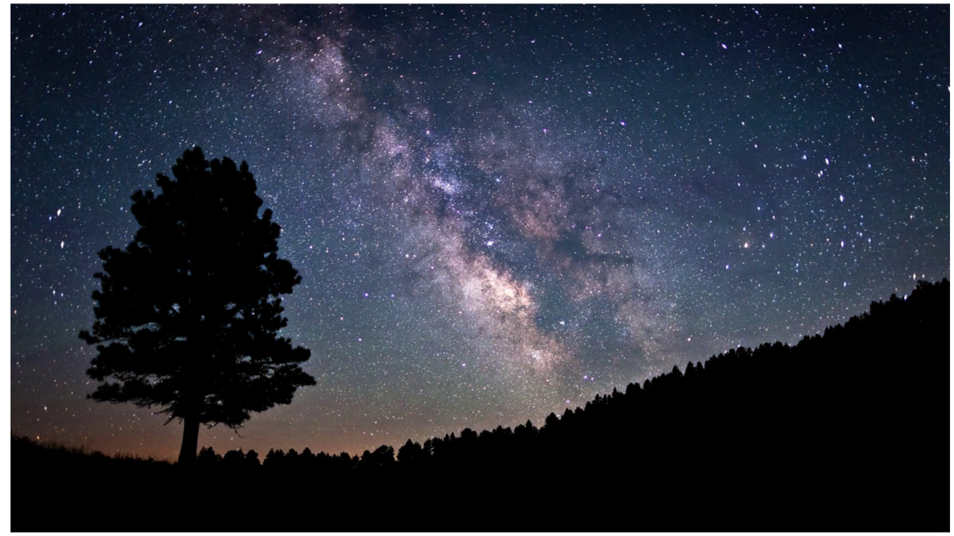
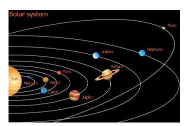
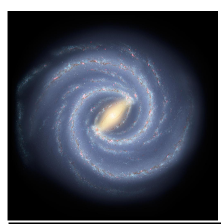
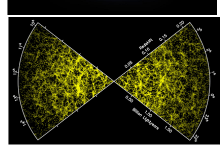
Questions?



Sizes







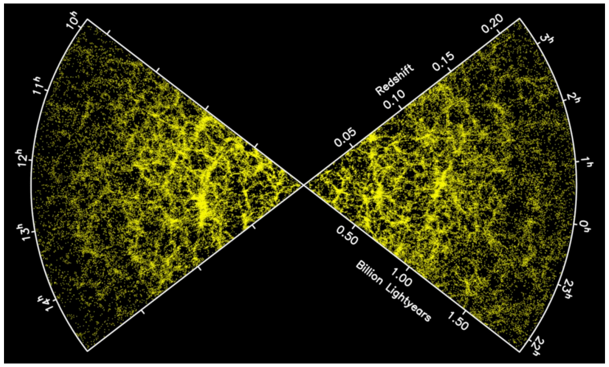
- The Solar System is 770,000 times the size of the Earth
  - Earth about a billionth of a light year across
  - Solar System about a thousandth of a light year across
- Our Galaxy is 100 million times the size of the Solar System
  - The nearest star (4.3 light years) is about 3400 times farther than the size of the Solar System
  - The Galaxy is about 120 thousand light years across
- The Visible Universe is about 775,000 times the size of our Galaxy
  - The visible universe is about 93 billion light years across

Why Do We Believe The Universe Is Expanding?

- When we look at distant galaxies they seem to be moving away from us
- When we look in all directions we see the same distribution of matter on very large scales
- Our best theory of gravity tells us that in this case the universe is either getting bigger or smaller
- As we look out vast differences we are looking back in time, and the universe looks different in the past
  - Cosmic Background Radiation

Large-Scale Galaxy Survey

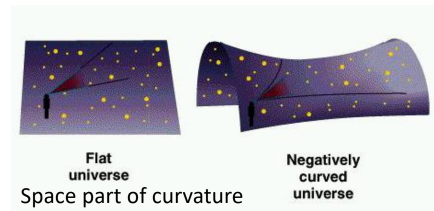
- At each distance, galaxies look approximately evenly distributed
  - Remember, distances are views into the past, so at each time in the past matter is evenly distributed



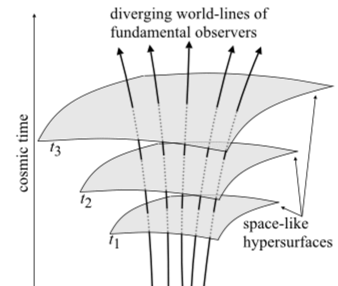
Gravity = Curvature in Space and Time

"Spacetime tells matter how to move; matter tells spacetime how to curve"

- John Archibald Wheeler



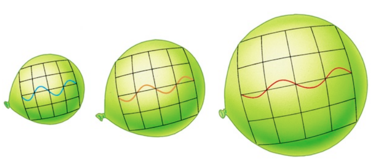
Space part of curvature

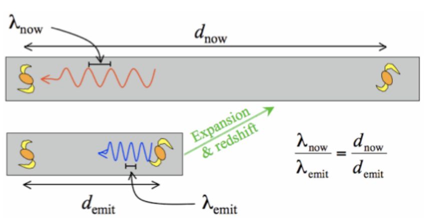


Time part of curvature

Another Interpretation of the Red Shift

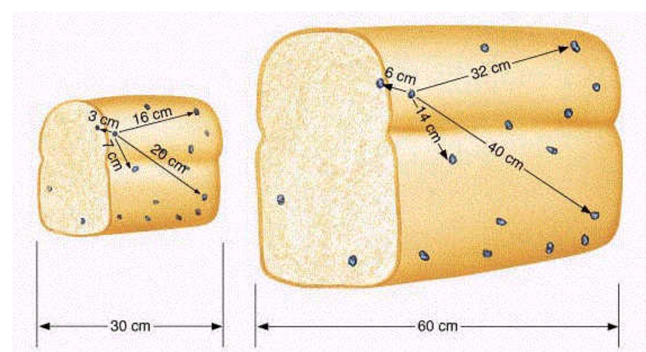
- We've been speaking of galaxies moving away from us because of the expansion of the universe
- We've also said that it is space that is expanding, so the galaxies are not really moving
- We can view redshift as the expansion of the light waves as the universe expands





Remember the Raisin Bread

- This is a very good model for the expansion of the universe, so long as the raisin bread is infinitely large



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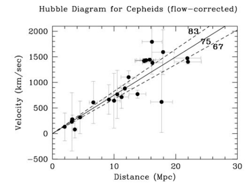
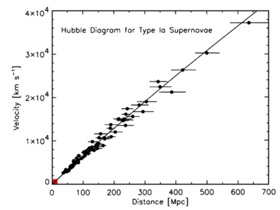
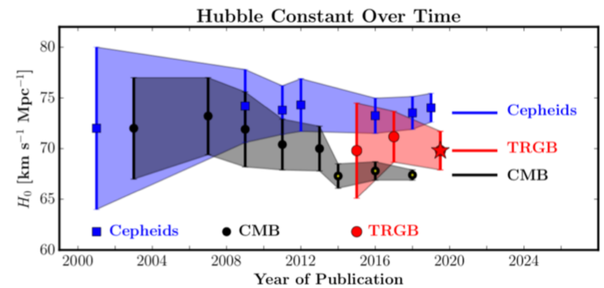
- Our best theory of gravity tells us that in this case the universe is either getting bigger or smaller

How Fast is the Universe Expanding?

- Hubble's constant is hard to measure exactly
- Last week stated ~70 km per second per megaparsec







Looking Into the Past

- As we look at the furthest galaxies, we are looking into the deep past
  - As much as 13 billion years (picture at right)
- The most distant galaxies do look different from current galaxies
  - Bluer (after correcting for redshift), as we'd expect because there have been fewer generations of stars so we're looking at more young, bright stars
  - More active star formation
    - More gas not yet in stars

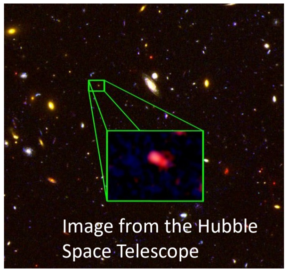
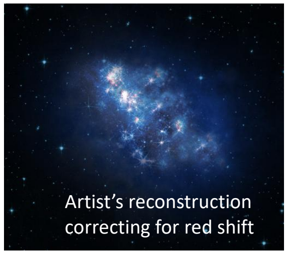


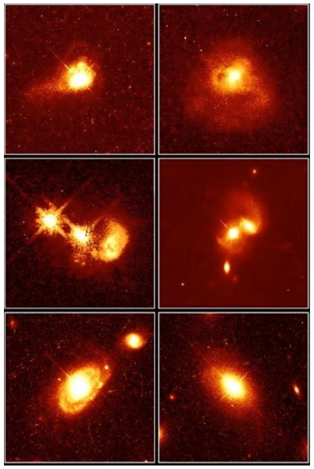
Image from the Hubble Space Telescope



Artist's reconstruction correcting for red shift

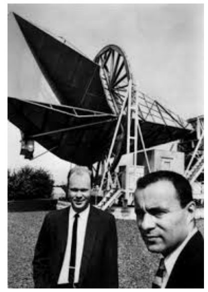
Quasars

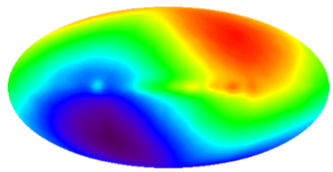
- Some of the most distant objects do not look like nearby galaxies
- Objects much brighter and much smaller than a galaxy, called "quasi-stellar objects" or quasars
  - Looked like stars when discovered in the 60's
    - But with very large red shifts
    - 600 million to billions of light years away
  - Later observations revealed that these are the very bright cores of galaxies
  - Now believed to be an early stage of galaxy formation
    - As the central black hole was forming/growing



Cosmic Background Radiation

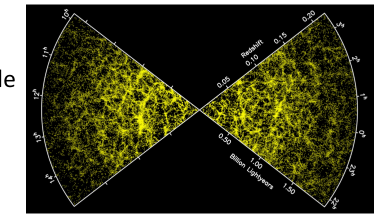
- Everywhere we look in the sky we see a constant microwave radiation
  - Has the same light as would be emitted by something at 2.7 Kelvins (= -454.81 degrees F)
- Almost exactly the same in all directions
  - We can see the red/blue shift due to the Earth's motion
- We believe this is the orange light from a hot gas of about 3000 Kelvins (= 4940 degrees F) redshifted by a very large amount
  - This gas completely filled the universe





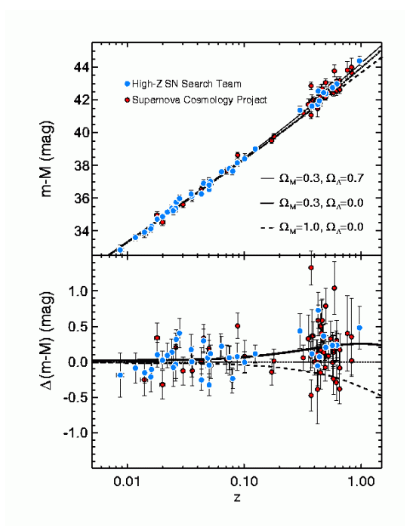
Subtle Mysteries

- Why is the universe so homogeneous?
  - When we look in opposite directions, we are looking at galaxies whose light just got to us
  - So galaxies on opposite sides of our sky cannot see each other
  - So they cannot effect each other (no signal can go faster than light)
  - So why do they look the same?
    - Same density on a large enough scale



Subtle Mysteries

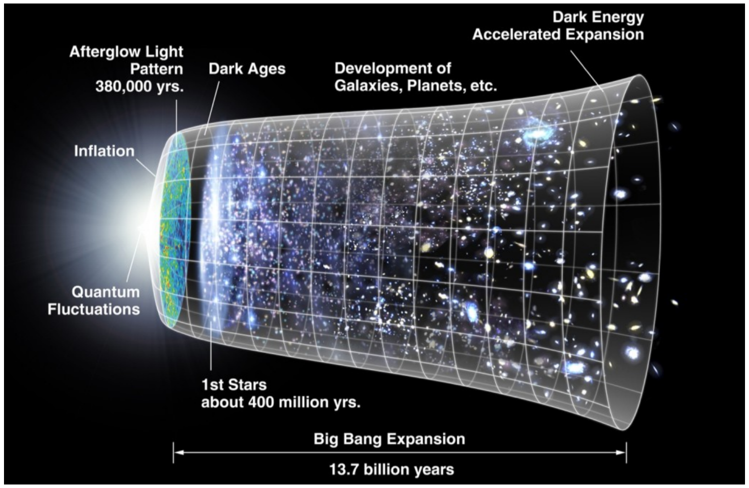
- Why is the universe so flat?
  - The data says that we have just about the right amount of matter and (dark) energy to make the universe flat



The Universe Has a History

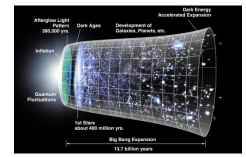
- It appears that the universe in the past looks different from the universe in the present
- This is not too surprising: if we back up the expansion of the universe, it gets a lot smaller and a lot more crowded
  - In early enough times the universe was so small all the galaxies we see now would overlap
  - Before that all the stars would overlap
  - At that time things must have been very very different!

Living in an Expanding Universe



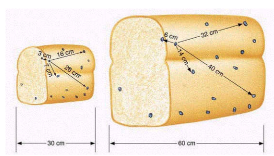
So In the Past The Universe Was Smaller

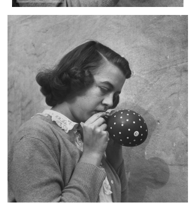
- This means the “visible universe” (the part we can see) was in a smaller volume
- About 13.8 billion years ago this volume was very very small
  - If our current theories of matter and forces is correct, it actually became zero volume at that time
    - Mathematical proof by Stephen Hawking based on General Relativity
  - We call that zero time the “time of the big bang”
  - But at some point our current theories are probably not correct



Where Did the Big Bang Happen?

- Remember: it is space itself that is expanding
  - So as we go back in time it is space itself that shrinks
    - Like the *surface* of the balloon
  - The points of space are moving closer together
- The point in space where I am now gets closer and closer to every other point
  - True for every point
- When *all* the points come together is what we call “the Big Bang”
- So all the points in space is where the Big Bang happened.
- The Big Bang happened everywhere!



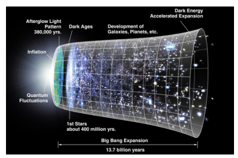


How Far Back in Time Can We Go?

- As the universe gets smaller, it gets hotter
- Our theories are tested up to very high temperatures
  - In particle accelerators such as CERN and Fermilab
  - Up to about 10 thousand trillion trillion (10^{28}) degrees F
    - Compare with ~30 million degrees F in center of Sun
  - Hotter then that our theories become less certain
- When was the universe this hot?
  - About 1/(10 million trillion trillion) seconds after “big bang” (10^{-32} seconds)
    - So we can get really close to the time of the “big bang”
- Before then, we know less: topic for last class
  - Inflation, multiverses, etc…

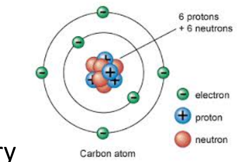
So Based on Our Tested Theories

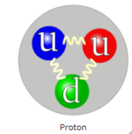
- We can pick up the story at 10^{-32} seconds
- At this time the visible universe was a few centimeters across
  - Containing all the matter and energy we see in hundreds of billions of galaxies
- Obviously things were very different then
  - Very very hot gas, with all matter decomposed into its most basic parts
- So we need to know something about the most basic parts of matter

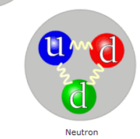


What is Matter Made Of?

- Molecules are made of *atoms*, which are made of *protons*, *neutrons* and *electrons*
- Protons and neutrons are made of *quarks* (called up and down)
  - Quarks are never seen in isolation except at very high temperature (> 20 trillion degrees F)
- There are actually six kinds of quarks
  - Up, down, charm, strange, top, bottom
    - Electrically charged
  - Heavier quarks decay into the lighter up and down quarks
- Quarks are held inside protons and neutrons by the *Strong Nuclear Force*
  - Which also holds protons and neutrons together in the nucleus of an atom

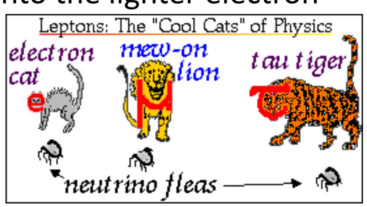






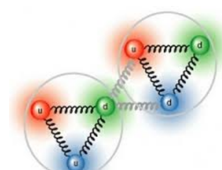
What is Matter Made Of?

- There are three particles a lot like electrons
  - Electron, muon and tau, electrically charged
  - The two heavier ones decay into the lighter electron



- There are three neutrinos
  - Very very light particles with no electric charge
  - A lot like dark matter, but too light to be the missing dark matter
- These six particles are called *leptons*

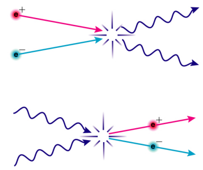
The Forces



- Gravity (done that…)
- Electromagnetism
  - Holds atoms together, make electricity, etc.
- Strong nuclear force
  - Holds protons and neutrons together in nuclei of atoms, quarks together inside protons and neutrons
- Weak nuclear force
  - Very strange: primary action is to change one particle type into another
    - Up <-> charm, electron <-> muon etc.
    - The reason heavy particles decay into lighter particles
    - When things are very hot, lighter particles can change into heavier particles

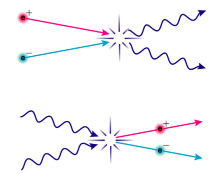
Antimatter: Not Science Fiction

- All fundamental particles (quarks, leptons) have antimatter counterparts
  - Same mass, opposite electric charge
    - Anti-proton observed by Owen Chamberlain (1955)
- When a particle (like an electron) meets its antimatter counterpart (like a positron) both disappear with a flash of energy
  - $E = mc^2$
- This is reversible: when it is very hot so there is a lot of radiation or force, a matter – antimatter pair can be created (like an electron and positron popping into existence)



Matter Creation?

- Can matter-antimatter creation explain the existence of matter?
- No: matter and antimatter are almost always created together, according to our current theories
  - There is a known exception ("CP violation"), but it is too rare to explain all matter
- There is a lot of matter in the universe without the corresponding antimatter
  - This is still a mystery to be solved



Back to the Big Bang: 10^{-32} Seconds

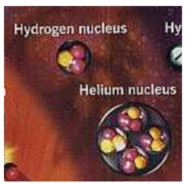
- Visible Universe size: a couple inches
- Temperature: 10^{28} degrees F
- Hot enough for free quarks and leptons flying around at very high speeds
  - Very Strong forces at work
  - Matter-antimatter pairs constantly coming into existence and quickly vanishing
  - Very uniform, dynamic opaque gas
    - Electrically charged particles absorb light

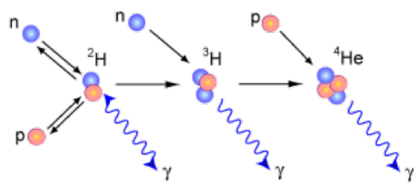
Expanding, it Cools: 10^{-6} Seconds

- A millionth of a second after the "big bang"
- Visible Universe size: about a half mile
- Temperature: 2×10^{13} degrees F
- The universe is cool enough for quarks to group into protons and neutrons
  - Still lots of matter-antimatter pairs coming and going
  - Still a bright, opaque uniform gas

Expanding, it Cools: 3 minutes

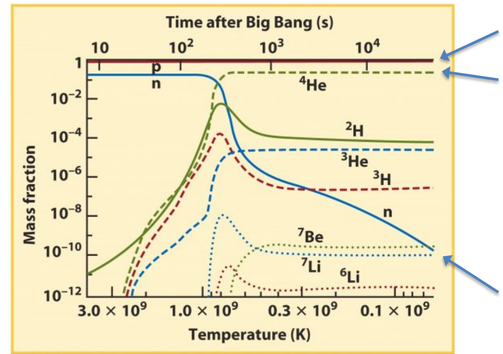
- Visible Universe size: 6.2 million miles
- Temperature: about 200 million degrees F
- Too cool for matter-antimatter creation
- Some protons and neutrons form nuclei of atoms
  - Without the electrons
    - electrons are still moving too fast because it is too hot
  - With further cooling, the relative abundance of the different nuclei becomes fixed
  - Still a bright, opaque uniform gas
    - Because of all the free electrically charged electrons and protons absorb light





Our First Cosmological Prediction

- From the temperature and density, and what we know about protons and neutrons, we can compute how many of which type of nucleus was formed

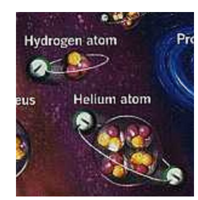


Comparison with Observation

- The predicted amount of Hydrogen compared with Helium (both He-4 and He-3) are in excellent agreement with what we actually observe
  - After taking into account Helium production in stars
- The amount of Lithium we see is about 3 times less than predicted
  - But the predicted value is very small and difficult to measure
  - Difficult to account for what happens to lithium in stars
- Creation of Helium 3 minutes after the big bang is the only way we've explained the amount of Helium we see
  - Stars don't make enough Helium

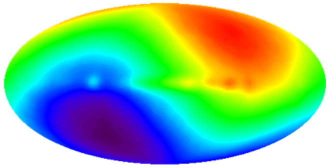
Expanding, it Cools: 400,000 years

- Visible Universe size: 42 million light years
- Temperature: about 5,000 degrees F
- At this temperature, the electrons slow down enough to be captured by the nuclei, forming the first atoms!
  - A proton captures and electron and becomes Hydrogen
  - A Helium nucleus captures 2 electrons, becomes Helium
  - There are about as many electrons as there are nuclei, so the gas is no longer electrically charged
  - Suddenly the gas becomes transparent
  - The Universe is now a hot, bright orange gas
    - Nearly as bright as the Sun
    - Very nearly completely uniform
      - Small non-uniformities are not washed out



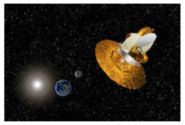
Our Second Cosmological Prediction

- We should see the light from this hot gas
- The expansion of the Universe from 300,000 years to now (13.5 billion years later) causes that light to redshift all the way to microwaves
  - Wavelength expands by a factor of 1,091
- We should see this microwave signal everywhere
  - And we do! The *Cosmic Microwave Background*

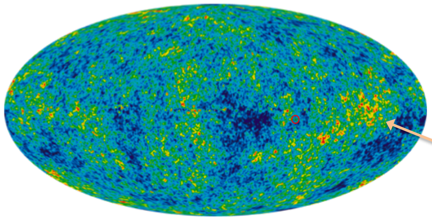


Observing the Cosmic Microwave Background (CMB)

- After adjusting for the motion of the Earth and sources in our Galaxy, we see that the CMB is almost completely uniform
- But careful measurements by space telescopes show very small variations
  - COBE, WMAP, Planck
  - Many ground-based and balloon telescopes



- These variations show regions of higher gas density, and are the seed for the eventual formation of galaxies



Expanding, it Cools: 100 Million Years

- The gas cools, becomes darker
- The higher-density clumps slowly exert local gravity
  - Stars start to form!

Movie at https://svs.gsfc.nasa.gov/10123

As the Universe Expands Galaxies Form in Abundance

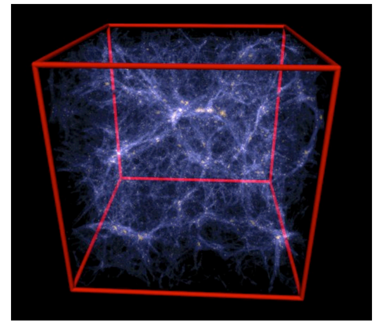
Movie at
http://www.illustris-project.org/movies/illustris_movie_rot_sub_frame.mp4

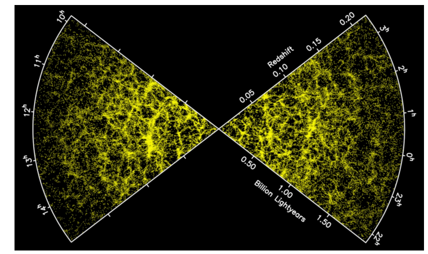
Simulated Formation of a Large Elliptical Galaxy via Galaxy Collisions

Movie at
http://www.illustris-project.org/movies/
illustris_movie_elliptical_formation_1pMpc.mp4

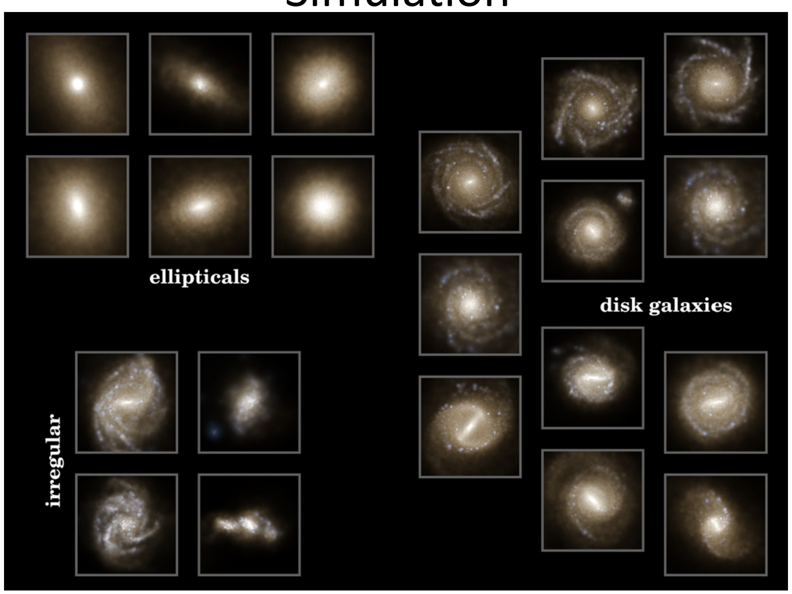
How to Get The Universe We See

- For our simulations to end up with something like the distribution of galaxies we observe, we have to have cold dark matter
  - Hot dark matter washes out the clumps





Galaxies Formed by the Illustris Simulation

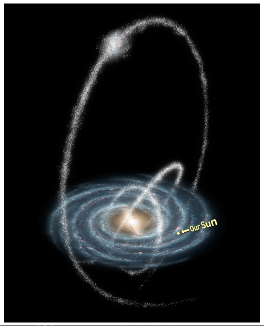


Early Lives of Galaxies Was Exciting

- Simulations tell us that there were many galaxy collisions in the early universe
  - Now understood as a normal part of galaxy evolution
- We see many colliding galaxies even now

Our Galaxy Had Several Collisions

- We see a stream of stars above our Galaxy, likely the remains of a small galaxy that collided with ours
- Studies of star groups hint that some of them probably are from other galaxies that were absorbed by our Galaxy
- The Andromeda galaxy and our Galaxy are on a collision course
  - Will hit in about 4 billion years

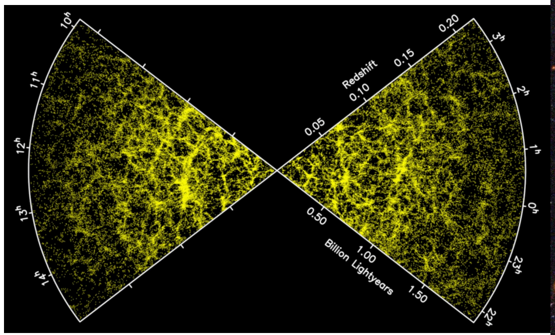


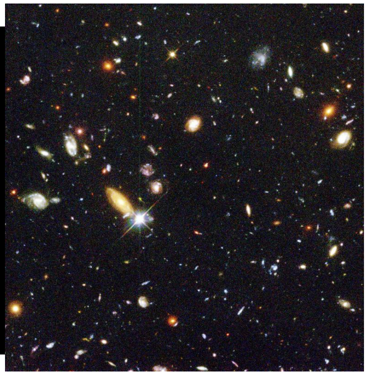
What About Acceleration (Dark Energy)?

- If acceleration is due to a cosmological constant
  - The total negative pressure depends on the amount of space
  - As the universe expands there is more negative pressure overcoming gravity
  - In the early universe, gravity from the density of matter overcame acceleration
    - The expansion slowed down
  - As the universe expands, matter density decreases and the negative pressure increases
  - The universe started expanding at about 8 billion years

Expanding, it Cools: 13.8 Billion Years (now)

- Visible Universe size: 93 billion light years
- Temperature: -454.81 degrees F (2.7 K)
- Many many Galaxies





Hot Big Bang