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The Big Bang, the genesis of the Universe, the origin of the microwave background

a(t) = 0

Fred Hoyle (1915 – 2001)

- The origin of the universe: a(t) = 0
- "Big Bang" coined by Fred Hoyle
  - he calculated the ratio of elements created during the cooling
- Concept includes
  - expansion of the universe
  - microwave background
  - primordial element abundance

How far back can we go?

Einstein & Lemaitre, courtesy: http://www.astronomija.co.yu/teorije/kosmologija/kosmologijaireligija2.htm

- Very far!
  - to within about 10^{-40} s of the Big Bang
- The concept of an origin goes back to Friedmann and George Lemaitre
- George Gamov (~1948) used physics to predict conditions in the very early universe

George Gamov (1904 – 1968)

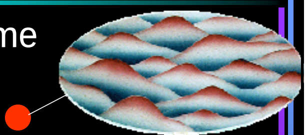
Planck units of space and time

- Planck units are formed from a combination of fundamental constants

Max Planck (1858 – 1947)

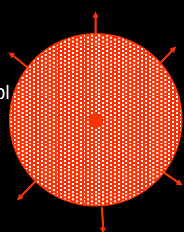
- Length: ℓ_{pl} $\quad l_{pl} = \left(\frac{Gh}{c^3}\right)^{1/2} = 4.13\times10^{-35}$ m
- Time: t_{pl} $\quad t_{pl} = \left(\frac{Gh}{c^5}\right)^{1/2} = 1.38\times10^{-43}$ s

The beginning of time



- 10^{-40}s or $1000t_{pl}$
- Size universe: $1000l_{pl}$
- Wein's law: $T = 3\times10^{-3}/\lambda_{max}$
  - $T \approx 10^{30}$ K
- 3 fundamental forces unified
- radiation ↔ particles + anti-particles
  - 1 part in a billion imbalance

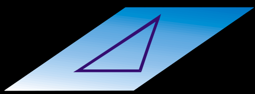
Inflation



- Start of inflation, size ~ 10^8 l_{pl}
- 10^{-35} to 10^{-33} s
- Doubling in size every 10^{-35} s (every 10^8 t_{pl})
  - faster than the speed of light
  - boundaries could no longer affect each other
- End of inflation: size ~ 10^{38} l_{pl}
  - age of universe ~ 10^{10} t_{pl}

Inflation implications

- Sides of universe not in radiation contact
- Universe much bigger than we can explore with light or radio waves
- The geometry of the universe will be 'flat'



First separation of forces

- After inflation, the temperature has fallen to about 10^{23} K
  - universe consists of a soup of free quarks and electrons
- Strong force and the electroweak force become distinct
  - strong force governs binding of quarks
  - electroweak force is carried by W & Z particles (observed at CERN)
    - Rubbia & Van de Meer won Nobel Prize in Physics in 1984 for their work
    - Glashow, Salaam & Weinberg won the 1979 Nobel Prize for theory of electroweak force

Second separation of forces

- After about 10^{-12} s ($\sim 10^{30}\ t_{pl}$), T ~ 10^{15} K separation of electroweak force into weak nuclear force and electromagnetic force (carried by photons)
- Weak force controls β decay and fusion processes in stars

Temperatures quoted in eV

- KE particle at temp T is ~kT, where k is Boltzmann's constant (1.38×10^{-23} J K^{-1})
- Rest mass energy $E = mc^2 = eV$ and V gives the energy in 'electron volts'
    - $e = 1.6\times10^{-19}$ C
    - proton rest mass ~ 10^9 eV = 1 GeV = 1.6×10^{-10} J
  - setting $1.6\times10^{-10} = kT$ gives $T \approx 10^{13}$ K
  - expect protons and neutrons at this temp
- Generally $eV = kT$ and hence $V \propto T$

Formation of hadrons

- About 10^{-6} s, the temperature about 1 GeV, free quarks combine into hadrons
- Baryons form from 3 quarks (e.g. p, n)
  - 1 each of r, g, b quarks

- Mesons from 2 quarks (e.g. pions)
  - 1 each of quark and anti-quark

Neutrinos decouple

- When neutrons and protons first form they are in equilibrium with each other

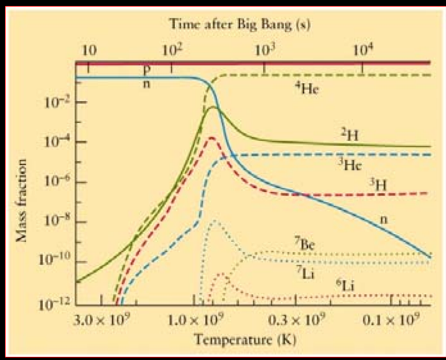
$$e^+ + n \leftrightarrow p + \bar{\nu}_e; \qquad \nu_e + n \leftrightarrow p + e^-$$

- Soup of protons, neutrons, electrons, positrons neutrinos and anti-neutrinos
- With progressive cooling these reactions stop about 1s after the Big Bang, leaving a background of neutrinos
  - decoupling of cosmic neutrinos

~ 1 s: neutrino decoupling

- After neutrino decoupling there will be a decreasing no. of neutrons
  - neutrons have more energy than protons and free neutrons decay into protons
  - ^2H forms from 1 p and 1 n (deuterium)
  - ^4He forms from 2 p and 2 n
- After 1 min, T ~ 10^{10} K, comparable to the core of the Sun
- After ~ 3 minutes, too cool for element creation

Primordial nucleosynthesis



Courtesy: http://www.phys.lsu.edu/faculty/tohline/astr1102/Pics/Fig29-06.jpg

~1000 s

Blue-hot and opaque

- Plasma of electrons, light elements and electromagnetic radiation (and decoupled neutrino background)
- For radiation: T $\propto$ 1/(a(t)); E = σT^4
  - energy density decreases as $1/[a(t)]^4$
- For matter: energy density decreases as $1/[a(t)]^3$
- Radiation energy density decreases faster

Matter dominates after ~ 50,000 years

- At ~50,000 years, matter and radiation had about the same energy density
  - afterwards, matter became dominant
- Temperature was still too hot for atoms to form
- Universe was opaque and white hot
  - free electrons create opacity

White-hot and opaque

The atomic universe ~380,000 yr

- Temp ~ 3000 K; a(t) $\approx a_0/1000$
- Atomic hydrogen forms
- Electrons are now bound
- Universe becomes transparent
- Radiation decouples
  - cools independently from matter
  - now cooled to become microwave background (2.725 K)
- At this time the universe was highly isotropic

Yellow-hot and transparent

The dark ages

- From about 2 Myr background radiation had cooled into IR
- 200 – 400 Myr before first stars

A hot topic

- Modern ideas suggest that the first stars were few but very large

Public interest in astronomy remains high

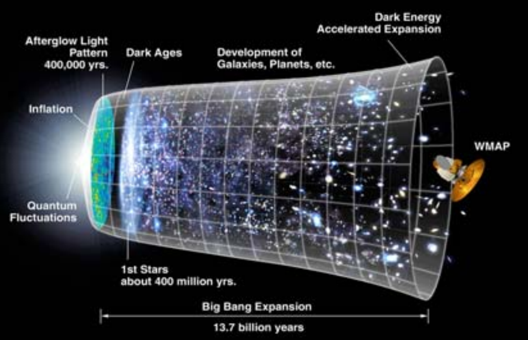
Cosmic microwave background

- Temperature 2.725 K
  - Planck black-body spectrum
  - isotropic
  - our earliest view of the Universe



Robert Wilson & Arnold Penzias

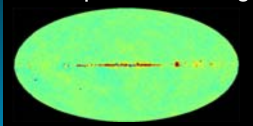
Looking back in time

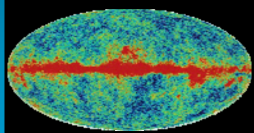


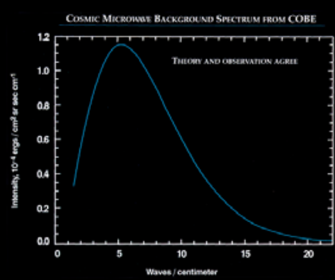
Courtesy: NASA/WMAP

Microwave distribution

- Foreground and background sources
  - peak wavelength 1.8 mm; freq 176 GHz


http://lambda.gsfc.nasa.gov/toolbox/skyviewer/screenshot2.jpg

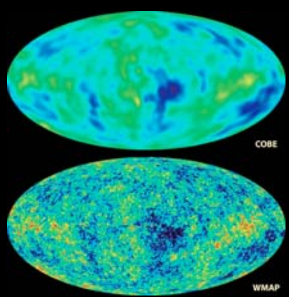

Cosmic microwaves at 41 GHz
Courtesy:http://map.gsfc.nasa.gov/m_or.html



Space probe measurements

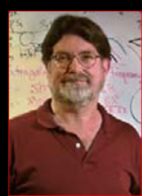
- COBE (Cosmic Background Explorer)
  - launched 1989
- WMAP
  - launched 2001

WMAP heading to L2 courtesy:
http://map.gsfc.nasa.gov/m_ig/990387/WMAPSpacecraft990387_72.jpg



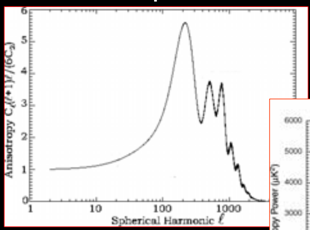
2006 Nobel Prize in Physics

- *for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation*
- John C. Mather
  - NASA Goddard Space Flight Centre
  - prime mover of the COBE mission
- George F. Smoot
  - University of California, Berkeley
  - senior investigator of the COBE anisotropy measurements

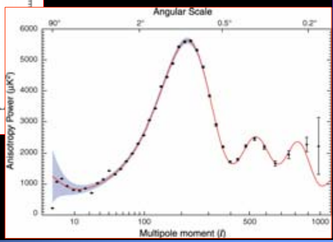


Mather ↑
← Smoot

Ripples in the sky

- Power spectrum of ripples



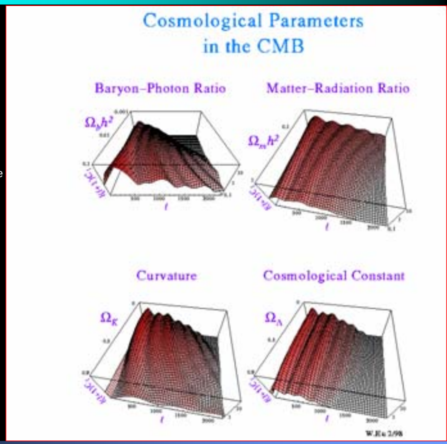
← Computational model expectation



WMAP results →

Ripples and cosmological parameters

Diagram by Wayne Hu http://background.uchicago.edu/%7ewhu/metaanim.html



All action

- Polarisation structure gives extra info
  - CBI (Cosmic Background Imager)
  - CAPMAP (Cosmic Anisotropy Polarisation MAPper)
  - AMI (Arc-minute Microkelvin Imager)
  - QUIET (Q/U imaging experimenT)
  - QUAD
  - CLOVER
  - PLANCK
  - + more

Timeline of the Universe