Einführung in die Astronomie II
Teil 17

Peter Hauschildt
yeti@hs.uni-hamburg.de

Hamburger Sternwarte
Gojenbergsweg 112
21029 Hamburg

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Overview part 17

- Cosmology
- The Early Universe

Cosmology !!

- Why is the sky dark? (Olbers, 1800's; Kepler)
  - infinite space
  - stars scattered within it
  - $\rightarrow$ should see a star in every possible direction
  - so starlight should fill the entire sky
  - $\rightarrow$ it should be as bright as an average star
  - it isn't.
- $\rightarrow$ *Olbers's paradox*

Cosmology !!

- Newton: gravitational force of infinite number of stars should crunch everything together
- $\rightarrow$ something's fishy with an infinite static universe
- Einstein: space and time closely coupled space-time
- general relativity (GR) $\rightarrow$ no static universe!
- Einstein didn't like that, introduced ad hoc fix $\rightarrow$ *cosmological constant* Λ
- produces pressure to balance universe to make it static
- today's term: 'Dark Energy'

The expanding universe !!

- Hubble law $\rightarrow$ universe expands with

$$v = H_0 d$$

- this is an expansion of space itself!!
- 2D analogy: balloon
- no center, expansion follows Hubble law
- explains redshift of remote galaxies as *cosmological redshift*
- photon on its way to Earth $\rightarrow$ space expands $\rightarrow$ wavelength gets longer
- this is *not* a Doppler shift

The expanding universe

- expansion factor of the universe:
- solve redshift relation

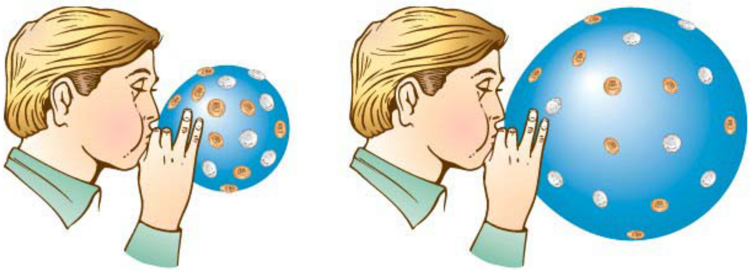
$$z = \frac{\lambda - \lambda_0}{\lambda_0}$$

for λ/λ_0 as a measure of the stretching:

$$\lambda/\lambda_0 = 1 + z$$

- example: $z = 3 \rightarrow$ universe stretched by a factor of 4!

Expansion of the universe



The expanding universe !!

- Cosmology: no experiments possible
- needs to try to use a few assumptions/axioms and go from there
- *cosmological principle*:
  - the universe is *homogeneous* (every region looks the same)
  - the universe is *isotropic* (every direction looks the same)

The Big Bang !!

- universe is expanding for billions of years
- $\rightarrow$ early on, it must have been smaller
- beginning as a single "point" with a *Big Bang*
- we know the speed of the expansion and the distance to galaxies
- calculate how long ago the Big Bang happened:

$$T_0 = \frac{d}{v}$$

The Big Bang

- use Hubble law to eliminate v

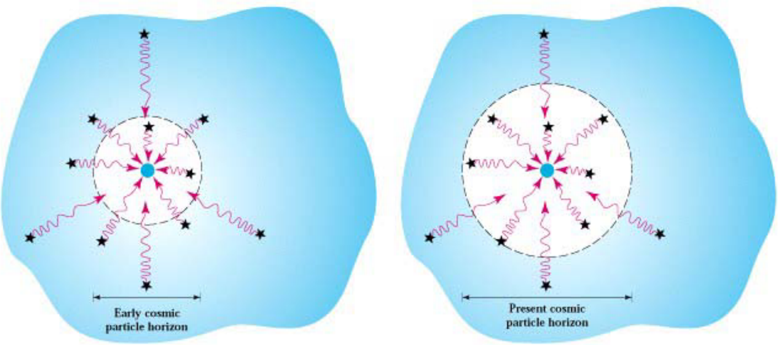
$$T_0 = \frac{d}{v} = \frac{d}{H_0 d} = \frac{1}{H_0}$$

- $\rightarrow$ inverse of H_0 gives estimate for the age of the universe!
- standard value of $H_0 \rightarrow$ universe is 11-16 billion years old
- if rate of expansion was faster in the past $\rightarrow$ universe is younger
- if rate of expansion was slower in the past $\rightarrow$ universe is older

The Big Bang !!

- finite age solves Olbers's paradox
- light from stars farther away than 15 billion ly has not reached us yet!
- $\rightarrow$ *cosmic particle horizon*:
  size of the *observable universe*
- cannot see beyond this!
- cosmological redshift also helps to solve Olbers's paradox

Particle Horizon



The Big Bang

- at the Big Bang, the universe was comparable to a BH
- center of a BH $\rightarrow$ singularity
- $\rightarrow$ *cosmic singularity*
- space-time completely mixed up
- can't know anything prior to the *Planck time*

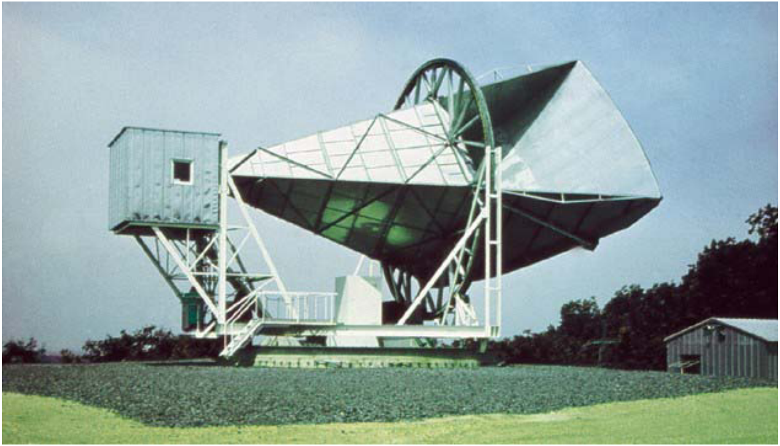
$$t_P = \sqrt{\frac{Gh}{c^5}} = 1.35 \times 10^{-43}\,\mathrm{s}$$

- laws of physics only work after t_P

Microwave Background !!

- matter shortly after Big Bang extremely hot
- produces He nuclei in the early universe
- and lots of high energy photons (thermal radiation)
- universe has expanded enormously since then!
- cosmological redshift $\rightarrow$ these photons are now low-energy long wavelength photons
- changes the apparent temperature of the radiation "field" to a few K
- should peak around 1mm wavelength

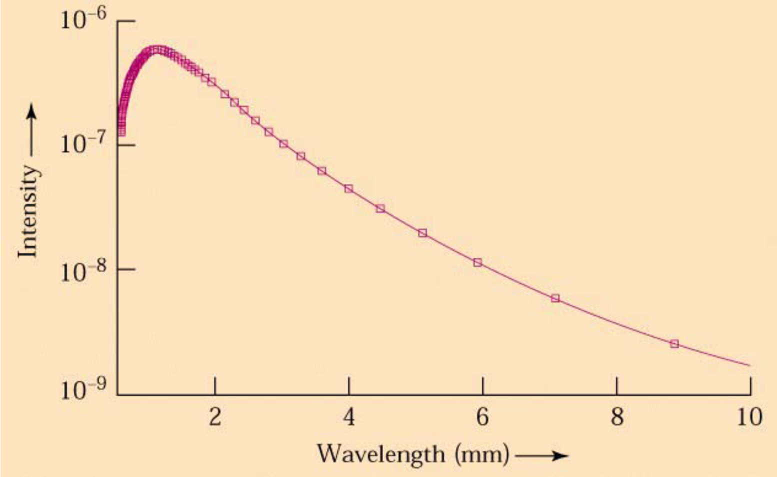
Microwave Background Radiation



Microwave Background Radiation

- was detected by accident as faint background noise
- best observed from space (atmosphere opaque for it!)
- nearly perfect black body with $T = 2.726\,\mathrm{K}$
- $\rightarrow$ *cosmic microwave background (CMB)*

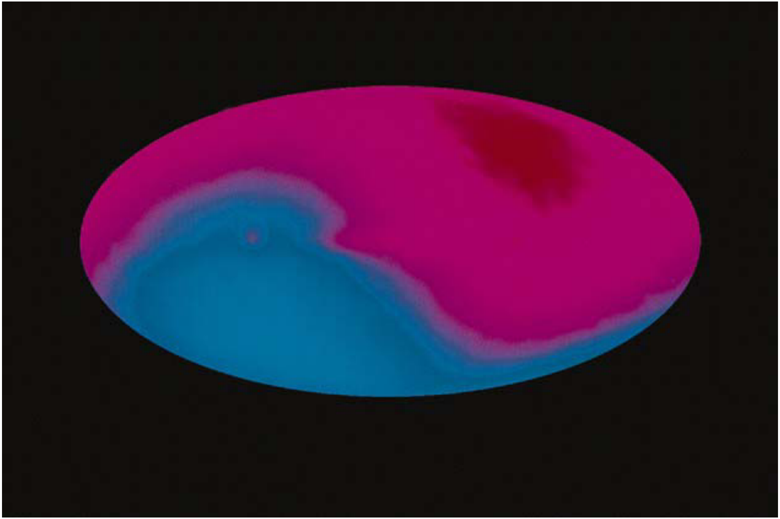
Microwave Background Radiation



Microwave Background Radiation

- slight temperature variation observed:
  - slightly “warmer” toward Leo
  - slightly “cooler” toward Aquarius
  - explained by overall motion of the Earth relative to the CMB
  - Doppler effect results in apparent temperature change
  - corresponds to 0.0033 K or $370\,\mathrm{km\,s^{-1}}$
  - $\rightarrow$ solar system is traveling in the direction of Leo

Microwave Background Radiation



Microwave Background Radiation

- account for motion of the Sun within the Milky Way
- $\rightarrow$ Milky Way moving at $600\,\mathrm{km\,s^{-1}}$ toward the Hydra-Centaurus supercluster
- more galaxies (including the supercluster) appear to move in the same direction
- $\rightarrow$ toward the *Great Attractor*

The young Universe !!

- what is more important in the universe: matter or radiation?
- both carry energy or, equivalent via $E = mc^2$, mass
- compare mass densities to learn more
- *mass density of radiation*
- combine $E = mc^2$ with Stefan-Boltzmann law $\rightarrow$

$$\rho_{\mathrm{rad}} = \frac{4\sigma T^4}{c^3}$$

- today: $T = 2.72\,\mathrm{K} \rightarrow$

$$\rho_{\mathrm{rad}} = 4.6 \times 10^{-31}\,\mathrm{kg/m^3}$$

The young Universe

- *average density of matter:*
- measure mass in some large region
- $\rightarrow$ hard to do!
- presently best estimate $\rho_{\mathrm{m}} = 2 \ldots 11 \times 10^{-27}\,\mathrm{kg/m^3}$
- about 1 to 6 H atoms per m^3
- $\rho_{\mathrm{m}} \gg \rho_{\mathrm{rad}}$
  $\rightarrow$ *matter dominated universe* (today!)

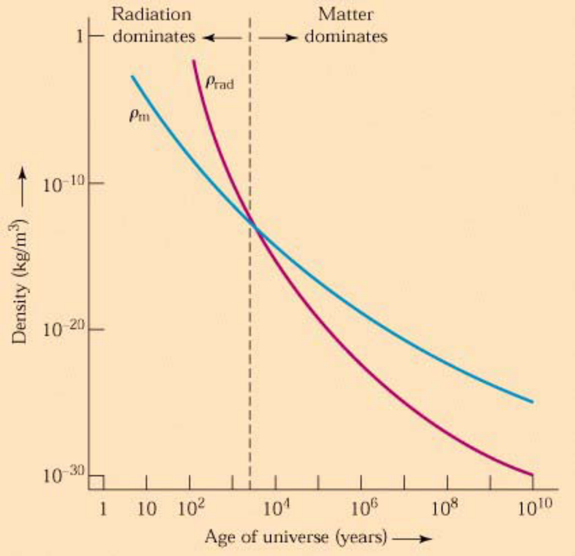
The young Universe

- in the past: universe was smaller!
- smaller volume $\rightarrow$ greater mass density
- same for photons!
- but in addition they were also less redshifted (larger T)
- $\rightarrow \rho_{\mathrm{rad}}$ increases faster than ρ_{m} going back in time
- $\rightarrow$ earlier, the universe was *radiation dominated*

The young Universe

- transition: about 2500 yr after the Big Bang at $z = 25,000$
- space was smaller by a factor of 25,000 compared to today
- $\rightarrow$ CMB peak wavelength from 1mm to $40\,\mathrm{nm}$!
- $\rightarrow$ temperature of CMB was $75,000\,\mathrm{K}$

The young Universe !!



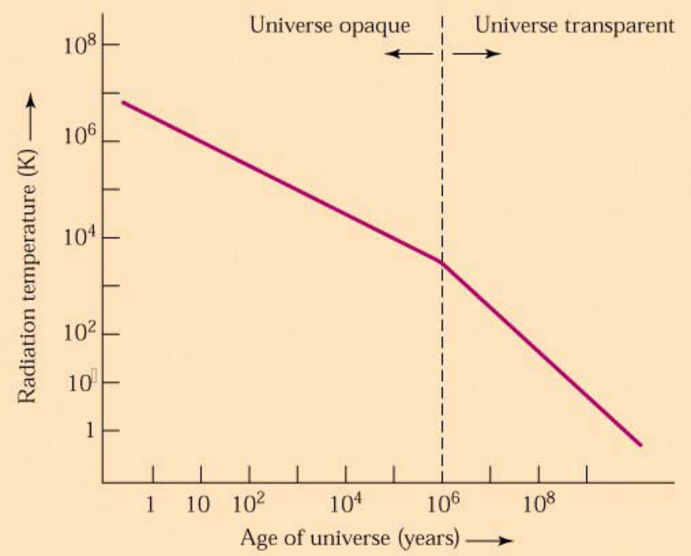
The young Universe !!

- 300,000 yr after Big Bang:
- T of CMB drops to 3000 K
- this is the temperature where protons and electrons can combine to form hydrogen!
- $\rightarrow$ *era of recombination*
- before this, the plasma filling the universe was very opaque
- $\rightarrow$ *primordial fireball*

The young Universe !!

- after the era of recombination, the material is more transparent
- photons and matter decouple and start having different temperatures
- $\rightarrow$ we cannot see farther back than the era of recombination
- tiny deviation from isotropy measured for the CMB
- $\rightarrow$ matter and radiation not perfectly uniform at the era of recombination
- these small effects might be the seeds of superclusters etc

The young Universe



The young Universe

- presently, it is expanding
- does the expansion slow down, stay the same or even accelerate?
- $\rightarrow$ depends on the average matter density
- *relativistic cosmology* uses GR to describe the overall structure and evolution of the universe

The young Universe

- average matter density small $\rightarrow$ expansion will continue forever
- $\rightarrow$ universe *unbounded* or *open*
- average matter density high $\rightarrow$ gravity will slow/stop/reverse expansion
- $\rightarrow$ universe *bounded* or *closed*
- in the middle: *marginally bound*

The young Universe !!

- this corresponds to a *critical matter density* ρ_c given by

$$\rho_c = \frac{3H_0^2}{8\pi G}$$

- for the standard H_0 we have

$$\rho_c = 1.1 \times 10^{-26}\,\mathrm{kg/m^3}$$

- luminous matter $\rightarrow \rho_m \approx 2 \ldots 4 \times 10^{-29}\,\mathrm{kg/m^3}$
- total matter: $\rightarrow \rho_m \approx 2 \times 10^{-27}\,\mathrm{kg/m^3}$
- $\rightarrow$ both appear to be too small!

The young Universe !!

- more often the *density parameter*

$$\Omega_0 = \frac{\rho_m}{\rho_c}$$

  is used
- $\Omega_0 < 1 \rightarrow$ open
- $\Omega_0 = 1 \rightarrow$ marginal
- $\Omega_0 > 1 \rightarrow$ closed
- today: $\Omega_0 \approx 0.2 \ldots 0.3$
- the above assumes $\Lambda = 0$, which is not the case...

The deceleration parameter !!

- expansion slowed by gravity
- $\rightarrow$ causes deviations from Hubble law for extremely remote galaxies
- no deceleration $\rightarrow$ Hubble law holds perfectly
- changes parameterized with *deceleration parameter* q_0
- $q_0 = 0 \rightarrow$ no deceleration
- $q_0 = 1/2 \rightarrow$ marginally bound universe (barely expands forever)
- $0 < q_0 < 1/2 \rightarrow$ open universe, expands forever
- $q_0 > 1/2 \rightarrow$ closed universe, expansion will halt

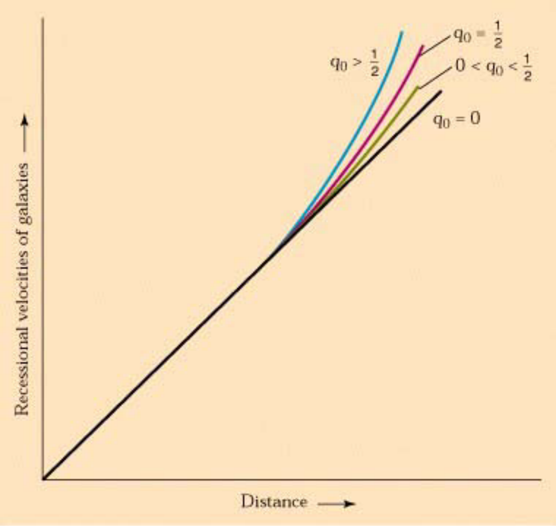
The deceleration parameter !!

- relation between Ω_0 and q_0:

$$\Omega_0 = 2q_0$$

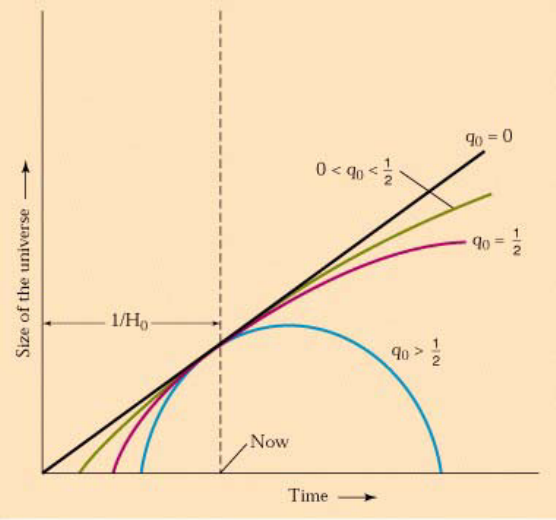
- should be possible to determine q_0 by observing far away galaxies
- $\rightarrow$ very difficult to do! (need distance!)
- SN Ia appear to work pretty well
- observations $\rightarrow$ expansion *accelerates*!
- $\rightarrow$ "Dark Energy"

The deceleration parameter



a

The deceleration parameter

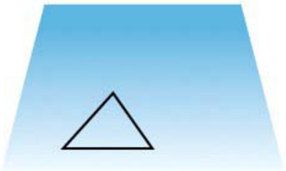


b

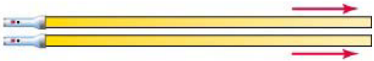
The shape of the universe

- GR: gravity shapes space-time
- space has a curvature (like a 2D surface!)
- this depends on the mass in the universe
- curvature very difference for open, marginal and closed universes
- *flat space (zero curvature)*:
  parallel lines stay parallel, marginal
- *spherical space (positive curvature)*:
  parallel lines converge, closed

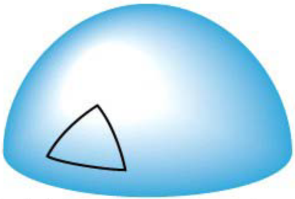
Flat space



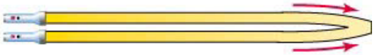
b Flat space $\rho = \rho_c$



Spherical space



a Spherical space $\rho > \rho_c$



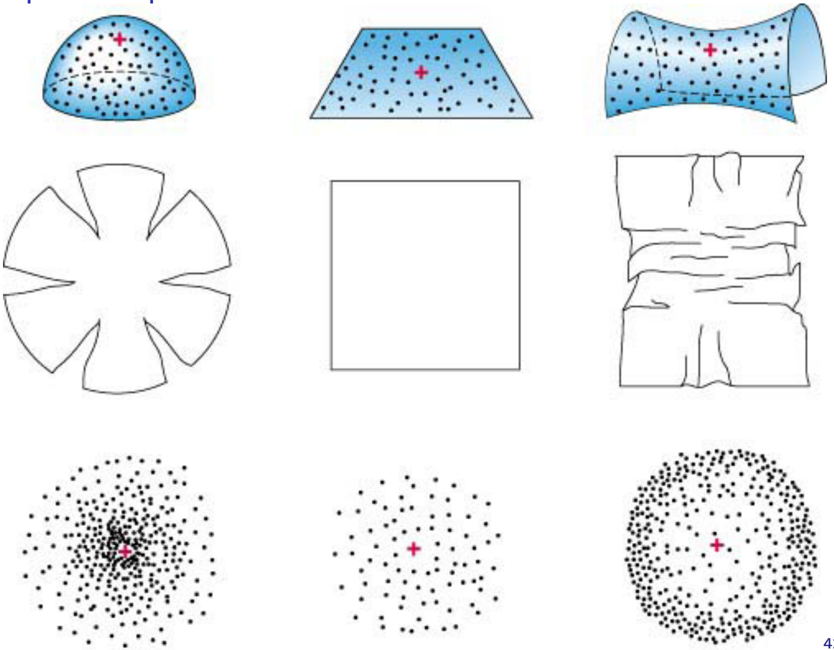
The shape of the universe

- *hyperbolic space (negative curvature)*:
  parallel lines diverge, open
- can be measured by making a map of the density of galaxies
- independent method of determining the geometry/fate of the universe
- hard to do...

Hyperbolical space

c Hyperbolical space $\rho < \rho_c$

shape of space !!



The shape of the universe

- if the universe is closed, it will eventually contract toward the
- *Big Crunch*
- this would be the end of the current universe
- we cannot tell at all what would happen after the Big Crunch

The shape of the universe !!

- if the universe is open, the it will expand forever
- much of its matter will eventually (10^{27} yr) collect in huge BH
- these will then merge to hypermassive BHs ($10^{15}\,M_{\odot}$) within 10^{31} yr

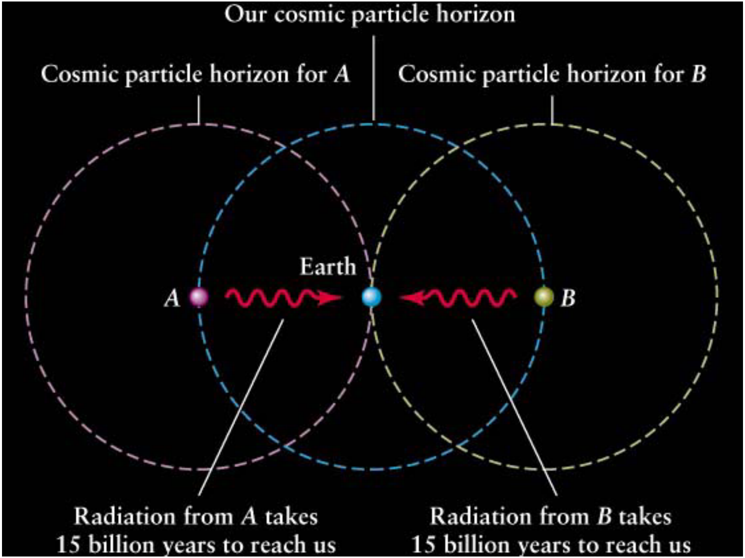
The shape of the universe

- the BHs don't last forever, either
- quantum mechanics $\rightarrow$ matter can with small chance be emitted by BHs
- $\rightarrow$ BH evaporates
- this takes extremely long:
  stellar mass BH: 10^{67} yr
  hypermassive BH: $10^{97...106}$ yr
- very small (low mass) BH evaporate fast and become *white holes*

Early Universe: Inflation

- universe is very isotropic
- how did it become so isotropic?
- locations that are outside their cosmic particle horizons were never in contact

Isotropy Problem !!



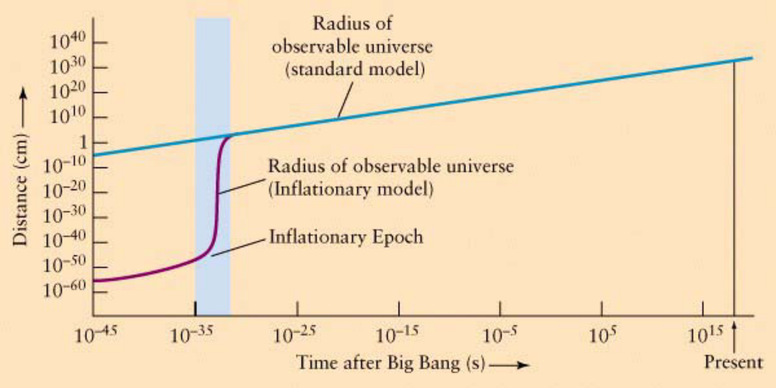
Early Universe: Inflation !!

- why are (and were) their temperatures so close?
- $\rightarrow$ *isotropy/horizon problem*
- another problem: why is the universe very nearly flat? $\rightarrow$ *flatness problem*
- Ω_0 must be very close to one
- $\rightarrow$ very special case!
- Ω_0 must have been *extremely* close to one shortly after the Big Bang
- any deviation would have sky-rocketed within seconds

Early Universe: Inflation !!

- possible solution: *inflation* (Guth, 1980s)
- short period (10^{-24} s) of extremely fast expansion of the universe (factor 10^{50})
- triggered by a cosmological constant $\neq 0$ for a short time
- before inflation, the universe was in close contact and had a single T
- after inflation, this situation was still preserved
  $\rightarrow$ solution of isotropy/horizon problem
- also addresses the flatness problem
- note: expansion of space, nothing moved faster than c

Inflation



Radius of observable universe (standard model)
Radius of observable universe (Inflationary model)
Inflationary Epoch
Distance (cm)
10^{40}
10^{30}
10^{20}
10^{10}
1
10^{-10}
10^{-20}
10^{-30}
10^{-40}
10^{-50}
10^{-60}
10^{-45}
10^{-35}
10^{-25}
10^{-15}
10^{-5}
10^{5}
10^{15}
Present
Time after Big Bang (s)

Origin of matter

- inflation helps to explain the origin of matter
- quantum mechanics limits the amount of information we can have about a particle
- $\rightarrow$ *Heisenberg uncertainty principle*

$$\Delta E \times \Delta t = \frac{h}{2\pi}$$

- using $\Delta E = \Delta m c^2$ we can write this in form of mass:

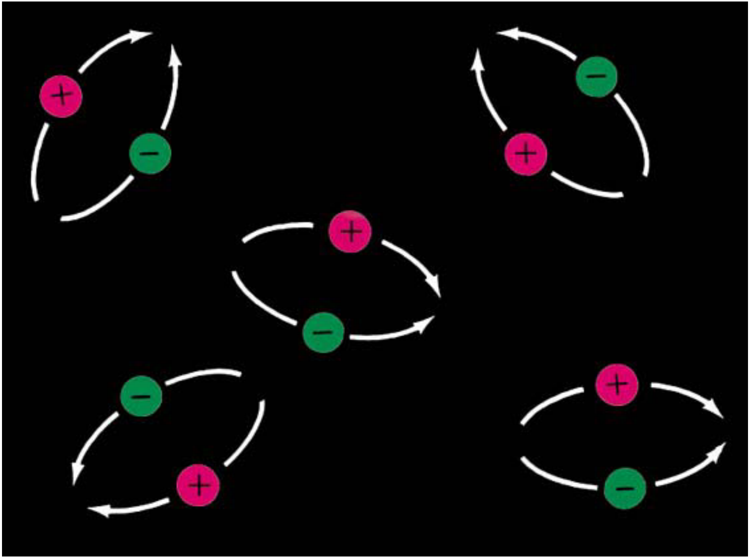
$$\Delta m \times \Delta t = \frac{h}{2\pi c^2}$$

- $\rightarrow$ over a very small Δt we cannot tell how much matter is in any location (even "empty")

Origin of matter

- for each particle of matter, a corresponding particle of *antimatter* is produced
- $\rightarrow$ *symmetry*
- these pairs last only for a very short time
- example: electron-positron pairs last for $\approx 6 \times 10^{-22}\,\mathrm{s}$
- worse for more massive particles

Virtual Pairs



Origin of matter

- spontaneous matter creation can happen anywhere anytime
- but cannot be observed due to the uncertainty principle
- $\rightarrow$ *virtual pairs*
- their effect can actually be observed as tiny shifts of spectral lines
- when matter and antimatter come together
  $\rightarrow$ *annihilation*
- produces high-energy gamma rays
- during inflation, virtual pairs were rapidly separated and became real particles

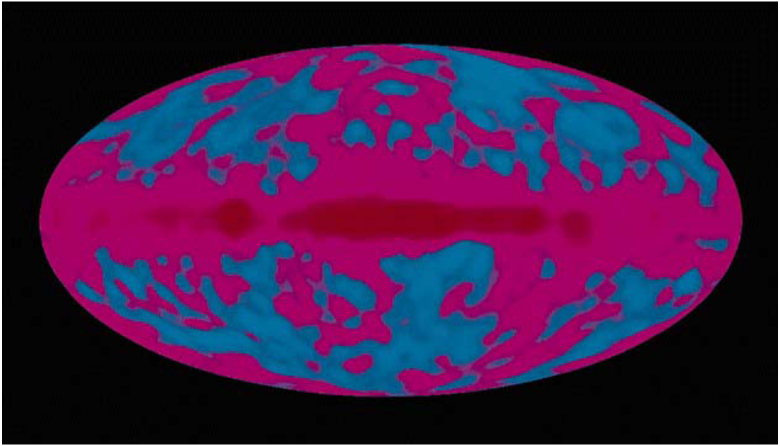
Origin of matter !!

- when inflation stopped, the annihilation began!
- normally, we would expect full symmetry
- but this didn't happen, for every billion antiprotons/protons there was one excess proton
- $\rightarrow$ universe is filled with particles
- $\rightarrow$ *symmetry breaking*
- during the first 15min after the Big Bang, the universe was hot enough to produce He (and Li) nuclei
- this produced a (today) 2K neutrino background

Density Fluctuations

- universe was not perfectly uniform
- tiny *density fluctuations* affected the distribution of material

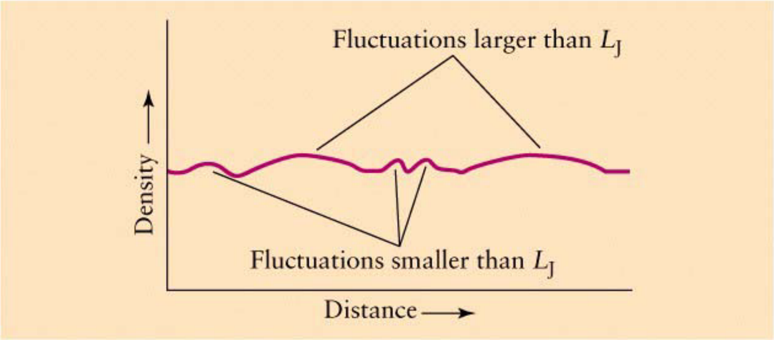
Density Fluctuations



Density Fluctuations

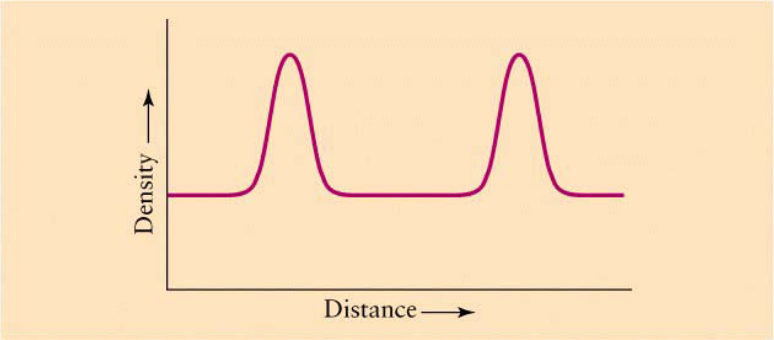
- at the era of recombination, these fluctuations could grow
- estimates show that they are comparable to globular clusters

Density Fluctuations



a At an early time

Density Fluctuations



b At a later time

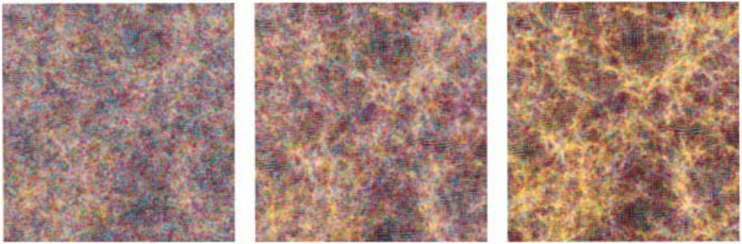
Density Fluctuations !!

- explain the large scale structure of the universe with different types of dark matter:
  - *hot dark matter*: light particles traveling at high speed
  - *cold dark matter*: massive particles traveling at low speed

Density Fluctuations !!

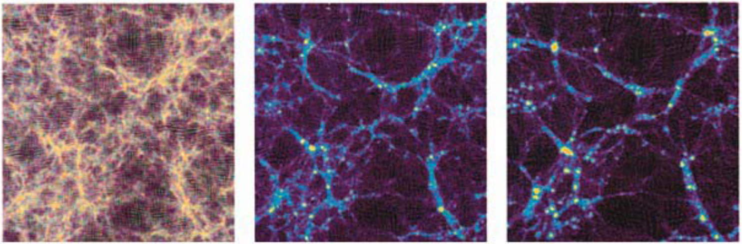
- simulations: starting from a nearly perfectly smooth distribution
- $\rightarrow$ produce intricate structures
- cold and hot dark matter calculations differ in the order of building structures
  - hot dark matter: top down
    (big structures first, small later)
  - cold dark matter: bottom up
    (small structures first, big later)
- observations seem to favor bottom up (cold dark matter)

Cold Dark Matter



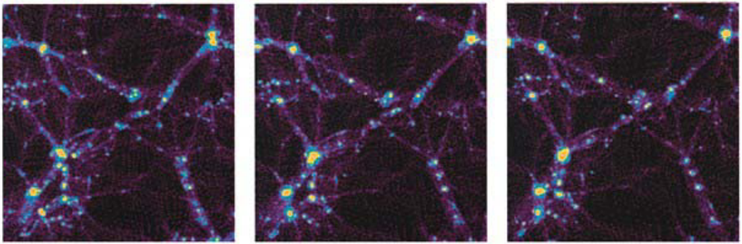
a =004 a =006 a =008

Cold Dark Matter



$a = 010$ $a = 020$ $a = 040$

Cold Dark Matter



a = 060 a = 080 a = 100

Grand Unified Theories

- 4 forces (gravity, electromagnetism, strong/weak nuclear)
- strong/weak nuclear forces: short ranged
- strong force: holds nuclei together
- weak force: certain types of radioactive decay
- electromagnetic/gravity: long range forces
- electromagnetic force: 10^{39} times stronger than gravity

Grand Unified Theories

- but can be *shielded* (requires net charge to operate)
- $\rightarrow$ runs the small scale world (atoms, chemistry)
- gravity: weak, but cannot be shielded (it just curves space!)
- $\rightarrow$ it runs the large scale universe

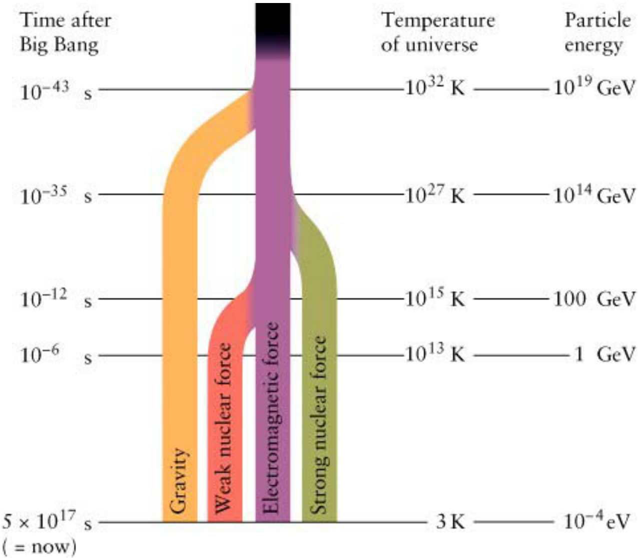
Grand Unified Theories

- can these forces be unified into a single model?
- at extremely large energies (100 GeV) the weak and electromagnetic force merge and become *unified*

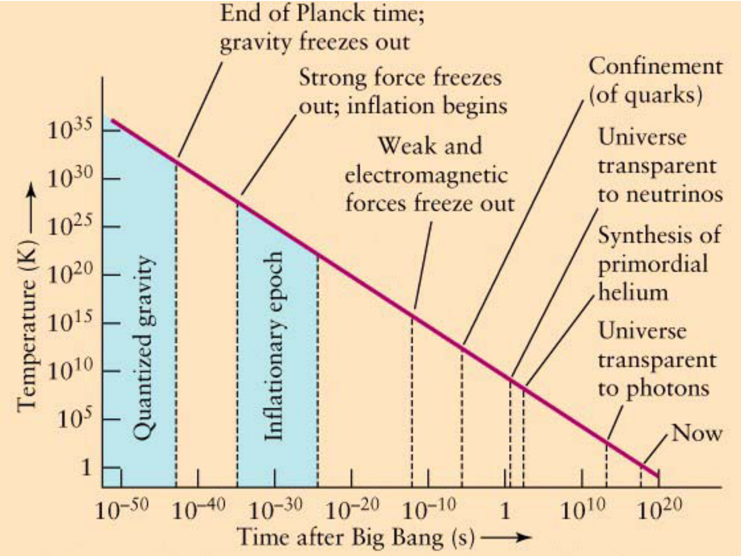
Grand Unified Theories !!

- *Grand Unified Theory (GUT)*: predicts that above 10^{14} GeV the strong forces unifies with the weak and electromagnetic force
- now: search for the *theory of everything (TOE)* that will add gravity to the other 3 forces
- that might require energies larger than 10^{19} GeV
- $\rightarrow$ relevant for different ages of the universe!
- might be the cause for the asymmetry between matter and anti-matter!

GUTs


Time after
Big Bang
Temperature
of universe
Particle
energy
10^{-43} s
10^{32} K
10^{19} GeV
10^{-35} s
10^{27} K
10^{14} GeV
10^{-12} s
10^{15} K
100 GeV
10^{-6} s
10^{13} K
1 GeV
5×10^{17} s
(= now)
3 K
10^{-4} eV
Gravity
Weak nuclear force
Electromagnetic force
Strong nuclear force

TOEs



End of Planck time; gravity freezes out
Strong force freezes out; inflation begins
Weak and electromagnetic forces freeze out
Confinement (of quarks)
Universe transparent to neutrinos
Synthesis of primordial helium
Universe transparent to photons
Now
Quantized gravity
Inflationary epoch
Temperature (K)
10^{35}
10^{30}
10^{25}
10^{20}
10^{15}
10^{10}
10^{5}
1
10^{-50}
10^{-40}
10^{-30}
10^{-20}
10^{-10}
1
10^{10}
10^{20}
Time after Big Bang (s)