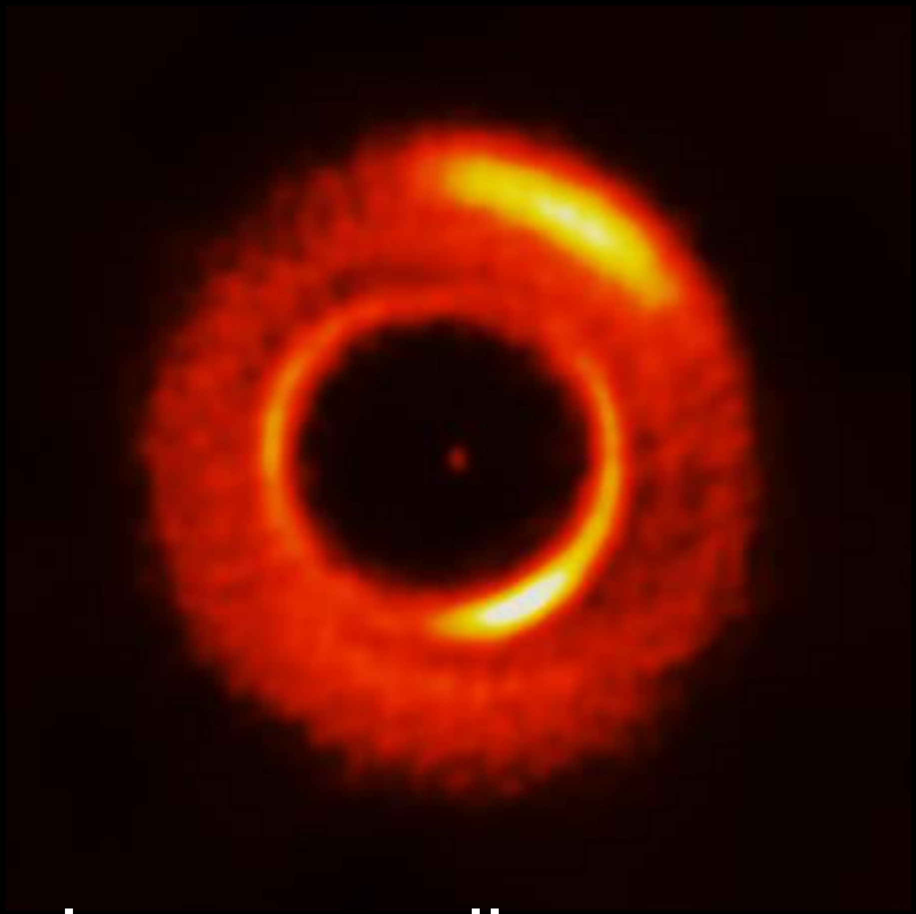
The Sun condenses from a cloud of gas and dust.

The planets form from a spinning protoplanetary disk around the young Sun.



Credit: Pearson Education





Modern infrared telescopes allow us to actually see protoplanetary disks around other stars

Credit: ALMA (ESO/NAOJ/NRAO), S. Andrews et al.; NRAO/AUI/NSF, S. Dagnello; ESO/R. Dong et al.; ALMA (ESO/NAOJ/NRAO)

An Astrobiological History of the Universe

Part 2: From the Formation of Earth to the Cambrian Explosion

We can express time in billions of years (Gy) after the beginning of the universe or in billions of years before the present (Gya). To convert, remember that the universe is about 13.8 billion years old.

9.2 Gy = 4.6 Gya

9.2 billion (giga) years, implying “after the beginning of the universe”

4.6 billion (giga) years **ago**, implying “before the present”

4.6 Gya = 13.8 Gy – 9.6 Gy

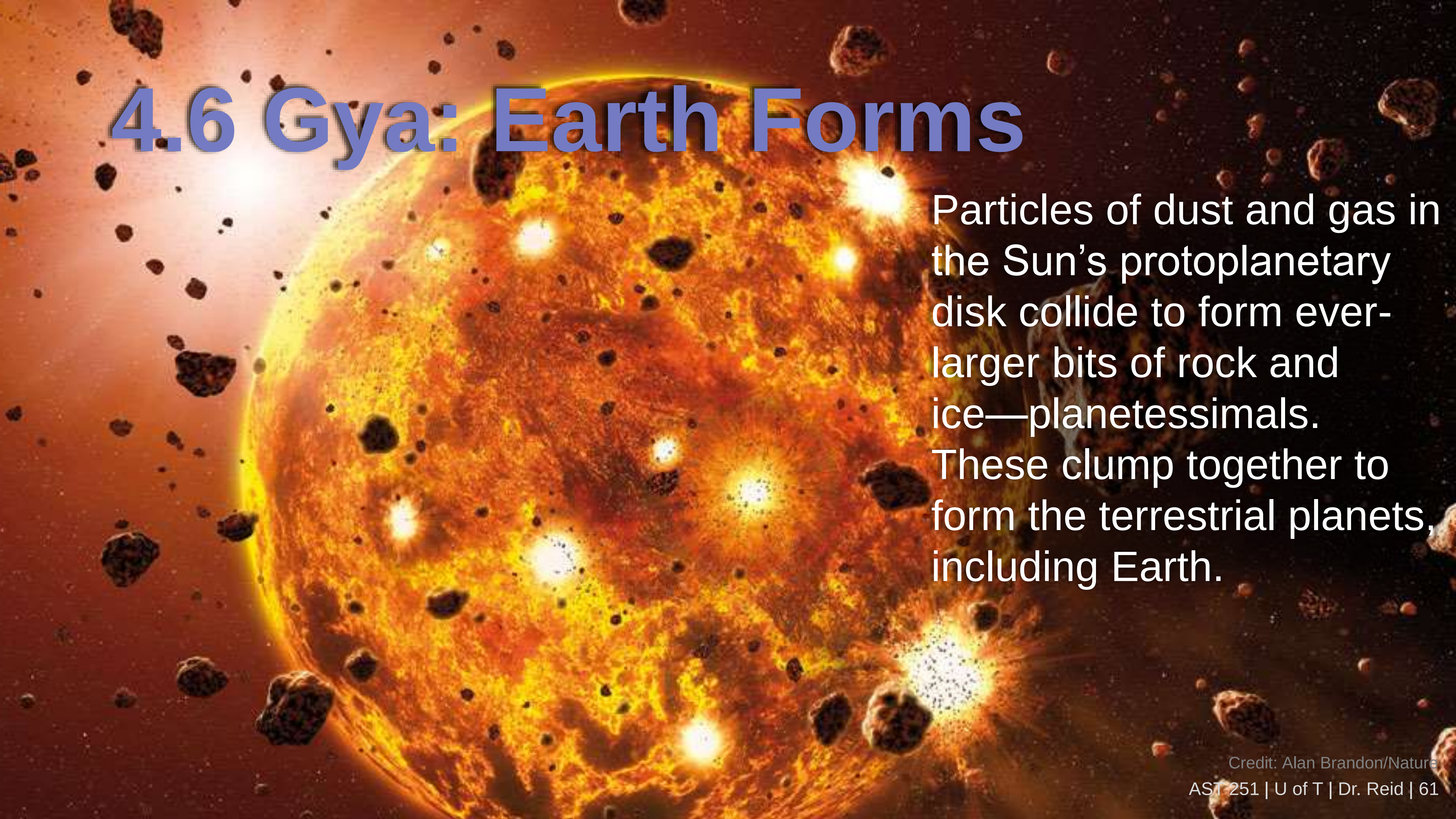
4.6 Gya: Carbonaceous Chondrites

Carbonaceous chondrite meteorites are chunks of rock that predate planets. They contain round globules called "chondrules" that are some of the oldest minerals in the solar system. They're rich in carbon and "pre-biotic" chemicals.

Credit: Mario Muller

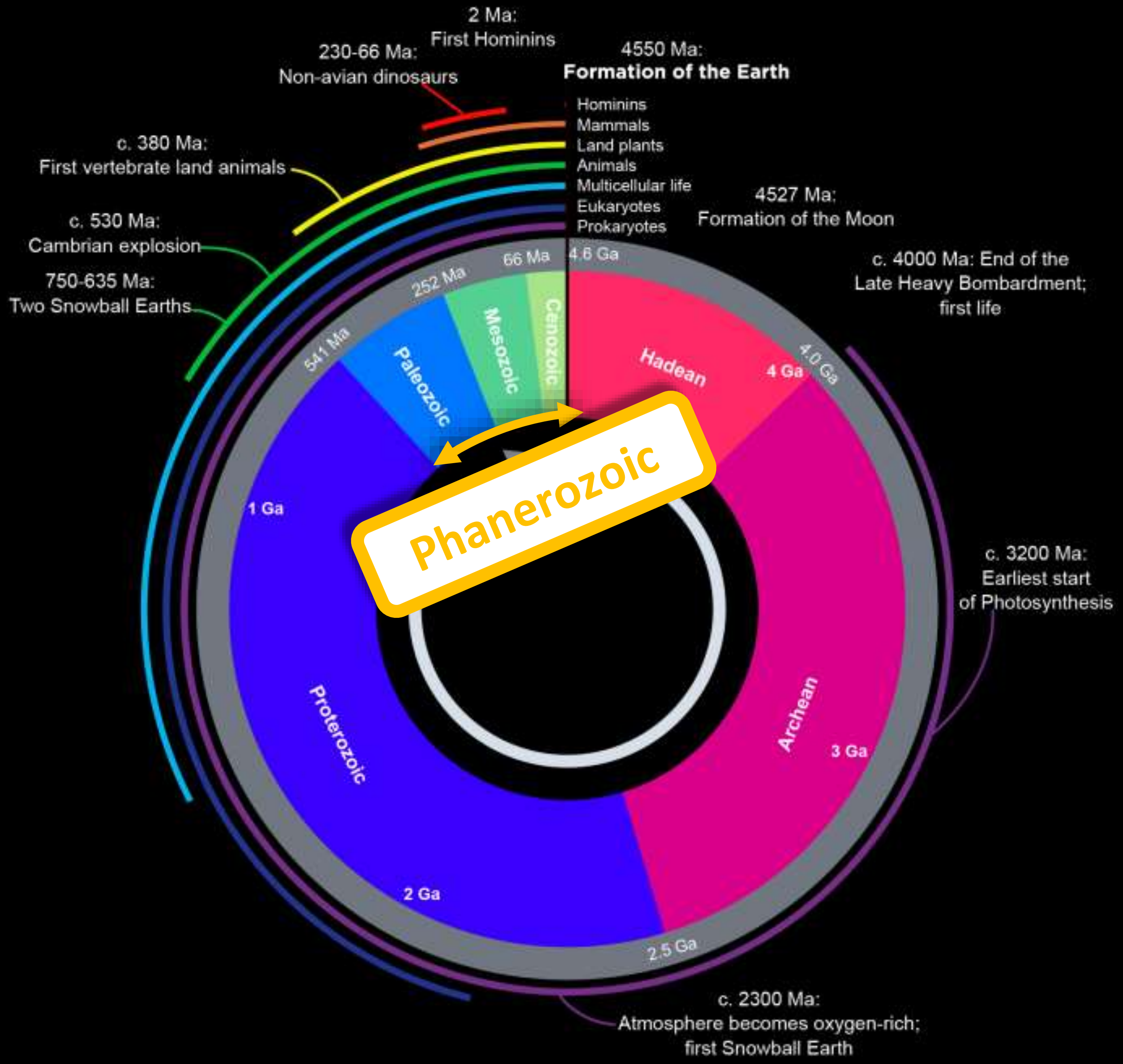

Artist concept

4.6 Gya: Earth Forms

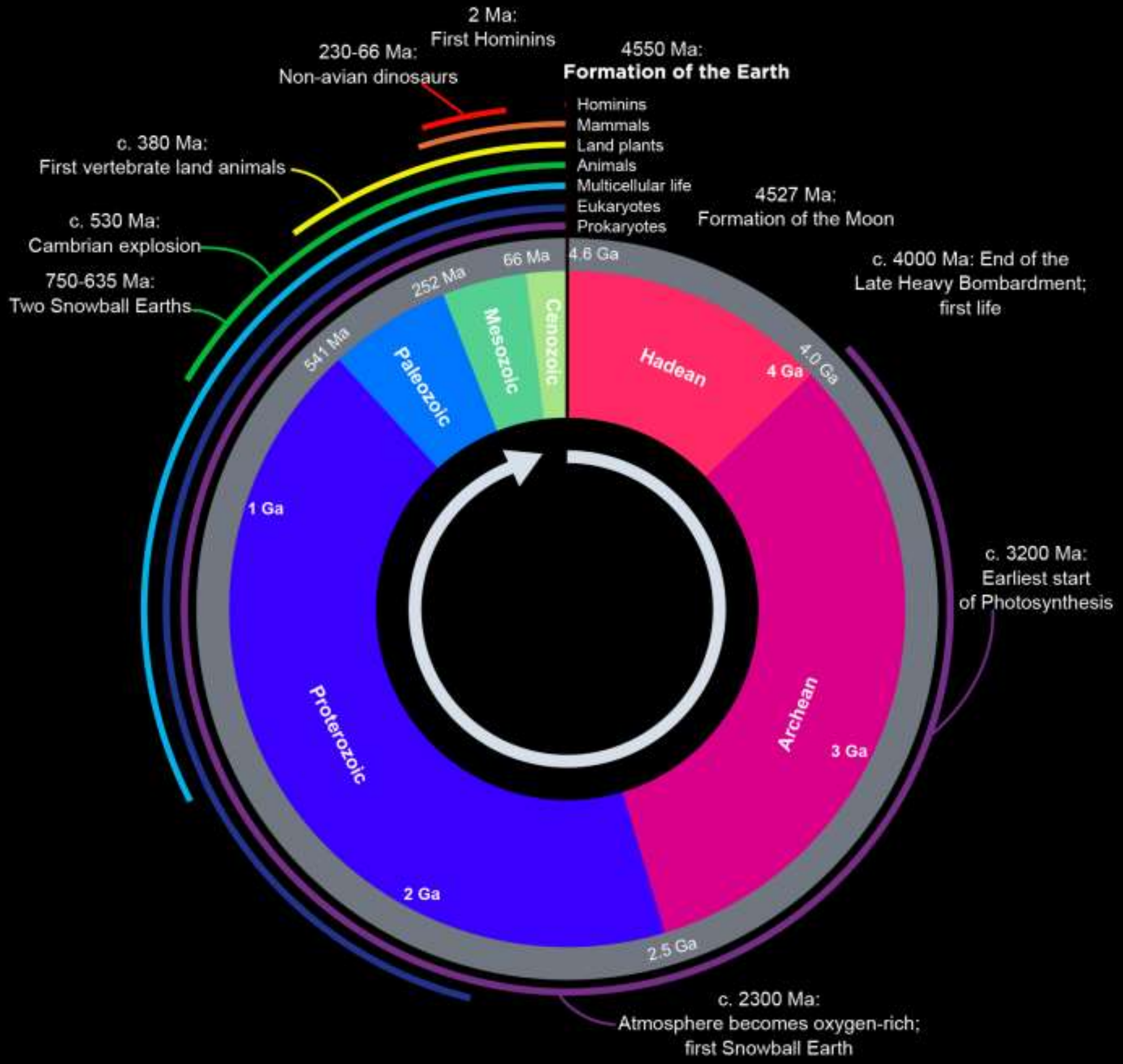


Particles of dust and gas in the Sun’s protoplanetary disk collide to form ever-larger bits of rock and ice—planetessimals. These clump together to form the terrestrial planets, including Earth.

Credit: Alan Brandon/Nature



Credit: Wikimedia Commons



Credit: Wikimedia Commons

Hadean	Archean	Proterozoic	Phan.




Credit: T. Bertelink, P. Sawyer, P. G. Werner, G. Boeggeman

4.5 Gya: The Moon Forms

A protoplanet roughly the size of Mars collides with Earth. Debris ejected into space forms the Moon. Moons—and their tides—may be crucial for evolving complex life.

Credit: NASA/JPL-Caltech

4.4-3.8 Gya: Oceans Form on Earth

Evidence from ancient zircon crystals suggests that pools of water existed on Earth as long as 4.4 Gya (Wilde et al., 2001, Nature)

Water outgassed from the interior of Earth and deposited by comets formed oceans by around 3.8 Gya.

Credit: NASA/JPL-Caltech

4.4-3.8 Gya: Earliest Claimed Evidence for Life

The earliest evidence of life on Earth derives from possible fossil microorganisms in 3.8-4.4 Gy old rocks in Quebec.
(Dodd et al., 2017, Nature)

This evidence is disputed.

Credit: NASA/JPL-Caltech

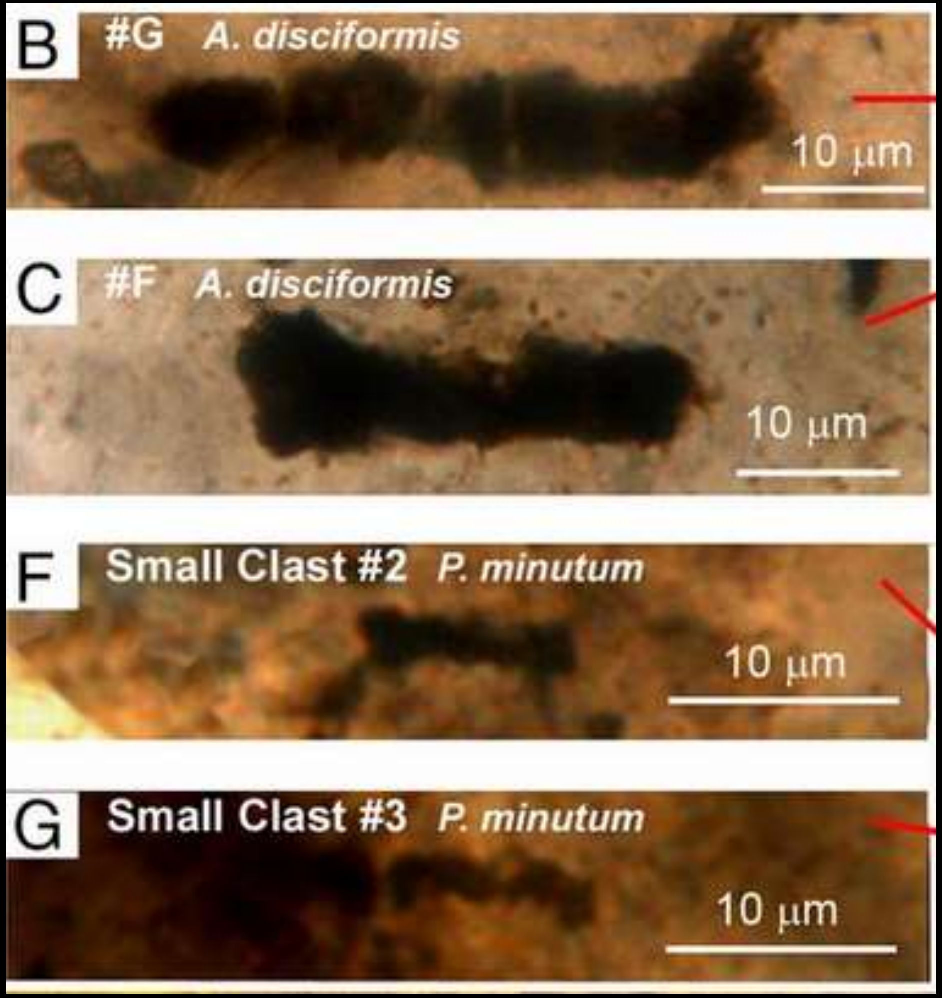
4.1-3.8 Gya: Late Heavy Bombardment

Evidence from Moon rocks suggests Earth and the other terrestrial planets were bombarded by asteroids at an unusually high rate, possibly because migration of the giant planets disturbed the reservoir of asteroids and comets in the outer solar system.

Credit: universetoday.com

3.5 Gya: Earliest Definite Evidence for Life

Life had certainly formed on Earth by 3.5 Gya. The evidence comes from microfossils from rocks in Australia, which have carbon isotope ratios consistent with life (we'll return to this later).
(Schopf et al., 2018, PNAS)

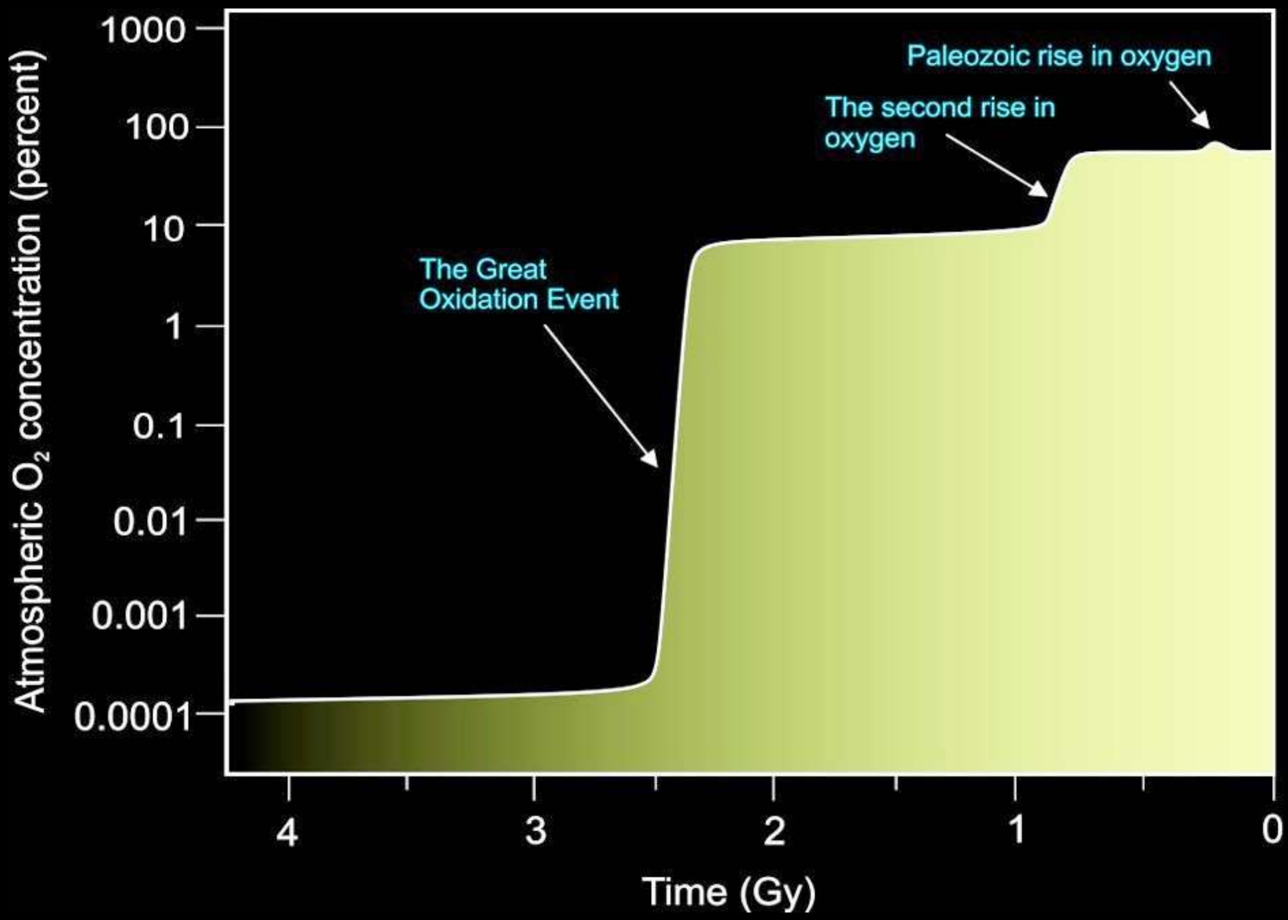


Credit: universetoday.com

^

2.45 Gya: The Great Oxygenation Event

Atmospheric O_2 levels rapidly increased by more than 10,000 times, permanently altering the chemistry of the rocks and biosphere. This may have happened long after the development of photosynthesis, because it took time to oxidize all the Fe and S in the crust.

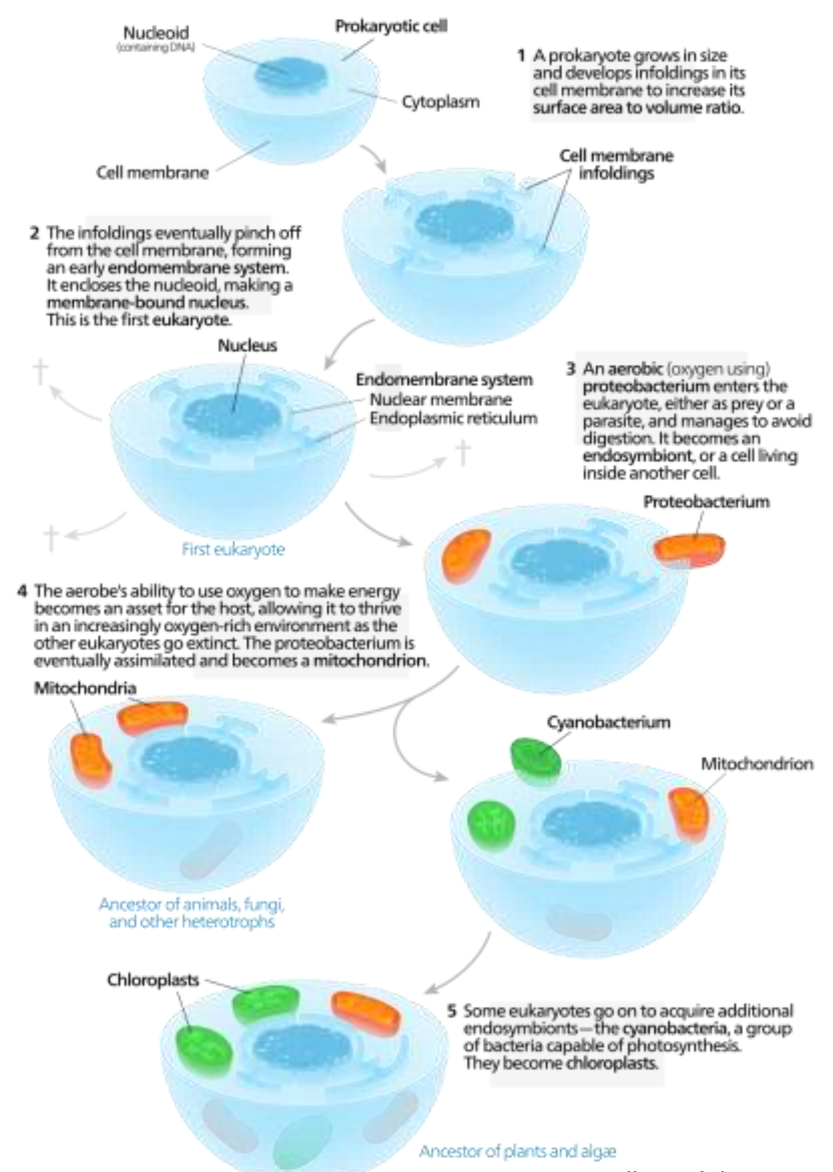


Credit: Charles Cockell

2.1-1.6 Gya: Eukaryotes Evolve

Prokaryotes ("before nut") absorb proteobacteria which become their mitochondria. They also segregate their genetic material into a nucleus. Thus the eukaryotes ("true nut") are born.
(Knoll et al., 2006; Martin & Koonin, 2006)

There are *many* competing models for this process.

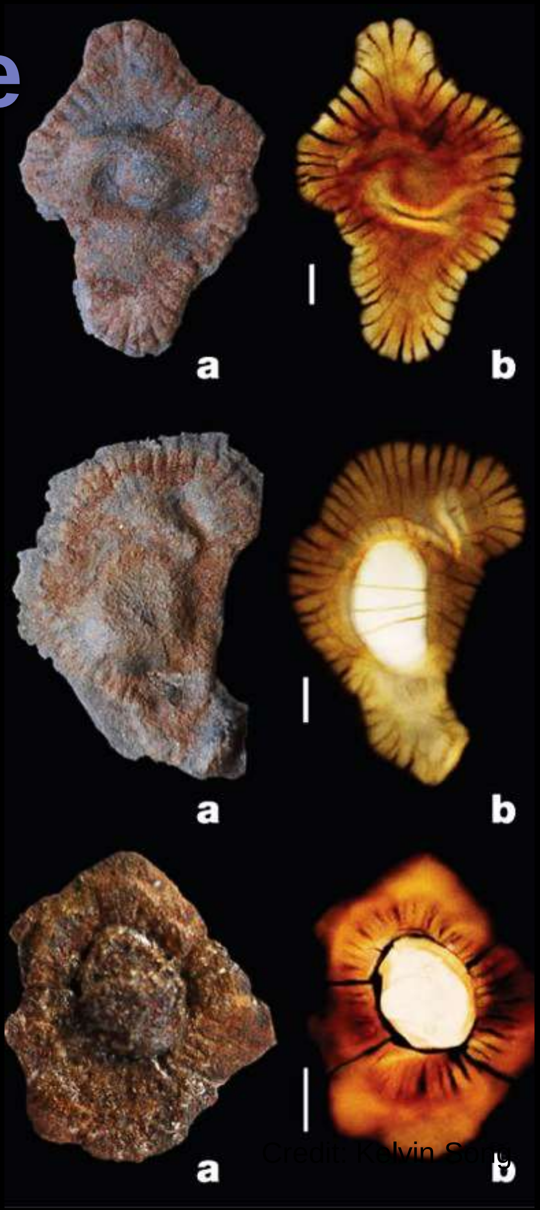


Credit: Kelvin Song

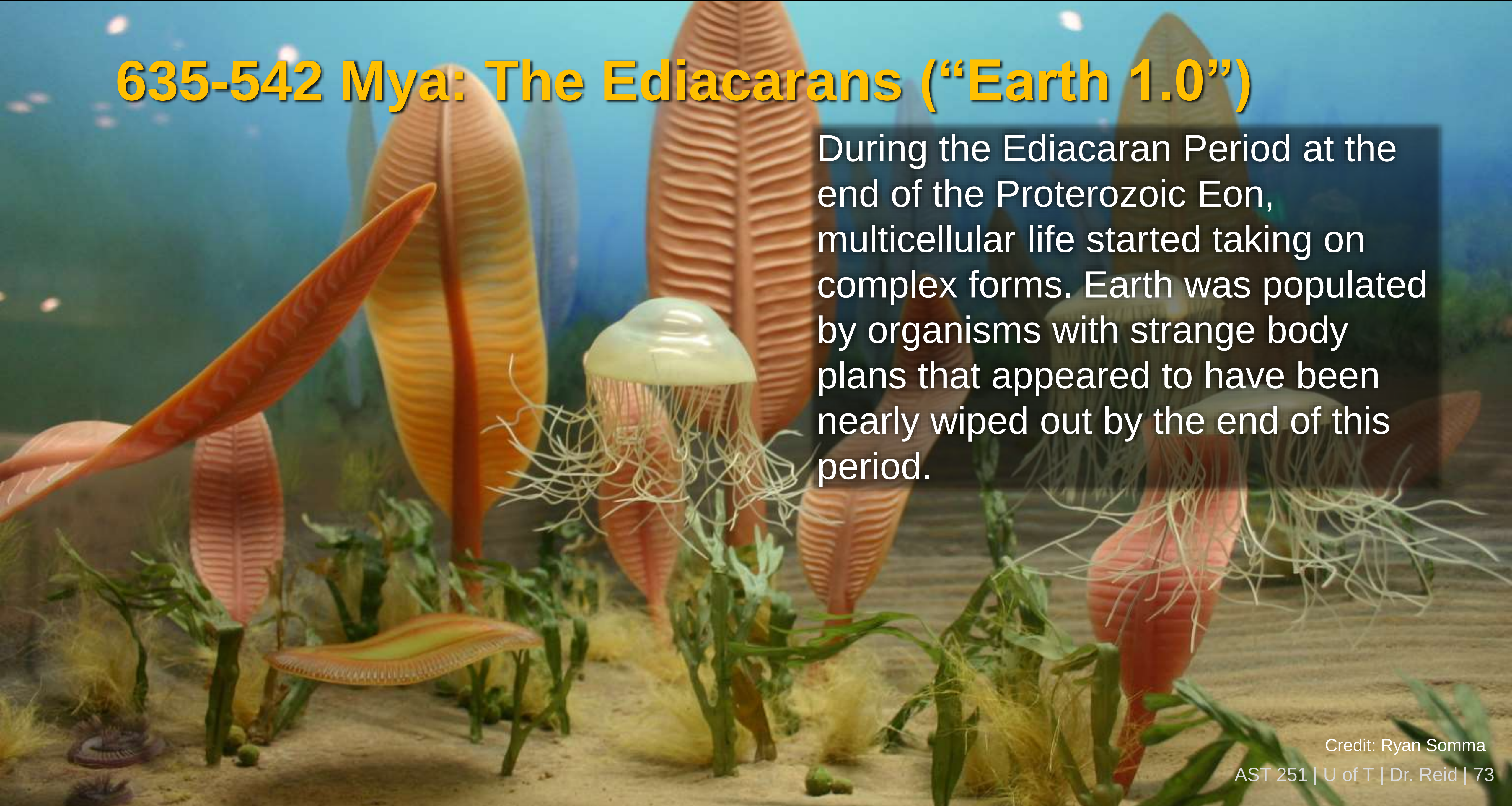
1.9 Gya: First Claimed Multicellular Life

Multicellularity has evolved many times, perhaps because all the O_2 released by the GOE allowed for more energy to be derived from aerobic respiration than was possible anaerobically.

One of the earliest claimed instances is *Grypania spiralis*
(El Albani, 2010, Nature)



635-542 Mya: The Ediacarans ("Earth 1.0")



During the Ediacaran Period at the end of the Proterozoic Eon, multicellular life started taking on complex forms. Earth was populated by organisms with strange body plans that appeared to have been nearly wiped out by the end of this period.

Credit: Ryan Somma

541 Mya: The Cambrian Explosion (“Earth 2.0”)

Marking the start of the Phanerozoic Eon, the Cambrian Explosion was the biggest ever sudden increase in the diversity of organisms on Earth.

Credit: Smithsonian Institution

~500 Mya: Life Moves Onto Land

There is much debate about which were the first multicellular organisms to move onto land. They may have been Ediacarans. But there are fairly strong claims of fossilized tracks on land as early as 530 Mya.

(MacNaughton et al. 2002, Geology)

An Astrobiological History of the Universe

Part 3: From the Great Dying to Today

The Great Dying

The Worst Thing That Ever Happened

About 252 million years ago volcanoes in what we now call Siberia began erupting. They didn’t stop for *thousands* of years.

(Reichow et al. 2009)

Credit: Rachel Cifelli

The lava covered an area of up to 5,000,000 km²—about half the area of Canada. (Reichow et al. 2009)

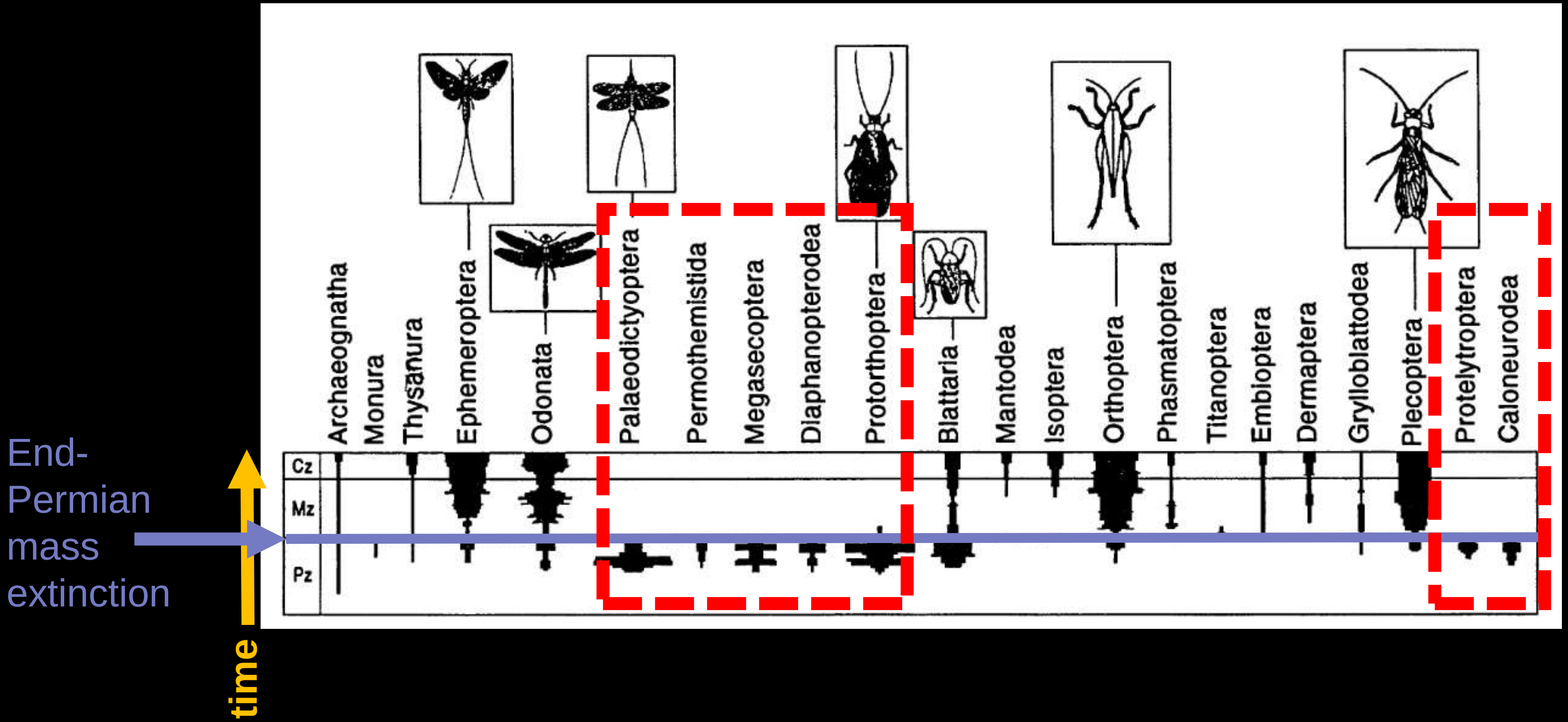
Image credit: Ron Miller

The eruptions formed the **Siberian Traps** and appear to have caused a cascade of interrelated catastrophic environmental changes:

- Massive increase in atmospheric CO_2 (McElwain & Punasenya, 2007)
- 8^{o}C rise in atmospheric temperature (McElwain & Punasenya, 2007)
- Release of a burst of methane, CH_4 (Palfy et al., 2001)
- Ocean anoxia (Song et al., 2014)
- Release of a burst of toxic, ozone-destroying H_2S (Song et al., 2014)
- Widespread wildfires (Shen et al., 2011)
- “Hypercanes?”

In the resulting end-Permian mass extinction, nearly everything on Earth died—up to 96% of marine species.

(Sahney & Benton, 2008)



The end-Permian is the only known mass extinction of insects, as shown in this diagram of fossil species diversity. (Labandeira & Sepkoski, 1993)

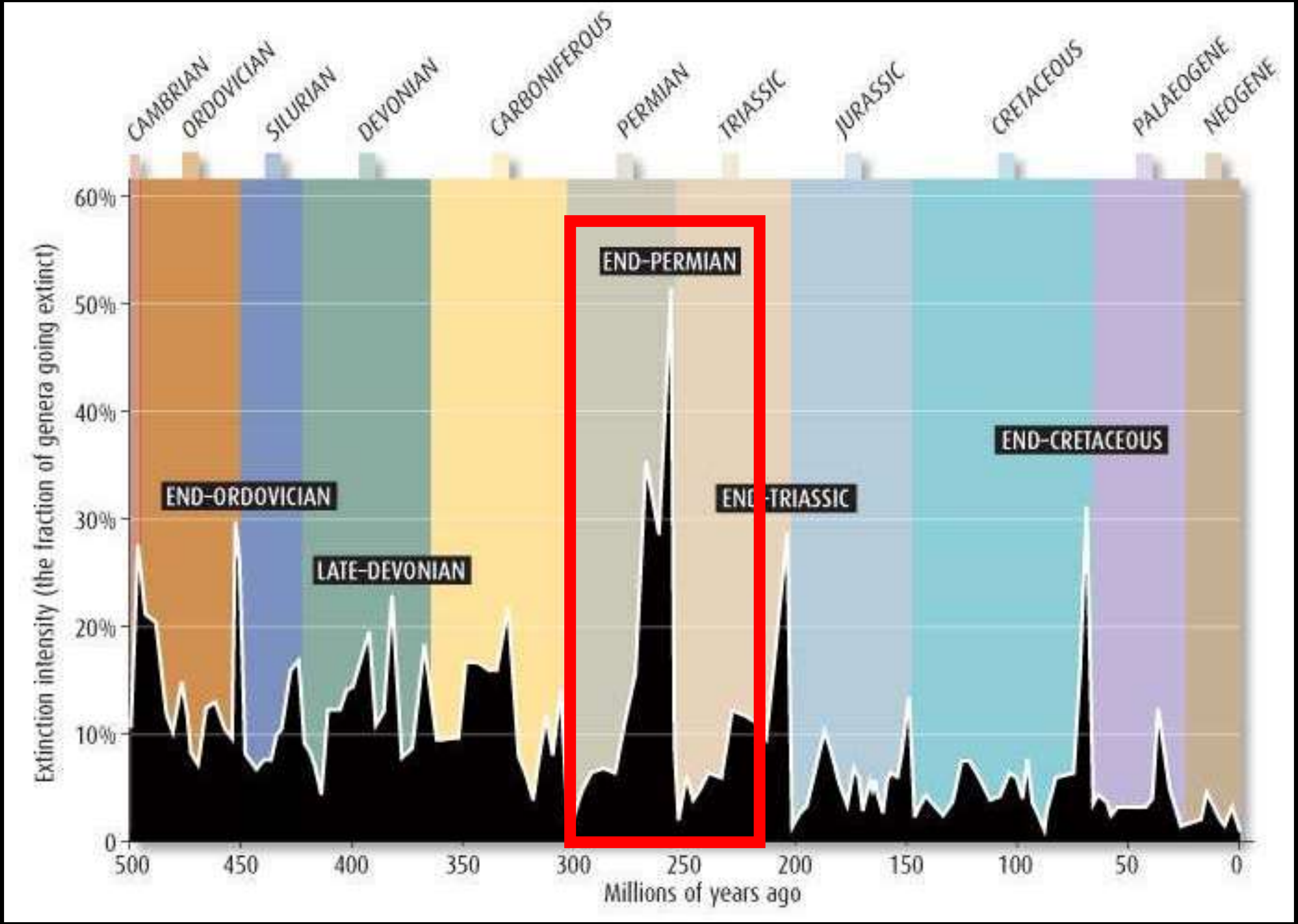


Image credit: New Scientist

The end-Permian mass extinction was so bad, it is sometimes called the Great Dying.

250Mya: The Great Dying

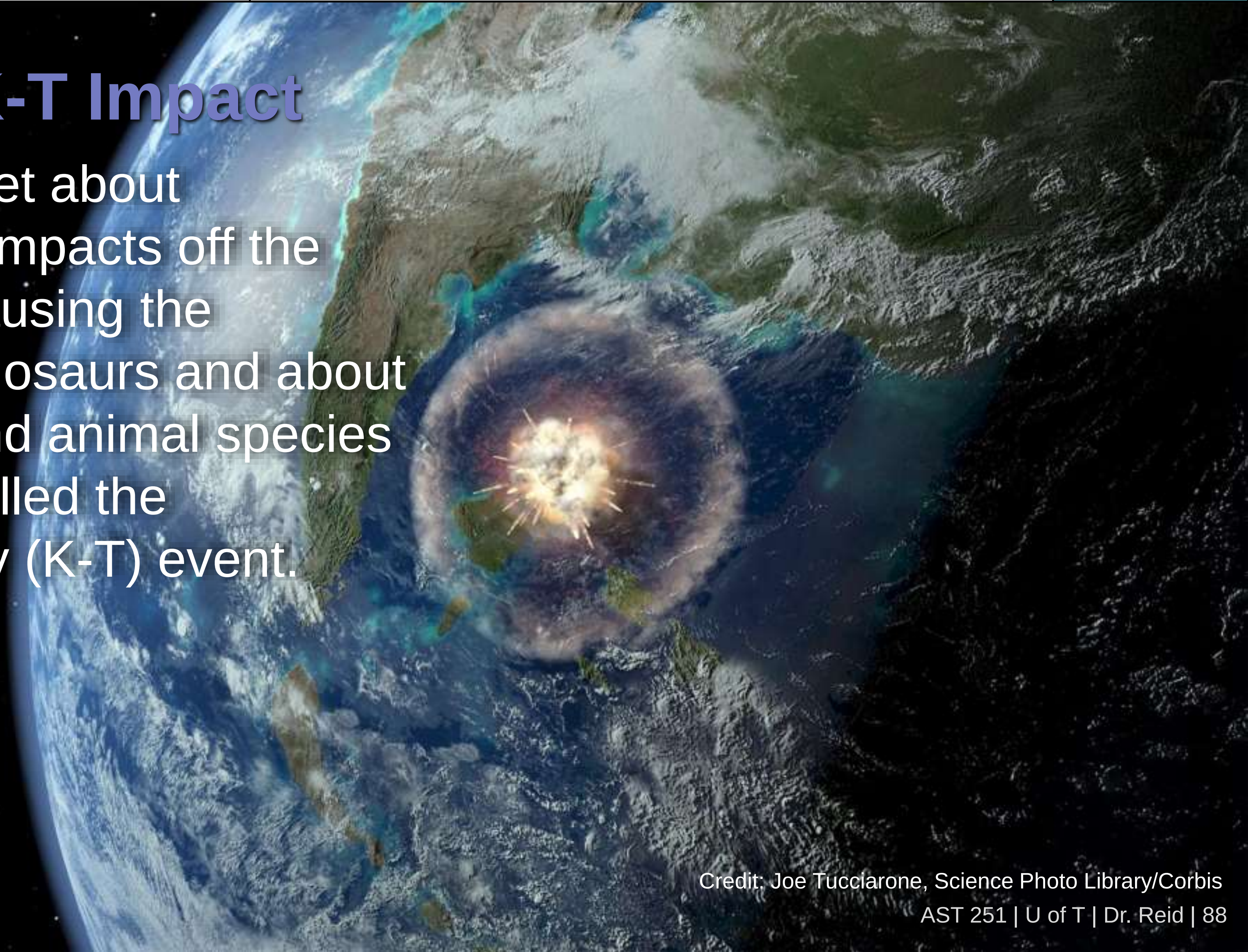
At the end of the Permian period, nearly everything on Earth died.

Image credit: Julius Csotonyi

The end-Permian was far from the only time life on Earth was dealt a colossal blow.

65 Mya: The K-T Impact

An asteroid or comet about 10 km in diameter impacts off the coast of Mexico, causing the extinction of the dinosaurs and about 75% of the plant and animal species on Earth. This is called the Cretaceous-Tertiary (K-T) event.



Credit: Joe Tucciarone, Science Photo Library/Corbis

This Cretaceous-Tertiary extinction or K-T impact cleared the way for the ascension of mammals.

Credit: Getty/Karsten Schneider

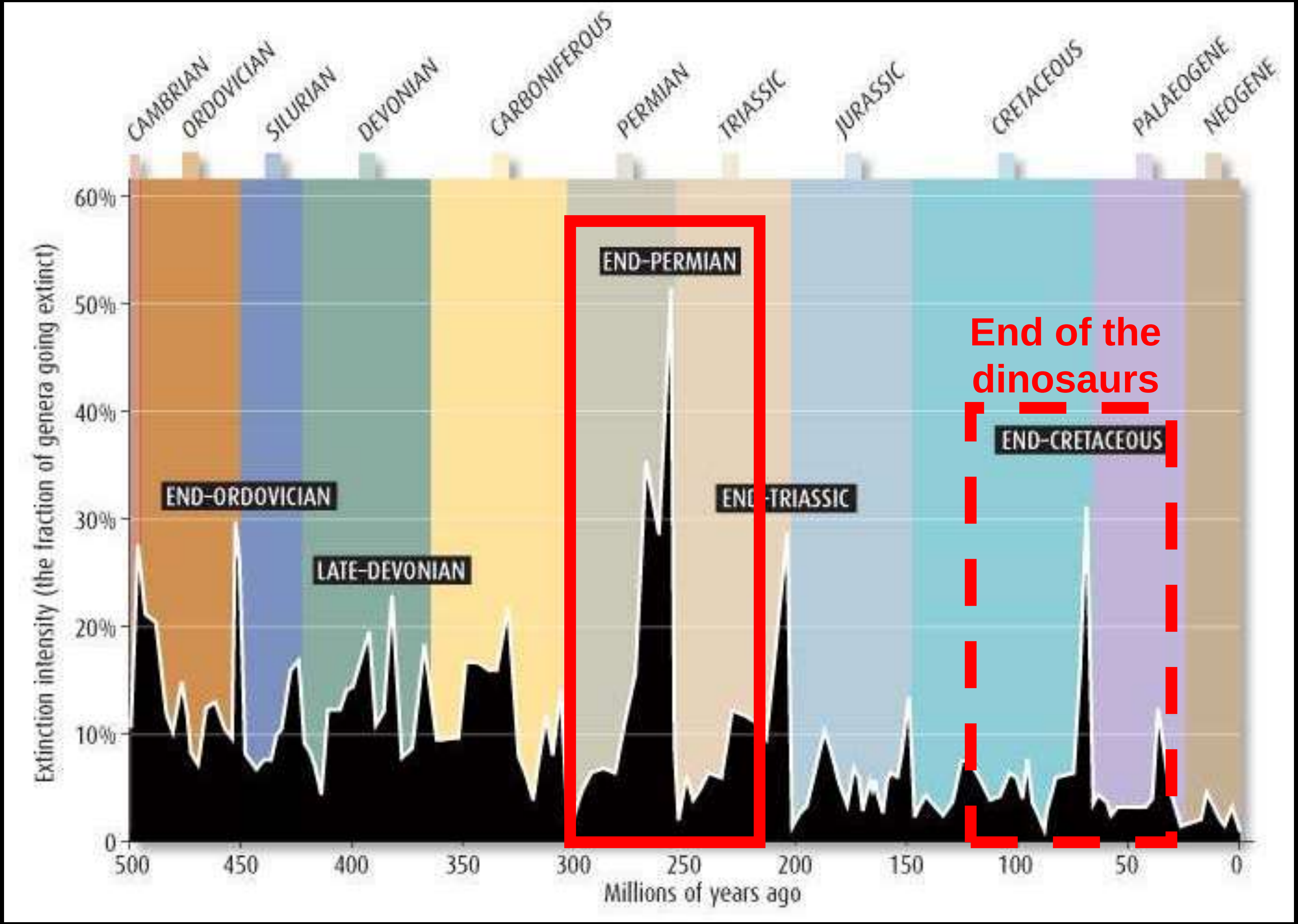
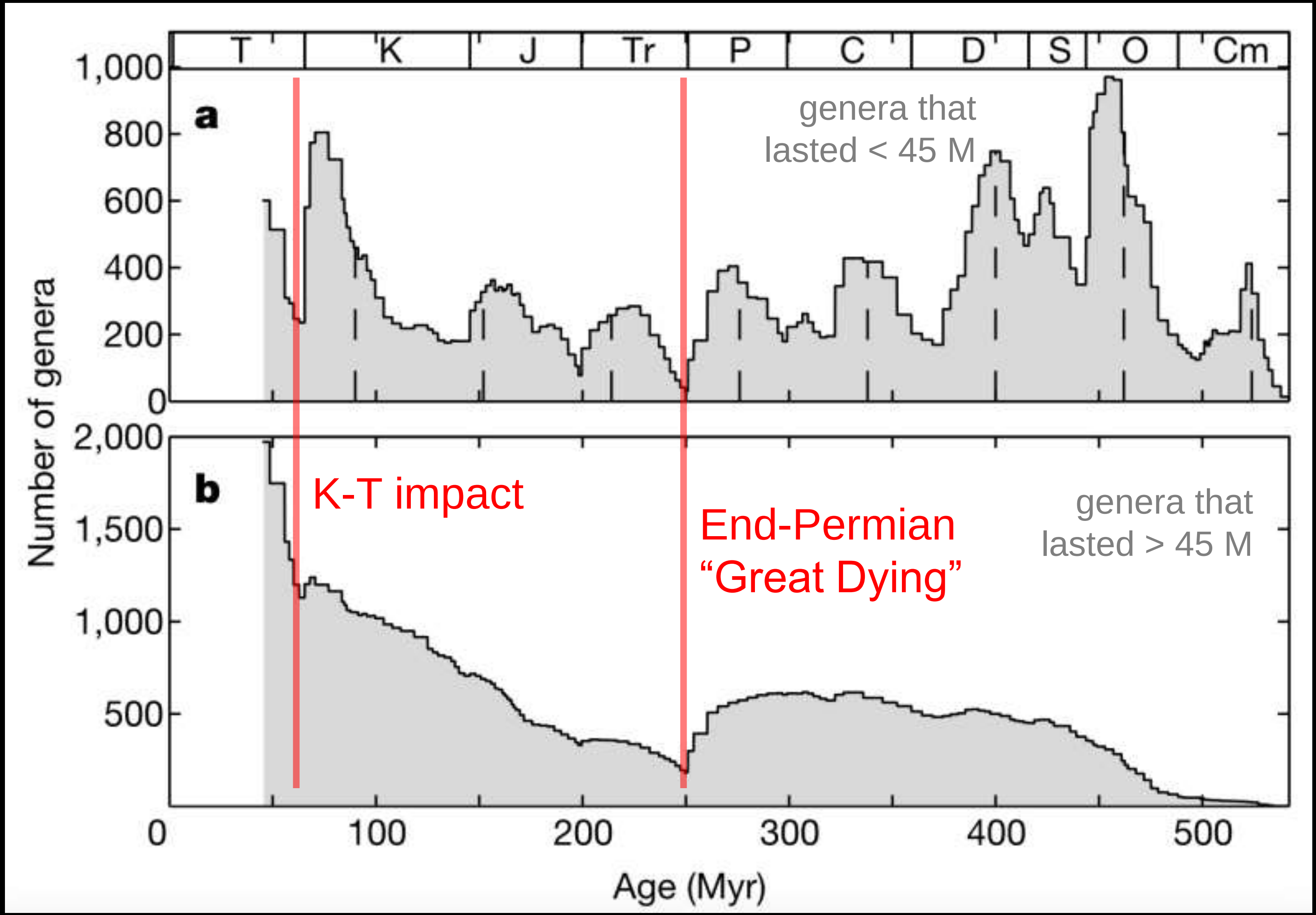


Image credit: New Scientist



Number of marine fossil genera as a function of time, showing the cycle of mass extinctions with a ~62 M periodicity.

(Rohde and Muller, Nature, 2001)

The history of mass extinctions on Earth teaches us that, astrobiologically speaking, life is both vulnerable and resilient.

6 Mya: Early Humans Diverge

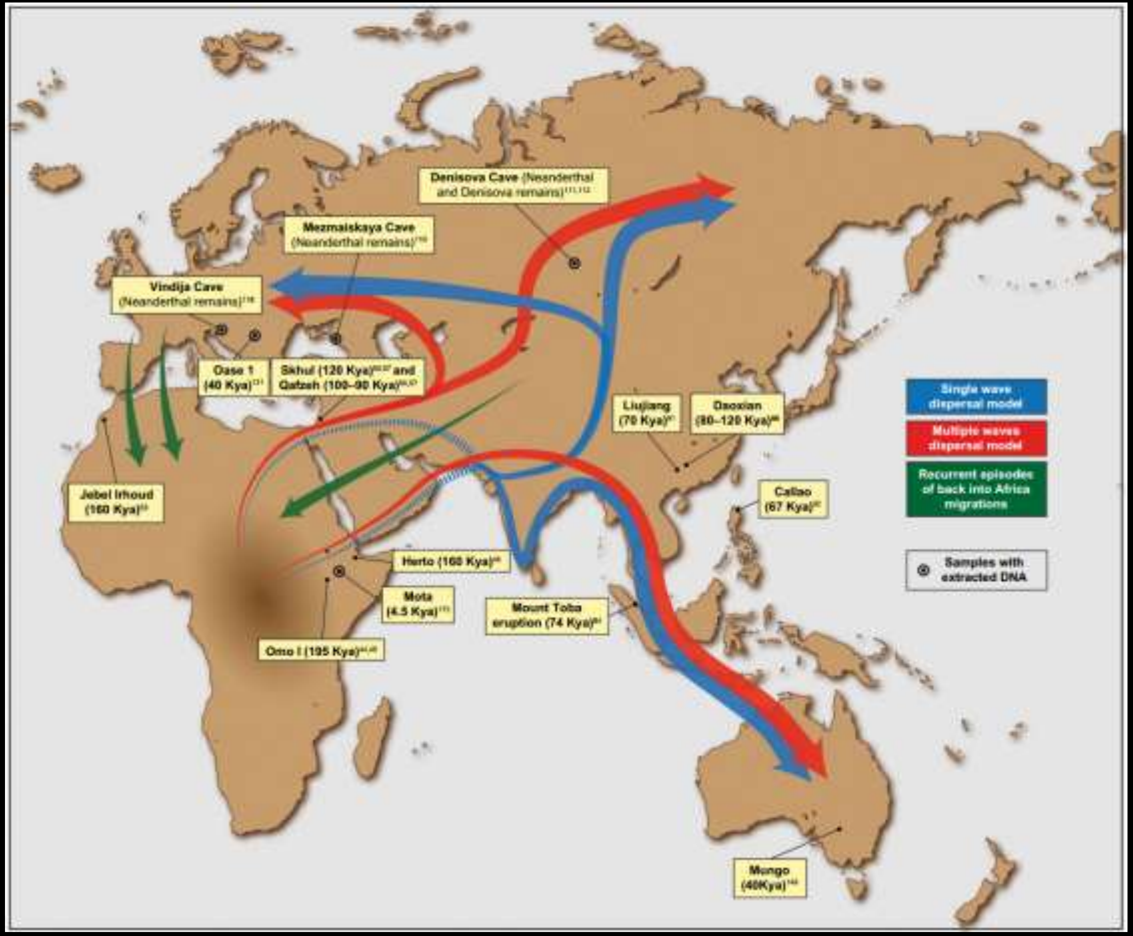
The current consensus is that the last common ancestor of humans and chimpanzees existed about 6-8 Mya.

Credit: Didier Descouens

~100,000 ya: Humans Leave Africa

Anatomically modern humans (homo sapiens) probably began substantial migration out of Africa about 100,000 ya.

(Lopez et al. 2015, EBO)



1961: Humans Leave Earth

Cosmonaut Yuri Gagarin is the first human to fly to space.

Credit: Didier Descouens

1995: Humans Discover Exoplanets

For the first time, we had conclusive evidence that there were other planets out there—and perhaps other life.

Credit: ESO/M. Kornmesser/Nick Risinger

Concept Check

If human beings represent the only intelligent life in the universe, then for what fraction of the history of the universe did it lack intelligent life?

a. 0.9%
b. 9%
c. 90%
d. 99%
e. 99.99%

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