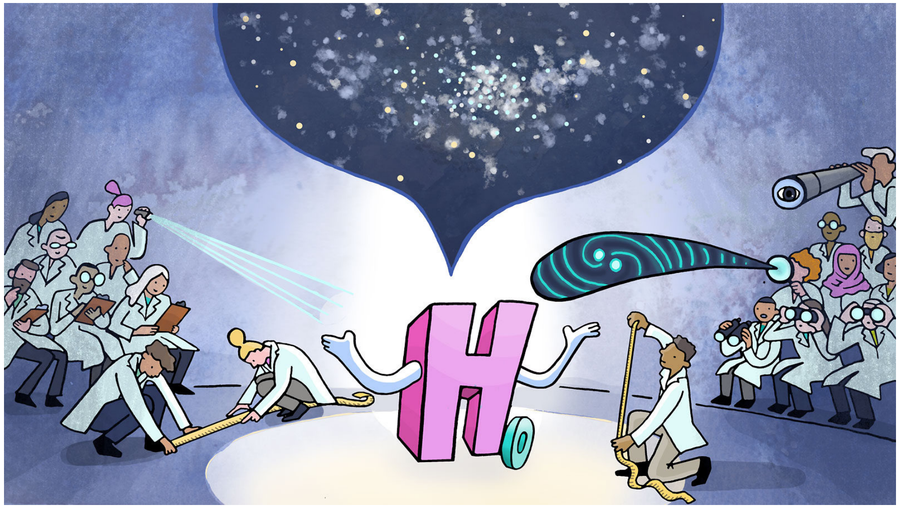
Progress in an Unexpected Direction: Exciting Challenges in Fundamental Physics



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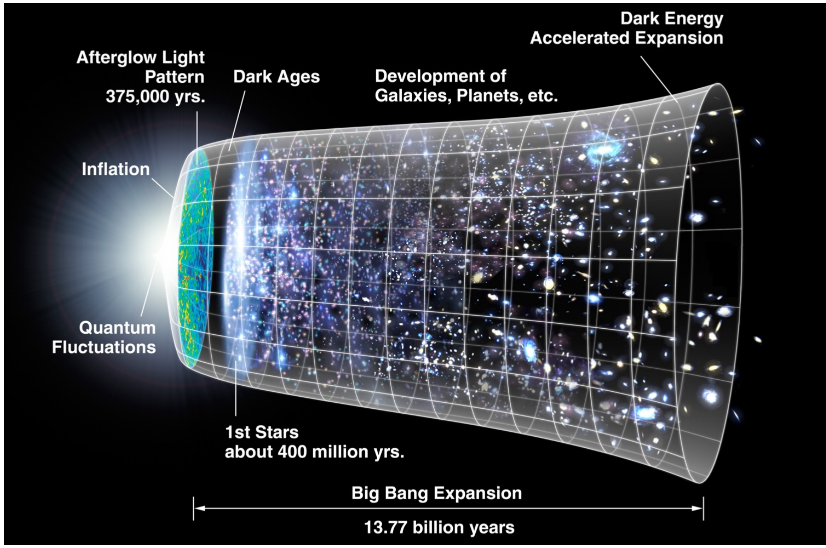
Today I'll discuss 2 instances of **unexpected evidence** (or lack thereof) that has come to light in fundamental physics, and the challenges that evidence has presented



I'll end by looking at how fundamental physics was in a similar state over a hundred years ago – presented with unexpected evidence – which became the **opportunity** that led to the revolution in physics in the middle decades of the 20th century, the development of *quantum mechanics, relativity, particle physics, cosmology, and much more*

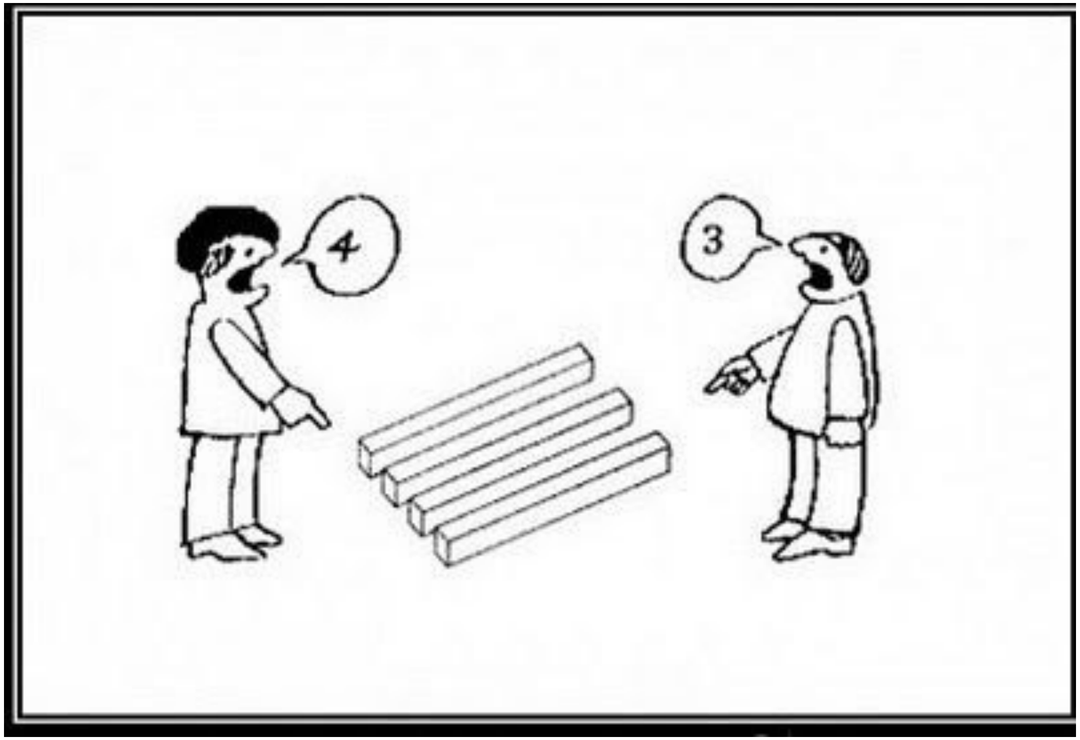
My hope is to help you understand some interesting physics, but also to show you that science isn’t always steadily progressing forward as scientists might expect, and sometimes problems go unsolved for a very long time

A quote from Isaac Asimov sums it up:

“The most exciting phrase to hear in science, the one that heralds new discoveries, is not “Eureka!” (I found it!) but “That’s funny…”

Unexpected Problem #1

The Hubble Tension

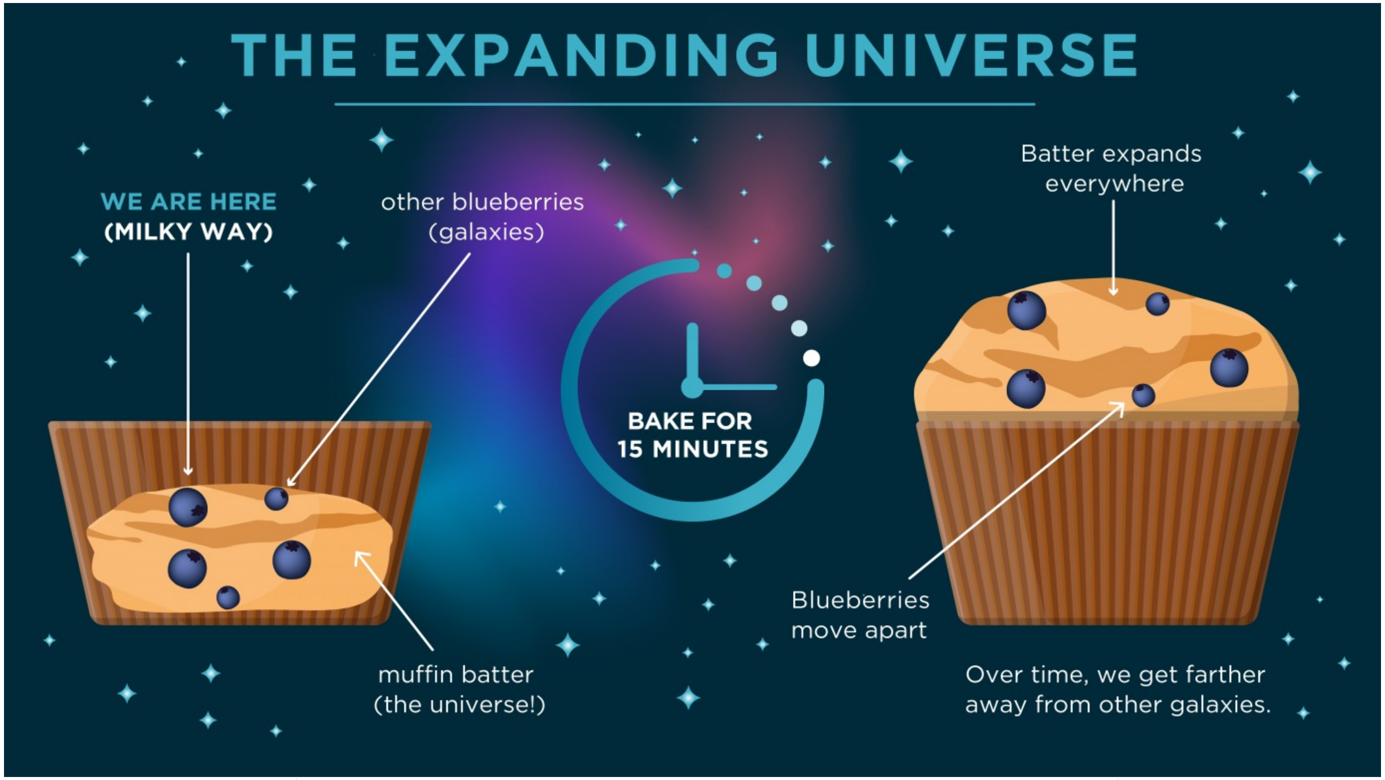


The Hubble Tension

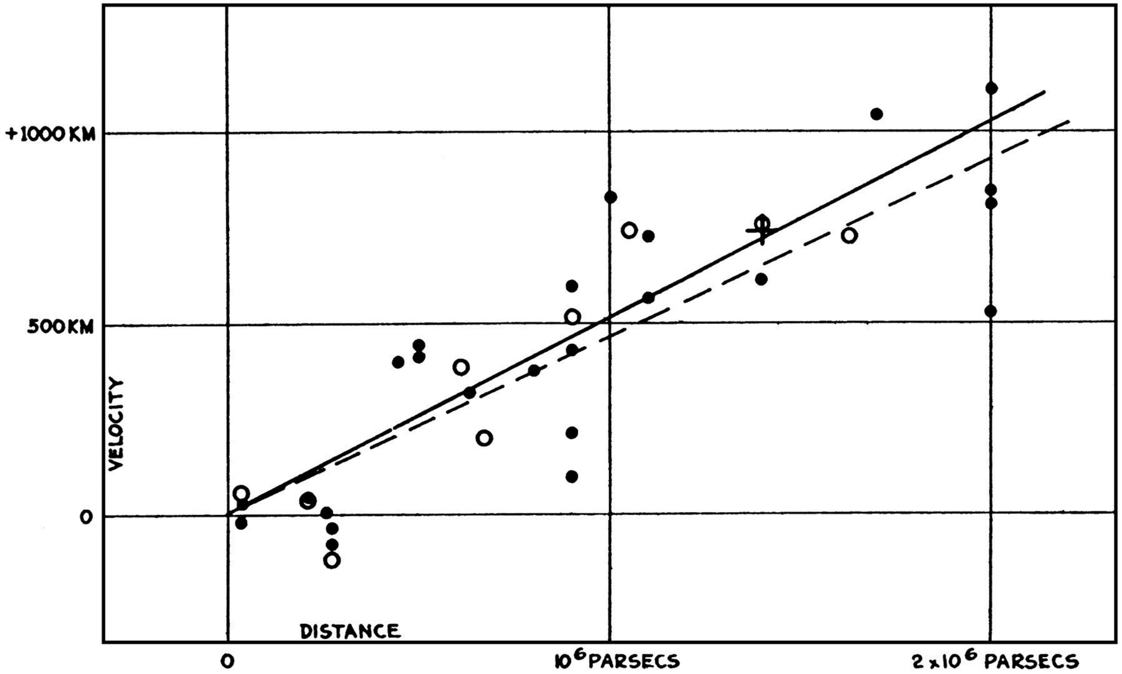
An arena of modern physics research is *cosmology,* the study of the overall structure and formation of the universe

Our current best picture of cosmology begins with the Big Bang when the Universe began to expand

- Hubble discovered that the universe is still expanding today! What does that mean?
  - Stars and galaxies are **<u>not</u>** just spreading out into empty space – *space itself* is expanding. There's just more space than there used to be
  - The result is that most things in space are moving away from us when we look at them
  - But, since every bit of space is expanding, things further away will be moving away from us faster than things that are closer



Hubble was able to measure how quickly far away galaxies were moving from earth in 1929 and determined how fast the universe was expanding – he measured 500 kilometers per second per megaparsec



That means that every megaparsec you go away from earth, galaxies are on average moving away 500 km/s faster

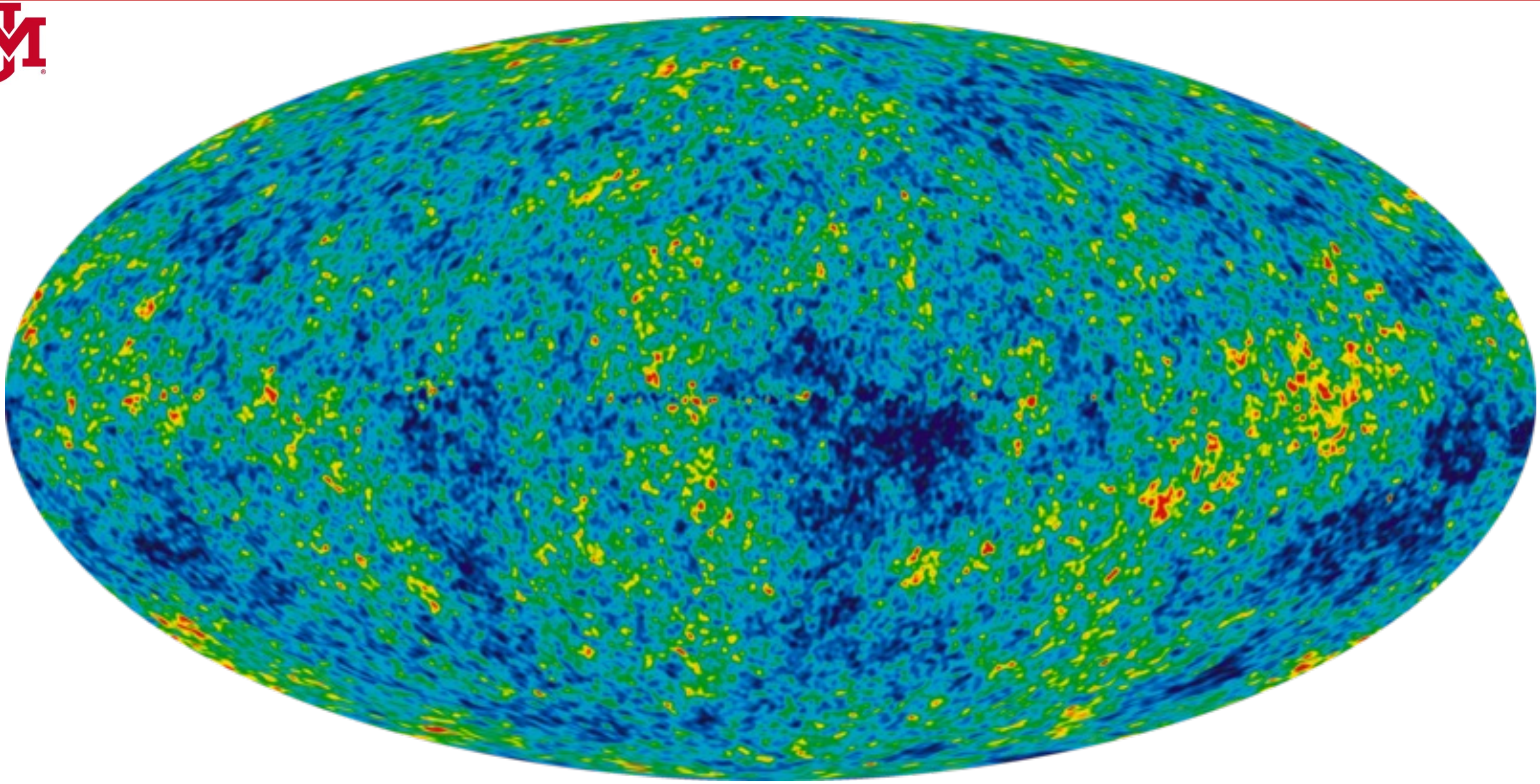
It also means a bubble of space that is 1 Mpc in diameter gets 500 kilometers larger every second

We call this value the 'Hubble Constant' or H_0, and it's one of the most important values in cosmology

We have made a lot of progress since then and it turned out Hubble made some mistakes. Today, cosmologists have made very precise measurements using similar methods

Basically, the method is the same - we look at a lot of galaxies, measure how fast they are moving away from us and how far they are away, and that lets us calculate H_0

Using this method, the most recent measurements give a value of **73.04 ± 1.04 km/s/Mpc**



Cosmologists have come up with another way to measure $H_{0,}$ using the Cosmic Microwave Background (CMB)

The CMB is microwave radiation that is all around us that is left over from processes in the very early universe – the radiation is over 13 billion years old!

That radiation has a temperature of about 2.7 Kelvin, but it has tiny variations in temperature, which cosmologists have measured very precisely

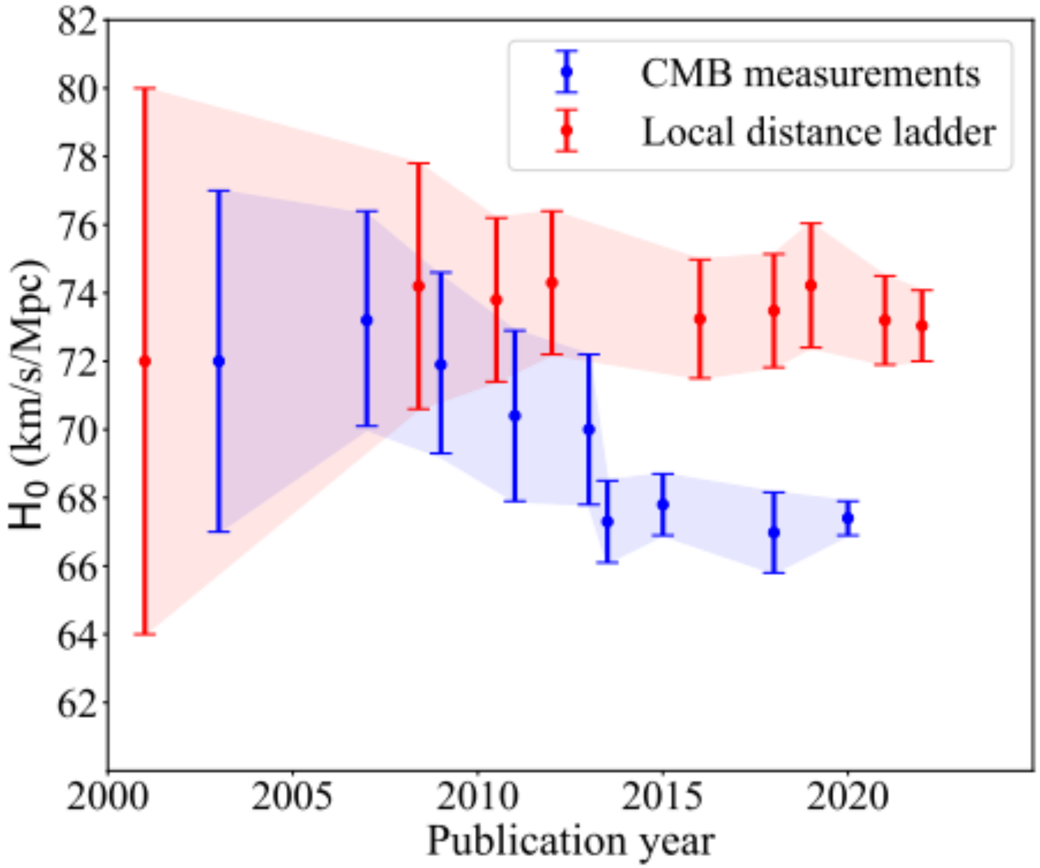
These little variations in temperature tell us about how the early universe evolved

We then use our best cosmological model, the ΛCDM model, and we can ask "what value of H_0 would give us the pattern of variation that we see?"

Using this method, cosmologists have measured a value of **67.4 ± 0.5 km/s/Mpc**

Over the last 20 years, these two types of measurements have shown increasingly different results

Today, the 2 measurements are well outside the margin of error – they **fundamentally disagree** even though they are supposed to be measuring the same thing



Why?

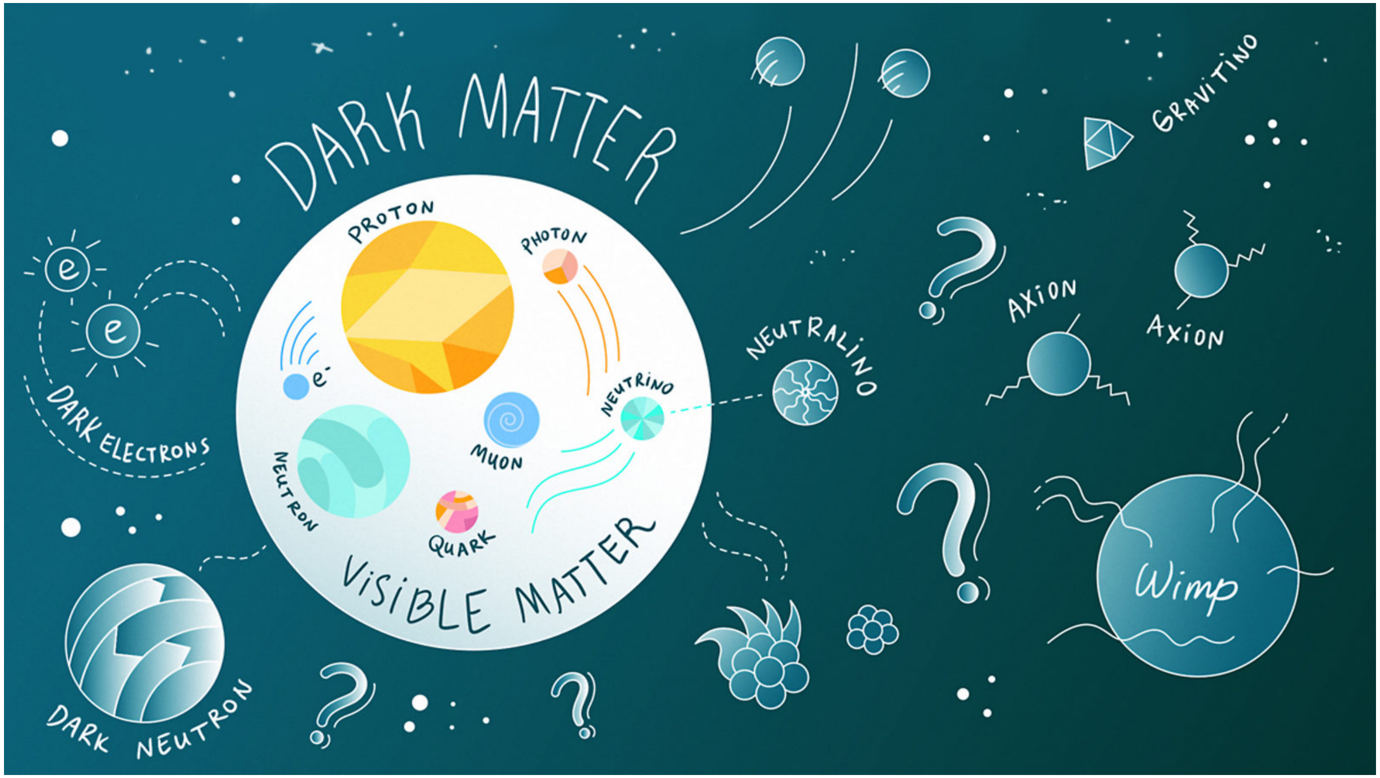
Basically, the answer is we don’t know - yet

One or both of them must be wrong

Cosmologists are hard at work trying to figure this out. This measurement difference is what we call the **Hubble Tension**

Unexpected Problem #2

What is Dark Matter?



Dark Matter

Particle physicists study the fundamental constituents of nature, and the forces via which they interact

Our best current theory is called the 'Standard Model'

The Standard Model was developed by the end of the 70's and has been experimentally confirmed over and over again since then

In fact, nothing has ever happened in a particle physics experiment that wasn't predicted within a margin of error by the Standard Model

There are just a few issues that we know of. One comes from Astrophysics:

Astrophycists can use telescopes to measure the orbital path and period of orbit for stars around a galaxy

The path and how long it takes to orbit should be predictable by Einstein's theory of general relativity

We just need to count the stars, figure out how much mass they have, and that should tell us how any one star should orbit

Astrophysicists have done this, but they found that many stars aren’t moving in the path we predict

In fact, it doesn’t seem like there’s enough mass in many galaxies to ‘hold onto’ stars near the edge of the galaxy – according to our best understanding of gravity, **they should be flying out into empty space**

If we assume there’s extra mass in the galaxy, and then make a prediction for the path and period of orbit for a star, then we can get a good prediction

This indicates that there is indeed some extra mass inside of these galaxies that we can’t see with our telescopes. We refer to this extra hidden mass as **Dark Matter**

But the question remains – what is Dark Matter? All we know is that it has mass and that there is a lot of it out there – in fact there seems to be about 5 times as much dark matter as "regular" matter

Everything we can see in the universe behaves in ways that make sense according to the Standard Model

There is no particle in the Standard Model that should be "Dark" – it should sometimes interact in ways we can trace with a telescope

Despite looking for 50 years, no one has yet found any of these theoretical dark matter particles

But that **doesn't** mean that no progress has been made

Theoretical physicists have theories by the thousands, but experiments have *dramatically* constrained the possible scenarios for what will eventually be the correct one

Every time we have come up empty handed, we learn that many old ideas are incorrect, and have the opportunity to come up with newer, better ideas, and we **keep searching for the answers**

Now for a look back in history…

It turns out in the late 1800's physicists were in a place where we had really good theories that explained virtually every observation in every physics experiment, we just had a few nagging issues that we needed to understand…

By the late 1800's many physicists thought they had figured out the fundamentals of physics

The theories consisted primarily of:

- Newton's theory of gravity and mechanics
- James Clerk Maxwell's theory of Electromagnetism

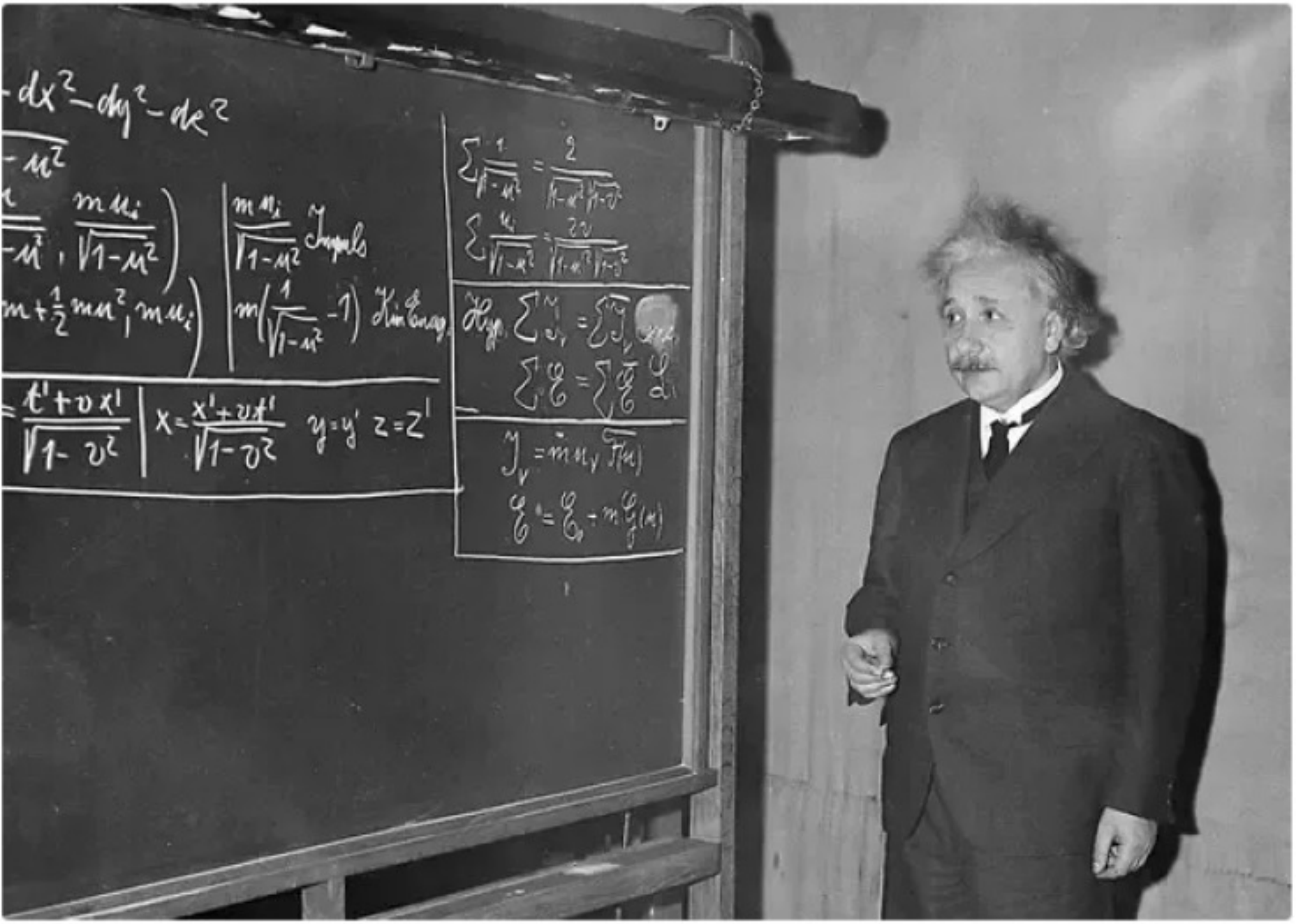
formulated in the 1860's

- The theory of classical Thermodynamics
- Atomic theory, that the fundamental building blocks of nature were atoms, the different types of which are on the periodic table

Many experiments were done that showed that these theories predicted a huge array of physical phenomena in nature, making many physicists confident that humans pretty much had a complete picture of physical reality

There is a famous quote that sums up the viewpoint of many physicists of the time, from the famous physicist Albert Michelson:

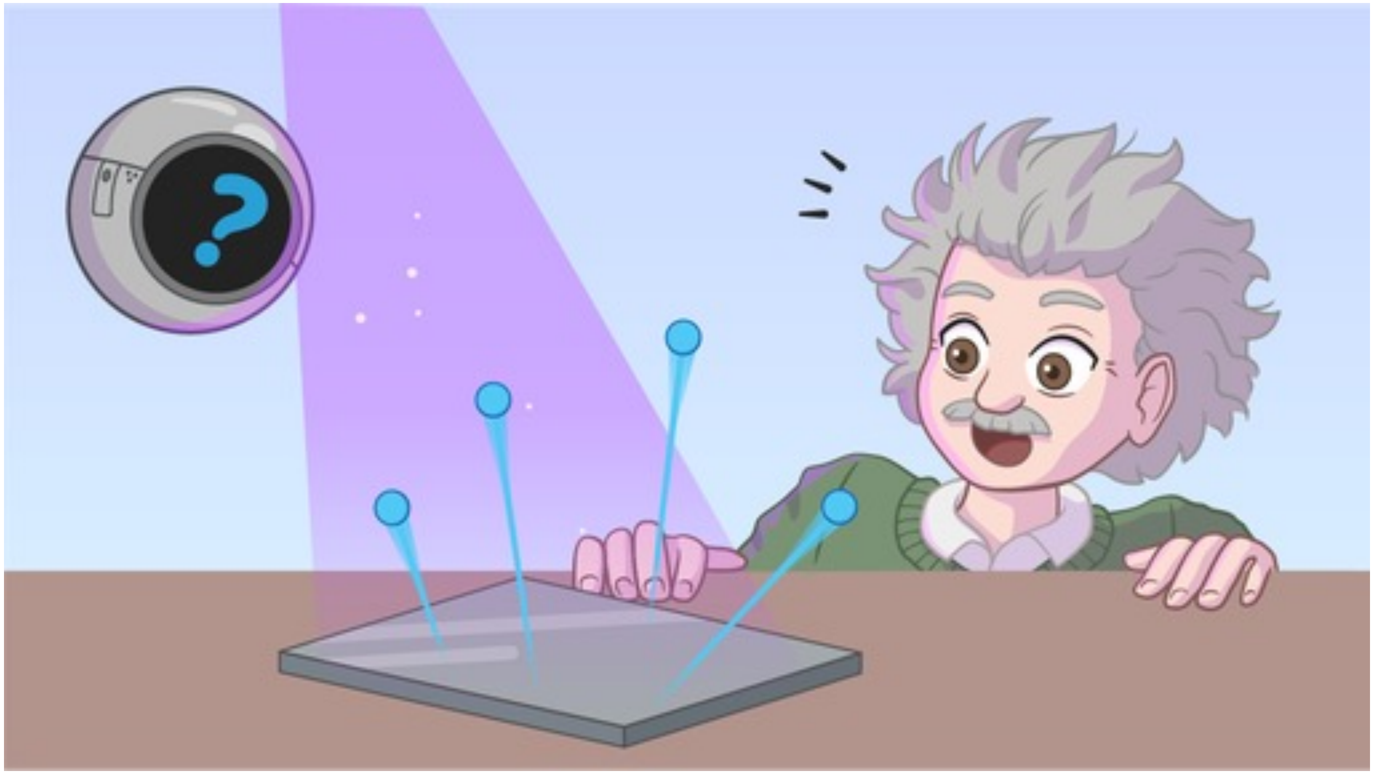
"While it is never safe to affirm that the future of Physical Science has no marvels in store even more astonishing than those of the past, it seems probable that **most of the grand underlying principles have been firmly established… the future truths of physical science are to be looked for in the sixth place of decimals"**

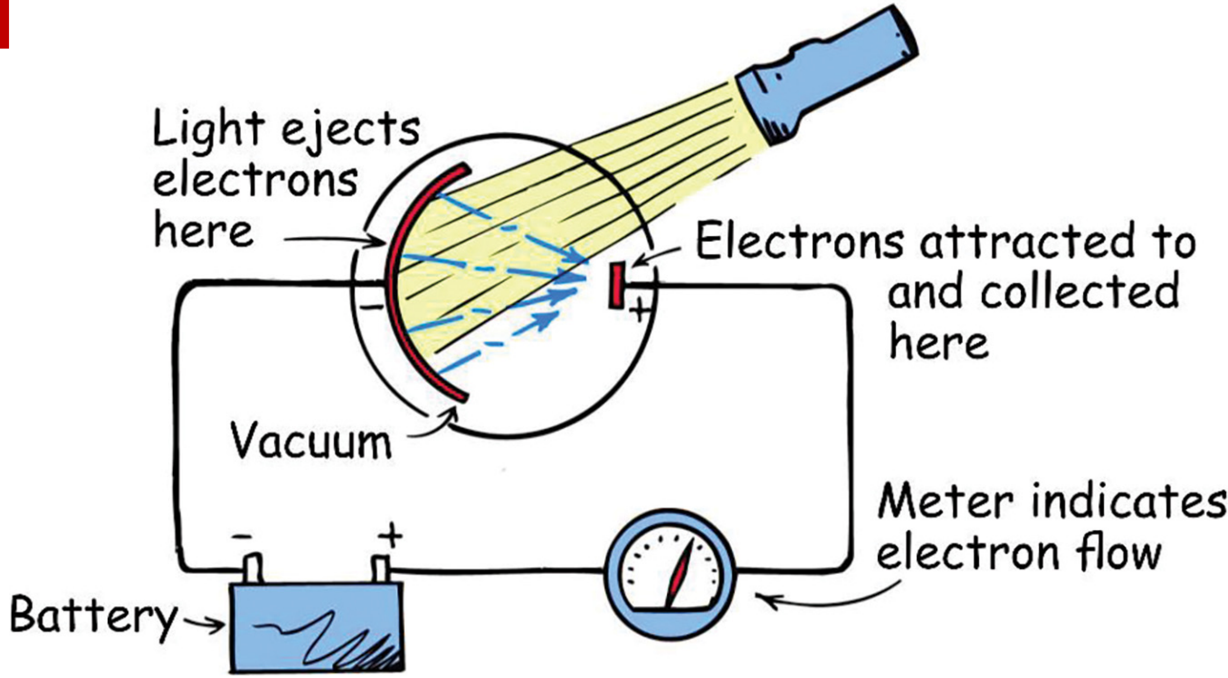


However, around 1890-1910 many problems reared their heads, one notable one was called…

Unexpected Problem #3

The Photoelectric Effect





Physicists had figured out that if you shine a light on certain metals, it will eject charged particles (we now know them as electrons)

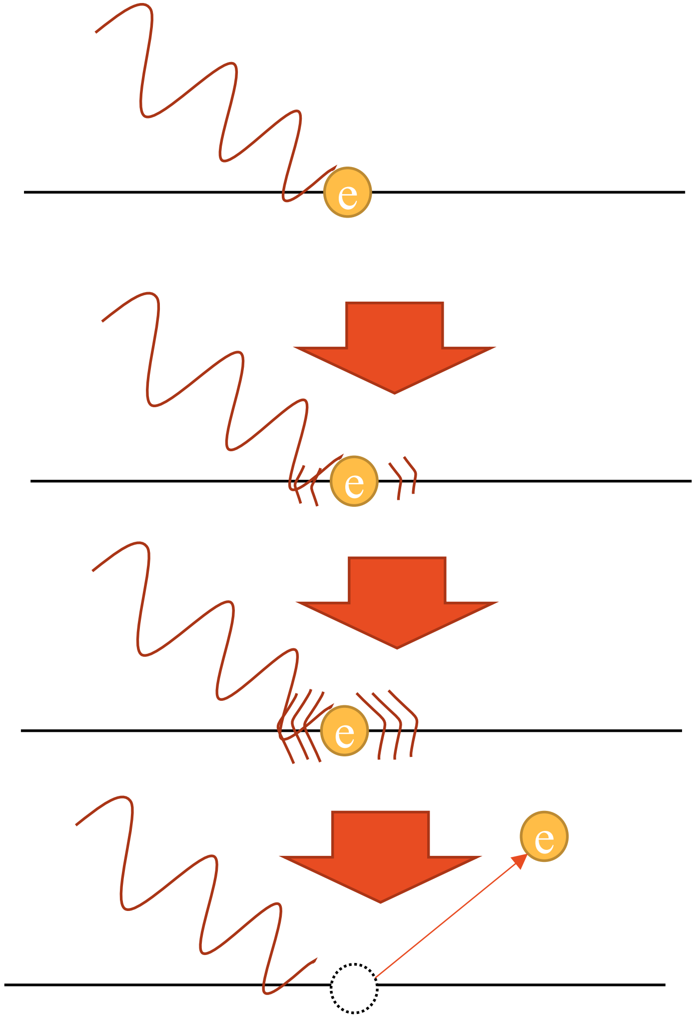
At the time, light was understood to be a continuous wave. It does not have any one particular location, it is spread out in space

The amount of energy delivered was thought to be based solely on the intensity of the light – basically how bright the light was (More light = more energy)

It stood to reason, then, that if **more intense light** were used, the ejected electrons would be **more energetic**

Another prediction based on the best physics of the time was that it would take a bit of time for the light to gradually transmit energy, since light was a continuous wave

Because of this, there should be some time delay to release the electrons, because they are initially ‘stuck’ to the metal sheet and need to be gradually energized – like a water molecule being freed once the water has gotten hot enough to boil



What actually happened in 1887 when Heinrich Hertz did this experiment?

Hertz discovered that if he used low-frequency electromagnetic waves (light), like infrared radiation, the electrons would **not** be released, even if he used a very intense light

If he used high frequency light, like UV light, the electrons would be released. Higher frequency light made the electrons escape with higher energy. Intensity had nothing to do with it

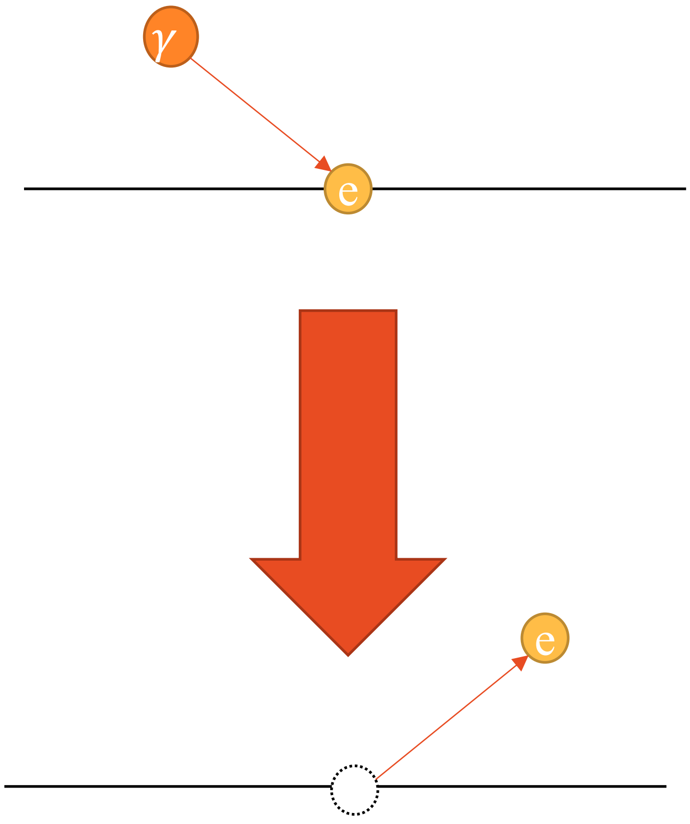
Further, there was no time delay, the electrons would be freed instantaneously from the metal

This was a very unexpected result, and confused physicists for almost 20 years

In 1905, Einstein figured out what was happening:

He said that the light was actually made up of little ‘corpuscles’ or discrete packets, which would eventually be called photons

The energy of a single photon depended on the frequency, and only one photon could knock out one electron, so there was no gradual energizing



This theory was unexpected, it was thought to be well established that light was a continuous wave, not a particle.

Newton had though light was a type of particle, and one of the great triumphs of 19^{th} century physics was finding conclusive evidence that Newton was wrong!

This certainly wasn’t a deviation “in the 6^{th} decimal place”

A famous physicist named Robert Millikan is quoted 10 years after Einstein’s paper, saying that this theory was “quite unthinkable”

Eventually, Millikan himself did experiments that helped prove the particle nature of light

This result is often pointed to as one of the first inklings that led to the development of **Quantum Mechanics**, which became the new paradigm through which all of fundamental physics is now understood

Quantum mechanics is also the basis of our understanding of almost all of chemistry, semiconductors (the basis of all computers), and much more

The unexpected result of Hertz in 1887 took 18 years before Einstein could figure it out, and was still highly disputed among scientists for another 15 years, when evidence for Einstein's theory became overwhelming and he was awarded the 1921 Nobel Prize

This unexpected problem has been definitively solved!

Conclusions

- The Hubble Tension and Dark Matter are two big mysteries in physics today
- The Hubble Tension is relatively new, but we've been coming up empty in Dark Matter searches for several decades
- We haven't been spinning our wheels - we've just learned a lot about what the true theory of fundamental physics **isn't**
- We need the next generation of physicists to come up with new ideas to continue to push our theories closer to the truth
- We've been here before – presented with unexpected evidence that is not just a little bit different from our expectation, but WAY off – and through theories, observations and long debates, the truth won out