The Early Universe
A Journey into the Past

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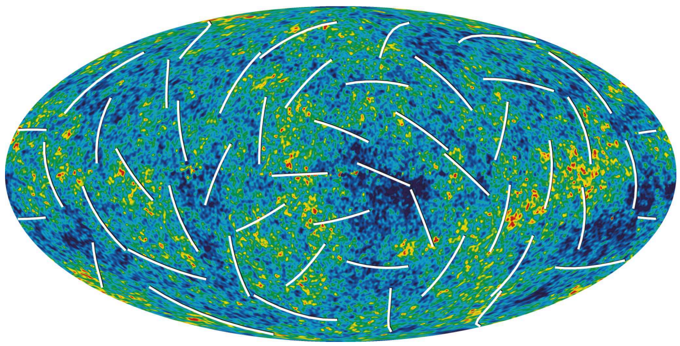
March 16, 2006



Gravity: Einstein's General Theory of Relativity
Cosmology: History of the Universe
What is the Universe made of?

Outline

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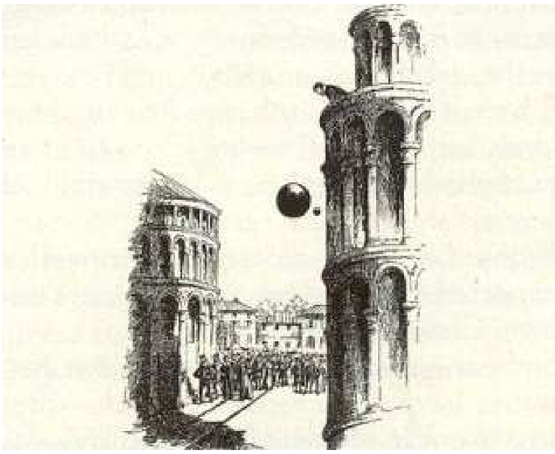
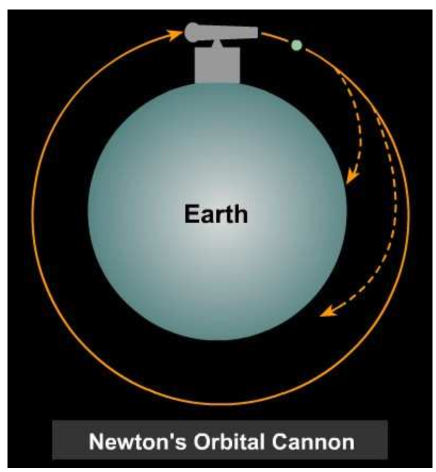
Galileo and falling bodies



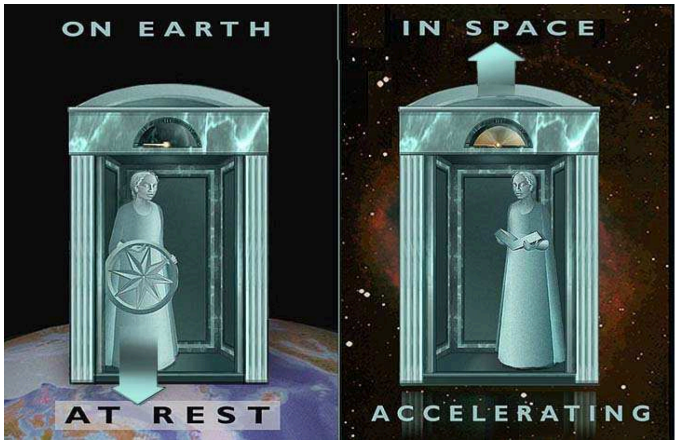
- Galileo Galilei: all bodies fall at the same speed
- force needed to accelerate a body is proportional to its mass: $F = ma$
- gravitational force also proportional to mass: $F = mg$
- acceleration independent of mass: $a = g$

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

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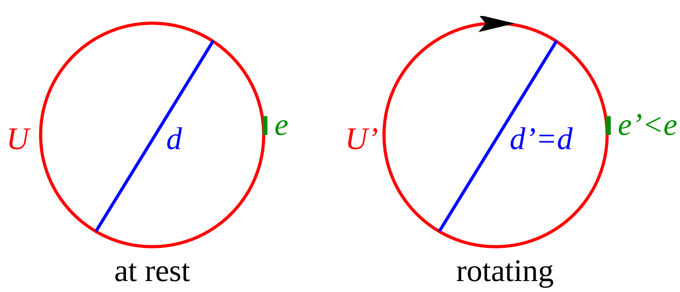
Gravity = warped space-time



- measure circumference and diameter of a circle
  - as observer at rest: $\frac{U}{d} = \pi = 3.1415\dots$
  - as observer in rotating system: unit measure $e' < e$ contracted
    $\Rightarrow U' > U$, 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

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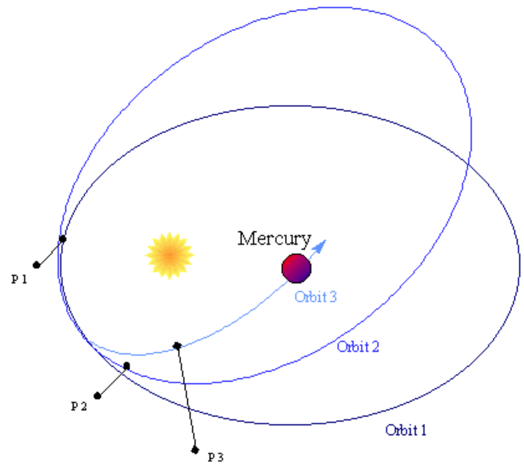
Is Einstein's General Theory of Relativity right?

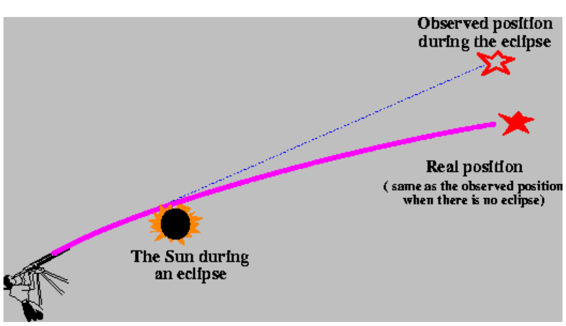
- Precession of Mercury's perihelion (closest point to the sun)

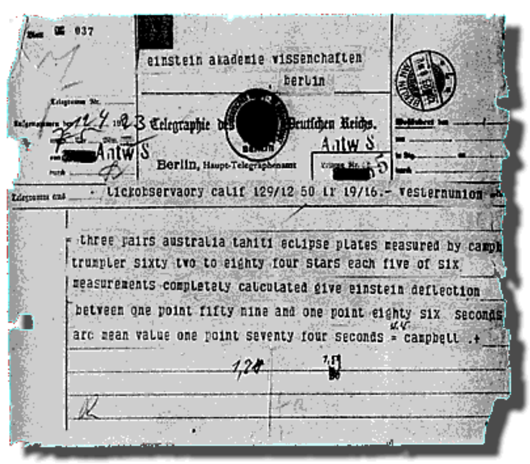


- Perihelion rotates about 5600" per century
- after corrections from gravity of other planets:
  43" per century from Einstein's GTR!

Is Einstein's General Theory of Relativity right?

- Bending of light by gravity

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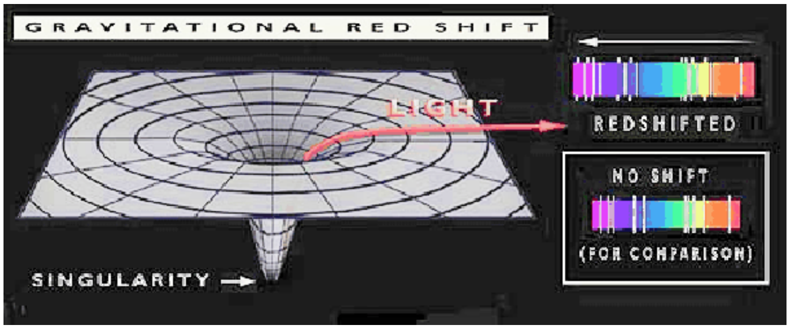
three pairs australia tahiti eclipse plates measured by campbell
trumpler sixty two to eighty four stars each five of six
measurements completely calculated give einstein deflection
between one point fifty nine and one point eighty six seconds
arc mean value one point seventy four seconds = campbell .+

- 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

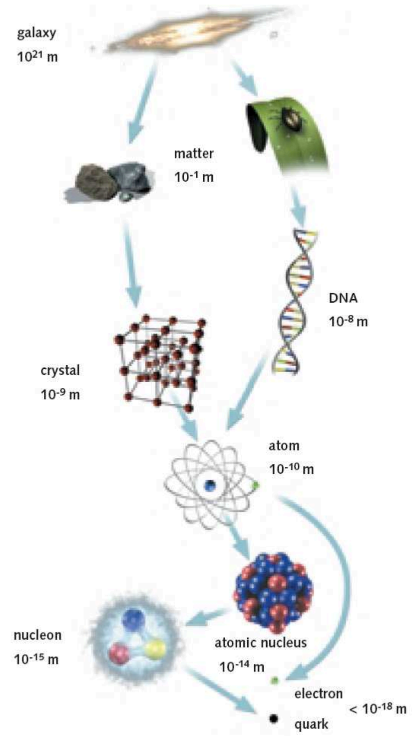


- loses energy when moving from heavy body ⇒ frequency lowered
- could be tested on earth by high-precision spectroscopy ⇒ GTR works right!

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

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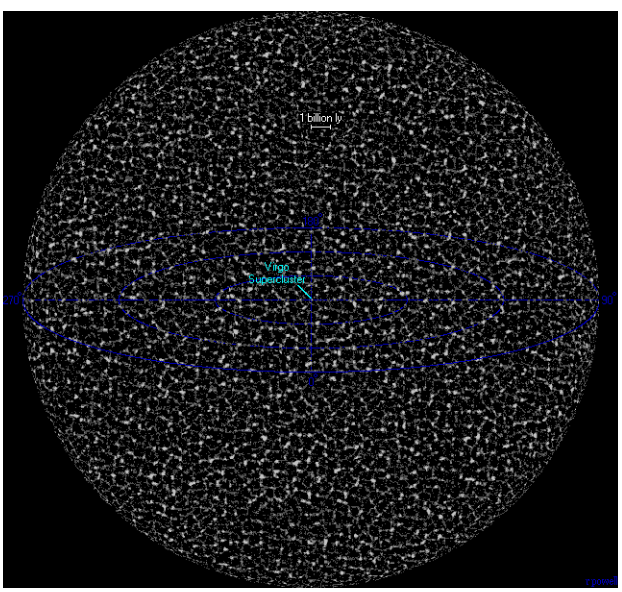
The cosmological principle

- cosmological principle: space filled homogeneously and isotropically with matter (on large scales)



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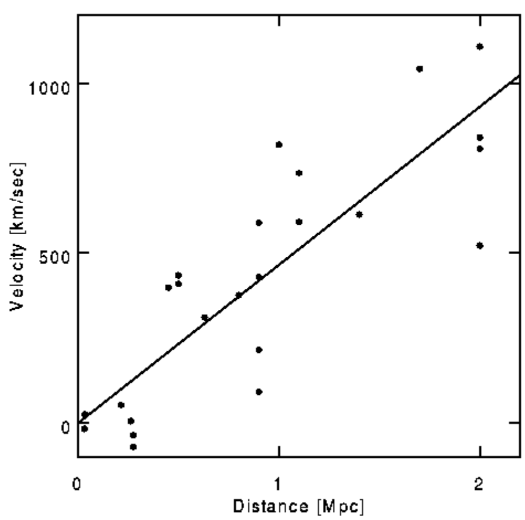
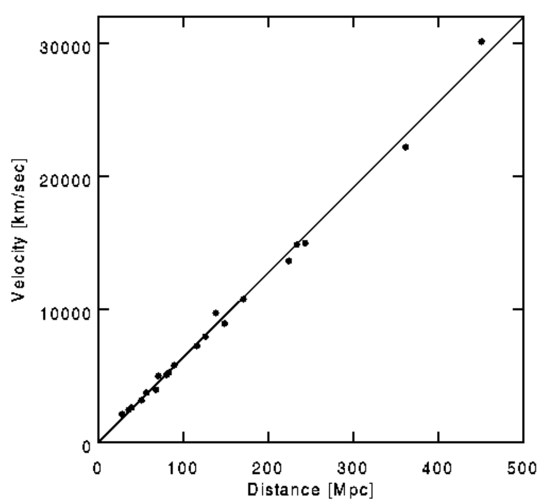
General Relativity: the large-scale structure of space-time

- 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: $v = Hd$

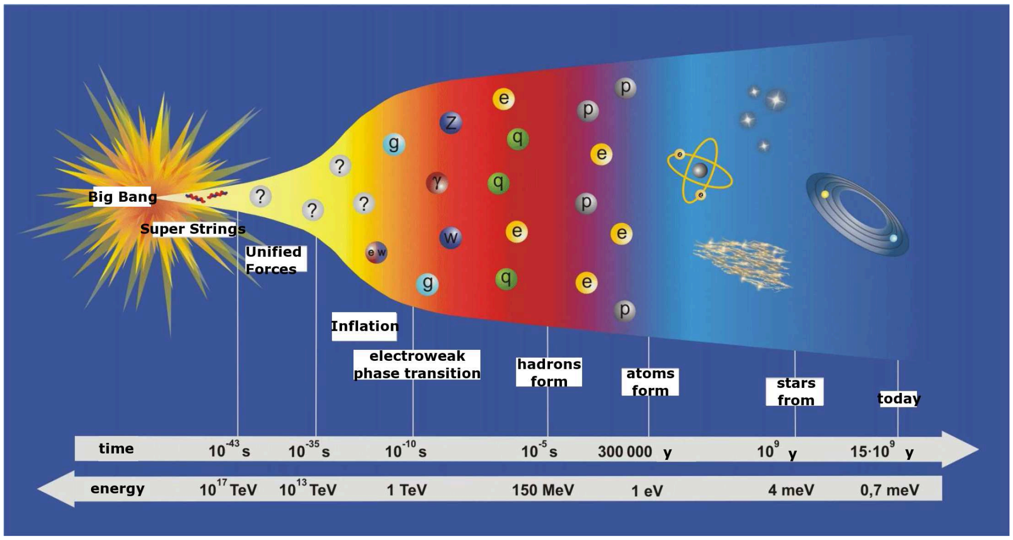




1 Mpc $= 3.1 \cdot 10^{22}$ m $= 3.3 \cdot 10^{6}$ ly

History of the universe

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

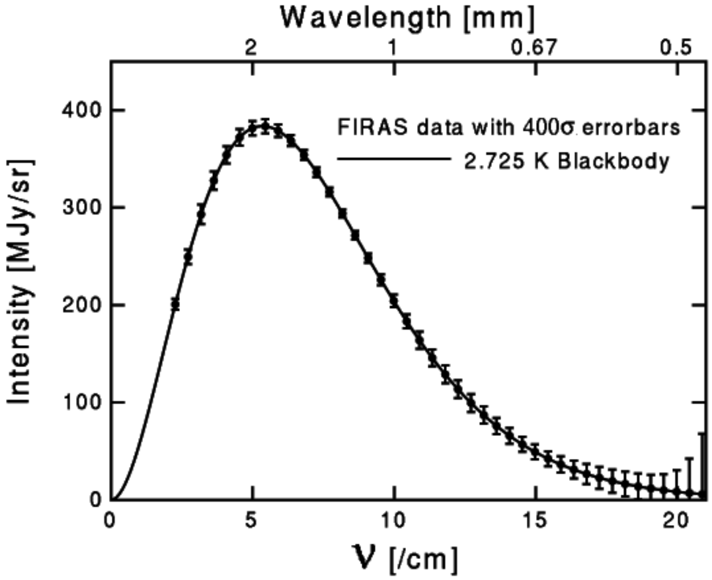


- in the following: what is the matter content of the universe?

The Cosmic Microwave Background

- hot and dense charged particles ⇒ 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 ⇒ 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

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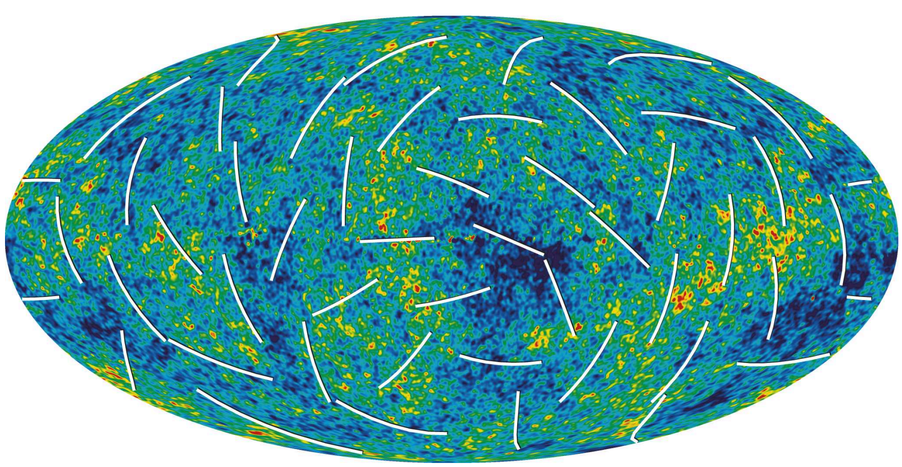
Fluctuations in the CMBR

- small density fluctuations of matter before decoupling
- photons have to run through regions of different gravitation
- different temperature $\Rightarrow$ temperature fluctuations $\delta T/T \simeq 10^{-5}$



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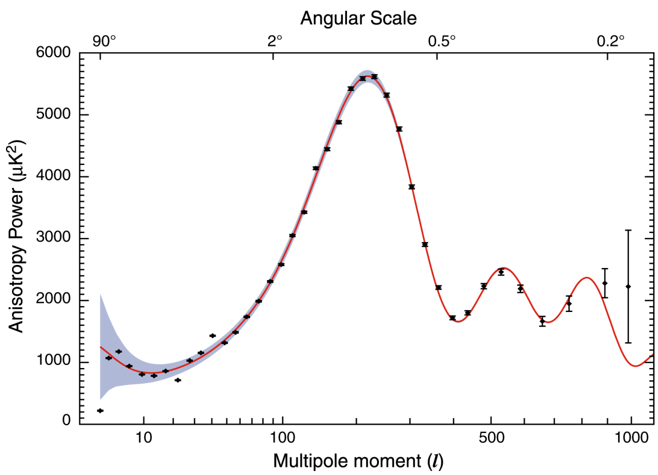
Total amount of energy in the universe

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

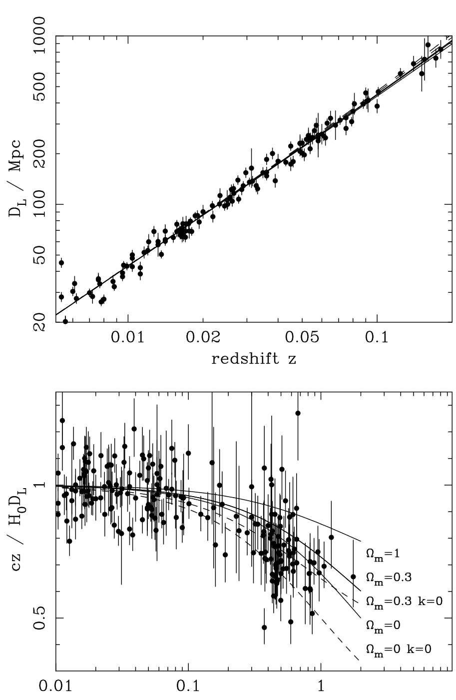


WMAP satellite (NASA)

$\Rightarrow 0.98 < \Omega_{\text{total}} < 1$

our universe is flat!

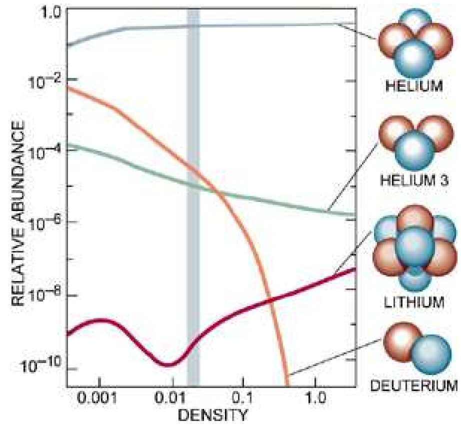
How much matter is in the universe?



- 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?

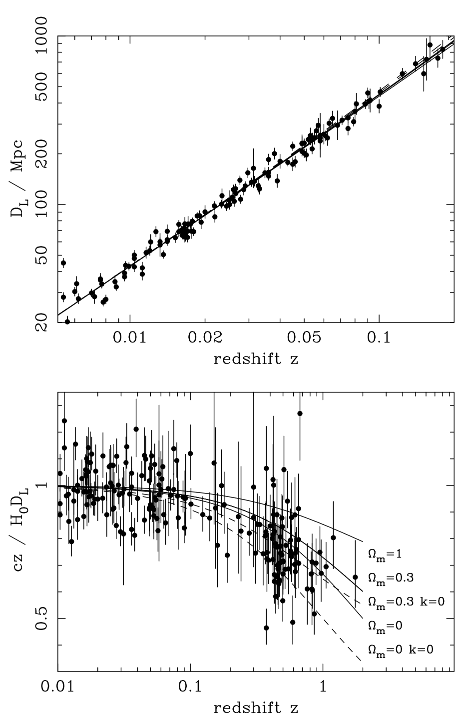
What kind of matter is in the universe?

- known nuclear physics tells us about reaction rates, Γ, of creation and destruction of light elements d, ^{3}He, ^{4}He, ^{7}Li
- stops when $\Gamma < H$ (~ 1 sec after big bang)



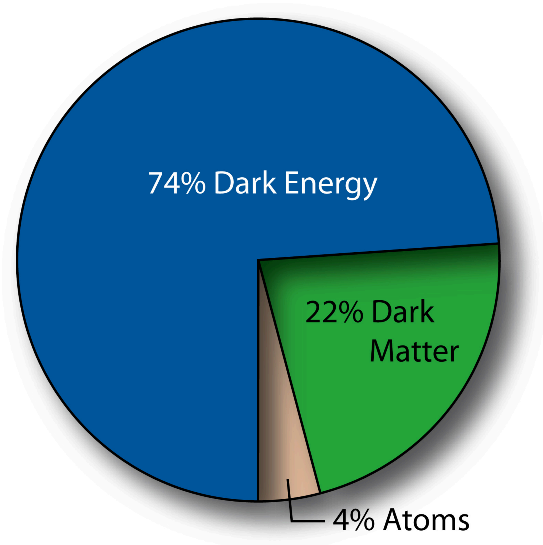
- measure abundancies of light elements in nebulae
- $\Omega_{\text{baryons}} = 0.04 \pm 0.02$
- Nature of $\sim 25\%$ unknown $\Rightarrow$ "dark matter"
- "dark matter" also seen from motion of stars in our galaxy!

What's the "rest"?



- $\Omega_{\text{tot}} \simeq 1$, $\Omega_{\text{matter}} \simeq 0.3$ $\Rightarrow 70\%$ 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 $\Omega_\Lambda \simeq 0.7$

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!

Summary