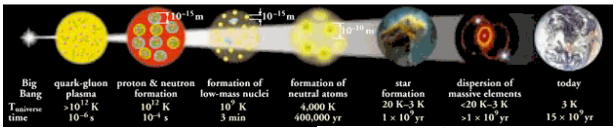
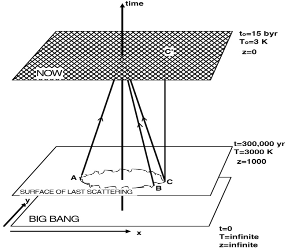
History of the Universe - according to the standard big bang



- Radiaton dominated era
- Matter dominated era
- Decoupling - CMB emission
- Star and structure formation

- Successes
  - Explains redshifts
  - Explains CMB
  - Explains creation of the light elements

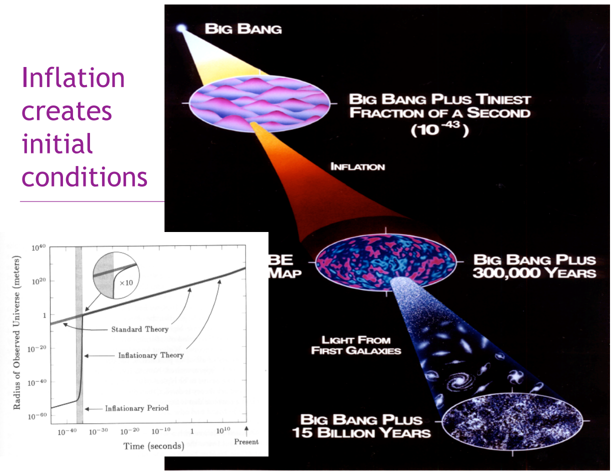


The Big Bang: problems

- Flatness Problem
  - Why is the universe flat? Unless born flat, it should gradually move away from Flatness in the matter/radiation era.
- Horizon Problem
  - Why is the CMB The same temperature in all directions?
- Structure Problem
  - What seeded the structures we see today?

- INITIAL CONDITIONS SOLVES ALL!!
  - The universe started out perfectly flat
  - The universe started out all the same temperature
  - The universe started with the seeds of structure

Inflation creates initial conditions



Flatness

- Friedmann's Equation

$$H^2 = \frac{8\pi G}{3}\rho_{tot} - \frac{kc^2}{a^2}$$

$$\rho_{crit} = \frac{3H^2}{8\pi G}$$

- Rearranged, $\Omega_{tot} = \rho/\rho_{crit}$

$$\Omega_{tot} - 1 = \frac{kc^2}{H^2a^2} = \frac{kc^2}{\dot{a}^2}$$

$$H^2 \propto \rho_{tot} \propto a^{-4}$$

$$\frac{t_{now}}{t_{planck}} = \frac{3\text{x}10^{17}s}{1\text{x}10^{-43}s} = 3\text{x}10^{60}$$

$$a \propto t^{1/2} \rightarrow \frac{a_{now}}{a_{Planck}} = \left(3\text{x}10^{60}\right)^{1/2}$$

- Fine tuning problem,most of way, Radiation dominated.

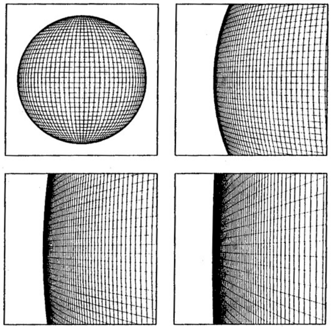
$$\frac{(\Omega_{tot} - 1)_{now}}{(\Omega_{tot} - 1)_{Planck}} = \left(\frac{a_{now}}{a_{Planck}}\right)^2 \approx 10^{60}$$

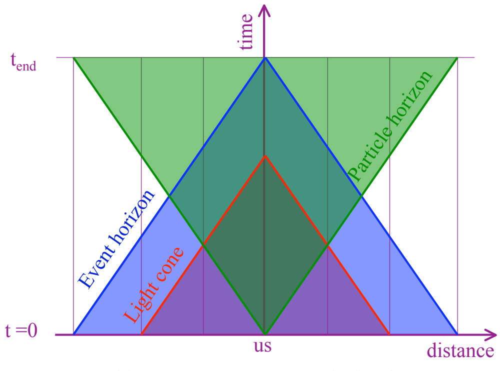
Universe is 60 orders of magnitude less Flat than it was at the Planck time!

Flatness

- Solved by accelerating expansion (not just increase in size)

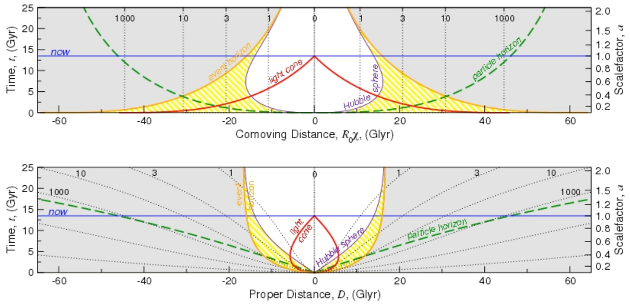
$$\Omega_{tot} - 1 = \frac{Kc^2}{H^2a^2} = \frac{Kc^2}{\dot{a}^2}$$

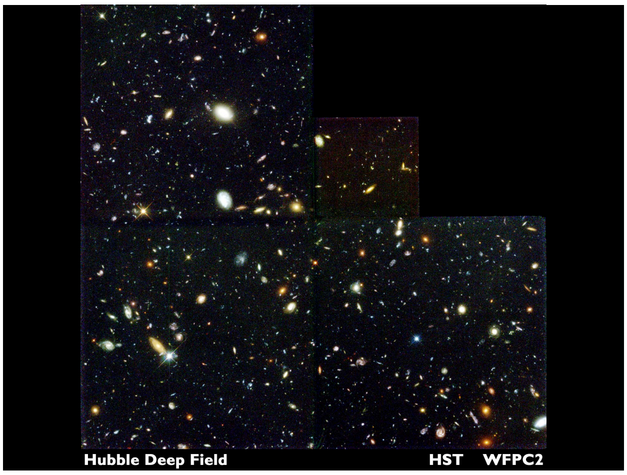




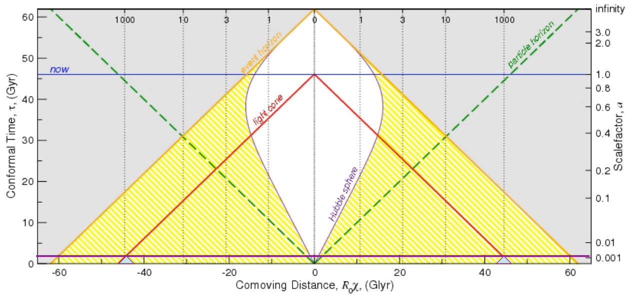
[illegible] particular time

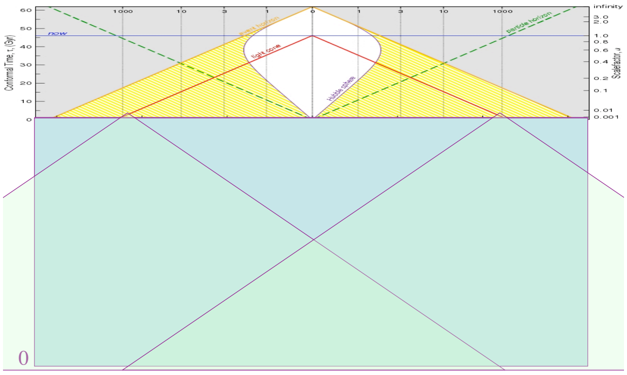
Our Universe





Our Universe





Horizon Problem

Relevant Equations from Earlier On...

$$ds^2 = (cdt)^2 - a^2(t)\left(\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2\theta d\phi^2\right)$$

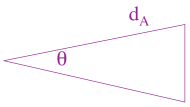
$$ds = 0, d\theta = 0, d\phi = 0$$

$$\int cdt = \int_0^r \left(\frac{a(t)dr}{\sqrt{1-kr^2}}\right) = a(t)r \quad \text{(flat case)}$$

$$d_{comoving}^{light} = a_0 r = \int \frac{a_0 cdt}{a(t)}$$

$$d_{proper}^{light}(t_0,r) = \frac{a}{a_0} d_{comoving}^{light}$$

$$d_A^{light} = \frac{d_{proper}^{light}}{(1+z)}$$



What is the Horizon length at epoch of CMB?

(t =100,000yrs)

$$d_{horizon}^{proper} = d_{proper}^{light} = \frac{a_0}{a} d_{comoving}^{light}$$

$$d_{comoving}^{light} = \int_0^{10^5\,yr} \frac{a_0 cdt}{a(t)} \qquad a(t) = a_0(2H_0 t)^{1/2}$$

How big does this horizon appear now?

$$\theta = \frac{L}{d_A^{\text{to horizon}}} = \frac{d_{horizon}^{proper}}{d_A^{\text{to horizon}}}$$

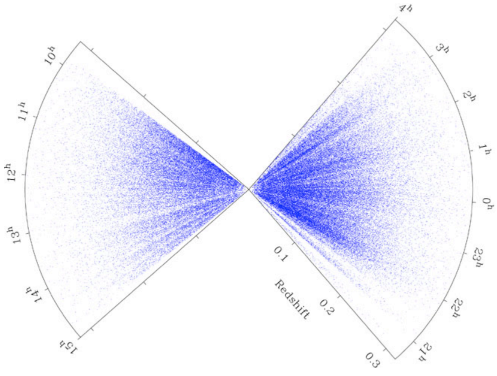
$$d_A = \frac{d_{proper}}{(1+z)}$$

$$d_{proper}^{\text{CMB to present}} = \frac{a_0}{a(t_0)} d_{comoving}^{CMB-present} = 1\int_{10^5\,yr}^{9.3x10^9\,yr} \frac{a_0 cdt}{a(t)} \qquad a(t) = a_0(\frac{3}{2}H_0 t)^{2/3}$$

$$\theta = \frac{L}{d_A^{light}} \approx .5^\circ$$

L=d_{proper} (Horizon)

Structure



Structure

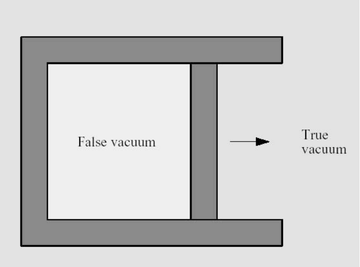
- Quantum fluctuations are the seeds of structure
- Quantum fluctuations produce real fluctuations when virtual particle pairs find themselves separated by more than a Hubble distance

$$\Delta t \leq \hbar / \Delta E$$

If the Universe is exponentially expanding, then this can happen quite a lot!

Conditions for inflation

- Need accelerated expansion for inflation
- Negative pressure will accelerate the expansion
- The cosmological constant has negative pressure



Scalar fields and their potentials

- In particle physics, a scalar field is used to represent spin zero particles.
  - It transforms as a scalar (that is, it is unchanged) under coordinate transformations.
  - In a homogeneous Universe, the scalar field is a function of time alone.
  - In particle theories, scalar fields are a crucial ingredient for spontaneous symmetry breaking. The most famous example is the Higgs field which breaks the electro-weak symmetry, whose existence is hoped to be verified at the Large Hadron Collider at CERN when it commences experiments.
  - Any specific particle theory (eg GUTS, superstrings) contains scalar fields. · No fundamental scalar field has yet been observed. ·

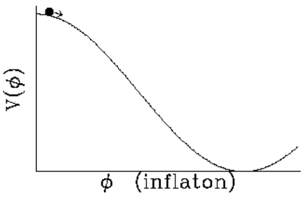
What drives inflation?

- Scalar Fields
  - A potential that depends on one parameter only.
  - It can depend on position but does not have a direction
  - e.g. temperature, or potentials…
- Usually represented V(ϕ), and $\phi(t)$ is assumed homogeneous, and associated with a “inflaton”

$$\rho_\varphi = \frac{\dot{\phi}^2}{2} + V(\phi)$$

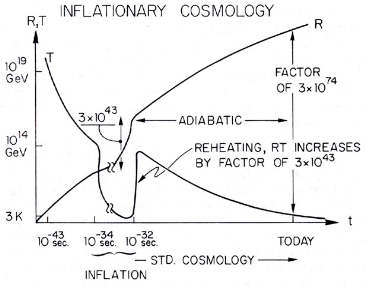
$$p_\varphi = \frac{\dot{\phi}^2}{2} - V(\phi)$$

$$w = \frac{p}{\rho}$$



Reheating

- Inflation cools down the universe - some mechanism is needed for reheating and particle creation
  - Decay of the particle responsible for inflation might create a wealth of particles and energy.



So What does Inflation give us…

- Inflation invented to solve how the Cosmic Microwave Background is uniform in temperature without seemingly ever having been in causal contact.
- It naturally predicts that the Universe should be observed to be exactly flat. (It was sort of designed to do this too). This has been measured now.
- Predicts that the seeds of structure should be ~gaussian and ~scale invariant (that means equal power on all logarithmic scales).
  - scale independent density fluctuations measured by COBE+2dF/WMAP

- Very little more that it can predict… So is it a matter of philosophy now, rather than science? Is the above enough?

See Liddle article on inflation for a more complete Story on the course website.