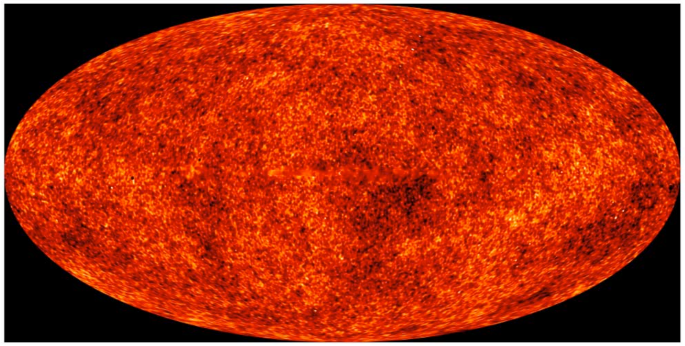
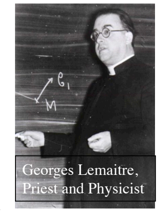
# Lecture 20: Cosmology and the Big Bang
A2020 Prof. Tom Megeath



## Review
## Cosmology: Study of the Universe as a Whole




Alexander Friedmann and Georges Lemaitre first applied Einstein's general relativity to Cosmology.

They assumed (as an approximation) that the universe is isotropic and homogeneous

1. Isotropic - the distribution of stars and galaxies looks the same in every direction to every observer
2. Homogeneous - the distribution of stars and galaxies is relatively smooth and constant (i.e no *big* lumps, just little ones like *galaxies*)

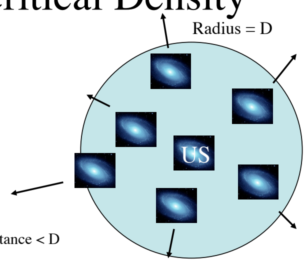
Solving Einstein's equations, they predicted in 1927 that Universe is *expanding*!

Einstein did not believe the Universe was expanding, and so he introduced a new "force" in his equation: the cosmological constant. This new force would balance gravity so that the Universe could be static (no expansion).

In 1929, Edwin Hubble showed that the universe was indeed expanding.

Einstein later referred to the cosmological constant as his *greatest blunder*.

## Review: Critical Density




Kinetic Energy of Galaxy = $1/2\ m\ V^2$

m = Mass of Galaxy
V = Velocity of Galaxy

V = Ho D (Hubble's Law)

D = distance to Galaxy

Gravitational energy of Galaxy = $-G\ M\ m/D$

Where M is total mass of all galaxies at a distance < D

$M = 4/3\ \pi\ \rho\ D^3$ where $\rho$ is the density of all matter (dark, baryonic, whatever)

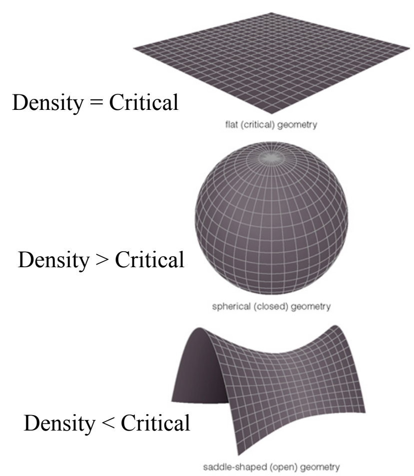
Critical density when Kinetic Energy + Gravitational Energy = 0

Kinetic Energy = -1 * Gravitational Energy

$1/2\ m\ (HoD)^2 = G\ m\ 4/3\ \pi\ \rho\ D^3/D$

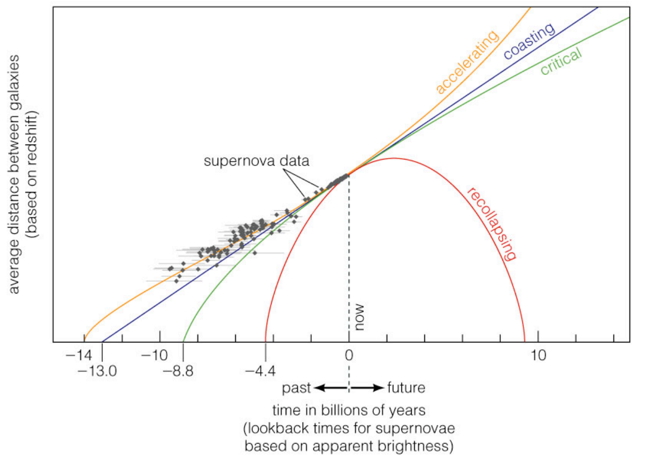
$\rho = 3/8\ Ho^2 / G\ \pi = 1.4 \times 10^{-36}$ gm cm$^{-3}$

*Critical density = 25 hydrogen atom per cubic kilometer (averaged over universe)*




Review:

Overall geometry of the universe is closely related to total density of matter & energy




Review: Accelerating universe is best fit to supernova data

## Review: Unseen Influences

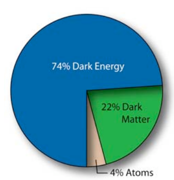
***Dark Matter:*** An undetected form of mass that emits little or no light but whose existence we infer from its gravitational influence

***Dark Energy:*** An unknown form of energy that seems to be the source of a repulsive force causing the expansion of the universe to accelerate

## Review: Contents of Universe

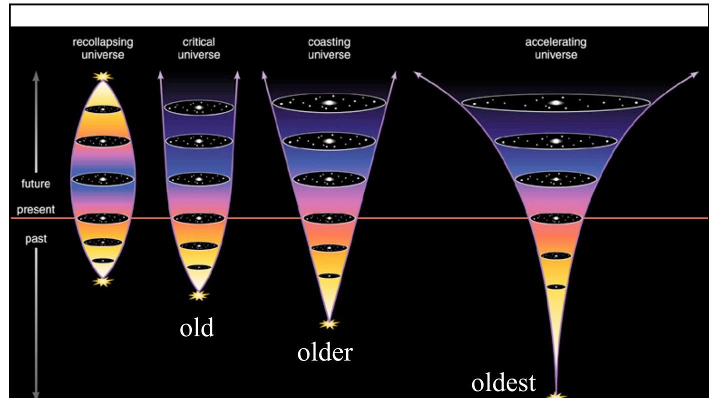
Current data indicate the following breakdown:

- "Normal" Matter: ~ 4.4%
  - Normal Matter inside stars: ~ 0.6%
  - Normal Matter outside stars: ~ 3.8%
- Dark Matter: ~ 22%
- Dark Energy ~ 75%



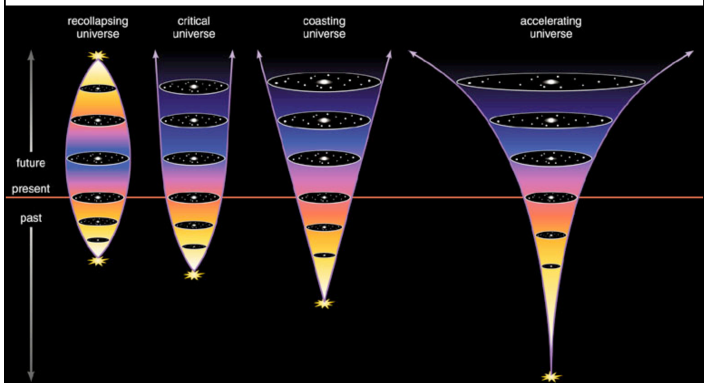

Density of Baryonic Matter + Dark Matter + Dark Energy = Critical Density

The Universe appears to be Flat (or very close to Flat) !!!

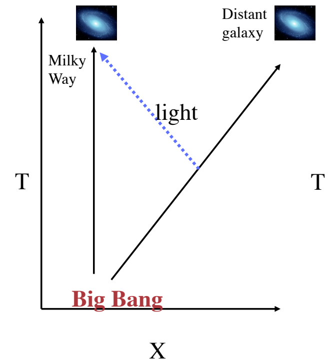



Review:
Estimated age depends on both dark matter and dark energy

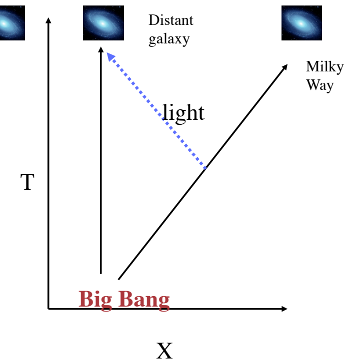
## Visualizing Cosmology




## Looking Back in Distance and Time



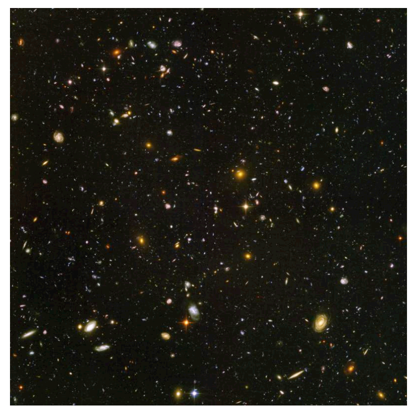

Spacetime diagram: Milky Way Reference Frame

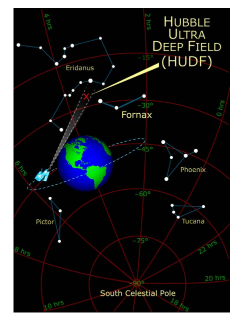



Spacetime diagram: Other Galaxy Reference Frame

## The Hubble Ultra Deep Field: Looking Back in Time with the Hubble Space Telescope

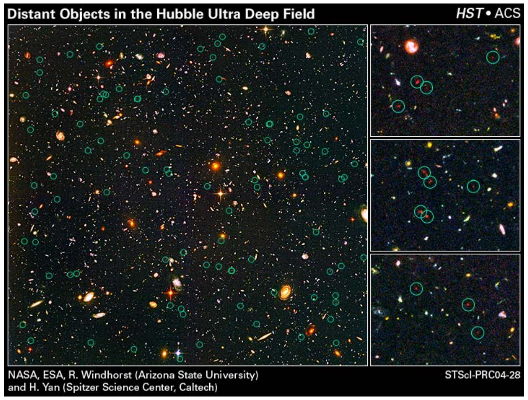

## The Hubble Ultra Deep Field: Looking Back in Time with the Hubble Space Telescope






Around 400 hours of valuable Hubble Space Telescope time observing one tiny spot in the sky (1/10th diameter of the full moon).

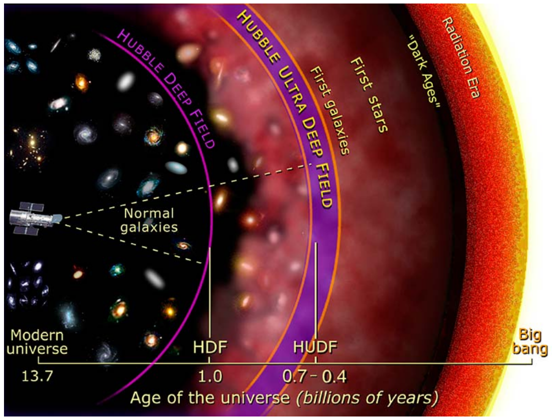
The Hubble Ultra Deep Field: Looking Back in Time with the Hubble Space Telescope




The circles are the most distant galaxies in the Hubble Ultra-Deep Field: z=6-8

(12.5 billion -13 billion light years away, and only 1.2 to 0.7 billion years after the Big Bang.

The Hubble Ultra Deep Field: Looking Back in Time with the Hubble Space Telescope




Why is the darkness of the night sky evidence for the Big Bang?

***Olbers' Paradox***

If universe were

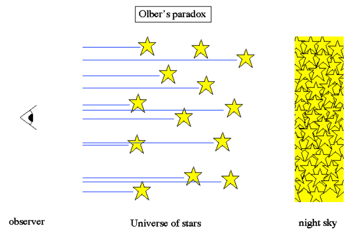
1) infinite

2) unchanging

3) everywhere the same

Then, stars would cover the night sky

http://abyss.uoregon.edu/~js/ast123/lectures/lec15.html




### *Olbers' Paradox*

If universe were

1) infinite

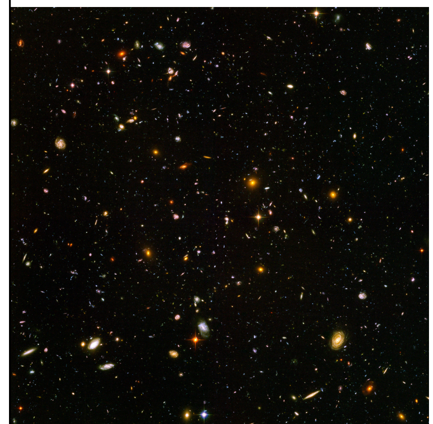
2) unchanging

3) everywhere
the same

Then, stars would cover the night sky.

Night sky would glow at approximately 5000 K.

### *Olbers' Paradox*



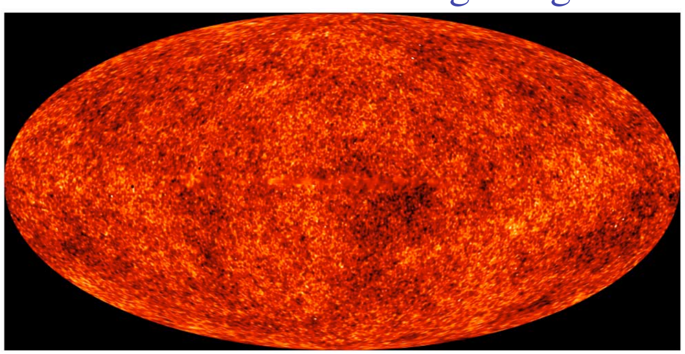
**Two solutions:**

1: Night sky is dark due to cosmic expansion. More distant sources are redshifted (lower temperature).

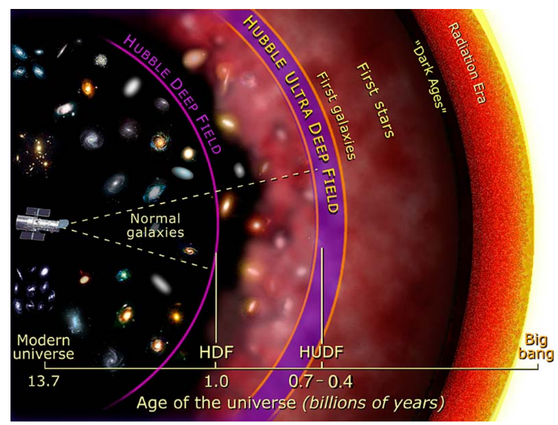
2: Night sky is dark because the universe changes with time. As we look out in space, we can look back to a time when there were no stars

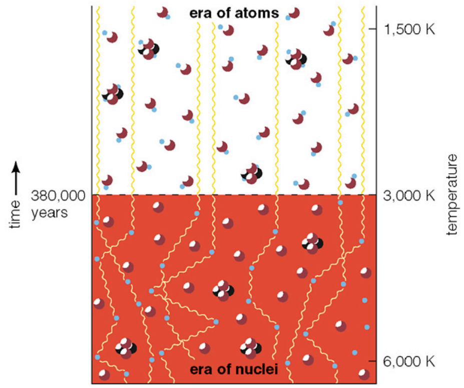
*Both of these are a consequence of the Big Bang.*

## How do we observe the radiation left over from the Big Bang?



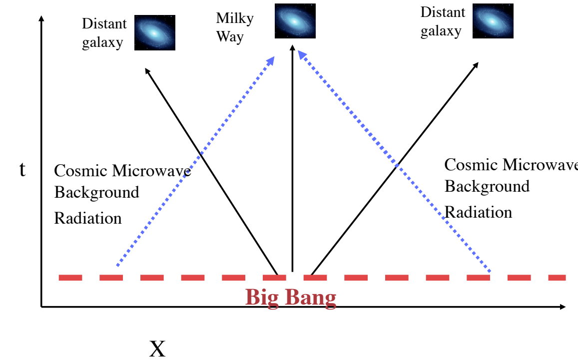
## Looking Back to the Big Bang






Background radiation from Big Bang has been freely streaming across universe since atoms formed at temperature ~ 3,000 K: *visible/IR*

## Looking Back in Distance and Time




Spacetime diagram: Milky Way Reference Frame

We see radiation from big bang in every direction

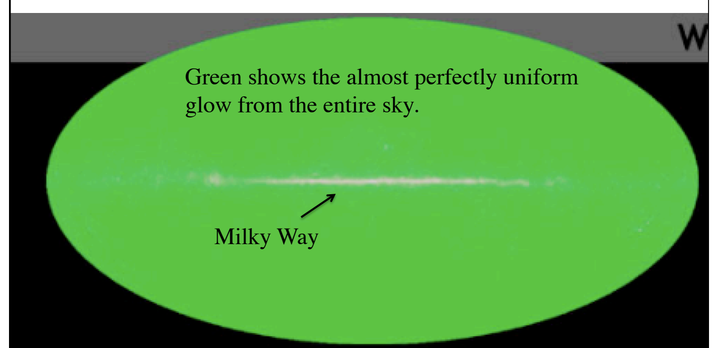
## The Cosmic Microwave Background


In 1965, Arno Penzias and Robert Wilson mapped the sky in microwave (a type of electromagnetic radiation with a wavelength of millimeters – somewhat shorter than radio waves).

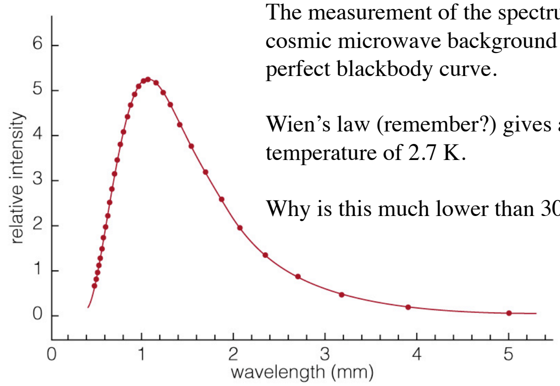
They discovered that the entire sky was emitting radio waves.

They tried to discover if it was a problem with their telescope – but despite all their skepticism and hard work, they could not disprove the emission.

## The Cosmic Microwave Background




- This glow is now known as the cosmic microwave background.
- It is radiation emitted 400,000 years after the big bang – it had been predicted in 1948
- In 1979 Arno Penzias and Robert Wilson received the Nobel Prize for their discovery



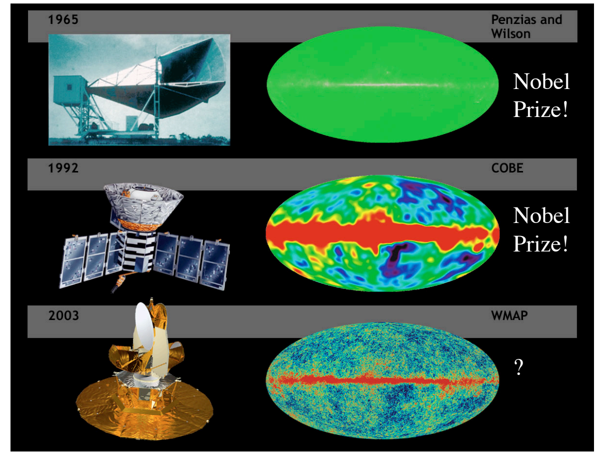

The measurement of the spectrum of the cosmic microwave background shows a perfect blackbody curve.

Wien's law (remember?) gives a temperature of 2.7 K.

Why is this much lower than 3000 K?

Answer: Expansion of universe has redshifted thermal radiation from that time to ~1000 times longer wavelength: *microwaves*

## Mapping the Cosmic Microwave Background




## Why Doesn't the Sky Glow at 3000 K?

A. Because the background radiation is too distant

B. Because there are too many galaxies in the way

C. Because the background radiation is redshifted

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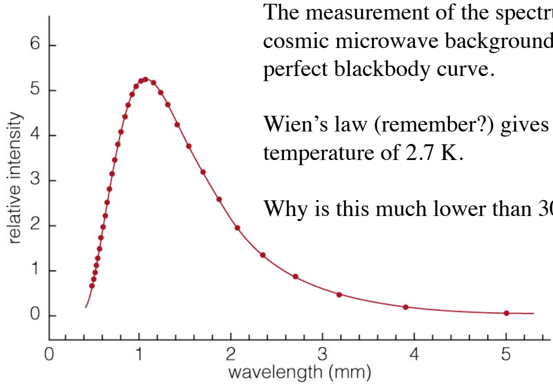


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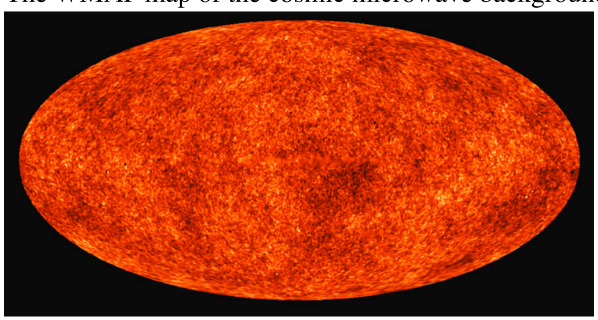
Why is this much lower than 3000 K?

Answer: Expansion of universe has redshifted thermal radiation from that time to ~1000 times longer wavelength: *microwaves (redshift Z = 1000)*

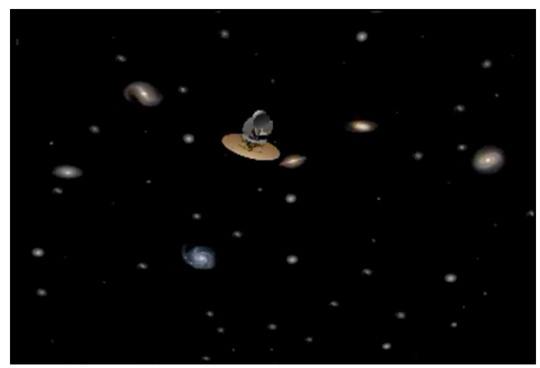
## Searching for Variations in the Cosmic Microwave Background with WMAP

## The WMAP map of the cosmic microwave background



1. The cosmic microwave background is not perfectly smooth
2. The tiny ripples are due to tiny variations in the *temperature* of the cosmic microwave background..
3. These variations are due to slight variations in the density of matter.
4. Areas with higher density can collapse through gravity and form galaxies.
5. The ripples in this maps are the seeds that formed galaxies.

## Using WMAP Data to Measure the Geometry of the Universe



*WMAP data favors a flat universe.*

# What have we learned?

Obler's paradox: If universe were finite and static - the entire sky should be 6000 K

- This doesn't happen since the universe is expanding and finite in time (we can only look back so far).

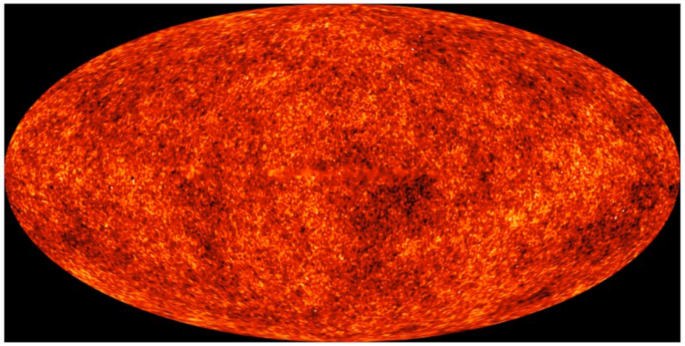
If we look back far enough, we see the fireball from the big bang:

- The traces the moment when the universe cooled to the point electrons and protons combined into hydrogen atoms (3000 K)
- Redshifted to microwave wavelengths: corresponding to a blackbody temperature of 2.7 K

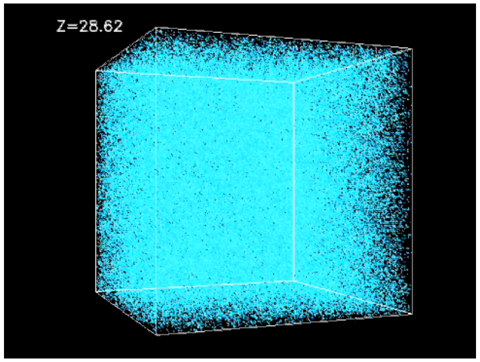
Called the *Cosmic Microwave Background*

- Small variations in the microwave background have been detected
- Background fluctuations consistent with flat universe
- *The fluctuations are the seeds of cosmic structure and galaxies*.

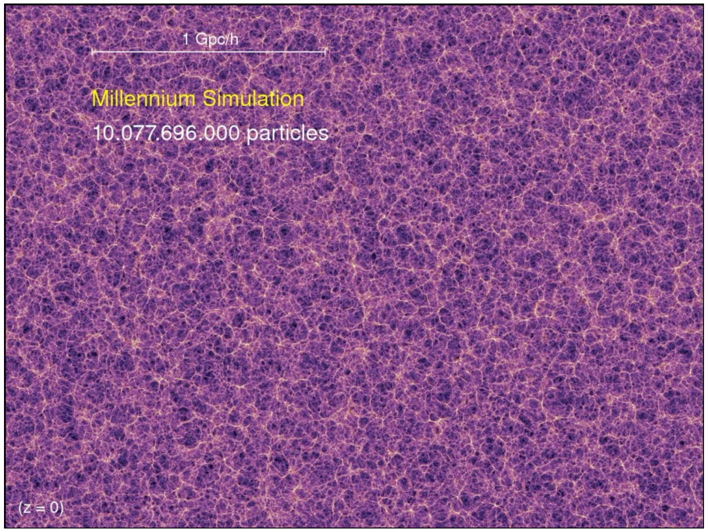
# What aspects of the universe were originally unexplained with the Big Bang theory?



# Formation of the Cosmic Web




http://cosmicweb.uchicago.edu/filaments.html

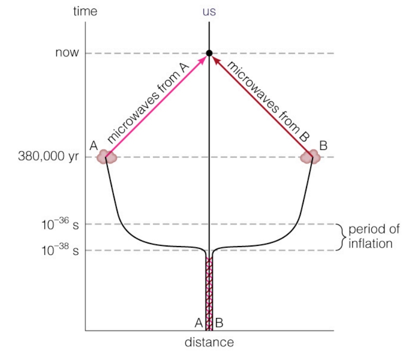


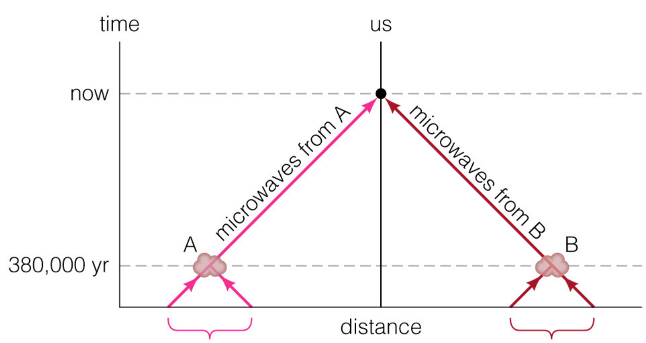
## Mysteries Needing Explanation

1) Where does structure come from (i.e. the seeds of galaxies seen by WMAP)?
2) Why is the overall distribution of matter so uniform (i.e. isotropic and homogenous)?
3) Why is the density of the universe so close to the critical density?

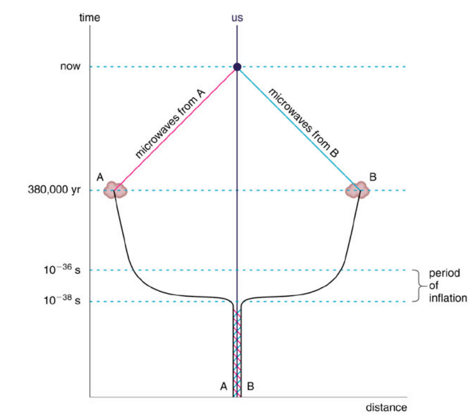
***An early episode of rapid inflation can solve all three mysteries!***

## How does inflation explain these features?

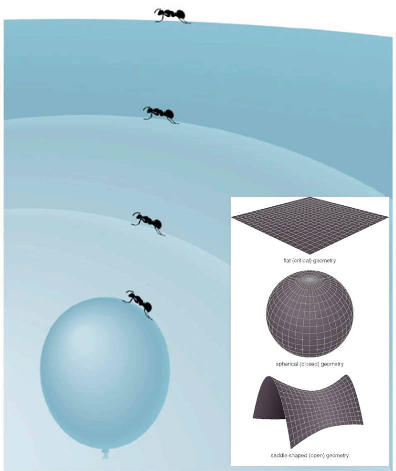


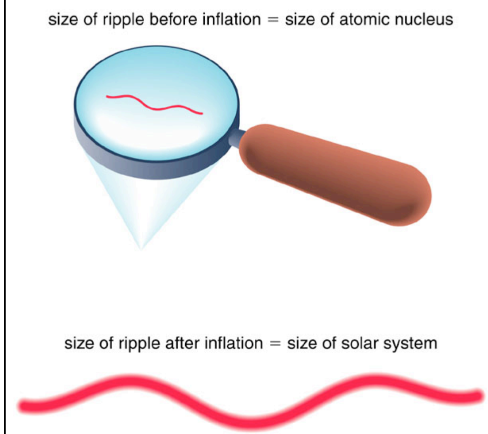

How can microwave temperature be nearly identical on opposite sides of the sky?




Regions now on opposite sides of the sky were close together before inflation pushed them far apart

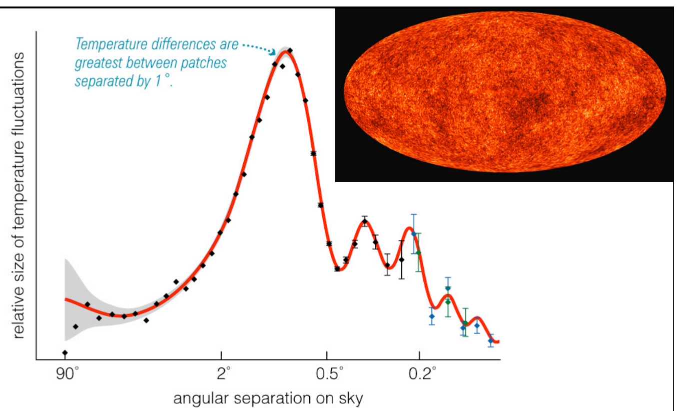


Inflation of universe flattens overall geometry like the inflation of a balloon, causing overall density of matter plus energy to be very close to critical density




Inflation can make all the structure by stretching tiny quantum ripples to enormous size

These ripples in density then become the seeds for all structures




The ripples seen in WMAP data have a characteristic size of 1 degree (about twice the diameter of a full moon).
Observed patterns of structure in universe agree (so far) with the "seeds" that inflation would produce

# What have we learned?

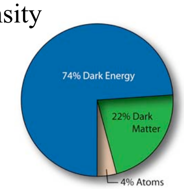
- What aspects of the universe were originally unexplained with the Big Bang theory?
  - The origin of structure, the smoothness of the universe on large scales, the nearly critical density of the universe
- How does inflation explain these features?
  - Structure comes from inflated quantum ripples
  - Observable universe became smooth before inflation, when it was very tiny
  - Inflation flattened the curvature of space, bringing expansion rate into balance with the overall density of mass-energy

## What have we learned?

- How can we test the idea of inflation?
  - We can compare the structures we see in detailed observations of the microwave background with predictions for the "seeds" that should have been planted by inflation
  - So far, our observations of the universe agree well with models in which inflation planted the "seeds"

## The State of Cosmology in 2009

- Overall geometry is flat
  - Total mass+energy has critical density
- Ordinary matter ~ 4% of total
- Total matter is ~ 26% of total
  - Dark matter is ~ 22% of total
  - Dark energy is ~ 74% of total
- Size of Ripples consistent with seeds due to inflation.
- Age of the Universe is 13.7 billion years




***In excellent agreement with observations of present-day universe and models involving inflation and WIMPs!***