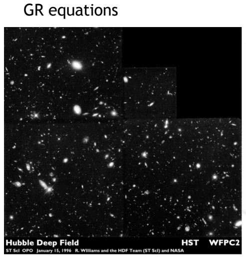
Lecture 17 *: The Cosmic Microwave Background*

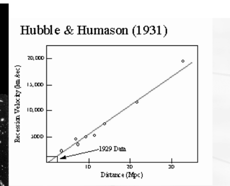
- Discovery of the Cosmic Microwave Background (ch 14)
- The Hot Big Bang

This week: read Chapter 12/14 in textbook

Let's think about the early Universe…

- From Hubble's observations, we know the Universe is expanding
  - This can be understood theoretically in terms of solutions of GR equations





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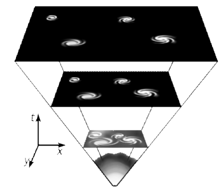
  - If crushed together at high enough density, the galaxies, stars, etc could not exist as we see them now -- everything must have been different!



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- What was the Universe like long, long ago?
  - What were the original contents?
  - What were the early conditions like?
  - What physical processes occurred under those conditions?
  - How did changes over time result in the contents and structure we see today?

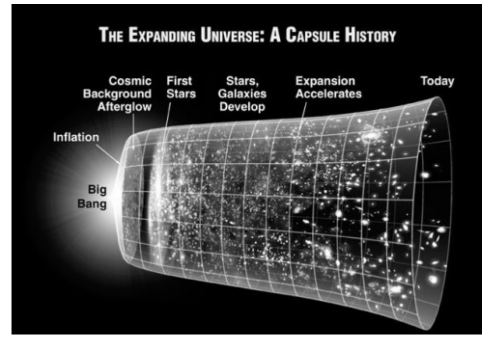
The Poetic Version

- *In a brilliant flash about fourteen billion years ago, time and matter were born in a single instant of creation. An immensely hot and dense universe began its rapid expansion everywhere, creating space where there was no space and time where there was no time. In the intense fire just after the beginning, the lightest elements were forged, later to form primordial clouds that eventually evolved into galaxies, stars, and planets."*

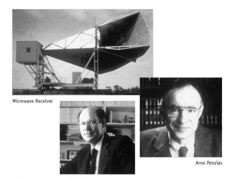
From AFTER THE BEGINNING
A Cosmic Journey through Space and Time
by Norman K Glendenning

- At very early times, the Universe was relatively simple - a very hot, smooth gas of photons, baryons and dark-matter particles.
- The Cosmic Microwave Background (CMB) radiation is a snapshot of the Universe 300,000 years after the beginning- the remnant of the hot glow of the very early universe
- At 300,000 years after the big bang the gas (baryons) had finally cooled down enough to become transparent

- See *The Cosmic Rosetta Stone*,Physics Today (November 1997, p.32) Chuck Bennett, Michael Turner and Martin White. (astron.berkeley.edu/~mwhite/rosetta)



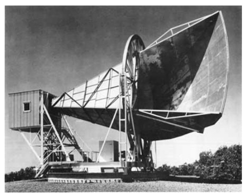
I : The Cosmic Microwave Background



- Discovered by Arno Penzias & Robert Wilson (1964) – Nobel Prize 1978
- http://www.nobelprize.org/nobel_prizes/physics/laureates/1978/speedread.html

I : The Cosmic Microwave Background

- Arno Penzias & Robert Wilson (1964)- Nobel Prize 1978
  - Attempted to study radio emissions from our Galaxy using sensitive antenna built at Bell-Labs, driven by first communications satellites



At the same time in a nearby university…

- Robert Dicke (Princeton Univ) and colleagues reasoned that the Big Bang must have scattered not only the matter that condensed into galaxies but also must have released a ***tremendous blast of radiation***
- The characteristics of the radiation detected by Penzias and Wilson ***fit exactly the radiation predicted*** by Dicke
- see astro.berkeley.edu/~mwhite/rosetta/node1.html

I : The Cosmic Microwave Background

- Arno Penzias & Robert Wilson (1964)- Nobel Prize 1978
  - Attempted to study radio emissions from our Galaxy using sensitive antenna built at Bell-Labs, driven by first communications satellites
  - Worked hard to characterize and eliminate all sources of noise (…bird droppings)
  - They never could get rid of a certain noise source… noise had a characteristic temperature of about 3 K ***(3 degrees above absolute ZERO)***.
  - They figured out that the noise was coming from the sky, and was approximately ***the same in all directions***…
  - ***Discovered the cosmic background radiation,*** or CBR (**or CMB, for Cosmic Microwave Background**, since there are other backgrounds)

A bit of history…

Dicke's first radio experiment was in 1946, but his equipment was not sensitive enough to detect the CMB (and he was not looking for it).

However, in the same issue of Physical Review letters, Gamow first predicted the existence of the CMB (20 years before Dicke!).

Unfortunately, the radiation was thought to be impossible to observe, and the result was forgotten for two decades.

How does the CMB tell us about the Big Bang?

Two key facts to note:

✦ ***The Universe cools as it expands***

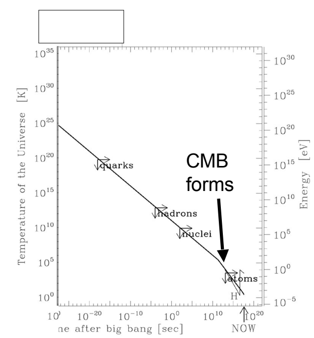
✦ ***The Universe is lumpy***

The Universe cools as it expands

• Working the Hubble expansion backwards -- the 'early' universe could have been very hot ***(> 10 billion degrees!)***.

- **At such temperatures:**
  - ***Nuclear fusion*** takes place
  - Can build chemical elements from elementary particles (1st suggested by Gamow in the 1940s).
  - Huge amounts of ***high-energy radiation*** should be released

- **As the Universe expands:**
  - The amount of energy per unit volume decreases – the ***radiation cools over time***.
  - Predicted present-day temperature: ***3K above absolute zero***
  - The ***wavelength*** of the radiation also decreases (like the Doppler effect, or "redshift" of light from distant galaxies)
  - Predicted wavelength of radiation at present day: ***microwaves***



The Universe cools as it expands

A special moment happens about 300,000 years after the Big Bang:

- The Universe has cooled enough become ***transparent***
- After this, ***radiation can stream freely*** without being constantly scattered by particles of matter
- The CMB is a "snapshot" of the Universe at this moment – ***we can't directly observe any earlier point*** in time, because the Universe was opaque.
- This point when the CMB forms is called ***decoupling*** (of light and matter), ***(re)combination*** (of protons and electrons into atoms), or the ***surface of last scattering***

The Universe is lumpy

- If the universe were homogeneous and isotropic before the moment of decoupling (formation of CMB), we would observe a homogeneous universe today.
- But we don’t! We see structure in the Universe (stars, galaxies, planets, …)
- ***Hence, the CMB must not be completely homogeneous and isotropic!***
- The “anisotropies” in the CMB can tell us a great deal about the structure of the Universe (more on this later)

Not all CMB anisotropy is primordial

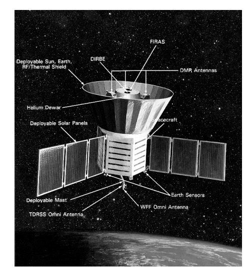
- The radiation is a few millidegrees hotter in the direction of Leo, and cooler in the direction of Aquarius. The spread around the mean describes a cosine curve.
- This is consistent with the ***Doppler effect*** for our ***motion relative to the rest frame of the CMB***
- Based on the measurements of anisotropy, ***the entire Milky Way is calculated to move through the intergalactic medium at approximately 600 kms***

From Penzias and Wilson to COBE

- Penzias and Wilson detected the CMB and showed that it was more or less uniform
- More precise measurements to detect anisotropy were very difficult with 1960’s technology
- First detection of anistropy in 1971
- Major advances used rockets and balloons to get above the atmosphere
- *(See “The cosmic background radiation and the new aether drift,” Scientific American 238, 64 (1978). R. Muller for the early history)*

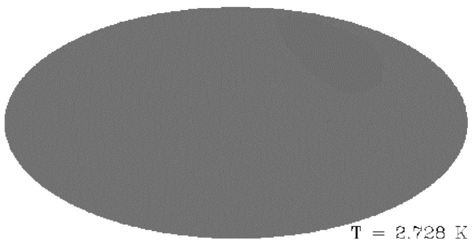
20 years of Ground Based Experiments Later…

- **The COBE mission**
  - Built by NASA-Goddard Space Flight Center
  - Launched Nov. 1989
  - Surveyed infra-red and microwave emission across the whole sky.
  - ***Primary purpose – to characterize the CMB.***



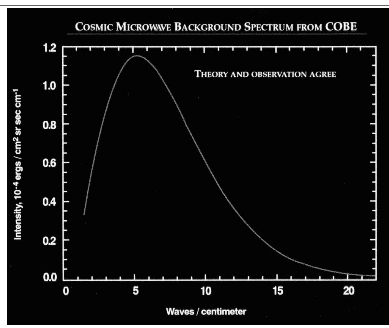
- Had 3 instruments on it:
  - FIRAS (Far infra-red absolute spectrophotometer)- **Precision spectrum of the CMB**
  - DMR (Differential Microwave Radiometer)- **fluctuations in the brightness**
  - DIRBE (Diffuse Infrared background Experiment)- **Infrared spectrum of the sky (dominated by the MilkyWay)**

*Almost uniform intensity of microwaves in all directions (isotropic 2.7K **black body radiation**)*



Properties of the CMB

- Pervasive throughout Universe
- Range of wavelengths, with peak in microwave range
- Present density is 411 photons/cubic centimeter
- ***Spectrum perfectly consistent with a black body***
- ***Shape of a black body spectrum and flux per unit area <u>depends only on the temperature</u>***

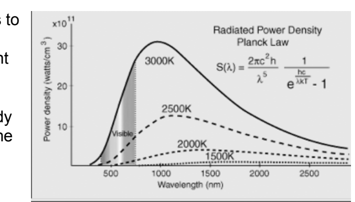


This is the actual data- the error bars are tiny !
when this was shown at an AAS meeting people applauded - 2006 Noble prize to John Mather (at Goddard) and George Smoot

Properties of the CMB

- ***Spectrum perfectly consistent with a black body***
- ***Shape of a black body spectrum and flux per unit area <u>depends only on the temperature</u>***

"Blackbody radiation" refers to an object or system which absorbs all radiation incident upon it and re-radiates the energy with a spectrum characteristic of a black body only, not dependent upon the type of radiation which is incident upon it.



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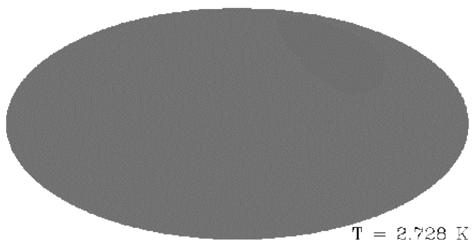
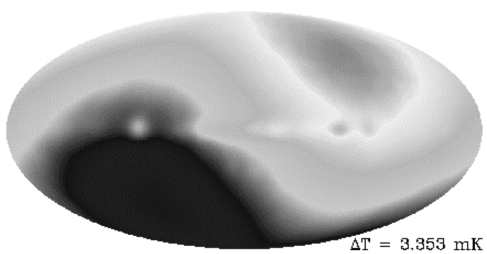
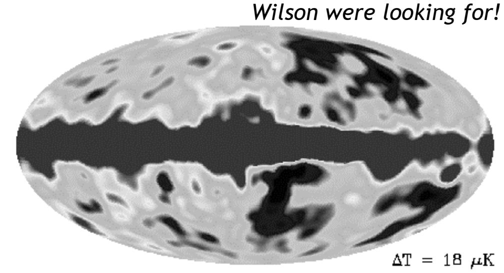


Subtracting off the mean level leaves with a "dipole" pattern… what is this??

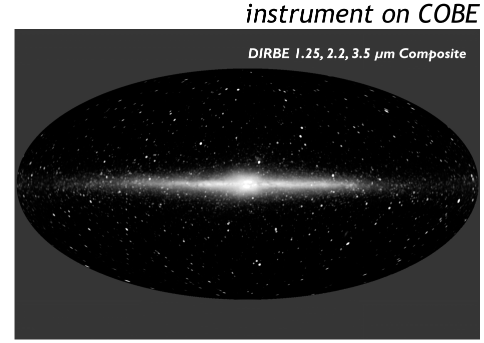


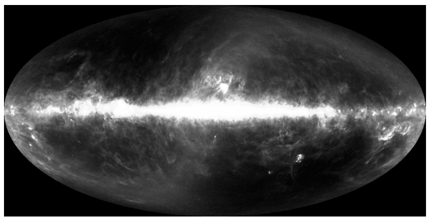
The motion of the earth with respect to the reference frame of the CMB-The Solar System is moving at 600 km/sec relative to the Universe and we can measure this using the dipole anisotropy

Subtracting off the dipole finally reveals the emission from the Galaxy that Penzias and Wilson were looking for!

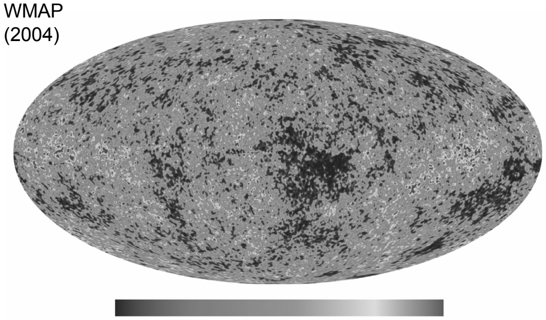


Our Galaxy observed by the DIRBE instrument on COBE

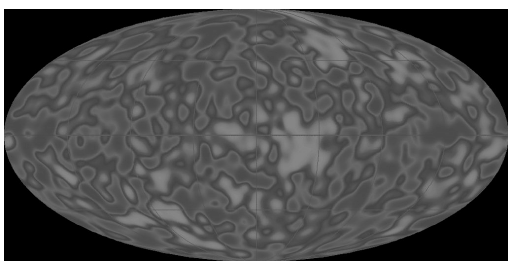




WMAP
(2004)



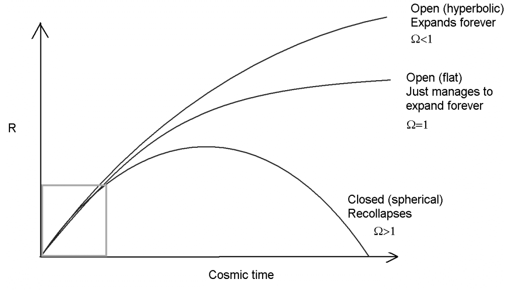
Subtracting contribution from Galaxy reveals fluctuations in the CMB

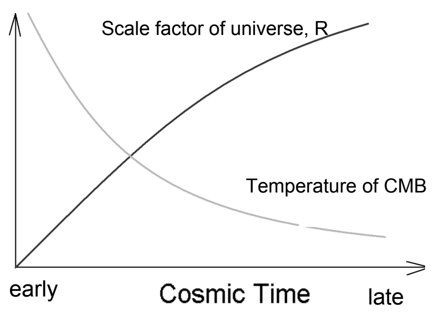


These 'fluctuations' are the seeds of later structures- galaxies and clusters

II : THE HOT BIG BANG MODEL

- Penzias & Wilson had discovered radiation left over from the early universe…
- The hot big bang model…
  - Independently developed by James Peebles and George Gamov
  - They suggested that the universe started off in an extremely hot state.
  - As the Universe expands, the energy within the universe is spread over in increasing volume of space, thus…
  - ***The Universe cools as it expands***





Cosmic radiation

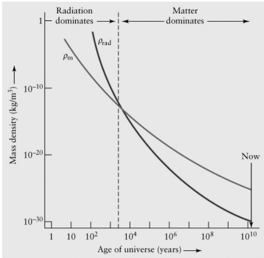
- How does the radiation change with time?
  - The total number of photons per "co-moving volume" remains constant
  - So… number of photons per unit (normal) volume proportional to $(R_0/R(t))^3$
  - Photons get stretched by expanding space (Sort of like the Doppler effect)… so energy of photon is proportional to $R_0/R(t)$
  - So, energy density of radiation scales as $(R_0/R(t))^4$
- The CMB has a "blackbody" spectrum characterized by a temperature T
  - The energy density of blackbody radiation is proportional to T^4.
  - So… **T(t) ~** $R_0/R(t)=1+z$

Cosmic radiation

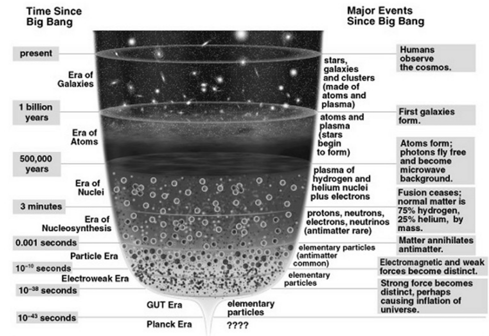
- At earlier times, this radiation field must have been ***more intense and hotter***
- Energy density of background radiation ***increases*** as cosmic scale factor *R(t)* *decreases* at earlier time *t*:
  - Multiply current number of photons/volume by: $(R_0/R(t))^3=(1+z)^3$
  - Multiply current energy per photon by: $(R_0/R(t))=(1+z)$
    - Another way to think about it: photon energy is inversely proportional to wavelength, and wavelength at earlier time = present wavelength × $(R(t)/R_0)$
  - **Overall, radiation energy density must vary as** $(1+z)^4$

Matter and radiation densities compared

- Already know matter density varies inversely with volume
- Thus:
  - $\rho_{matter} \propto (R_0/R(t))^3 = (1+z)^3$
  - $\rho_{radiation} \propto (R_0/R(t))^4 = (1+z)^4$
- ***At early times, energy density of CMB must have exceeded energy density of matter!***
- When radiation field is strong, matter is heated up
- Therefore earlier and earlier in the Universe, it must have been hotter and hotter
- This suggests that origin of the Universe was a ***hot, dense Big Bang***!



*Remember its the sum of matter-energy that is conserved



(*Lots* of technical details in this diagram – don't need to understand it all. Will cover some of this next time.)

Why did Gamov and Peebles suggest this model?

If the early Universe was hot (full of energy), a lot of features of the current universe could be explained…

- Could explain where the matter that we see around us came from (**baryogenesis** occurred well within first second)
- Could explain the observed ratio of H,He Li *****

(**nucleosynthesis** occurred within first few minutes)

- This scenario predicted that there should be left over radiation in the present Universe…
- This radiation redshifts as the Universe expands… nowadays should be redshifted to microwave/radio wave frequencies (CMB)

***** cannot explain the existence and amount of 'heavier'elements (e.g. C,N, O, ...Fe) which are created in stars and supernova (later lecture)

Summary: CMB and Cosmology

- The CMB was created at very early times
- It is a 'fossil' of the big bang
- Its detailed properties reveal a lot about the early universe, the creation of the elements and depends sensitively on cosmological parameters (H_o,ρ,Λ, lumpiness of the universe (σ_8))

- We will come back to this !