A Little Astrophysics-From the Big Bang to Now

II Big Bang Model

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All scientific knowledge is provisional, and completely subject to revision

Big Bang Theory

- Space, matter and energy of the universe were contained in a volume smaller than a period

- How this tiny pinpoint universe came into existence is unknown
- It could only expand
- Its expansion is called the Big Bang

Big Bang Theory

- The big bang theory describes the development of the universe from the time just after it came into existence up to today
- It's one of several scientific models that attempts to explain why the universe is the way it is
- The theory makes several predictions, many of which have been proven through observational data
- As a result, it's the most popular and accepted theory regarding our universe's development.
- Many people think that the big bang is about a moment in which all the matter and energy in the universe was concentrated in a tiny point
- Then this point exploded, shooting matter across space, and the universe was born
- In fact, the **big bang** explains the **expansion of space itself**, which in turn means everything contained within space is spreading apart from everything else
- *At the earliest moments of the **big bang**, all of the matter, energy and space we could observe was compressed to an area of zero volume and infinite density*
- Cosmologists call this a **singularity**
- A **gravitational singularity** (or space-time singularity) is a point in which all physical laws are indistinguishable from one another, where space and time are no longer interrelated realities, but merge indistinguishably and cease to have any independent meaning

Big Bang Theory

- What was the universe like at the beginning of the big bang?
- According to the theory, it was extremely dense and extremely hot
- There was so much energy in the universe during those first few moments that matter as we know it couldn't form
- But the universe expanded rapidly, which means it became less dense and cooled down
- As it expanded, matter began to form and radiation began to lose energy
- In only a few seconds, the universe formed out of a singularity that stretched across space
- At the beginning of the big bang there was one **unified force**
- As the universe expanded the **unified force** was split into the four basic forces in the universe

  Electromagnetism

  Strong nuclear force

  Weak nuclear force

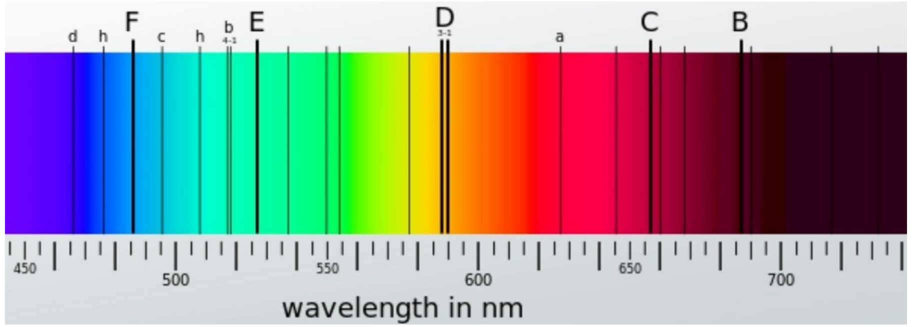
  Gravity
- How these forces were once part of a unified whole is a mystery to scientists
- Many physicists and cosmologists are still working on forming the **Grand Unified Theory**, which would explain how the four forces were once united and how they relate to one another

Big Bang Theory

- The big bang theory is the result of both **theory** and **observations**
- Theory from:
  - Newton
  - Einstein
  - Lemaitre
  - Friedmann
- Observations from:
  - Doppler
  - Hubble
  - Penzias and Wilson
- Basic physics experiments by many others

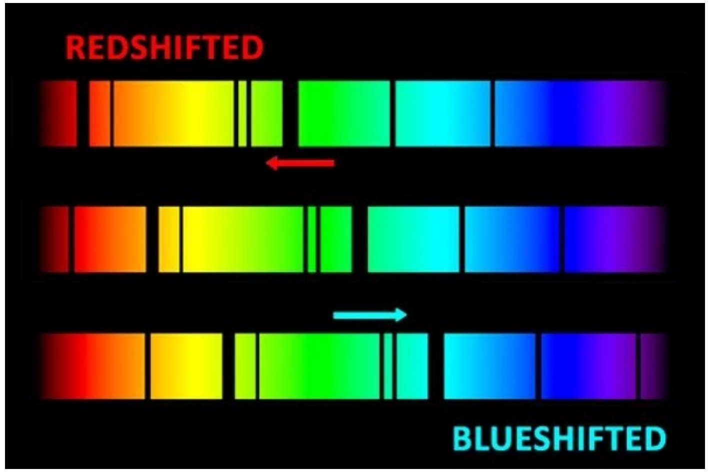
- The big bang theory is the result of both **theory** and **observations**

- In the 1800s, astronomers began to experiment with tools called **spectroscopes**
- A spectroscope is a device that divides light into a **spectrum** of its **component wavelengths**
- Spectroscopes showed that with the light from a specific material you could figure out what kind of **elements** were in a light source



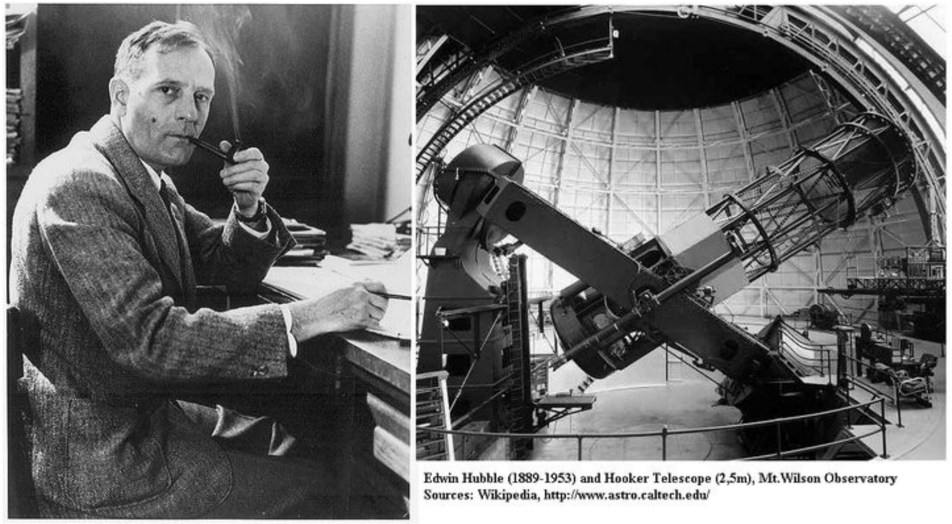
Big Bang Theory

- Austrian physicist **Christian Doppler** discovered that the frequency of a sound or light wave depended upon the relative motion of the source of wave
- As an object approaches, the waves compress
- As an object moves away, the waves stretch
- The **Doppler effect**
- Astronomers discovered that some stars had more light falling into the red side of the spectrum
- This meant the stars were moving away from Earth
- As the stars move away, the wavelengths from the light they emit stretch shifting to the red part of the spectrum
- The **redshift**
- The farther toward the red end of the spectrum the light shifts, the faster the star is moving away



Big Bang Theory

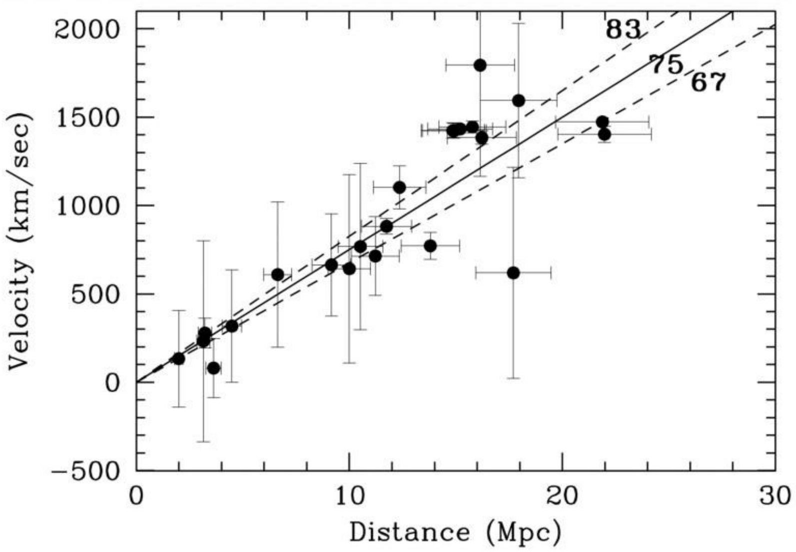
- In the 1920s **Edwin Hubble** observing stars' red shifts found that the velocity of a star appeared to be proportional to its distance from the Earth
- The farther away a star was from Earth, the faster it appeared to move away from us
- This meant the universe itself was expanding



Edwin Hubble (1889-1953) and Hooker Telescope (2,5m), Mt.Wilson Observatory
Sources: Wikipedia, http://www.astro.caltech.edu/

- This relationship is called the **Hubble constant-** not really a constant
- **Hubble Constant** - 67.4 kilometers/second per megaparsec
- Megaparsec is equal to more than 3.08×10^{22} meters (or 1.9×10^{19} miles)

Hubble's Law (modern data)



Big Bang Theory

- **Hubble** theorized that the universe expands as time passes
- That meant billions of years ago, the universe would have been much smaller and more dense
- If you go back far enough, the universe would collapse into an area with infinite density, containing all the matter, energy, space and time of the universe
- In a way, the big bang theory came as a result of backwards engineering

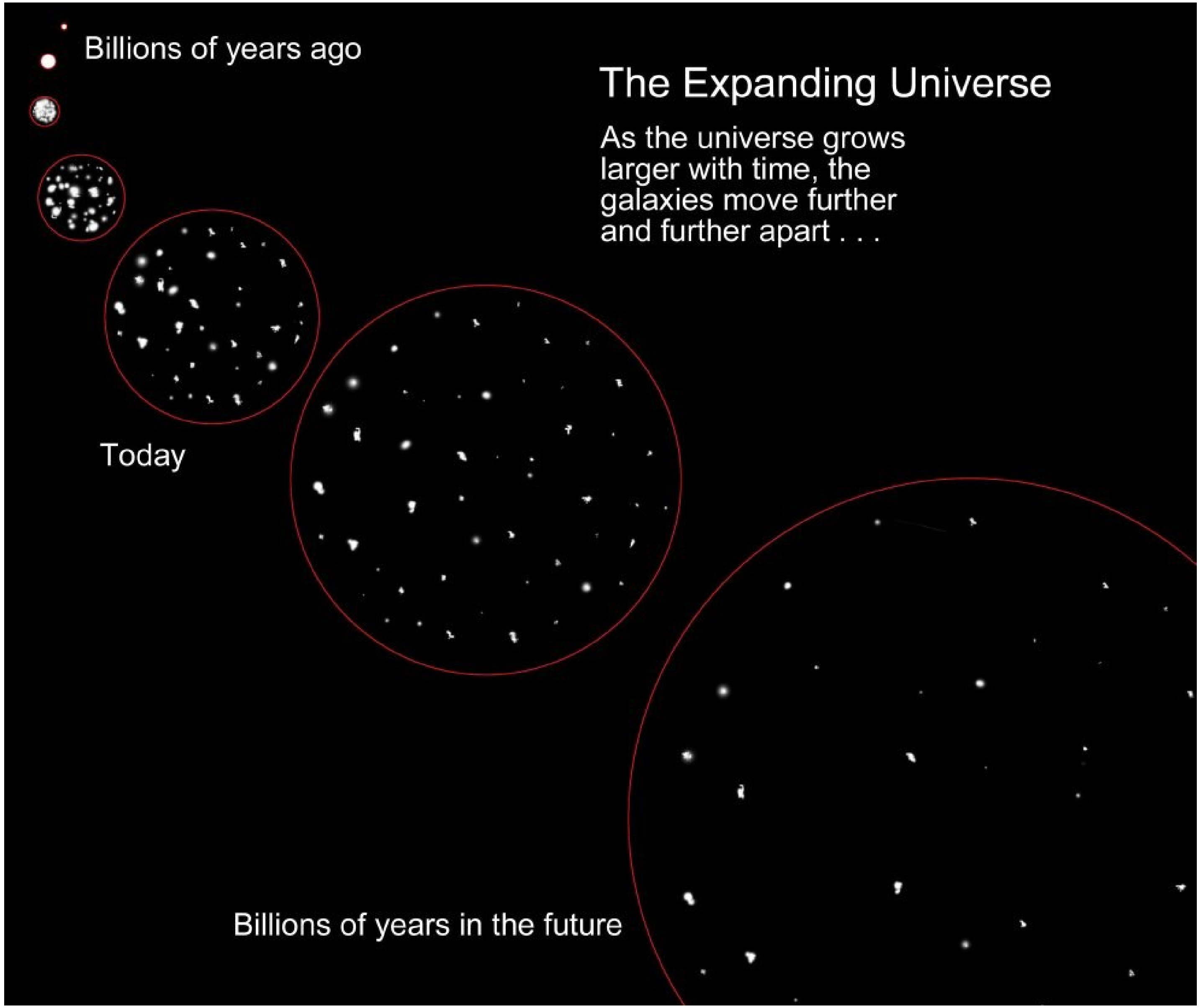
- Some people had a real problem with this theory
- Among them was **Albert Einstein**
- **Einstein** subscribed to the belief that the universe was **static**
- **Einstein** hoped his theory of **general relativity (GR)** would give him a deeper understanding of the structure of the universe

Big Bang Theory

- **Einstein** was surprised to discover that according to **GR** calculations, the universe would have to be expanding or contracting
- He proposed a **cosmological constant** Λ a number that, when included in his general theory of relativity, explained away the apparent necessity for the universe to expand or contract
- When confronted with Hubble's findings, Einstein admitted that he was mistaken

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + g_{\mu\nu} \Lambda = \frac{8\pi G}{c^4} T_{\mu\nu}$$

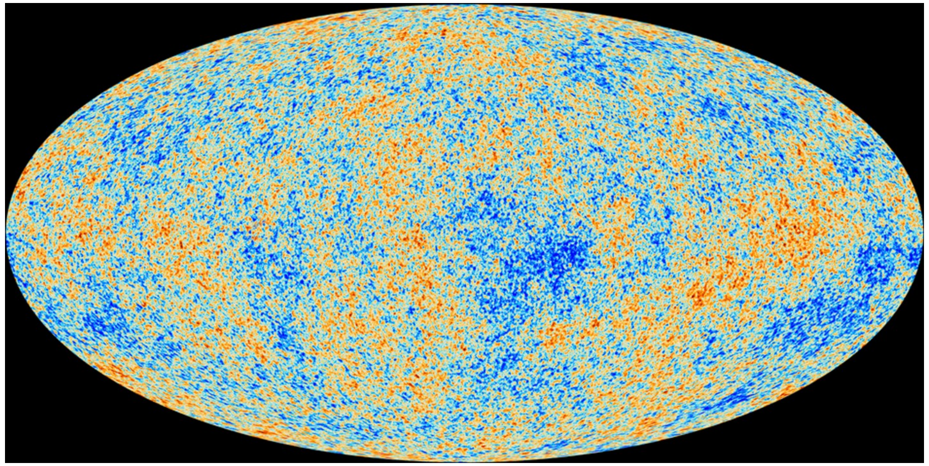
- The universe did seem to be expanding, and Einstein's own theory supported the conclusion
- The theory and observations gave rise to predictions, many of which have since been observed
- One of those predictions is that the universe is both **homogeneous** and **isotropic**
- Essentially, that means the universe **looks the same** no matter what the perspective of the observe


Billions of years ago
The Expanding Universe
As the universe grows
larger with time, the
galaxies move further
and further apart . . .
Today
Billions of years in the future

Big Bang Theory

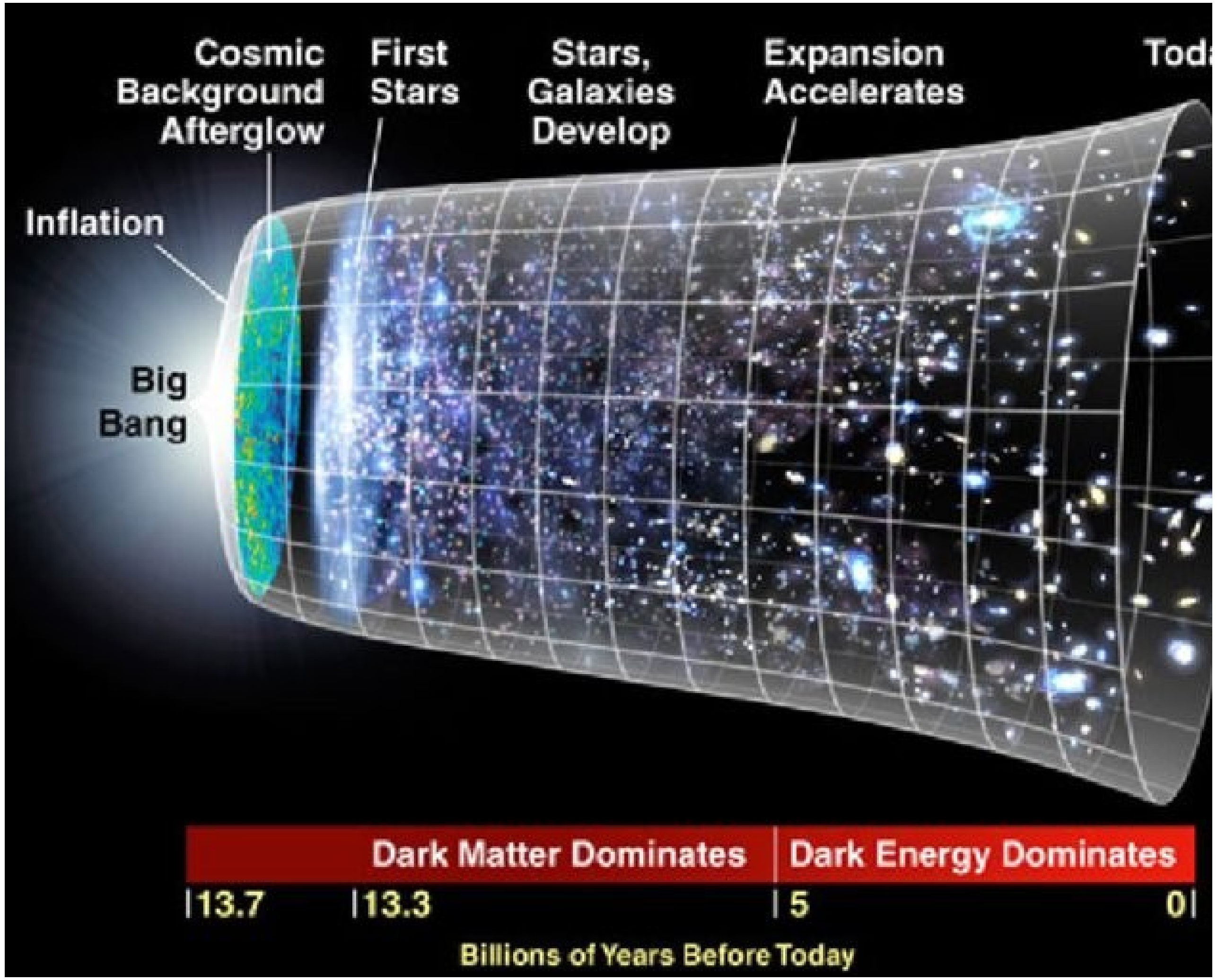
- On a macroscopic level that spans millions of light years, the distribution of matter in the universe is statistically homogeneous
- Another prediction: the universe would have been intensely hot during the earliest stages of the big bang
- The radiation from this period would have been phenomenally large, and there would have to be some evidence of this radiation left over
- Since the universe must be homogeneous and isotropic, the evidence should be evenly distributed throughout the universe
- Scientists discovered evidence of this radiation as early as the 1940s, though at the time they didn't know what they had found

- It wasn't until the 1960s when two separate teams of scientists discovered what we now call the **cosmic microwave background radiation** (**CMB**)
- The **CMB** is the remnants of the intense energy emitted by the primordial fireball in the big bang
- It was once intensely hot, but now has cooled to a chilly 2.725 degrees Kelvin (-270.4 degrees Celsius or -454.8 degrees Fahrenheit)
- These observations helped solidify the big bang theory as the predominant model for the evolution of the universe



Big Bang Theory

- Because of the limitations of the laws of physics, we can't make any guesses about the instant the universe came into being
- Instead, we can look at the period immediately following the creation of the universe
- Right now, the **earliest moment** scientists talk about occurs at $t = 1 \times 10^{-43}$ seconds (the "t" stands for the time after the creation of the universe)
- At the earliest moments of the big bang, the universe was so small that classical physics didn't apply to it
- At $t = 1 \times 10^{-43}$ seconds, the universe was incredibly small, dense and hot
- This homogenous area of the universe spanned a region of only 1×10^{-33} centimeters (3.9×10^{-34} inches)
- Today, that same stretch of space spans billions of light years
- During this phase, matter and energy were inseparable
- The four primary forces of the universe were also a united force


Cosmic Background Afterglow
First Stars
Stars, Galaxies Develop
Expansion Accelerates
Tod
Inflation
Big Bang
Dark Matter Dominates
Dark Energy Dominates
13.7
13.3
5
0
Billions of Years Before Today

Big Bang Theory

- As the universe expanded, it cooled
- At around t = 1 x 10^{-35} seconds, matter and energy decoupled
- Cosmologists call this **baryogenesis** -- **baryonic matter** is the kind of matter we can observe
- In contrast, we can't observe **dark matter**, but we know it exists by the way it **affects** energy and other matter
- At t = 1 x 10^{-11} seconds a period of **particle cosmology** followed
- This is a phase that scientists can recreate in lab conditions with **particle accelerators**
- That means that we have some observational data on what the universe must have been like at this time
- The **unified force** broke down into components
- The forces of **electromagnetism** and **weak nuclear force** split off

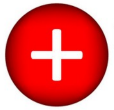
Big Bang Theory

- **Photons** (EMR) outnumbered matter particles, but the universe was too dense for light to shine within it
- 0.01 seconds after the beginning of the Big Bang came the period of **standard cosmology**
- From this moment on, scientists feel they have a pretty good handle on how the universe evolved
- The universe continued to expand and cool, and the **subatomic particles formed** during baryogenesis began to bond together
- They formed **neutrons** and **protons**
- By the time a full second had passed, these particles could form the nuclei of light elements like hydrogen (in the form of its isotope, **deuterium**), helium and lithium
- This process is known as **nucleosynthesis**
- But the universe was still too dense and hot for electrons to join these nuclei and form stable atoms
- Next we'll find out what happened over the next 13 billion years

Big Bang Theory

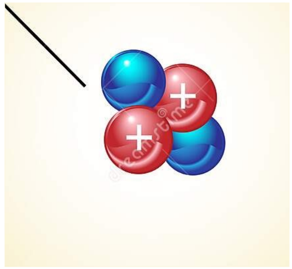
- After 100 seconds, the universe's temperature cooled to 1 billion degrees Kelvin (1 billion degrees Celsius, 1.8 billion degrees Fahrenheit)
- Subatomic particles continued to combine
- By mass, the distribution of elements was approximately **75 percent hydrogen nuclei and 24 percent helium nuclei** (the other percent consisted of other light elements like **lithium**)

Hydrogen nucleus



Proton

Helium Nucleus

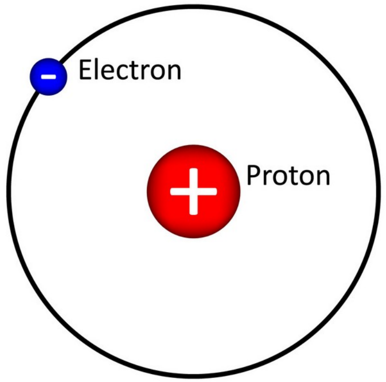


- The universe continued to expand and cool
- After about 56,000 years, the universe had cooled to 9,000 degrees Kelvin (8,726 degrees Celsius, 15,740 degrees Fahrenheit)
- At this time, the density of the matter distribution in the universe matched the density of radiation
- After another 324,000 years, the universe had expanded enough to cool down to 3,000 degrees Kelvin (2,727 degrees Celsius, 4,940 degrees Fahrenheit)

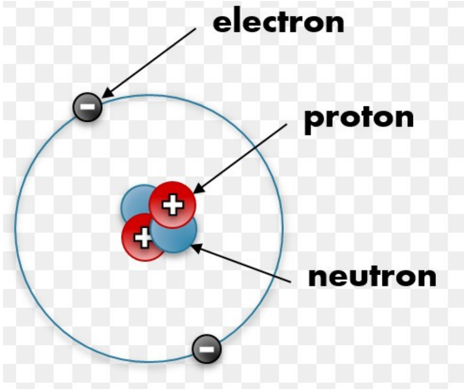
Big Bang Theory

- Finally, protons and **electrons** could combine to form neutral **hydrogen atoms**
- It was at this time, 380,000 years after the initial event, when the universe became transparent
- Light could shine throughout the universe
- The radiation that humans would later identify as **cosmic microwave background** radiation locked into place
- When we study the **CMB** today, we can extrapolate a picture of what the universe looked like then

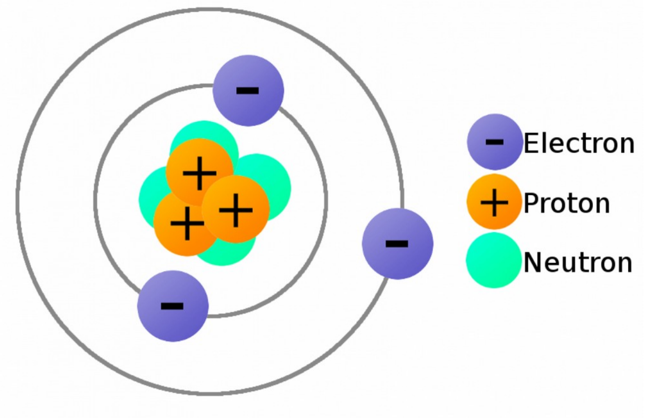
Hydrogen atom



Helium atom



Lithium atom



Big Bang Theory

- For the next 100 million years or so, the universe continued to expand and cool
- Small **gravitational fluctuations** caused particles of **matter** to cluster together
- Gravity caused gases in the universe to collapse into tight pockets

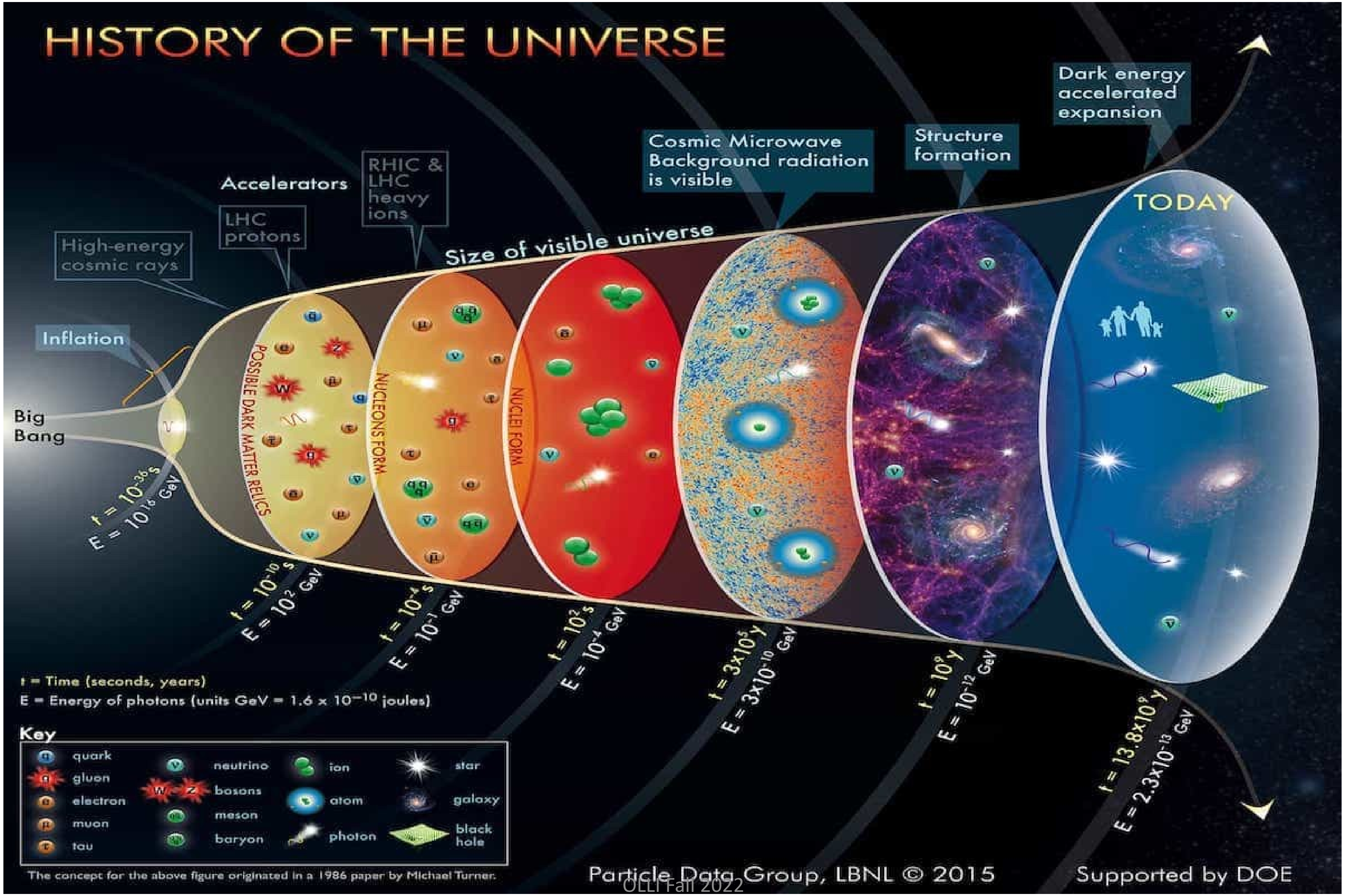
$$F = G\frac{m_1 m_2}{r^2}$$

- As gases contract, they become more dense and hotter
- Some 100 to 200 million years after the big bang , **stars formed** from these pockets of gas
- Stars began to cluster together to form **galaxies**
- Galaxies in turn formed their own clusters
- Eventually, some stars went **supernova** - exploded
- As they exploded, they ejected matter across the universe
- This matter included all the heavier elements we find in nature (everything up to **uranium**)
- This is the source of the matter of other stars and planets
- Our own solar system formed around 4.6 billion years ago

Big Bang Theory

- Today, the temperature of the universe is 2.725 degrees Kelvin (-270 degrees Celsius, -455 degrees Fahrenheit), which is only a couple of degrees above absolute zero
- The universe that we can **physically observe** using our most advanced astronomical instruments is about **93 billion light years** across
- Using the big bang theory to estimate the age of the universe yields an **age of about 13.8 billion years**

- Diameter of the observable universe: 8.8×1026 m (28.5 Gpc or 93 Gly)
- **Mass** (ordinary matter) At least ***10^{53} kg***
- **Average density** (including the contribution from energy) ***9.9 x 10−30 g/cm3***
- **Average temperature** ***2.72548 K*** (-270.4 °C or -454.8 °F)
- **Main contents**
  - **Ordinary matter** ***(4.9%)***
  - **Dark matter** ***(26.8%)***
  - **Dark energy** ***(68.3%)***


HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Cosmic Microwave Background radiation is visible
Structure formation
TODAY
RHIC & LHC heavy ions
Accelerators
LHC protons
High-energy cosmic rays
Size of visible universe
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10⁻³⁶ s
E = 10¹⁶ GeV
t = 10⁻¹⁰ s
E = 10² GeV
t = 10⁻⁴ s
E = 10⁻¹ GeV
t = 10² s
E = 10⁻⁴ GeV
t = 3x10⁵ y
E = 3x10⁻¹⁰ GeV
t = 10⁹ y
E = 10⁻¹² GeV
t = 13.8x10⁹ y
E = 2.3x10⁻¹³ GeV
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6 x 10⁻¹⁰ joules)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
The concept for the above figure originated in a 1986 paper by Michael Turner.
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Supported by DOE

Big Bang Theory

- **The discovery th**at the universe is expanding led to another question

  Will it expand forever?

  Will it stop?

  Will it reverse?

- According to the **general theory of relativity**, it all depends on how much matter is within the universe

- **It boils down to gravity**
- If there's enough matter in the universe, the force of gravity will eventually slow the expansion and cause the universe to contract
- Cosmologists would designate this as a **closed universe** with **positive curvature**

Big Bang Theory

- Not enough matter to reverse expansion, the universe will expand forever
- Such a universe would either have **no curvature** or **negative curvature**
- If we are in a closed universe, eventually the entire universe will contract and collapse in on itself
- Cosmologists call this the **big crunch**

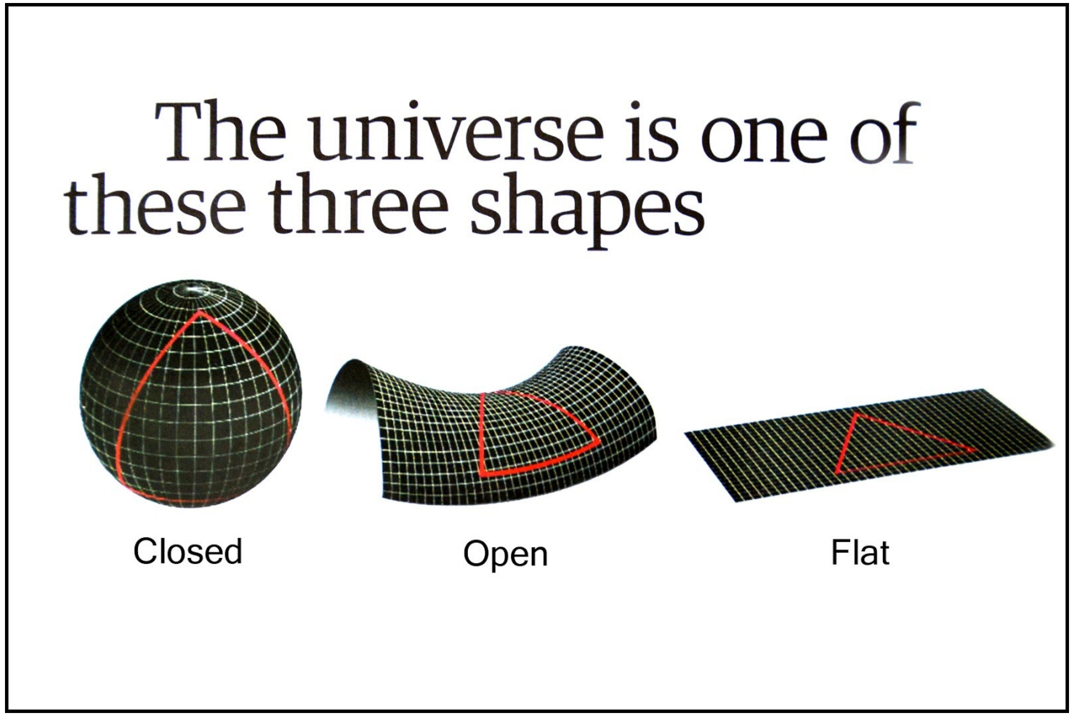
- Some theorize that our universe is just the latest in a series of universes generated in a **cycle of space expanding and contracting**
- According to the big bang theory, there's no center of the universe
- Every point in the universe is the same as every other point, with no centralized location
- This is difficult to imagine, but it's a requirement for a universe that is both homogeneous and isotropic

Big Bang Theory

- Not everyone subscribes to the big bang theory
- There are also some very big questions the big bang theory doesn't address:
- **What happened before the big bang?**
- According to our understanding of science, we can't know
- The very laws of physics break down as we approach t = 0 seconds
- In fact, since the general theory of relativity tells us that space and time are coupled, **time itself ceases to exist**
- The answer to this question lies outside the parameters of what science can address
- What lies beyond the universe?
- This is a question science can't address
- That's because we can't observe or measure anything that lies outside the boundaries of the universe
- The universe may or may not be expanding within some other structure, but it's impossible for us to know either way

Big Bang Theory

- What is the shape of the universe?
- There are many theories about what shape the universe might have
- Some believe that the universe is **unbounded** and **shapeless**
- Others think the universe is **bounded**
- The big bang theory doesn't specifically address the issue



CMB studies suggest Flat

Big Bang Theory   Problems

- Some of the most common criticisms of the big bang theory:
- It violates the **first law of thermodynamics**, which says you can't create or destroy matter or energy
- Critics claim that the big bang theory suggests the universe began out of nothing
- Proponents of the big bang theory say that such criticism is unwarranted for two reasons
- The first is that the big bang doesn't address the creation of the universe, but rather the evolution of it
- The other reason is that since the laws of science break down as you approach the creation of the universe, there's no reason to believe the first law of thermodynamics would apply
- The formation of stars and galaxies violates the law of **entropy**, which suggests systems of change become less organized over time
- But if you view the early universe as completely homogeneous and isotropic, then the current universe shows signs of obeying the law of entropy
- Scientists have misinterpreted evidence like the redshift of celestial bodies and the cosmic microwave background radiation
- Some cite the absence of exotic cosmic bodies that should have been the product of the big bang according to the theory

Big Bang Theory   Problems

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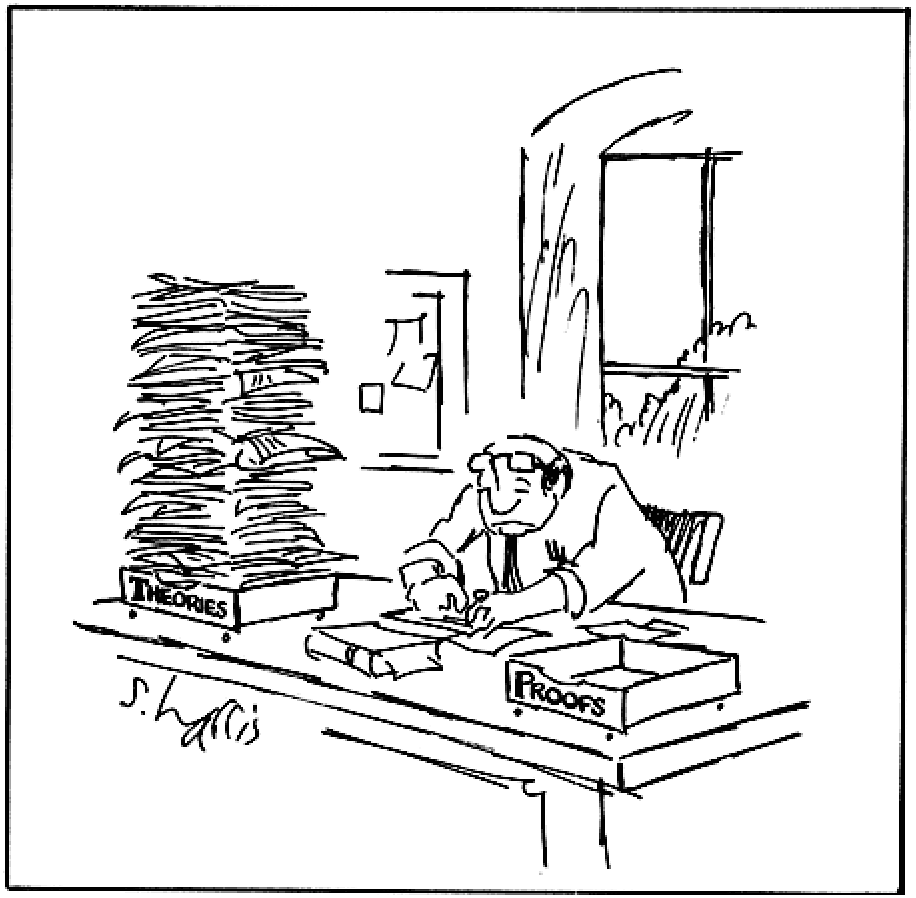
- The early inflationary period of the big bang appears to violate the rule that nothing can travel faster than the speed of light
- At the start of the big bang, the theory of relativity didn't apply
- As a result, there was no issue with traveling faster than the speed of light
- Another related response is that space itself can expand faster than the speed of light, as space falls outside the domain of the theory of general relativity gravity

Big Bang Theory Alternate Theories

- The **steady-state** model of the universe suggests the universe always had and will always have the same density
- The theory reconciles the apparent evidence that the universe is expanding by suggesting that the universe generates matter at a rate proportionate to the universe's rate of expansion
- The **Ekpyrotic model** suggests our universe is the result of a **collision** of two three-dimensional worlds on a **hidden fourth dimension**
- It doesn't conflict with the big bang theory completely, as after a certain amount of time it aligns with the events described in the big bang theory
- The **big bounce** theory suggests our universe is one of a series of universes that first expand, then contract again
- The cycle repeats after several billion years

Alternate Theories



Big Bang Theory

- There are several other models as well
- Could one of these theories (or other ones we haven't even thought of) one day replace the big bang theory as the accepted model of the universe?
- It's quite possible
- For now the **Big Bang Model** is the best theory of the **evolution** of the universe that we have

Nest Session

- Dark Energy
- Dark Matter