Homework for next ~~Wed. Nov. 14~~:
CO 30.4, 27.10, 27.12
(= 28.10, 25.10, 25.12 1st ed.)
In 30.4, use $T_{\text{end of GUT epoch}} = 10^{28}$ K

Due Friday Nov. 16

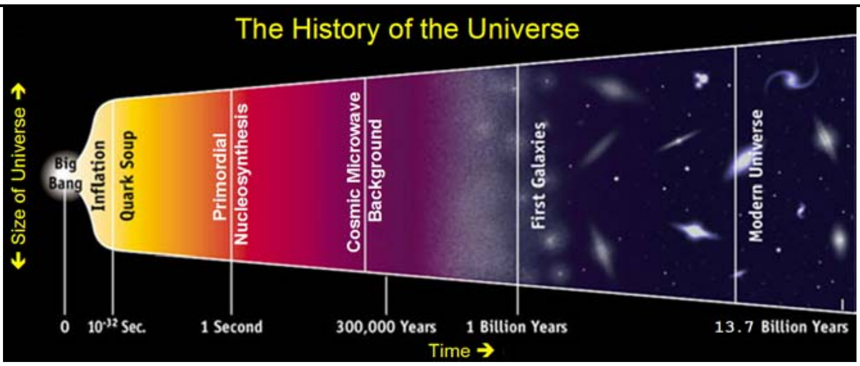
The actual agenda:

- Inflation

- Present-day structure
- The case for dark matter
  - Gravitational lenses
- The nature of dark matter
- The growth of structure
  - Galactic evolution

The Syllabus:

Wednesday 11/7	**Midterm 2**
Week 11: 11/9	[30.1] The very early universe and inflation
Week 12: 11/12–11/16	**The Structure of the Universe & Evolution of Galaxies** [27.3] Clusters of galaxies [28.4] Using quasars to probe the universe (grav. lenses) *What is dark matter?*
Week 13: 11/19+11/21	[30.2] The origin of structure; WMAP measurements.
Friday 11/23	**Thanksgiving Holiday**
Week 14: 11/26–11/30	[26.1] Interaction of galaxies [26.2] The formation of galaxies *Steller Population Synthesis*
Week 15: 12/3–12/7	Quasars & Active galactic Nuclei (AGN) *We may not get to here.* [28.2] Unified model of AGN … *(Skip [28.1], [28.3])* [18.2] Accretion Disk description pp. 661-666 [24.4] The Galactic Center
Tuesday 12/11	**Final Exam 3–5PM**

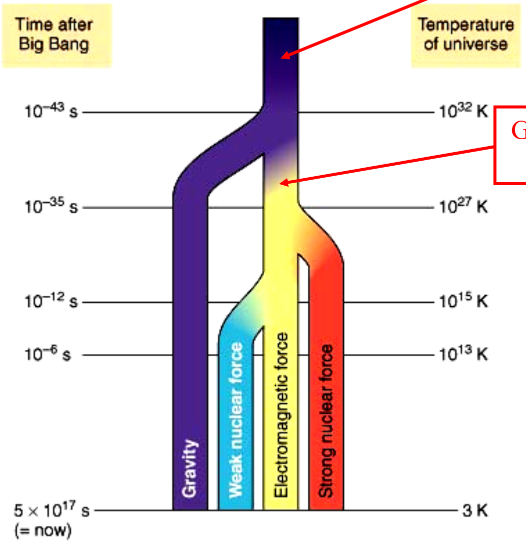


Event	Age of U.	Redshift	°K
Planck time; Gravity separated out	10^{-43} sec	10^{74}	10^{32}
Strong nuclear force separated out	10^{-38} sec	10^{71}	10^{29}
Inflation	10^{-36} sec	---	---
Electromagentic, Weak nuclear forces	10^{-12} sec	10^{14}	10^{15}
Nucleosynthesis of H, He, Li	1 sec - 3 min	10^{8}	10^{9}
Decoupling of CMB	300,000 yrs	1100	3000
Galaxy Formation	950 million yrs	6	19
Now	13.7 billion yrs	0	2.73

hot
↓
cool

high density
↓
low density

Freezing out the forces.



Theory of Everything

Grand Unified Theory

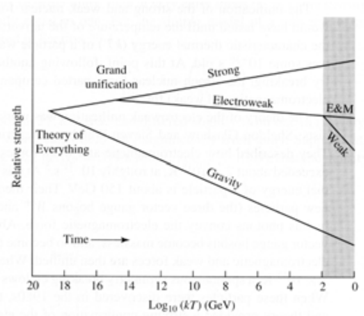
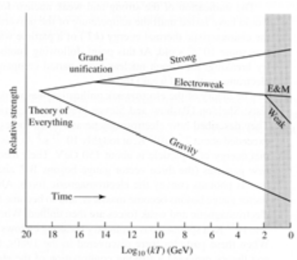


Fig. 30.2

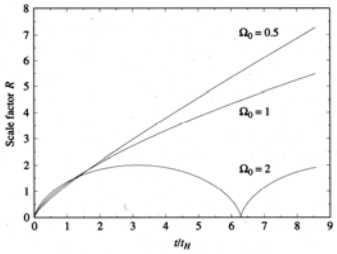
The Planck Time



- Dimensional arguments
  - Planck time $t_p = \sqrt{\frac{\hbar G}{c^5}} =$ 5 x 10^{-44} s
  - Planck mass $m_p = \sqrt{\frac{\hbar c}{G}} =$ 2 x 10^{-8} kg
  - Planck length $\ell_p = \sqrt{\frac{\hbar G}{c^3}} =$ 2 x 10^{-35} m
- Before this, everything fuzzed out by uncertainty principle.

Three Problems for
Friedmann-Robertson-Walker Universes

1. Causality and the particle horizon
2. Flatness
3. Matter-antimatter asymmetry
3. Absence of magnetic monopoles



The Particle Horizon

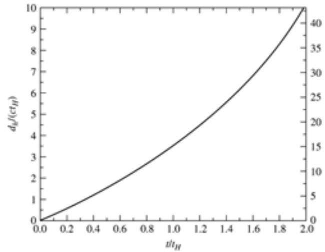


Fig. 29.22
Proper distance from Earth to particle horizon as function of time, including Λ.

For $k = 0$, $\Lambda = 0$, $\Omega = 1$ example:

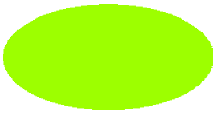
- Radiation era: $R(t) \sim t^{1/2}$ $d_h(t) = 2ct$ $\varpi_h(t) = d_h(t)/R(t) \sim t^{1/2}$
- Matter Era: $R(t) \sim t^{2/3}$ $d_h(t) = 3ct$ $\varpi_h(t) = d_h(t)/R(t) \sim t^{1/3}$

As time passes, we can see larger and larger fraction of universe.

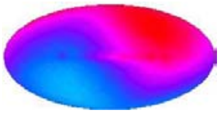
➔ *causally connected fraction of universe is constantly growing.*

Cosmic Microwave Background is smooth to about 1 part in 10^5

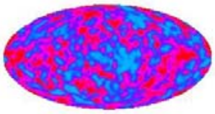
- Yet regions in causal contact at time of decoupling should subtend only ~2° on sky.
- How do regions 180° apart know about each other?



Blue = 0°K
Red = 4°K



Blue = 2.724°K
Red = 2.732°K
Dipole Anistropy
~ 1 part in 300



After removing dipole
Red – blue = 0.0002°K
~ 1 part in 10^5

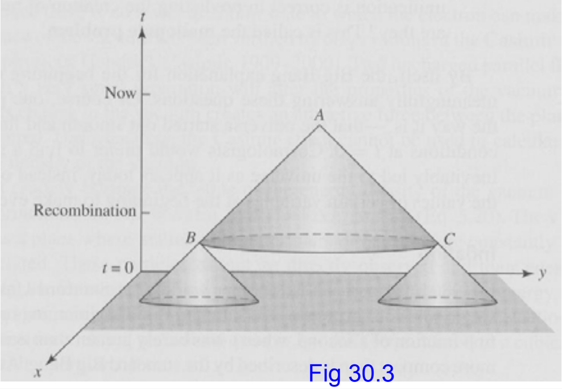


Fig 30.3

All Universes ~ "flat" ($\rho \sim \rho_c$) at early times.

- Homework problem 29.9 will show:

$$\Omega(t) = \frac{\rho(t)}{\rho_c(t)} = 1 + \frac{kc^2}{(dR/dt)^2} \qquad (29.194)$$

  $dR/dt \to \infty$ as $t \to 0$

- In terms of redshift, for large z :

$$1 + z \gg \left| \frac{1}{\Omega_0} - 1 \right|$$

$$\frac{t(z)}{t_H} = \frac{2}{3} \frac{1}{(1+z)^{3/2} \Omega_0^{1/2}} \qquad (29.43)$$

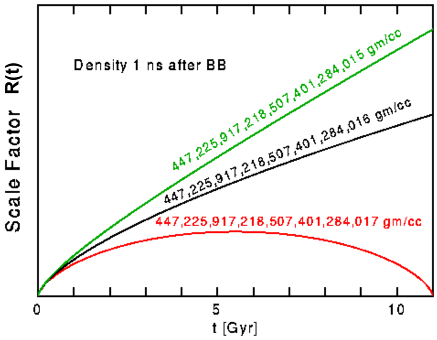
  for all values of k.

- Tiny departures from ($\rho = \rho_c$) at small t (large z) grow into much larger departures than are observed.

The Flatness Problem:

Ω_0 close to 1 at present time.

- But this requires incredible precision at start (t = 0).
- ➔ Ω_0 *exactly* = 1



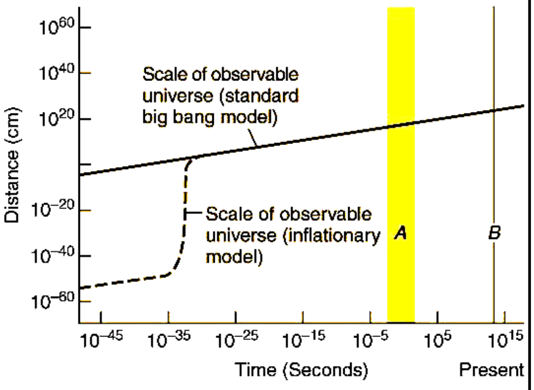
The solution: Inflation

(probably)

(maybe)

Extremely rapid expansion of universe

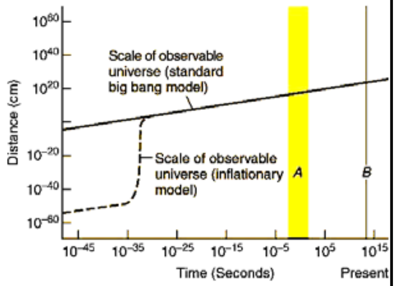
- due to release of energy in "phase change" .
- like ice to water.



Universe became 10^{43} times larger within 10^{-32} seconds.

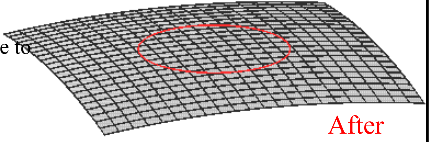
What does inflation predict for geometry of present universe?

Universe became 10^{43} times larger within 10^{-32} seconds.



- Predicts a flat universe
  - $\Omega_0 = 1.000000$….
  - As far out as we can see
    - red circle = horizon

      = most distant place from which light has had time to travel.
- Solves flatness and horizon problems.



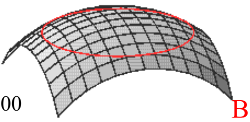
After Inflation

Ball ➔ Earth

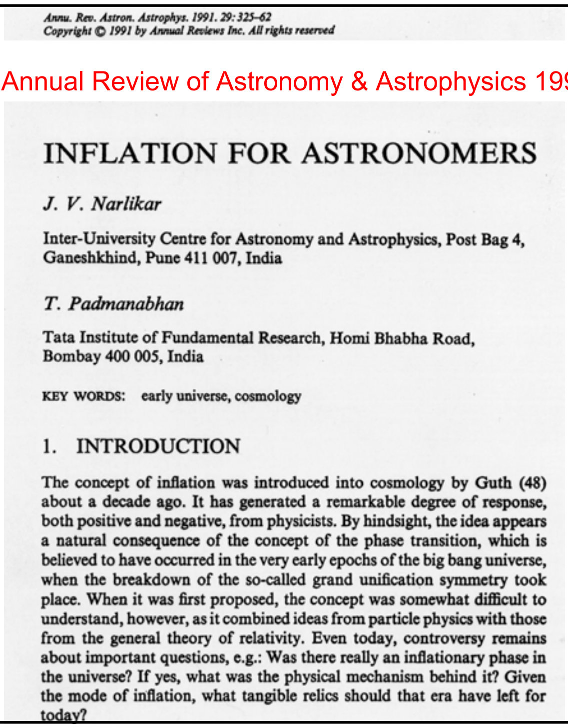
= 10^7 = 10,000,000 times bigger.

Inflation of universe

= 10^{43} = 10,000,000,000,000,000,000,000,000,000,000,000,000,000,000 times bigger.



Before Inflation



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INFLATION FOR ASTRONOMERS

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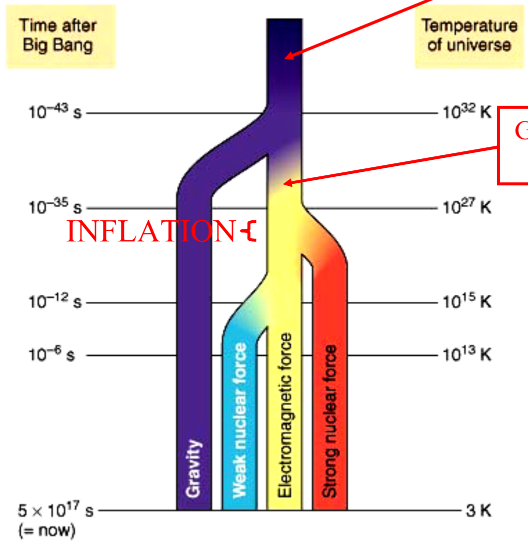
KEY WORDS: early universe, cosmology

1. INTRODUCTION

The concept of inflation was introduced into cosmology by Guth (48) about a decade ago. It has generated a remarkable degree of response, both positive and negative, from physicists. By hindsight, the idea appears a natural consequence of the concept of the phase transition, which is believed to have occurred in the very early epochs of the big bang universe, when the breakdown of the so-called grand unification symmetry took place. When it was first proposed, the concept was somewhat difficult to understand, however, as it combined ideas from particle physics with those from the general theory of relativity. Even today, controversy remains about important questions, e.g.: Was there really an inflationary phase in the universe? If yes, what was the physical mechanism behind it? Given the mode of inflation, what tangible relics should that era have left for today?

Freezing out the forces.



Theory of Everything

Grand Unified Theory

INFLATION {

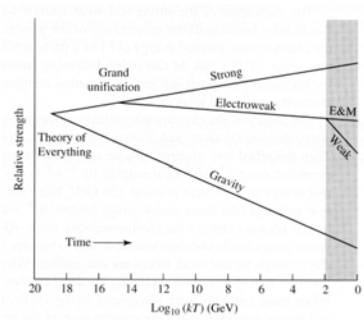
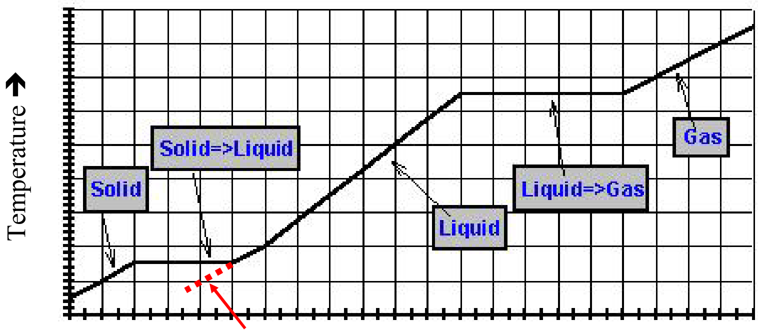


Fig. 30.2

Phase changes and latent heat

- Apply heat energy at a steady rate to a fixed quantity of H_2O
- How does the temperature change?

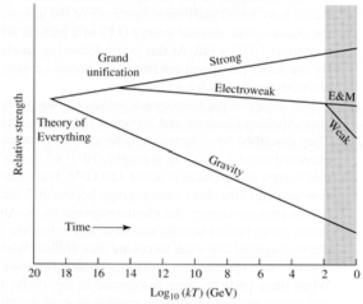


Supercooling

Time ➔

Inflation

- At *extremely* early stage of universe:
  - $t \sim 10^{-34}$ s
  - $T \sim 10^{32}$ K
  - $r = ct \sim 3\text{x}10^{-26}$ m
  - No baryons yet
  - Gravity is a separate force, but E&M, strong, weak forces still joined (GUT)



- Expansion ➔ cooling ➔ “false vacuum”
  - Quasi-stable energy state above true ground state

From
“Inflation for ~~Dummies~~” Astronomers

Potential Energy ➔

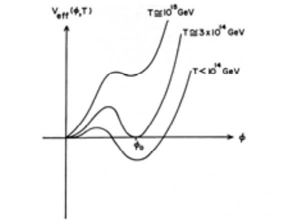


Figure 3 The potential energy of the Higgs field ϕ at various temperatures in the original model proposed by Guth.

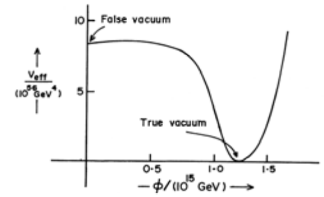


Figure 4 The Coleman-Weinberg potential that was used in the first major revision of the inflationary model.

Strength of Higgs field ➔

False Vacuum ➔ Inflation

- Fixed energy density.
- Same effect as *large* value of cosmological constant.

$$\left[\left(\frac{1}{R}\frac{dR}{dt}\right)^2 - \frac{8}{3}\pi G\left(\frac{u}{c^2}\right)\right]R^2 = -kc^2$$

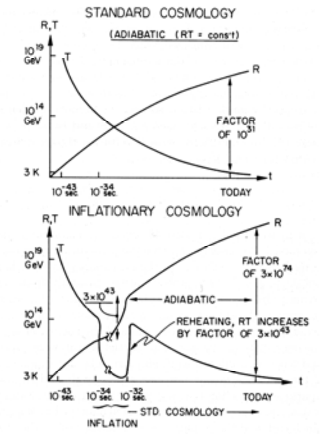
$$\uparrow u = \rho_m c^2 + u_{rad} + u_{vac}$$

$$R(t) = R_i e^{t/\tau_i}$$

$$\tau_i = \sqrt{\frac{3c^2}{8\pi G u_{vac}}}$$

- Exponential expansion until universe falls into true lowest energy state.
- Then, *reheating*.
  - Vacuum energy density (latent heat) gets converted back to radiation energy.

False vacuum: $u = 10^{98}$ J m^{-3}



Vacuum Energy ≠ Λ

Predict $u_{vac} \sim 2c^7/\hbar G^2 = \overset{10^{111}}{\cancel{10}^{114}}$ J m^{-3}

vs. Observed $u_\Lambda = 6 \times 10^{-10}$ J m^{-3}

Effects of inflation

- Amount of expansion
  - Inflation ends when strong nuclear force separates off.
  - Duration: ~10^{-32} s
  - Size increase: $A \sim e^{100} \sim 3\times10^{43}$
    - [Narlikar, Liddle & Lyth give $e^{70} = 10^{30}$]
- Effect on curvature

$$\left[\left(\frac{1}{R}\frac{dR}{dt}\right)^2 - \frac{8}{3}\pi G\rho\right]R^2 = -kc^2$$

$$\frac{\dot{R}^2 + kc^2}{R^2} = \frac{8}{3}\pi G\frac{u}{c^2} \longleftarrow \text{Energy density: mass + radiation + vacuum}$$

large $R \Rightarrow \frac{kc^2}{R^2} \sim 0 \Rightarrow$ post-inflation universe
<u>very</u> close to flat.

Example for flat Λ = 0 case.

- Effect on particle horizon
  - Co-moving coordinate distance to last scattering surface:

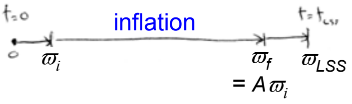
Use $R(t) = \left(\frac{3}{2}\right)^{2/3}\left(\frac{t}{t_H}\right)^{2/3}$

$$\varpi(t_0, t_{LSS}) = \int_{t_{LSS}}^{t} \frac{c\,dt}{R(t)} = \frac{3c\,t_{LSS}^{2/3}}{R_{LSS}}\left[t_0^{1/3} - \overset{\sim 0}{\cancel{t_{LSS}^{1/3}}}\right]$$

Size of Today's Observable Universe	
Now	$4\text{x}10^{26}$ m
t_{LSS}	$4\text{x}10^{23}$ m
t_f	4 m
t_i	10^{-43} -10^{-30} m

  - Co-moving coordinate distance *from* last scattering surface to particle horizon seen from that surface:

$$\varpi_{LSS} = \varpi(t_{LSS}, 0) = \int_0^{t_{LSS}} \frac{c\,dt}{R(t)}$$



$$\varpi_i = \varpi(t_i, 0) = \frac{2ct_i}{R_i}$$

$$\varpi(t_{LSS}, 0) \sim A\varpi(t_i, 0) = \frac{2ct_i}{R_{LSS}}\left(\frac{t_{LSS}}{t_f}\right)^{1/2} \cdot A \qquad \text{using } \frac{R_f}{R_{LSS}} = \frac{AR_i}{R_{LSS}} = \left(\frac{t_f}{t_{LSS}}\right)^{1/2}$$

  - Ratio of these distances:

$$\frac{\varpi(t_{LSS}, 0)}{\varpi(t_0, t_{LSS})} \sim 10^{-26} A \qquad \gg 1 \text{ for } A \sim 10^{30} - 10^{43}$$

- Dilution of monopole density by factor $A^{-3} \sim 10^{-130}$ $[10^{-90}]$
- (Effects on growth of structure)