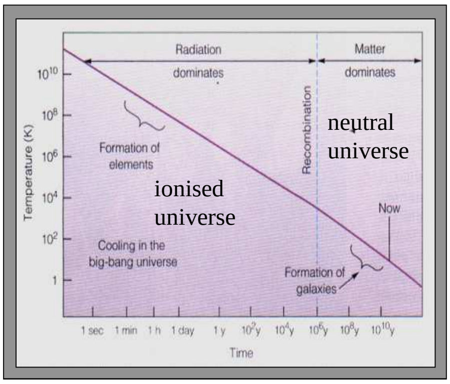
The first 400,000 years…

All about the Big Bang…

- Temperature
- Chronology of the Big Bang
- The Cosmic Microwave Background (CMB)
- The VERY early universe

Temperature and the Big Bang

The universe cools & becomes less dense as it expands.
Redshifted photons have less energy – radiation less important



Temperature plays a VERY important role in the evolution of the universe…

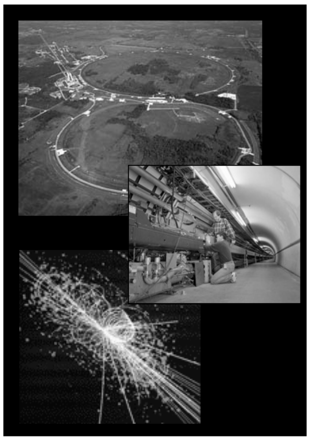
- Different physical processes occur at different times & temperatures.
- To understand physics in early universe we need to understand physics at high temperatures (or energies)

Temperature & the Big Bang…

How far back can we look?

- Depends on accelerator & particle physics technology…
  - Colliding particles mimic early universe.
  - Higher energy -> Higher temp -> Earlier universe

Date	Accelerator	Beam Energy	Equivalent Temperature	Time after Big Bang
1930	**1st Cyclotron** (Berkely)	80 KeV	10^{9}K	200 secs
1952	**Cosmotron** (Brookhaven)	3 GeV	10^{12}K	10^{-8} secs
1987	**Tevatron** (Fermilab)	1000 GeV	10^{16}K	10^{-13} secs
2009	**LHC** (CERN)	>7000 GeV	10^{18}K	10^{-14} secs



Temperature & the Big Bang…

What have colliders told us so far?

The 'Standard Model' of Particle physics.

Forces

Gravity (mass)
Electromagnetic (charge)
Strong } Nuclear
Weak } forces

Particles

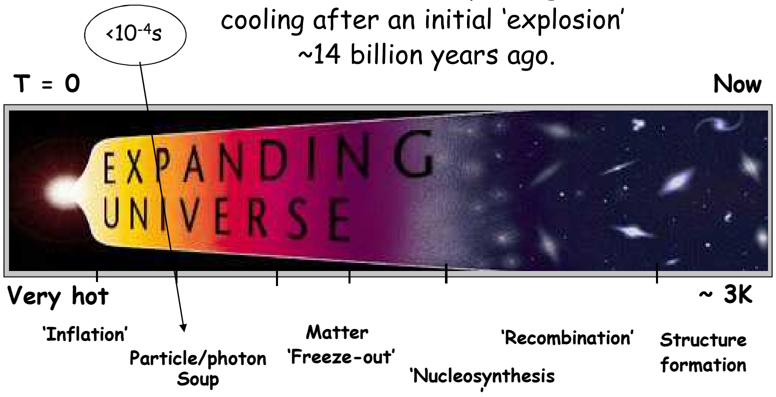
Matter
'Hadrons'
(made of Quarks)
Protons (p)
Neutrons (n)
(etc)…
'Leptons'
Electrons (e-)
Neutrinos (ν)
(etc)…

Anti-matter
'Hadrons'
(made of antiquarks)
anti Protons (p̄)
anti Neutrons (n̄)
(etc)…
'Leptons'
Positrons (e+)
anti Neutrinos (ν̄)
(etc)…

Photons (γ) and other force particles

Quick chronology of the Big Bang…

The universe is expanding & cooling after an initial 'explosion' ~14 billion years ago.

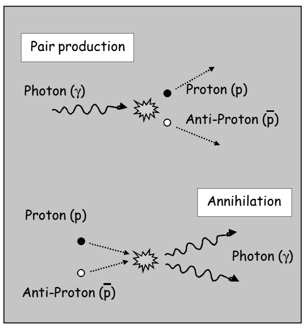


Quick chronology of the Big Bang

Hot particle & photon soup…

Time < 10^{-4}s
Temp > 10^{12}K

- The universe a dense soup of rapidly interacting photons & elementary particles (matter & anti-matter).
- 2 reactions governed the balance of particles and photons :
  1. Matter and antimatter produced by 'pair production'
  2. Photons produced by matter & antimatter annihilation
- Particle production is reliant on high temperature (by $E = mc^2$)

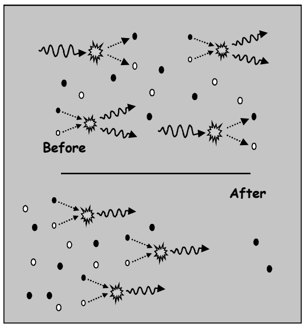


Quick chronology of the Big Bang

Matter 'Freeze-out'…

Time ~ 10^{-4}s
Temp ~ 10^{12}K

- Universe becomes too cool for pair production.
  - Photon energy becomes < particle/anti-particle mass energy ($E < mc^2$)
  - MOST existing particles & anti-particles annihilate leaving small amount of matter
- Why is there any matter at all!?
  - Because of a TINY imbalance of matter over antimatter in particle photon soup.

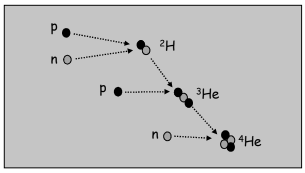


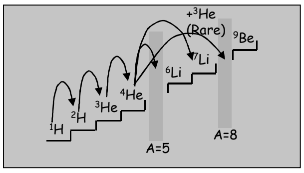
Quick chronology of the Big Bang

Nucleosynthesis

Time ~ 2 mins
Temp ~ 10^9K

- Protons and neutrons combine to form atomic nuclei
  - Protons and neutrons combine to form deuterium (^2H)
  - 1 proton and 1 neutron combine with deuterium to form Helium (^3He and ^4He).
- Production of nuclei in the early universe stops at Helium
  - There are no stable elements with mass 5 or 8 - which stops synthesis of heavier elements.



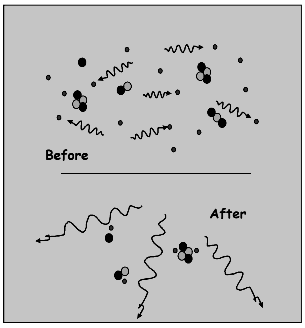


Quick chronology of the Big Bang

Recombination…

Time ~ 380,000 yrs
Temp ~ 3000K

- Electrons combine with nuclei forming atoms.
  - Before now the temperature is too high for electrons and nuclei to bind
- The universe becomes Transparent
  - Photons readily interact with free electrons - so early universe is **OPAQUE**
  - Photons interact with bound electrons much less - so the universe becomes **TRANSPARENT**

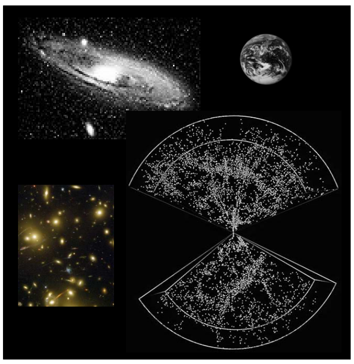


Quick chronology of the Big Bang

Structure formation

380,000 yrs → Now
3000K → 3K

- Under the pull of gravity - all the matter in the universe condenses to form the structures we see today.
  - Gravitation attraction results in gas clouds, stars, galaxies, clusters and super-clusters
  - Heavier elements formed by nuclear fusion in stars
- Later on….
  - The Earth formed ~ 4.6 billion yrs ago
  - Humans appeared ~ 2-4 million yrs ago

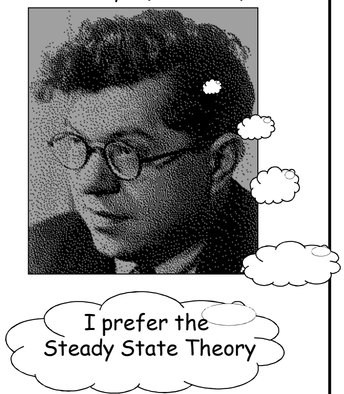


Do we know everything?

No!... Still some long-standing questions about the Big Bang…

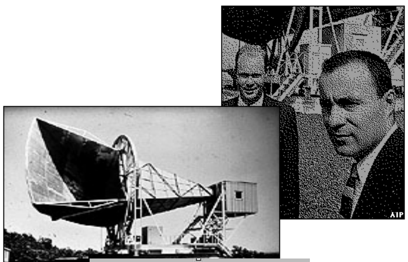
- How/why did the Big Bang start in the first place?
- Why was there a matter/antimatter imbalance?
- What happened in the VERY early universe?

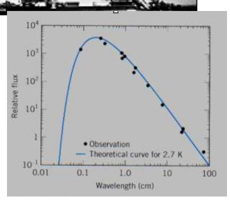
Fred Hoyle (1915-2001)



The Cosmic Microwave Background (CMB)

- 1965 - Penzias & Wilson discover background 'noise' in new radio antenna.
- 1964 - Princeton group predicted radiation left over from big bang:
  - Black body distributed
  - In microwave region: (λ ~mm)
  - T < 50 K
- Actually predicted earlier (1950) – but prediction forgotten!





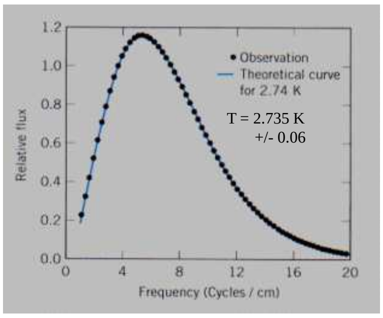
1968 results

The Cosmic Microwave Background (CMB)

- Background radiation found to be almost perfect blackbody spectrum.

'Proof' of the Hot Big Bang

* Nobel Prize 1978 *
Penzias & Wilson

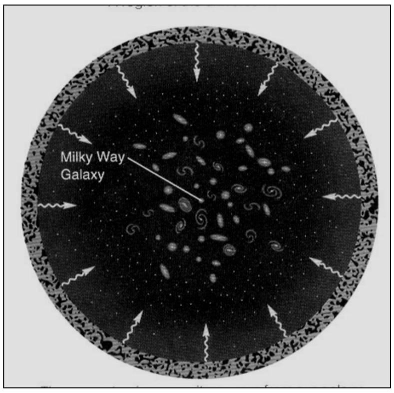


COBE Results
(1990s)

The Cosmic Microwave Background

What is the CMB?

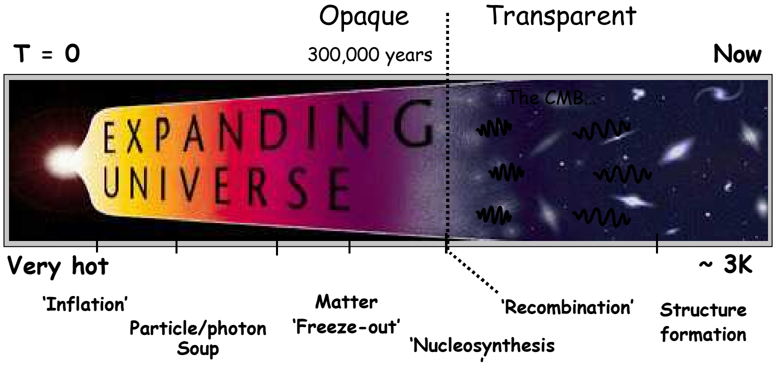
- Radiation left-over from the 'recombination' period of the hot Big Bang.
- Emitted with hot black body spectrum ~300,000 years after Big Bang.
- Photons stretched & cooled by the expansion of the universe (×1000).
- Then: $\lambda \sim 10^{-6}$m T~3000 K
  Now: $\lambda \sim 10^{-3}$m T~3 K



The Cosmic Microwave Background

What is the CMB?

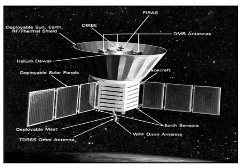
The universe is expanding & cooling after an initial 'explosion' ~14 billion years ago.

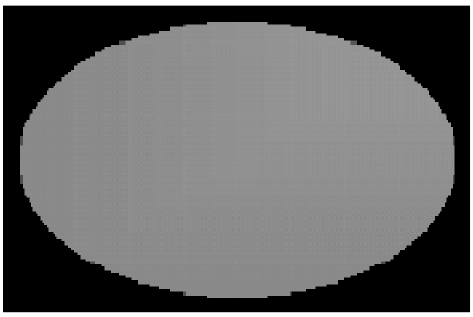


The Cosmic Microwave Background

Mapping the CMB sky

- Cosmic Background Explorer satellite (COBE) launched 1989
- All sky 'temperature' map





CMB is mostly VERY UNIFORM (smoother than 1 in 100,000)
T = 2.728 Kelvin

The Cosmic Microwave Background

Mapping the CMB sky

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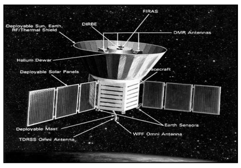
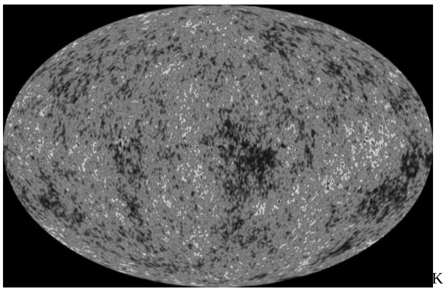
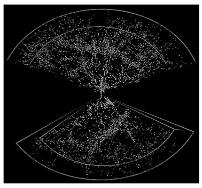




TINY temperature & density fluctuations.

'Seeds' for → today's structure



The Cosmic Microwave Background

CMB Summary

The origins of the CMB…

- Primordial blackbody radiation released after recombination 380,000 years after the big bang.
- Cooled from 3000K to 3K by the expansion of the universe
- Strong Evidence in favour of the Hot Big Bang.

The CMB sky…

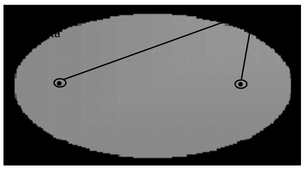
- CMB is mostly VERY UNIFORM (smoother than 1 in 100,000)
- Ripples show temperature & density fluctuations of the early universe.
- Fluctuations = seeds of later structure formation

What happened in the VERY early universe?

Clue 1…
The 'Horizon Problem'
'Why is the Cosmic Microwave Background so UNIFORM?'

- Distant points too far apart to have reached thermal equilibrium before recombination.

limit of influence < 2°

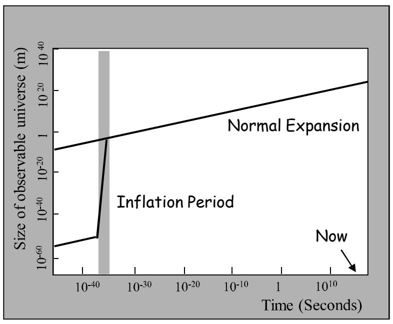


Clue 2…
The 'Flatness Problem'
'Why is the curvature of the Universe so SMALL?'

- If $\rho \neq \rho_c$, difference should grow quickly over time
- Universe should *either* recollapse almost immediately *or* rapidly expand into nothingness.

The VERY early universe
The era of INFLATION (10^{-35}s)

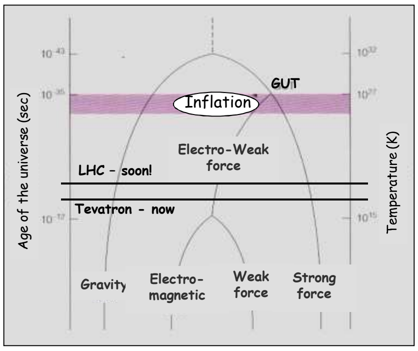
- The theory of 'Inflation' (1980) predicts a period of RAPID expansion.
  - Begins at 10^{-35} seconds after the Big Bang
  - Size of universe increases by 10^{30} - 10^{50}!
- Solves Horizon problem
  - Limits of influence massively increased.
- and Flatness problem
  - Huge expansion factor makes our small part of Universe look very flat.



The VERY early universe

The era of INFLATION (10^{-35}s)

- What caused inflation??



Not sure but…

- Theoreticians think….
  - At high temperatures the forces of nature combine.
  - Inflation occurred when the strong and weak nuclear forces separated.
- Efforts continue to look further and further back.

Summary

The universe is expanding & cooling after an initial 'explosion' ~14 billion years ago.

Opaque | Transparent

T = 0 300,000 years Now

Very hot ~ 3K

'Inflation' Particle/photon Soup Matter 'Freeze-out' 'Nucleosynthesis' 'Recombination' Structure formation