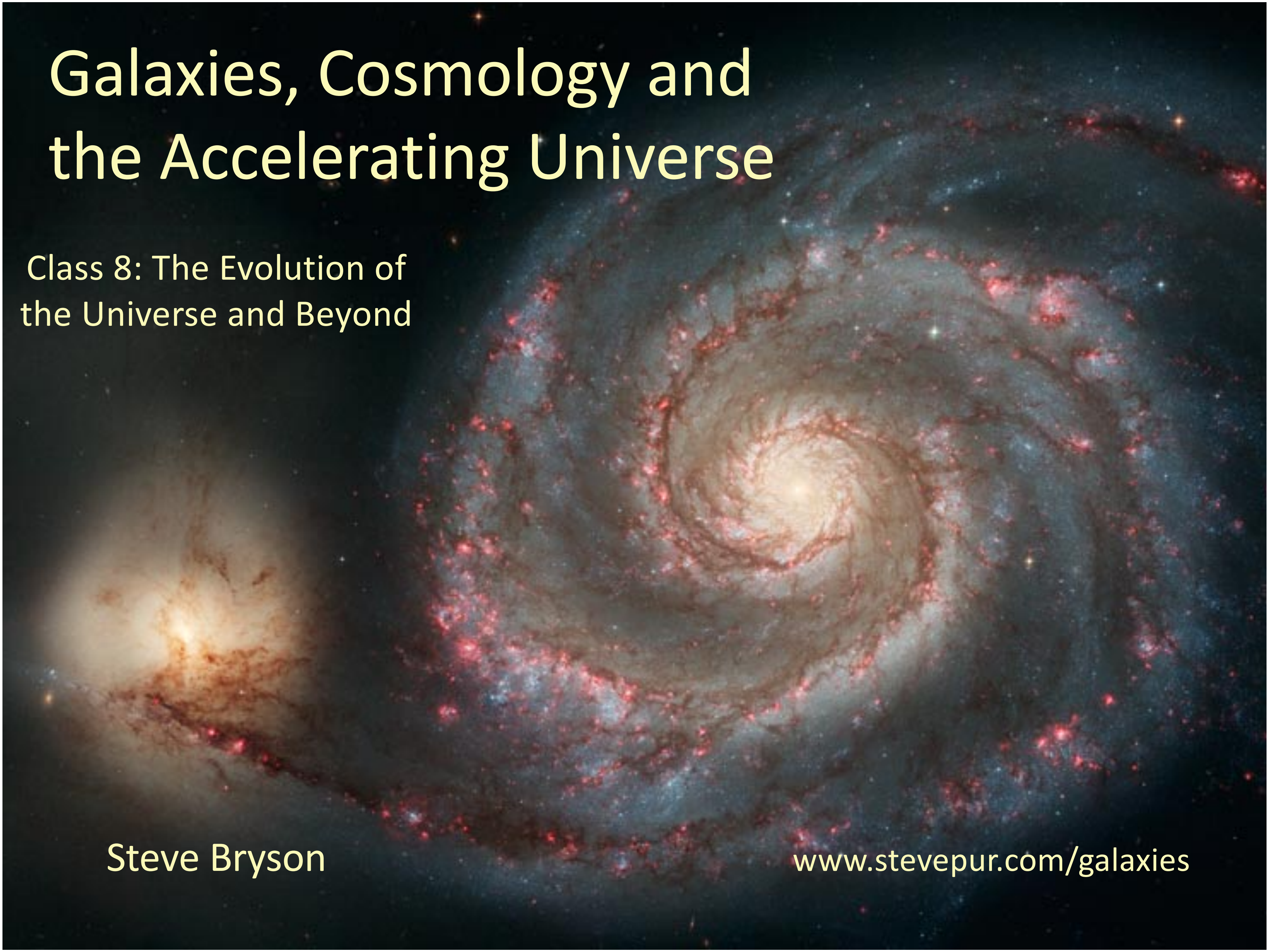

Galaxies, Cosmology and the Accelerating Universe
Class 8: The Evolution of the Universe and Beyond
Steve Bryson
www.stevepur.com/galaxies

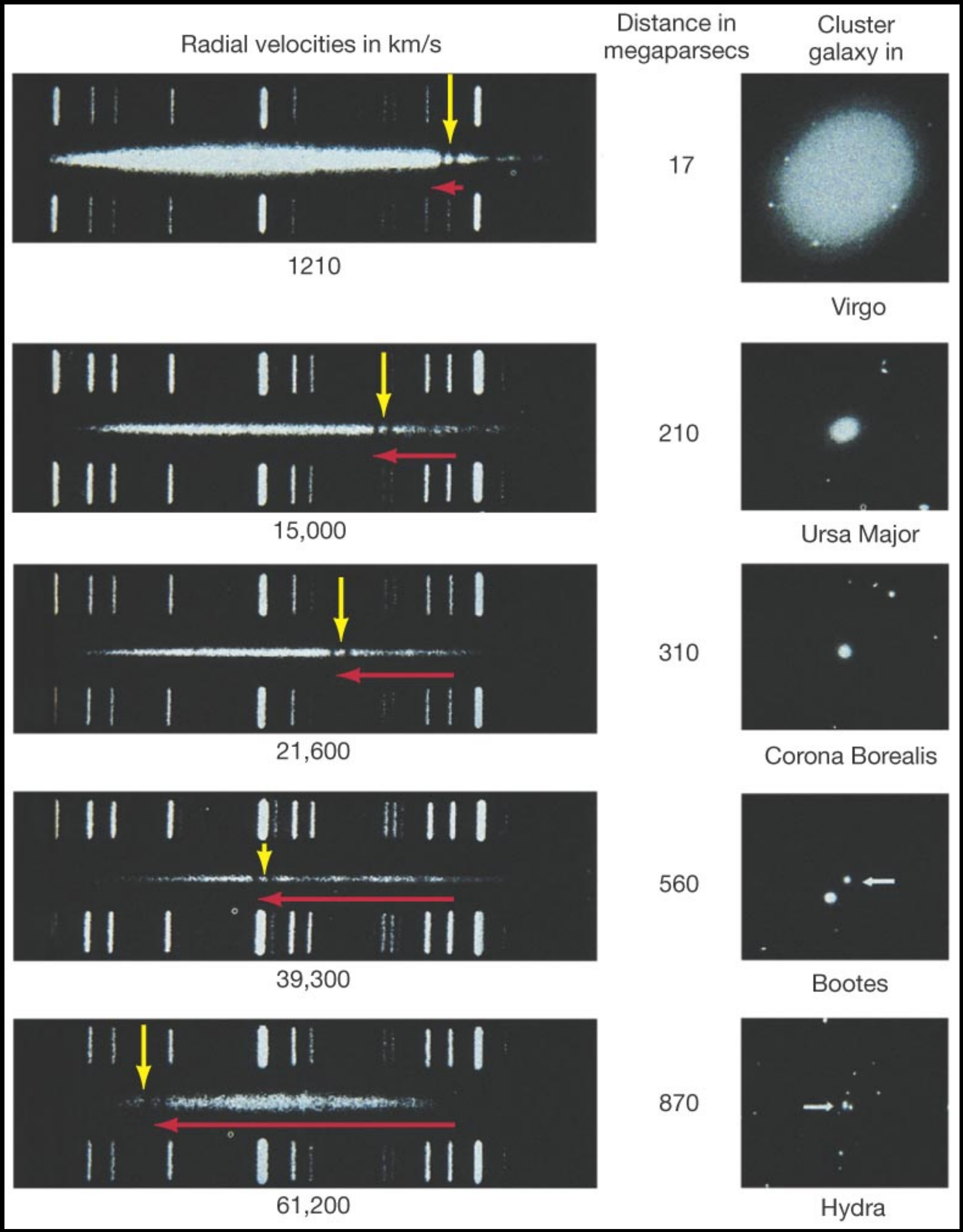
Questions?

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

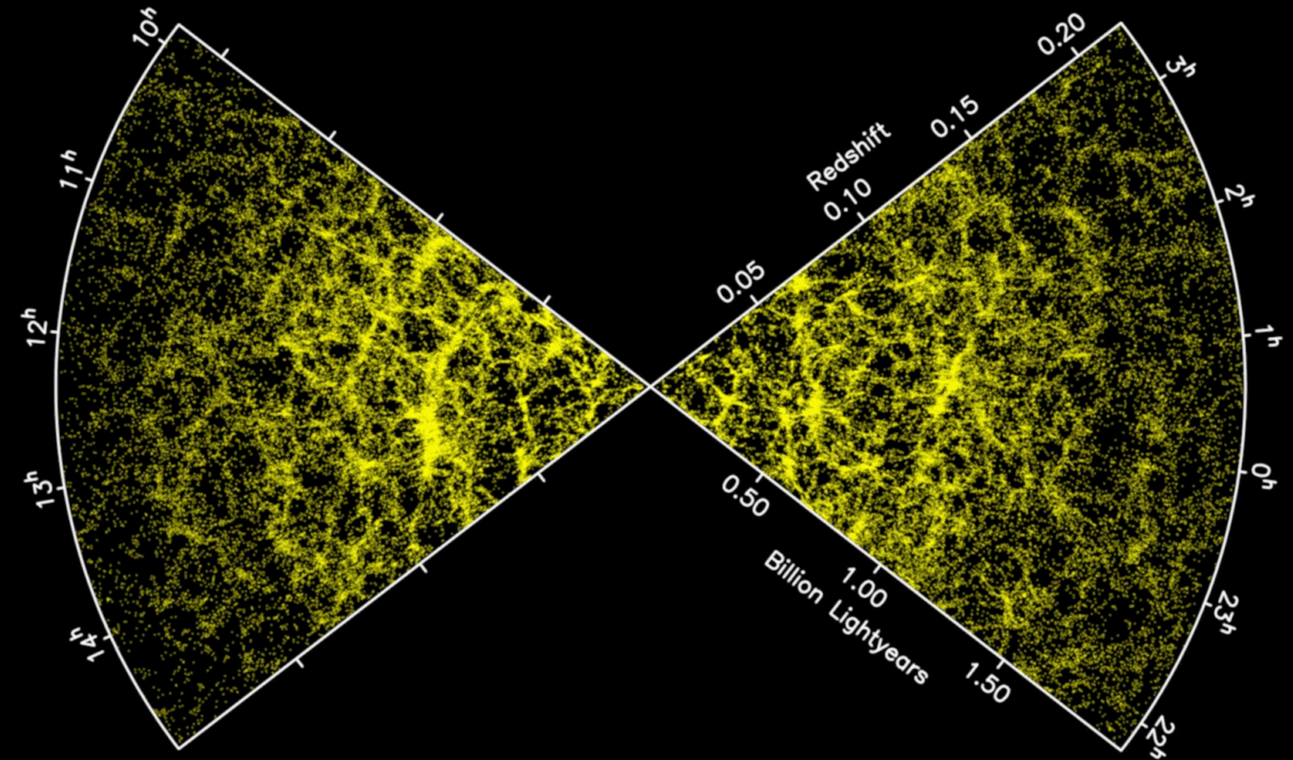
Galaxies are Moving Away From Us

- Most galaxies have a red shift
  - Indicating that they are moving away from us
- The more distant the galaxy the larger the red shift
  - In all directions!



Large-Scale Distribution of Matter

- 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

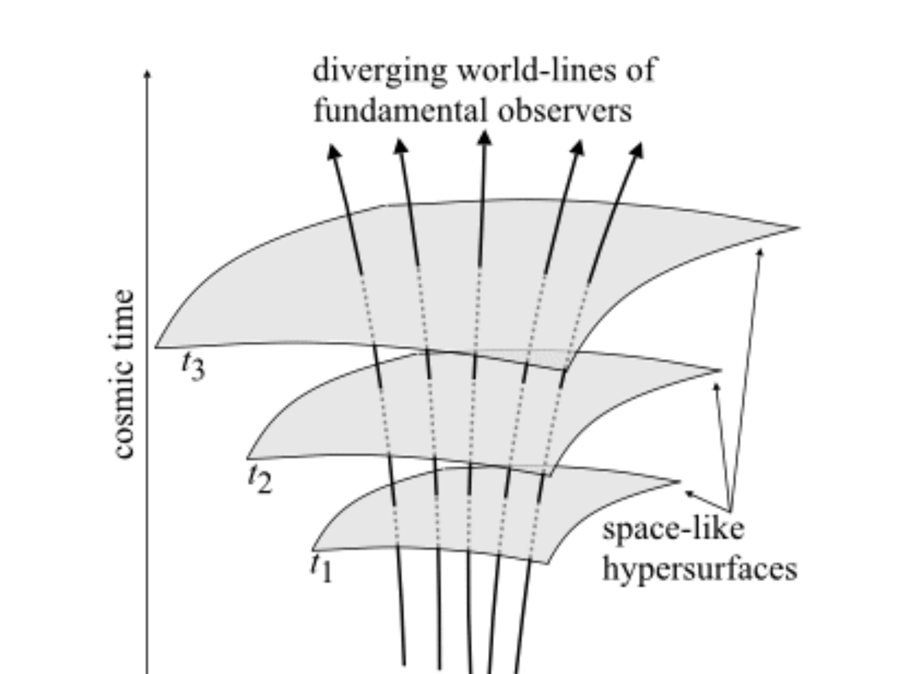


Even Distribution of Matter Means Expanding Curved Space

“Spacetime tells matter how to move; matter tells spacetime how to curve”

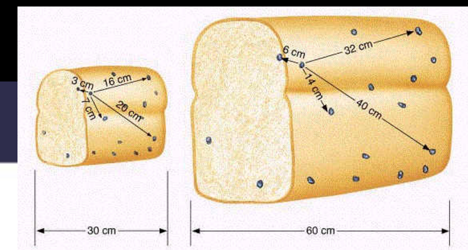
- John Archibald Wheeler

Space part of curvature



Time part of curvature

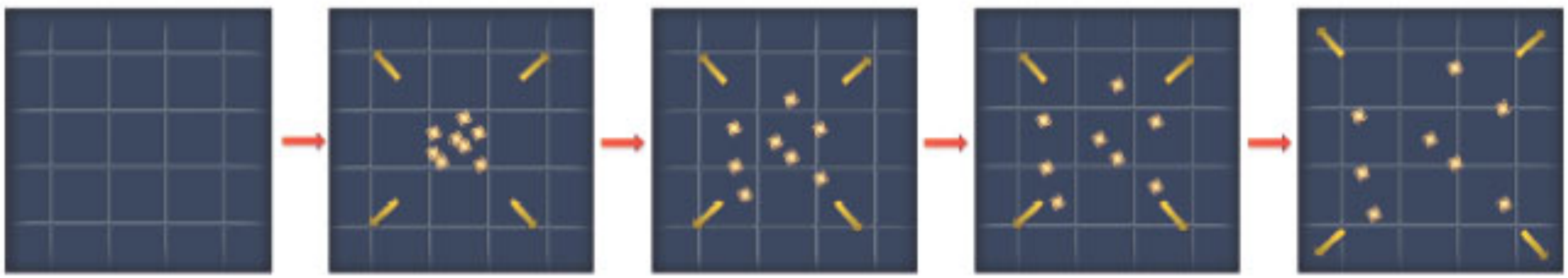
An Expansion of Space: Remember the Raisin Bread



WHAT KIND OF EXPLOSION WAS THE BIG BANG?

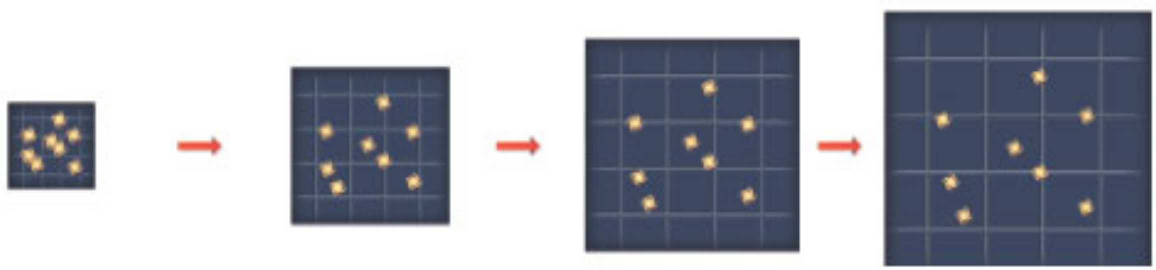
***WRONG:* The big bang was like a bomb going off at a certain location in previously empty space.**

In this view, the universe came into existence when matter exploded out from some particular location. The pressure was highest at the center and lowest in the surrounding void; this pressure difference pushed material outward.



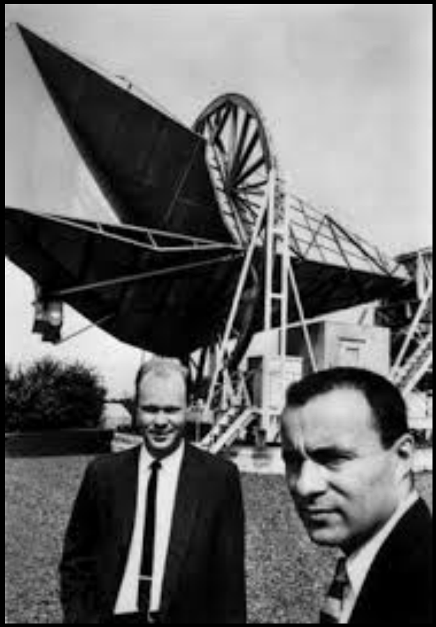
***RIGHT:* It was an explosion of space itself.**

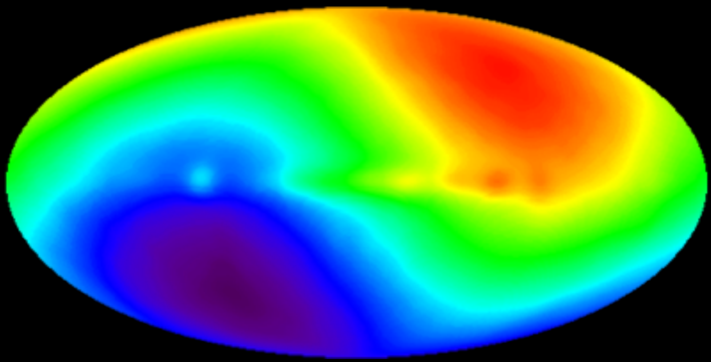
The space we inhabit is itself expanding. There was no center to this explosion; it happened everywhere. The density and pressure were the same everywhere, so there was no pressure difference to drive a conventional explosion.



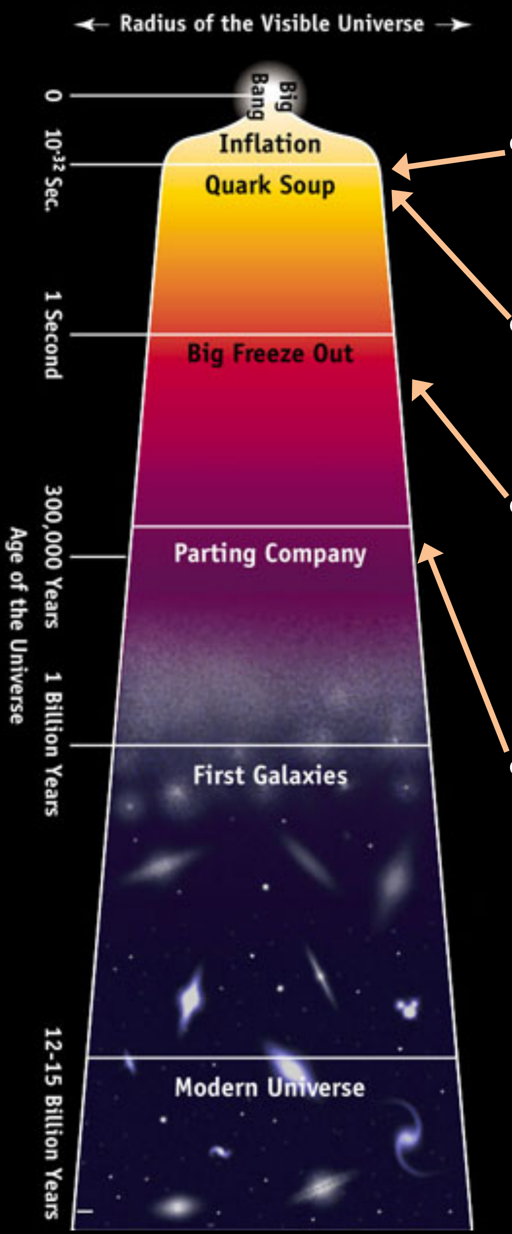
Dramatic Evidence: the Cosmic Background Radiation

- 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





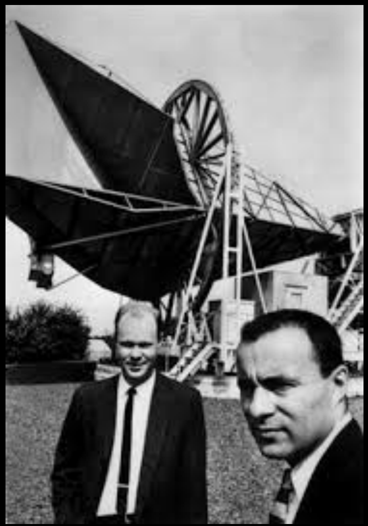
The Big Bang

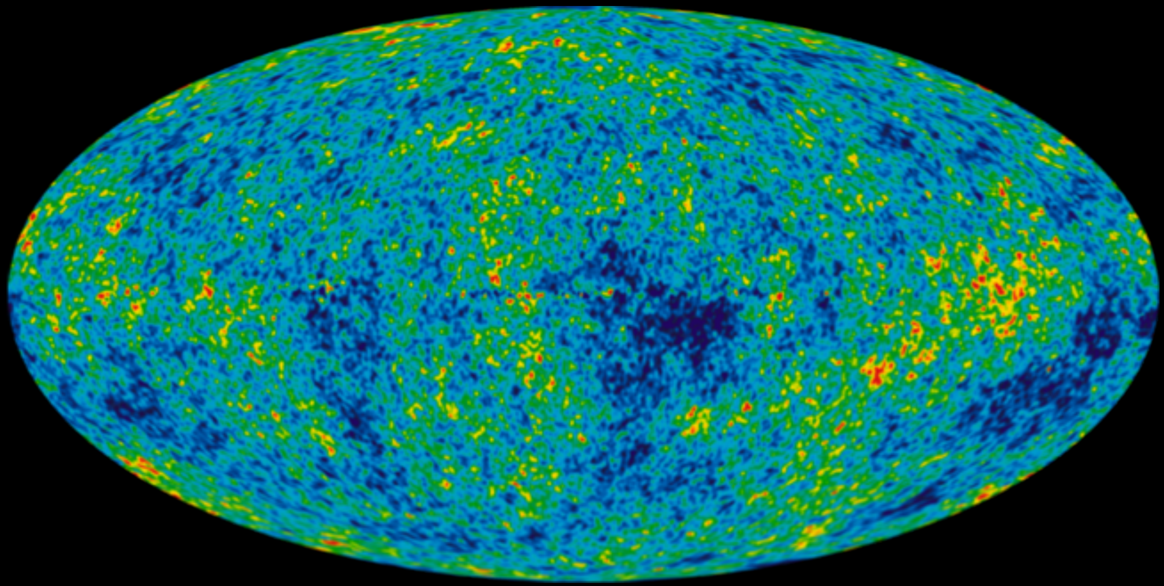


- Start: 10^{-32} sec., a couple inches, temp = 10^{28} F, free quarks and leptons, very strong forces
- 10^{-6} sec: half mile, temp = 2 x 10^{13} F, quarks group into protons and neutrons
- 3 min: 6.2 million miles, temp = 200 million F, protons and neutrons combine to form nuclei
  - Mostly Hydrogen and Helium
- 400,000 years: 42 million light years, temp 5,000 F, electrons and nuclei combine to form atoms
  - Electrically neutral, gas becomes transparent
  - Still glowing bright orange everywhere

Cosmic Microwave Background (CMB)

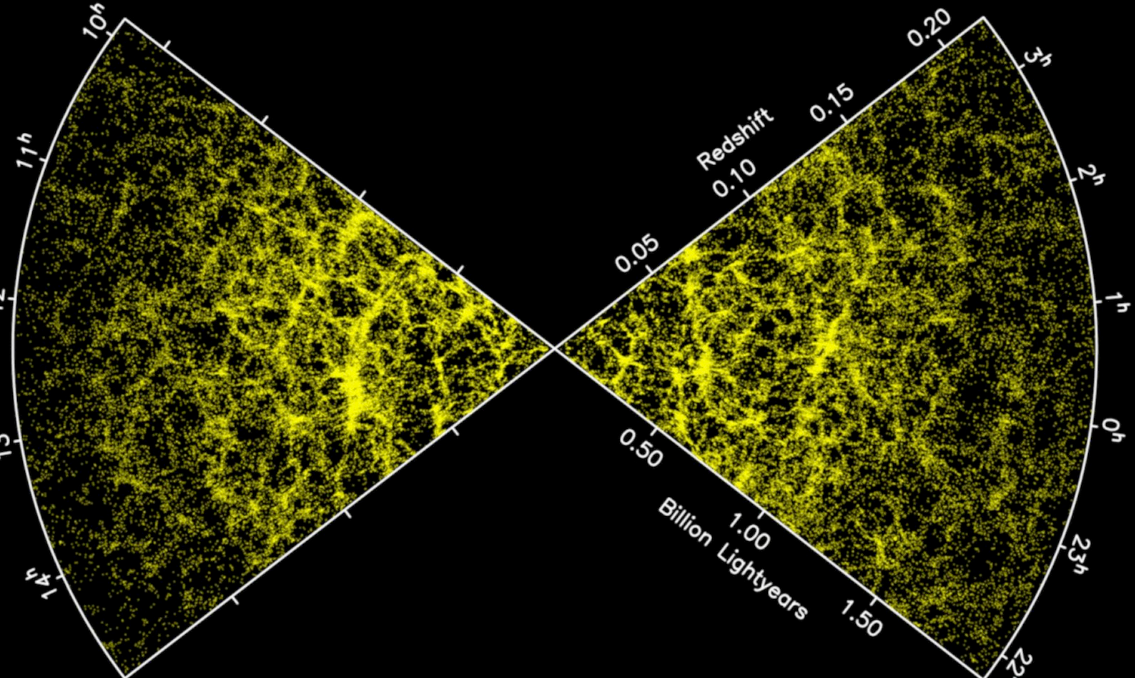
- The expansion of the Universe from 300,000 years to now (13.5 billion years later) causes the orange glow to redshift all the way to microwaves
- Very uniform, with very small variations
- These variations show regions of higher gas density, and are the seed for the eventual formation of galaxies

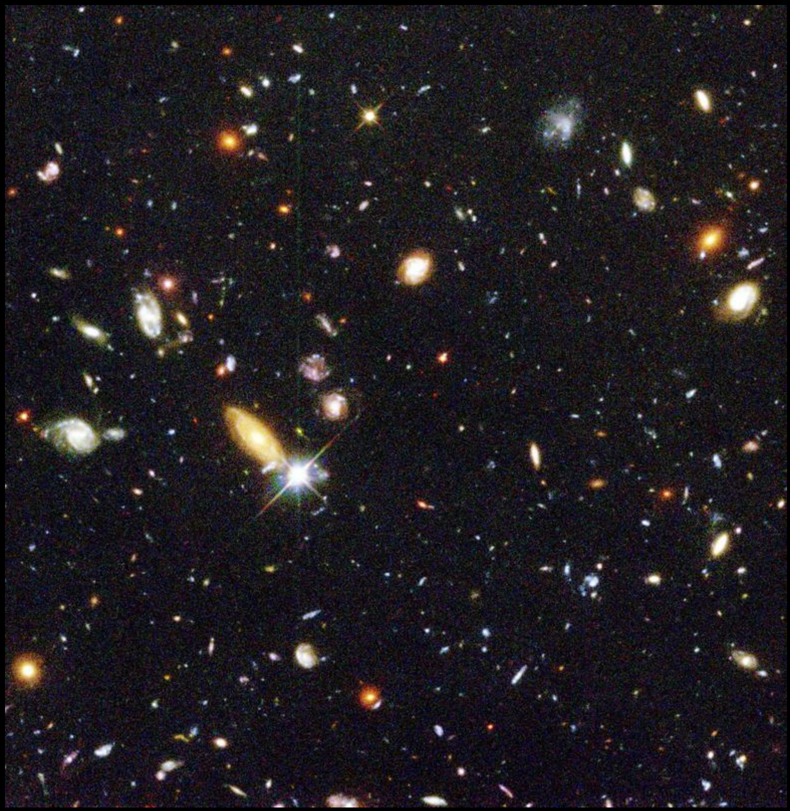




Expanding, it Cools: 13.8 Billion Years (now)

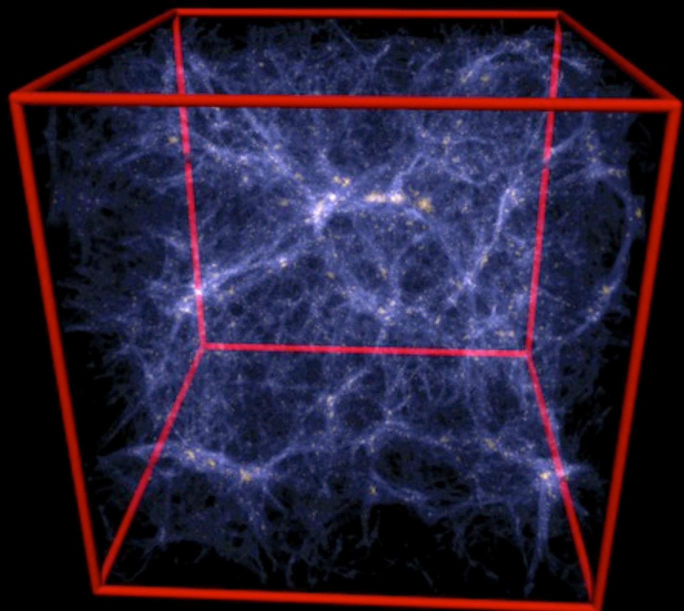
- Visible Universe size: 93 billion light years
- Temperature: -454.81 degrees F (2.7 K)
- Many many Galaxies

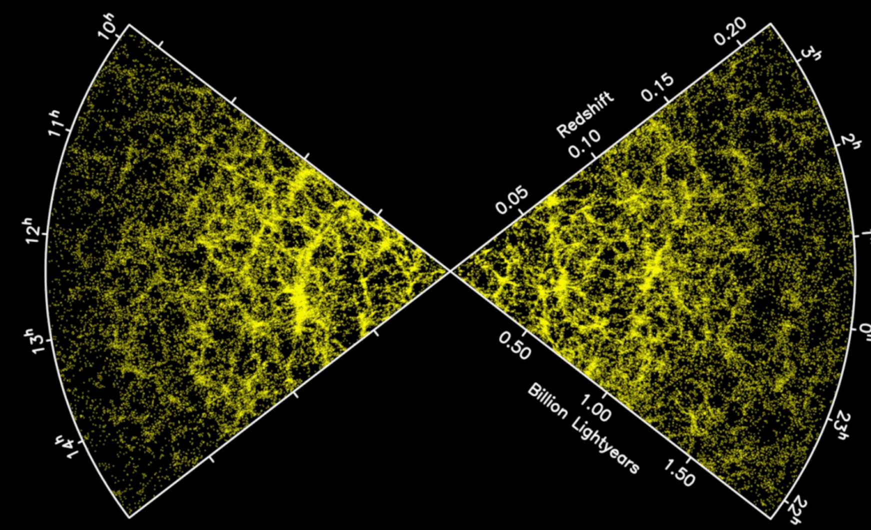




How to Get The Universe We See

- 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

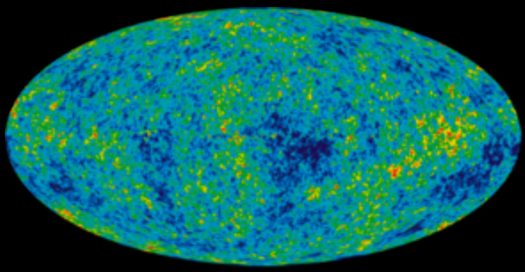




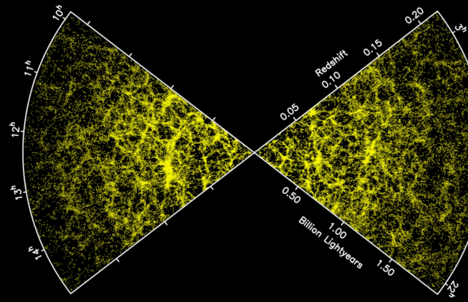
Successful Predictions of the Big Bang

- The Amount of Hydrogen and Helium in the Universe
  - After taking into account Helium production in stars

- The Cosmic Background Radiation

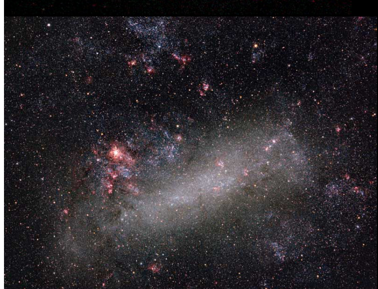


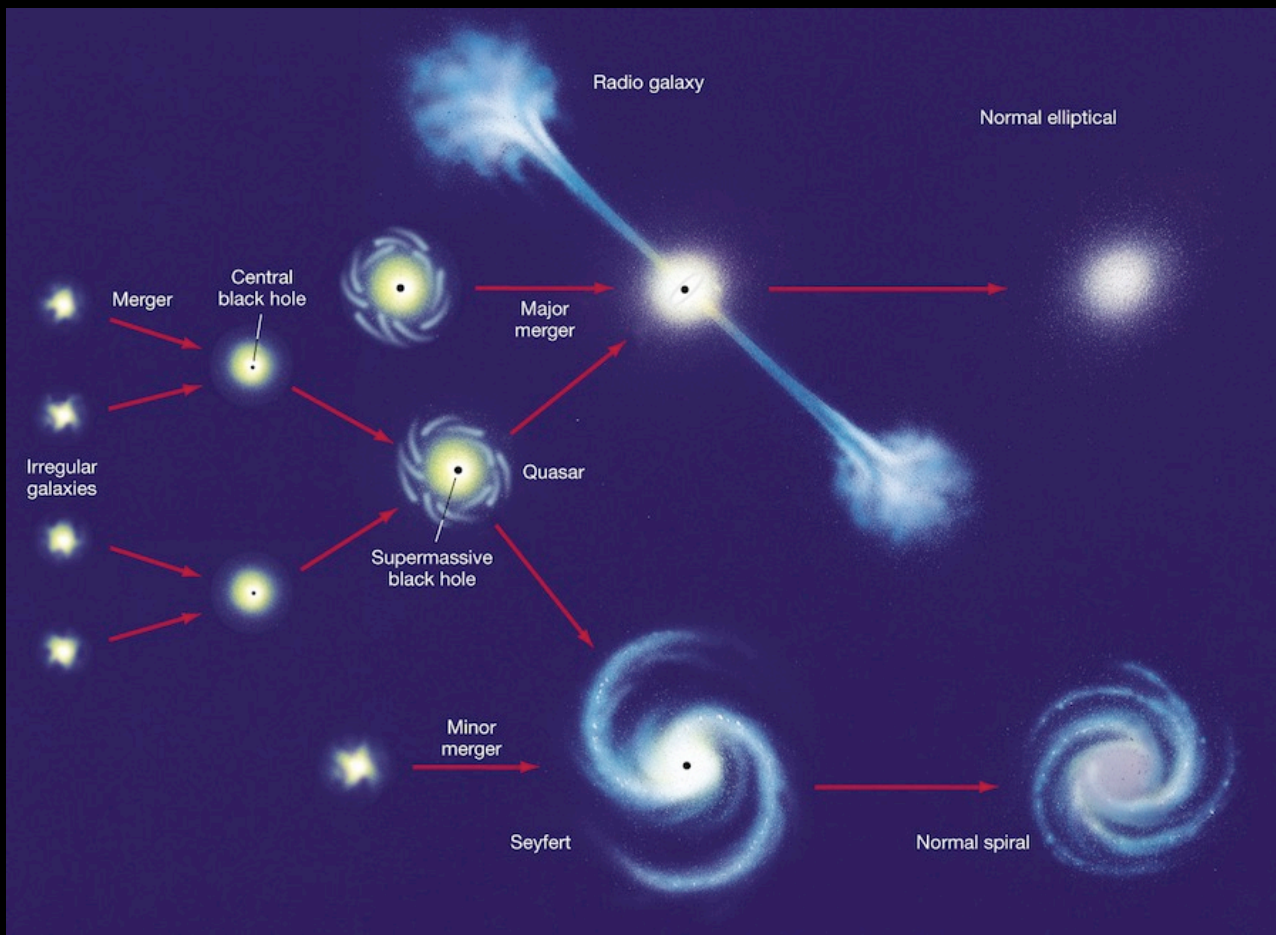
- The Large-Scale Distribution of Galaxies



Early Galaxies

- We believe early galaxies were small and irregular
- Larger galaxies built up from the small irregulars
  - Early in this process central black holes formed





Galaxy Collisions Were Common

- Early galaxies had much more gas, and collisions caused this gas to compress
  - Very active star formation
- We see many colliding galaxies even now





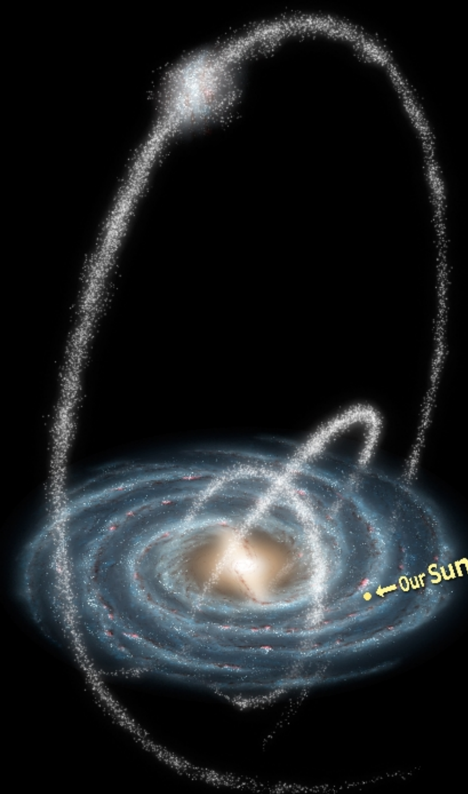


Formation of the First Galaxies

This movie shows a simulation, where color shows gas density

Our Galaxy Formed Early from Smaller Galaxies

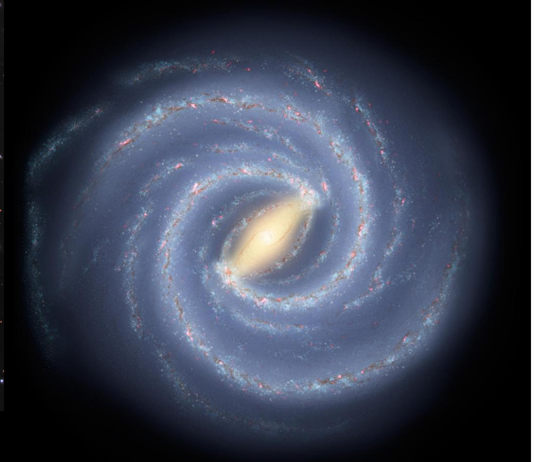
- We see a stream of stars above our Galaxy, likely the remains of a small galaxy that collided with ours
- Studies of star groups hint that some of them probably are from other galaxies that were absorbed by our Galaxy
- 4 billion years ago our Sun and Earth formed



Spiral Galaxy Structure

- Spiral arms are regions of high gas density
  - So high rates of star formation
  - Large, bright, short-lived stars most visible
  - Longer-lived dimmer stars move out of the spiral arms



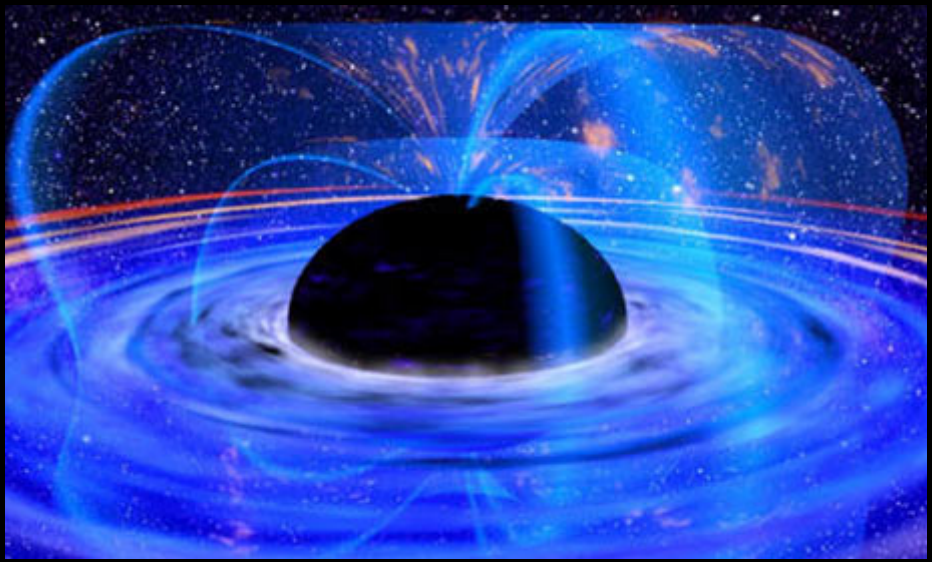



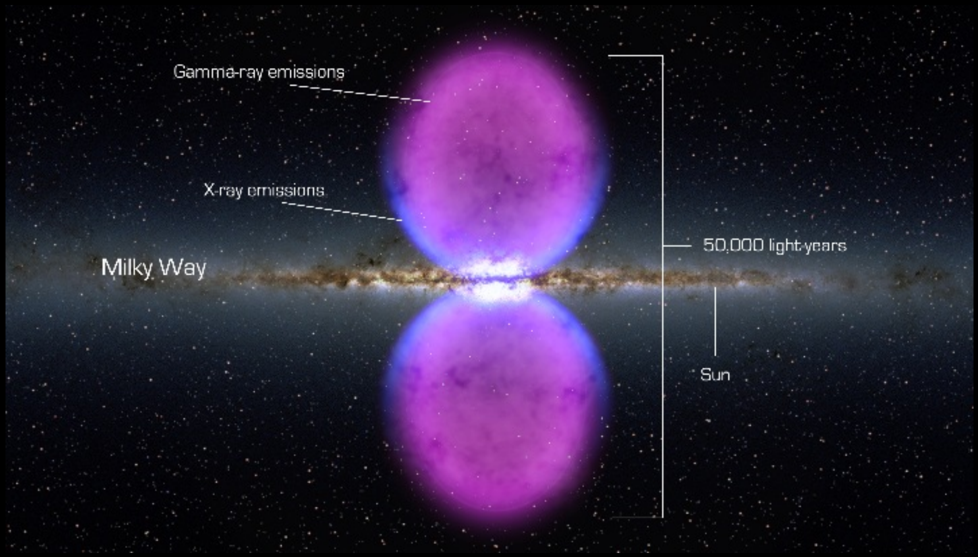
Elliptical Galaxies have Very Little Gas

- Used up in early star formation
  - Likely due to large collisions triggering star formation

Galaxies and Black Holes

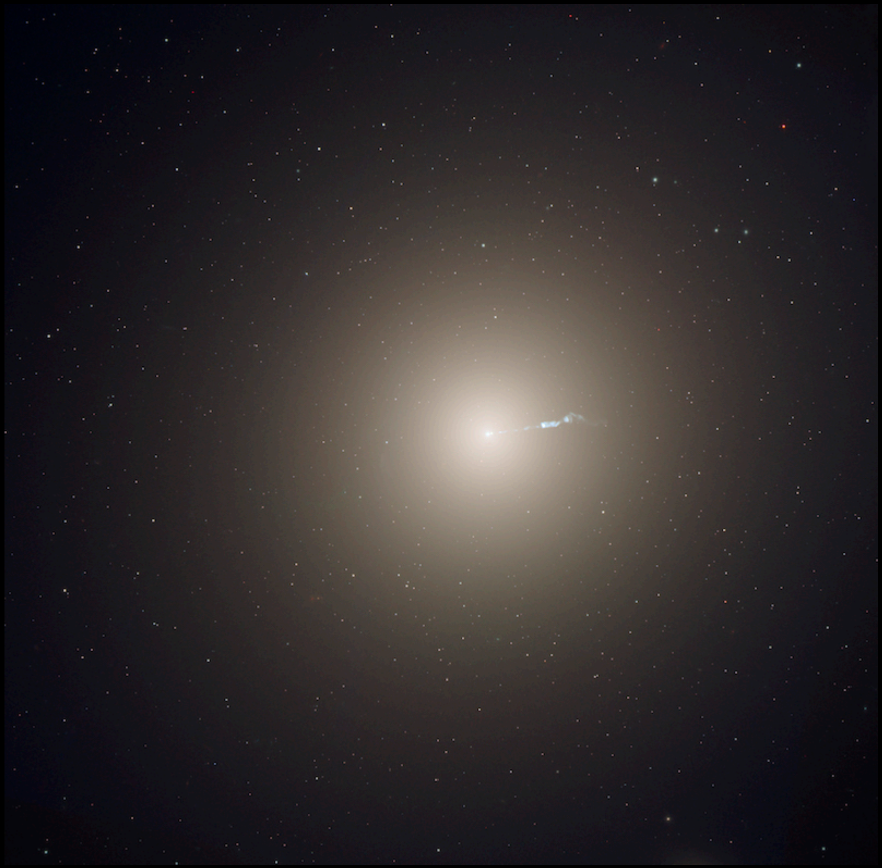
- All large galaxies have supermassive black holes in their center (probably)
  - Black hole in the center of the Milky Way is 4 million times as heavy as the Sun
  - Causes occasional very large explosions
- Larger galaxies have larger black holes

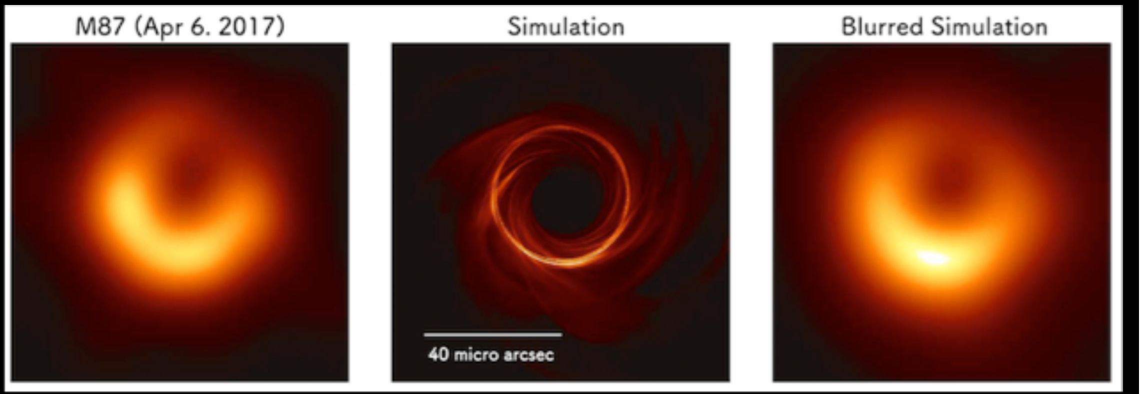




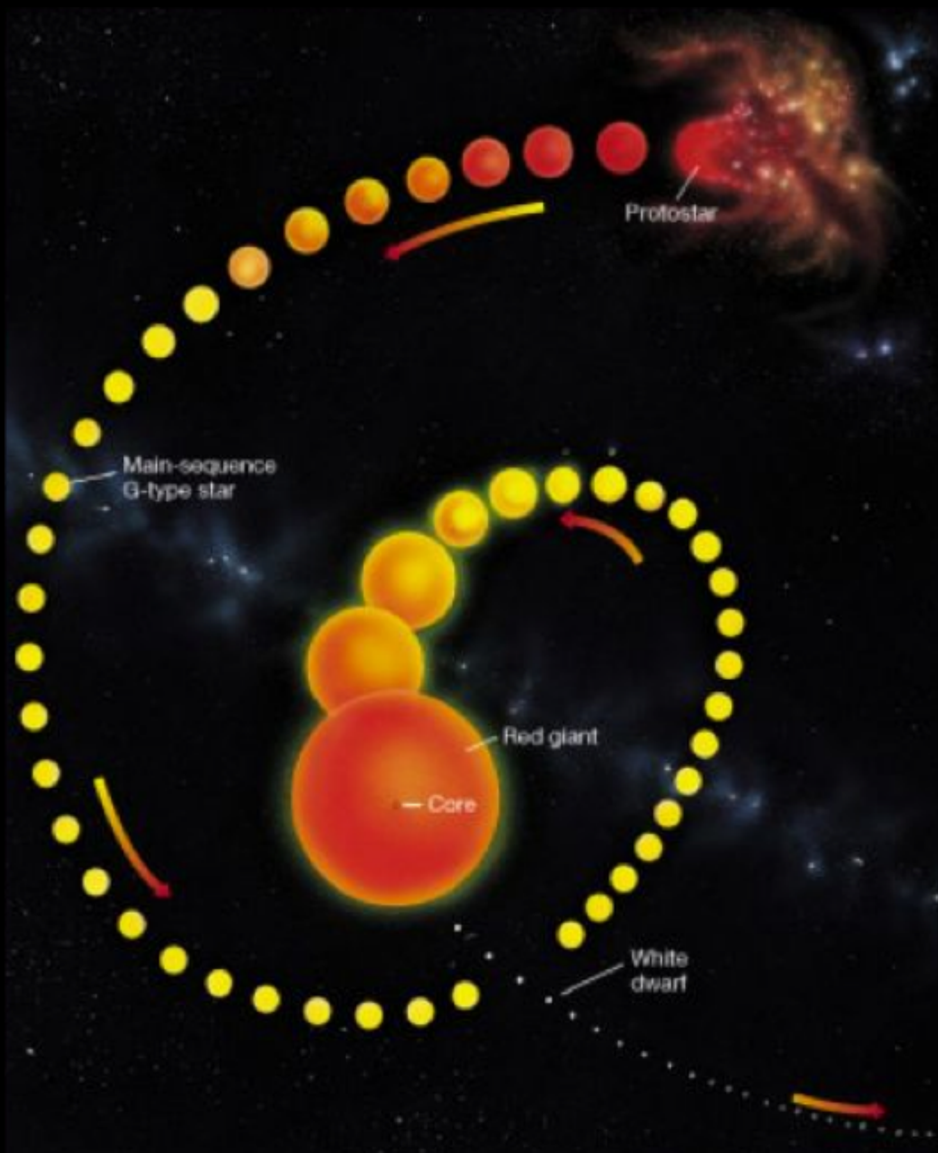
The Black Hole in the Center of M87

- M87 is a very large elliptical galaxy, with a large jet of material coming from its center
  - 54 million lightyears away
- A picture was taken of the light around the black hole last April
  - The picture is blurred: the simulation shows what we think it actually looks like
- The picture says the black hole has 6.5 billion times the mass of the Sun!
  - And is spinning very rapidly





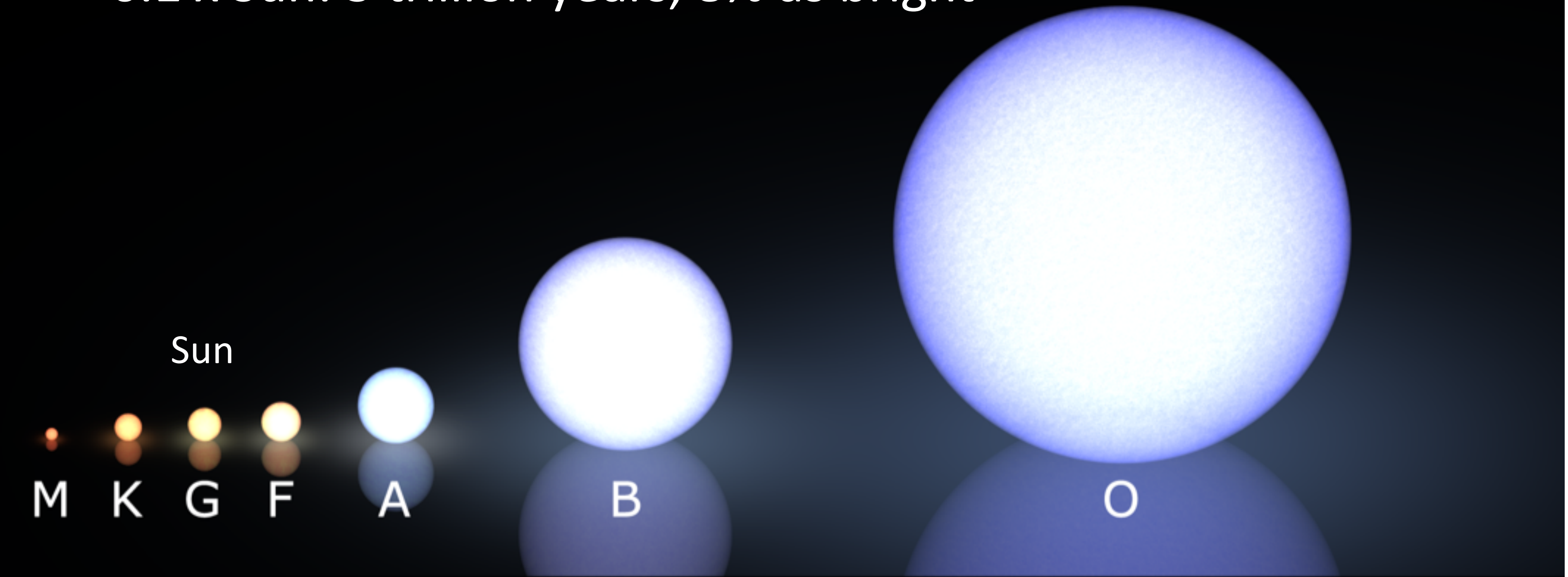
Life Cycle of Stars



- Most of the time in the "Main Sequence"
  - Burn Hydrogen to Helium
- At the end, burn Helium to Carbon to Oxygen to … to Iron
- Heavier elements born in supernovae

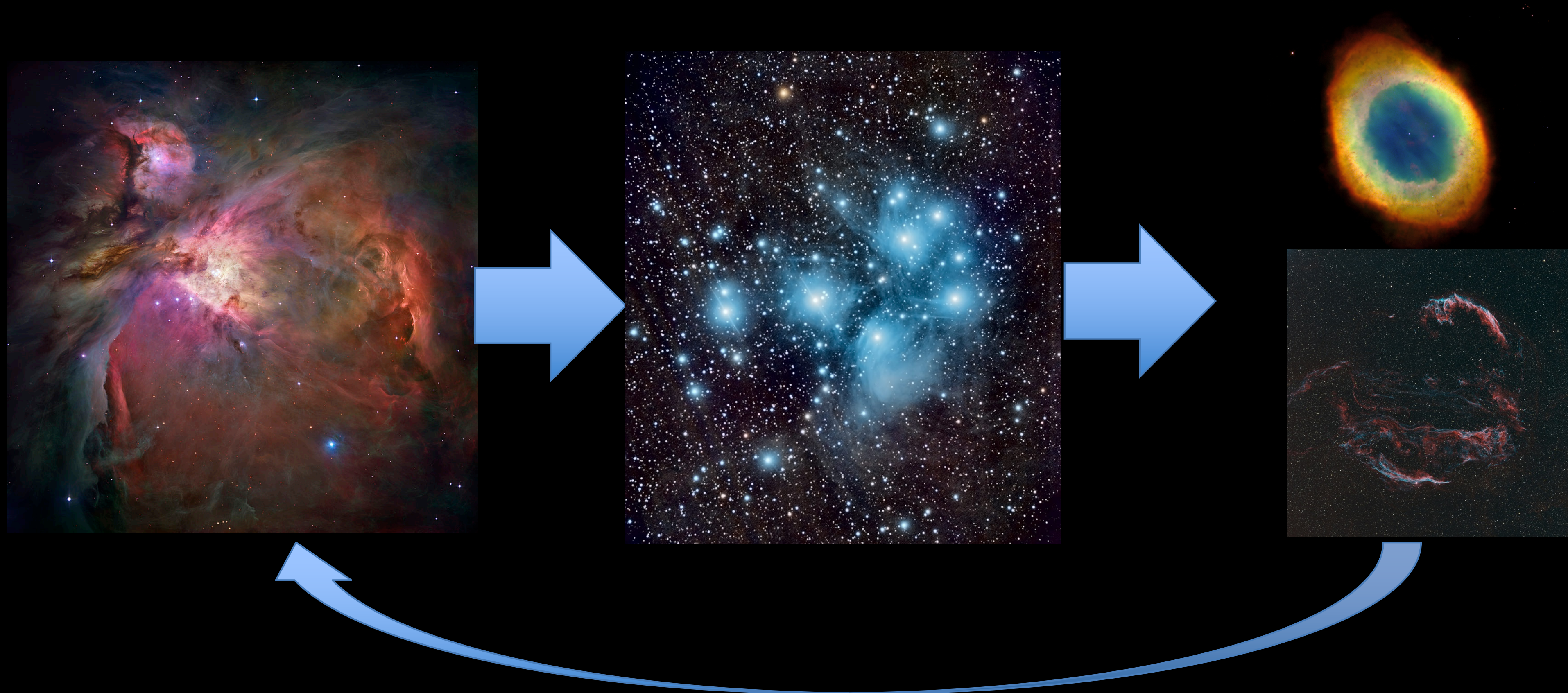
Size, Color and Lifetime Depend on Mass

- Heavier stars burn faster and hotter
  - 10 x Sun: 32 million years, up to 1 million times brighter
  - Sun: 10 billion years
  - 0.1 x Sun: 3 trillion years, 8% as bright



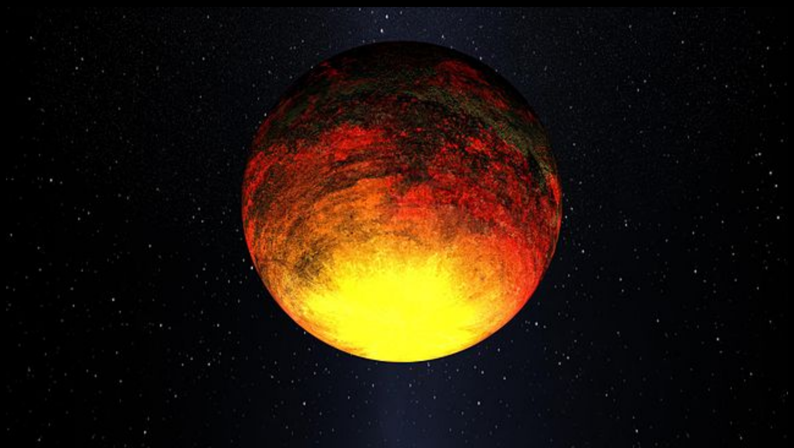
As the Universe Ages it Makes More Heavier Elements

- Elements created in stars, which blow off their gas and spread the elements to clouds that create more stars…



Planets Formed Early

- Planets orbiting the star HIP 11952 are 12.8 ± 2.6 billion years old (!)
  - Big bang was only 13.8 billion years ago
  - These planets are gas giants
  - The star HIP 11952 has very little heavy material
    - About 1% of the Sun's heavy material
    - Planets are probably about the same
- The Kepler-10 system is 10 billion years old
  - Has a rocky planet



To the Universe We See Today

Our Future?

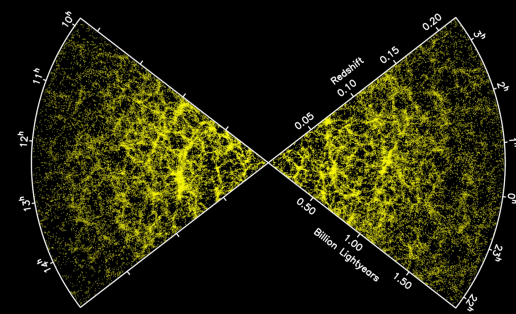
- The Andromeda Galaxy and the Milky Way are moving towards each other and will collide in about 4.5 billion years
  - Won’t effect the orbits of the planets
  - Right about when the Sun becomes a red giant

Long-Term Fate of the Universe

- We believe the universe will expand forever
  - Stars will eventually burn out
    - The lightest stars last trillions of years, but as they burn out the put out little gas to make new stars
  - Cold and Dark
    - Gas, Dust, Planets, Remnants of Stars, Black Holes

Still two mysteries (class 6)

- 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



- 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

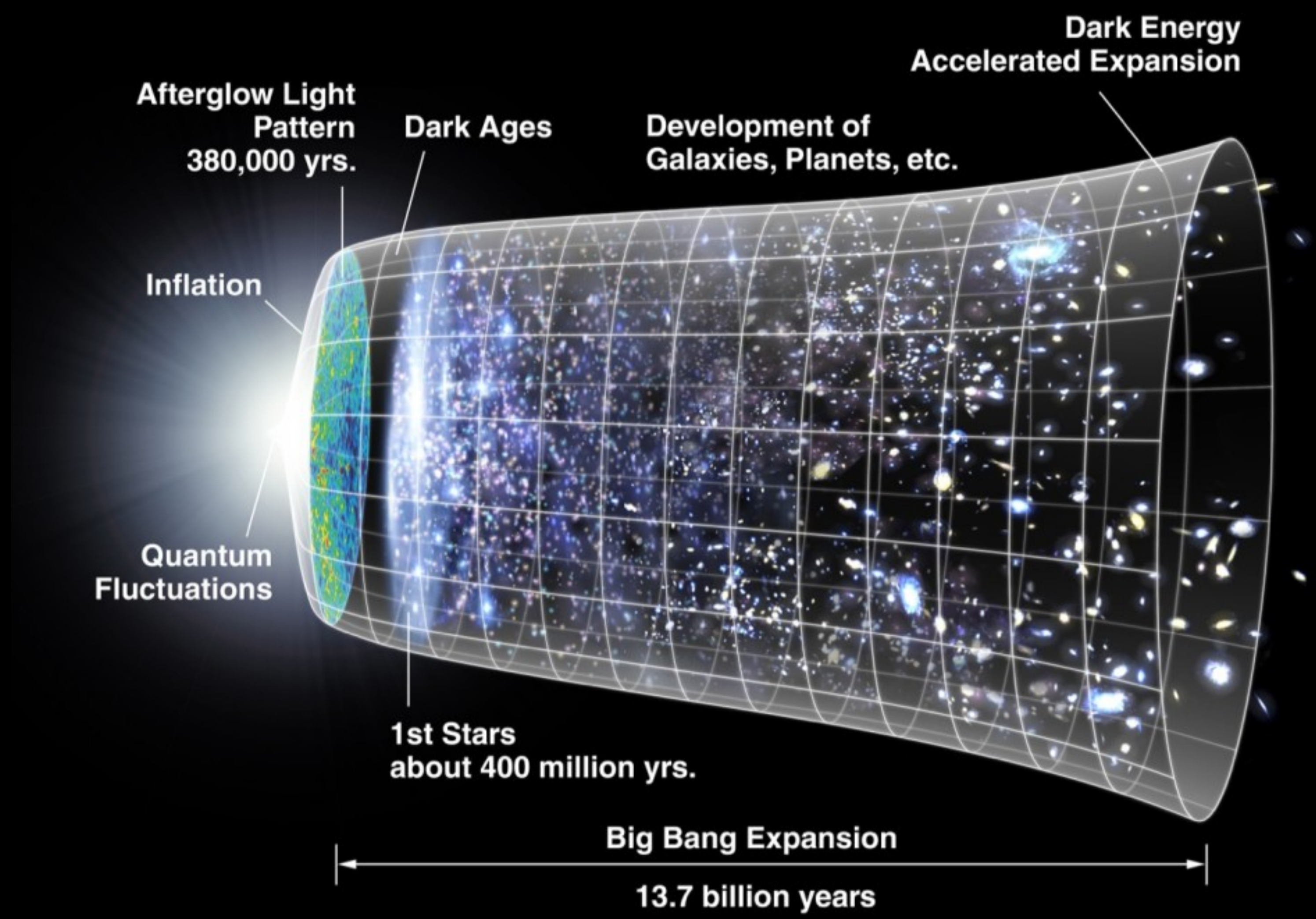
Back to the Beginning: Before 10^{-32} Seconds

- Before 10^{-32} seconds, the Universe was hotter and denser than any kind of matter we've ever experimented with
- We believe that when things are hot enough and dense enough our current theories break down
  - Replaced by better "Grand Unified" theories
    - Supersymmetry, string theory, others
    - None of these theories have any observational support
- We are no longer in the realm of known physics
  - The expected discovery of supersymmetry at the LHC has not happened

Cosmic Inflation

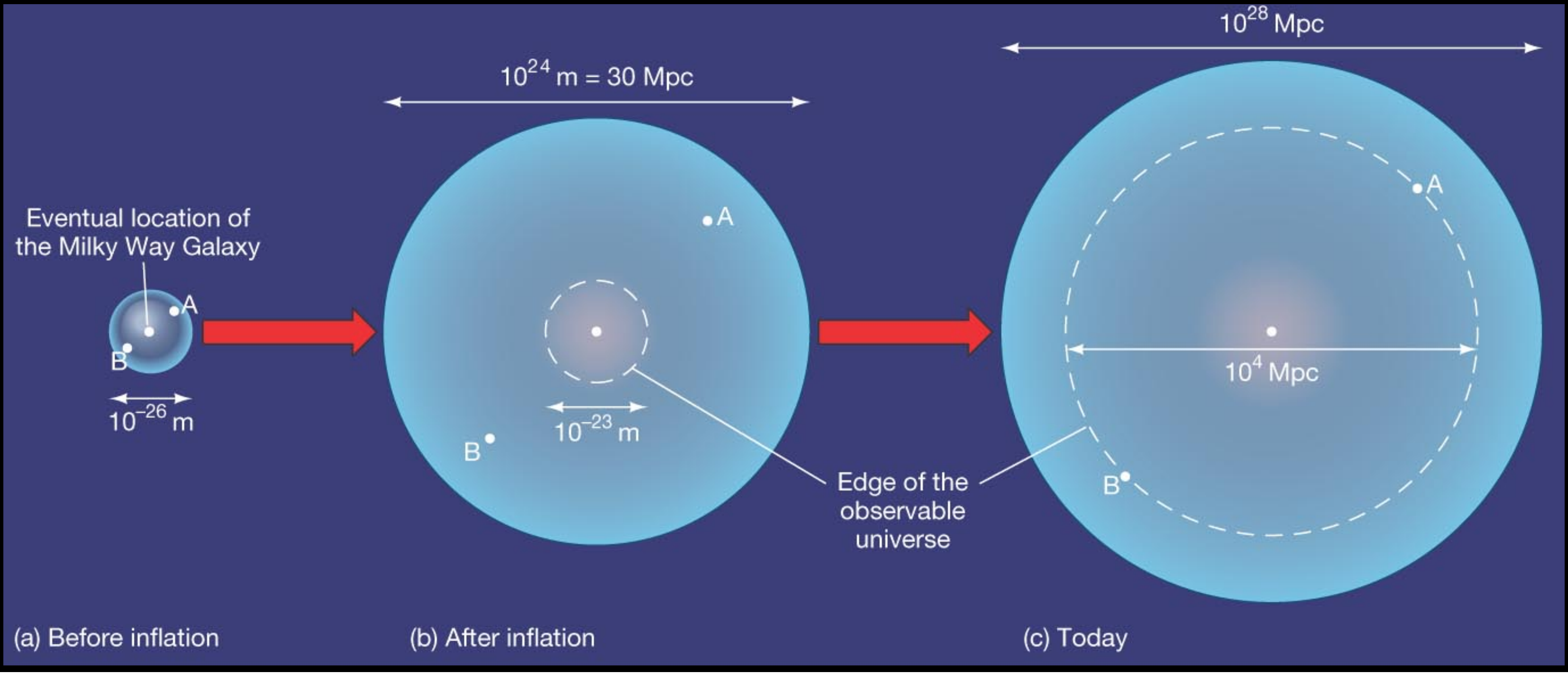
- Natural (but speculative) extensions of our theories of particles and forces predicts a large cosmological constant when the temperature is very very high
  - Similar to the physics behind the Higgs particle
  - Alan Guth, Andrei Linde, Andreas Albrecht and Paul Steinhardt
- A large cosmological constant means negative pressure
  - Like the recently discovered accelerating expansion of the universe
    - possibly due to a small cosmological constant
- The temperature would have been high enough from 10^{-36} to 10^{-32} seconds
  - A very short time, but the universe would have expanded by a factor of maybe 10^{78} = a million trillion trillion trillion trillion trillion trillion times!

Cosmic Inflation



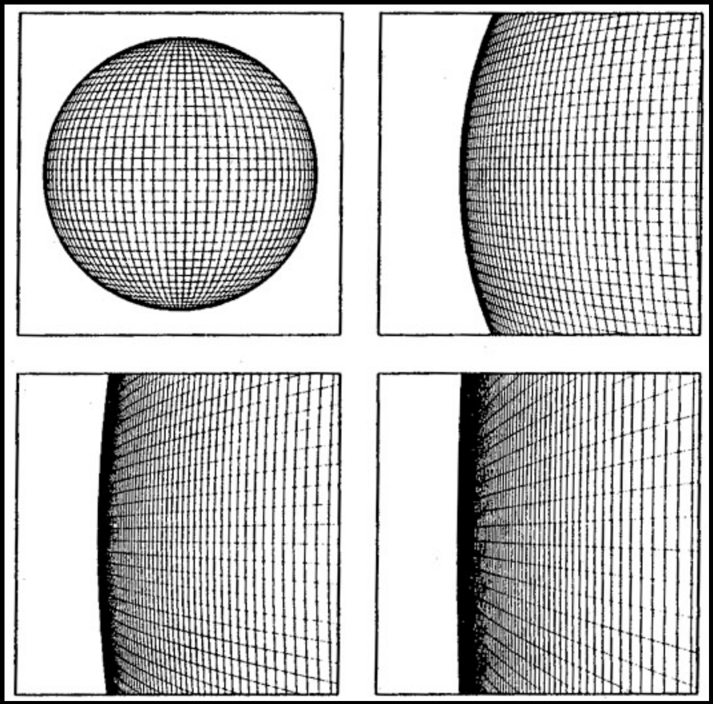
Inflation Explains Homogeneity

- At the very beginning the observable universe was very very small
  - From 10^{-36} to 10^{-32} seconds the universe would have expanded by a factor of maybe 10^{78} = a million trillion trillion trillion trillion trillion trillion times!
  - So things that are far apart now, like opposite sides of the observable universe, were close enough to interact



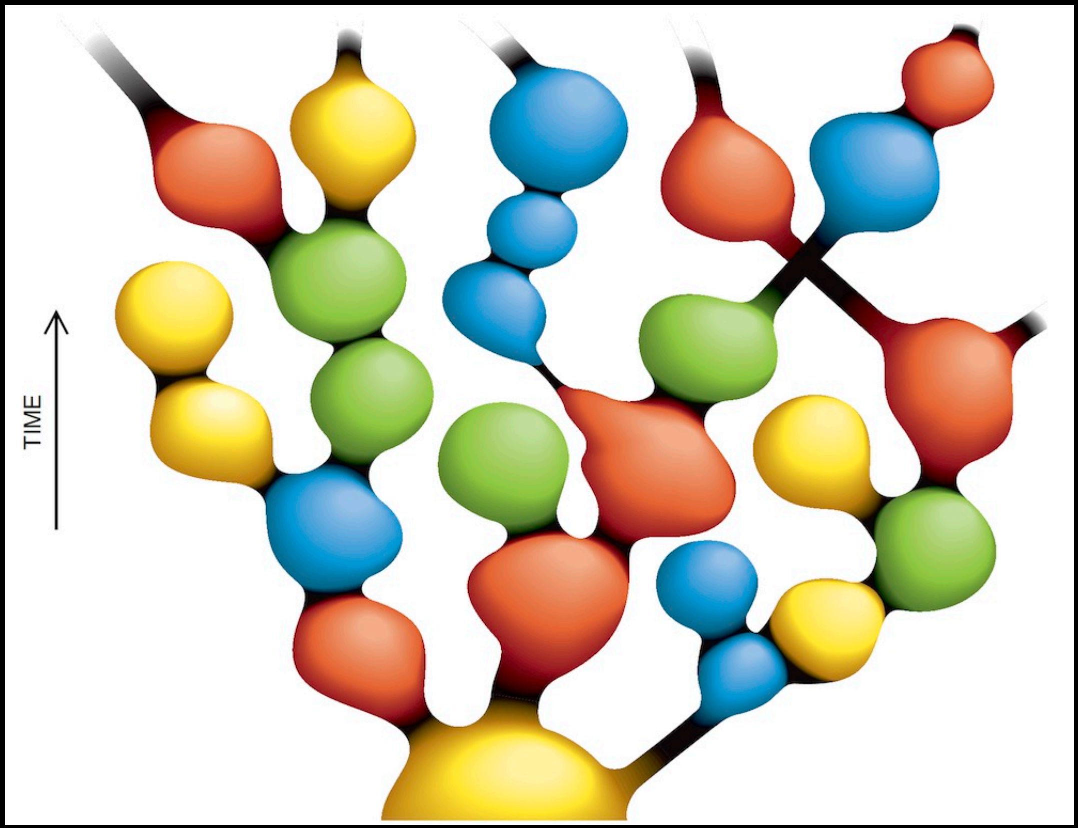
Inflation Explains Flatness

- Whatever curvature there was before inflation would now be spread out over a much larger volume
  - Like blowing up a really really big balloon: if it gets large enough it looks pretty flat



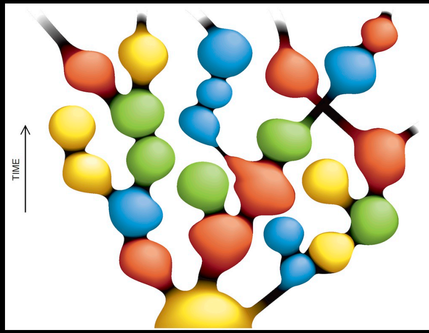
Eternal Inflation

- The Inflation idea naturally leads to the possibility that the inflation happens differently, at different times in different parts of the universe
  - First example of a Multiverse



Eternal Inflation

- In eternal inflation, anytime you get the temperature high enough you can have a little universe popping off
  - Experiments in very high energy accelerators?
- These "baby universes" never intersect
- Maybe the laws of physics are different in each one
- But they probably do not exist: this is very highly speculative

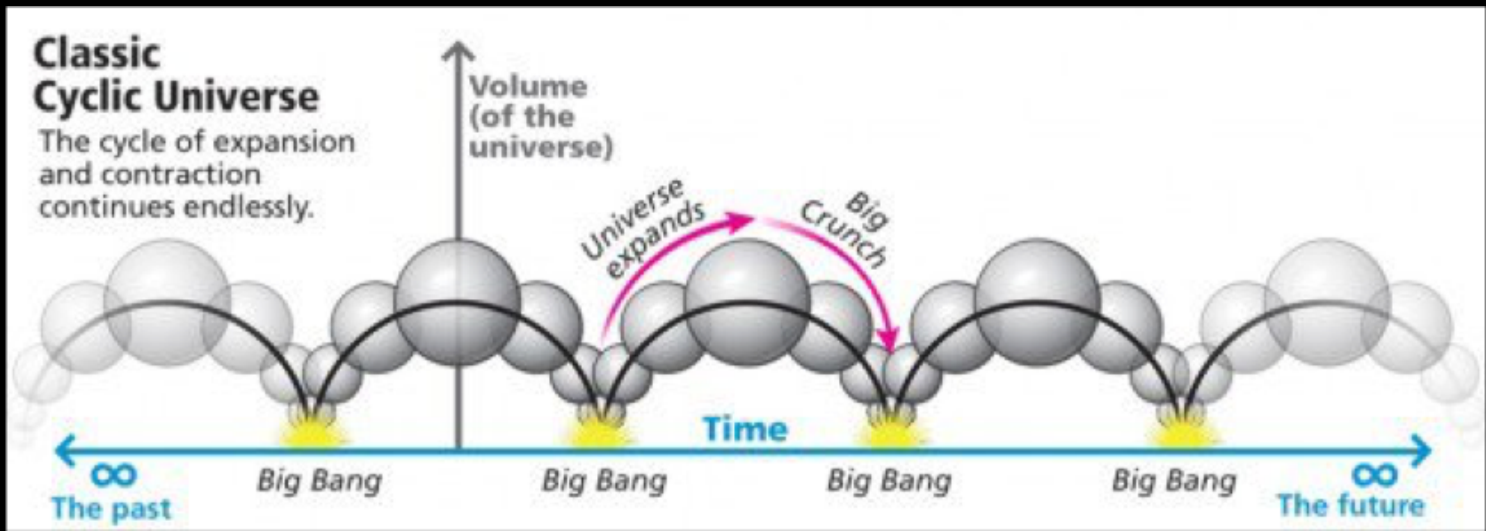


Other Multiverse Ideas

- The multiverse concept appears in several places in physics
  - Normal quantum mechanics: the “many worlds” interpretation
  - String theory: requires 10 dimensions, where 6 of them are twisted into loops too small to see
    - There are many many ways to do that twisting, and they all have different laws of physics
      - “string theory landscape”
  - Brane theory: our 4-dimensional universe is in a higher dimensional space, and there are other 4-dimensional spaces
- These concepts of multiverse have nothing to do with each other, and are probably wrong

Cyclic Universe

- If the spatial curvature of the universe is positive, it gets bigger, stops, then gets smaller
  - If inflation is true, the universe would look flat whether it's positive or negative curvature, so we can't tell
- What happens when everything comes back together again?
  - Another big bang?
  - This would mean the universe recycles, maybe with new laws of physics
- But it probably doesn't, especially considering the accelerating expansion



What About t = 0 Seconds?

- Did the observable universe ever have zero volume?
  - Called the "initial singularity"
  - If General Relativity as we know it today is always true (and matter behaves as we think it does) then we can prove that zero volume must have occurred
    - "Singularity theorem" by Stephen Hawking
- But we're pretty sure that as you get down to sizes like 10^{-34} inches then General Relativity breaks down and we need "quantum gravity"
  - But we have no idea what quantum gravity is
    - Two main schools, but neither is convincing
      - Loop quantum gravity
      - Supersymmetric string theory

What About Creation?

- Physics has no mechanism for the creation of energy from nothing
  - Popular speculative theories don't either
- The question is subtle: time is part of the space and time that is curved
  - There really is no clear meaning of "time" before the big bang
    - The "no boundary" proposal of Stephen Hawking