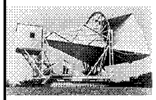
More Fun with Microwaves!

Wednesday, November 4

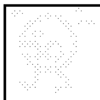
Pick up Problem Set 5: due **Friday, Nov 13**



Cosmic Microwave Background = light left over from early, hot, dense, opaque universe.

Universe became transparent when the scale factor was $a \approx 1/1000$, time was $t \approx 400{,}000$ years.

Since then, CMB photons have been streaming through transparent space.



Why doesn't the CMB cook us like a microwave oven?

A microwave oven at full power contains 10^{18} microwave photons.

The same volume of space contains 10^{7} CMB photons.

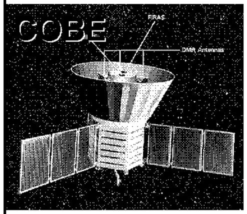
Too dilute for cooking...

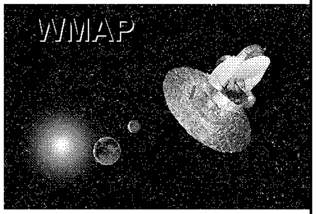
When we observe the CMB, we see a message direct from the early universe.

What is this message telling us?

Messages are often (1) hard to observe & (2) hard to interpret.

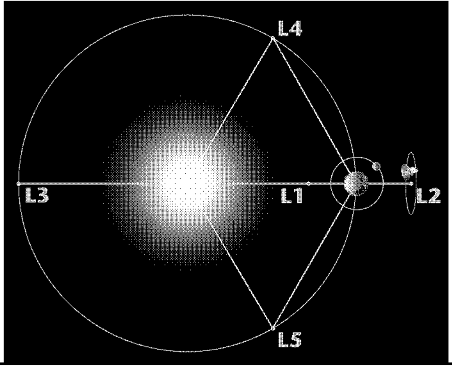
Observing the CMB





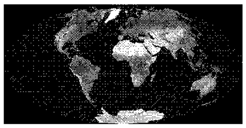
Water vapor in Earth’s atmosphere absorbs microwaves: go **above** the atmosphere!

WMAP (Wilkinson Microwave Anisotropy Probe) is beyond the Moon’s orbit.

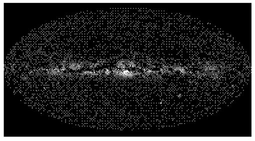


We've looked at the spectrum of the CMB (it's a blackbody), now let's look at a map.

Spherical Earth can be projected onto a flat map:

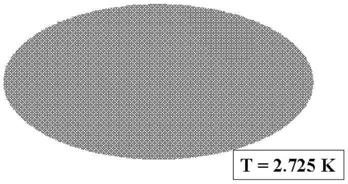


So can the celestial sphere:



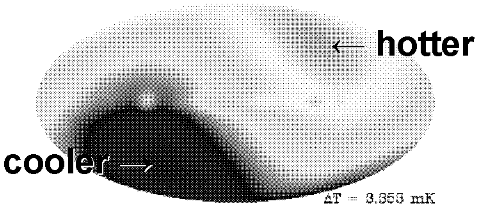
(visible light)

Mapping the CMB (color = temperature)



Observation: Temperature of CMB is nearly **isotropic** (the same in all directions).

Interpretation: early universe was nearly **homogeneous** (the same in all locations).



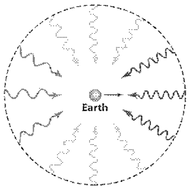
Observation: Temperature of CMB is slightly **hotter** toward Leo, **cooler** toward Aquarius (on opposite side of sky).

Temperature fluctuation = 1 part per 1000.

Interpretation: difference in temperature results from a **Doppler shift**.

Earth orbits Sun
(v ≈ 29 km/sec)
Sun orbits center of the Galaxy
(v ≈ 220 km/sec)
Galaxy falls toward Andromeda Galaxy
(v ≈ 50 km/sec)
Local Group falls toward Virgo Cluster
(v ≈ 200 km/sec)

Net motion: toward Leo, with a speed
v ≈ 300 km/sec ≈ 0.001 c.

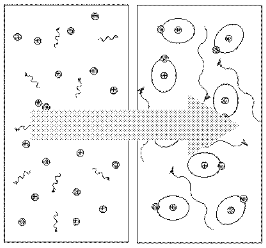


redshifted
(Aquarius)

blueshifted
(Leo)

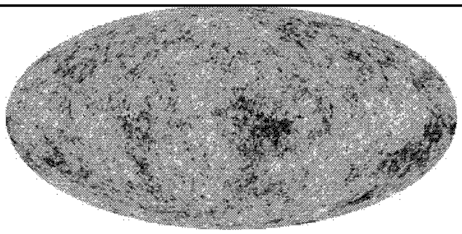
Cosmic light from direction of Leo is slightly **blueshifted** (shorter wavelength, higher temperature).

What can the CMB tell us about the early universe, at the time everything became transparent?



hot
dense
ionized
opaque

cool
tenuous
neutral
transparent



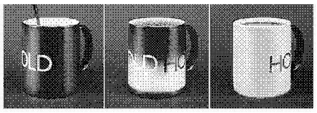
Observation: After subtracting the effect of our motion through space, CMB still shows hot & cold spots, about 1 degree across.

Temperature fluctuation = 1 part per 100,000

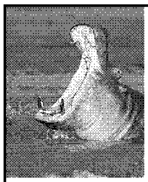
Interpretation: observed temperature fluctuations result from **density** fluctuations in the early universe.

Regions that were compressed had higher **density**, but also higher **temperature** (gases heat up as they are compressed).

Hot spots in the CMB are higher in temperature than **cold** spots by only 1 part per 100,000.



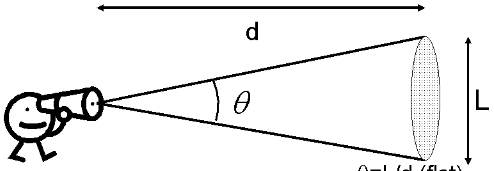
Implication: the **density fluctuations** in the early universe were also small (about 1 part per 100,000).



Why do we care about such tiny density fluctuations?

(If the Earth were smooth to within 1 part per 100,000, highest mountains would be just 70 yards above the deepest valleys.)

One reason why astronomers care: the hot & cold spots are the **most distant** objects we can see.

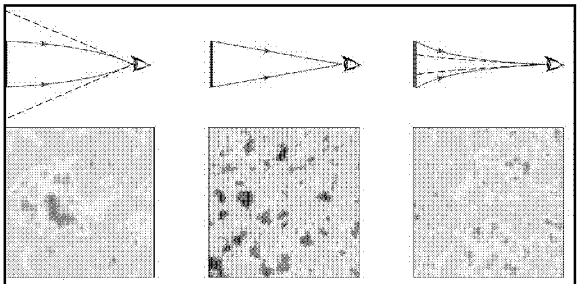


θ=L/d (flat)

θ>L/d (positive)

θ<L/d (negative)

Excellent for testing whether space is flat or curved!



Angular size of hot & cold spots gives the best limits on the curvature of space.

Another reason why astronomers care about tiny density fluctuations:

Low-amplitude density fluctuations at t ≈ 400,000 years give rise to high-amplitude fluctuations at t ≈ 14 billion years.

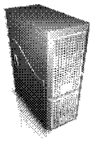
The Rich Get Richer, the Poor Get Poorer.

A region that was **slightly** denser than average will eventually become **much** denser than average; it’s compressed by its own gravity.

Great Oaks from Tiny Acorns Grow.

A dense region that initially has a **small** mass will become **more massive** with time; its gravity attracts surrounding matter.

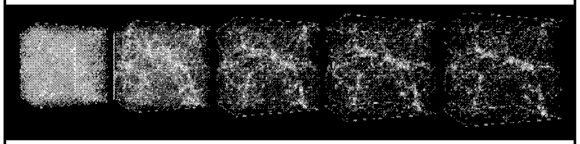
It’s possible (with a big computer) to simulate the growth of density fluctuations.



- Make a large (imaginary) box.
- Fill it with (simulated) massive particles.
- Make sure particles are packed a little closer together in some places than others.
- Let ’er rip.

---

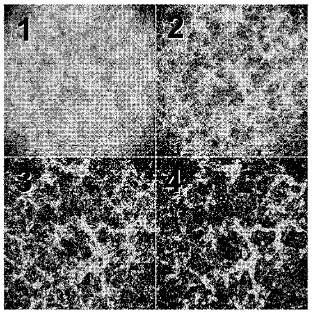
then → now



redshift z=29 → redshift z=0

(The size of the box grows from 1.5 Mpc to 43 Mpc.)

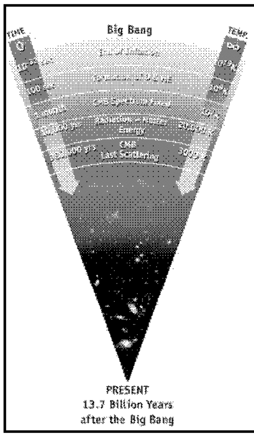
Generic result: matter distribution goes from smooth to lumpy.



"The past is a foreign country; they do things differently there." – L. P. Hartley

The past (t ≈ 400,000 years):
Hot, dense, opaque, nearly homogeneous.

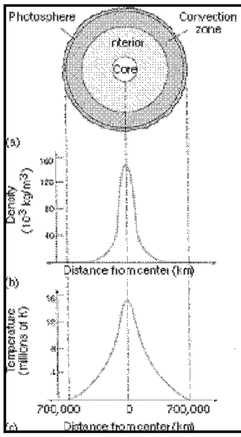
Now (t ≈ 14 billion years):
Cold background radiation, low average density, mostly transparent, very lumpy



What lies beyond the surface of the "fog"?

Since the very early universe was opaque, we can't see it directly.

Can we deduce **indirectly** what the universe was like then?



There is hope!

The Sun is opaque, but from our knowledge of physics, we can deduce what it's like inside.

When the universe became transparent, its temperature was like that of a star's surface.

Earlier, its temperature was like that of a star's **center**.

Nuclear fusion in the early universe??

Friday's Lecture:

Energy & Power

Reminders:

Have you read chapters 1 – 8 ?

Have you picked up your corrected problem sets and midterm?

Have you picked up Problem Set 5?