The History of the Universe in 200 Words or Less

Quantum fluctuation. Inflation. Expansion. Strong nuclear interaction. Particle-antiparticle annihilation. Deuterium and helium production. Density perturbations. Recombination. Blackbody radiation. Local contraction. Cluster formation. Reionization? Violent relaxation. Virialization. Biased galaxy formation? Turbulent fragmentation. Contraction. Ionization. Compression. Opaque hydrogen. Massive star formation. Deuterium ignition. Hydrogen fusion. Hydrogen depletion. Core contraction. Envelope expansion. Helium fusion. Carbon, oxygen, and silicon fusion. Iron production. Implosion. Supernova explosion. Metals injection. Star formation. Supernova explosions. Star formation. Condensation. Planetesimal accretion. Planetary differentiation. Crust solidification. Volatile gas expulsion. Water condensation. Water dissociation. Ozone production. Ultraviolet absorption. Photosynthetic unicellular organisms. Oxidation. Mutation. Natural selection and evolution. Respiration. Cell differentiation. Sexual reproduction. Fossilization. Land exploration. Dinosaur extinction. Mammal expansion. Glaciation. Homo sapiens manifestation. Animal domestication. Food surplus production. Civilization! Innovation. Exploration. Religion. Warring nations. Empire creation and destruction. Exploration. Colonization. Taxation without representation. Revolution. Constitution. Election. Expansion. Industrialization. Rebellion. Emancipation Proclamation. Invention. Mass production. Urbanization. Immigration. World conflagration. League of Nations. Suffrage extension. Depression. World conflagration. Fission explosions. United Nations. Space exploration. Assassinations. Lunar excursions. Resignation. Computerization. World Trade Organization. Terrorism. Internet expansion. Reunification. Dissolution. World-Wide Web creation. Composition. Extrapolation?

Sex in Space: Astronomy 330

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T: 10:30-11:30 a.m.

W: 3:00-4:30 p.m. or by appointment

This class (Lecture 3):

Cosmology and the Origin of Elements

Next Class:

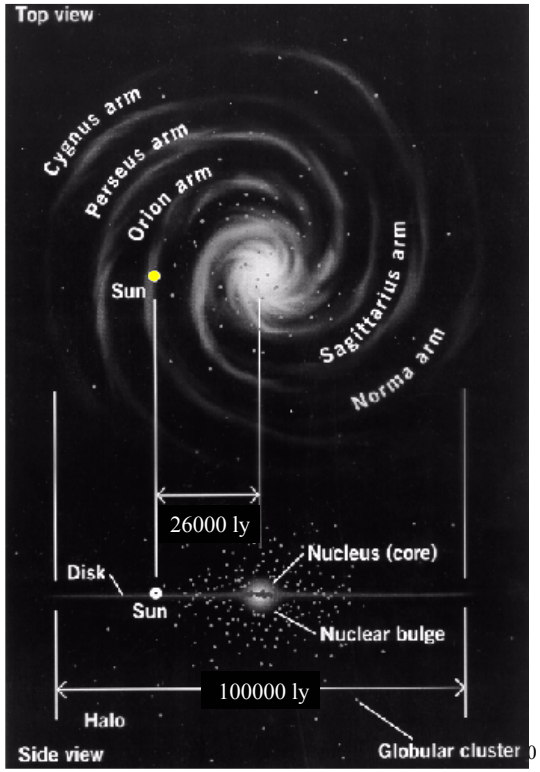
The Early Galaxy and the First Stars

HW1 due today.

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

Outline

- Where did HONC come from?
  i.e. where did the atoms in our bodies come from?
- How old is the Universe?
- Big Bang Nucleosynthesis
- Cooling into normal stuff.
- The seeds of galaxies.
- What is the probable fate of the Universe?



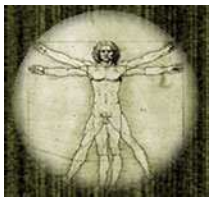
Our Galaxy

(movie)

Defining Life

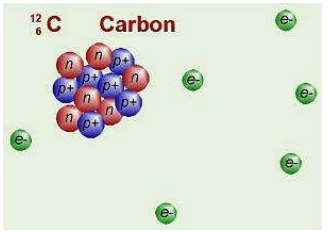
As we will discuss later, defining life is very difficult. Traditional attributes of life define it as:

1. Comprised of organic molecules.
2. Engaged in metabolism– exchange of matter and energy.
3. Engage in reproduction– sex in space!
4. Able to mutate– offspring are not identical to parents.
5. Sensitivity to environment.



Elements of Life

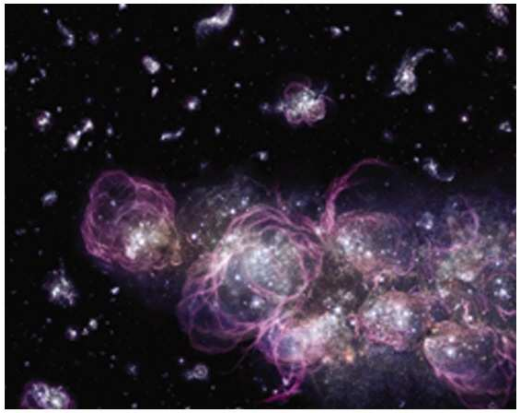
- Carbon is the most important element in life on Earth with oxygen and nitrogen coming in a close second. And there is a lot of hydrogen. **HONC**. But where did they come from?
- To understand this question, we need to address the origin of the Universe and the elements crucial to life.
- In other words, Cosmology.



http://biology.clc.uc.edu/courses/bio104/atom-h2o.htm

Cosmology

- What is the Universe?
  - All the matter, energy, and spacetime we can ever detect
- **Cosmology** is the study of the origin, structure, and evolution of the Universe

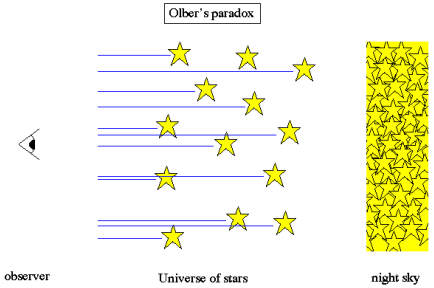


The Universe

- Began with a Big Bang
  - 13.7 billion years ago
- Still expanding and cooling
  - The rate of expansion is known
- It is BIG
  - As far as we are concerned, it is infinite in any direction
- The universe is homogeneous and isotropic
  - **Homogeneous** - The same "stuff" everywhere
  - **Isotropic** - The same in all directions
- Our place in the Universe is not special
  - Extension of the Copernican revolution
- The center of the Universe is everywhere or nowhere!

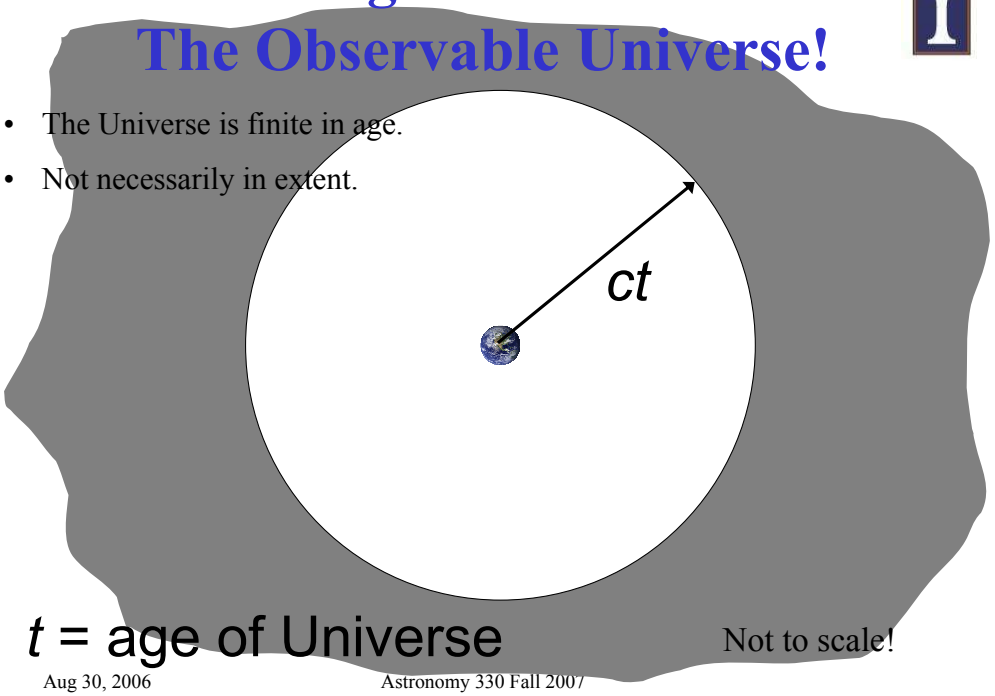
The Night Sky:
Olber's Paradox

- What is special about the night sky?
- Why isn't the night sky bright?
- If the Universe is infinite, why don't we see light everywhere from all the stars.
- Even if dust blocked the light, it would heat up and emit in the optical too.
- The Universe has not existed forever. It must have started from something.



Looking Back in Time:
The Observable Universe!

- The Universe is finite in age.
- Not necessarily in extent.



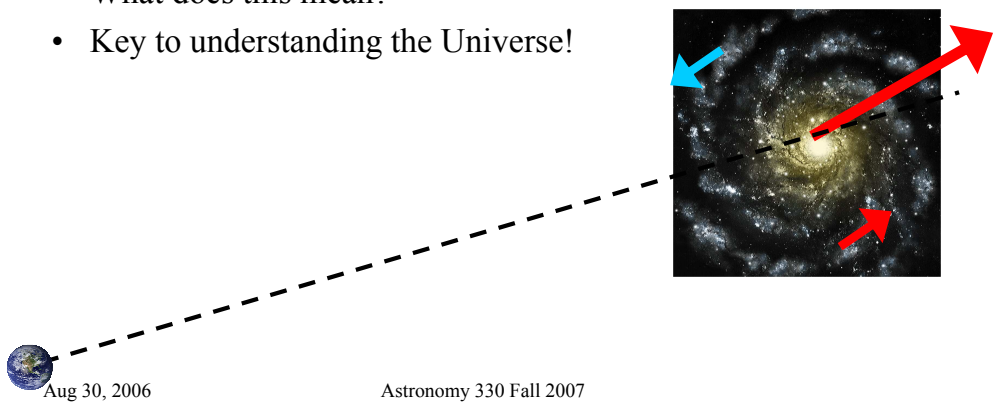
How are Galaxies Moving?

It's 1928 and Edwin Hubble is measuring how galaxies move. What does he find?

a) More galaxies receding than approaching.
b) More galaxies approaching than receding.
c) About equal numbers of each.

Redshift of Galaxies

- Most galaxies are moving away from us.
- The farther away, the faster they are moving away.
- Or $V = H_o \times D$
  - $H_o = 72$ km/s /Mpc
- What does this mean?
- Key to understanding the Universe!



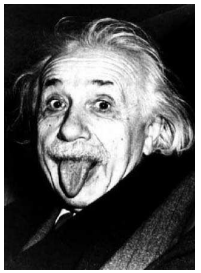
Apply it?

- In a homogenous Universe, what does the farther away the faster the galaxies move away mean?
- Draw it.

Interpretation: View of the Universe

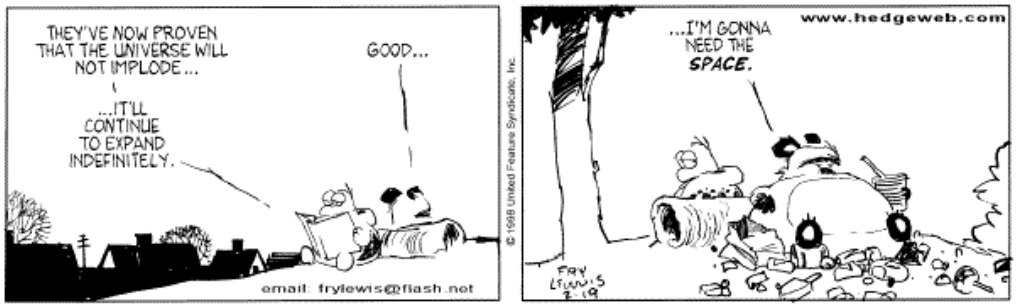
Egoist view– We are at the center of the Universe.

Einstein's view– The Universe is expanding, and there is no center!

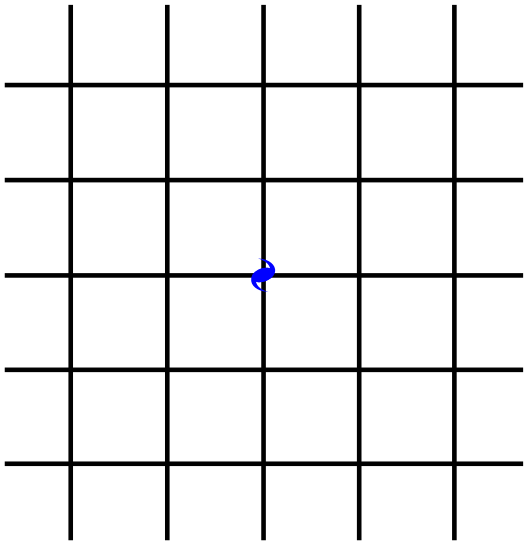


The Expanding Universe

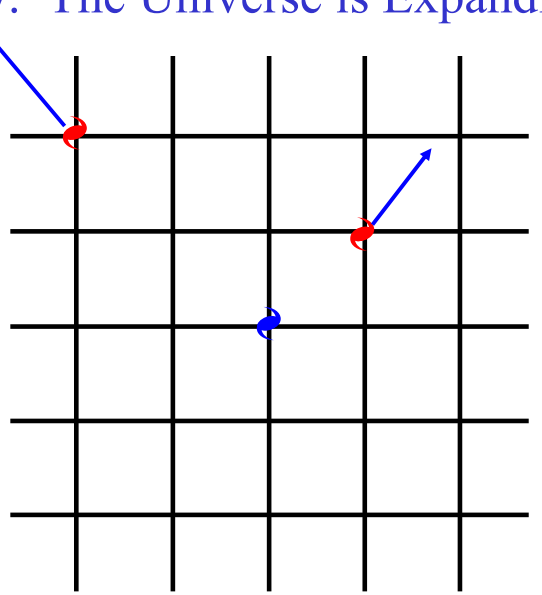
- To describe the motion of all the galaxies in the Universe, we use General Relativity (due to gravitation effects)
- General Relativity predicts that we live in an *expanding Universe*.
  - Einstein didn't buy it at first, so made a cosmological constant to get rid of it.
- In other words, space is stretching in all directions. This completely explains Hubble's Law.



Dude, The Universe is Expanding.



Wow. The Universe is Expanding.



Hold on a minute there!

- Why don't we expand with the Universe?
- Other forces hold us together
  - Atoms - nuclear forces
  - Molecules & living beings – electromagnetic forces
  - Planets, stars, and galaxies – gravity
- But gravity can't hold galaxy superclusters together
  - Expansion grows stronger with distance (more expanding space)
  - Gravity grows weaker with distance (inverse square law)
- **Brooklyn isn't expanding!**

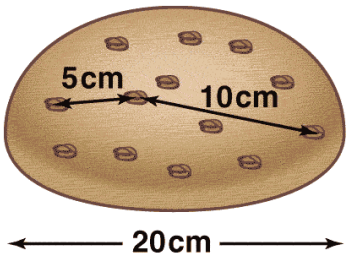
What do you think?

- The Universe is expanding, how do you feel about that?

http://www.calresco.org/ewp/confuse.htm

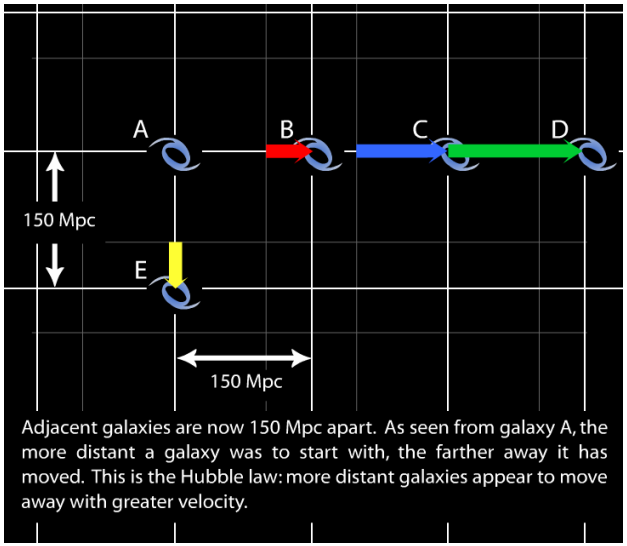
Analogy– Raisin Bread

The raisins are like galaxies.



Raisins stay the same size, like Brooklyn.

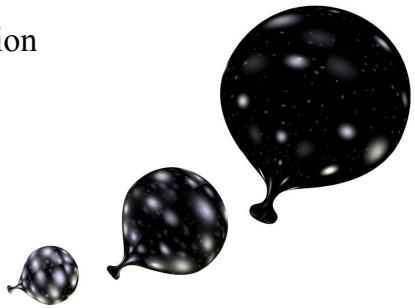
Another Expansion Graphic



~~Expanding into What?~~

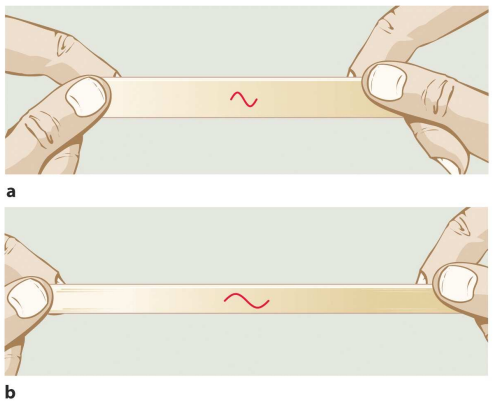
Common Misconception

- Its common to think of the expansion of the Universe like an explosion
  - Galaxies hurled away from each other through space
- This is incorrect!
- Einstein's Theory of Relativity tells us that spacetime itself is expanding!
  - Like an inflating balloon



Analogy - Rubber Band

- Spacetime expands, like stretching a rubber band
- Not only do distances grow…
- Even the photons' wavelengths get stretched!
  - Increasing wavelength = redshift!
  - **Cosmological redshift**



Reality

- The analogies are just to help us visualize, don't get stuck in the specifics.
- The Universe has no center.
- The Universe has no edge.
- Concept of time and space began with the Universe, can not apply the concepts so easily.

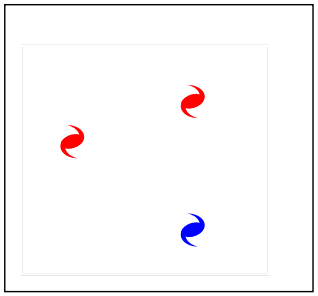
http://universe.gsfc.nasa.gov/images/reach-for-the-universe.jpg

Living in an Expanding Universe

Consider a large "box" containing many galaxies

- Total mass in box today: M_{today}
- Total volume in box today: V_{today}
- ***Density today*** $= M_{today} / V_{today}$

The Universe box



Tomorrow

How does the density of the Universe change with time?

Living in an Expanding Universe

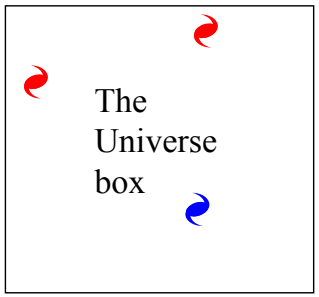
How does the density of the Universe change with time?
As the Universe expands:

- $M_{tomorrow}$ stays the same
- $V_{tomorrow}$ becomes larger
- Density $M_{tomorrow}/V_{tomorrow} \Rightarrow$ ***smaller***

$M_{tomorrow}/V_{tomorrow} < M_{today}/V_{today}$

Density changes with time!

- Universe was denser in the past
- Universe will be less dense in the future



Putting it all together:

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

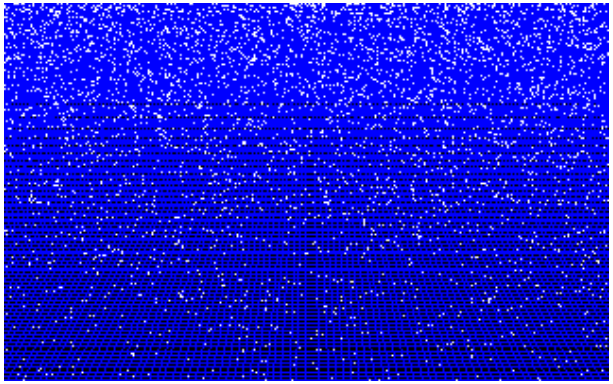
The origin of the Universe can be described by the idea of the Big Bang. Where did the Big Bang happen? Remember the Universe is homogenous & isotropic.

The Biggest Bang since the Big One

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

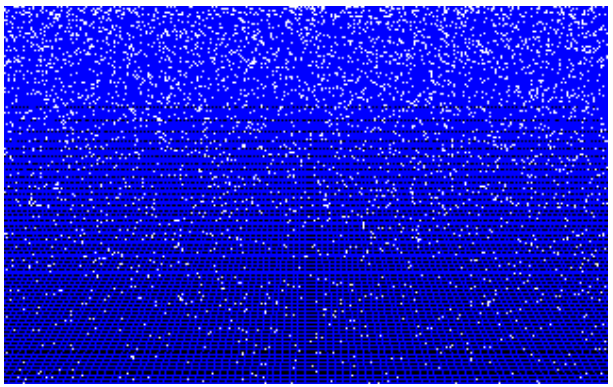
The Big Bang

- 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



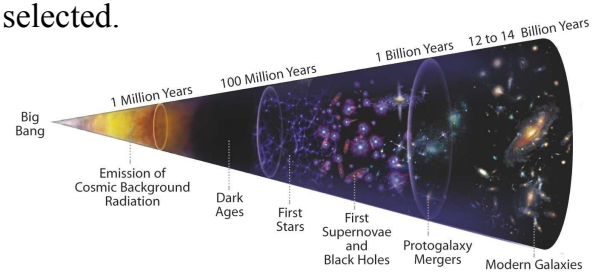
The Big Bang

- 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 **right here!** ...smooshed up small, but still **right here!**



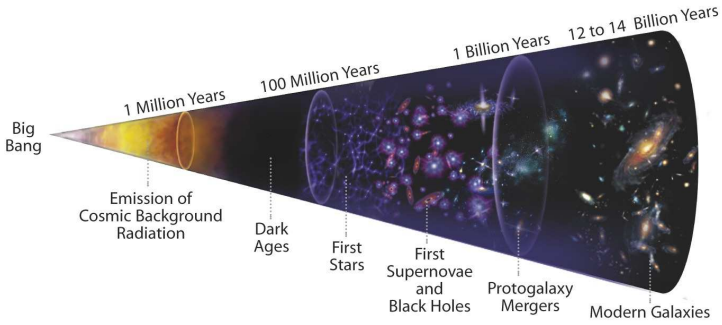
The Big Bang

- 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.

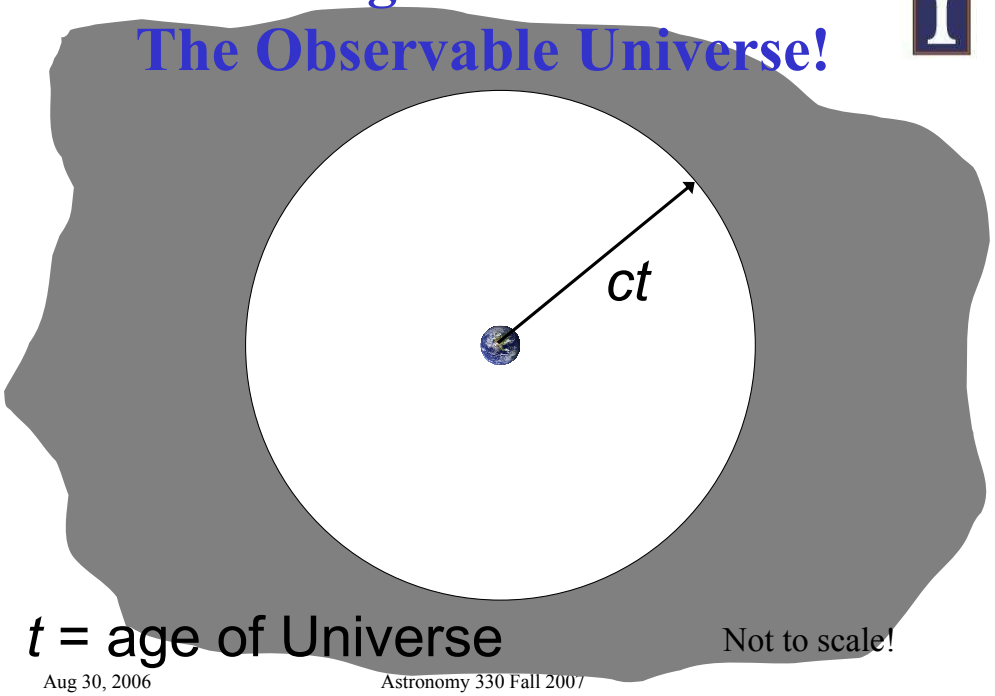


The Big Bang

- 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.

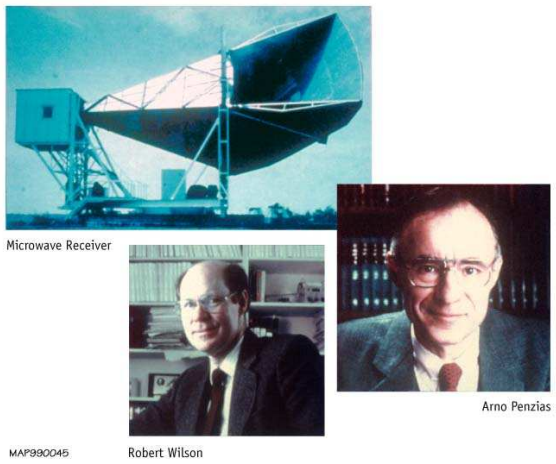


Looking Back in Time: The Observable Universe!

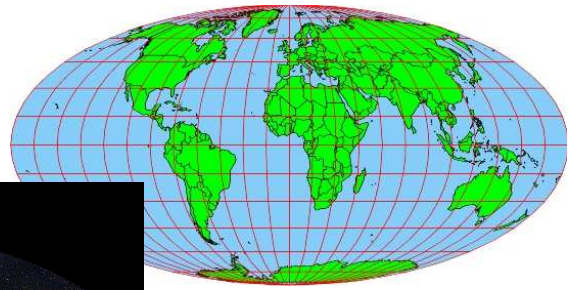


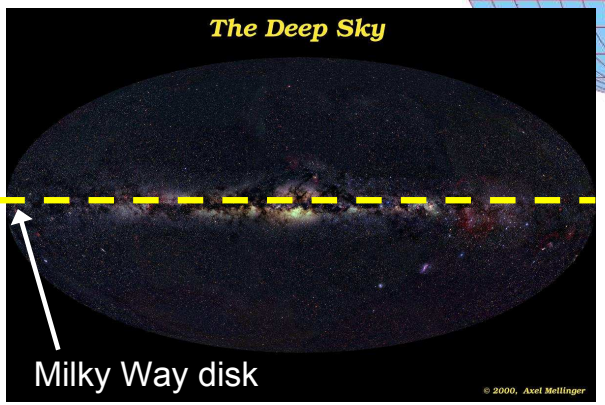
The Early Universe was *HOT*!

- 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.



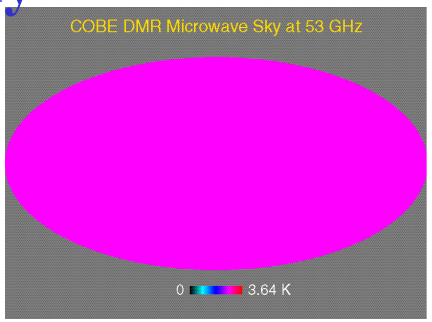
How to Understand Sky Maps



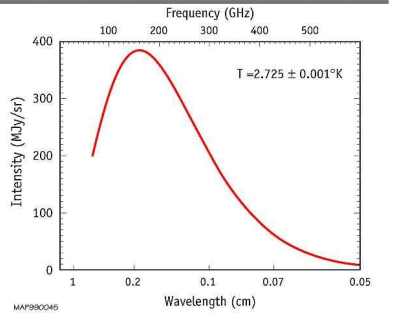


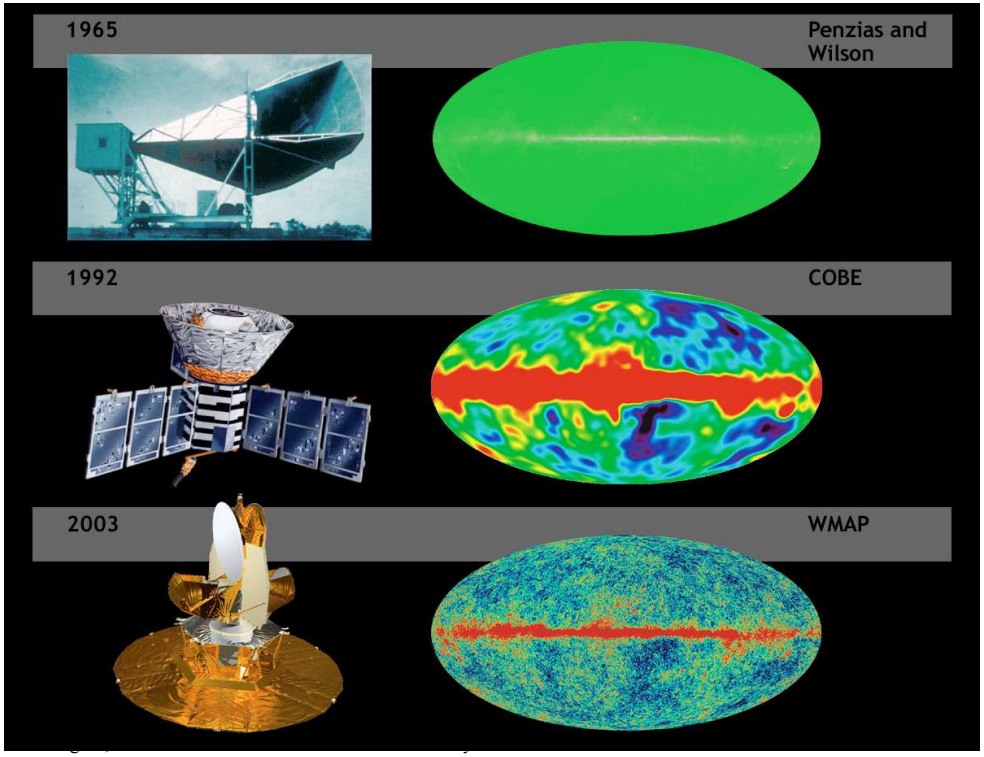
In Fact, a Rather Uniform Blackbody

- 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

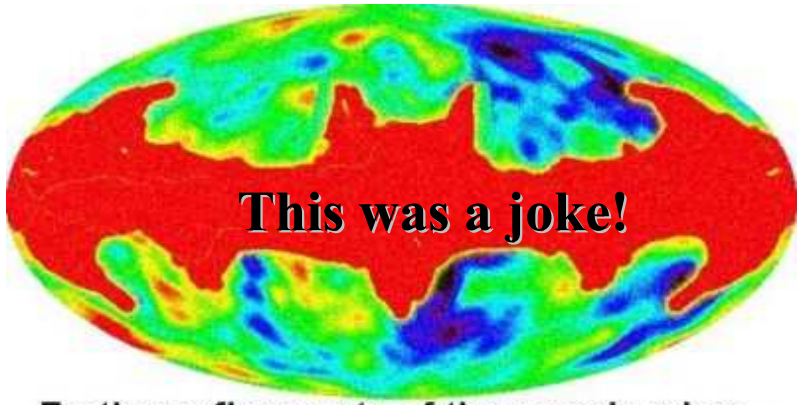


Cosmic Background Explorer (COBE) satellite (launched 1989)



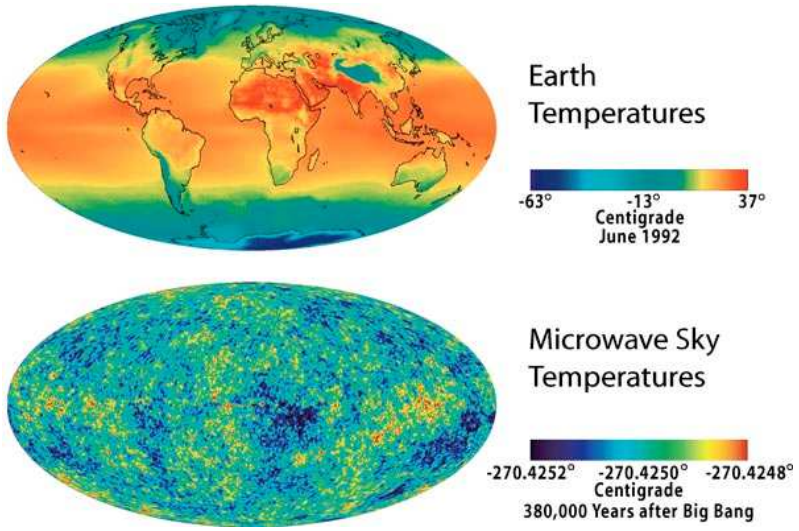


Unknown Fluctuations…

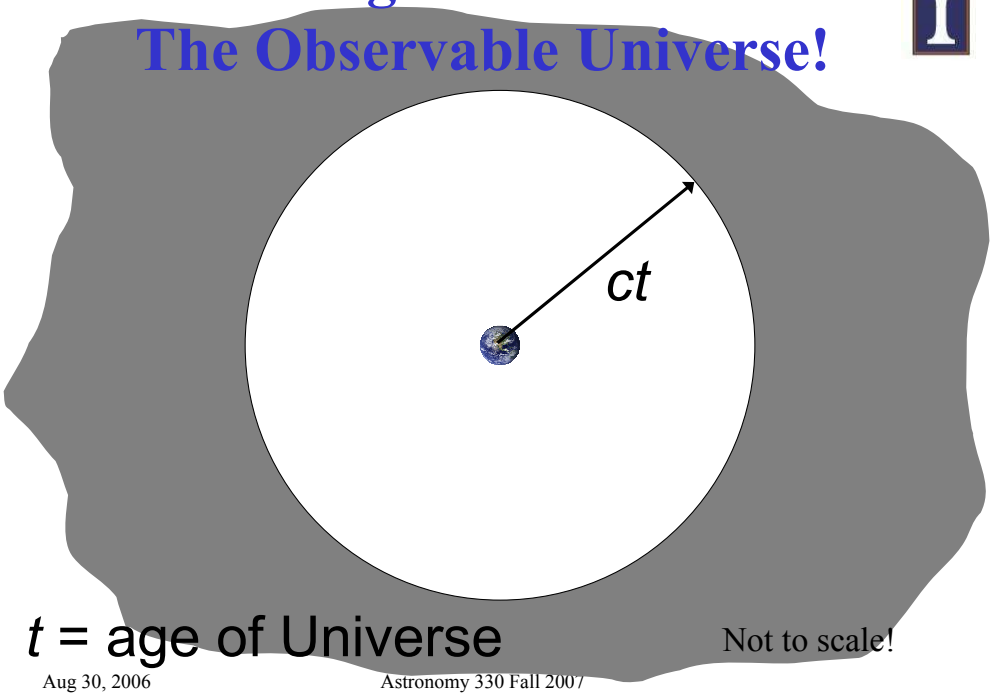


Further refinements of the cosmic microwave background reveal a deeper meaning for physicists to ponder.

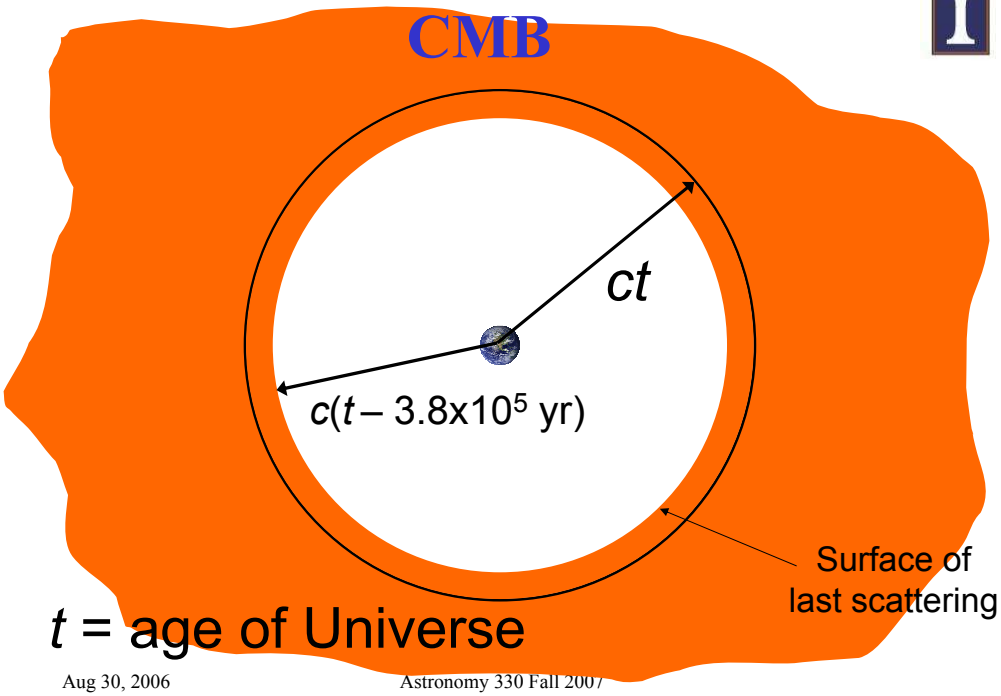
WMAP took a "baby picture" of the Universe– only 400000 yrs old.



Looking Back in Time: The Observable Universe!

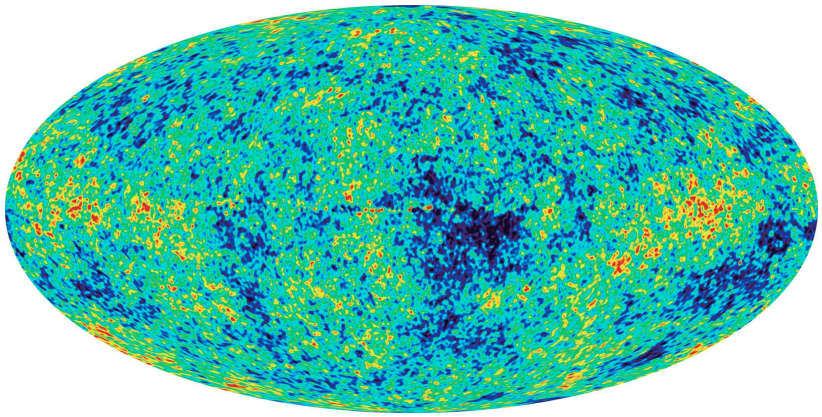


Looking Back in Time to the CMB



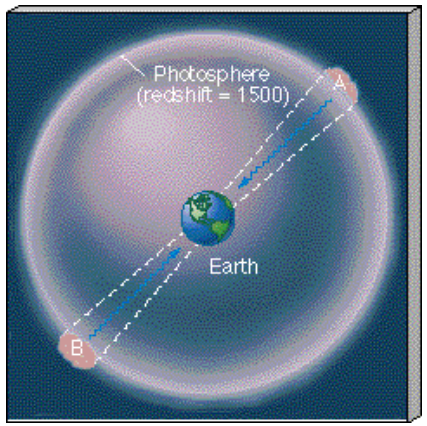
The Seeds of Galaxies

These small perturbations in temperature are the fluctuations (smaller than 1 in a 100000) 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.

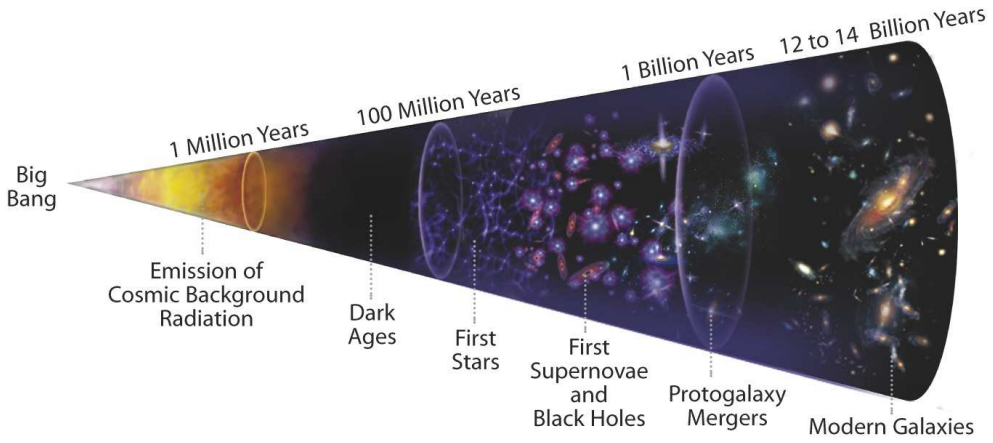


The Isotropy Problem

- The CMB looks very much the same all over the sky
- Thus, regions A and B were very similar to each other when the radiation we observe left them
- But there has not been enough time since the Big Bang for them ever to have interacted physically with one another
- Why then do they look the same?



A Brief History of Time



THE VERY EARLY UNIVERSE

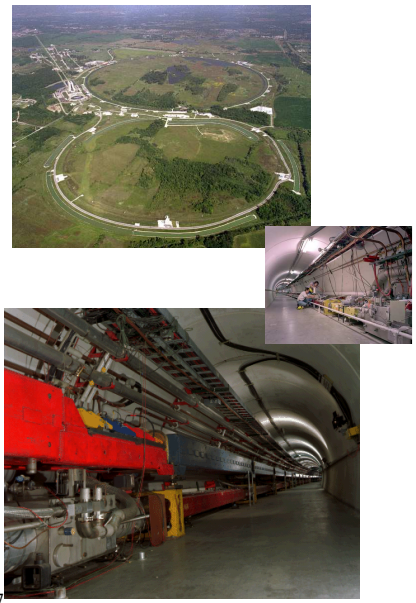
Since Big Bang works well so far, we have confidence to think about very early times:

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

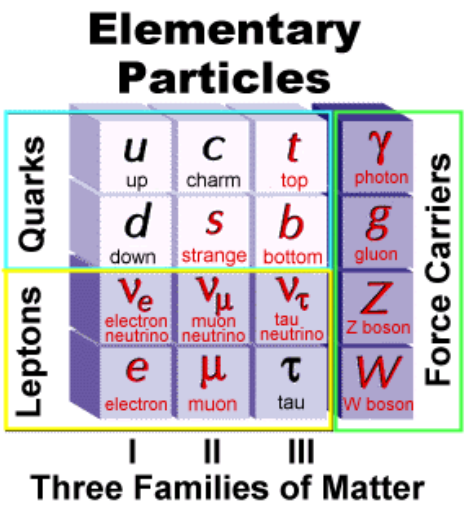
A Little Background Info

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

1. Basic Particles
2. Matter and Anti-matter
3. The Four Forces of Nature

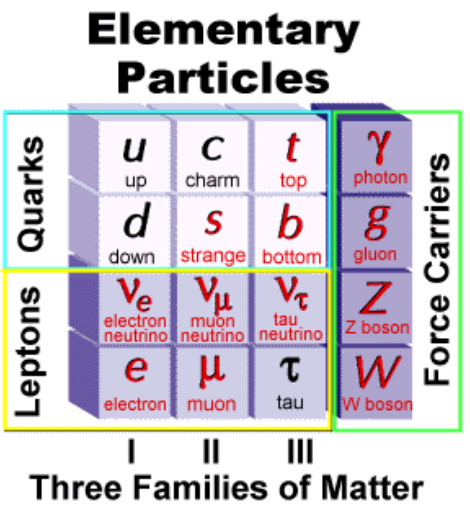
Basic Particles

- 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

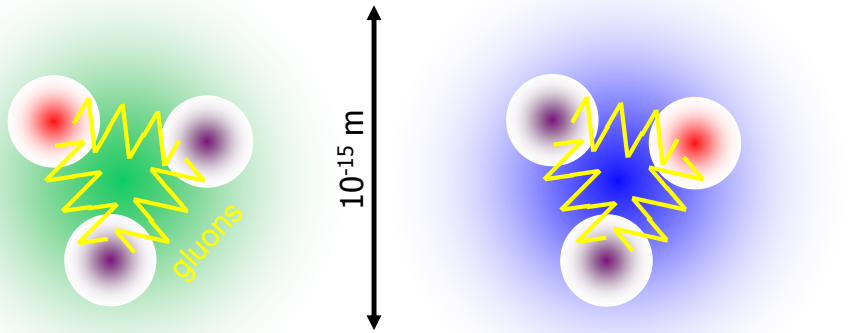
Basic Particles



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

Quarks

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



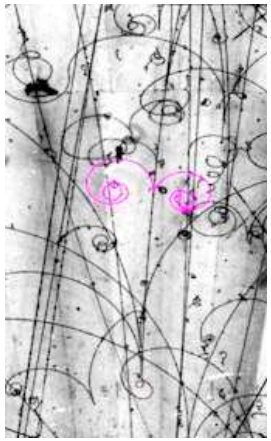
Proton (charge +1) =
2 "up" quarks (+4/3) +
1 "down" quark (-1/3)

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

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?

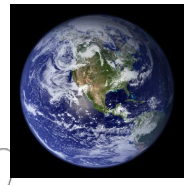
Matter & Anti-Matter

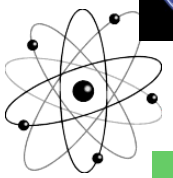


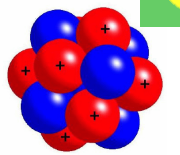
- Partner for each type of matter particle
  - Anti-electron=positron, anti-quarks, anti-neutrinos
- Anti-matter is stable by itself
  - Can have anti-protons, anti-atoms, anti-rocks, anti-people, anti-stars, anti-galaxies
- But when matter & anti-matter partners combine
  - **Annihilation** – matter converted to energy – $E=mc^2$
  - Example: paperclip + anti-paperclip annihilation – Energy release equal to a small nuclear bomb!

The Fantastic Four:

4 Fundamental Forces

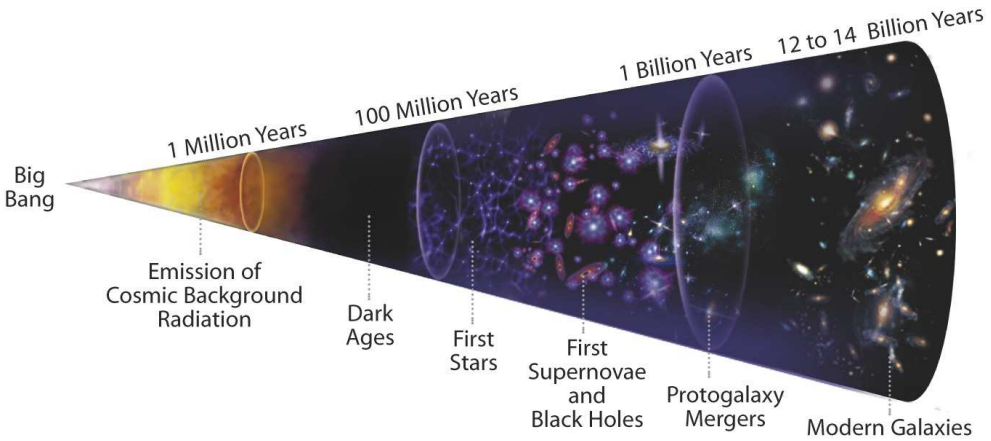






- **Gravity** - dominates large-scale action
- **Electromagnetism** - dominates chemical and magnetic interactions
- **Nuclear Weak** - controls nuclear reactions
- **Nuclear Strong** - binds atomic nuclei together

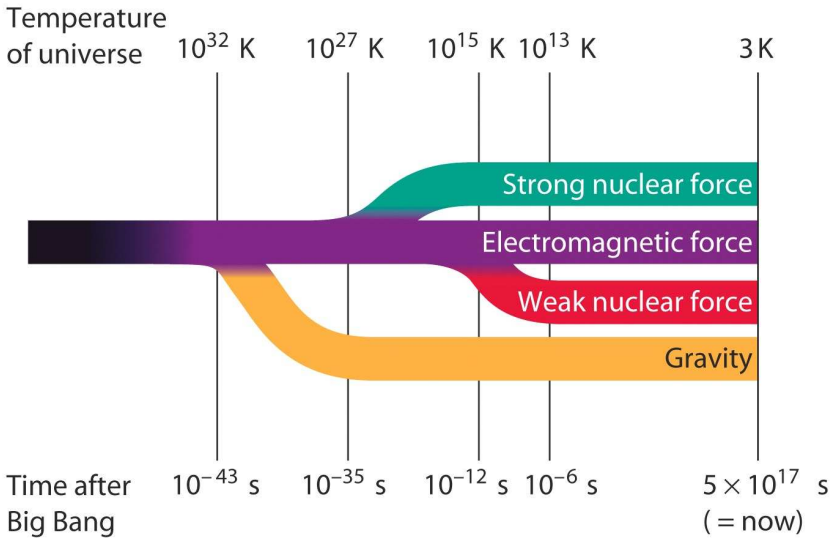
A Brief History of Time



The First Instant (to 10^{-43} sec)

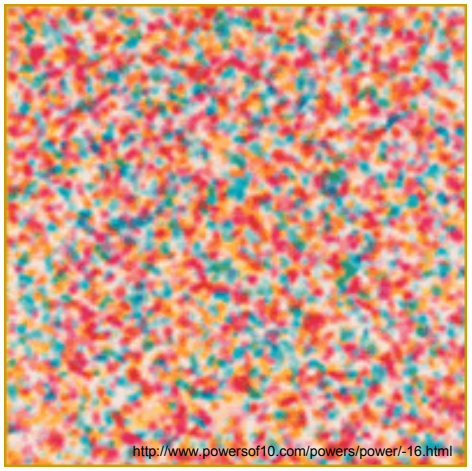
- Incredibly hot (more that 10^{32} K)
- Our current hypothesis – only one force in nature
  - The four forces were unified
  - Remains to be proven, as the theories we use to describe nature don't work in this era
- At the end of this era, gravity became a separate force
- Want a Nobel Prize? Develop a theory to describe this era of the Universe!

Dis-Unification of the Forces



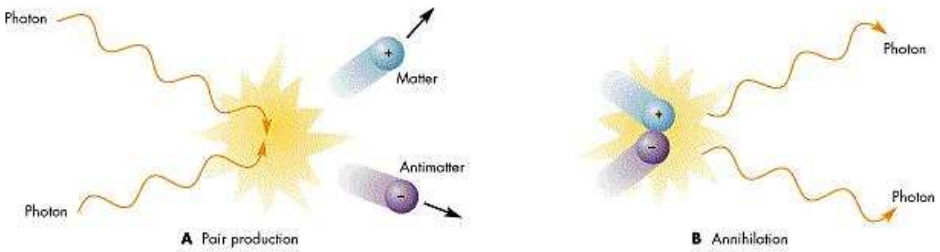
The GUT Era (until 10^{-35} sec)

- GUT = "Grand Unified Theory"
- Sea of free quarks (and anti-quarks) + photons + other basic particles
- Random fluctuations in density



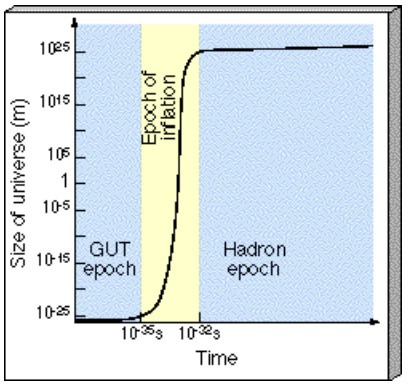
Matter and Anti-Matter

- 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



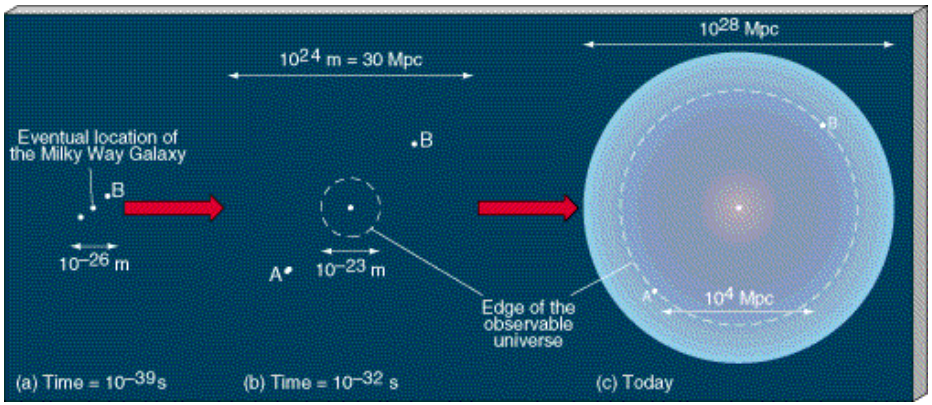
Inflation (10^{-35} to 10^{-32} sec)

- Universe went through a period of extremely rapid expansion
- Expansion by more than a factor of $\mathbf{10^{50}}$!!
- Expansion driven by the splitting of strong and electro-magnetic/weak forces
- Areas that were close before inflation were now separated by millions of parsecs!



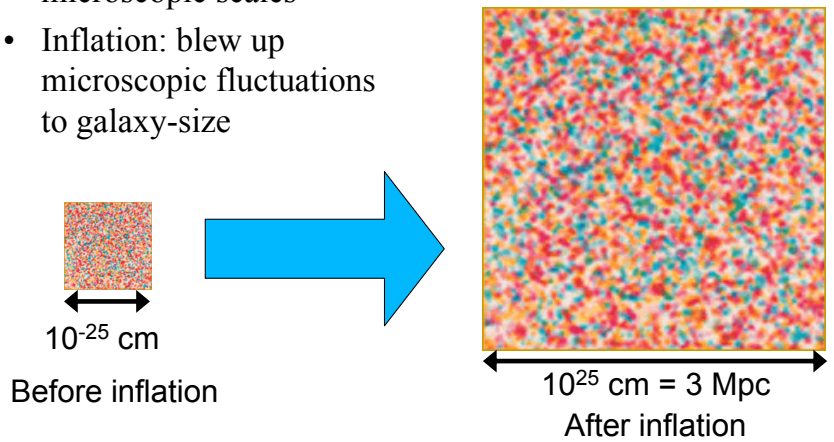
Inflation Solves the Isotropy Problem!

Regions that were close enough to interact in the early Universe were separated by inflation!



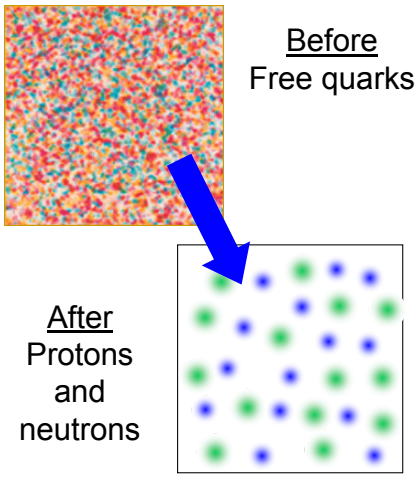
Origin of the CMB Fluctuations

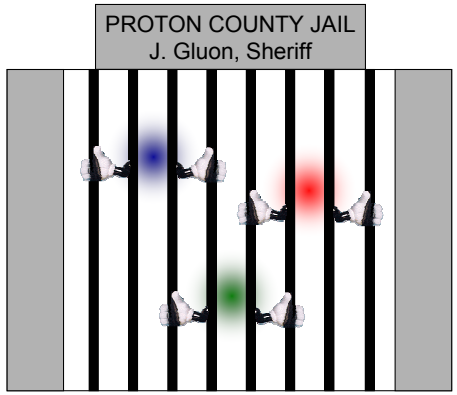
- Early Universe: a sea of particles & energy
- Density was constantly fluctuating on microscopic scales
- Inflation: blew up microscopic fluctuations to galaxy-size



Quark Confinement

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

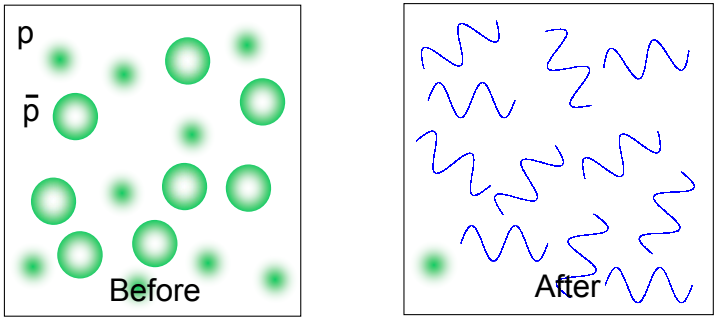




10^{31} years to life
Little chance of parole

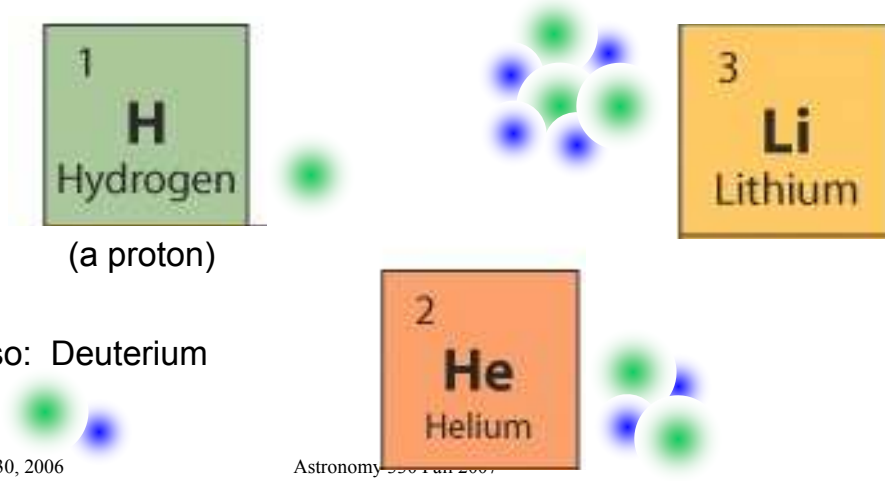
Annihilation of the Anti-matter

- 10^{-4} seconds:
  - Temperature dropped below the level at which photons have enough energy to create proton-anti-proton pairs
  - Remaining pairs annihilated → radiation
  - 1 proton in 10^{9} had no partner! That's us



Big Bang Nucleosynthesis

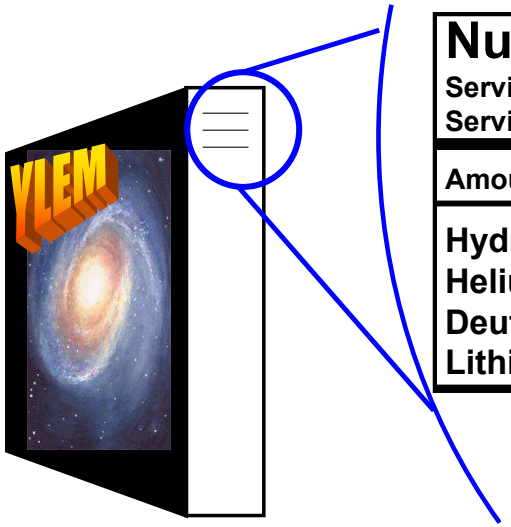
When the Universe was 1 sec to 3 mins old, the temperature fell to 10^9 K and protons and neutrons can "shack-up" to form the first light elements.



(a proton)

Also: Deuterium

End Result: Big Bang Correctly Predicts Abundances



Nutrition Facts

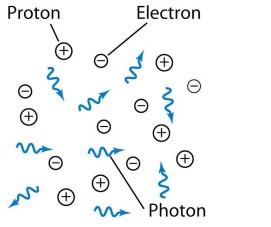
Serving Size 1 g
Servings Per Universe many many

Amount Per Serving

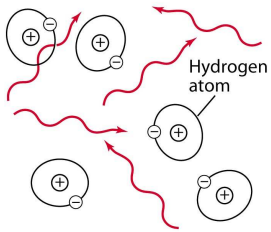
Hydrogen	**0.75 g**
Helium	**0.25 g**
Deuterium	**10^{-4} g**
Lithium, etc.	**10^{-10} g**

Era of Recombination

- In the early Universe, photons were energetic enough to keep atoms ionized
  - protons and electrons couldn't make neutral hydrogen atoms
- After 500,000 years, photons couldn't ionize hydrogen anymore
  - Expansion of space stretched photons' wavelengths
  - Not enough energy to ionize hydrogen
  - Universe became transparent to photons
- This radiation is the source of the Cosmic Microwave Background!

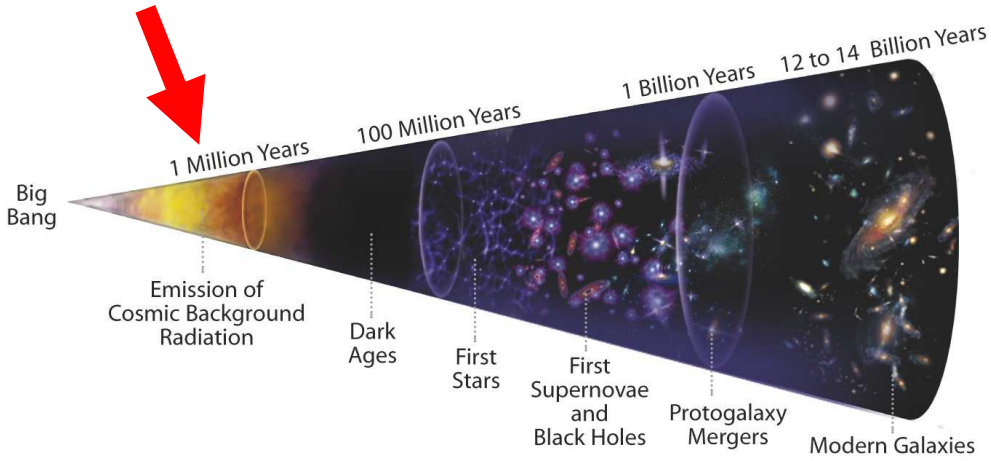


a Before recombination



b After recombination

Origin of the CMB

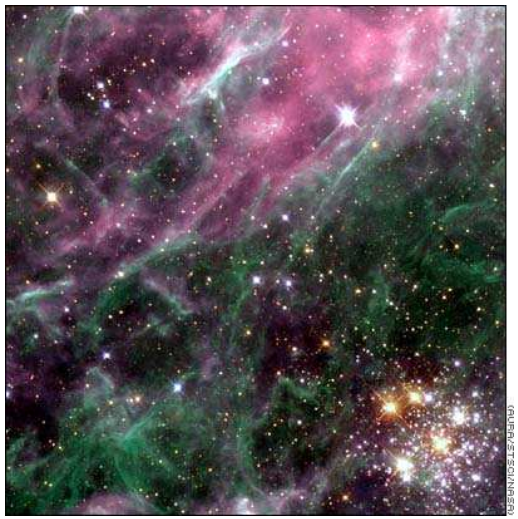


- After recombination came a period known as the Dark Ages
  - 500,000 to 100 million years
  - No light comes to us from this period
- Matter consists of warm clouds of hydrogen and helium
  - Too hot for star formation to occur
  - Gravity slowing drawing clouds together into bigger and bigger clumps

http://www.darkages.com/

The First Stars

- We think the first stars began to form after about 200 million years
- Proto-galactic clouds are slowly collapsing – no galaxies yet

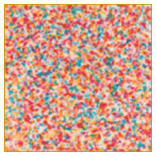


"Thinking Cap"

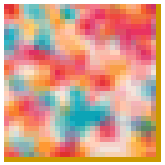
What if our solar system formed with the first generation of stars? How would our solar system be different? Would the Earth exist as a habitable planet?

The Beginnings of Galaxies

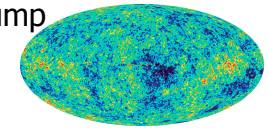
Quantum fluctuations during GUT era (before 10^{-35} s)



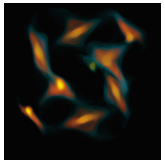
Inflation stretches fluctuations to galaxy size (before 10^{-32} s)

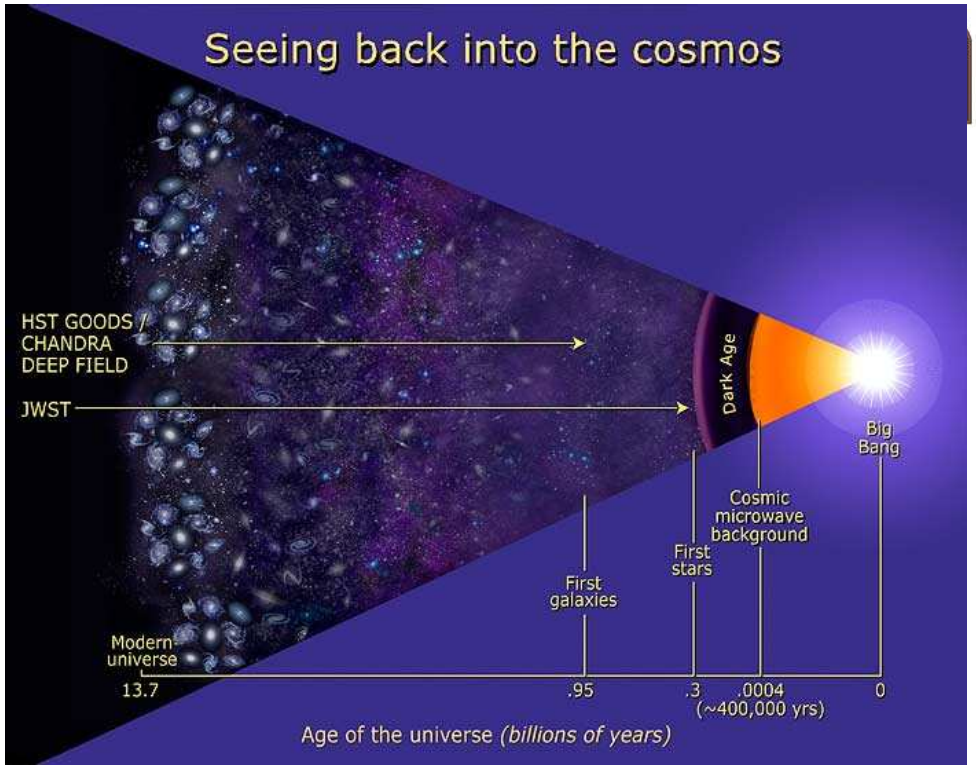


Before recombination, particles moving too fast to clump



After recombination, gravity of denser regions draws particles together





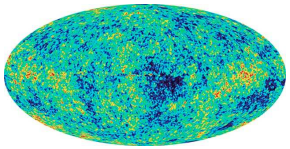
From the Home Office in Urbana, IL

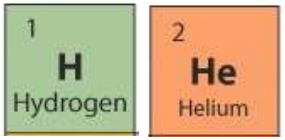
Top 3 Reasons We Believe in the Big Bang

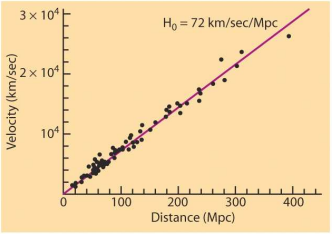
1. Cosmic Microwave Background
   - Big Bang working at about 500,000 yrs
   - Tiny fluctuations: "seeds" of galaxies
2. Big Bang Nucleosynthesis
   - H and (almost all) He come from the Big Bang
   - Big Bang working at 1 sec
3. The Hubble Law: $v=H_0 d$

   + Einstein's General Relativity

   = Expanding Universe with an age of 13.7 billion yrs







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