Cosmology - The Story of our Universe

Lecture 3

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Cosmology

PAST ← PRESENT → FUTURE

- Observational Astronomy and the Theory of General Relativity has given us today an understanding of our past, and possible future

Observations

- Important observations

  Milky Way is not the entire Universe

  Our Universe is expanding (Hubble 1920s)

The Theory of General Relativity

- Mass (or energy) curves space
- Objects moving in this space change their motion because of the curvature of space
- Gravitational field replaced by modification of space

Tests of General Relativity

Predicted differences from Newtonian gravity

- Close to a massive object (star)
  Precession of the perihelion of Mercury

- At relativistic speeds (v ~ c)
  Gravitational bending of light

- Applied to the Universe (FLRW Universe)

GR and Our Universe

- $d_{AB}(t_2) = d_{AB}(t_1)\, R(t_2)/R(t_1)$;   R is the scale factor

$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G}{3}\rho - \frac{k}{R^2} + \frac{\Lambda}{3}$$

$$\frac{\ddot{R}}{R} = -\frac{4\pi G}{3}(\rho + 3p) + \frac{\Lambda}{3}$$

ρ is the energy density

G is Newton's gravitational constant

Λ is the cosmological -- positive acceleration

k = 1,0,-1

FLRW Equations and Expansion Rate

$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G}{3}\rho + \frac{\Lambda}{3} \qquad \text{(k=0)}$$

- $\rho \sim 1/R^4$ for relativistic particles ($v \sim c$), $R \sim t^{1/2}$

  $\sim 1/R^3$ for non-relativistic particles, $R \sim t^{2/3}$

If Λ dominates, $R \sim \exp At$ $\quad A^2 = \Lambda/3$

Our Universe

- Using the Friedmann-Lemaitre (+ Robertson-Walker) solutions of the equations of General Relativity can explain the past history and possible future of our Universe, given observational inputs

1. Our Universe is expanding

2. $\rho_r \ll \rho_m < \Lambda$

History of our Universe

- First second – hot primordial soup
- 1 s – 3 min – light nuclei (helium, lithium, ..)
- 77,000 years – Univ becomes matter dominated

History of our Universe

- 77,000 years – Univ becomes matter dominated
- 400,000 years – Atoms form
- 300 million years – First stars form
- 1 billion years – First galaxies form
- 9 billion years – Universe is accelerating, Λ dom
- 14 billion years – Today

Our Universe – Big Bang Cosmology

- Using the Friedmann-Lemaitre (+ Robertson-Walker) solutions of the equations of General Relativity can explain the past history and possible future of our Universe, given observational inputs
- Correctly predicted the existence of the cosmic microwave background radiation
- Correctly predicted light element abundances

The Planck era

- While the FLRW solutions imply that any finite region will be concentrated at a point in the past, the solutions are not valid up to R=0.

- At t ~ 10^{-43}s (the Planck time) quantum gravity effects become important.

Books on Cosmology

- The First Three Minutes by S. Weinberg
- The Big and the Small vII by G. Venkataraman
- Also see Cosmology and Relativity Tutorials on Ned Wright's (UCLA) homepage

  http://www.astro.ucla.edu/~wright/intro.html ,

  and on John Baez's (UCR) webpages **http://math.ucr.edu/home/baez/gr/** and **http://math.ucr.edu/home/baez/physics/**

THE FIRST STARS IN THE UNIVERSE

Exceptionally massive and bright,
the earliest stars changed the course of cosmic history

Scientific American, Dec. 2001, 64-71

Course Outline

I. Overview of what we know about our Universe

II. Laws governing the evolution of the Universe

III. Constituents of our Universe

(radiation, matter incl. dark matter, dark energy)

IV. Formation of Structure

V. Physics of the very early Universe ($t < 10^{-6}$ s)

Interface with Particle Physics

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Interface with Particle Physics

Composition of our Universe

- Photons (CMBR) and neutrinos – negligible
- Protons, neutrons and electrons – 5%
- Dark Matter – 25%
- Dark Energy – 70%

What is the CMBR?

- The **C**osmic **M**icrowave **B**ackground **R**adiation is a background of photons that we detect in all directions in the sky
- Extremely isotropic
- Temperature is 2.725 K

CMBR

The CMBR was theoretically predicted by Alpher and Herman in 1948 while studying the creation of nuclei in the early universe. (Gamov, Dicke, Zeldovich)

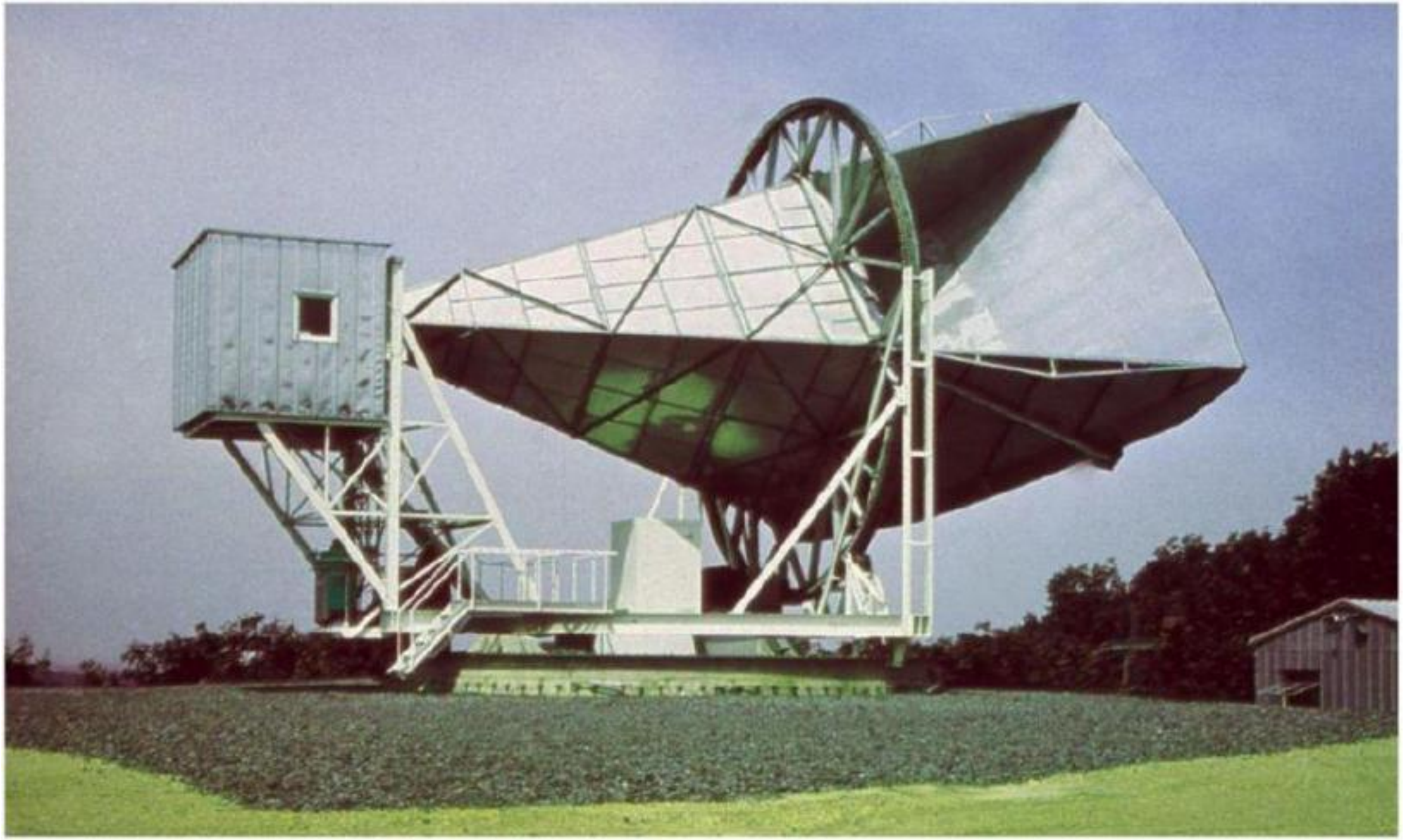
Primordial nucleosynthesis requires a hot gas of protons, neutrons, photons, etc. and the photons should have been freely travelling through the Universe after neutral atoms were formed and should exist today as background radiation of temperature ~ 5 K. (Estimates varied)

CMBR

- In 1964 Doroshkevich and Novikov suggested looking for this radiation and emphasised its blackbody characteristics.

- Accidentally discovered by Penzias and Wilson of Bell Labs, Holmdel in New Jersey 1965

  Working on microwave antenna to study signals from radio sources in the sky detected a persistent noise in their antenna



Holmdel antenna

CMBR

- Despite all efforts to eliminate sources (Milky Way, sun, NYC, antenna, pigeons), kept detecting a signal

- Other scientists (Dicke, Peebles, Roll and Wilkinson at nearby Princeton University) preparing to look for the CMBR identified it as the cosmic radiation

Important verification of Big Bang cosmology

History of our Universe

- First second – hot primordial soup
- 1 s – 3 min – light nuclei (helium, lithium, ..)
- 400,000 years – Atoms form

Once neutral atoms form, photons decouple from the atoms, photons free-streaming, frequency decreases, and detected today as CMBR

Infrared → microwave, $T_i \sim 3000$ K → $T \sim 3$ K

CMBR Discovery

Arno Penzias and Robert Wilson

- Awarded Nobel Prize in Physics 1978

  "for their discovery of cosmic microwave background radiation".

Characteristics of the CMBR

1. Non-thermal but with an effective temperature (Richard Tolman 1934)

- Before t ~ 400,000 yr, photons have a Planckian spectrum.

- Neutral atoms form, photons decouple from the atoms

- Photons free-streaming , not in thermal equilibrium
  Technically they no longer have a temperature

Characteristics of the CMBR

- Initial Planckian distribution when photons decouple

$$f(\nu_i, T_i, t_i) = \frac{1}{e^{\frac{h\nu_i}{k_B T_i}} - 1}$$

- As the universe expands, $\nu(t) = \nu_i / R(t)$.
- Re-express distribution in terms of ν.

- Define $T(t) = T_i / R(t)$

$$f(\nu, T, t) = \frac{1}{e^{\frac{h\nu}{k_B T}} - 1}$$

- **Planckian distribution** at 'temperature' T

Characteristics of the CMBR

2. Expect Variations in the CMBR

- Distribution of matter is not smooth – stars, galaxies, clusters
- Theory of structure formation:

  Initial almost smooth distribution of matter with slight spatial variations

  Overdense regions grew more dense over time and collapsed into stars and galaxies and clusters

- Primordial fluctuations in matter should be reflected in the CMBR– intrinsic and induced

Characteristics of the CMBR

1. Planckian distribution

2. Variations

From 1965 onwards, many experiments to study the CMBR.

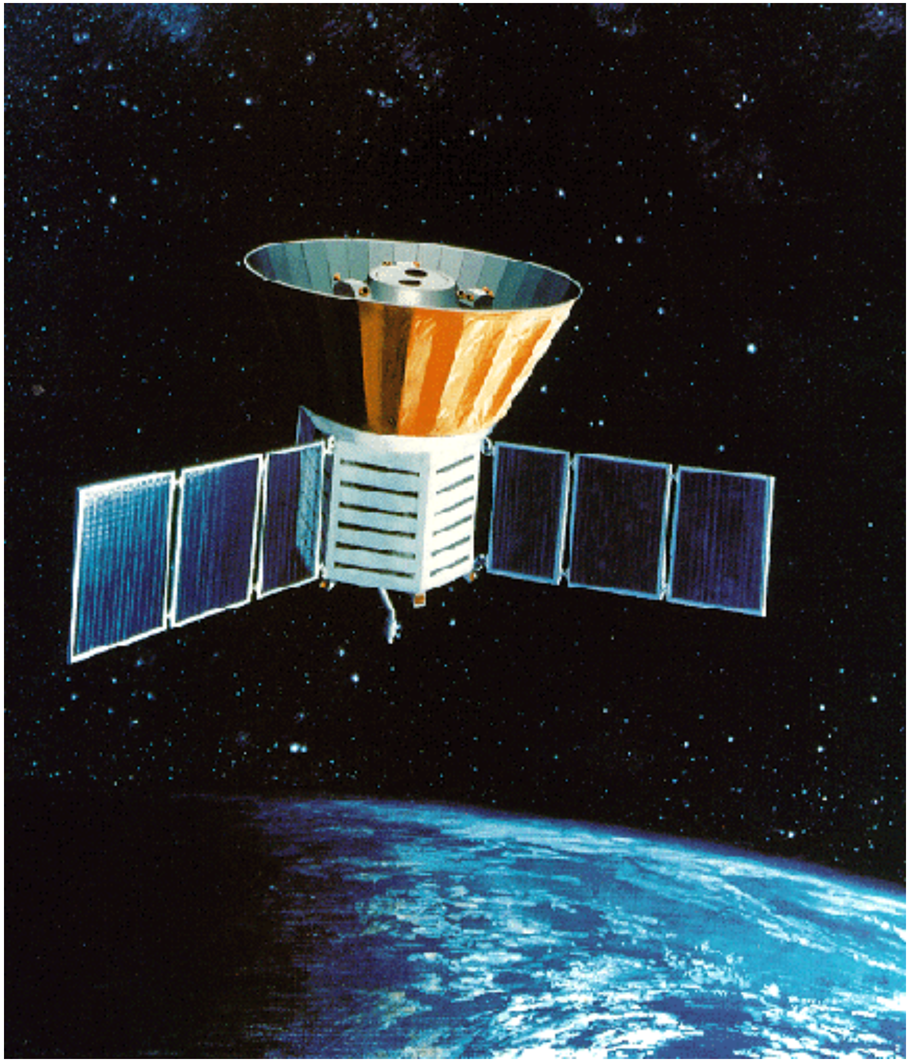
There were conflicting observations about 1.

There was no detection of 2, only upper bounds.

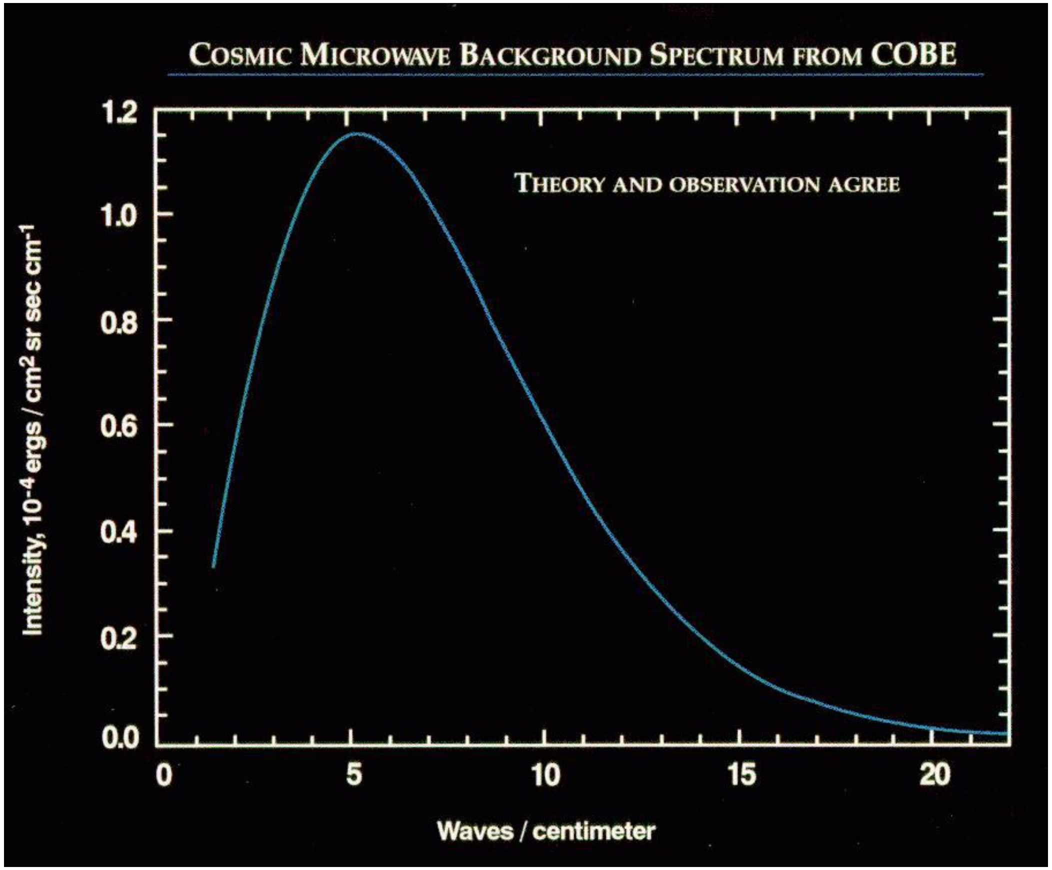
COBE Mission

- In 1989 the **Co**smic **B**ackground **E**xplorer (COBE) satellite mission was launched by NASA

COBE Mission 1989-1992



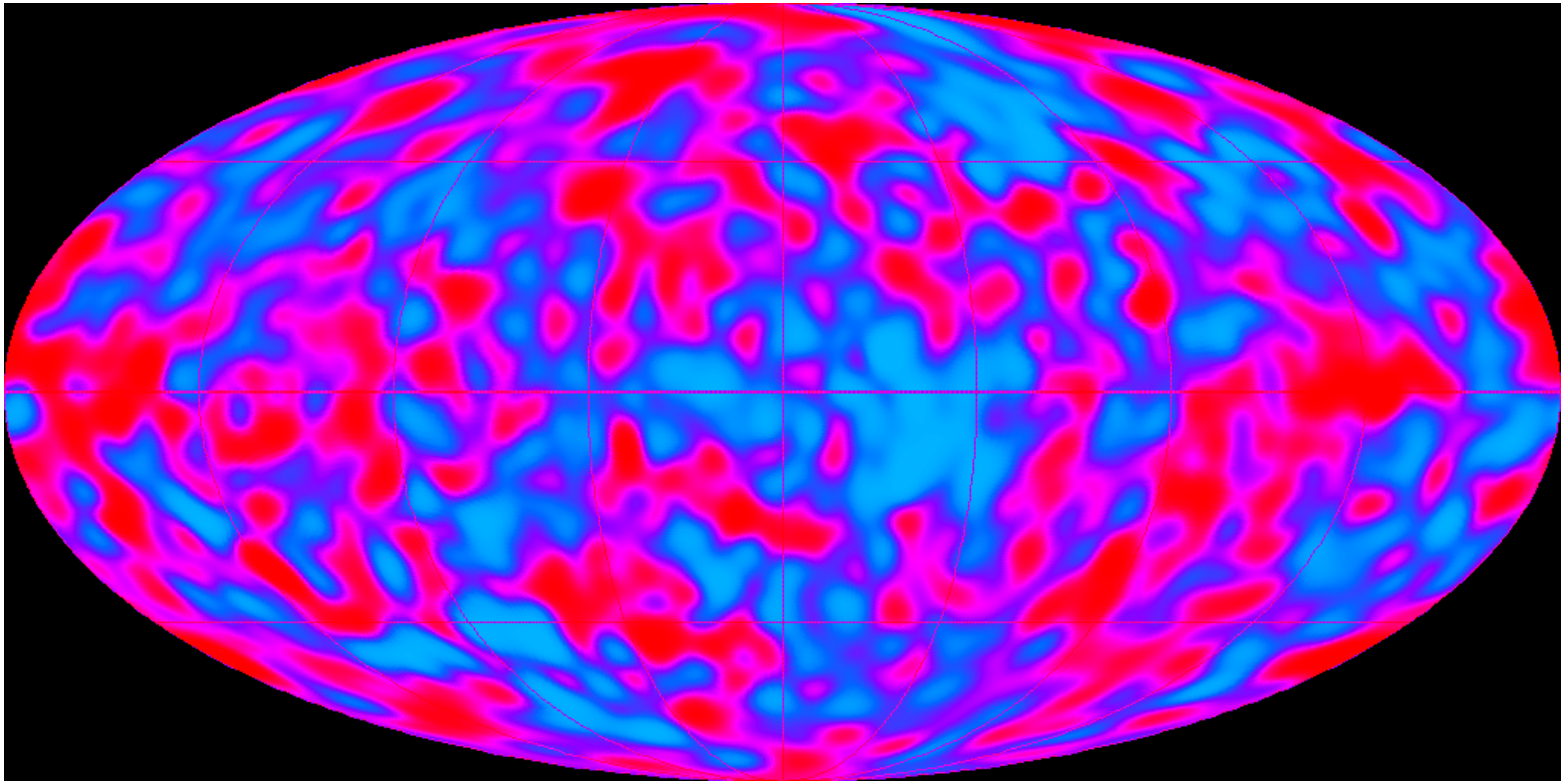
CMBR has a Planckian spectrum



Best blackbody spectrum ever observed T = 2.725 ± 0.002 K

Ave. error in mment of temp at a point ↑

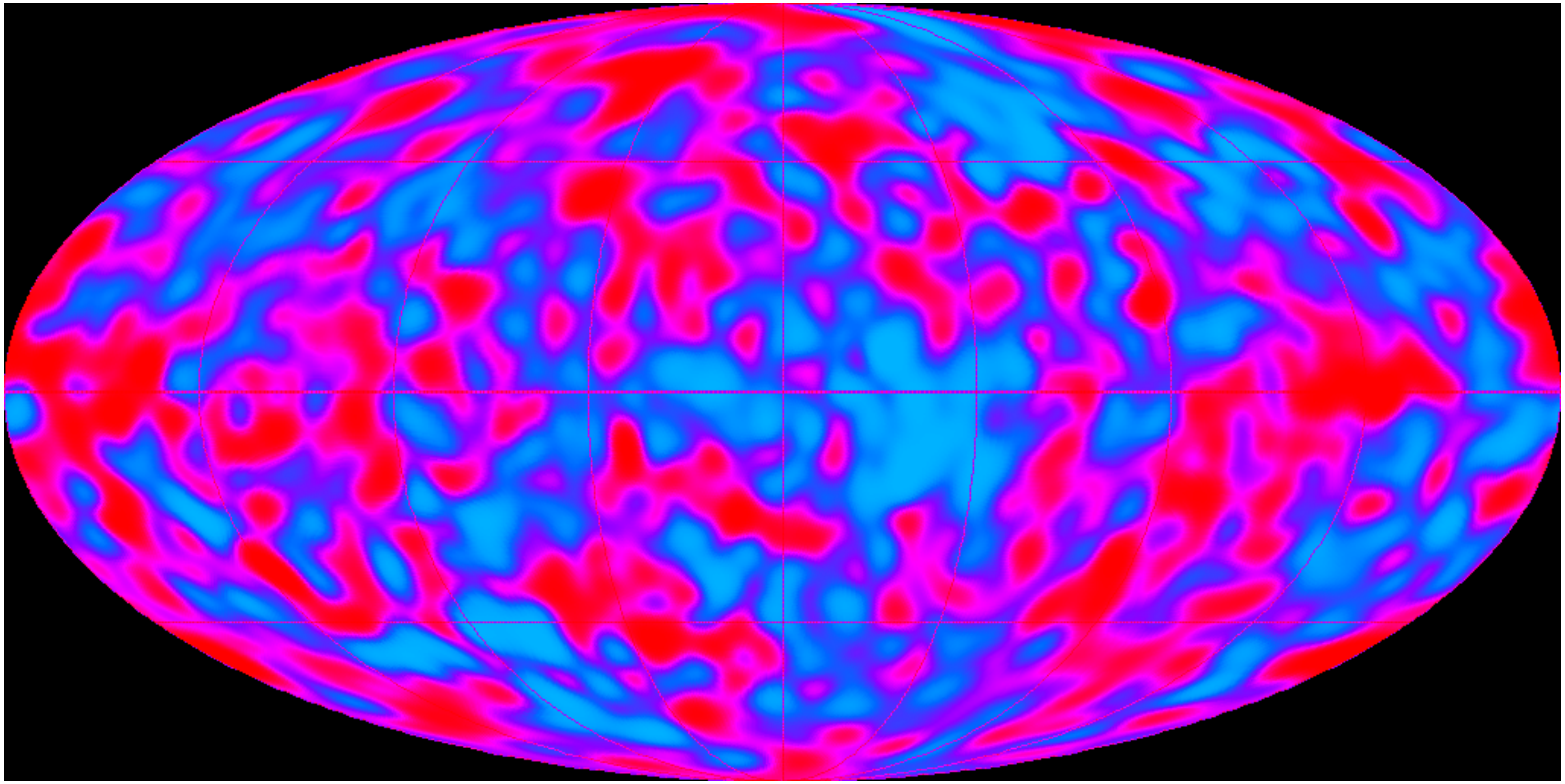
CMBR Anisotropy



-150μK – +150 μK

CMBR Temperature is not uniform – it has spatial variations

CMBR Anisotropy ~ 10^{-5}



-150μK – +150 μK

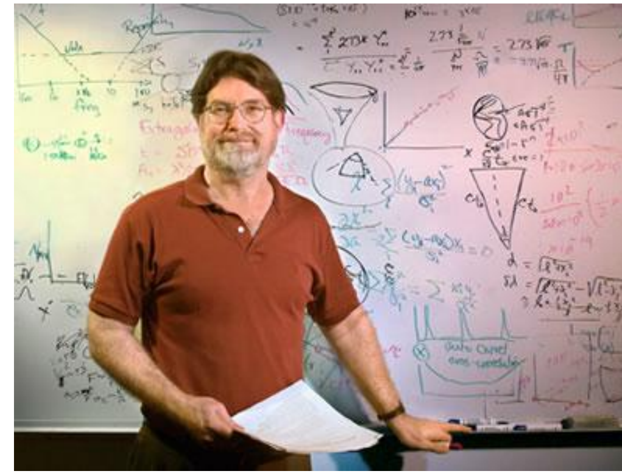
CMBR Temperature = 2.725 ± 0.00003 K

(Spatial variation in temperature on angular scales 10° – 60° ↑)

2006 Nobel Prize in Physics

John Mather
NASA GSFC

COBE



George Smoot
LBL, UC Berkeley

for "their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation" using the Cosmic Background Explorer (COBE).

CMBR

- RELIKT-1 Soviet CMB anisotropy mission 1983
- RELIKT-1 also discovered anisotropy 1992 on re-analysis of their data

The pattern of fluctuations seen by COBE can again be well explained in the context of Big Bang cosmology, not others.

Composition of our Universe

- Photons (CMBR) and neutrinos – negligible
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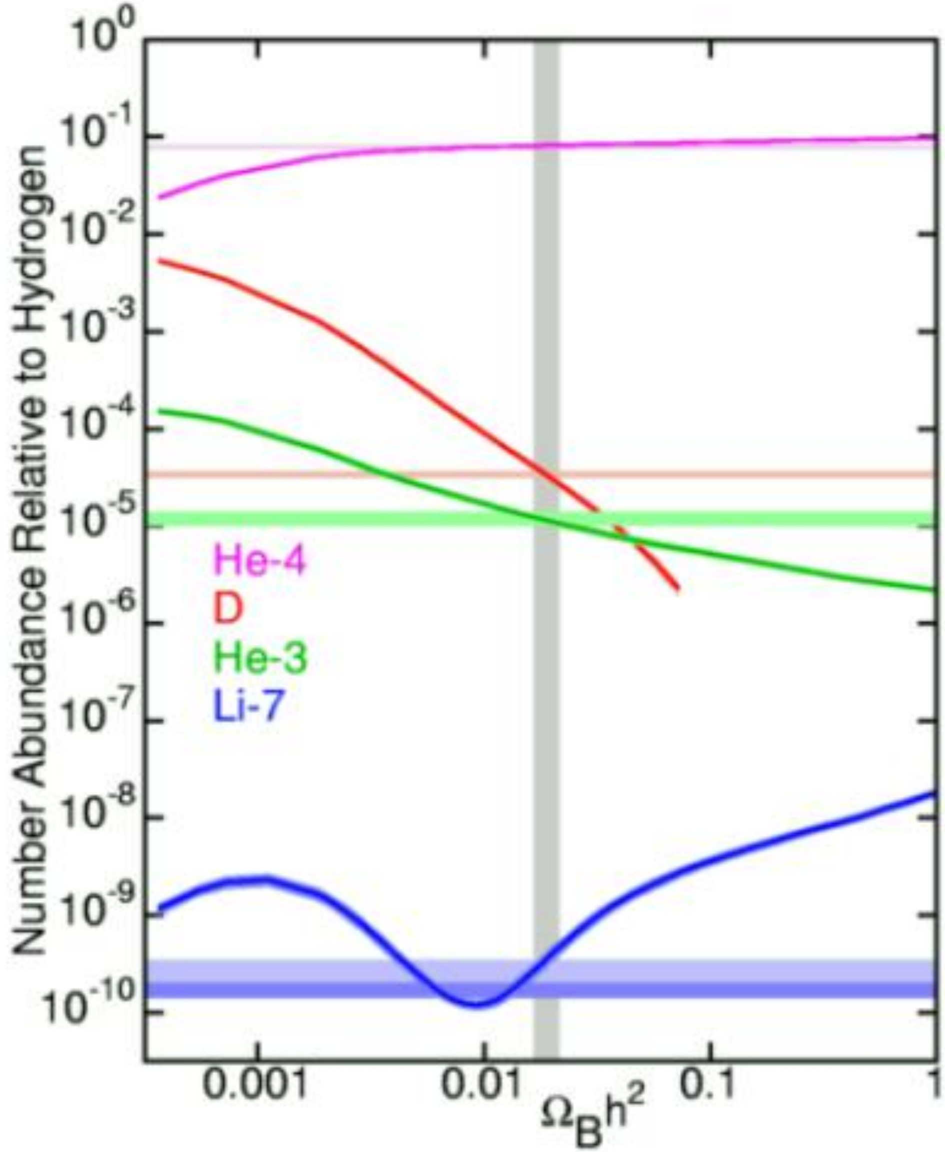
Baryonic matter (n, p)

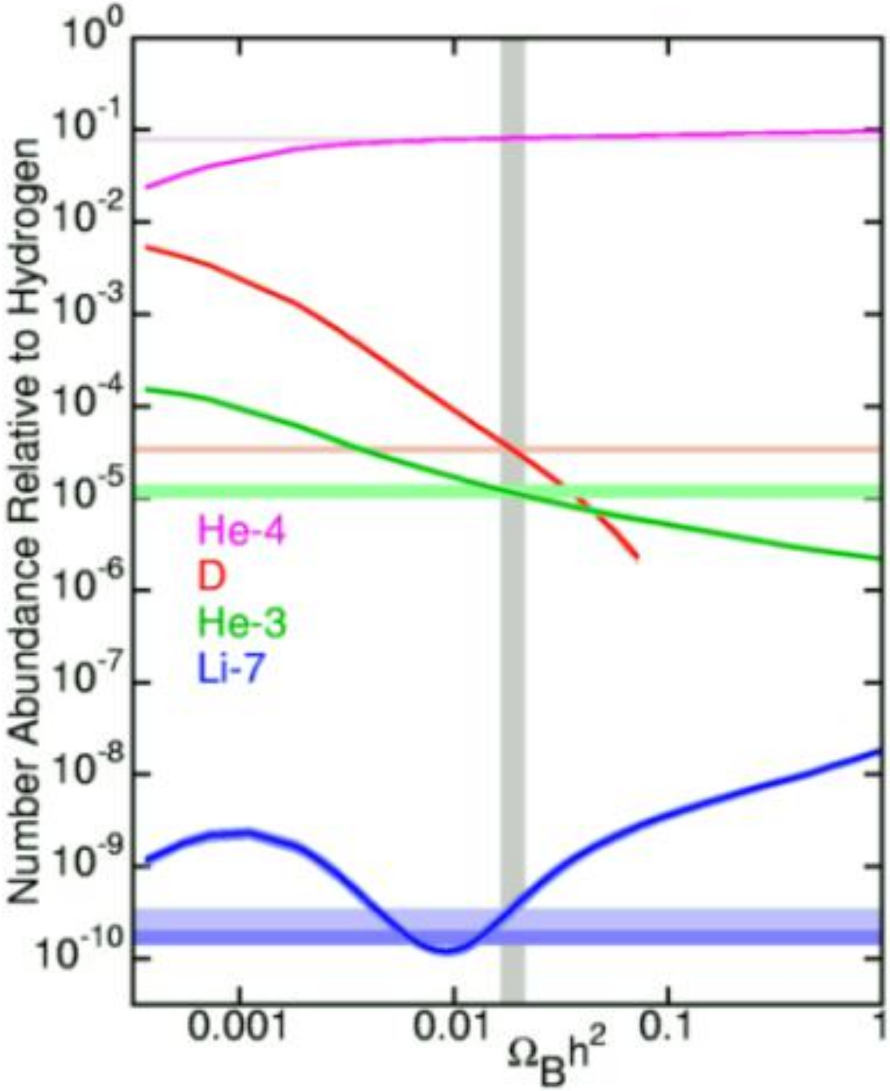
- Neutrons and protons combine to form nuclei of light elements -- deuterium, ^{3}He, ^{4}He, lithium – in the first three minutes

- Their abundances can be calculated in the context of Big Bang cosmology



$\Omega_B\ h^2 \sim \rho_B \sim n_B$

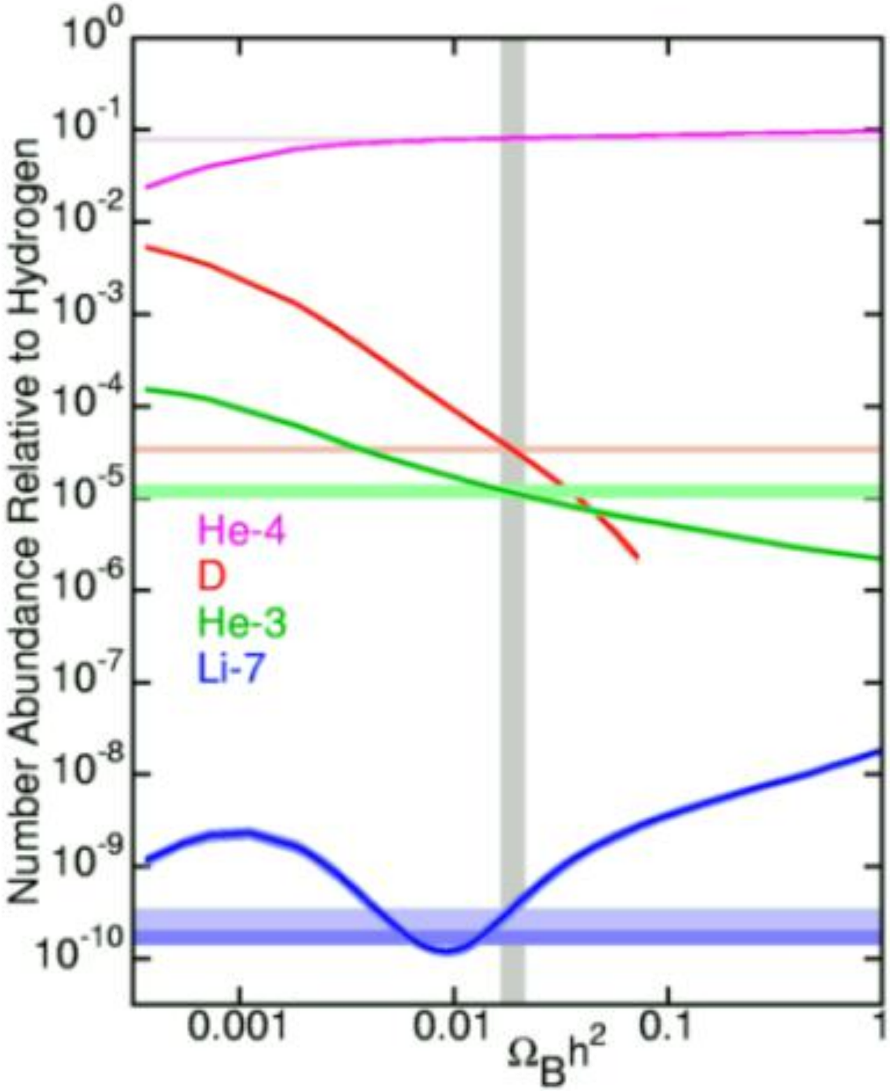
The observed light element abundances indicate they all prefer the same baryon density (5%)



- The theoretical calculations explicitly included the expansion of our Universe, with

$$R(t) \sim t^{1/2}$$

- If different elements required different values of the baryon density, there would be an inconsistency, and it would imply that we did not properly understand the processes in the early Universe



- The observation that the different element abundances were consistent with the same value of the baryon density (5%) indicated our calculations were correct.
- This was another important confirmation of Big Bang theory of cosmology.

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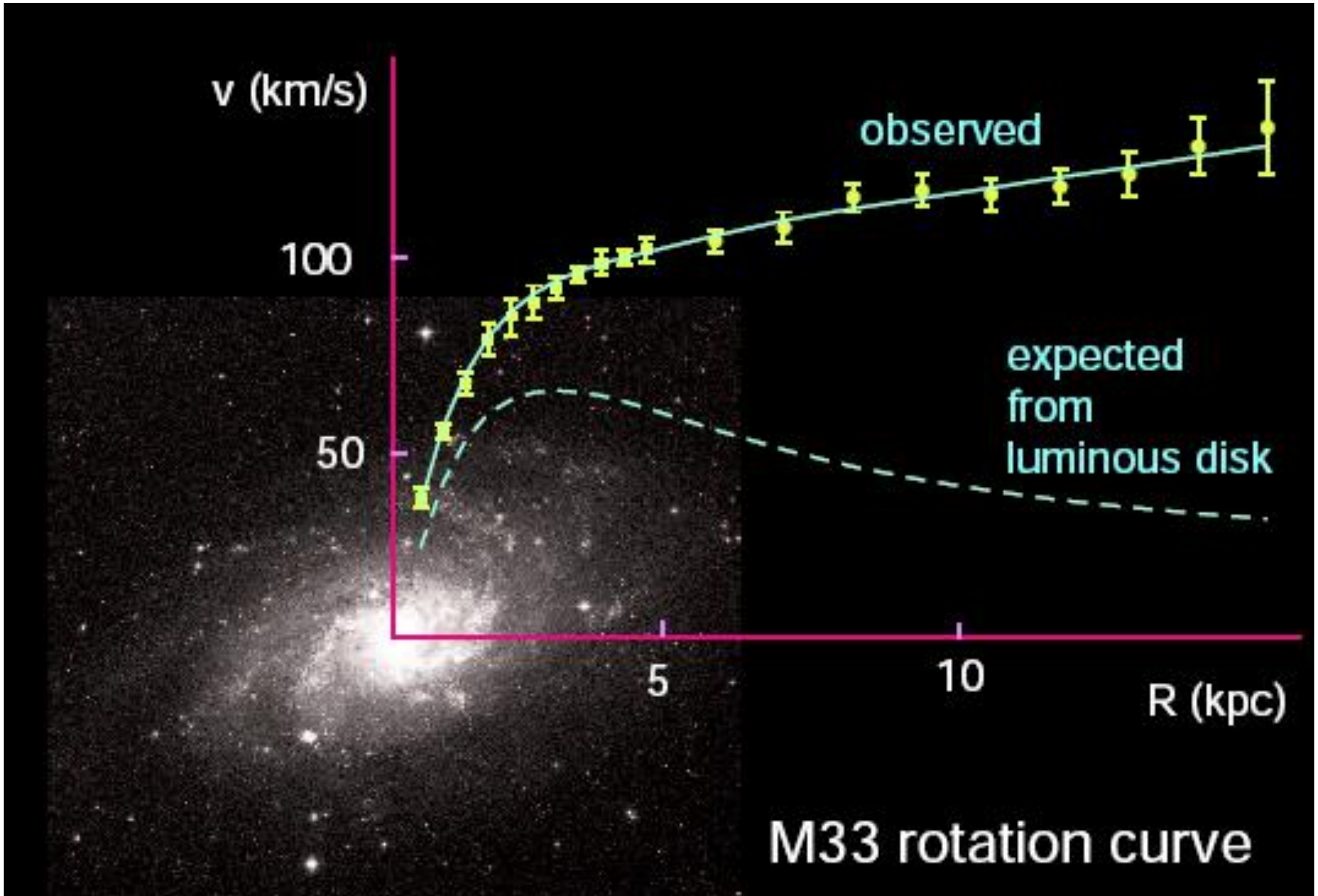
Dark Matter

- Velocity rotation curves of galaxies

Expect v ~ $1/r^{1/2}$ because $$m\frac{v^2}{r} = G\frac{Mm}{r^2}$$ and M is const.
But ….



v (km/s)
100
50
observed
expected
from
luminous disk
5
10
R (kpc)
M33 rotation curve

(fig. 1)

- Take v ~ constant. How can this be explained ?

$$m\frac{v^2}{r} = G\frac{Mm}{r^2}$$

- If M(r) = A r, then v ~ constant
- But if M(r) = A r then there is matter outside the central luminous bulge which we can not see.

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$$m\frac{v^2}{r} = G\frac{Mm}{r^2}$$

- If M(r) = A r, then v ~ constant
- But if M(r) = A r then there is matter outside the central luminous bulge which we can not see.
- This non-luminous matter (does not emit or scatter light) is called Dark Matter

- Dark matter does not emit or scatter light so it is difficult to detect (not means feebly)

- Pervades our Universe. What is it?

- Consists primarily of non-standard matter – supersymmetric particles, axions, massive neutrinos, … WIMPS

- Dark matter does not emit or scatter light so it is difficult to detect (not means feebly)
- Pervades our Universe. What is it?
- Consists primarily of non-standard matter – supersymmetric particles, axions, massive neutrinos, … WIMPS
- Large Hadron Collider (LHC) – if SUSY

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Dark Energy

- Discovered by looking at the dimming of light from supernovae, which are standard candles in astronomy

Dark Energy

- Imagine you have a 100 watt bulb. You know how bright it is. You also know how its brightness dims with distance. So if you measure its apparent brightness, you know how far it is.
- In astronomy look for such objects whose brightness is known. Standard Candles

Dark Energy

- Supernovae – Stellar explosion, very bright (brighter than the galaxy!)
- Maximum intensity is the same
- Used as standard candles

- SNIa is a very good standard candle

Seen in 185, 1006, 1054, 1572, 1604 (human eye)

Crab Nebula, remnant of 1054 supernova in our Milky Way
Bright enough to be seen in the day for 23 days, visible at night for 653 days. Neutron star at the centre.

Dark Energy

- Astronomers looked at many different supernovae and found that they appeared dimmer than expected in a decelerating Universe (1998)
- Could be explained only if the Universe is accelerating

Dark Energy

- Recall how get an accelerating Universe

$$\frac{\ddot{R}}{R} = -\frac{4\pi G}{3}\rho_{nr} + \frac{\Lambda}{3}$$

$p_{nr} \sim 0$

Whether the acceleration is due to a Cosmological Constant or due to some new constituent of our Universe (Quintessence) we do not yet know

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