ASTR 1P01
Brock University
Prof. Barak Shoshany

Lecture 1: Introduction

Goals

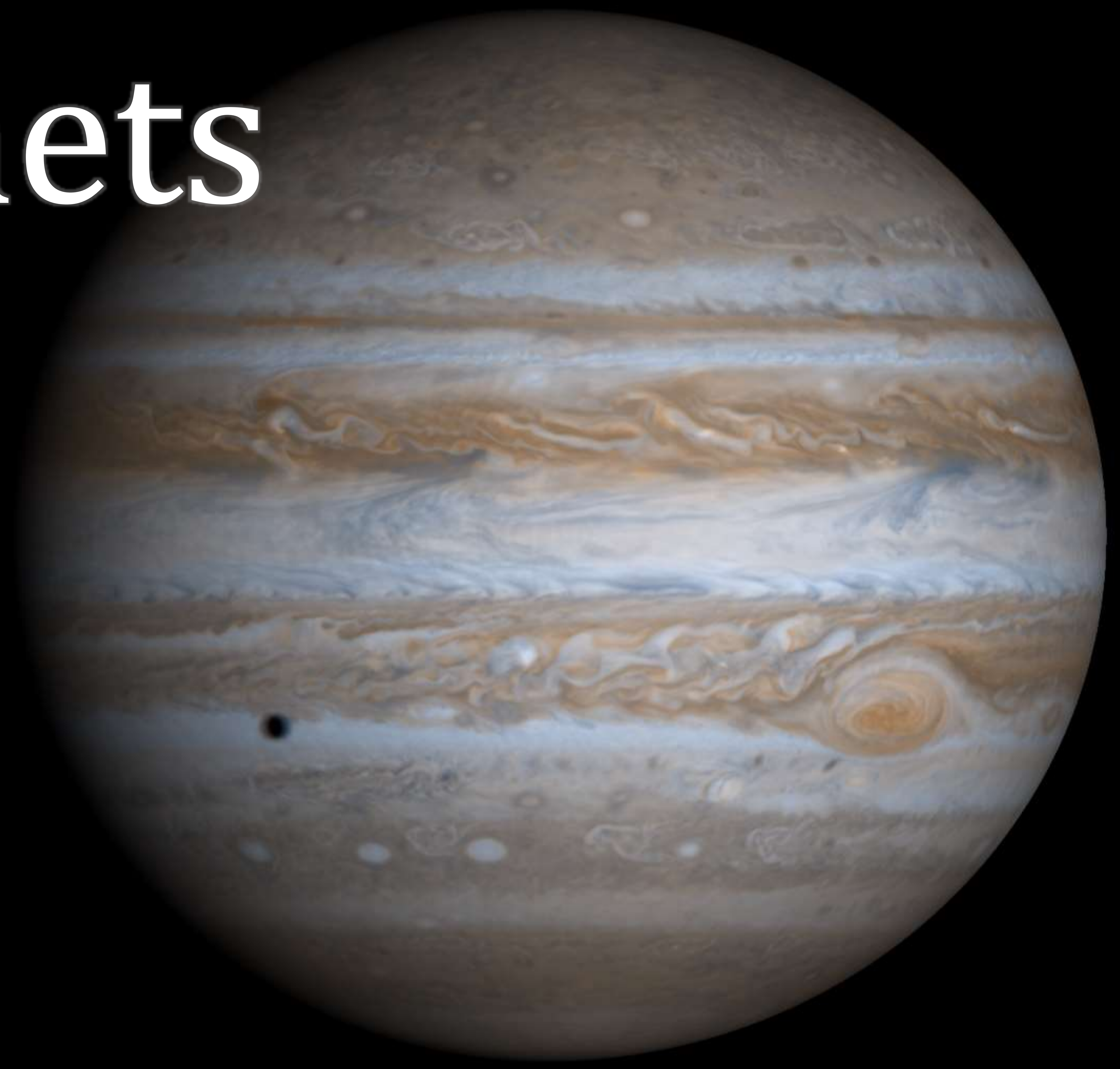
- Learn some basic concepts in science and astronomy.
- Get an overview of some of the fascinating things we'll learn about.
- Discuss scales: the smallest and largest things in the universe.

The Milky Way
Credits: ESO / S. Brunier

What is astronomy?

- Astronomy studies celestial objects: anything that exists outside of Earth.
- This includes objects such as ---

Planets

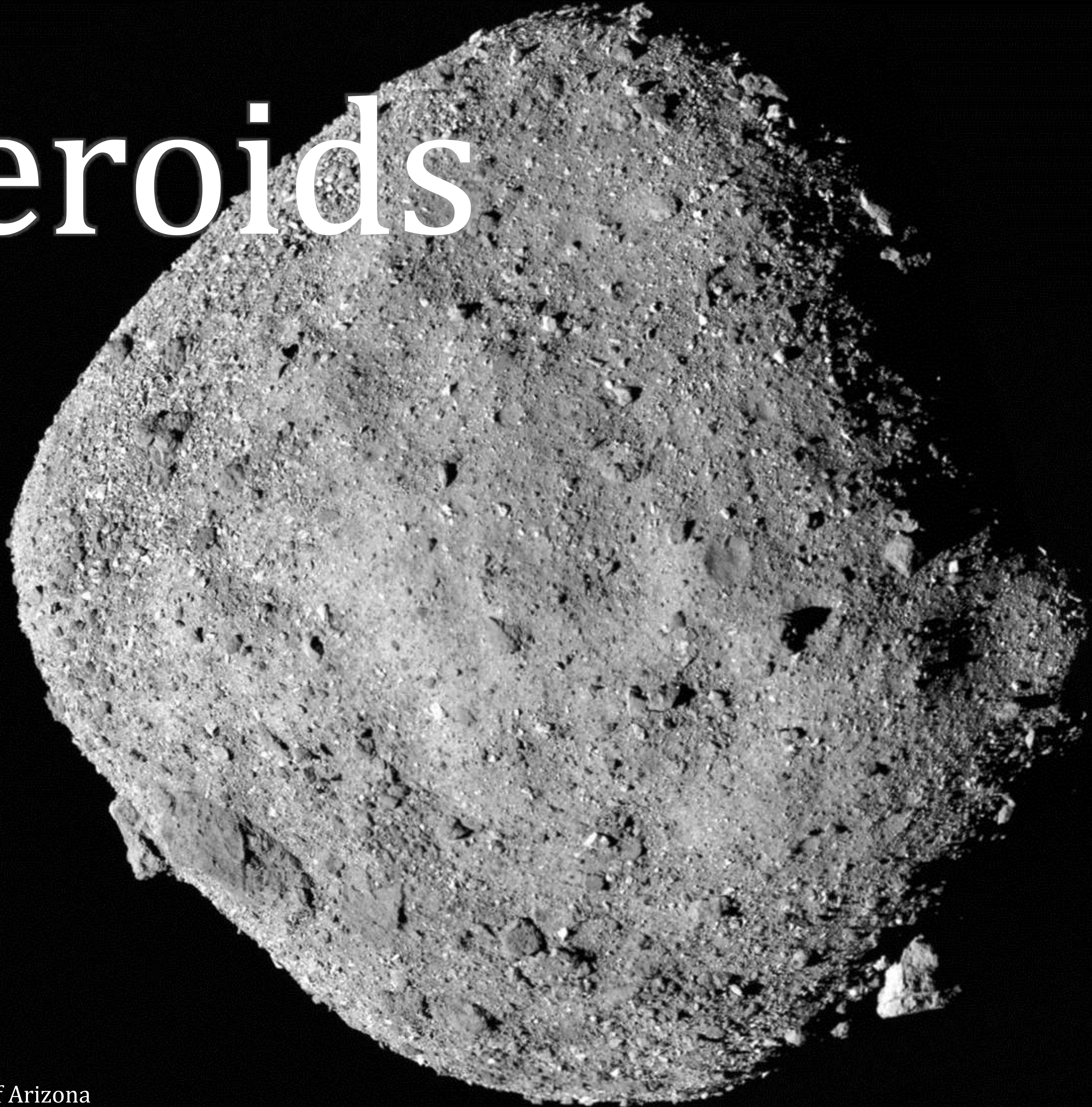


Jupiter
Credits: NASA / JPL / University of Arizona

Moons

The Moon
Credits: LROC / Seán Doran

Asteroids

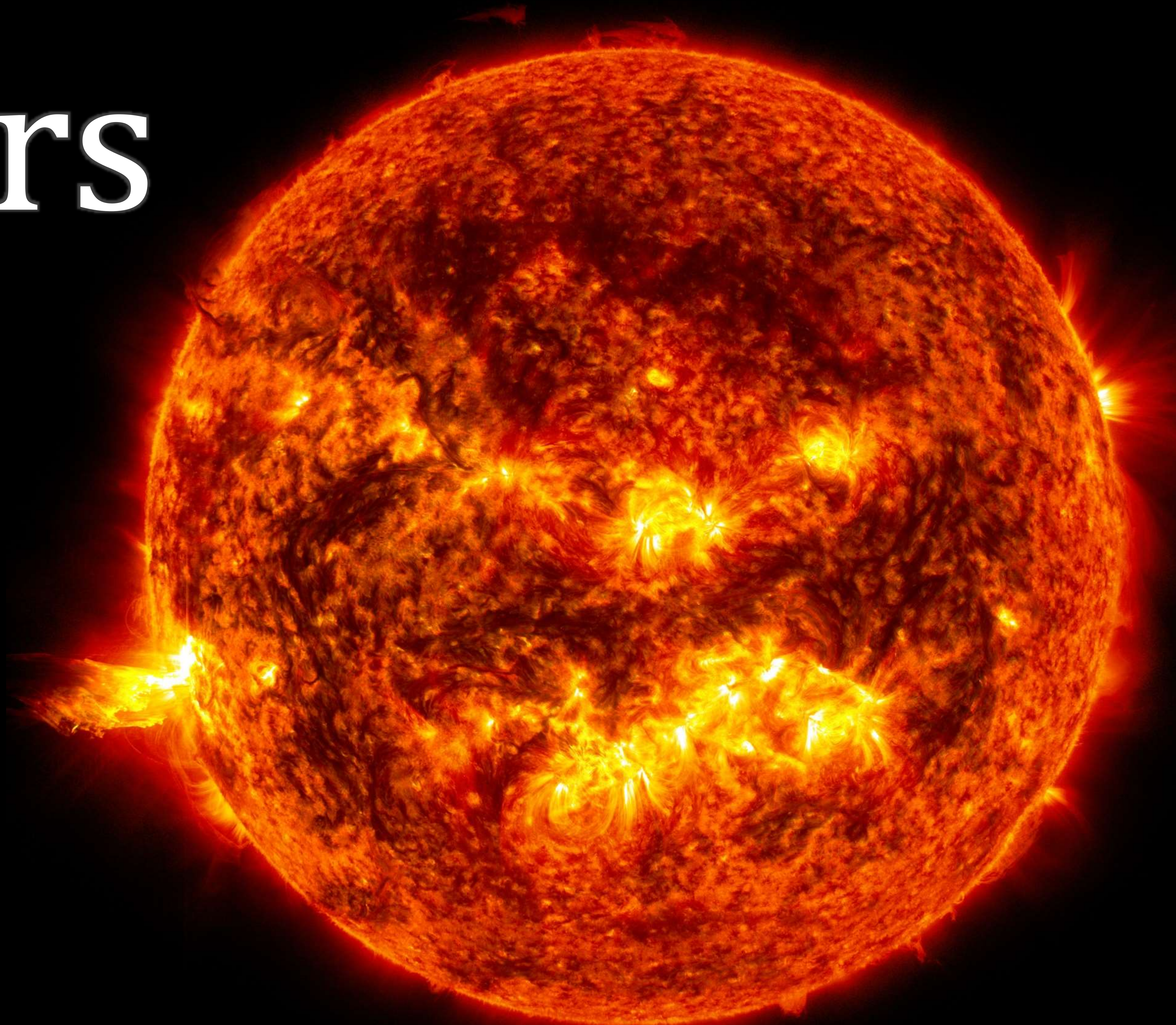


Asteroid Bennu
Credits: NASA / Goddard / University of Arizona

Comets

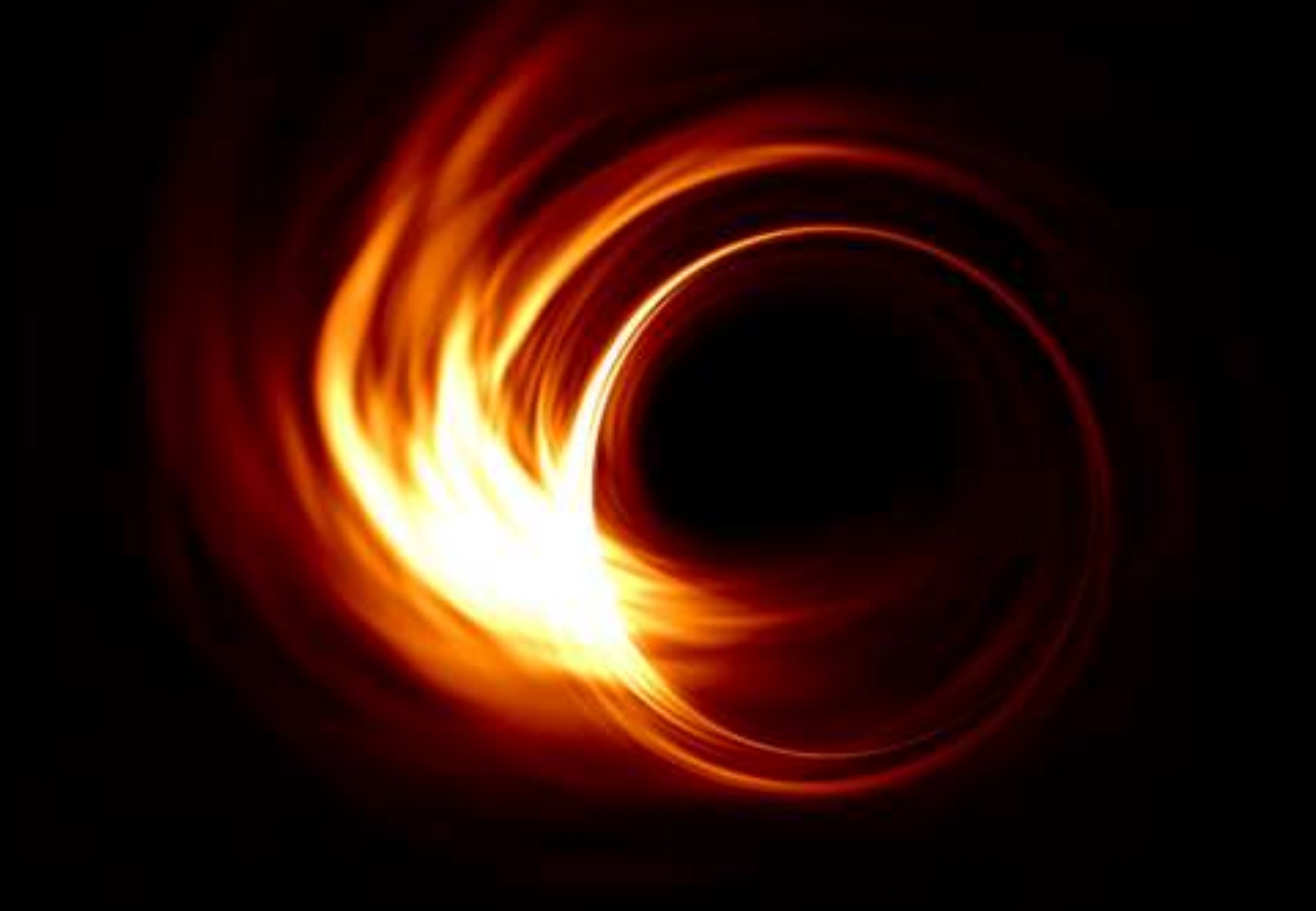
Comet ISON
Credits: Damian Peach / SkyandTelescope.com

Stars



The Sun
Credits: NASA / SDO

Black holes



Simulation of Black Hole Accretion Disk
Credits: Hotaka Shiokawa (EHT)

Galaxies

Andromeda Galaxy
Credits: David (Deddy) Dayag

The entire Universe

Map of the Cosmic Microwave Background
Credits: NASA / WMAP Science Team

Astronomy is a science

- To understand how astronomy works, we must first understand how science works.
- Science is not a body of knowledge. It's a method for obtaining and verifying knowledge about our universe.
- In science, we make observations and experiments, and use them to create hypotheses that try to explain how things work.

Astronomy is a science

- Scientific hypotheses have predictions, which need to be tested experimentally.
- If an experiment disagrees with a hypothesis, we need to modify or discard the hypothesis.
- If enough experiments agree with the predictions of a hypothesis, then it eventually becomes an established theory.

Astronomy is a science

- "Theory" in everyday language means the same thing as "hypothesis" or "speculation".
- But in science theory means a hypothesis that was rigorously tested and verified.
- A theory is an accurate explanation of how things work!

Astronomy is a science

- Once a hypothesis becomes a theory, we can use it to:
  - Understand the universe better.
  - Predict the results of future experiments or events.
  - Create new technologies.
- But it's always possible that other experiments in the future will contradict the theory.
- Then we will need to find an even better theory!

Astronomy is a science

- Science is self-correcting, and always moves forward.
- Our understanding of nature becomes better and more precise with each new theory.

Astronomy is a science

- This process of creating hypotheses and then testing them is called the scientific method.
- One of the most important components of this method is skepticism.
- Scientists remain skeptical about any new hypothesis until there is sufficient evidence supporting it.
- Because of skepticism, the scientific method is the only reliable and trustworthy method of obtaining knowledge.

Astronomy is a science

- Scientists don't trust theories based on belief or faith. We trust theories because we test them and find evidence for them.
- No theory is sacred. If we find any evidence that contradicts a theory, we don't trust it anymore and try find a better one.
- So anything you learn in this course might turn out to be false some time in the future…
- But that's a good thing. It means we further improved our understanding of the universe!

A bit of history

- Like any other science, astronomy changes constantly:
  - New theories attempt to explain things we could not explain before.
  - New instruments allow us to make more precise measurements.
- This goes all the way back to the beginning of astronomy ---

Ancient astronomers had a model of the universe with the Earth at the center.

But with more precise measurements, the predictions of this model failed.

The Geocentric (Ptolemaic) Model, 1550

Credits: Mauro Fiorentino, Theosebo, Phonasco, & Philopanareto

Eventually, astronomers realized that the Sun is actually at the center.

This is now the accepted theory, because its predictions fit our observations.

Actually, now we know that the Sun is just one of numerous stars and the universe has no center!

The Solar System
Credits: Harman Smith and Laura Generosa (NASA JPL)

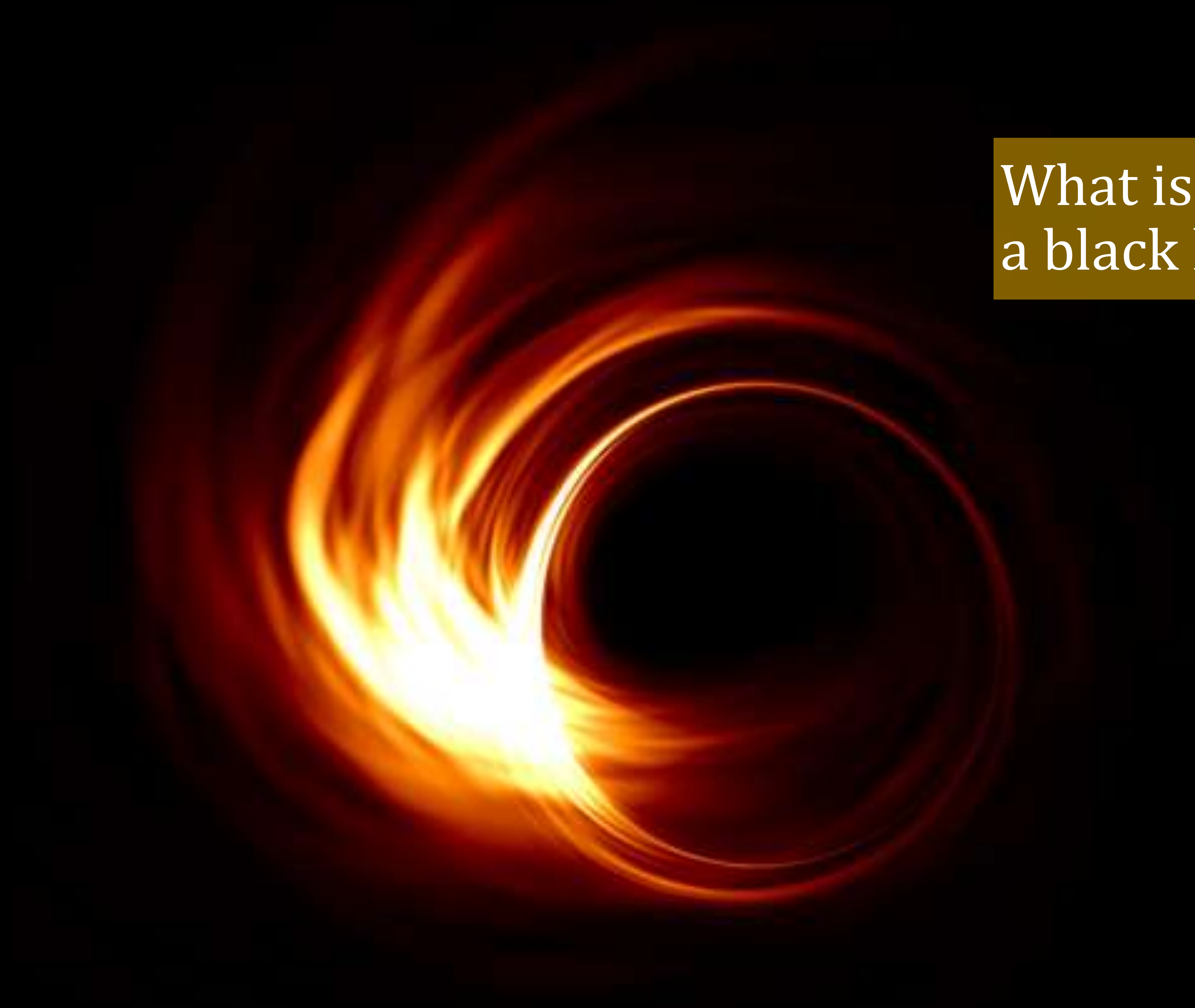
The future of astronomy

- You may think that in the 21st century, we already know everything we need to know about astronomy… but in fact, that is not the case.
- There are many unanswered questions, including ---

What are dark matter and dark energy?

Dark Matter (?) in the Bullet Cluster
Credits:
X-ray: NASA / CXC / CfA / M. Markevitch et al.
Optical: NASA / STScI; Magellan / U. Arizona / D. Clowe et al.
Lensing Map: NASA / STScI; ESO WFI; Magellan / U. Arizona / D. Clowe et al.

What is at the center of a black hole?



Simulation of Black Hole Accretion Disk
Credits: Hotaka Shiokawa (EHT)

Does life exist on other planets?

Artist's Conception of the Surface of an Exoplanet
Credits: NASA

The future of astronomy

- The main job of astronomers and astrophysicists is to answer such questions.
- It may take decades or even centuries to answer some of them!

Astronomical observations

- Astronomy is different from most other sciences, because ---

An Astronomer's Fantasy - Planets in the Lab (Illustration)
Credits: NASA / JPL-Caltech

They can only observe astronomical objects that are located incredibly far away,

Using instruments such as telescopes.

Observing the Sky with a Telescope
Credits: NASA / JPL-Caltech

Astronomical observations

- As technology improves, these instruments get better and better, and allow us to make observations in greater detail and different ways.
- Here's an example:
  - Light is a type of electromagnetic radiation that humans can see.
  - But there are other types of radiation, such as infrared, X-rays, and radio waves, which we cannot see but can be detected by instruments.
  - We can observe the sky not only with light telescopes, but also with ---

Radio telescopes, that see things we could not see using light.

Radio Telescope (Goldstone Observatory)
Credits: NASA

We can even place telescopes in outer space!

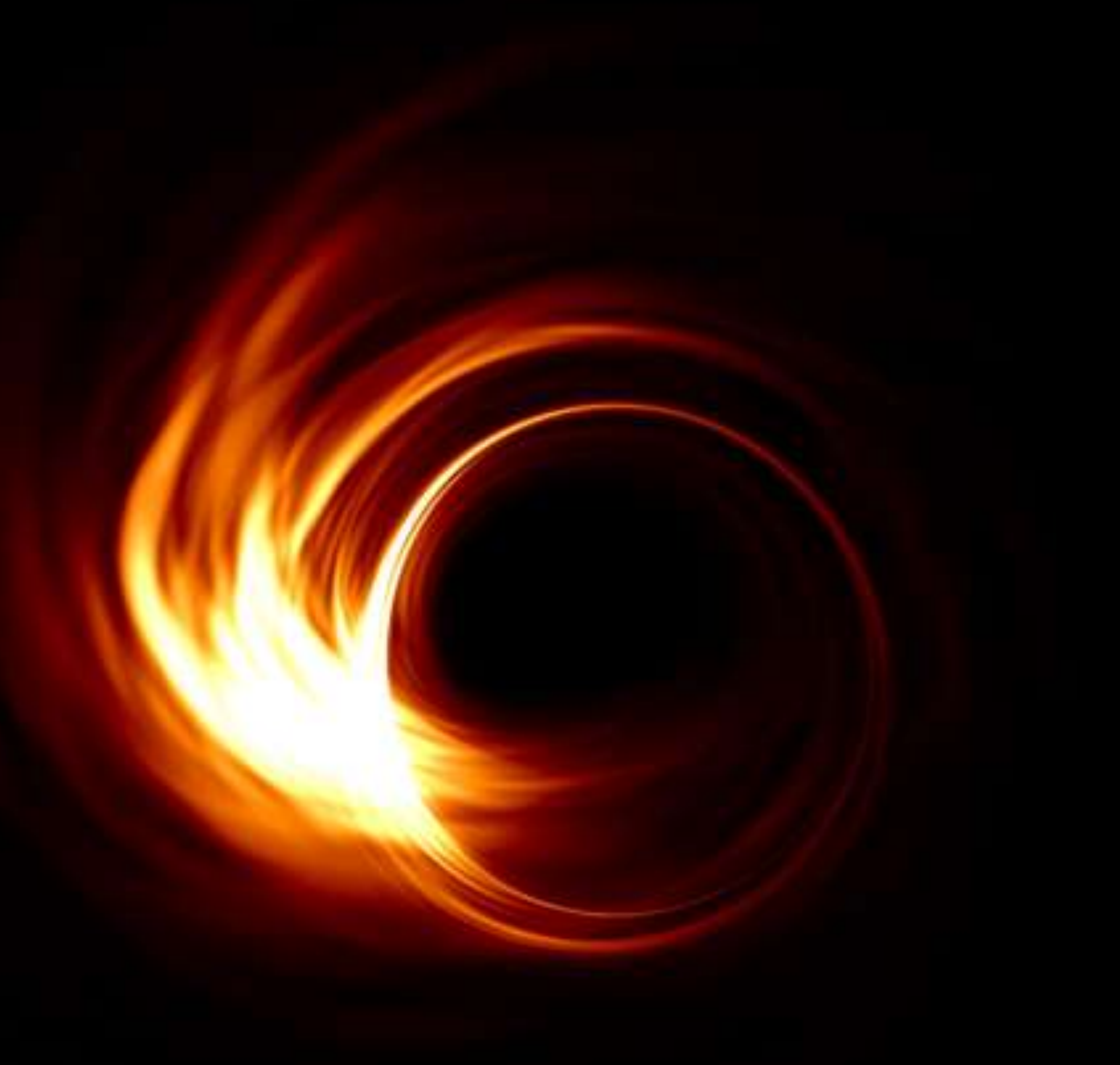
This allows us to observe without being obstructed by the Earth's atmosphere.

Astronauts Working on the Hubble Space Telescope
Credits: NASA

My research

- One of my main fields of scientific research is general relativity.
- This theory provides a precise description of the force of gravity, and explains how space and time work.
- General relativity completely revolutionized astronomy!
- It introduced --

New celestial objects such as black holes.



Simulation of Black Hole Accretion Disk
Credits: Hotaka Shiokawa (EHT)

New tools to probe the sky, such as gravitational lensing ---

Gravitational Lens (The Einstein Cross)
Credits: ESA / Hubble, NASA, Suyu et al.

And gravitational waves.

Artist's Impression of Gravitational Waves
Credits: R. Hurt / Caltech-JPL

Timeline of the Universe
Credits: N. R. Fuller, NSF

And it helped us understand the origin of our universe, in the form of the Big Bang.

My research

- I’ll talk much more about all these things in ASTR 1P02!

Light-years and the speed of light

- In astronomy, we often measure distances in a unit called a light-year.
- This is the distance light travels during one year.
- Even though it has the word "year" in it, a light-year is not a unit of time.
- To see why, remember that when you say “I’m 5 minutes away“ you’re actually saying how far away you are!
- “5 minutes away” is the average distance a human walks in 5 minutes.

Light-years and the speed of light

- No human walks at exactly the same speed all the time, but light always travels at the same speed, the speed of light.
- That's one of the most important lessons of the theory of relativity.
- Also, the speed of light is the fastest possible speed.
- Light always moves the same distance at the same amount of time, and it gets there faster than anything else, so it makes sense to use light-years as a unit of distance.

Light-years and the speed of light

- The speed of light is approximately:
  - 300,000 km/s (kilometers per second).
  - 1 billion km/h (kilometers per hour).
- Remember: distance = speed × time!
- To calculate how many kilometers are in a light-year, first we need to calculate how many seconds are in a year.

Light-years and the speed of light

- 1 Julian year = 365.25 days

  × 24 hours in a day

  × 60 minutes per hour

  × 60 seconds per minute

  ≈ 31.6 million seconds.

- 1 light-year = (300,000 km/s) × (31,600,000 s)

  = 9,480,000,000,000

  ≈ 9.5 trillion km!

Some common large numbers

- Thousand: 1 followed by 3 zeros, or 1,000.
- Million: 1 followed by 6 zeros, or 1,000,000.
- Billion: 1 followed by 9 zeros, or 1,000,000,000.
- Trillion: 1 followed by 12 zeros, or 1,000,000,000,000.
- Quadrillion: 1 followed by 15 zeros, or 1,000,000,000,000,000.
- Quintillion: 1 followed by 18 zeros, or 1,000,000,000,000,000,000.
- So 9.5 trillion km means 9.5 times 1,000,000,000,000.
- If you drive a car at 120 km/h, it will take you about 9 million years to drive a distance of one light year!

Astronomical distances

- In fact, astronomical distances are usually much larger than just one light-year!
- For example ---

The Orion Nebula
Credits: NASA, ESA, M. Robberto (Space Telescope Science Institute / ESA) and the Hubble Space Telescope Orion Treasury Project Team

Astronomical distances

- The speed of light is so fast that it traverses short distances almost instantaneously.
- So it usually seems to us that it travels infinitely fast.
- However, on astronomical scales, it can actually take light many years to travel from place to place.

Astronomical distances

- Since the Orion Nebula is 1,300 light-years away, light from it takes 1,300 years to reach us.
- When we see the Orion Nebula in the sky, we see it as it was 1,300 years ago, in the 8th century!
- We will only know what the nebula looks like today when the light emitted from it today will reach us, 1,300 years in the future.

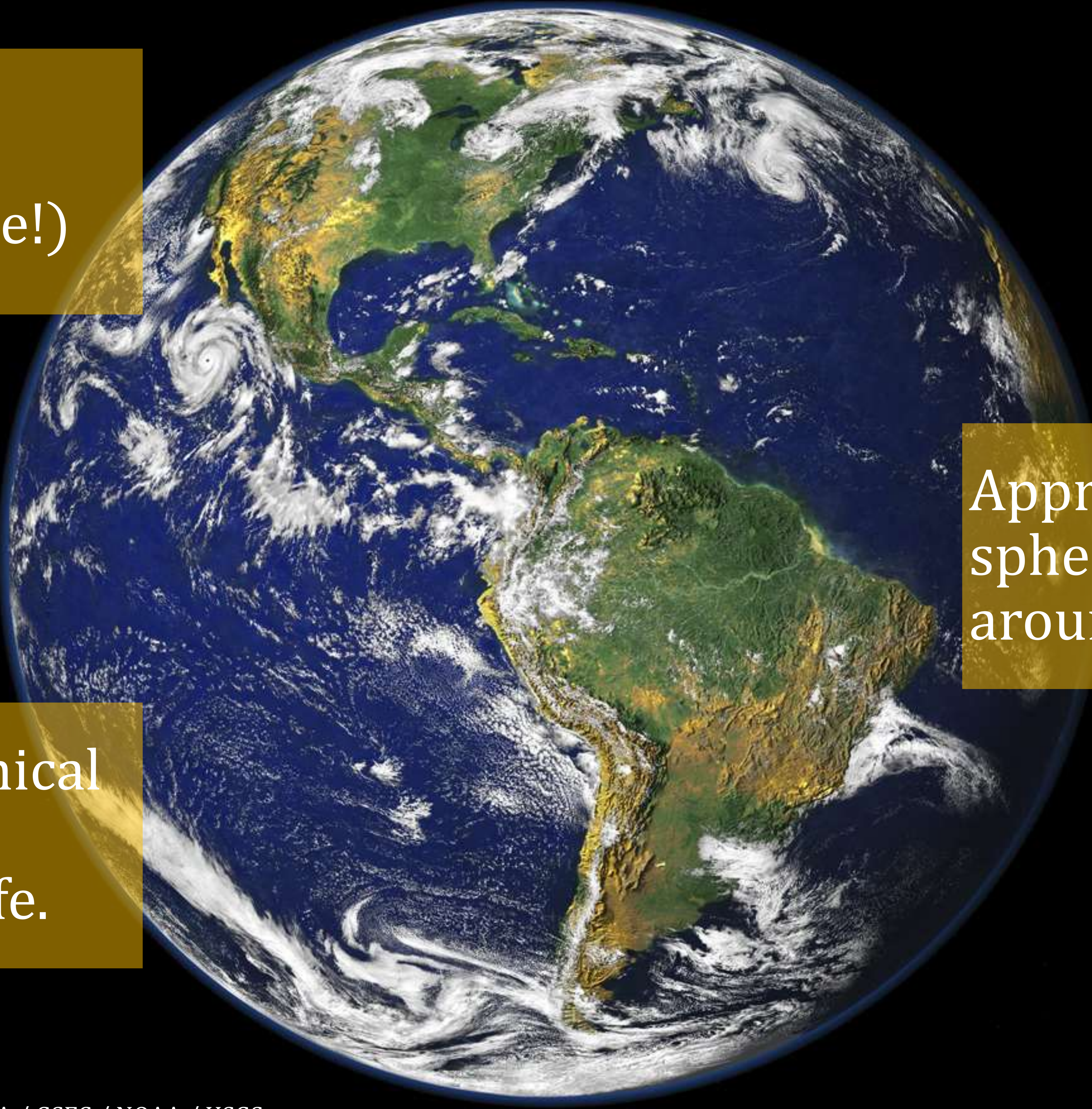
Astronomical distances

- This is quite amazing, but it is also very useful, because it means looking up into the sky is like having a time machine!
- The farther away we look, the farther into the past we see.
- This allows us to see how the universe looked like billions of years in the past, if we look far enough.
- We can use that information to reconstruct the history and evolution of our universe.


A brief tour of the universe

Planet Earth

(you are here!)



Approximately spherical, diameter around 13,000 km.

The only astronomical object (so far) we know to contain life.

Earth

Credits: R. Stockli, A. Nelson, F. Hasler, NASA / GSFC / NOAA / USGS

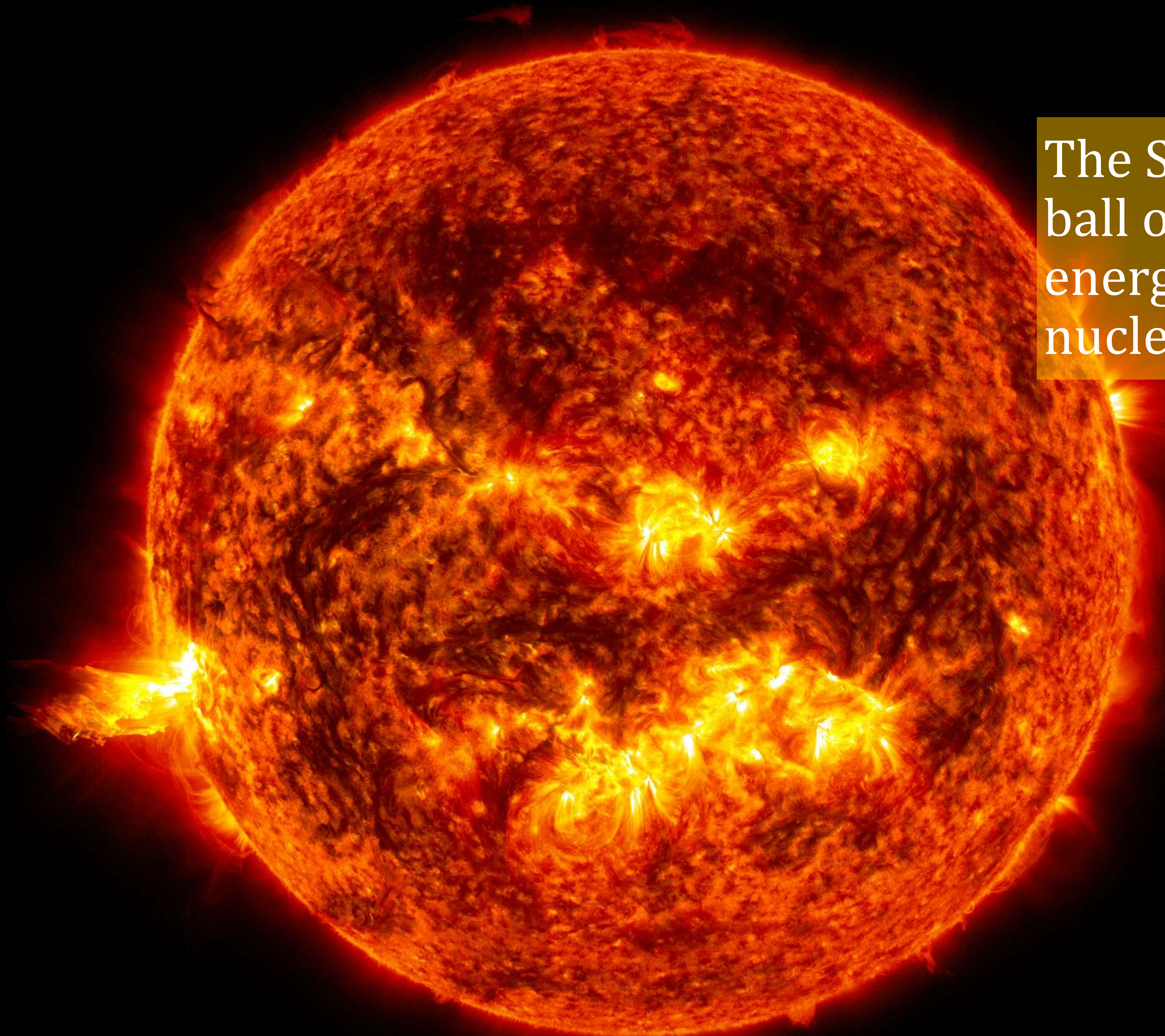
The Moon: the only celestial body that humans have visited in person (as of 2023).

Approximately spherical, diameter around 3,500 km.

Located an average distance of 384,000 km from Earth.

The Moon
Credits: LROC / Seán Doran

Buzz Aldrin on the Surface of the Moon During the Apollo 11 Mission (1969)
Credits: NASA



The Sun is a star: a huge ball of gas that generates energy and light by nuclear reactions.

The Sun
Credits: NASA / SDO

The next closest star is Proxima Centauri, 4.2 light-years or 40 trillion km away.

Proxima Centauri
Credits: ESA / Hubble & NASA

Including the Earth, there are 8 planets that revolve around the Sun.

Planets (and moons) don't generate their own light, but they reflect the Sun’s light.

(note: sizes are to scale, distances are not)

Planets of the Solar System
Credits: NASA

The Phantom Galaxy (M74)
Credits: ESA/Webb, NASA & CSA, J. Lee and the PHANGS-JWST Team

We are located in the Milky Way Galaxy, which contains 100-400 billion stars, including our Sun.

It’s 100,000-200,000 light-years wide and 1,000 light-years thick.

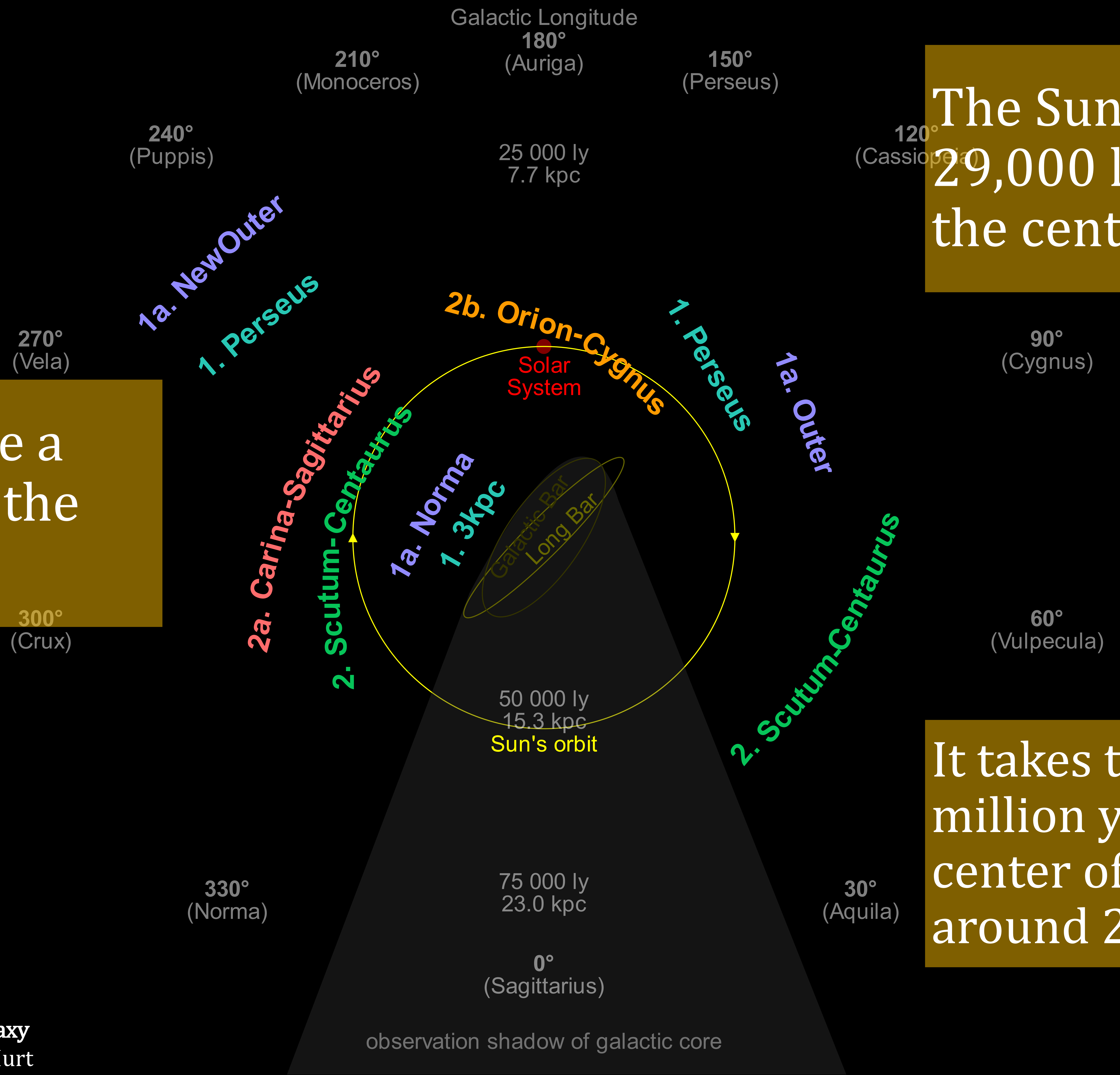
Map of the Milky Way Galaxy
Credits: Pablo Carlos Budassi

Barred Spiral Galaxy NGC 1073
Credits: NASA & ESA

The Sun is 25,000-29,000 light-years from the center of the galaxy.

It is located inside a spiral arm called the Orion Arm.

It takes the Sun 220-250 million years to orbit the center of the galaxy, at around 230 km/s.



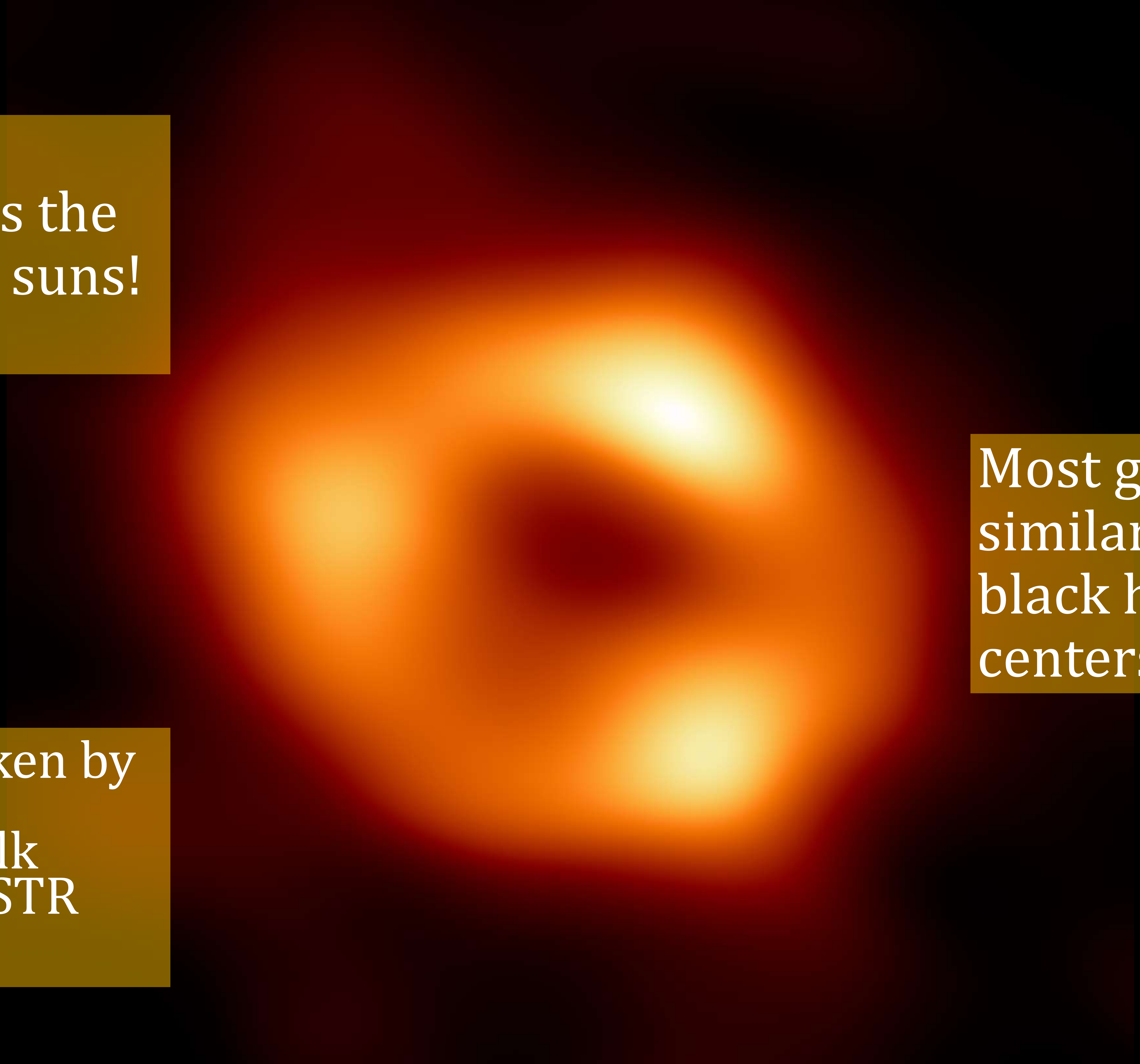
Artist's Impression of the Milky Way Galaxy
Credits: NASA / JPL-Caltech / ESO / R. Hurt

At the center of the galaxy, there is a supermassive black hole called Sagittarius A*.

A black hole is a region of space where gravity is so strong that nothing can escape it, not even light.

Sagittarius A*: The Supermassive Black Hole at the Center of the Milky Way Galaxy
Credits: EHT Collaboration

Sagittarius A* has the mass of 4 million suns!



Most galaxies have similar supermassive black holes at their centers.

This image was taken by the Event Horizon Telescope. We’ll talk more about it in ASTR 1P02.

Sagittarius A*: The Supermassive Black Hole at the Center of the Milky Way Galaxy
Credits: EHT Collaboration

In this Hubble image we see around 10,000 galaxies.

Each of these galaxies contains billions or trillions of stars!

The Hubble Ultra Deep Field
Credits: NASA, ESA, S. Beckwith (STScI) and the HUDF Team

The James Webb Space Telescope's First Deep Field
Credits: NASA, ESA, CSA, and STScI

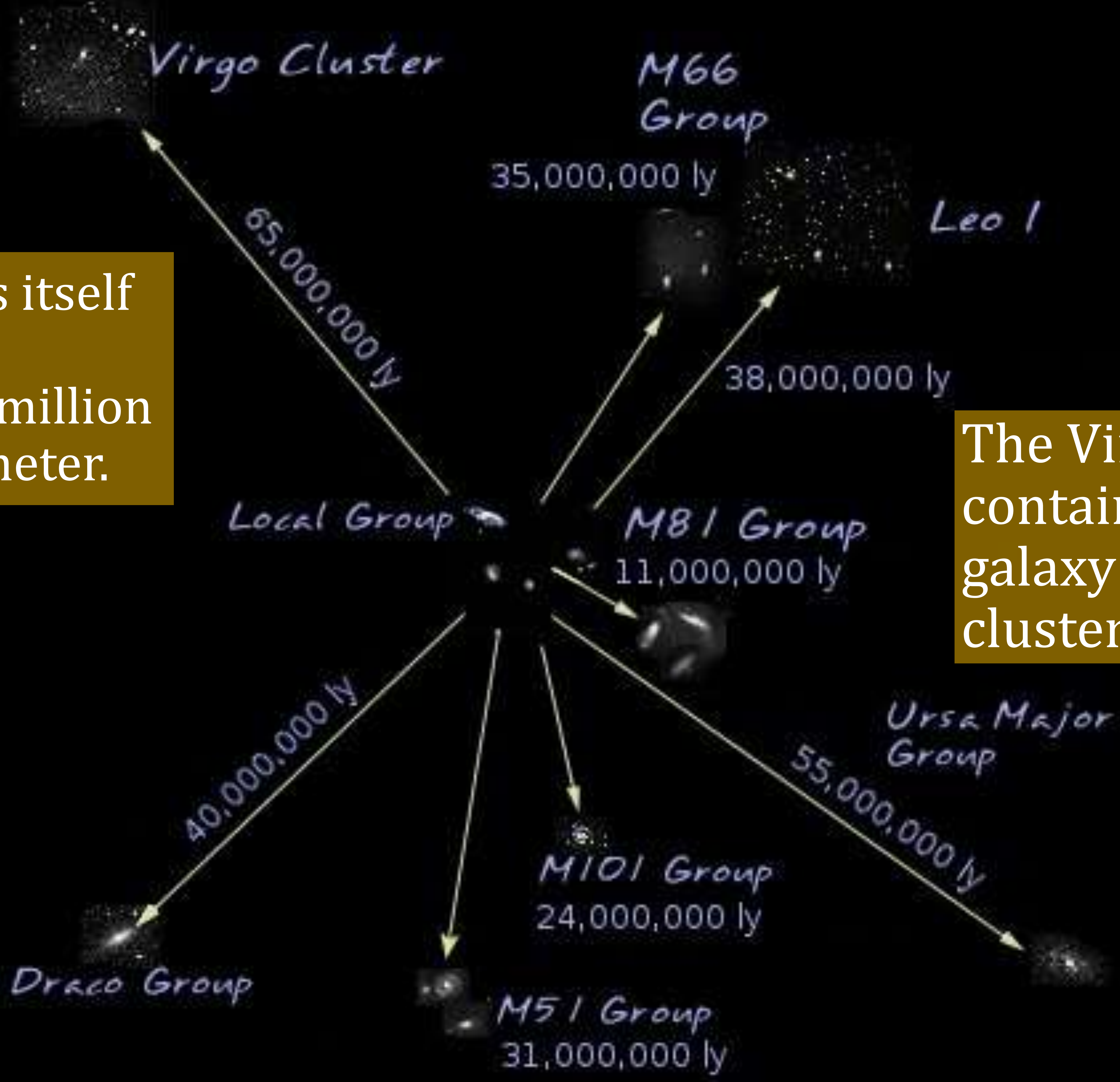
Andromeda Galaxy
Credits: David (Deddy) Dayag

The Milky Way, Andromeda, and at least 80 smaller galaxies form the Local Group.

The Local Group is 10 million light-years in diameter.

The Local Group
Credits: Antonio Ciccolella

The Local Group is itself part of the Virgo Supercluster, 110 million light-years in diameter.



The Virgo Supercluster contains at least 100 galaxy groups and clusters.

Distances within the Virgo Supercluster
Credits: NASA

The Virgo Supercluster, in turn, is part of the Laniakea (la-nee-uh-KEI-uh) Supercluster.

It contains more than 100,000 galaxies and has a diameter of 520 million light-years.

The Laniakea Supercluster
Credits: Andrew Z. Colvin

The most distant known galaxy as of 9/2022 is GN-z11 at 32 billion light-years away.

Galaxy GN-z11
Credits: NASA, ESA, P. Oesch (Yale University), G. Brammer (STScI), P. van Dokkum (Yale University), and G. Illingworth (University of California, Santa Cruz)

Around 13.8 billion years ago, at the “Big Bang”, the universe began to expand from a hot and dense state.

As it expanded, it became colder and less dense.

Eventually it reached a state where stars and planets could be formed.

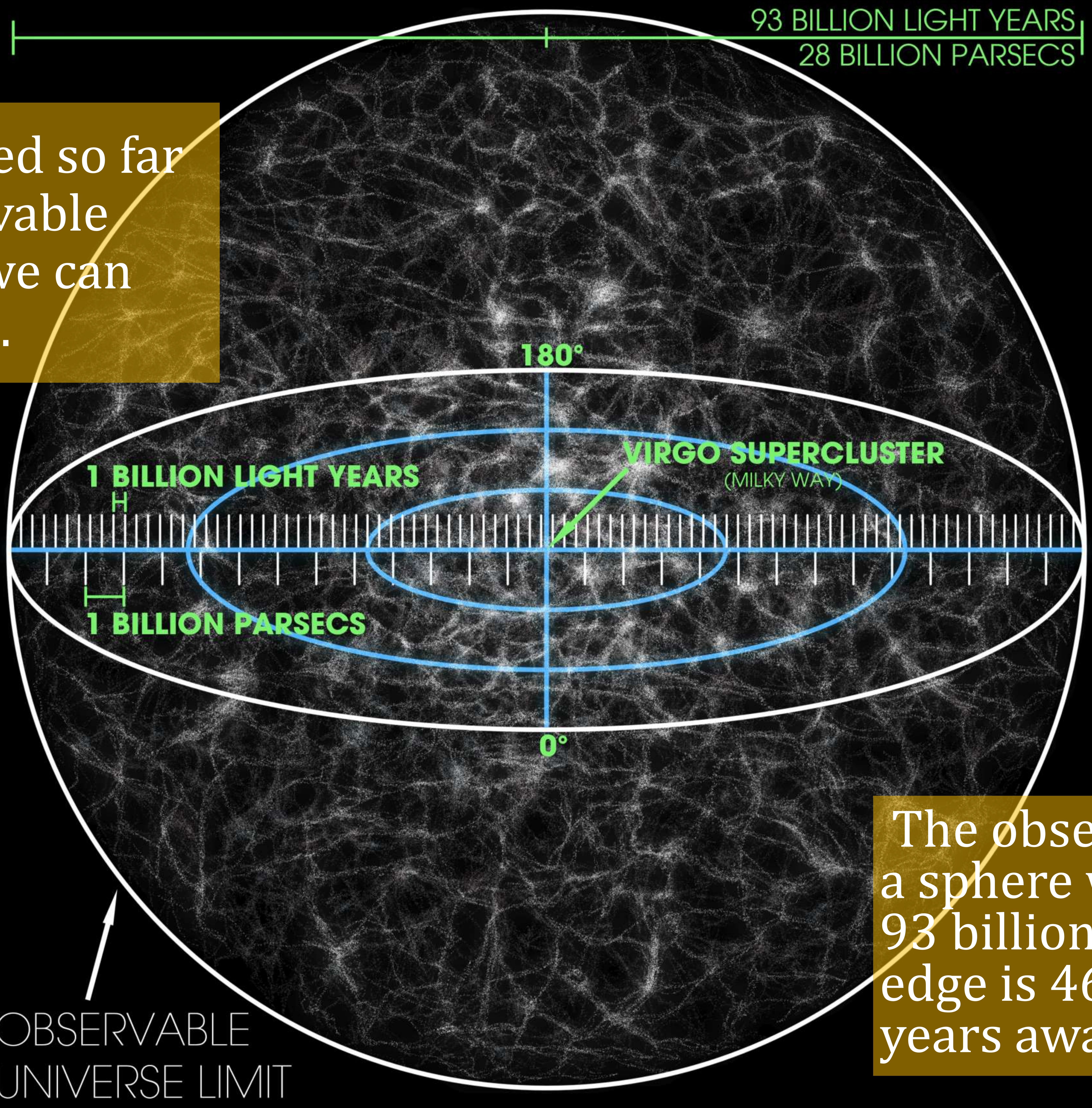
Timeline of the Universe
Credits: N. R. Fuller, NSF

The Big Bang

- Despite its name, the Big Bang wasn't an "explosion", it was simply the time when the expansion of the universe started.
- The universe has been expanding ever since, and might keep expanding forever.
- The universe isn’t expanding “into” anything. Instead, distances become longer.
- There are plenty of misconceptions about the Big Bang and the expansion of the universe! We'll discuss them in ASTR 1P02.

Map of the Cosmic Microwave Background
Credits: NASA / WMAP Science Team

Everything described so far is part of the observable universe: the part we can observe from Earth.



The observable universe is a sphere with a diameter of 93 billion light-years (the edge is 46.5 billion light-years away).

The Observable Universe
Credits: Andrew Z. Colvin

The observable universe

- The reason we can't see anything beyond the edge of the observable universe isn't that there's something in the way, or that our telescopes aren't good enough.
- It's because light takes time to travel. Objects outside the observable universe are so far away that the light from them has not had time to reach us yet.

The observable universe

- The "edge" of the observable universe is an imaginary line beyond which light cannot get to us.
- But there isn't any actual edge to the universe!
- Aliens living in a far away galaxy will see a different observable universe, with its edge at a different place.
- The aliens will see themselves at the center of their sphere.
- The size of the whole universe, including the parts that are NOT observable (but still exist), is unknown, and could potentially be infinite.

The observable universe

- The universe is 13.8 billion years old, and the edge of the observable universe is 46.5 billion light-years away.
- But if light travels at a rate of 1 light-year per year, then light could only have traveled 13.8 billion light-years since the Big Bang!
- So how can this be?
- The reason for this discrepancy is that the universe is expanding.
- The galaxies that are currently at the edge of the observable universe used to be much closer to us, but the distance to those galaxies expanded with time.

Powers of 10

- 10^n where n is any positive integer means 1 followed by n zeros.
- Thousand: $10^3 = 1{,}000$.
- Million: $10^6 = 1{,}000{,}000$.
- Billion: $10^9 = 1{,}000{,}000{,}000$.
- Trillion: $10^{12} = 1{,}000{,}000{,}000{,}000$.
- Quadrillion: $10^{15} = 1{,}000{,}000{,}000{,}000{,}000$.
- Quintillion: $10^{18} = 1{,}000{,}000{,}000{,}000{,}000{,}000$.

Powers of 10

- Multiplying two powers of 10:

$$10^n \times 10^m = 10^{n+m}$$

For example:

$$10^3 \times 10^9 = 10^{12}$$

$$\text{thousand} \times \text{billion} = \text{trillion}$$

Scientific notation

- Scientific notation is used to write very large numbers.
- It's always a number times a power of 10.

For example:

$$2.3 \times 10^6 = 2.3 \times 1{,}000{,}000 = 2{,}300{,}000$$

$$4.7 \times 10^{12} = 4.7 \times 1{,}000{,}000{,}000{,}000 = 4{,}700{,}000{,}000{,}000$$

Scientific notation

- Multiplying in scientific notation:

$$(a \times 10^n) \times (b \times 10^m) = (a \times b) \times 10^{n+m}$$

For example:

$$(1.5 \times 10^3) \times (3.0 \times 10^6) = 4.5 \times 10^9$$

$$(\text{because } 1.5 \times 3.0 = 4.5)$$

Quiz:

What is 2.0×10^9 times 4.0×10^6?

(A) 4.4×10^9

(B) 8.0×10^{15}

(C) 6.0×10^3

Answer: (B)

$$(2.0 \times 10^9) \times (4.0 \times 10^6) =$$

$$(2.0 \times 4.0) \times 10^{9+6} =$$

$$8.0 \times 10^{15}$$

Let's calculate the size of the observable universe:

$$\text{Size} = 93 \text{ billion ly} = 93 \times 10^9 \text{ ly}$$

$$(\text{ly} = \text{light-year})$$

$$1 \text{ ly} = 9.5 \text{ trillion km} = 9.5 \times 10^{12} \text{ km}$$

Quiz: Who can calculate the size in km?

$$\text{Size} = (93 \times 10^9 \text{ ly}) \times (9.5 \times 10^{12} \text{ km/ly})$$
$$= 883.5 \times 10^{21} \text{ km}$$

But 883.5 is almost 1,000, which is 10^3, so...

$$\text{Size of the observable universe} \approx 10^3 \times 10^{21}$$
$$= 10^{24} \text{ km}$$
$$= 1{,}000{,}000{,}000{,}000{,}000{,}000{,}000{,}000 \text{ km}$$

Video to watch

https://youtu.be/2iAytbmXYXE

An illustration of scales from humans to the whole universe.


The smallest things
in the universe

More math: negative powers of 10

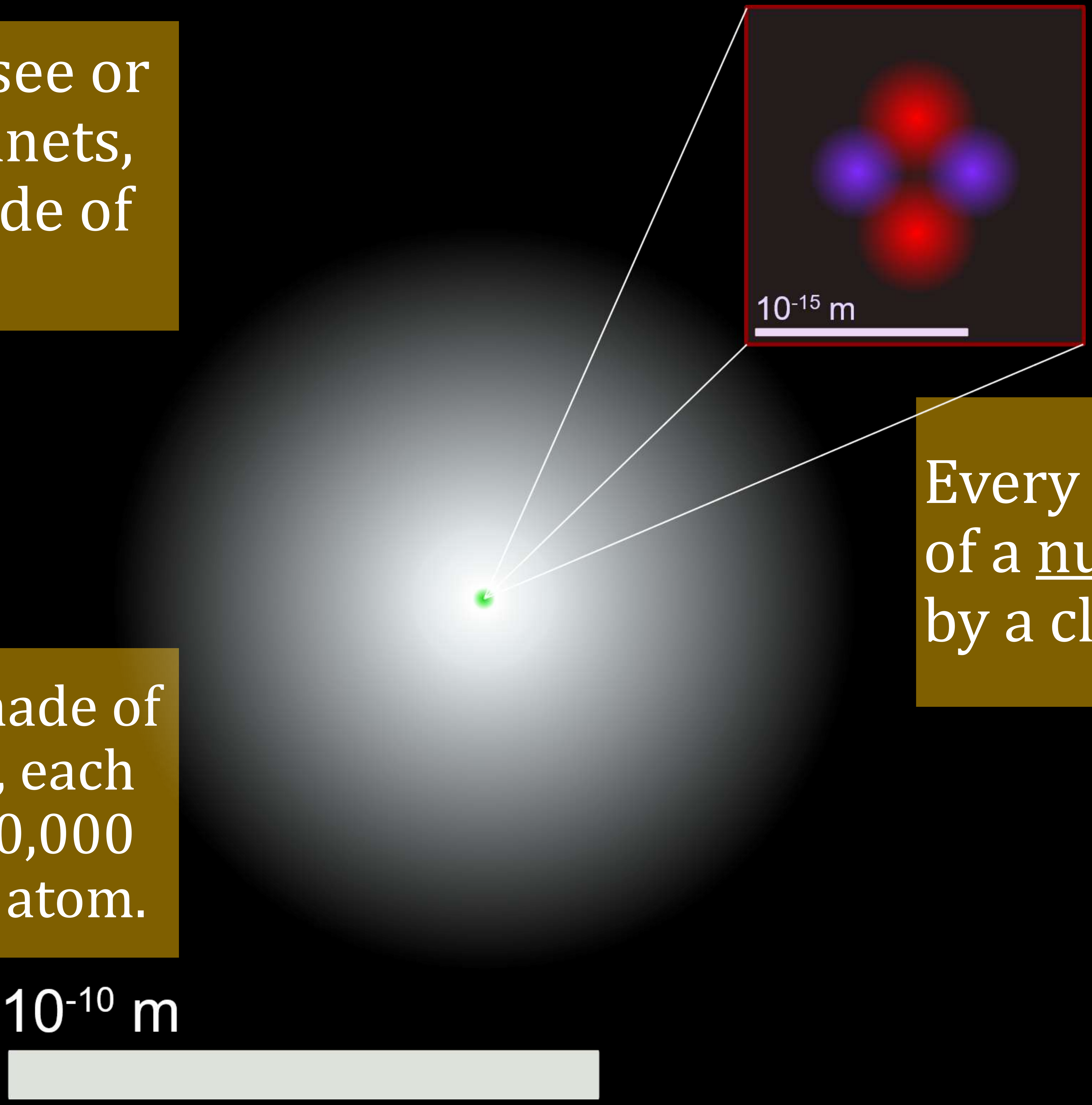
- 10^{-n} where n is any positive integer means 1 divided by 10^n.

$$10^{-n} = \frac{1}{10^n}$$

- 10^{-n} can also be written as n zeros followed by a 1 with a decimal point after the first zero. (Like an inverted 10^n.)

- Thousandth: $10^{-3} = \frac{1}{1,000} = 0.001$
- Millionth: $10^{-6} = \frac{1}{1,000,000} = 0.000\,001.$
- Billionth: $10^{-9} = \frac{1}{1,000,000,000} = 0.000\,000\,001.$

Most things we can see or detect, like stars, planets, and humans, are made of atoms.



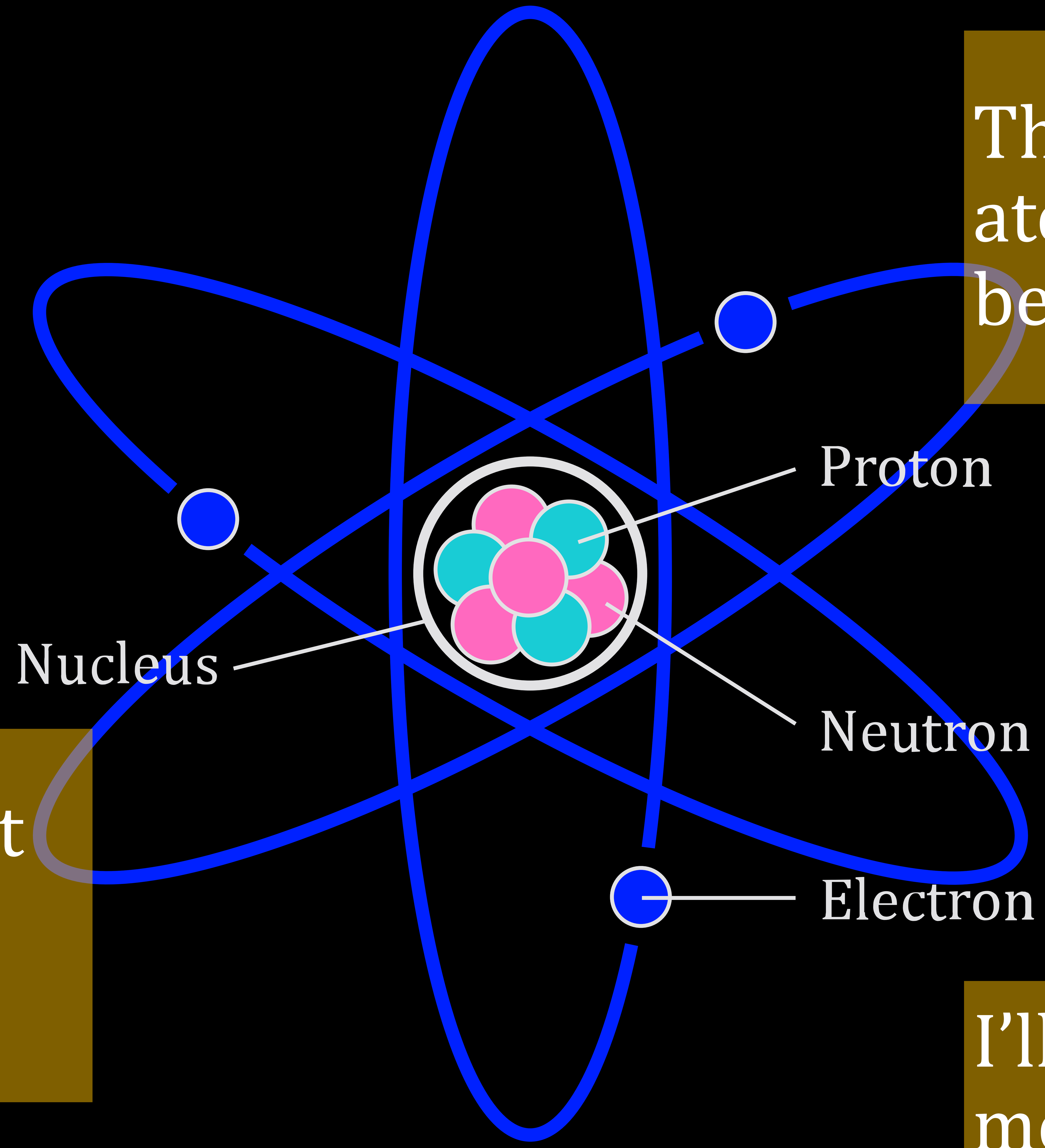
Every atom is composed of a nucleus, surrounded by a cloud of electrons.

The nucleus itself is made of protons and neutrons, each of which is around 100,000 times smaller than an atom.

A Helium Atom
Credits: Modification of work by Yzmo (Wikipedia)

Atomic scales

- Size of an atom: 10^{-10} m = 0.000 000 000 1 m
- Size of a nucleus: 10^{-15} m = 0.000 000 000 000 001 m
- Size of a proton or neutron: just a bit smaller than the nucleus.



This illustration of an atom you may have seen before is wrong!

The electrons don’t orbit the nucleus, they’re “probability clouds”.

I’ll explain what this means later when we learn about quantum mechanics.

Diagram of an Idealized Lithium Atom
Credits: Modification of work by AG Caesar (Wikipedia)

Elements

- There are 118 different types of atoms that we know of, which are also called chemical elements.
- All atomic matter in the universe is made of different combinations of these 118 elements.
- The number of protons, known as the atomic number, determines the type of the chemical element.
- Hydrogen has 1 proton, helium has 2 protons, and so on.

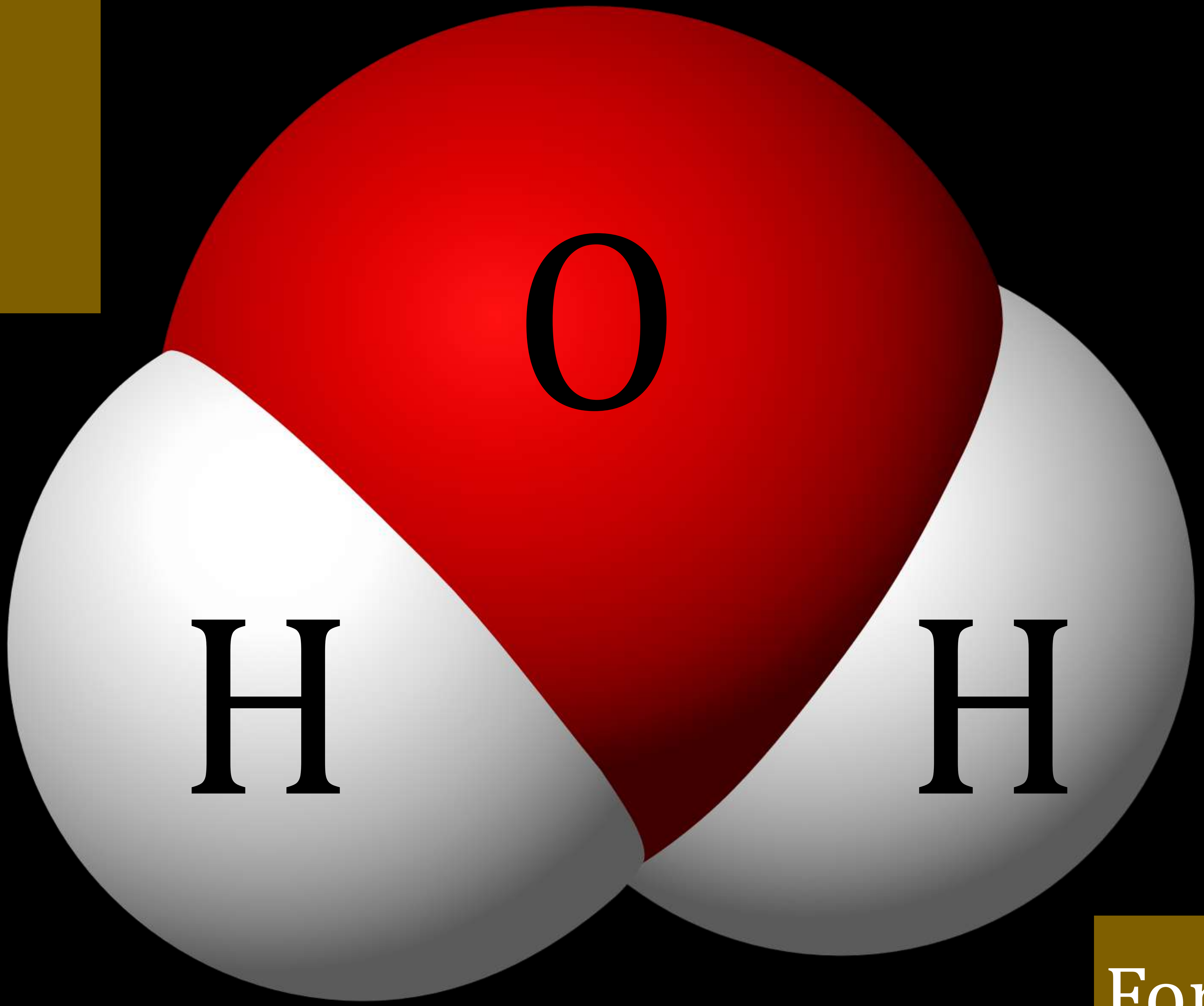
The Periodic Table of Elements

Credits: Modification of work by Robert Campion

Abundance of elements

- Hydrogen (1 proton) is the most common element. It makes up 74% of atomic matter.
- Helium (2 protons) makes up 24% of atomic matter.
- The other 116 elements make up the remaining 2%!

Some matter is made of molecules, which are groups of two or more atoms bonded together.



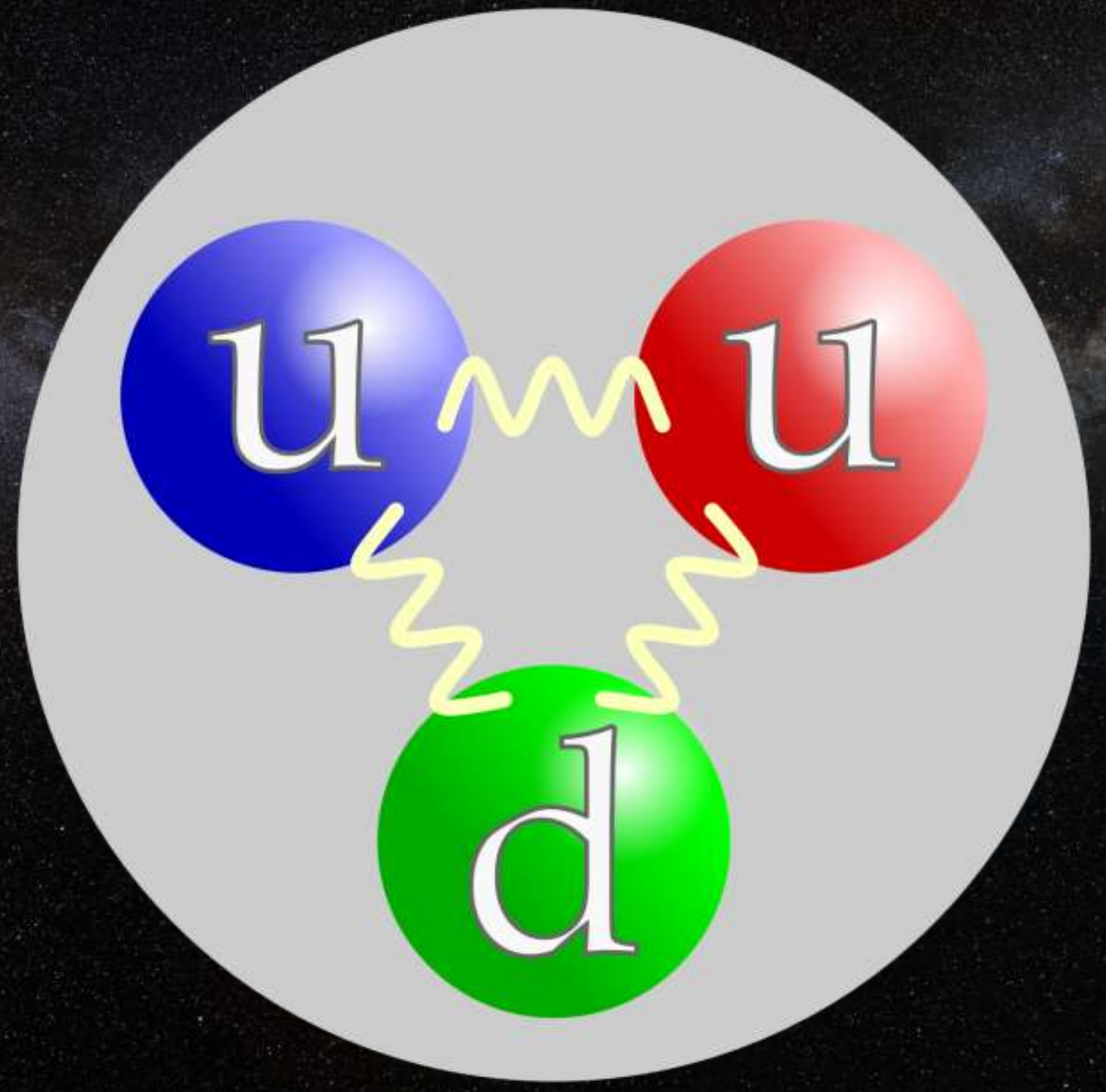
For example, water is made of water molecules, which consist of 2 hydrogen atoms and 1 oxygen atom.

A Water Molecule

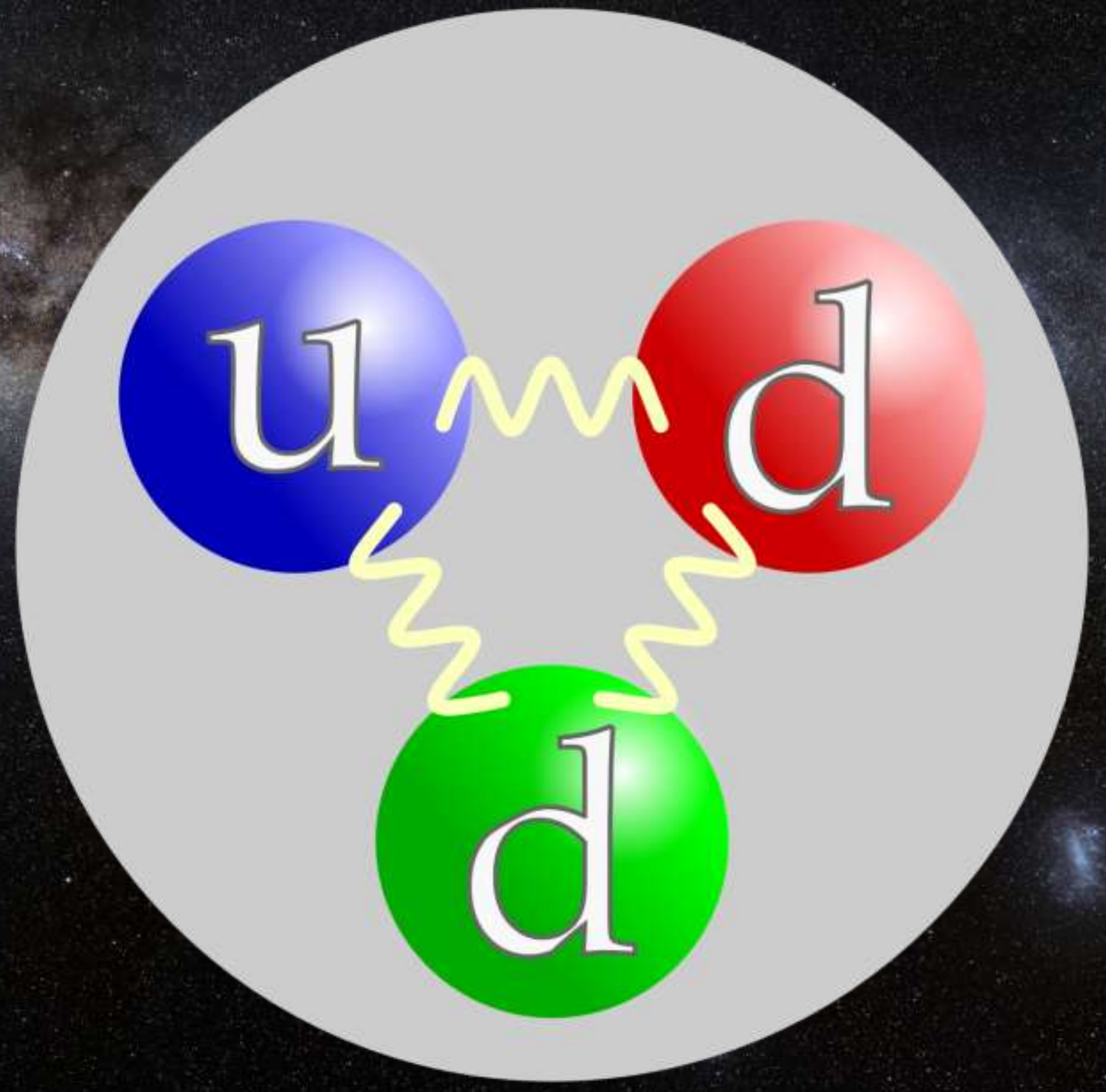
Credits: Modification of work by Dbc334 and Jynto (Wikipedia)

Elementary particles

- The protons and neutrons in the nucleus are made of particles called up and down quarks.



Proton:
2 up quarks
1 down quark



Neutron:
1 up quark
2 down quarks

Elementary particles

- So all atomic matter in the universe is actually made of just 3 kinds of particles: electrons, up quarks, and down quarks.
- As far as we know, electrons and quarks are not made of any smaller particles, which is why we call them elementary particles.
- Another common elementary particle is the photon: the particle of light and electromagnetic radiation.
- There are other more “exotic” elementary particles which we won’t learn about right now.

Subatomic scales

- The sizes of elementary particles are unknown and hard to define, since in quantum mechanics, small things are “fuzzy”.
- They might be just points with no size!
- Quark: less than 10^{-19} m = 0.000 000 000 000 000 000 1 m.
- Electron: less than 10^{-22} m = 0.000 000 000 000 000 000 000 1 m.

From smallest to largest scales

- Smallest thing – electron: less than 10^{-22} m
- Largest thing – observable universe: 10^{24} km $= 10^{27}$ m
- Difference: 49 orders of magnitude (powers of 10).

- An electron is (at least)…

10,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000

times smaller than the observable universe!

- And remember that the entire universe (including the non-observable parts) could be infinite.

Human scales

- Humans: around the middle at approximately $1 = 10^0$ m.
  - 27 orders of magnitude smaller than the observable universe. We are completely negligible!
  - 22 orders of magnitude larger than an electron.
- The farthest from Earth humans have been is the Moon, around 380,000 km $= 3.8 \times 10^8$ m away.
- That is like moving 1 atom away if the observable universe was the size of the Earth.
- We have a long way to go…

Human scales

- Where can we go?
- We've sent probes to other places in the solar system: planets, moons, asteroids… But not humans.
- Human missions to the Moon took 3-4 days.
- We want to send humans to Mars. This will take several months.

Human scales

- Closest star: Proxima Centauri, 4.2 light-years or 4×10^{13} km away.
- Fastest human-made spaceship: NASA's Parker Solar Probe, expected to reach 690,000 km/h.
- This is still just 0.06% of the speed of light.
- Traveling to Proxima Centauri at that speed will take 6,500 years!

Human scales

- The Andromeda galaxy is located 2.5 million light-years away.
- At 690,000 km/h, it would take 4 billion years to reach it.
- Even if could travel close to the speed of light, it would still take it at least 2.5 million years to travel to Andromeda. There's no way to travel faster than light.

Human scales

- Humans will never be able to travel to Andromeda with any conceivable technology.
- And that's the closest galaxy to us. The edge of the observable universe is 46.5 billion light-years away!
- We are stuck forever in the Milky Way galaxy.

Time scales

- Finally, let's talk a bit about time…
- The universe is 13.8 billion years old.
- Modern humans evolved from earlier hominid species around 300,000 years ago.
  - This is around 20,000 times shorter than the age of the universe.
- The recorded history of humanity only began around 5,000 years ago.
  - This is roughly 3 million times shorter than the age of the universe.

Time scales

- Recall: there are 31.6 million seconds in a year.
- If the universe only existed for one year, then…
  - Humans have only existed for the last 25 minutes of that year.
  - All of recorded history has only existed for the last 10 seconds of that year.
- So if the Big Bang took place at midnight on January 1st, then…
  - Humanity only appeared on December 31st at 23:35.
  - Recorded history only started at 23:59:50.

Conclusion

- I hope this lecture made you interested in learning more about astronomy and the universe!
- I tried to give you an idea of just how immense and astonishing the universe is in terms of distance and time scales.

- Reading: OpenStax astronomy, chapter 1 and appendices A-D.
- Further exploration: See the end of chapter 1 for some books, websites, and videos.
- Exercises: Practice questions are available in the textbook and on the course website.