The Early Universe
A Journey into the Past

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March 16, 2006

Outline

Gravity: Einstein's General Theory of Relativity

Cosmology: History of the Universe

What is the Universe made of?
Galileo and falling bodies

- Galileo Galilei: all bodies fall at the **same speed**
- **force** needed to **accelerate** a body is proportional to its **mass**: \( F = ma \)
- **gravitational force** also proportional to **mass**: \( F = mg \)
- **acceleration** independent of mass: \( a = g \)

Newton and the universality of gravitation

- Newton: Force pulling an **apple** on earth of same kind as force holding the **moon** in its orbit around the earth
- same mathematical laws apply to **planets** and **sun**
- Newton could explain motion of heavenly bodies from one **universal law of gravity**
Einstein and the equivalence principle

- observer cannot decide by any experiment whether his elevator is at rest in earth’s gravitational field or accelerating in empty space
- Gravity exactly equivalent to accelerating reference frame

Gravity = warped space-time

- measure circumference and diameter of a circle
  - as observer at rest: \( \frac{U}{d} = \pi = 3.1415\ldots \)
  - as observer in rotating system: unit measure \( e' < e \) contracted
    \[ \Rightarrow U' > U, \text{ but } d' = d \]
    \[ \Rightarrow \frac{U'}{d'} > \pi \]

- geometry not Euclidean for accelerated observer
- equivalence principle: gravity is curvature of space-time!

WWW: Geometric meaning of curvature
Is Einstein’s General Theory of Relativity right?

- Precession of Mercury’s perihelion (closest point to the sun)

  - Perihelion rotates about 5600” per century
  - after corrections from gravity of other planets: 43” per century from Einstein’s GTR!

- Bending of light by gravity

  - light bent by gravity (as any “matter”) by 1.75”
  - measured first by Eddington GTR works right!
Is Einstein’s General Theory of Relativity right?

- Gravitational red shift

  loses energy when moving from heavy body ⇒ frequency lowered

  could be tested on earth by high-precision spectroscopy ⇒ GTR works right!

Everyday use: the GPS

- GPS would not work if not corrected for relativistic effects!
The cosmological principle

- no point in space and time is special
- space homogeneous and isotropic
- laws of nature valid everywhere at every time

- cosmological principle: space filled homogeneously and isotropically with matter (on large scales)
General Relativity: the large-scale structure of space-time

- solution of Einstein’s equations with this symmetry depending on density and type of matter
  - space hyperbolic, flat, or spherical (curvature)
  - spatial distances of objects at rest can be time dependent
- observation (Hubble 1929): universe expanding
  - light emitted from stars: known spectra of chemical elements
  - light travelling through expanding universe: wavelengths become larger due to expansion of scale
  - apparent “velocity” of galaxies proportional to distance ("Hubble law")
- Early universe: dense and hot
- Big Bang!

Hubble expansion

Recession velocity: \( v = Hd \)

1 Mpc = \( 3.1 \cdot 10^{22} \) m = \( 3.3 \cdot 10^6 \) ly
History of the universe

- based on known physics: Standard model of particle physics...
- ... and guesses about “new physics”: inflation, super strings

- in the following: what is the matter content of the universe?

The Cosmic Microwave Background

- hot and dense charged particles $\Rightarrow$ lot of photons!
  - photons in thermal equilibrium with matter
- after about 400,000 years
  - universe cooled down ($T \approx 3000$ K)
  - electrically neutral atoms form
  - photons decouple
  - Hubble expansion $\Rightarrow$ wavelengths grow
  - Alpher, Bethe, Gamow (1949): we should see a thermal background of photons in micro-wave range!
  - cosmic microwave background discovered by Penzias and Wilson (1965)
The Cosmic Microwave Background

- nearly perfect black-body spectrum (Planck 1900)
- CMB photons in equilibrium at $T = 2.725 \, K$

Fluctuations in the CMBR

- small density fluctuations of matter before decoupling
- photons have to run through regions of different gravitation
- different temperature $\Rightarrow$ temperature fluctuations $\delta T / T \approx 10^{-5}$
Total amount of energy in the universe

- high-density region contracts under self-gravity at time scale $R$
- at the same time hubble expansion at rate $H_{\text{CMB}}$
- maximum anisotropy expected at a scale $R \approx H_{\text{CMB}}$
- calculate $H_{\text{CMB}}$ assuming total energy content of the universe
- space flat at critical density $\Rightarrow \Omega = \frac{\rho}{\rho_{\text{crit}}}$

$\Rightarrow 0.98 < \Omega_{\text{total}} < 1$
our universe is flat!

How much matter is in the universe?

- $D_L$: distance of galaxy
- $z$: redshift $\lambda_{\text{here}} = (1 + z)\lambda_{\text{star}}$
- If $H = \text{const} = H_0 \Leftrightarrow$ straight line in lower panel
- bending of this line tells us how $H$ changed with time
  $\Rightarrow$ how much matter is in universe
- best fit (given $\Omega_{\text{total}} = 1 \Leftrightarrow k = 0$)
  $\Omega_{\text{matter}} = 0.3$
- What's the rest of 0.7?
- What kind of matter?
What kind of matter is in the universe?

- known nuclear physics tells us about reaction rates, $\Gamma$, of creation and destruction of light elements $d$, $^3\text{He}$, $^4\text{He}$, $^7\text{Li}$
- stops when $\Gamma < H$ ($\sim 1$ sec after big bang)
- measure abundancies of light elements in nebulae
- $\Omega_{\text{baryons}} = 0.04 \pm 0.02$
- Nature of $\sim 25\%$ unknown $\Rightarrow$ “dark matter”
- “dark matter” also seen from motion of stars in our galaxy!

What’s the “rest”? 

- $\Omega_{\text{tot}} \approx 1$, $\Omega_{\text{matter}} \approx 0.3$
  $\Rightarrow$ 70% of energy content missing
- look again at Hubble expansion
- $\Rightarrow$ Universe must expand accelerated today!
- only kind of energy, known so far Einstein’s cosmological constant
- introduced 1918 to get static universe as solution of his equations
- “It’s my biggest blunder!”
- However $\Omega_{\Lambda} \approx 0.7$
Conclusion: We know only 4% of the matter!

- best fit values from WMAP March 2006
- 4% baryonic matter (known)
- 22% dark matter, only guesses what it might be (Supersymmetry?)
- 74% dark energy: THE enigma of modern physics!