Lecture 21 : The Cosmic Background Radiation

- Mapping of the CBR with COBE
- The results from WMAP & Planck
- Scale dependence of fluctuations in CBR
- Implications for cosmological parameters

Reading: Ch. 14 of text

"Vacuums, black holes, antimatter - it's the elusive and intangible which appeals to me."

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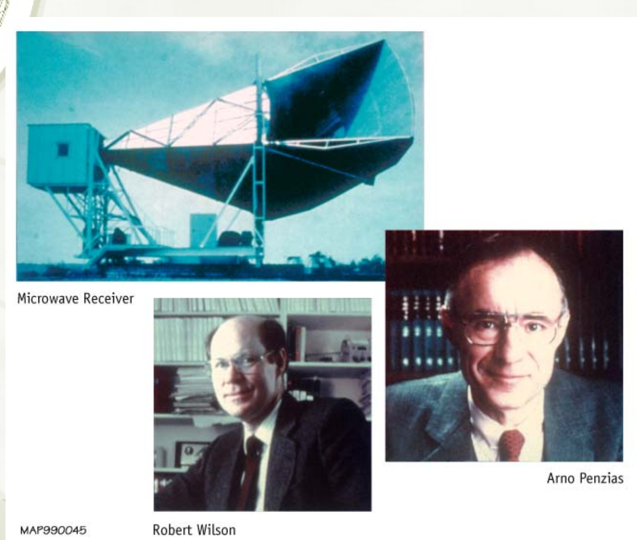
THE OBSERVATIONAL DISCOVERY OF THE COSMIC MICROWAVE BACKGROUND



- Arno Penzias & Robert Wilson (1964-1965)
  - Planning to study radio emissions from our Galaxy using new, sensitive antenna built at Bell Labs
  - Needed to characterize and eliminate all sources of noise
  - Could not get rid of or identify a certain noise source
    - characteristic "antenna temperature" of about 3 K.
  - Tests showed that the noise was coming from space, and was approximately the same in all direction -- origin must be cosmic, not Galactic

Cosmic Background Radiation

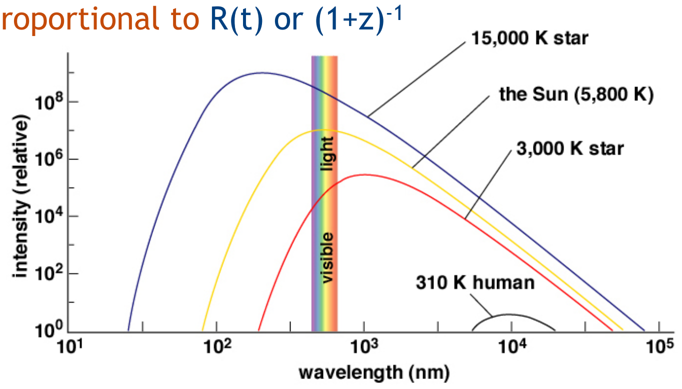
- Penzias & Wilson had serendipitously discovered radiation left over from the early universe!
- In fact, another group at Princeton U. had been looking for background radiation at the time of the discovery at Bell Labs
  - Recall that Gamow et al had predicted relic radiation from hot early universe
  - James Peebles independently rediscovered this idea
  - Peebles's colleagues Dicke, Roll, & Wilkinson were searching for CBR using receiver they built

Origin and evolution of CBR

- Recall that early Universe was hot
- Matter and radiation remained coupled until about 400,000 years after big bang, at $z = 1100$
- After recombination/decoupling, radiation has been free-streaming
- When we observe the CBR, we are looking at "surface of last scattering"
  - Similar to looking at glowing cloudbank from a distance
  - Observed properties of CBR directly trace conditions at $z = 1100$!
  - "cloudbank" is a sphere surrounding us, at radius corresponding to distance light travels over nearly 14 billion years (in expanding Universe)

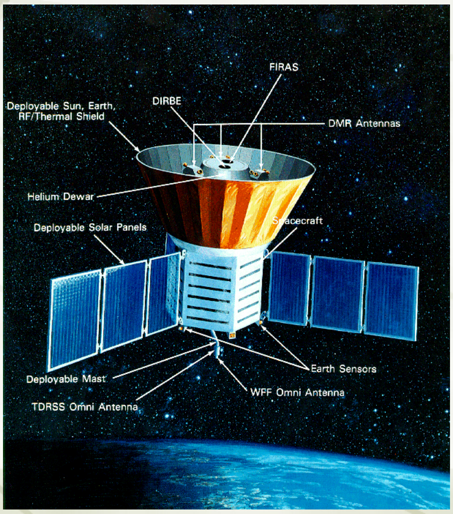
- Each photon of relic radiation has lost energy as the universe expanded
  - $E=hc/\lambda$
  - $\lambda(t)/\lambda(t_0)=R(t)/R_0=1/(1+z)$
- Relic radiation photons are spread over increasingly large volume
  - $Vol(t)/Vol(t_0)=(R(t)/R_0)^3=1/(1+z)^3$
- Overall, radiation energy density has decreased proportional to $R(t)^{-4}$ or $(1+z)^4$
- Radiation temperature changes with time (or redshift), with
  - $T(t)/T(t_0)=R_0/R(t)=(1+z)$
  - Temperature at surface of last scattering would have been ~3000K

- Overall shape of radiation spectrum is expected to be unchanged over cosmic time
  - Should follow “blackbody” shape
  - peak wavelength in spectrum would vary proportional to R(t) or $(1+z)^{-1}$



- Relic radiation at present is expected to peak at microwave/radio frequencies, with 411 photons/cubic cm in total
- Theory generally consistent with ground-based measurements, but atmosphere is opaque over large part of range where CBR is expected
  - Need observations from above atmosphere
  - Through late 1980s, observations were from balloons, rockets

THE COSMIC BACKGROUND EXPLORER (COBE)

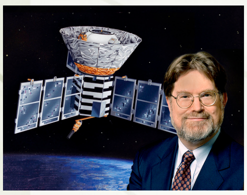


2006 Nobel prize in Physics!

- Awarded to John Mather (GSFC & UMD) and George Smoot (UC Berkeley)

"…for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation"

See: http://nobelprize.org/nobel_prizes/physics/laureates/2006/

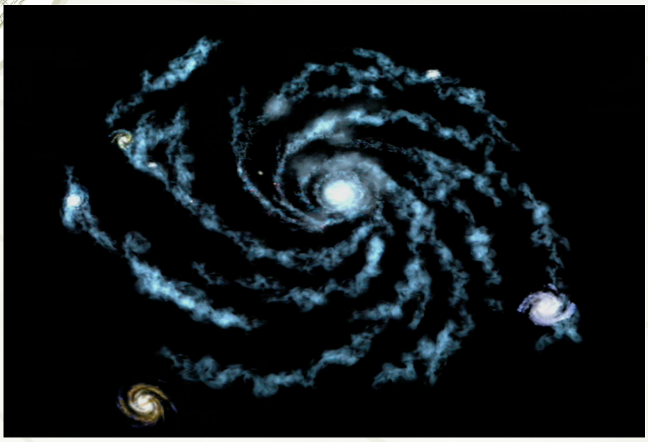


Note: COBE team involved >1000 scientists and engineers

- The COBE mission
  - Built by NASA-Goddard Space Flight Center
  - Launched Nov. 1989
  - Purpose was to survey infra-red and microwave emission across the whole sky.
  - Primary goals:
    - to characterize the spectrum of the CBR
    - to measure any variations in the CBR with direction
- Had a number of instruments on it:
  - FIRAS (**F**ar **I**nfra-**R**ed **A**bsolute **S**pectrophotometer)
  - DMR (**D**ifferential **M**icrowave **R**adiometer)
  - DIRBE (**Di**ffuse **I**nfraRed **B**ackground **E**xperiment)

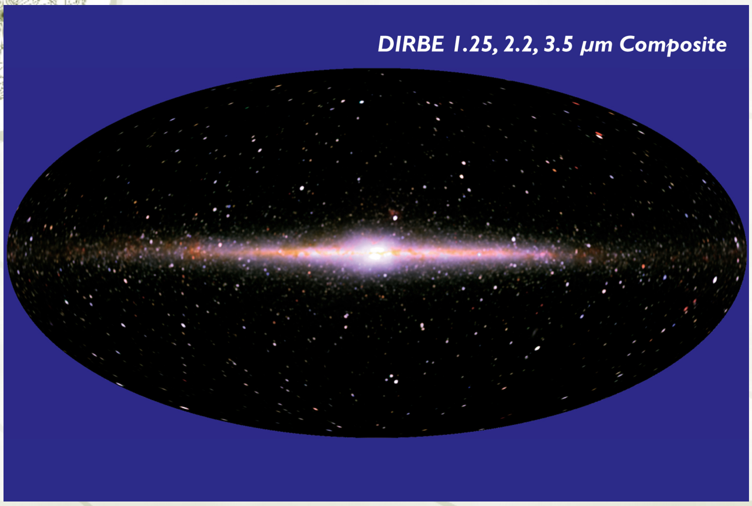
- Instruments measuring at different wavelengths “see” different structures…

WMAP movie of the sky at different wavelengths



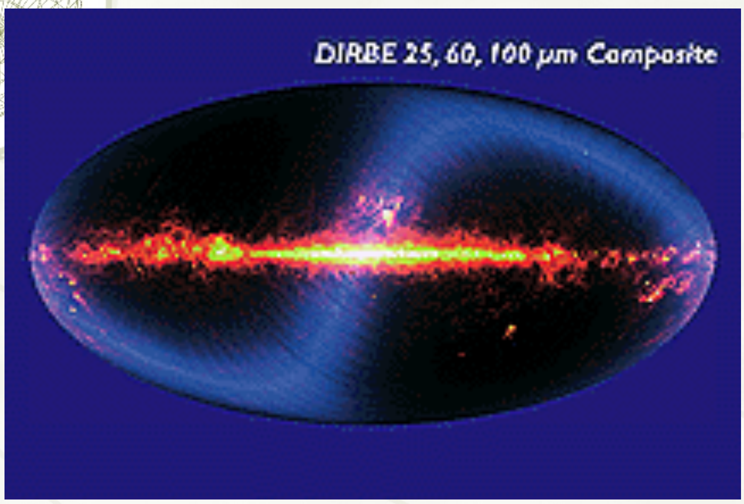
11/12/18 13

Our Galaxy observed by the DIRBE instrument on COBE



11/12/18 14

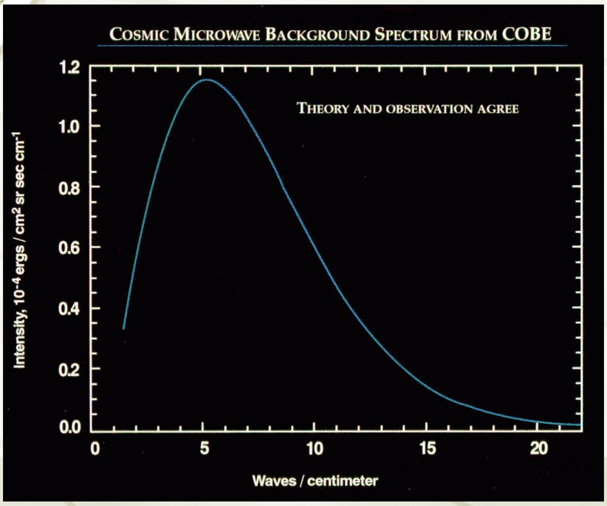
- High-frequency DIRBE image of our Galaxy
  - "Near infra-red" (slightly longer wavelengths then we can see by eye)
  - Can see…
  - Disk of our Galaxy
  - Bulge of our Galaxy
  - Dust in our galaxy (which makes the background stars look red)



- Low frequency DIRBE image
  - Far infrared (substantially longer wavelengths than we can see with our eyes)
  - Lower resolution image than at high frequency
  - Also see Galaxy (not as symmetric)… we're seeing active regions.
  - Also see a "band" of light across the image (light blue)…
  - This is the Zodiacal light: emission of IR by dust in our solar system.

- DIRBE measures strong signal at shorter wavelengths (0.0001cm-0.01cm=1-100μm) than peak emission expected from CBR
- By extrapolating this signal to longer wavelengths with same pattern, can help remove any "foreground" of galactic emission from CBR signal at 0.01-1cm (=100 μm -0.01 m) observed with FIRAS

The spectrum of the CMB (FIRAS)



- Spectrum has precisely the shape predicted by the theory of blackbody radiation (radiation in a thermal equilibrium)!
  - Shape of "blackbody" spectrum, within 0.03%
  - Characteristic temperature of 2.725K, within ±0.002K

Redshift of the Matter-radiation equality

- So, the density of matter decreases as $0.3(1+z)^3$ and that of radiation as $0.0001(1+z)^4$. When did matter radiation equality happened?
  a) When the universe was 13.4 Gyr old
  b) When the universe was about 3000 times smaller than today
  c) After the CMB radiation was emitted
  d) At redshift of 1 million

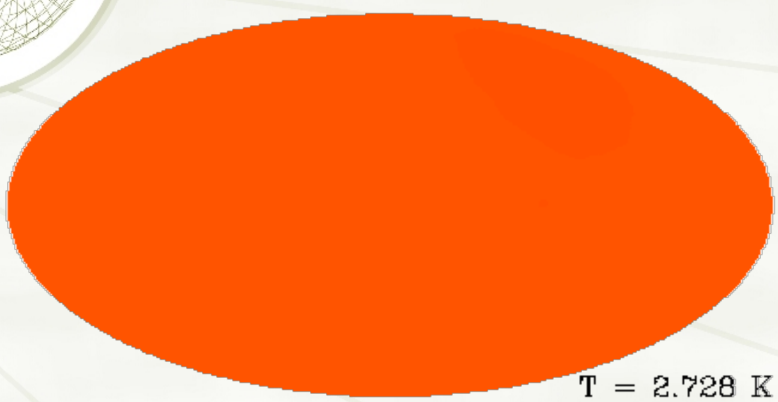
Redshift of the CMB

- So, the temperature of the CMB radiation decreases as T=3 K(1+z).The observed temperature of the CMB today is T_0=3 K, but it was T=3000 K at the time of emission. When was the CMB radiation emitted?
  a) When the universe was 13.4 Gyr old
  b) When the universe was about 1000 times smaller than today
  c) At a redshift of z=9
  d) At redshift z=999.

Variations in CBR

- CBR is expected to be *nearly* isotropic (same in all directions), since universe had *nearly* uniform conditions at epoch of decoupling
- But universe could not have been *exactly* uniform then…
  - if it had been perfectly uniform, there would be no galaxies, stars, planets today!
  - There must have been small fluctuations in density and temperature of both matter and radiation
  - Small fluctuations early on were "seeds" of structure that would grow later
- If universe was not exactly uniform at surface of last scattering, there should be small variations in CBR…
  - This is what the DMR instrument on COBE sought to measure

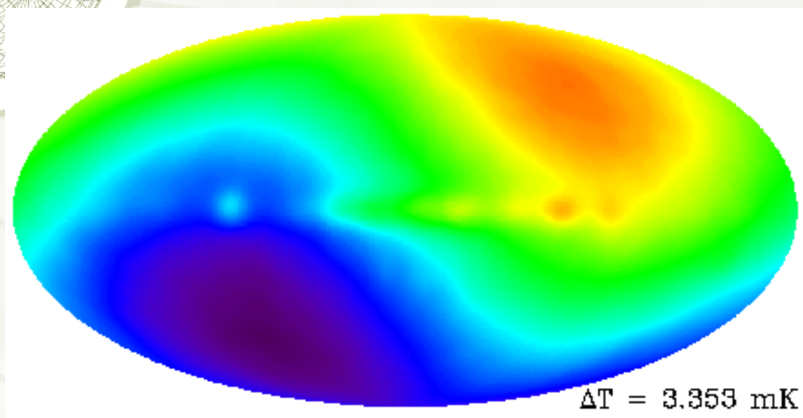
DMR map of the microwave sky



Raw DMR map

- Map of the microwave sky (frequency of 50GHz, or wavelength of 0.6cm)…
  - This is the CBR over the whole sky!
  - The map is very uniform.
  - Means that the CBR is extremely isotropic Supports the idea that the Universe is **isotropic** (one of the basic cosmological principles).
  - In fact, if we measure the universe to be isotropic, and we're not located at a special place in the Universe, we can also deduce that the Universe is **homogeneous**!

Subtract off average level…



- What causes this “dipole” pattern of redshift and blueshift in CBR?
- Class discussion!

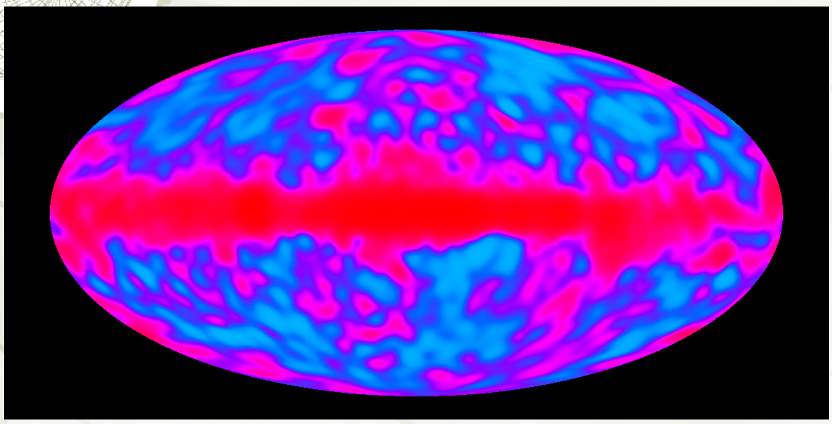
11/12/18 27

Motion of Earth through space

- Dipole pattern is caused by doppler shift of radiation frequencies because Earth moves relative to mean “cosmic rest frame” of CBR
- “Blue” direction (higher intensity/energy of CBR) is direction of Earth’s motion
- “Red” direction is opposite direction
- Total velocity is 390 km/s
- Components:
  - Earth orbits Sun at 30 km/s
  - Sun orbits Galactic center at 220 km/s
  - Milky Way Galaxy moves inside Local Group
  - Local group is falling into Virgo cluster
  - Virgo Cluster may have systematic motion

11/12/18 28

After removing mean and "dipole"

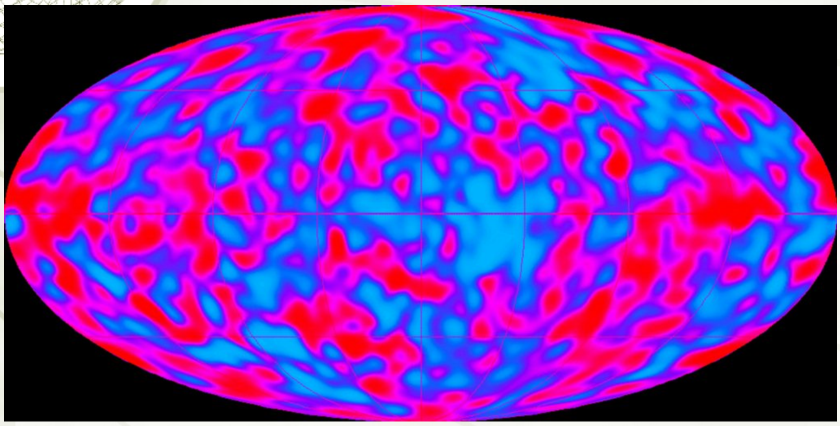


Removing galactic "foreground"

Different dependence of galactic dust emission and CBR on frequency can be used to separate the two…

- Short-wavelength IR from DIRBE is used as spatial "template"
- scale amplitude for dust emission in DIRBE map to long wavelengths
- Subtract off from long-wavelength DMR map…

Resulting map with galactic "foreground" removed



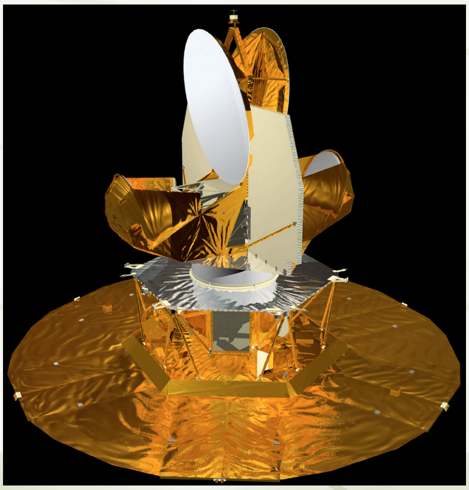
CBR fluctuations from COBE

- "Cleaned" map shows a random pattern of fluctuations in the CBR
- These correspond to temperature differences of 30 millionths of a Kelvin; i.e. fractional perturbations are about 3 parts in 10^5
- What are these fluctuations?
  - The early universe was very close to being perfectly homogeneous
  - But, there were small deviations from homogeneity… some regions were a tiny bit colder and some were a tiny bit hotter.
  - When matter and radiation decoupled, this pattern of fluctuations was preserved into the radiation field.
  - We see this now as fluctuations in the CBR.

Fluctuations as "seeds" of structure

- Why are the fluctuations important?
  - Before decoupling, fluctuations in the radiation field also meant fluctuations in the mass density
  - After decoupling, these small fluctuations in density can get amplified (slightly dense regions get denser and denser due to gravity).
  - These growing fluctuations eventually collapse to give galaxies and galaxy clusters.
  - So, by studying these fluctuations, we are looking at the "seeds" that grow to become galaxies, stars, planets, people, dogs, cats etc.

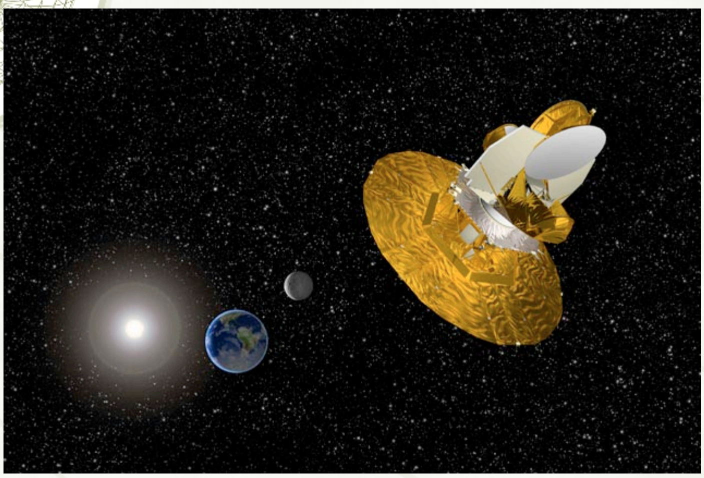
Wilkinson Microwave Anisotropy Probe (WMAP)



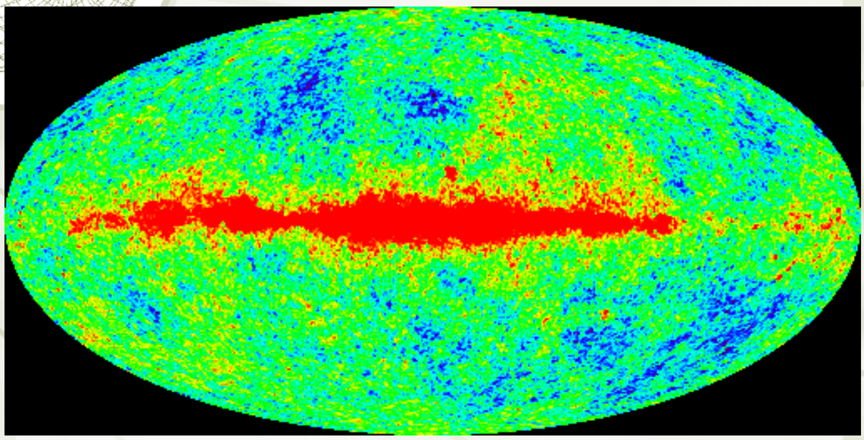
WMAP

- NASA mission to map out the fluctuations in the CMB in fine detail…
  - Determined fine detail of the CMB fluctuations that depends upon the curvature of space (k) and Ω.
  - Characterized the seeds for structure formation
  - Much higher spatial resolution (0.2°) than COBE (7°)
- Launched 2001, operated until very recently

The WMAP satellite in orbit

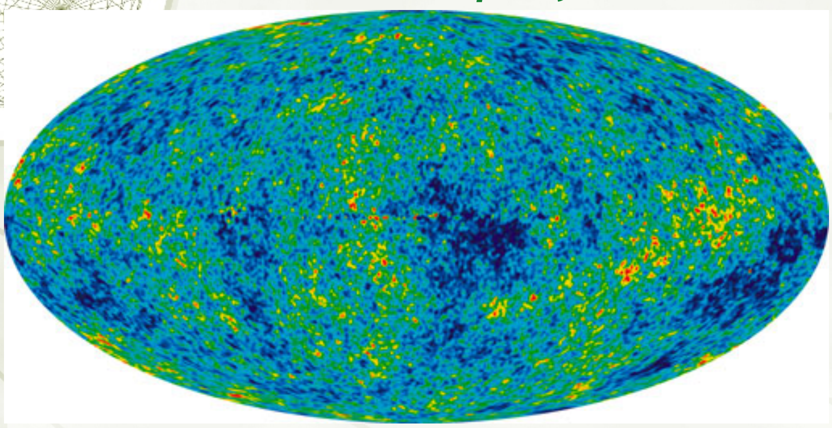


WMAP measurements of the microwave background radiation



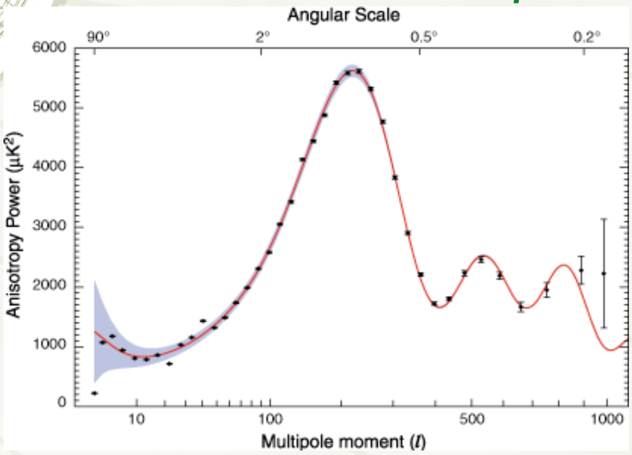
Images: NASA WMAP project

WMAP's map of the CMB



The microwave light captured in this picture is from 379,000 years after the Big Bang, over 13 billion years ago!

Cosmic lumps: the power spectrum



Meaning of the power spectrum

What causes fluctuations?

- In early universe, there were sound waves of various wavelengths, modified by gravity
- Oscillations could not grow before 10^{12} s (30,000 yr), because radiation damped them out. The universe was radiation-dominated
- After 10^{13} s, radiation and matter decoupled and CBR began free-streaming
- Imprint on CBR arises from 300,000 yrs between matter domination and recombination
- Photons that last scattered from high-density region are relatively redshifted; photons that last scattered from low-density region are relatively blueshifted
- Redshifts/blueshifts imply temperature variations on the sky map of CBR; temperature traces density

Power spectrum peaks and valleys

- Angular scale of first (large) peak corresponds to wavelength of sound wave that would have completed half an oscillation within 300,000 years
- This is the "fundamental" peak, at about 1° angular scale
- At larger scales, waves would have completed less than half an oscillation and no large densities were introduced on those scales
- Peaks at scales <1° are higher harmonics

Flat universe!

- Result:
  - The universe is **flat**
  - In terms of omega curvature parameter, $k = 0$ means $\Omega_k = 0$
  - Recall that the sum of all three omega parameters as measured at present time must be 1:

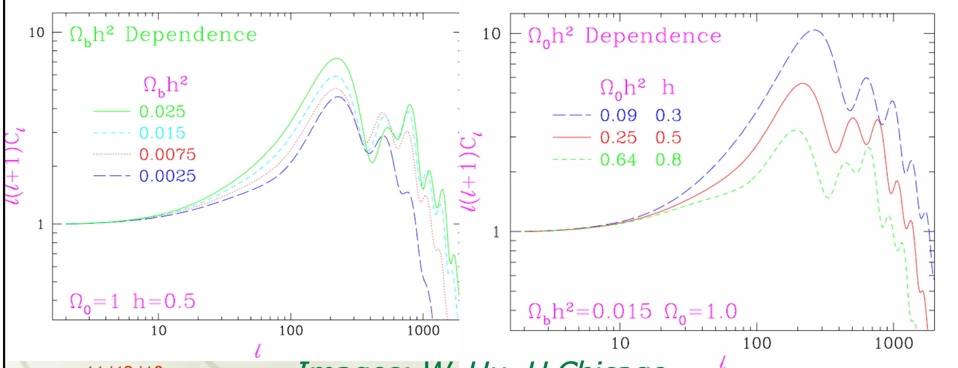
$$1 = \Omega_M + \Omega_\Lambda + \Omega_k$$

  - How do we reconcile $\Omega_k = 0$ with our measurement of the matter density, which indicates $\Omega_M = 0.26$?
  - There must be a nonzero cosmological constant, $\Omega_\Lambda = 0.74$!

$$\Omega_\Lambda \equiv \frac{\Lambda}{3H_0^2}$$

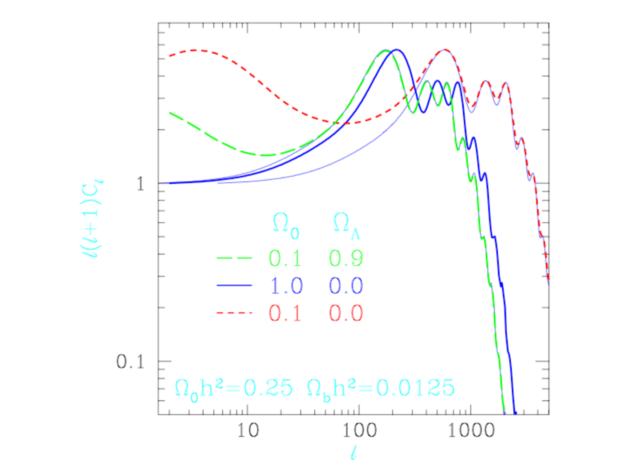
Spectral changes for varying parameters

- Spectra from CBR maps also help constrain other parameters…

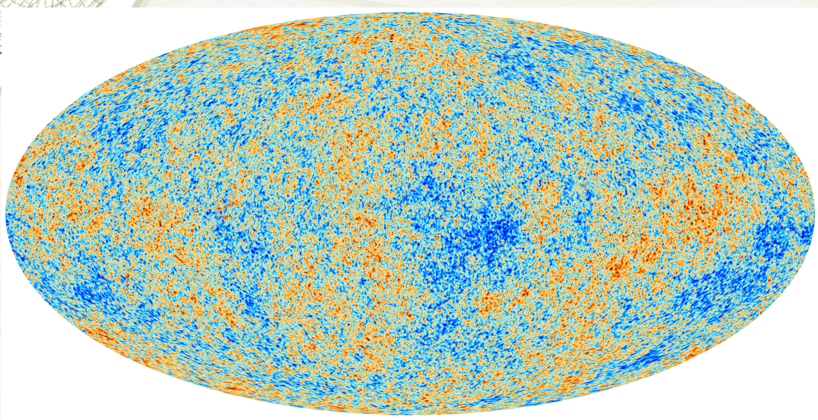


Images: W. Hu, U.Chicago

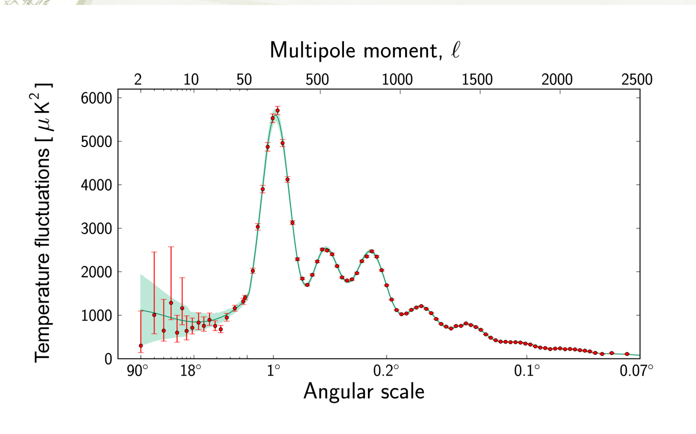
Constraining dark energy



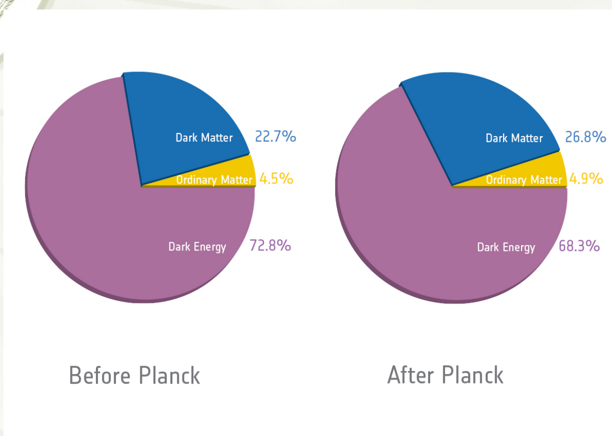
Planck



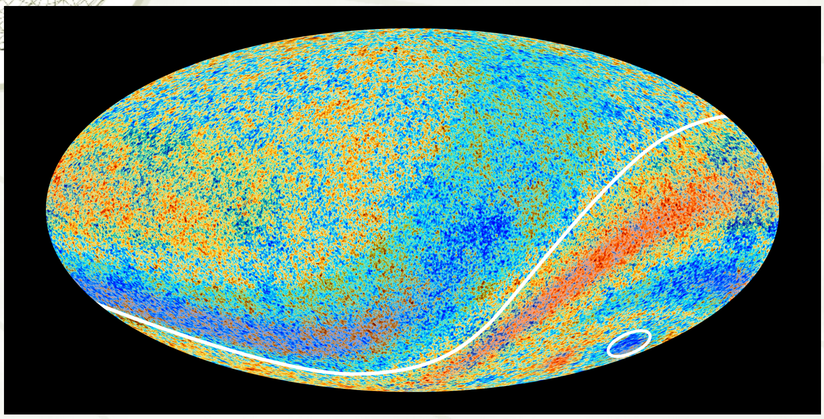
Power Spectrum



Cosmic Recipe



Planck Anomalies



11/12/18 49

Next time…

- How did structure emerge in the Universe? (What about us!!!???!!)

11/12/18 50