

Astronomy 330



This class (Lecture 4):

Cosmology and the
Origin of Elements

Next Class:

From Atoms to
Molecules to Clouds

**Presentation Synopsis
due next Thursday.**

Music: *Galaxies* – Laura Veirs

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Outline

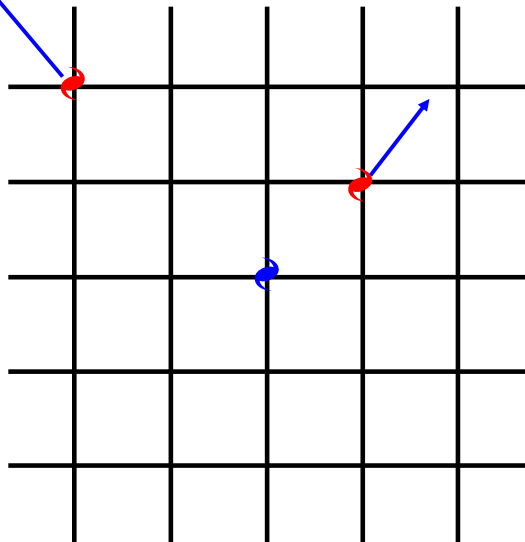


- The early Universe– The origin of H
- The probable fate of the Universe
- The Universe is mostly Dark Energy
- As the Universe cools....

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Wow. The Universe is Expanding.



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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!**



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What do you think?



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



<http://www.calresco.org/cwp/confuse.htm>

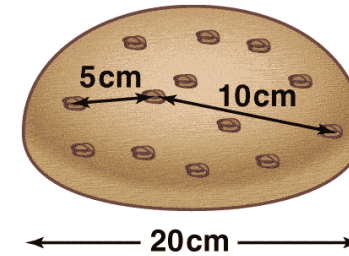
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Analogy– Raisin Bread



The raisins are like galaxies.

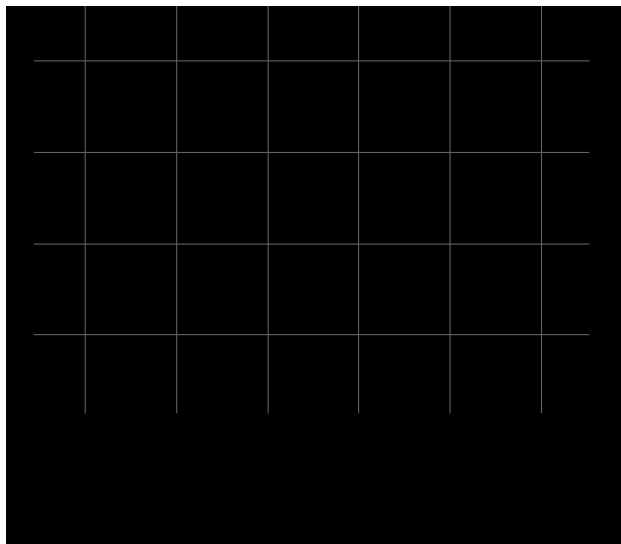


Raisins stay the same size, like Brooklyn.

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Another Expansion Graphic



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~~Expanding into What?~~



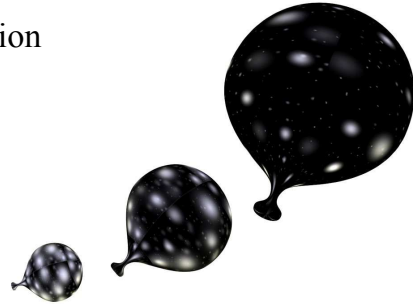
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Common Misconception



- It's 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



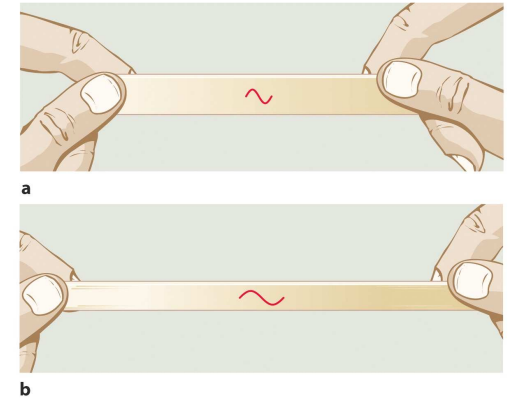
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Analogy - Rubber Band



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



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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>

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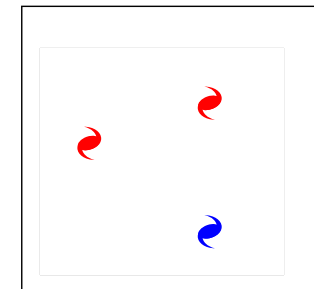
Living in an Expanding Universe



Consider a large "box" containing many galaxies

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

The Universe box



Tomorrow

How does the density of the Universe change with time?

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Living in an Expanding Universe



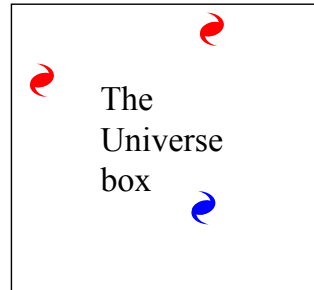
How does the density of the Universe change with time?
As the Universe expands:

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

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

Density changes with time!

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



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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.

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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



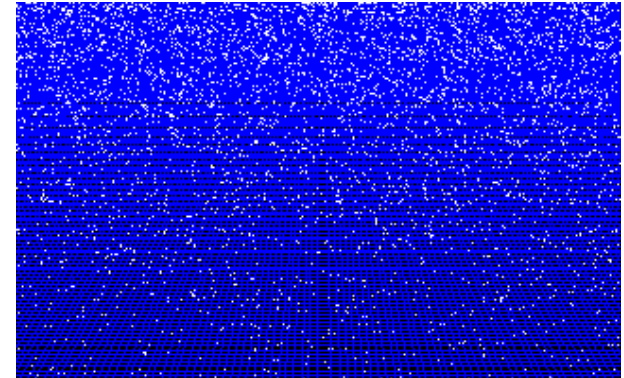
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The Big Bang



- 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



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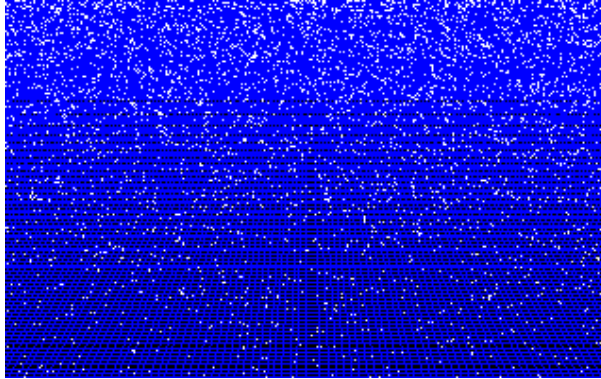
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<http://www.anzwers.org/free/universe/bigbang.html>

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



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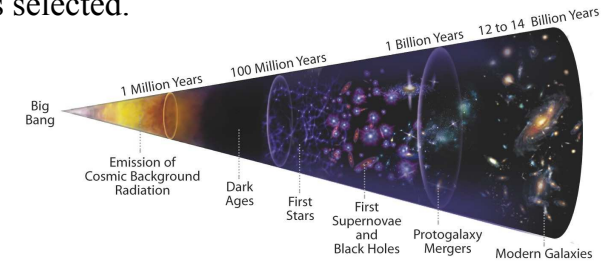
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<http://www.anzwers.org/free/universe/bigbang.html>

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.



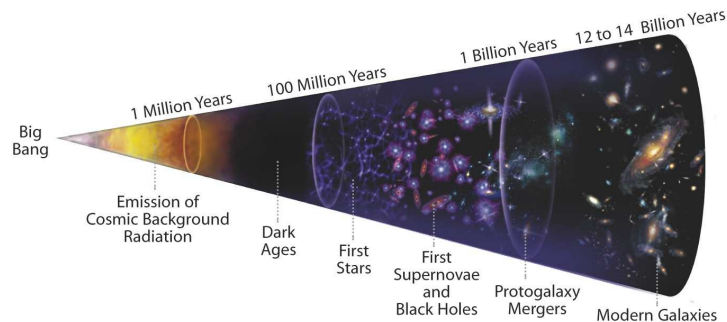
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The Big Bang



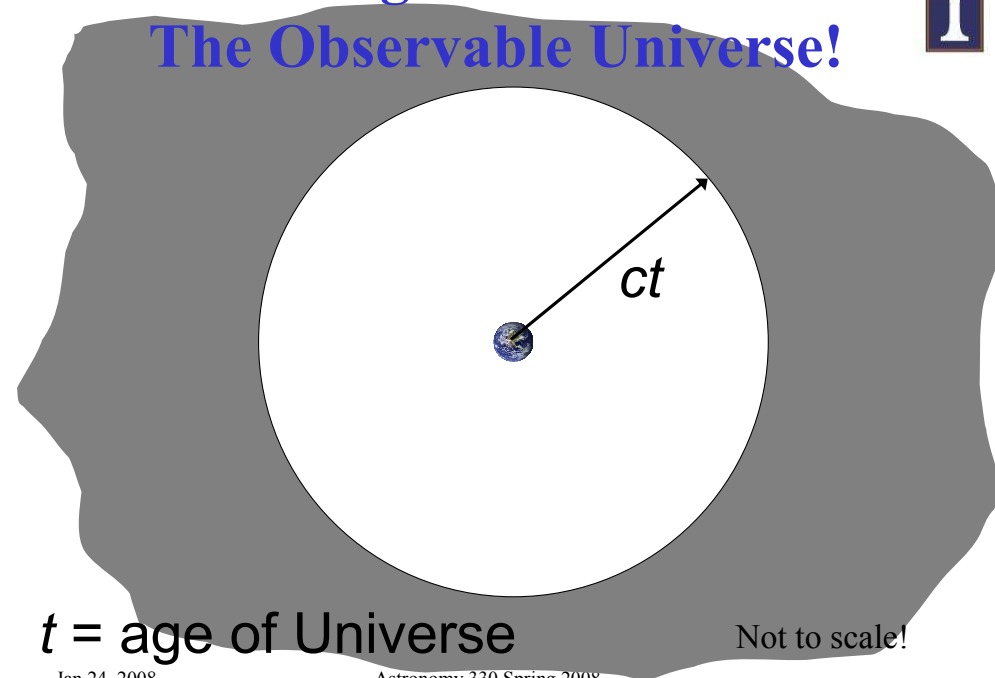
- Scientists do not have a definitive explanation for the Big Bang
- But, a growing body of observations supports the theory that the event did occur.



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Looking Back in Time: The Observable Universe!



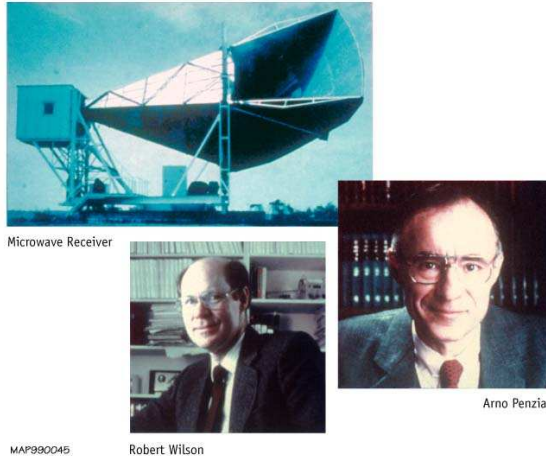
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The Early Universe was *HOT*!



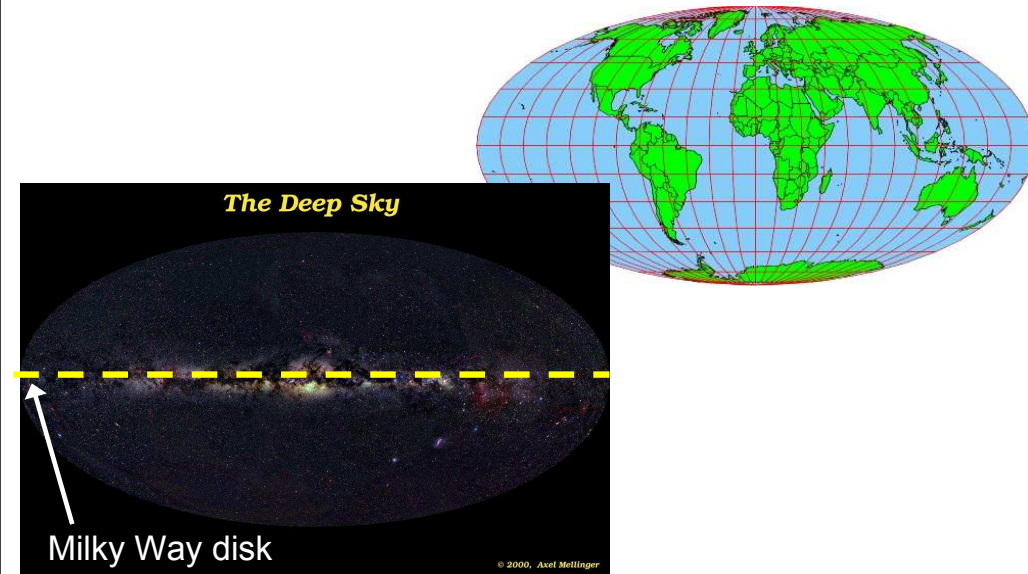
- If the early Universe was so hot, we should be able to see it glowing. Right?
- **Yep, we do!** But, as the Universe expanded, it redshifted down to the microwave.
- Now, it is called the Cosmic Microwave Background (CMB).
- First detected by Robert Wilson and Arno Penzias.



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How to Understand Sky Maps



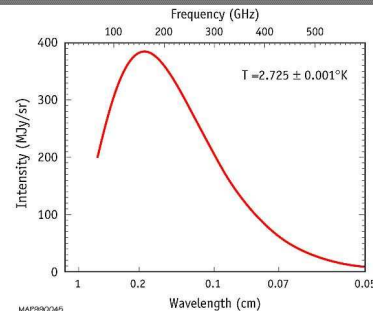
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In Fact, a Rather Uniform Blackbody

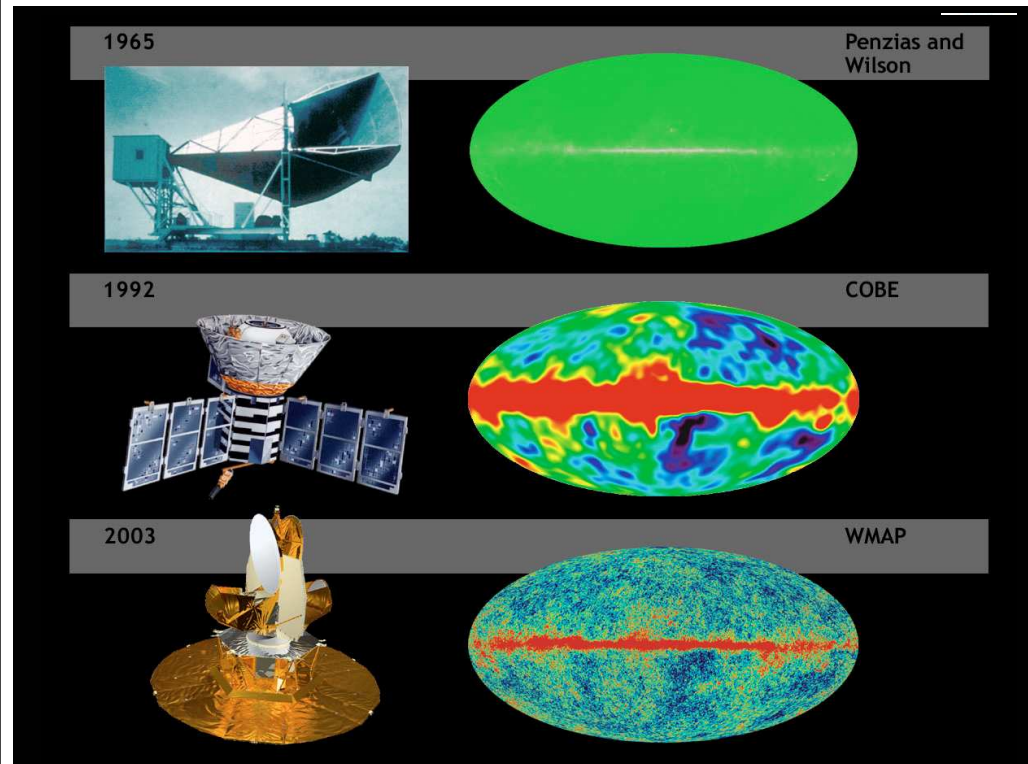


- All over the sky, we see blackbody radiation
 - Temperature = 2.73 K
- Provides compelling evidence for the Big Bang Theory
- Almost perfectly *isotropic*
 - Nearly the same in every direction
- Indicates that, over large scales, the Universe is uniformly spread out



Cosmic Background Explorer (COBE) satellite (launched 1989)

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Unknown Fluctuations...

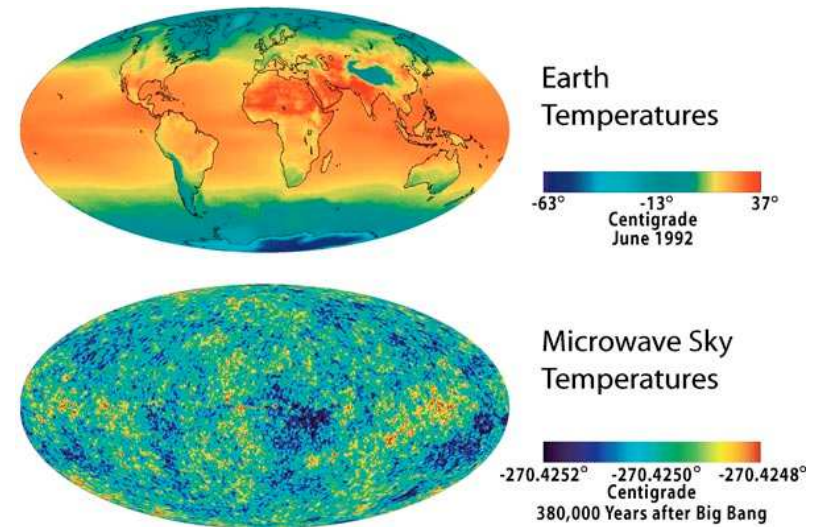


Further refinements of the cosmic microwave background reveal a deeper meaning for physicists to ponder.

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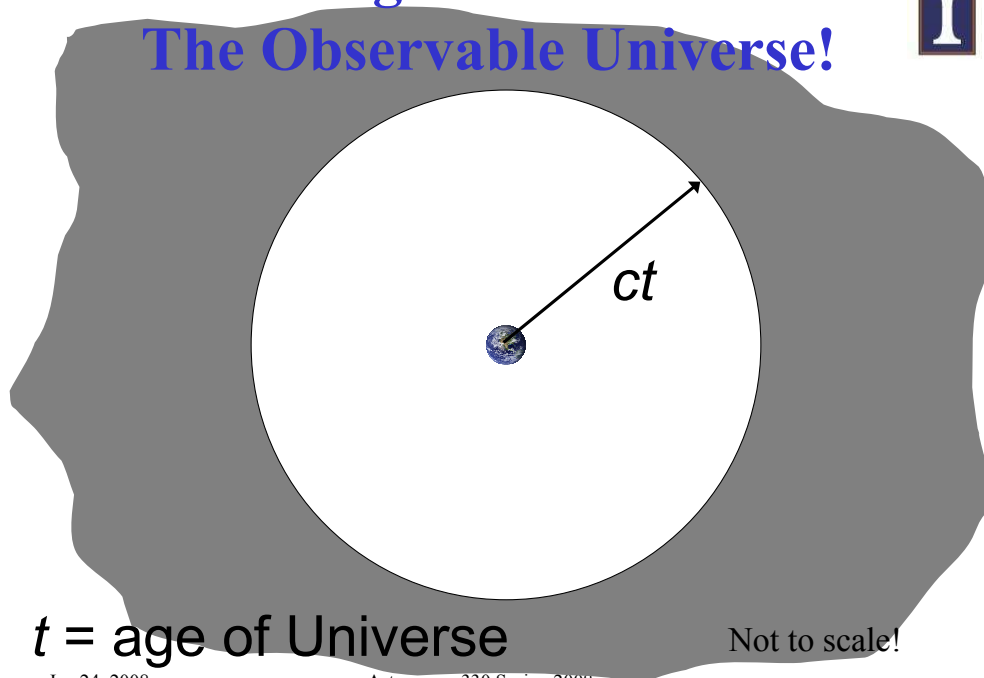
WMAP took a “baby picture” of the Universe— only 400000 yrs old.



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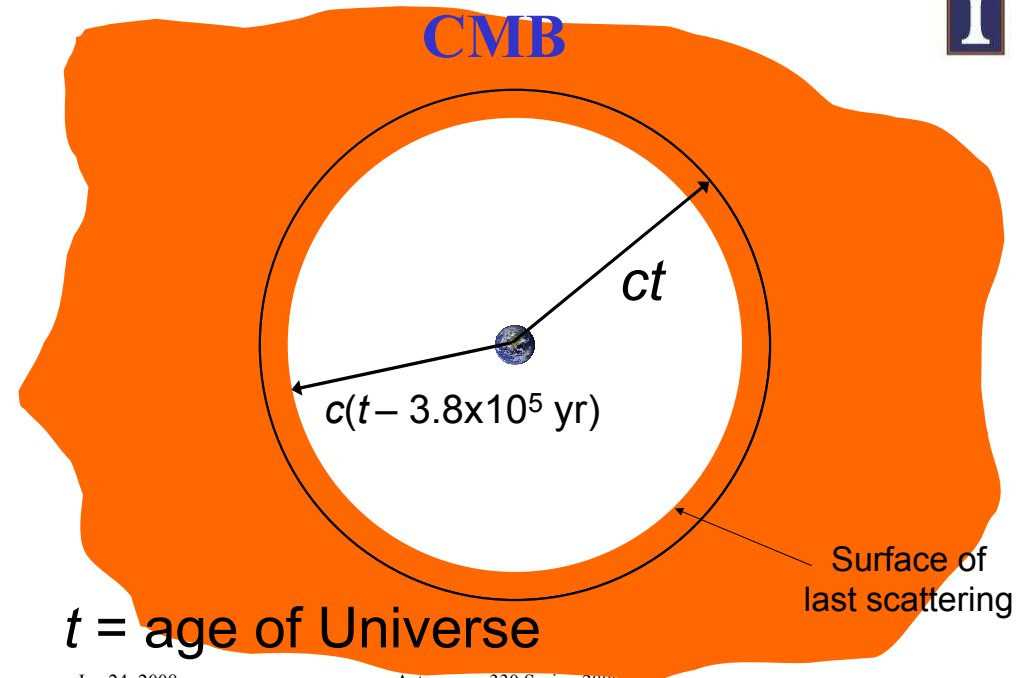
Looking Back in Time: The Observable Universe!



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Looking Back in Time to the CMB



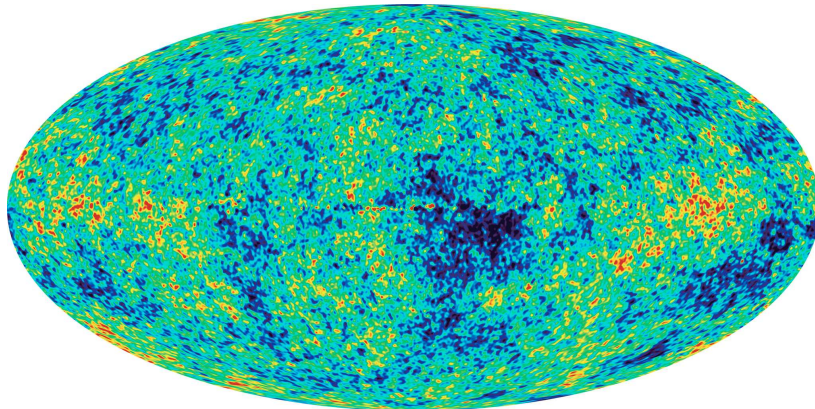
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The Seeds of Galaxies



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



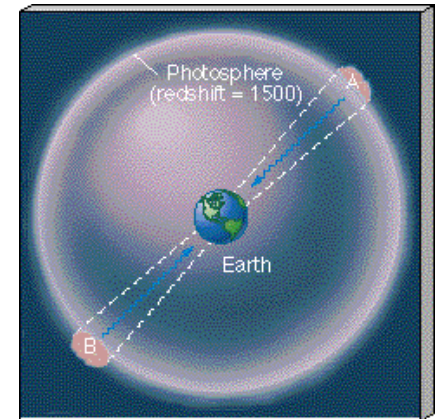
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The Isotropy Problem



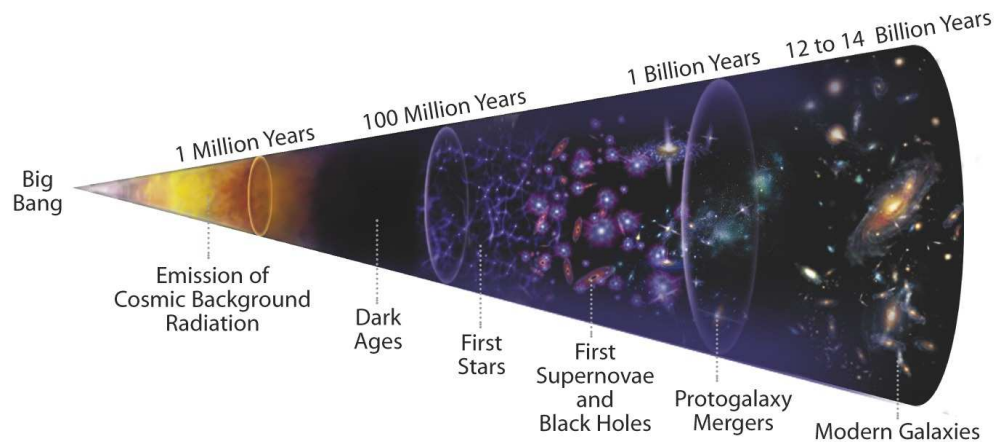
- The CMB looks very much the same all over the sky
- Thus, regions A and B were very similar to each other when the radiation we observe left them
- But there has not been enough time since the Big Bang for them ever to have interacted physically with one another
- Why then do they look the same?



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A Brief History of Time



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THE VERY EARLY UNIVERSE



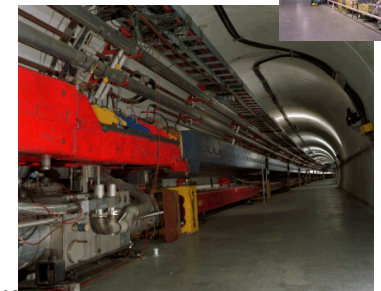
Since Big Bang works well so far, we have confidence to think about very early times:

$t \ll 1 \text{ sec} !$

- Temperature and energies are *ultra*high

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

Fermilab



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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



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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

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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?

Elementary Particles

	I	II	III	Force Carriers
Quarks	u up d down	c charm s strange	t top b bottom	γ photon g gluon
Leptons	ν_e electron neutrino e electron	ν_μ muon neutrino μ muon	ν_τ tau neutrino τ tau	Z Z boson W W boson

Three Families of Matter

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

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Basic Particles



Elementary Particles				
Quarks	u up	c charm	t top	Force Carriers
	d down	s strange	b bottom	
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	
	e electron	μ muon	τ tau	
				γ photon
				g gluon
				Z Z boson
				W W boson
	I	II	III	
Three Families of Matter				

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

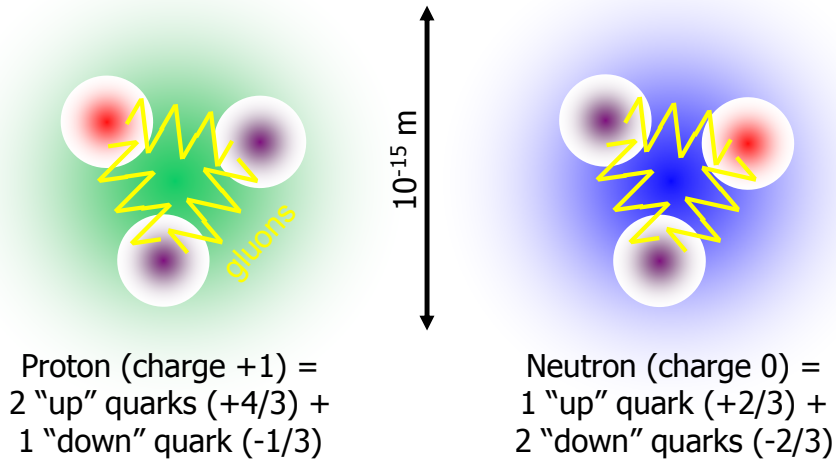
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Quarks



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



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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?



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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!



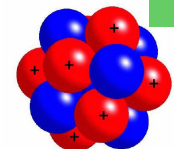
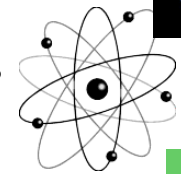
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The Fantastic Four: 4 Fundamental Forces



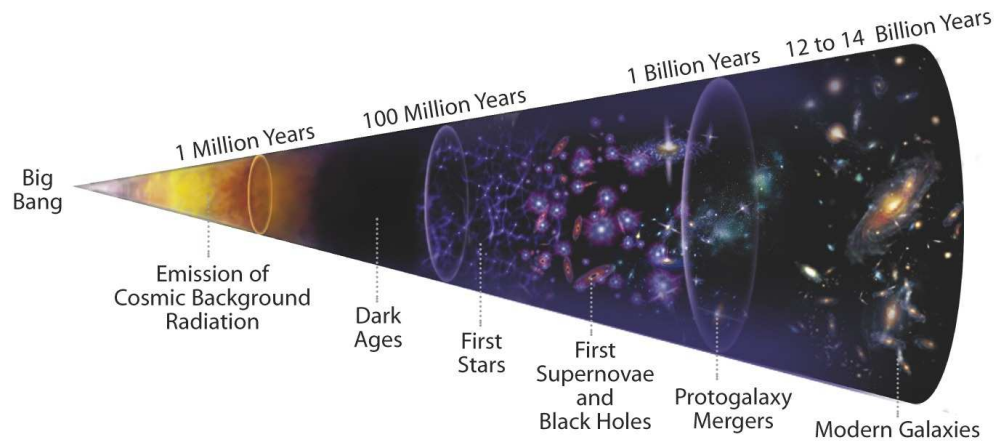
- Gravity** - dominates large-scale action
- Electromagnetism** - dominates chemical and magnetic interactions
- Nuclear Weak** - controls nuclear reactions
- Nuclear Strong** - binds atomic nuclei together



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A Brief History of Time



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

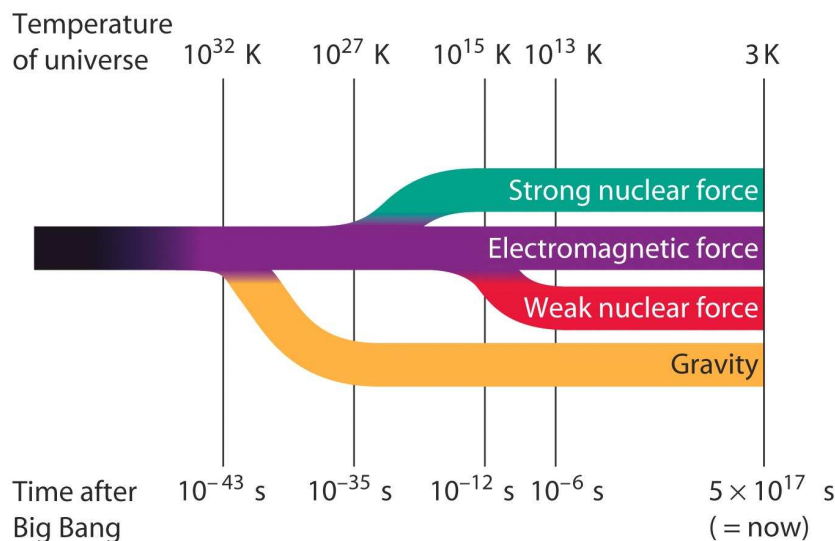


- Incredibly hot (more than 10^{32} K)
- Our current hypothesis – only one force in nature
 - The four forces were unified
 - Remains to be proven, as the theories we use to describe nature don't work in this era
- At the end of this era, gravity became a separate force
- Want a Nobel Prize? Develop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

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Dis-Unification of the Forces



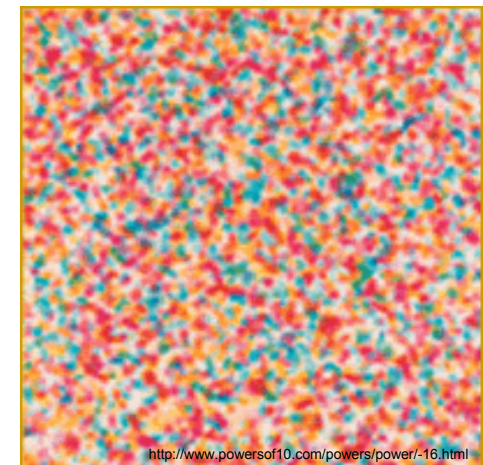
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The GUT Era (until 10^{-35} sec)



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



<http://www.powersof10.com/powers/power/-16.html>

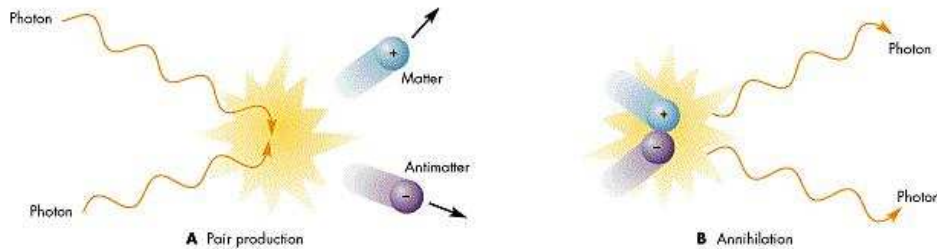
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Matter and Anti-Matter



- 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



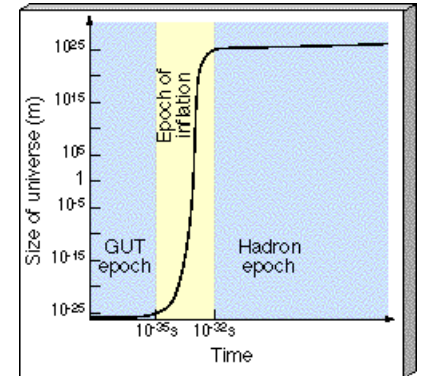
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Inflation (10^{-35} to 10^{-32} sec)



- Universe went through a period of extremely rapid expansion
- Expansion by more than a factor of $10^{50}!!$
- 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!



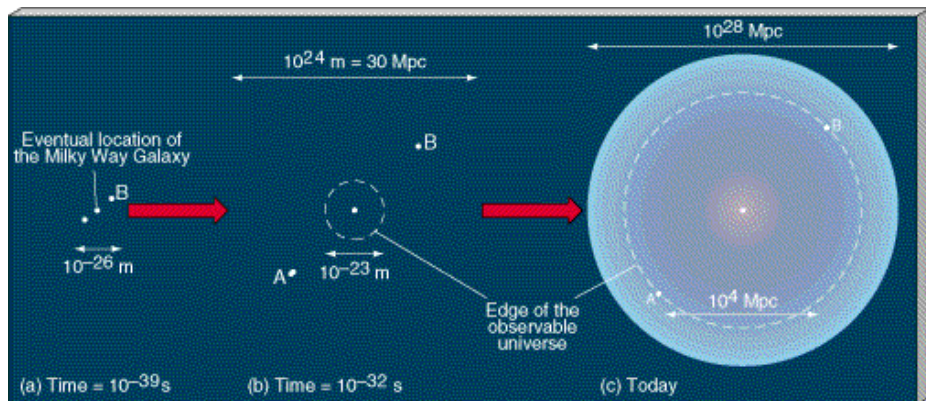
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Inflation Solves the Isotropy Problem!



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



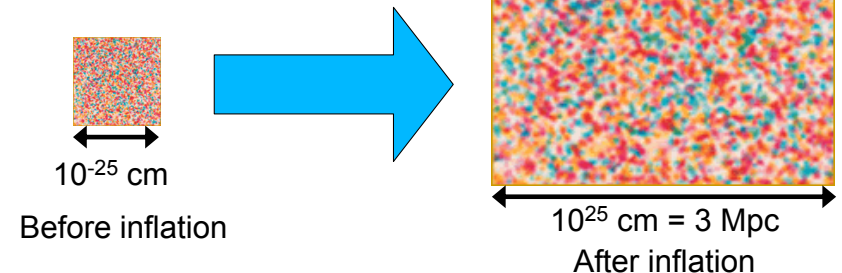
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Origin of the CMB Fluctuations



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



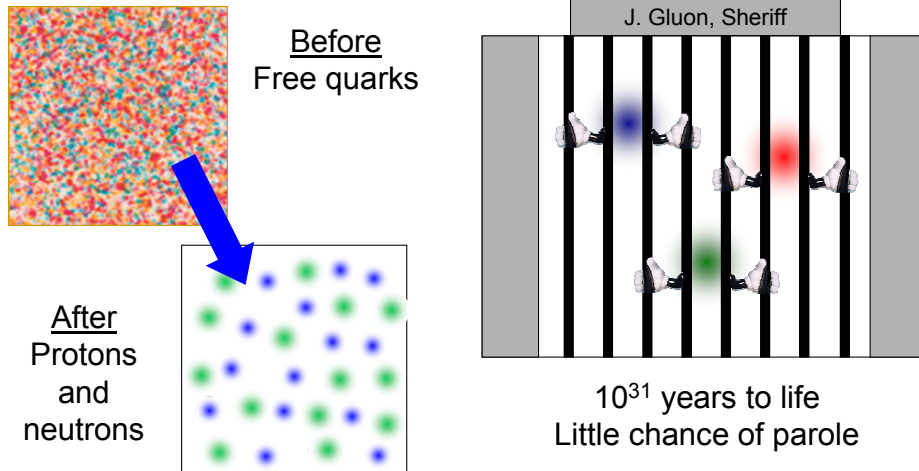
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Quark Confinement



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



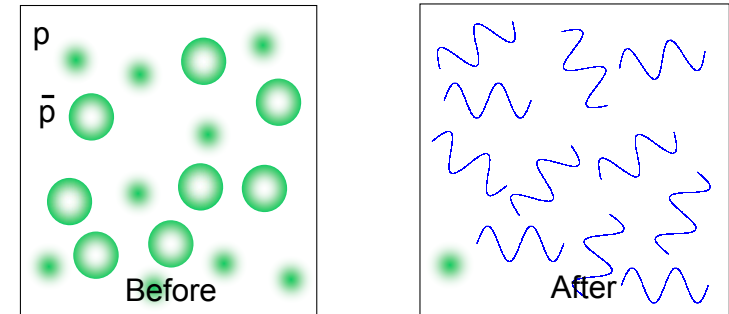
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Annihilation of the Anti-matter



- 10^{-4} seconds:
 - Temperature dropped below the level at which photons have enough energy to create proton-anti-proton pairs
 - Remaining pairs annihilated \rightarrow radiation
 - 1 proton in 10^9 had no partner! That's us.
 - The first hydrogen atoms (ionized but there)



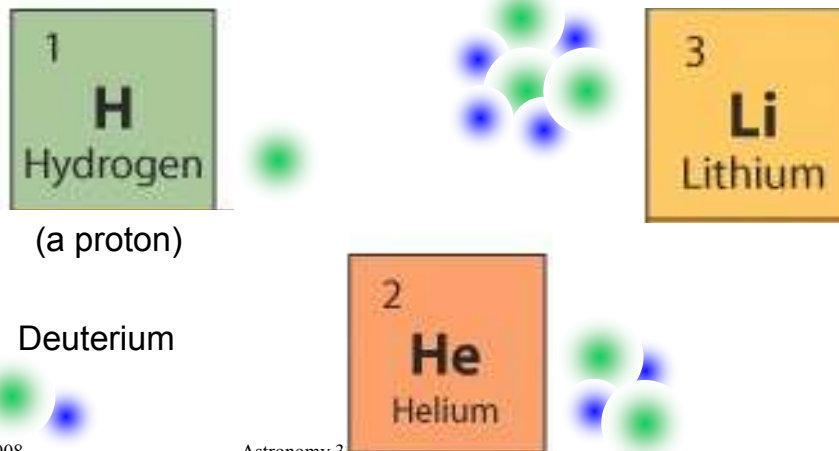
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Big Bang Nucleosynthesis



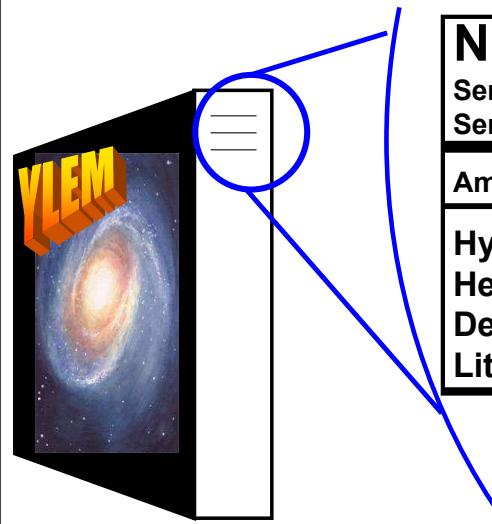
When the Universe was 1 sec to 3 mins old, the temperature fell to 10^9 K and protons and neutrons can “shack-up” to form the first light elements.



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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

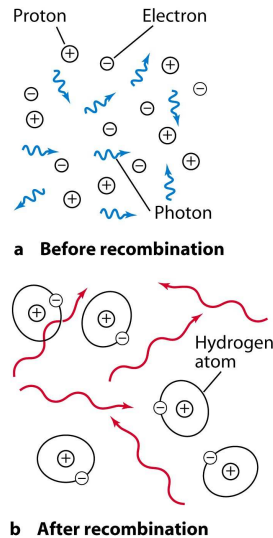
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Era of Recombination



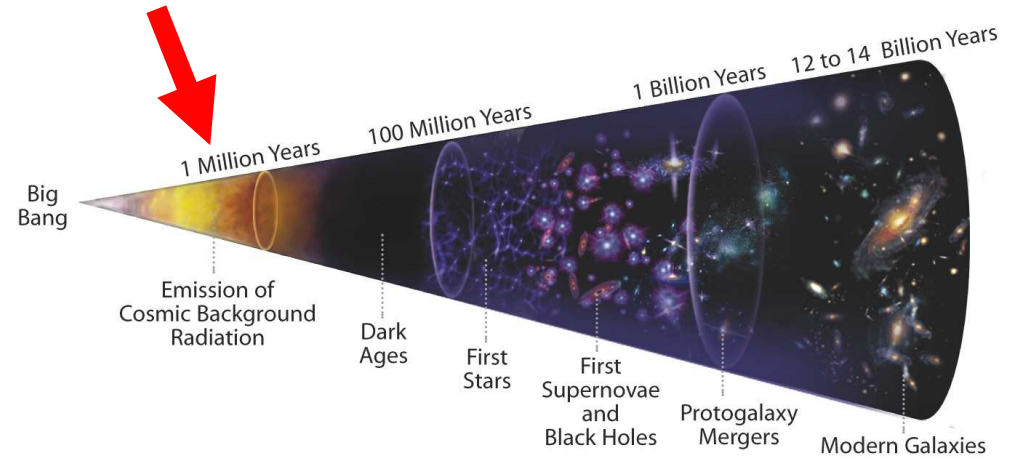
- In the early Universe, photons were energetic enough to keep atoms ionized
 - protons and electrons couldn't make neutral hydrogen atoms
- After 500,000 years, photons couldn't ionize hydrogen anymore
 - Expansion of space stretched photons' wavelengths
 - Not enough energy to ionize hydrogen
 - Universe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



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Origin of the CMB



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- 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 slowly drawing clouds together into bigger and bigger clumps

<http://www.darkages.com/>

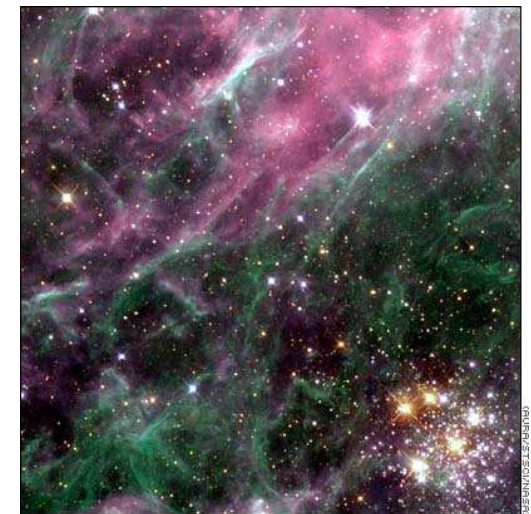
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The First Stars



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



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“Thinking Cap”

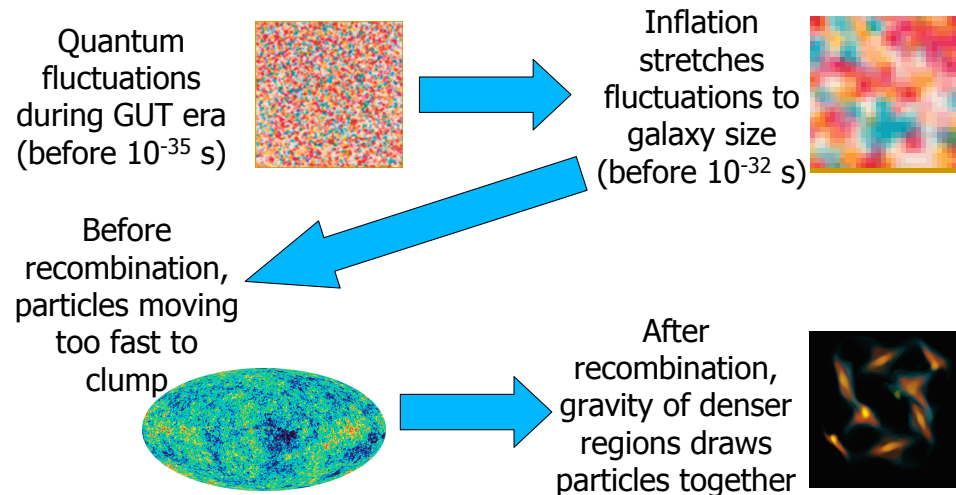


What if our solar system formed with the first generation of stars? How would our solar system be different? Would the Earth exist as a habitable planet?

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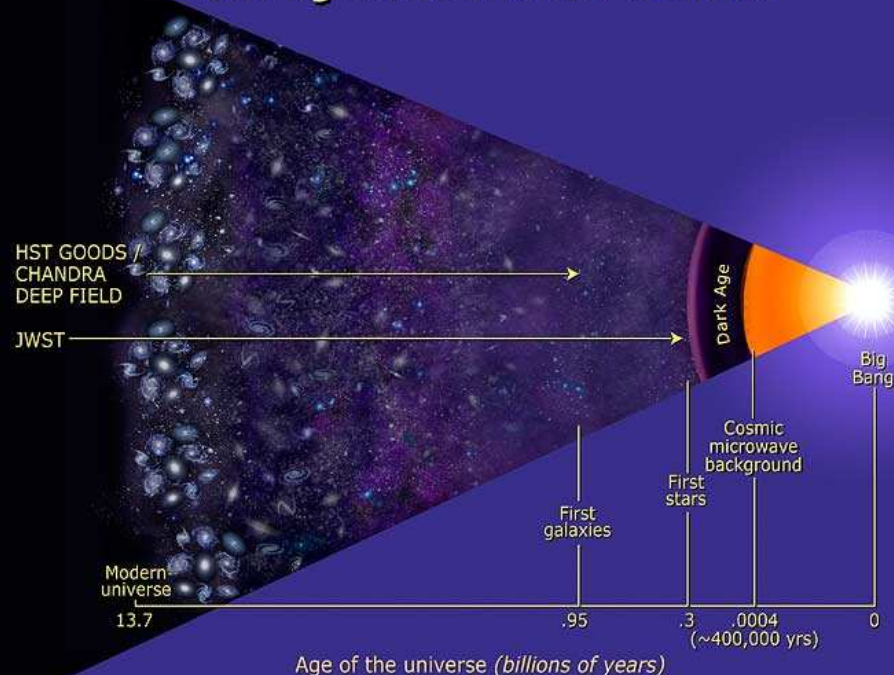
The Beginnings of Galaxies



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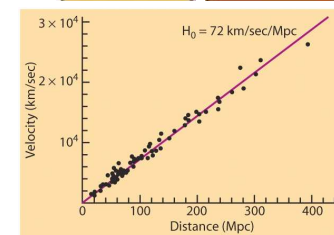
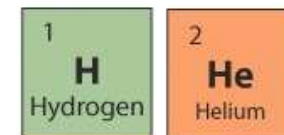
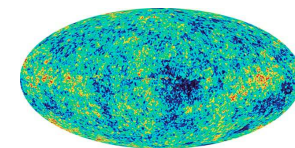
Seeing back into the cosmos



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: $v=H_0d$
+ Einstein’s General Relativity
= Expanding Universe with an age of 13.7 billion yrs



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What is the fate of the Universe?

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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

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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



?

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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.**



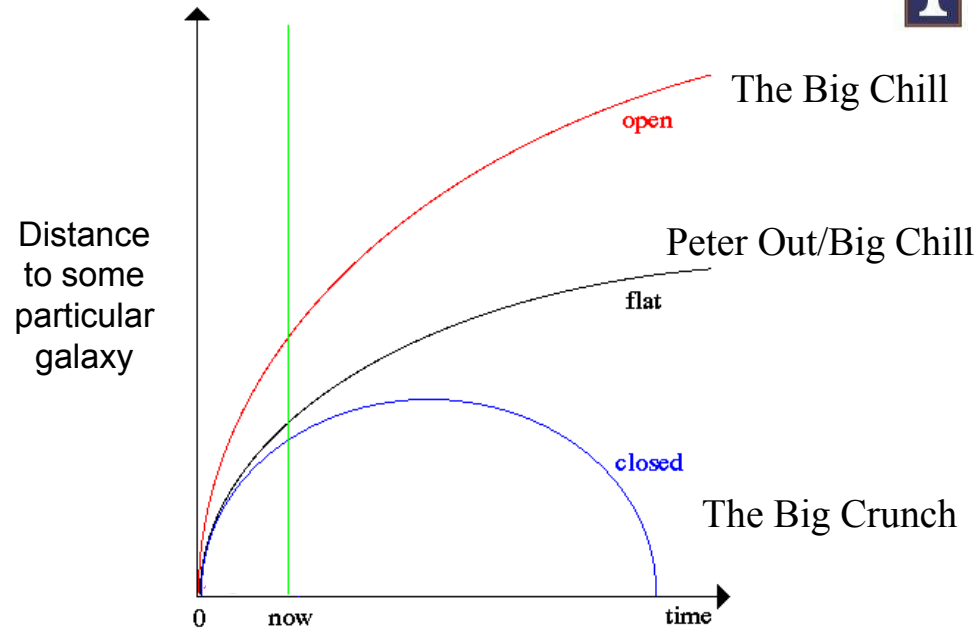
or



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What kind of Universe do we live in?



J

Think-Pair-Share



- What kind of a Universe would you want to live in? Open? Closed? Flat?

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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

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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 Not enough to close the Universe

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So we live in an open Universe?

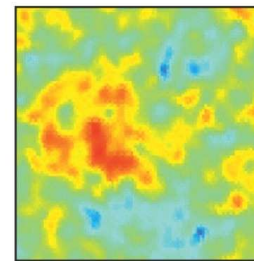
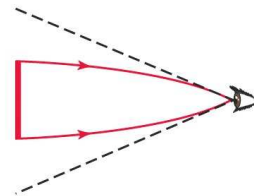
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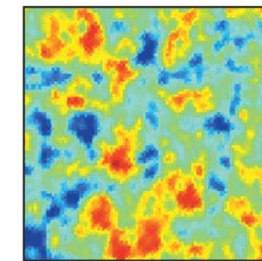
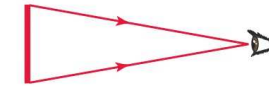
CMB Measurements



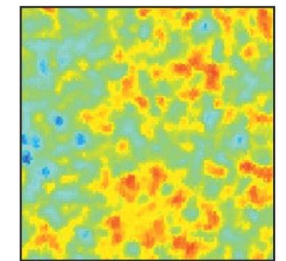
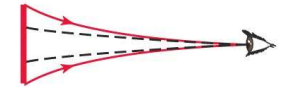
Universe is Flat!!!!



a If universe is closed, hot spots appear larger than actual size



b If universe is flat, hot spots appear actual size



c If universe is open, hot spots appear smaller than actual size

Peter Out/ Big Chill



- The Universe will just barely expand forever, getting cooler and cooler.
- If all of the mass, dark+regular, isn't enough, **then what's up?**
- The fate of the Universe is really dependent on the amount of matter and energy in the Universe $\rightarrow E = mc^2$



We must be missing some extra mass/energy?

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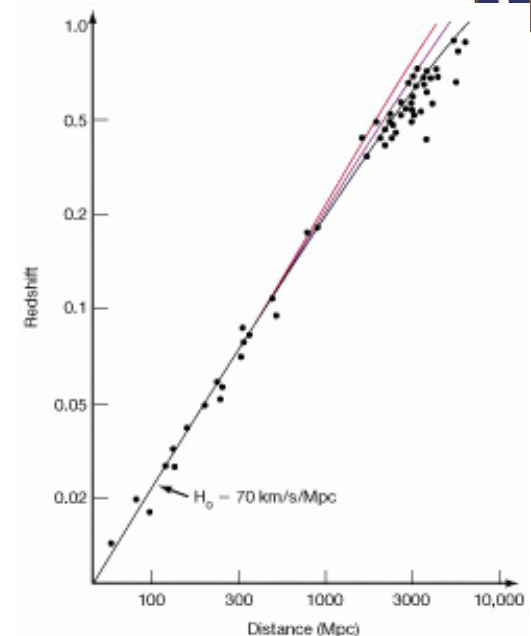
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The Accelerating Universe!!!



The universe is not slowing down at all. In fact, it's speeding up!!! We live in an accelerating universe!

It's as if there's another force pushing the universe apart – a **Cosmological Constant!!!**



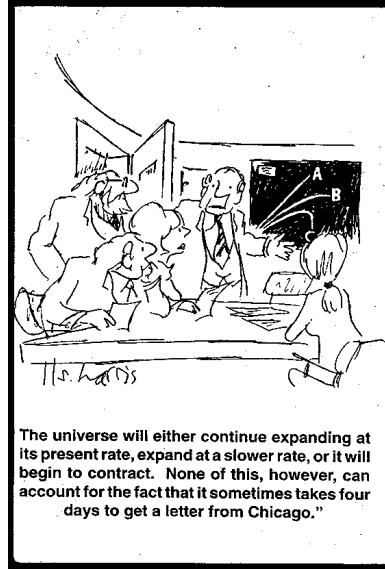
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Dark Energy



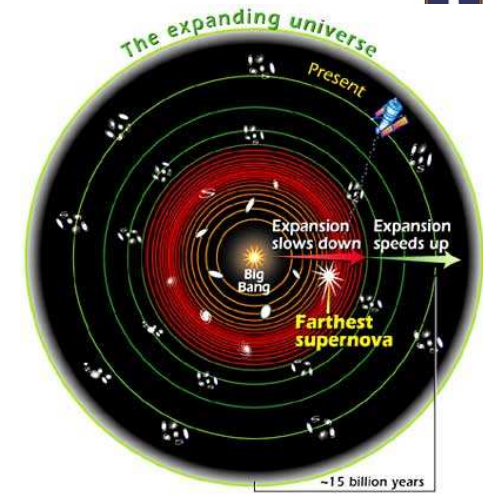
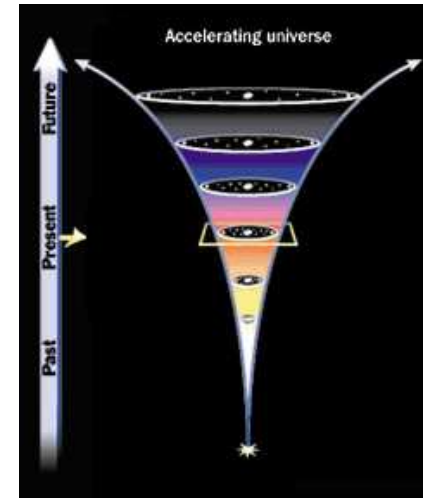
- The matter census isn't enough to be flat and the expansion is accelerating!
- So, a new type of energy called **dark energy** must exist
 - Not related to dark matter
 - Acts as repulsive gravity
- Dark energy is actually *accelerating* the expansion of the Universe!



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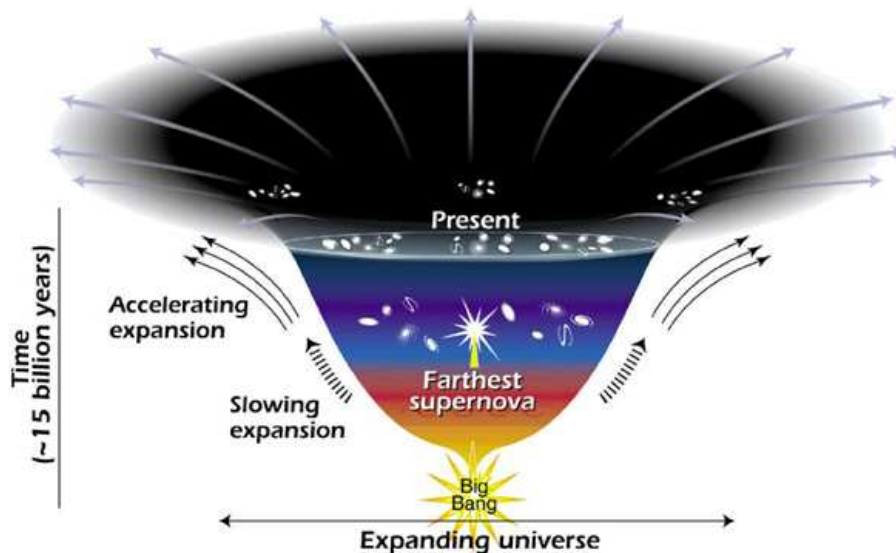
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The Accelerating Universe!!!



Whatever this force is, we *think* that it is growing stronger as the universe evolves. The more empty space in the universe, the greater the acceleration – as if the vacuum of space has energy.

Effects of Dark Energy



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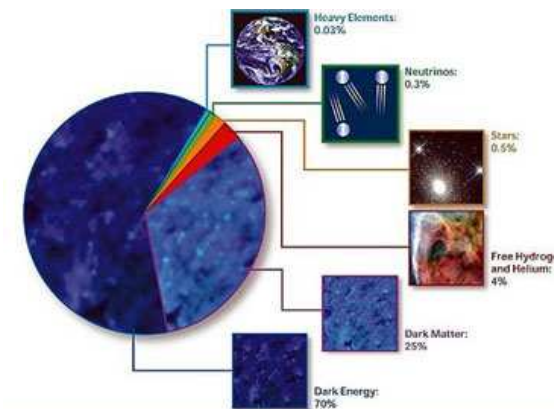
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<http://www.lbl.gov/Publications/Currents/Archive/Apr-06-2001.html>

The Accelerating Universe!!!



We appear to live in a universe with a flat shape, but which will go on accelerating forever. The universe is 13.7 billion years old, and is now dominated by dark energy. And it will only get worse – the more empty space, the more dark energy.



The Dark Energy even dwarfs dark matter! Regular matter is really insignificant. We *really* don't know anything about what's going on!!

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The Distant Future



- Now – the Universe is (nearly) flat
- But the expansion is accelerating
 - An open Universe?
- The future depends on the nature of dark energy

