Announcements

- Last Webwork (ever!) due on Friday!
- On Friday:
  - Aliens!
  - Evaluations! (of me)!
  - Please show up!
- Final next Wednesday!
  - 8am here!
  - Study materials posted!
  - Bring your calculator or email me if you need to borrow one
  - I'll be around at least all afternoon Monday and Tuesday for questions or Campuswire
- I've opened up all old homeworks for the max 75% credit until the date of the final. If you missed one or never completed one, now is your chance!
- Polling: `rembold-class.ddns.net`

Review Question

What is the current best description of dark energy?

A. Energy associated with the movement of dark matter
B. Energy that drives the increasing expansion rate of the universe
C. Energy released with dark matter and normal matter interact
D. Energy associated with the redshifted movement of distant galaxies

Review Question

What is the current best description of dark energy?

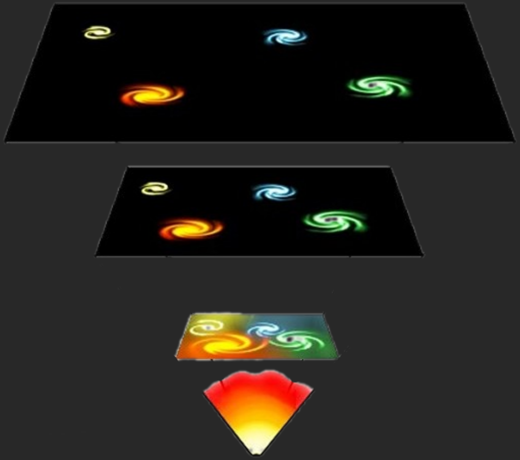
A. Energy associated with the movement of dark matter
B. Energy that drives the increasing expansion rate of the universe
C. Energy released with dark matter and normal matter interact
D. Energy associated with the redshifted movement of distant galaxies

Flat and Expanding

- Note that the sum of the two density factors now gives a value of 1
  - Supporting the findings that the universe seems to be flat!
- Dark energy provides the extra 70% of the mass/energy of the universe
- Results in an age of the universe very similar to the 14 billion years estimated from a constant expansion rate
- So, as far as we know, at the moment we think that our universe is:
  - Flat
  - Expanding increasingly quickly
  - About 14 billion years old
  - Infinite or Finite is not well determined yet

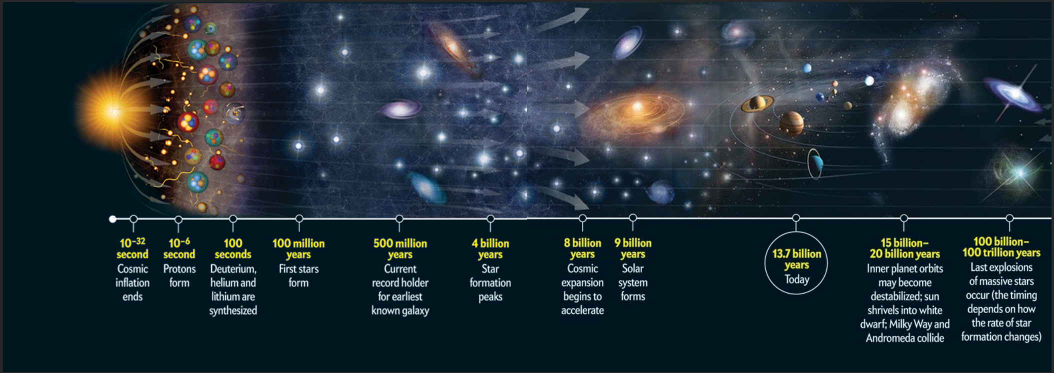
Taking it Back

- Long ago the universe was denser
- And hotter
- Can we look back far enough to “see” this “era”?



Physics In Reverse

- Moving backwards, and using what we know about stars, nuclear physics, and everything else, the history of the universe looks something like below:

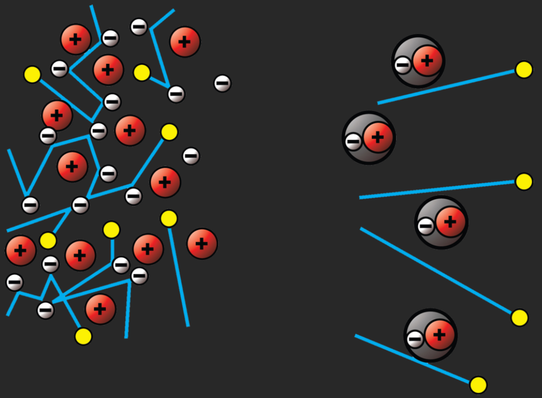


How far back COULD we see?

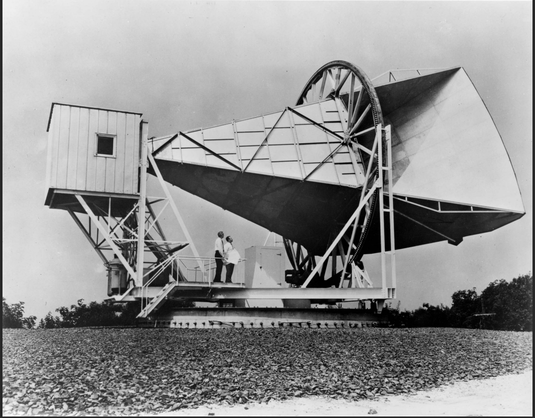
- Assuming perfect and huge telescopes, how far back could we see?
- Early universe very very hot
  - Hot enough for fusion
  - Hot enough that particles are charged
  - Fusion releases radiation, that interacts with particles
  - Light gets scattered $\Rightarrow$ opaque
- Once it cooled enough for non-ionized atoms to form, radiation no longer interacts
  - Can travel long distances
  - Transparent
- Called "Recombination"

Recombination

- Recombination is when the universe cooled to the point that atoms could become un-ionized and group together
- Allowed photons to pass through unhindered
- Universe became transparent (mostly)
- Models predict recombination should have happened several hundred thousand years after the Big Bang

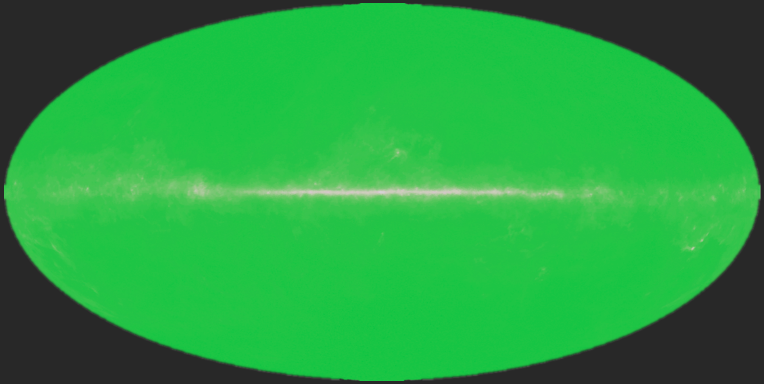


Background Radiation



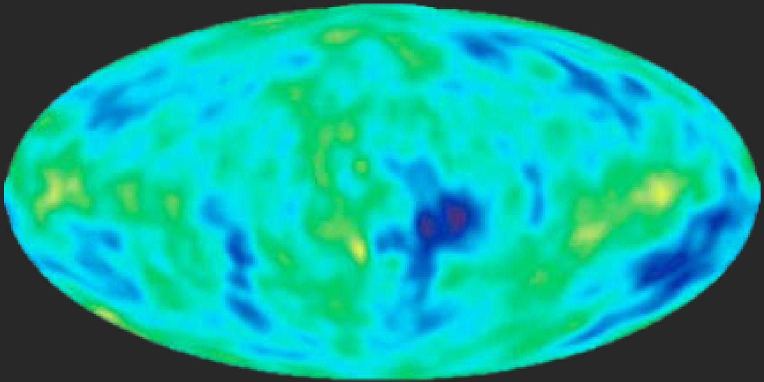
- Such an age would predict a very far distance from us
- Also predicts a high redshift (z=1100)
- If the universe was initially as hot and glowing as a star
  - Such light would be redshifted into microwaves these days
- 1965: Found weird radio signal coming equally from all parts of the universe
  - Like a background noise
  - Cleaning or calibrating their telescope couldn't get rid of it
- Now known as the Cosmic Microwave Background or CMB

The Cosmic Microwave Background



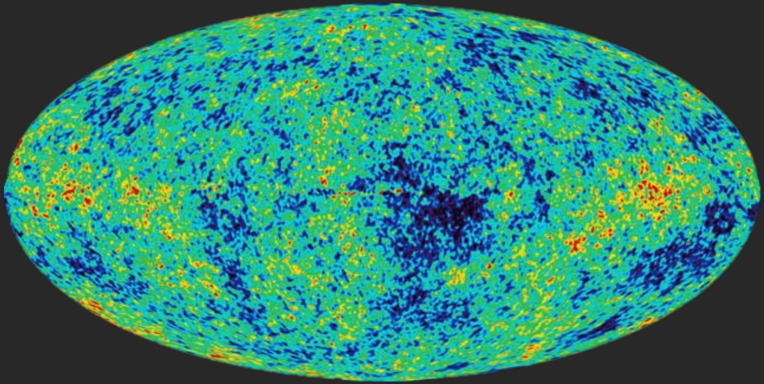
1965 Image

The Cosmic Microwave Background



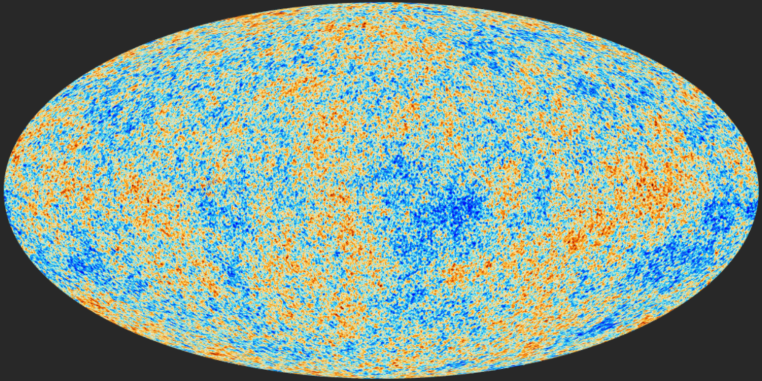
Cobe Satellite Image (2006)

The Cosmic Microwave Background



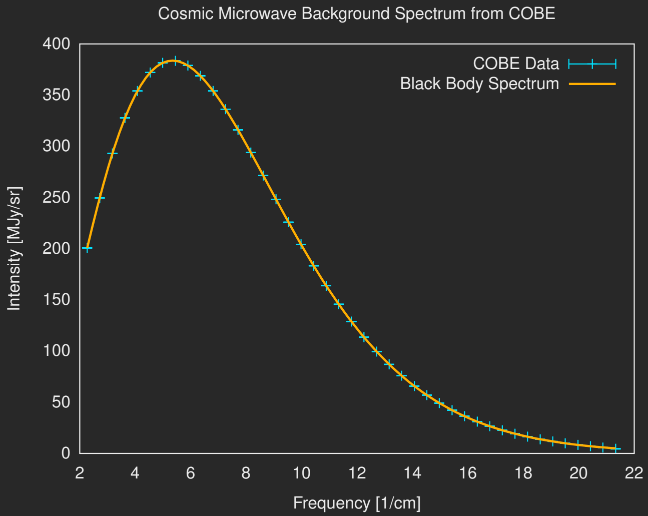
WMAP Satellite Image (2013)

The Cosmic Microwave Background



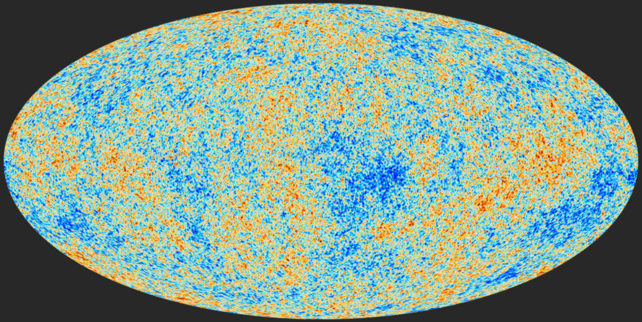
Planck Satellite Image (2016)

The Most Perfect Blackbody



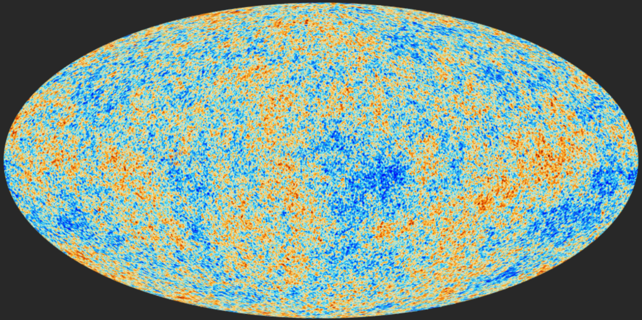
CMB Facts

- Originally about 3000 K now 2.7260 K
- The red and blue patches are hot/cold areas
  - Differ by less than 1×10^{-5} K!
  - Incredibly smooth
- Furthest back we can look directly



Conclusions

- Universe was much smoother than it is today
  - We see temperature variations of thousands of kelvin, not 10^{-5}...
- But still not PERFECTLY smooth
  - Some matter was still clumping before stars and galaxies
- Size scale of patches serves as a valuable tool for model fitting



Model Fitting with the CMB

http://map.gsfc.nasa.gov/resources/camb_tool

Other Support for the BBT

- We see Helium everywhere in the universe
  - Accounts for a solid 25% of all the mass in the universe
- Helium is spread move evenly across the universe than could be explained by star fusion
- Indicates things must have been hot enough in the early universe for large scale fusion to be occuring
- Also true of other trace elements like deuterium formed from fusion
- How much of the initial matter of the universe “started” as different elements influences the abundances we should see today

Understanding Check

Suppose the cosmic microwave background had been discovered instead at a much longer wavelength, say large radio waves. This could have implied any of the following except:

A. Our universe is older than we thought
B. Recombination happened earlier in the universe than we thought
C. The universe is smoother than we had thought
D. The early universe was not as hot as we thought

Understanding Check

Suppose the cosmic microwave background had been discovered instead at a much longer wavelength, say large radio waves. This could have implied any of the following except:

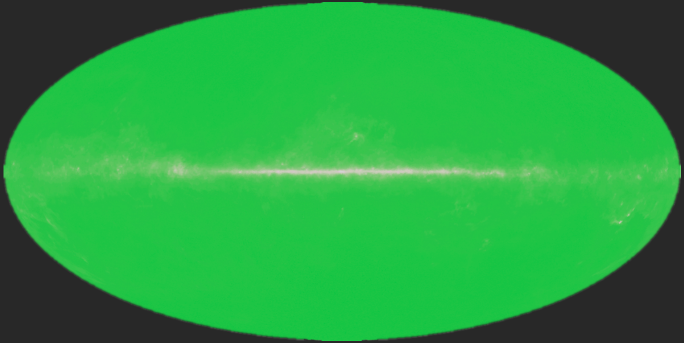
A. Our universe is older than we thought
B. Recombination happened earlier in the universe than we thought
C. The universe is smoother than we had thought
D. The early universe was not as hot as we thought

Peering past the CMB

- How could we peer back further than the CMB?
  - Neutrinos
    - Can we observe enough coming from that time to make a reasonable picture?
  - Gravity Waves
    - Recently confirmed to have been observed
    - Fluctuations in space-time, so "‘opacity" doesn't matter
    - How can we best use them? Still very new (and exciting!)

Other CMB Concerns

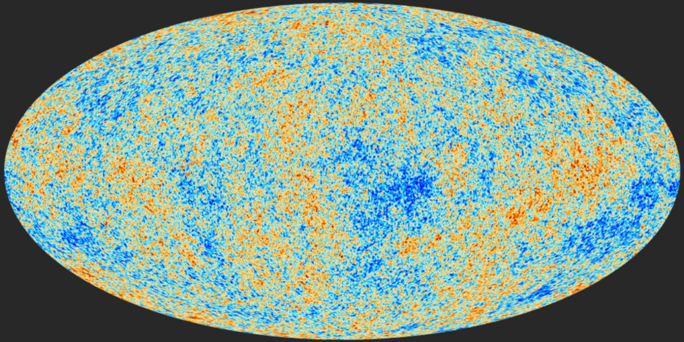
- Looking at the CMB, some other questions spring to mind:
  - Why is the universe flat?
  - Why is the universe so smooth on large scales, but so lumpy on small scales?



Smooth at large scales

Other CMB Concerns

- Looking at the CMB, some other questions spring to mind:
  - Why is the universe flat?
  - Why is the universe so smooth on large scales, but so lumpy on small scales?



Lumpy at small scales

Houston, We Have a Problem (Several actually)

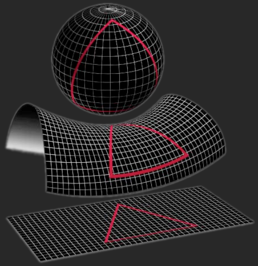
- Recall that:

Flat

Negative Curvature — Positive Curvature $\rightarrow \Omega$

- There are WAY more ways to be curved that flat!

- Does something in the underlying physics force flatness? Or how is this so finely tuned?
- Called the Flatness Problem

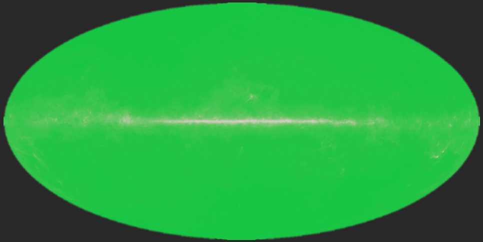


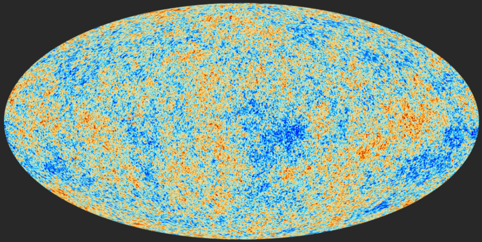
The Horizon Problem

- When we look one direction, we see the CMB 13.3 billion light-years from us
- When we look the other direction, we see the same
- These two points of the universe can not have “talked” to each other!
  - Too far apart for light to travel that far in the age of the universe
- So it is weird that they look so similar
  - We’d expect one to have no influence on the other, so they could look completely different
- Why are they the same?

The Lumpy Problem (Anisotropy)

- The universe is incredibly smooth on large scales
- But decidedly lumpy at small scales
- Why this difference?

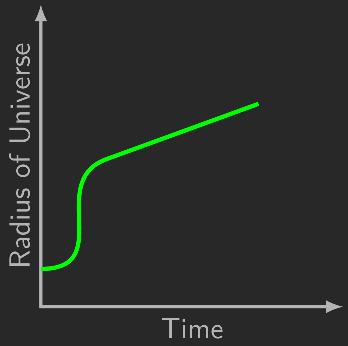




Inflation (Affecting the universe as well as your bank account. . .)

- Theorized that there must have been a period of EXTREME expansion in the VERY early universe
- Grew by some 58 orders of magnitude in maybe 10^{-32} seconds. . .

- Solves all three problems
  - Anything looks flat when large enough
  - Different parts of the universe could "talk" before inflation, equalizing themselves



Quantum Fluctuations

- Quantum mechanics says that, on the small scale, nothing can be known 100% certainly
- Heisenberg's Uncertainty Principle

$$\Delta x \cdot \Delta p \geq \frac{\hbar}{2}$$

- The more precisely you know something's position, the less precisely you'll know its velocity!
- Results in tiny quantum ripples, of deviance and change

Issues Solved! (Kinda)

- Inflation takes these tiny ripples and magnifies them to galactic scales
- Provide the initial deviations in the universe to start allowing gravity to start the real clumping process
- But what causes inflation?
    - Still not well understood
    - Generally accepted as true at the moment, because it explains most models so well
    - Perhaps neutrino or gravity wave detectors that could peer past the CMB could shed light ($\leftarrow$ anti-pun?) on the situation