Astronomy 330

This class (Lecture 4):

Origin of Elements

Next Class:

End of the Universe

Presentation Synopsis due Thur.

Music: *The Universe is You* – Sophie Ellis-Bextor

Outline

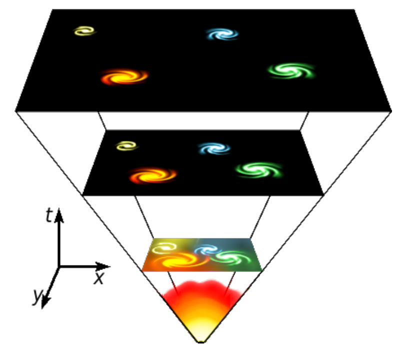
- The early Universe– The origin of H
- The probable fate of the Universe

Big Bang

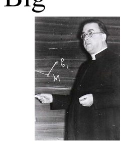
- We spent the last class discussing the Big Bang.
- In the same groups as last time, try to write a 4-5 sentence explanation of the Big Bang to a non-science major friend.
  - What are the essential points?

Putting it all together:

1. The Universe is expanding
2. Earlier Universe was more dense
3. Earlier Universe was hotter.



The origin of the Universe can be described by the idea of the Big Bang. Where did the Big Bang happen? The Universe is homogenous & isotropic.



Georges Lemaître

What is the history of the Universe according to the Big Bang theory?

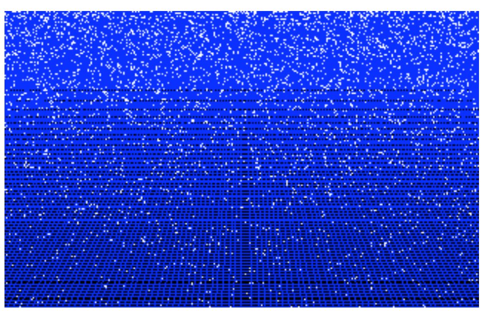
- Universe cooled as it expanded
- Cosmologists cannot begin their history of the big bang at time zero.
- No one understands the physics of matter and energy under such extreme conditions.
- Nevertheless, they can come amazingly close.

The Biggest Bang since the Big One

- Occurred everywhere at once
- <u>Not</u> an explosion into empty space.
- The Universe was suddenly filled with energy – hot and dense
- The **beginning** of spacetime, matter, and energy

The Big Bang

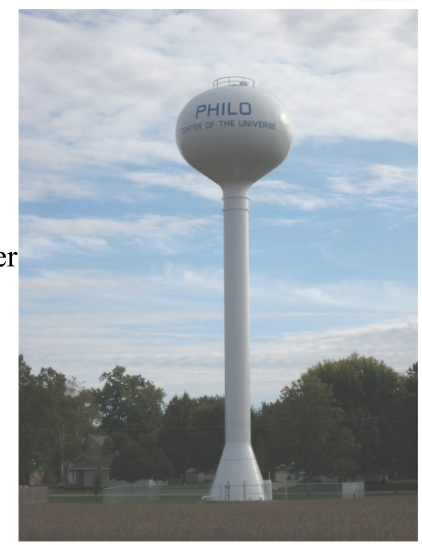
- No special points or locales
- Expansion of **all** space
- As spacetime expanded, the Universe became less dense and cooler
- Eventually forming the stars and galaxies we see today



http://www.atlasoftheuniverse.com/bigbang.html

The Big Bang

- Big Bang has no center
- Happened everywhere
- Wherever you go, there was the big bang
- So as we talk about the very dense early universe, remember that we are talking about what happened not just far away at the edge of the Universe, but **<u>right here!</u>** ...smooshed up small, but still **<u>right here</u>!**

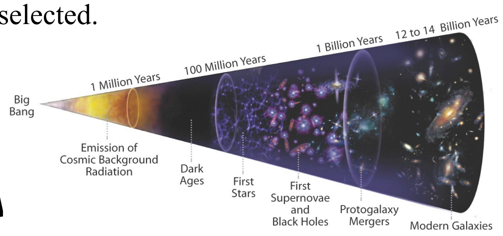


The 3rd Revolution

1. Copernicus and others: We are not the center of the solar system. The Earth is a typical planet.
2. Shapley and others: We are not the center of the Galaxy. The Sun is a typical star.
3. Hubble and others: We are not in the center of the Universe. The Milky Way is a typical galaxy.

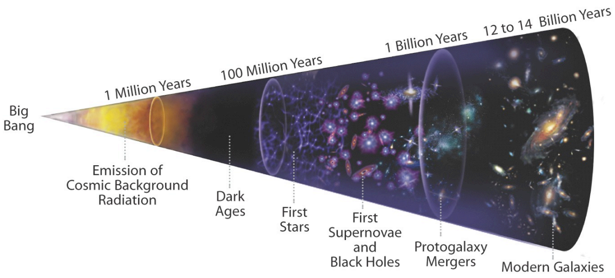
Naming the Big Bang

- In the 1940s, extrapolating on Hubble's Law, George Gamow proposed the the universe began in a colossal "explosion" of **expansion**.
- In the 1950s, the term BIG BANG was coined by an unconvinced Sir Fred Hoyle who tried to ridicule it.
- In the 1990s, there was an international competition to rename the BIG BANG with a more appropriate name, but no new name was selected.



The Big Bang

- Scientists do not have a definitive explanation for the Big Bang
- But, a growing body of observations supports the theory that the event did occur.

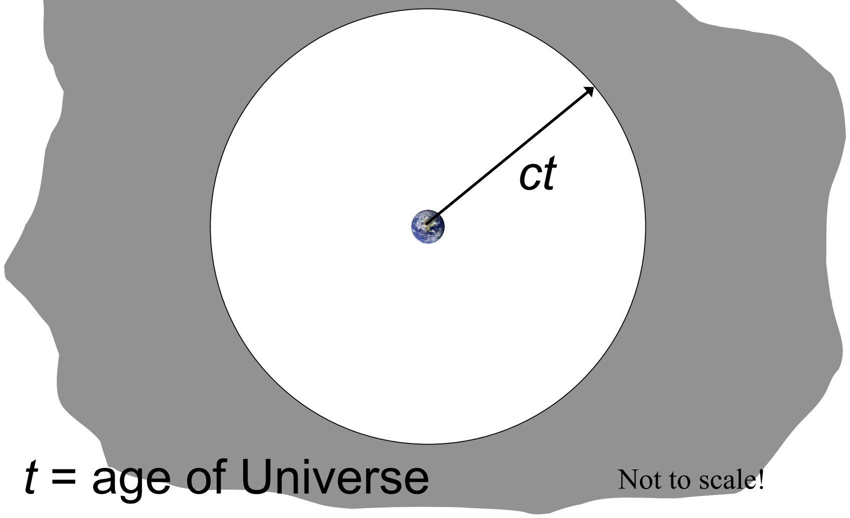


Question

Where did the Big Bang occur?

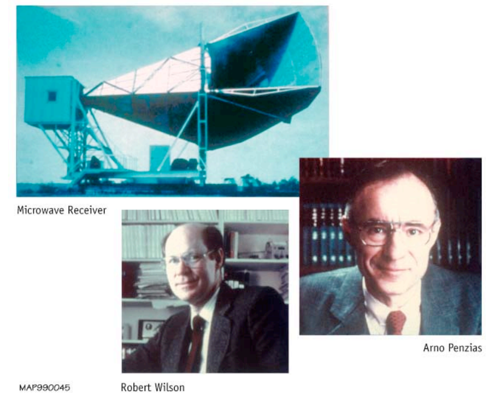
a) Everywhere.
b) At the edge of the Universe.
c) Just a little past the edge of the observable Universe.
d) Somewhere in the outer region of the Milky Way.
e) Snyder Hall, last Saturday night, 11:33 pm.

Looking Back in Time: The Observable Universe!

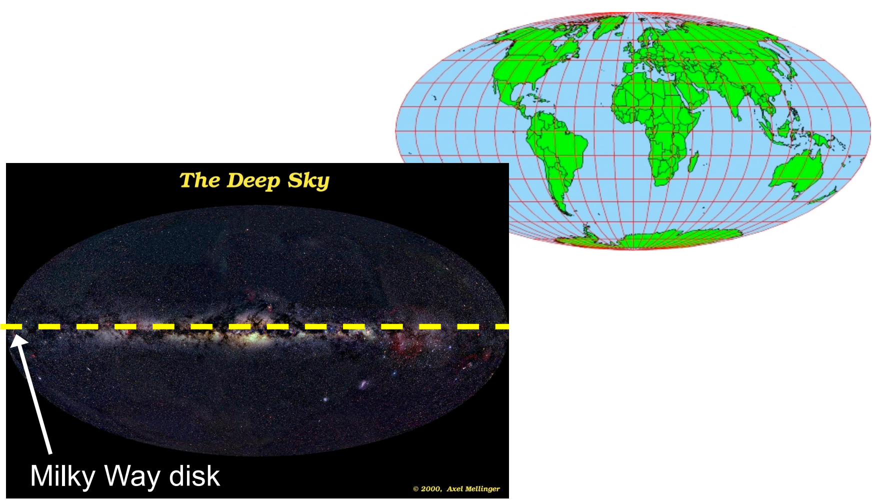


The Early Universe was *HOT*!

- If the early Universe was so hot, we should be able to see it glowing. Right?
- **Yep, we do!** But, as the Universe expanded, it redshifted down to the microwave.
- Now, it is called the Cosmic Microwave Background (CMB).
- First detected by Robert Wilson and Arno Penzias.

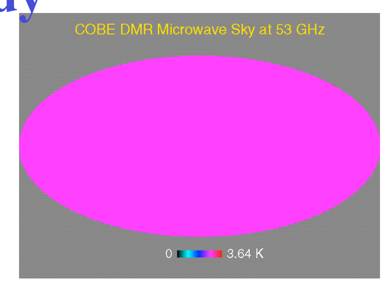


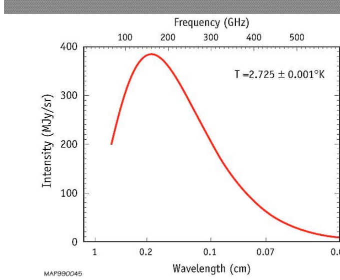
How to Understand Sky Maps

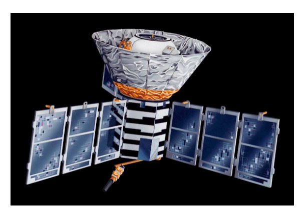


In Fact, a Rather Uniform Blackbody

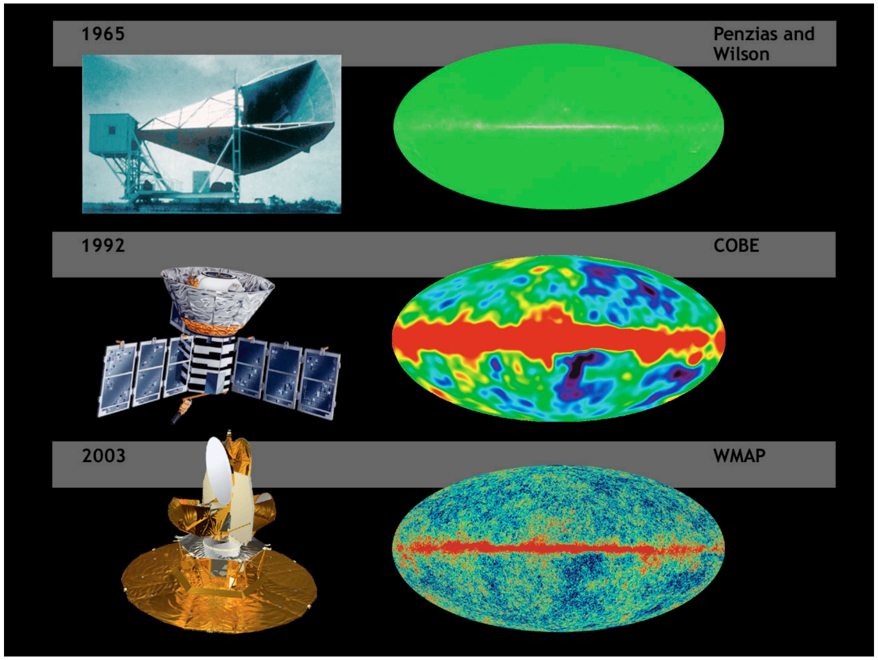
- All over the sky, we see blackbody radiation
  - Temperature = 2.73 K
- Provides compelling evidence for the Big Bang Theory
- Almost perfectly *isotropic*
  - Nearly the same in every direction
- Indicates that, over large scales, the Universe is uniformly spread out



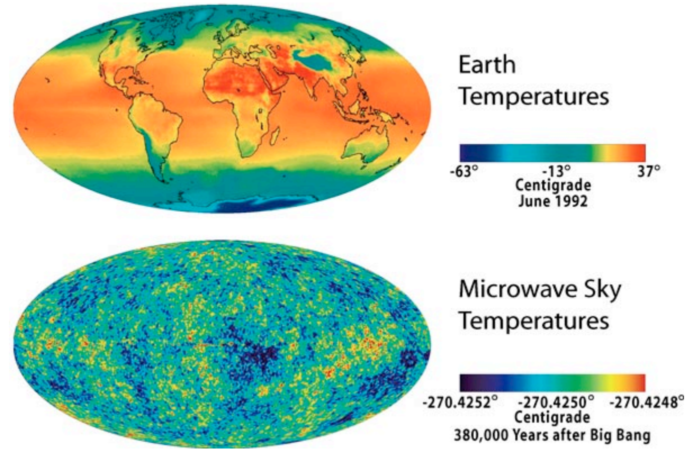




Cosmic Background Explorer (COBE) satellite (launched 1989)



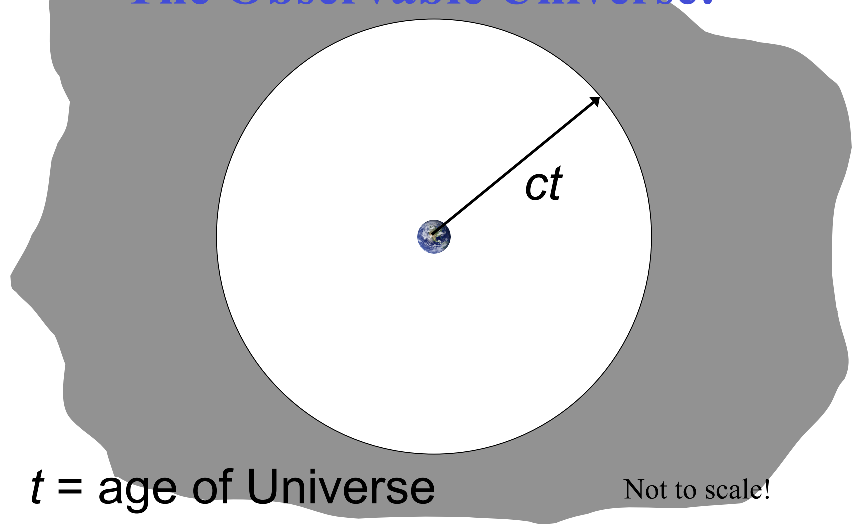
WMAP took a "baby picture" of the Universe– only 400000 yrs old.



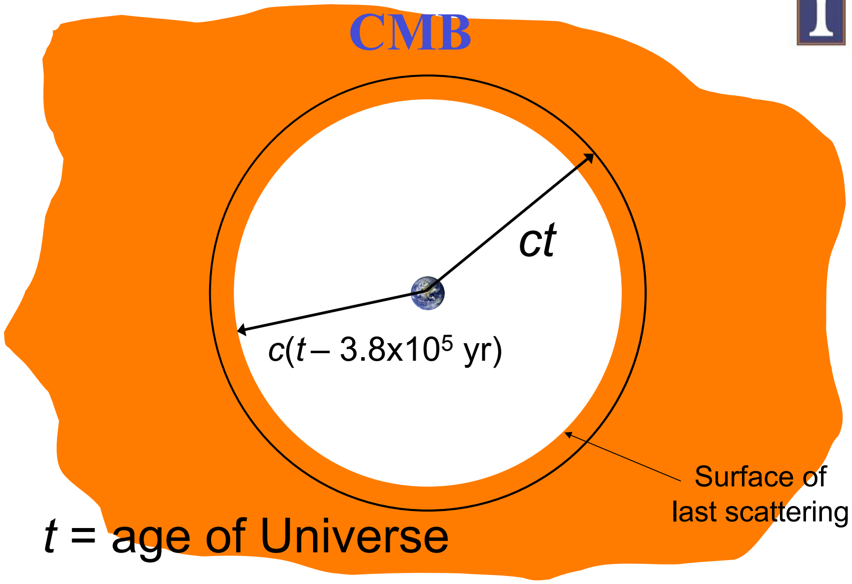
Unknown Fluctuations…

Further refinements of the cosmic micro-wave background reveal a deeper mean-ing for physicists to ponder.

Looking Back in Time: The Observable Universe!



Looking Back in Time to the CMB



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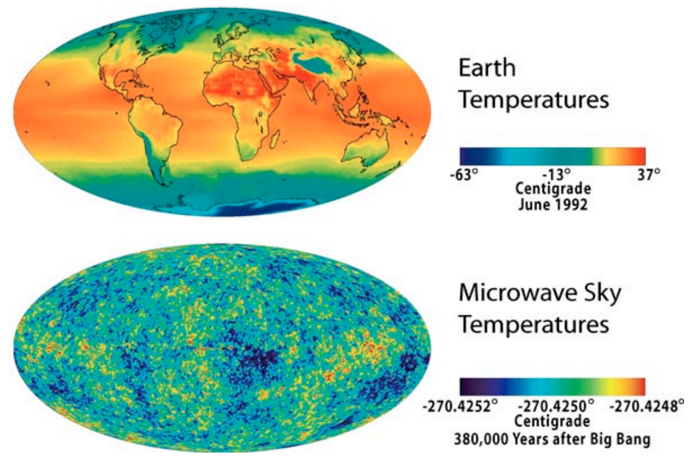
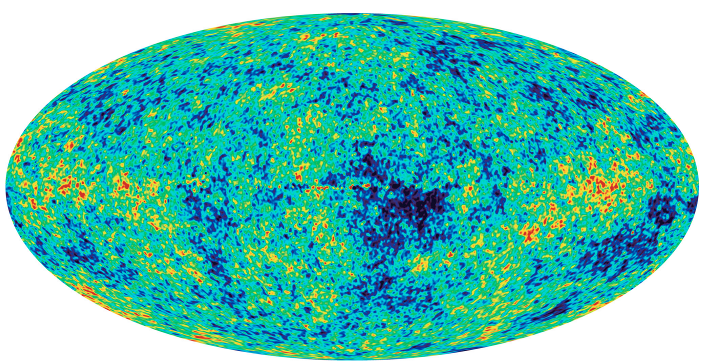


The Seeds of Galaxies

These small perturbations in temperature are the fluctuations (smaller than 1 in a 100,000) that caused the large scale structures we see today. This is what formed galaxies. All of this happened only 400,000 years after the Big Bang.



Galaxies

- Back to Cosmology… where did the seeds of today's Galaxies come from?

The Seeds of Galaxies

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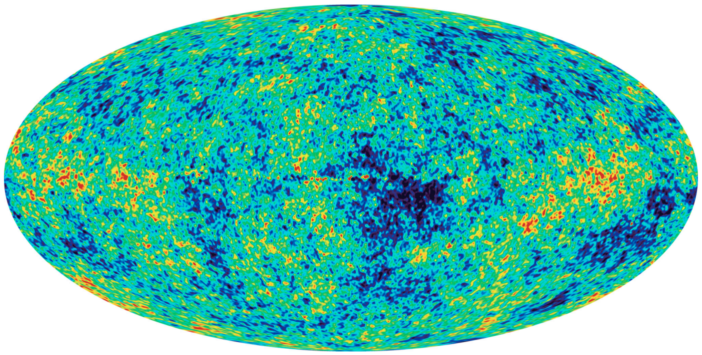
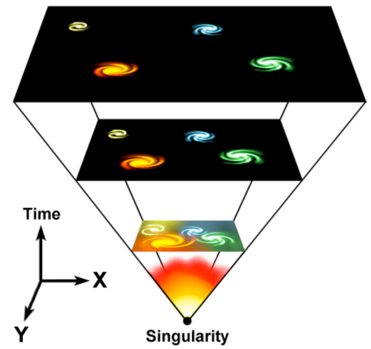


What is the history of the Universe according to the Big Bang theory?

- We begin at a 10-millionth of a second old
  - Current observable universe was the size of our solar system
  - Incredibly hot and dense
  - Cools as it expands in size



THE VERY EARLY UNIVERSE

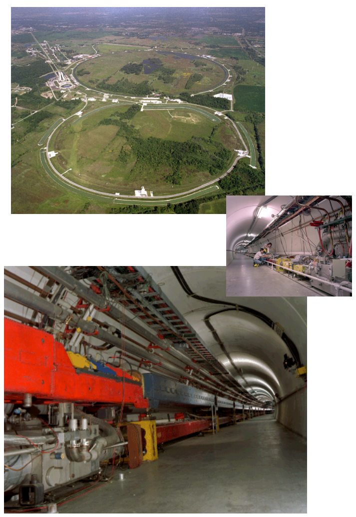
Since Big Bang works well so far, we have confidence to think about very early times:

t << 1 sec !

- Temperature and energies are ***ultrahigh***

Q: How to probe such high energies?
Hint: it's in the Great State of Illinois

Fermilab



INNER SPACE / OUTER SPACE

Fermilab is a telescope!

Probes conditions in Universe at 10^{-12} s

Universe was 10^{12} K hot!

…but also…

"The Universe is the poor man's accelerator"

Probes conditions inaccessible at laboratories

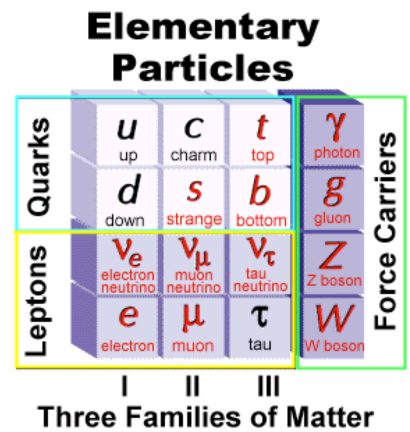
A Little Background Info

To better understand the early Universe, we need to talk about a few topics first:

1. Basic Particles
2. Matter and Anti-matter

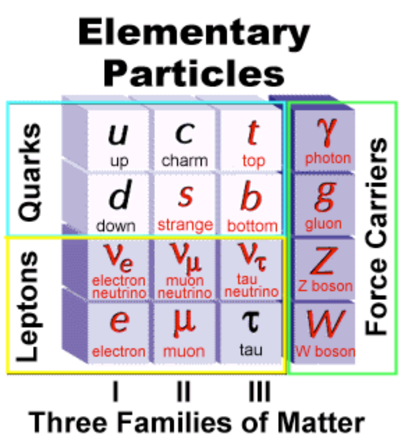
Basic Particles

- There are three types of basic particles in nature
- **Quarks** - matter
  - Building blocks of protons and neutrons
- **Leptons** - matter
  - Electrons and neutrinos
- **Force Carriers** - energy
  - Photons, gluons, gravitons?



http://sol.sci.uop.edu/~jfalward/elementaryparticles/elementaryparticles.html

Basic Particles



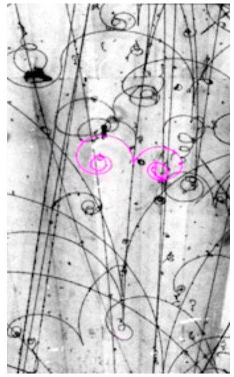
http://sol.sci.uop.edu/~jfalward/elementaryparticles/elementaryparticles.html

The Universe is Made of Matter

- You, and I, and the Earth are all made of matter not anti-matter
- The Moon is made of matter, not anti-matter
- Local "neighborhood" in Milky Way is matter, gas between the stars
- The Universe is made of matter
- How did this come to be?

Matter & Anti-Matter

- Partner for each type of matter particle
  - Anti-electron=positron, anti-quarks, anti-neutrinos
- Anti-matter is stable by itself
  - Can have anti-protons, anti-atoms, anti-rocks, anti-people, anti-stars, anti-galaxies

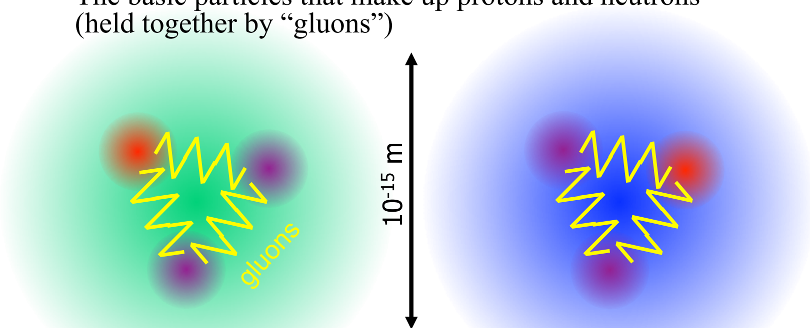


Matter & Anti-Matter

- But when matter & anti-matter partners combine
  - **Annihilation** – matter converted to energy – $E=mc^2$
  - Example: paperclip + anti-paperclip annihilation – Energy release equal to a small nuclear bomb!

Quarks

- The basic particles that make up protons and neutrons (held together by “gluons”)

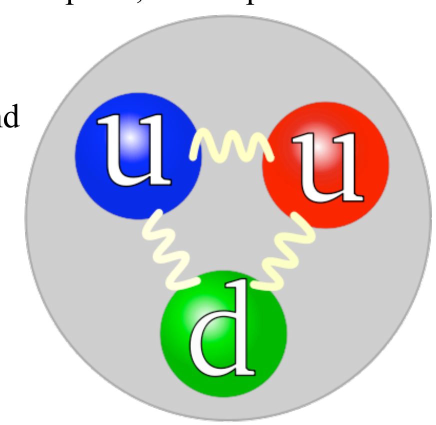


Proton (charge +1) =
2 “up” quarks (+4/3) +
1 “down” quark (-1/3)

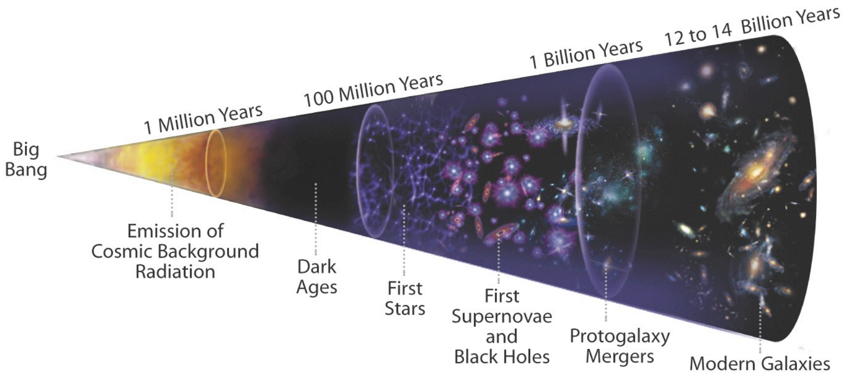
Neutron (charge 0) =
1 “up” quark (+2/3) +
2 “down” quarks (-2/3)

Point: Proton = 3 quarks!

- H is made up of a proton and an electron.
- Electrons are around at this point, but no protons yet.
- So, we have to get the quarks to cool down and get together…
- A social for particles…

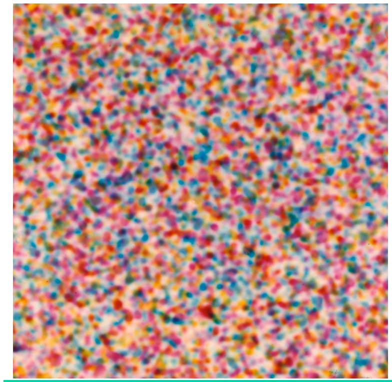


A Brief History of Time



The Universe at 0.0000001 seconds

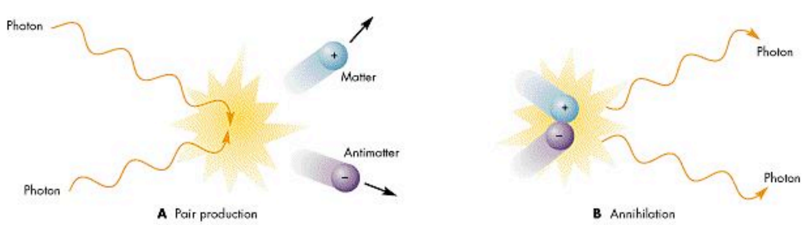
- Filled with high-energy gamma-ray photons and exotic particles
- Average temperature well over 1 trillion K (10^{12} K)!
- Average density is nearly that of an atomic nucleus



Early universe was a 'soup' of energetic particles and radiation

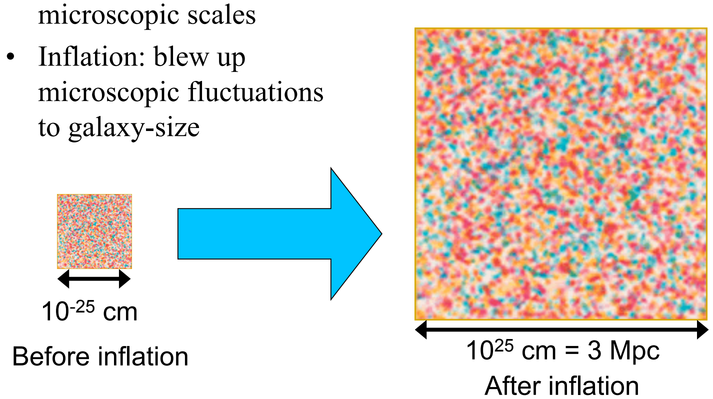
Matter and Anti-Matter

- In the early Universe, the photons were so energetic that photons could convert into matter/ anti-matter pairs
- The particles created would soon annihilate and convert back to energy



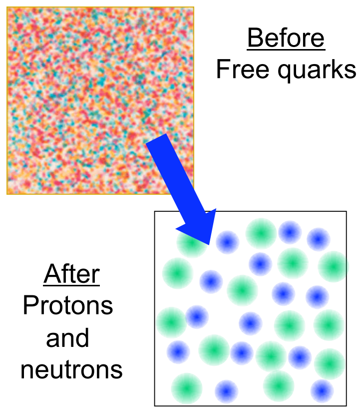
Origin of the CMB Fluctuations

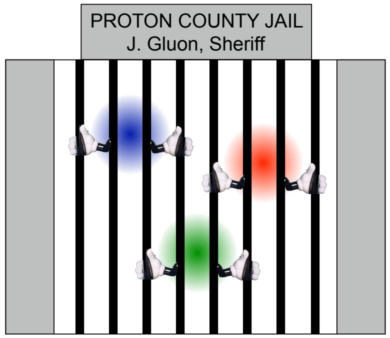
- Early Universe: a sea of particles & energy
- Density was constantly fluctuating on microscopic scales
- Inflation: blew up microscopic fluctuations to galaxy-size



Quark Confinement

- 10^{-6} seconds: free quarks condensed into protons and neutrons





10^{31} years to life
Little chance of parole

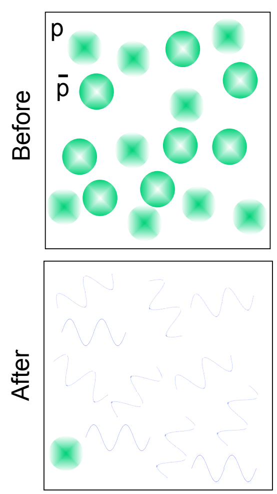
Question

The seeds of Galaxies were due to?

a) Large super structures in the early Universe.
b) Nuclear strong force fields.
c) Quantum fluctuations in quark density.
d) Gravitational instabilities in the fabric of space-time.
e) Unclear reasons.

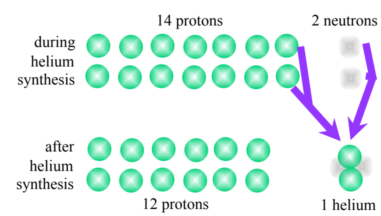
Why are we made of matter and not anti-matter?

- At 0.0001 s, universe cools below 10^{12} K
  - Photons no longer have the energy to create particle pairs
- Remaining pairs annihilated
- But, there was a slight excess of normal matter
  - For every 1 billion antiprotons there was 1 billion and 1 regular protons-- that left over proton is you
- So, we live in a world of matter



3 minutes old: The first elements!

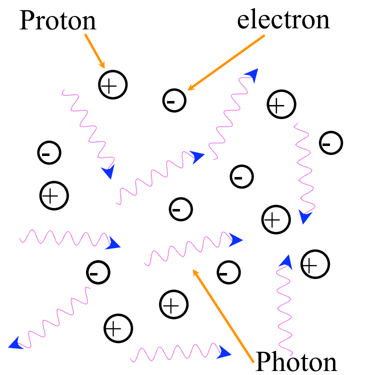
- Temperature ~ 10^9 K
- Protons and neutrons undergo fusion to form heavier atomic nuclei
- Fusion only lasts a few minutes - Universe is cooling as it expands
- Ratio of hydrogen to helium: 75% to 25%
- Very few atoms made heavier than helium



As the Universe cools, some protons and neutrons fuse to form helium nuclei

Radiation and Matter in the Early Universe

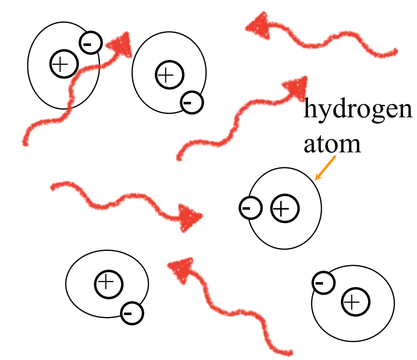
- In the young universe gas was ionized
- Free atomic nuclei and electrons
- Photons and matter interact continuously with each other and cool together as the universe expands
- Matter can't clump together



The young Universe was filled with hot, dense, ionized gas

380,000 years old: The first atoms!

- The universe cools to ~3,000 K
- Hydrogen & helium nuclei capture electrons & form neutral ***atoms***
- This neutral gas is transparent to light
- Matter and radiation are no longer at the same temperature



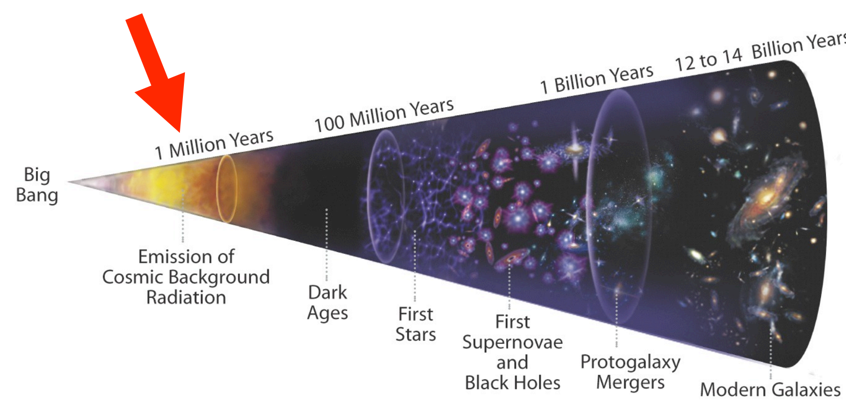
After atoms formed, the Universe was filled with hot, dense, neutral gas

Question

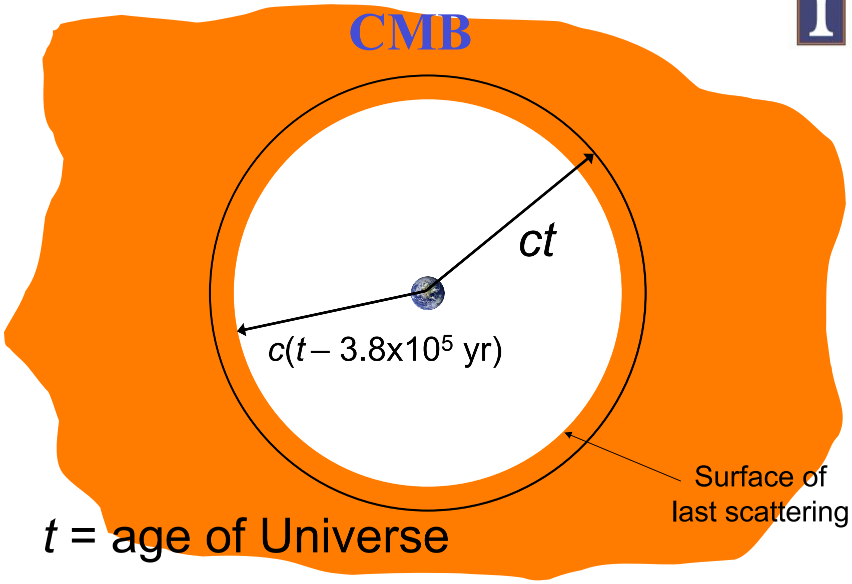
How did Hydrogen first appear in the Universe?

a) When the Universe cooled and quarks combined to form the first protons, eventually gaining an electron.
b) When the Universe cooled and the melted protons reformed, eventually gaining an electron.
c) When the Universe cooled and the antimatter turned into matter, eventually gaining an electron.
d) When the Universe cooled and the hydrogen atoms fused into helium atoms, eventually gaining an electron.
e) They always existed.

Origin of the CMB

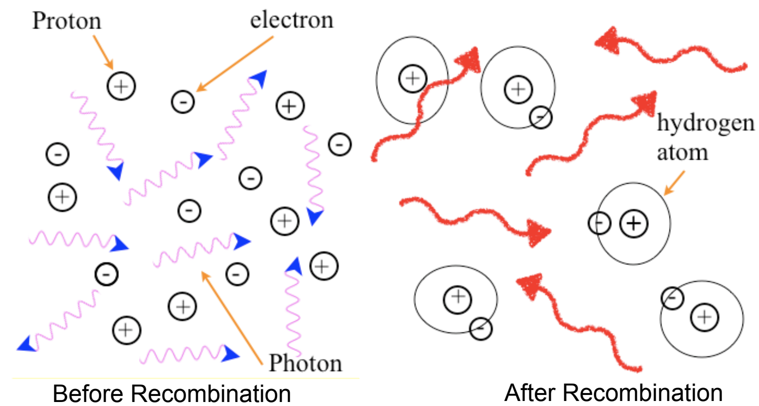


Looking Back in Time to the CMB



Looking Back in Time to the CMB

The CMB comes from the era of recombination. Before that, photons were stuck ionizing any hydrogen atoms that formed and they could not travel very far, but when the Universe cooled down enough, the photons did not have enough energy to ionize hydrogen and the Universe became transparent to the light, allowing the light to travel all the way to us. This is the CMB.



Why is light from the Big Bang observed in microwaves?

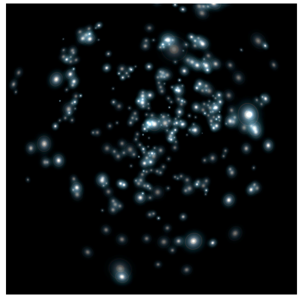
Expansion of the universe redshifted the light to ~1100 times longer wavelengths - microwaves!

- After recombination came a period known as the Dark Ages
  - 380,000 to 200 million years
  - No light yet detected from this period
- Matter consists of warm clouds of hydrogen and helium
  - Too hot for star formation to occur
  - Gravity slowing drawing clouds together into bigger and bigger clumps
  - Proto-galaxies

http://www.darkages.com/

The First Stars

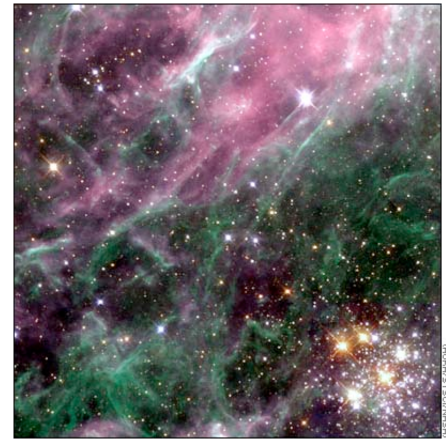
- From the initial seeds of the Big Bang, our local group of proto-galaxies are clumps of hydrogen and helium.
- Proto-galactic clouds are still slowly collapsing – no galaxies yet



http://www.blackshoals.net/ImageBank/gallery/gallery/huge/The-first-stars-clustering.jpg

The First Stars

- These clouds cool.
- The first stars began to form after about 200 million years after the Big Bang
- Remember mostly hydrogen gas with very few metals.



Question

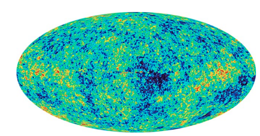
A planet forms around one of the first stars in the Universe, which of the following is the most correct?

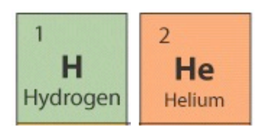
a) It will be a rocky planet.
b) It will be mostly made from hydrogen.
c) The life that forms on this planet will be very alien.
d) It will be a reddish-blue color.
e) It will be made in the outer reaches of the Galaxy.

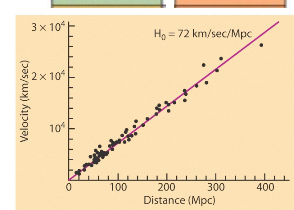
From the Home Office in Urbana, IL

Top 3 Reasons We Believe in the Big Bang

1. Cosmic Microwave Background
   - Big Bang working at about 380,000 yrs
   - Tiny fluctuations: "seeds" of galaxies
2. Big Bang Nucleosynthesis
   - H and (almost all) He come from the Big Bang
   - Big Bang working at 1 sec
3. The Hubble Law: $v=H_0d$
   + Einstein's General Relativity
   = Expanding Universe with an age of 13.7 billion yrs







One of the most successful scientific theories of all time!

The Universe: Timeline

- Big Bang: 13.7 billion years ago
- GUT era: $+10^{-35}$ second, energy and quarks
- Quark confinement: 10^{-32} to 10^{-6} seconds, protons and neutrons form
- Matter vs. antimatter: 10^{-6} seconds, matter wins
- Big Bang Nucleosynthesis: 10^{-4} seconds to 3 mins, He and some other nuclei form.
- Era of Recombination: 380,000 years. Universe becomes transparent, CMB
- Dark Ages: 380,000 to 200 million years, gravity works on stuff
- Stars: 200 million years, first stars form, protogalaxies

What is the fate of the Universe?

Fire and Ice

Some say the world will end in fire,
Some say in ice.
From what I've tasted of desire
I hold with those who favor fire.
But if it had to perish twice,
I think I know enough of hate
To say that for destruction ice
Is also great
And would suffice.

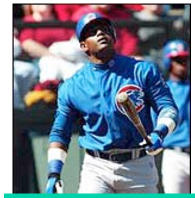
-- Robert Frost

What is the Universe's Fate?

Today: Universe is expanding. What do you expect to happen next?

Competition: gravity vs inertia

Compare: Pop fly and rocket!
- Quantitative question
- Launch speed vs speed to escape Earth



or

?

Which one do you expect to fall back to Earth and why?

What is the Universe's Fate?

For Universe it is still gravity vs speed.
- Gravity acts on mass of galaxies (pulling back)
- The speed is the speed of expansion

Both are observable!

Our fate is a **quantitative** question :

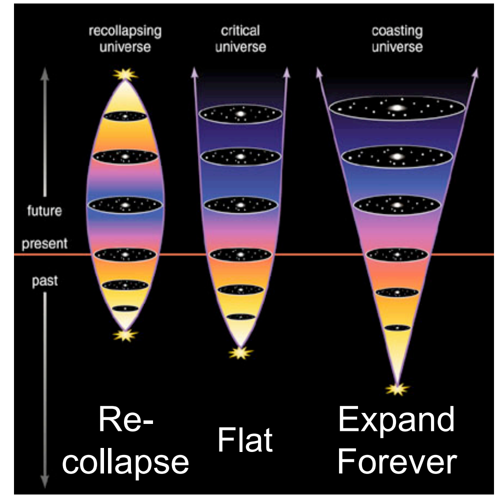
- **If our mass is small enough we expand forever.**
- **If our mass is large enough expansion halts, and we collapse back.**


or

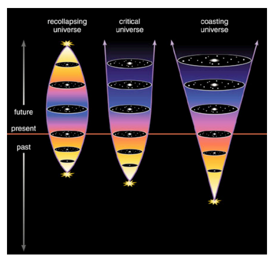

Which case is the Big Bang?

The fate of the Universe depends on the density of matter in it

- High density
  - Enough gravity to stop expansion
  - Space is finite
  - Closed Universe
- Low density
  - Not enough gravity to stop the expansion
  - Space is infinite
  - Open Universe

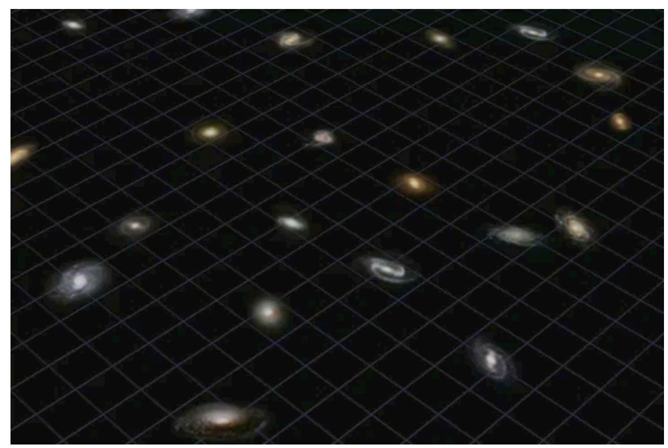


Big Chill/Big Crunch



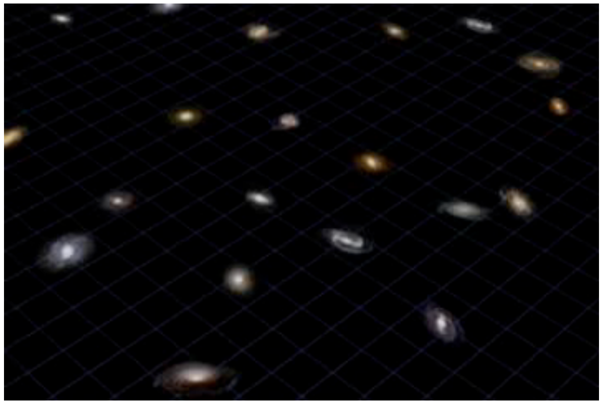
- **Less mass:**
  An open or flat Universe will end in a **Big Chill**:
  - Galaxies exhaust their gas supply
  - No more new stars
  - Old stars eventually die, leaving only dust and stellar corpses
- **More mass:**
  A closed Universe will end in a **Big Crunch**:
  - Expansion will stop, and the Universe will re-collapse
  - Ends as it began, incredibly hot and dense

Recollapsing Universe



If there is enough matter in the Universe to halt the expansion, it will eventually recollapse

Expanding Forever



If there is not enough matter in the Universe to halt the expansion, it will continue forever

Question

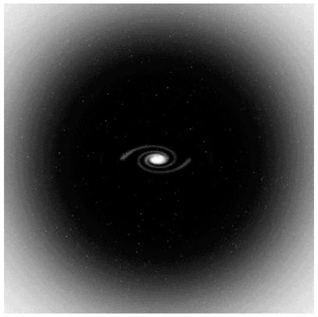
Our Universe could be one of three types: Open, Closed, or Flat. What would happen to a closed Universe?

a) No one else could get in.
b) It would expand forever.
c) It would just barely expand forever.
d) It would expand for a while, then eventually begin to re-collapse on itself.
e) It would expand, then slow down, then expand faster.

How Much Does the Universe Weigh?

- The first major component is luminous matter.
- The stuff (most of which will talk about soon)
  - You
  - Stars
  - Planets
  - Gas
  - Dust
  - Molecular clouds
  - White Dwarfs
  - Etc.

And Dark Matter

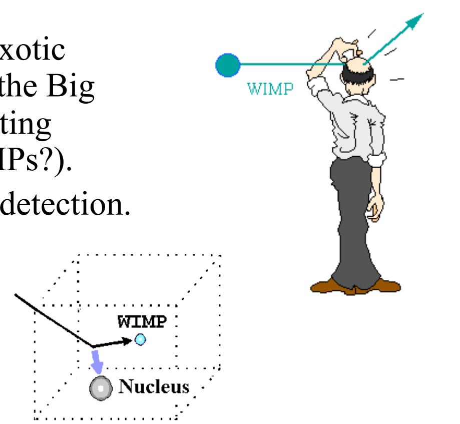


- The unseen mass in our Galaxy!
- Needed to explain stellar orbits.
- The dark matter in the Galaxy is in greatly extended halo
  - Up to 90% of the Galaxy's mass is dark matter!
- Most of our Milky Way is Dark Matter
  - We can't see it (only interacts via gravity)
  - We aren't sure what it is, but it is much more common than "normal matter"

Dark Matter

- Dark matter is likely streaming through us right now!
- Probably some heavy exotic particle created during the Big Bang. (Weakly Interacting Massive Particle– WIMPs?).
- Recent suggestion of a detection. Stay tuned!

How to search for WIMPs?



http://www.shef.ac.uk/physics/research/pa/DM-introduction-0397.html

How Much Do We Weigh?

% of mass for
closed Universe

22% Dark matter
Needed to explain:
galaxy rotation curves
clusters of galaxies

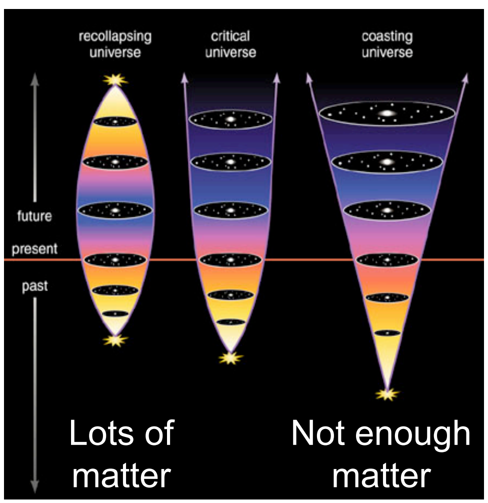
4.5% Ordinary matter
Made of protons, neutrons, and electrons

<1.5% Neutrinos

28% Total <u>Not enough to close the Universe</u>

Is there enough matter?

- In other words, the Universe does not weigh enough to bring the Universe back on itself
- In our analogy, the rocket keeps going.

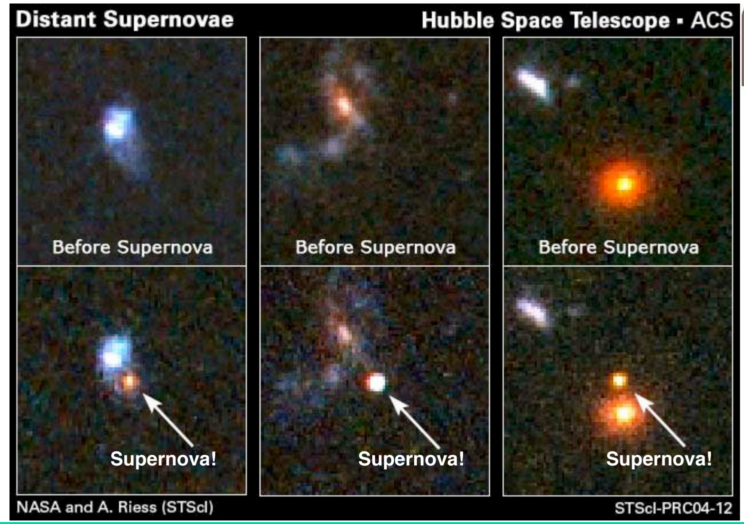


So we live in an open Universe?

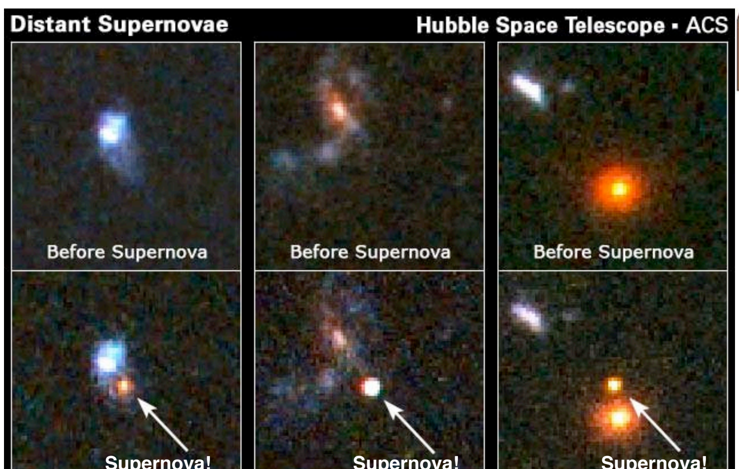
Measuring changes in the expansion of the Universe

- Step 1: measure the distances to many galaxies, from nearby to billions of light years away
- Step 2: measure the cosmic redshifts of those galaxies
- Step 3: compare distances with redshifts to measure changes in the expansion rate of the Universe

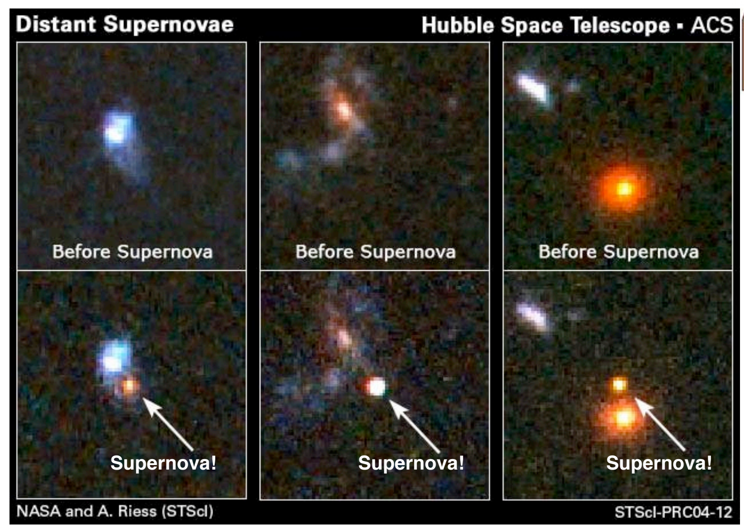
Expectation: The gravity of the matter (normal and dark) in the Universe is slowing down the expansion - even if its not enough to stop it.



Astronomers measure distances to very distant galaxies using supernova explosions



For decades, astronomers struggled to measure the distance to very distant galaxies directly, compare distances with redshifts, and thereby detect the slowing of the expansion. Measure distances to far galaxies using a certain class of supernovas. Type 1a supernovae have a known intrinsic luminosity and so bright they are visible billions of light years away. This makes them excellent standard candles for determining distances.



Reiss won the Noble Prize for this work in Oct 2011!!!

What if we measure our expansion?

- If we use supernova, we can estimate how far away the galaxies are and compare to what we expect from the Big Bang model.
- Consider a galaxy observed from some distance today with a measured distance and velocity

What if we measure our expansion?

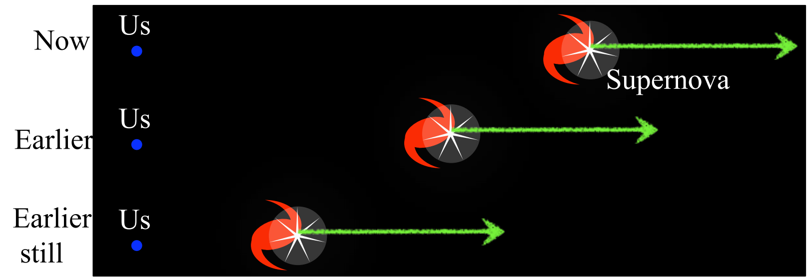
If there was no matter in the Universe how would things change in time?

No matter → no attraction between galaxies

→ nothing to change galaxy speeds

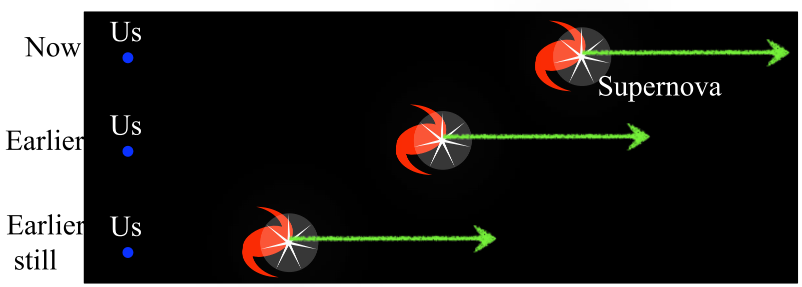
→ galaxies "coast" keeping constant velocity

⇒ same speeds in past



What if we measure our expansion?

- If matter is not important then
  - Galaxies have same speeds in past
  - Expansion rate: neither accelerated nor decelerated



What if we measure our expansion?

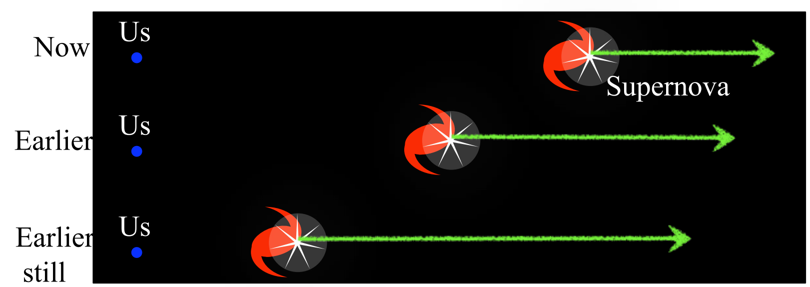
If matter play important role in the Universe how would things change in time?

– Attraction between galaxies

→ Gravity slows expansion

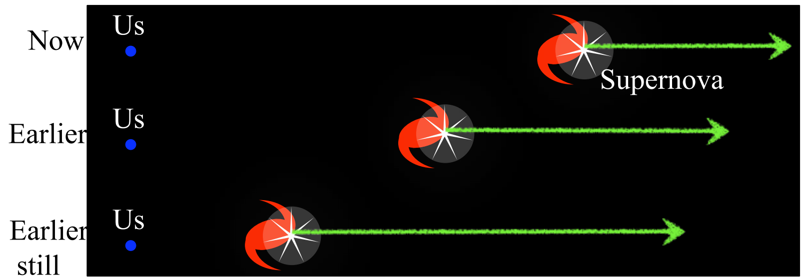
→ Speeds constantly decreasing

⇒ faster speeds in past



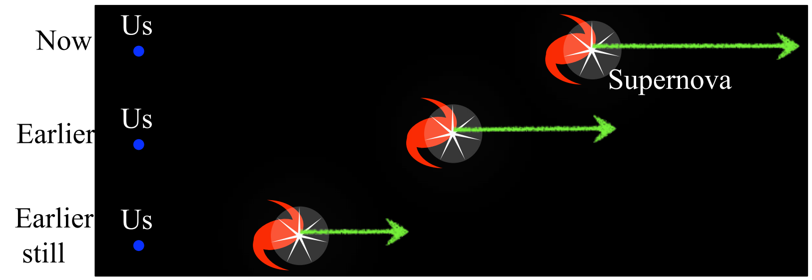
What if we measure our expansion?

- To achieve observed speed today, had to be faster in past
- Expansion rate: decelerated.
- Astronomers expected to see this. What do we see?



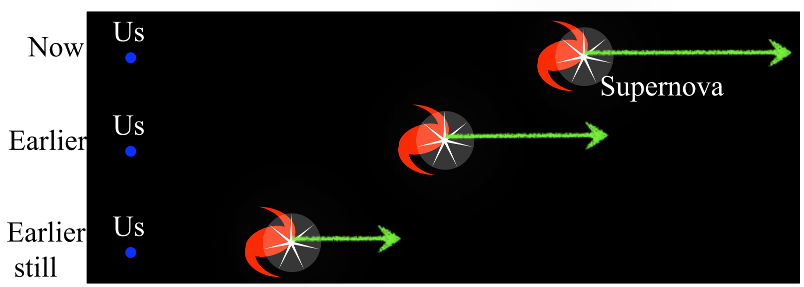
What if we measure our expansion?

- Galaxies were slower in the past and faster in the present!
- Expansion rate: accelerated!!!
- Opposite of what we expected.



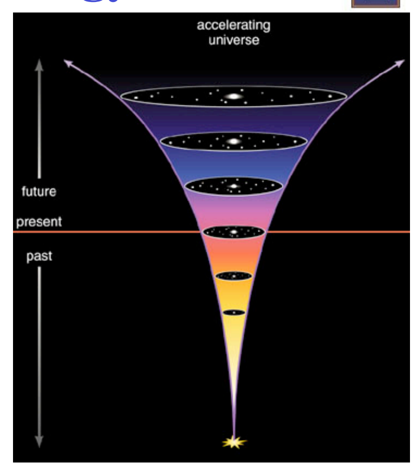
What if we measure our expansion?

- This is very weird!
- Toss Newton's apple in the air and expect it to slow down as it goes up, but instead it rockets away!
- What is up?



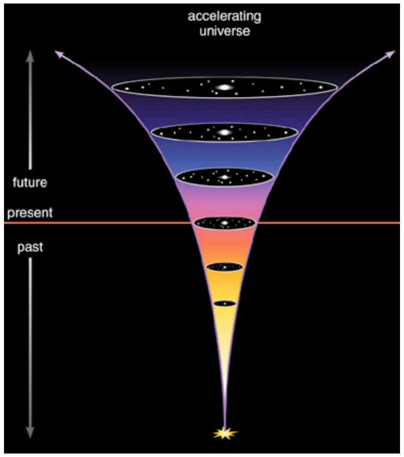
Dark Energy

- If the expansion of the universe is accelerating, then there must be a force of repulsion in the universe
- We call this force dark energy
- Astronomers today are struggling to understand what it could be
- This is the missing mass in the fate of the Universe since $E= mc^2$



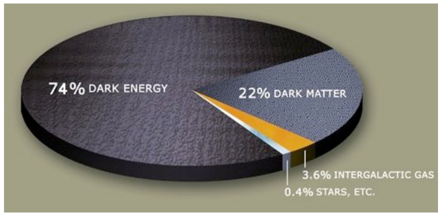
Dark Energy

- Spread throughout space
- Dark energy drives acceleration of the Universe today.
- This makes it the most abundant stuff in the Universe
- And we have NO idea what it is!!!!
- One of the greatest mysteries in science today!



Make-up of the Universe

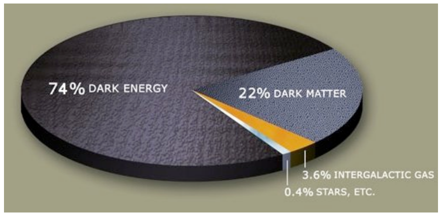
- The Universe is dominated by dark matter and dark energy
- Under 5% is in form of normal matter (atoms)
- Only the normal matter can be directly detected with telescopes



The "stuff" that makes up our world is only a small fraction of all the stuff in the universe

Make-up of the Universe

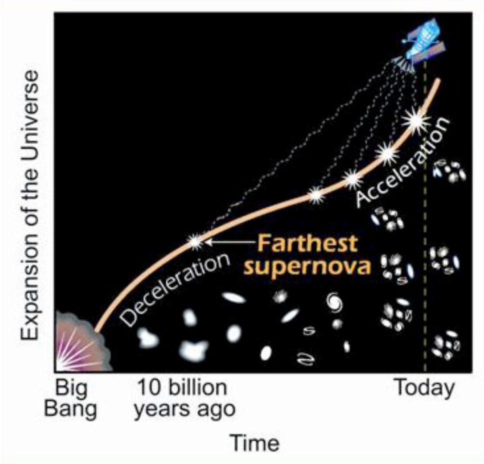
- Of the "normal matter" about 85% of that is in the hot intergalactic gas in galaxy clusters.
- All the stars, galaxies, you, your dog (what we used to think was the important stuff) make up only 15% of 5% (less than 1%) of the Universe!



The "stuff" that makes up our world is only a small fraction of all the stuff in the universe

Deceleration, Acceleration

Observations further show that the universe's expansion initially slowed down and started accelerating ~6 billion years ago



Deceleration, Acceleration

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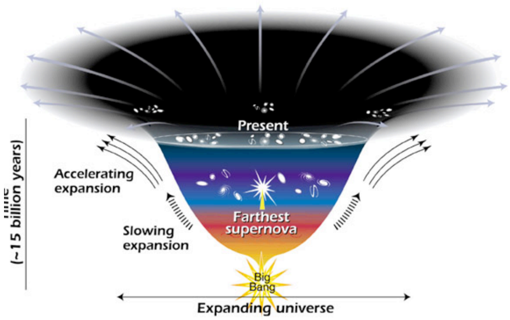
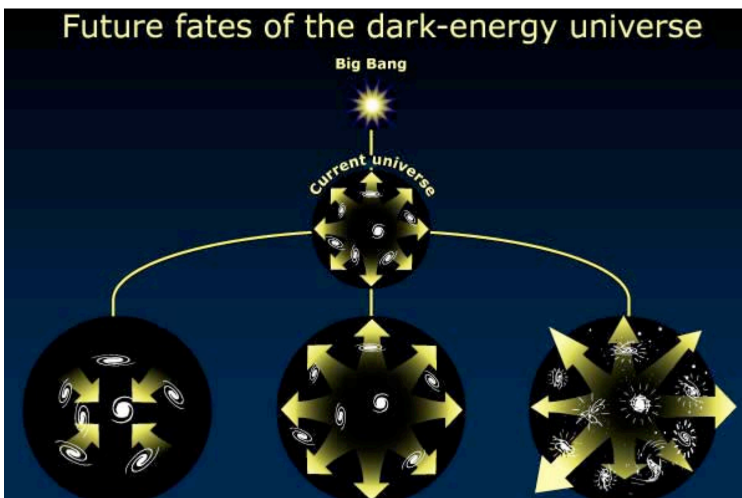
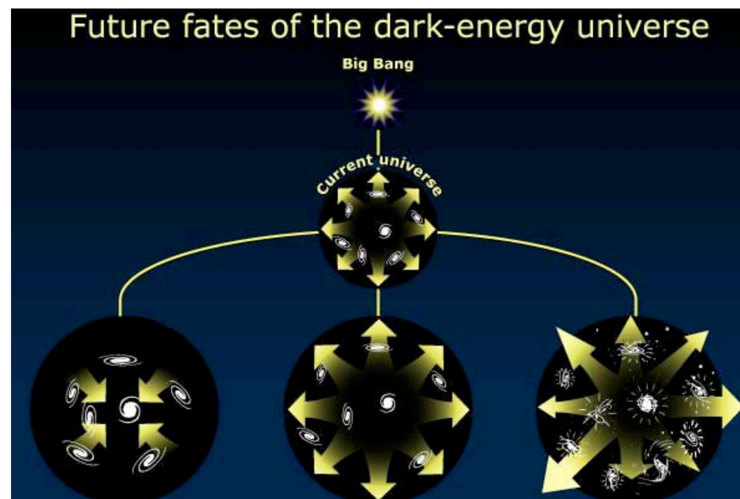


The Effects of Dark Energy

This animation shows the expansion history of the Universe (exaggerated)

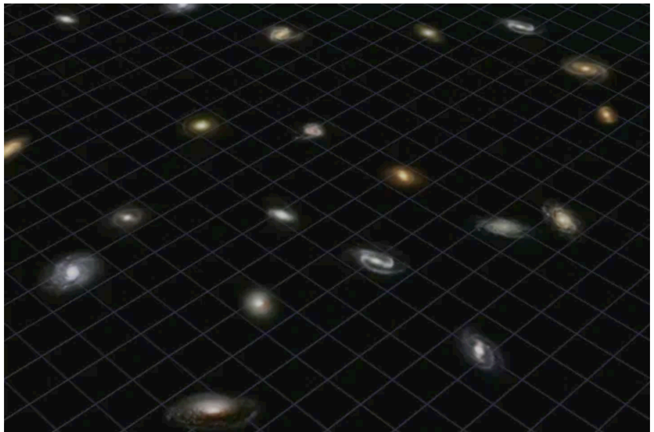


72% of the universe is dark energy, so the nature of dark energy greatly influences the ultimate fate of the universe.
Three possible fates for the Universe:
Expand forever, Big Rip, or Big Crunch



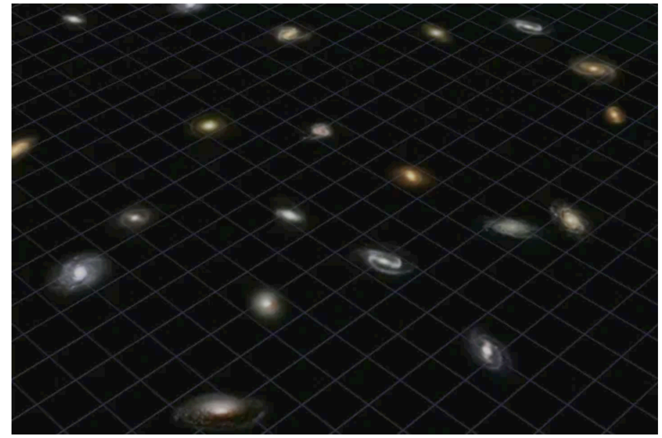
Big Crunch	**Big Freeze**	**Big Rip**
Dark energy is unstable and reverses	Dark energy is constant "energy of the vacuum"	Dark energy is unstable and increases with time

Reversing Dark Energy: Big Crunch



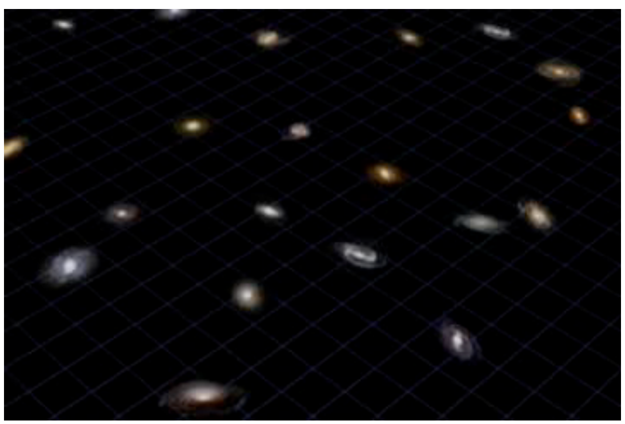
If dark energy is unstable, it could reverse the expansion and re-collapse the universe

Reversing Dark Energy: Big Crunch



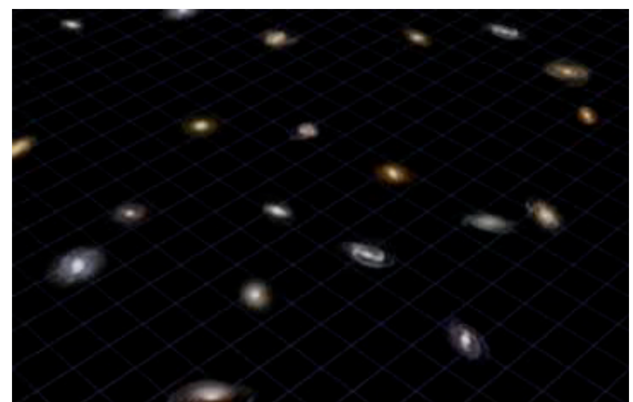
A contracting universe would become increasingly dense. Eventually all matter would collapse into black holes, which would then coalesce producing a unified black hole or Big Crunch singularity.

Constant Dark Energy: Big Freeze



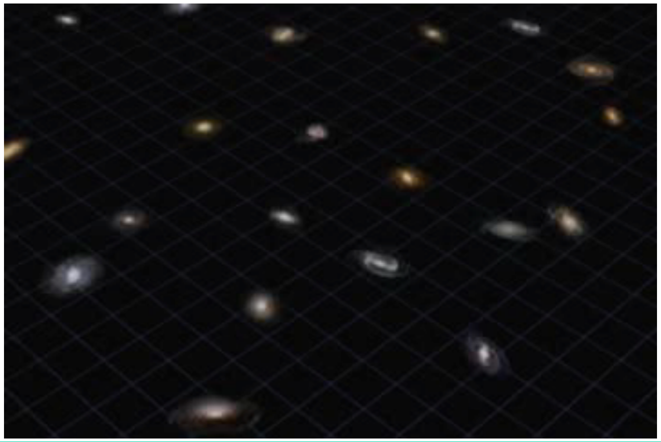
If dark energy is a constant "energy of the vacuum", it will expand forever

Constant Dark Energy: Big Freeze



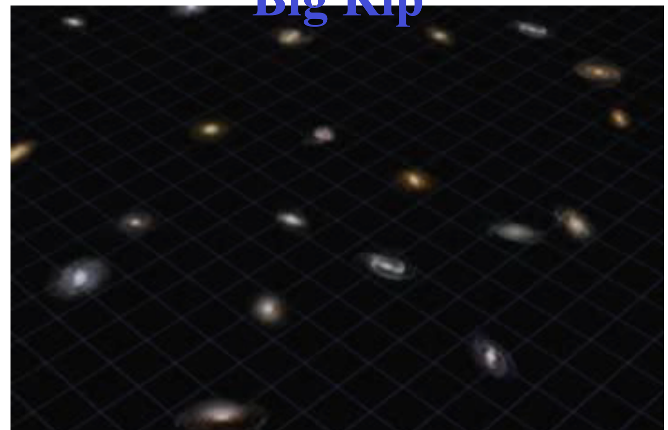
The galaxies will get farther and farther apart - we can no longer see galaxies beyond the local group in 2 trillion years due to accelerating expansion. Gas and dust to make new stars runs out within 100 trillion years, last stars die within 10 trillion years of that. Each galaxy will be isolated, burnt out, dark, and alone. This is the most likely scenario, according to observations

Increasing Dark Energy: The Big Rip



If dark energy grows stronger with time, the Universe may come apart in a Big Rip

Increasing Dark Energy: The Big Rip



In this scenario, the end of the universe is approximately 22 billion years from now. About 60 million years before the end, gravity would be too weak to hold the Milky Way and other individual galaxies together. Approximately three months before the end, the solar system would be gravitationally unbound. In the last minutes, stars and planets would be torn apart, and an instant before the end, atoms would be destroyed.

i>clicker poll

Do you prefer the fate of the universe to be the Big Crunch, Big Freeze, or Big Rip?

A. I'm more comfortable with a universe that will end in recollapse someday in the future.
B. I like the idea that the universe had a definite beginning but will continue without end.
C. I'm cool with having my atoms ripped apart by the accelerating expansion of the Universe.
D. I don't prefer one over the other.
E. Dude, you're freaking me out!!!!

The Early Universe?

- So, in the early Universe, the first elements formed were mostly Hydrogen (75%) and Helium (25%) by mass. What does that mean for life in the early Universe?
- Globular clusters contain the oldest stars in the Milky Way– about 10 to 13 billion years old. Should we look for life around these stars?

http://www.shef.ac.uk/physics/research/pa/DM-introduction-0397.html