Annu. Rev. Astron. Astrophys. 1991. 29: 325–62

Annual Review of Astronomy & Astrophysics 1991

INFLATION FOR ASTRONOMERS

J. V. Narlikar

Inter-University Centre for Astronomy and Astrophysics, Post Bag 4, Ganeshkhind, Pune 411 007, India

T. Padmanabhan

Tata Institute of Fundamental Research, Homi Bhabha Road, Bombay 400 005, India

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?

The Flatness Problem

- Tiny departures from ($\rho = \rho_c$) at small t (large z) grow into much larger departures than are observed.
- Ω_0 close to 1 at present time.
  - But this requires incredible precision at start (t = 0).
  - ➔ Ω_0 *exactly* = 1

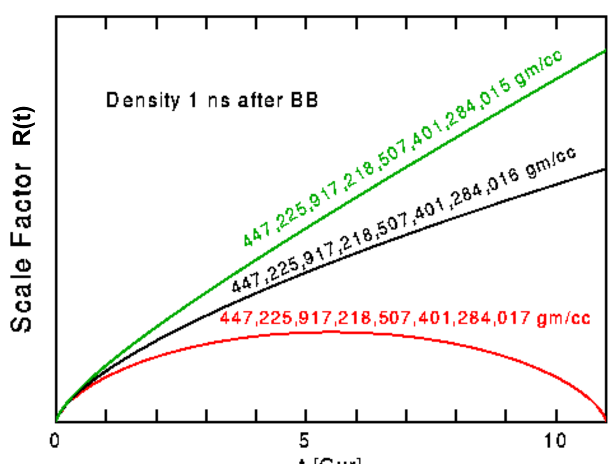
$$\left(\left(\frac{1}{R}\frac{dR}{dt}\right)^2 - \frac{8}{3}\pi G\rho\right)R^2 = -kc^2$$

Flat ➔ these add up to zero.

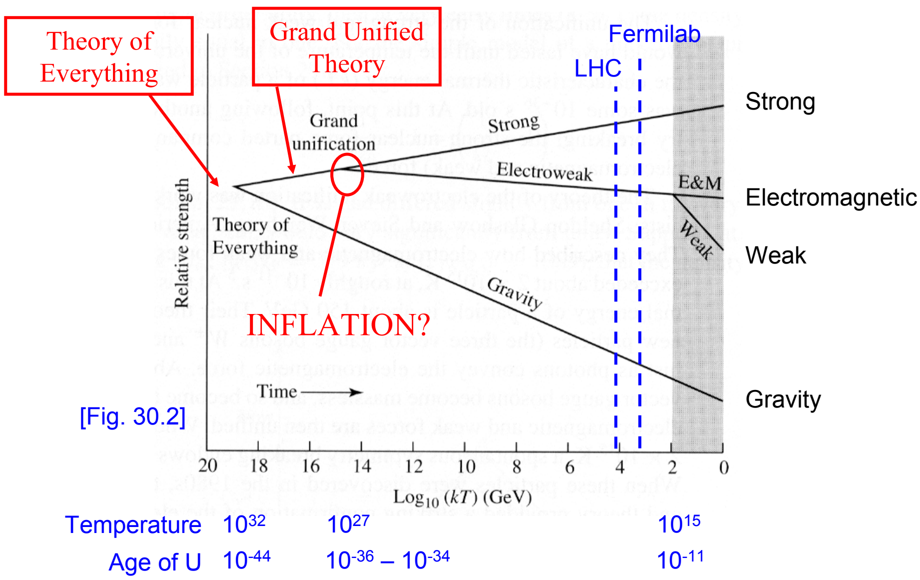
$$\frac{dR}{dt} = \left(\frac{8\pi G\rho_0}{3R} - kc^2\right)^{1/2}$$

0

Empty *expanding* U. is not flat (k ≠ 0).

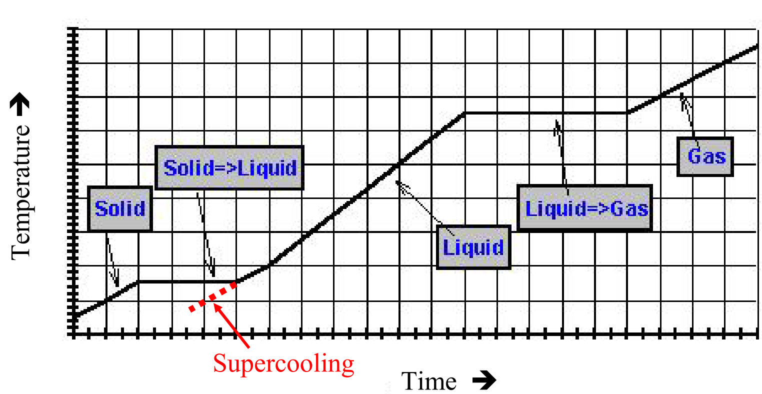


Freezing out the forces.

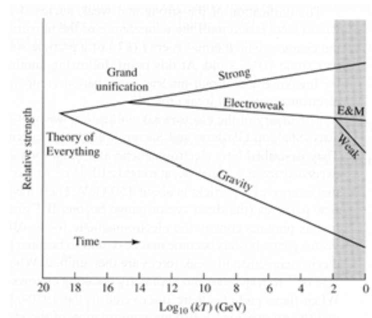


Phase changes and latent heat

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



Inflation



- At *extremely* early stage of universe:
  - $t \sim 10^{-36}$ s
  - $T \sim 10^{28}$ K
  - $r = ct \sim 3\times10^{-28}$ 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 ➔

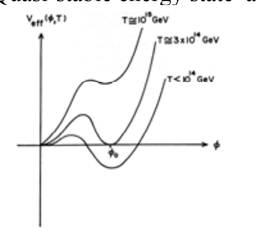


Figure 3 The potential energy of the Higgs field ϕ at various temperatures in the original model proposed by Guth.

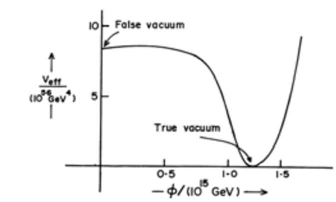
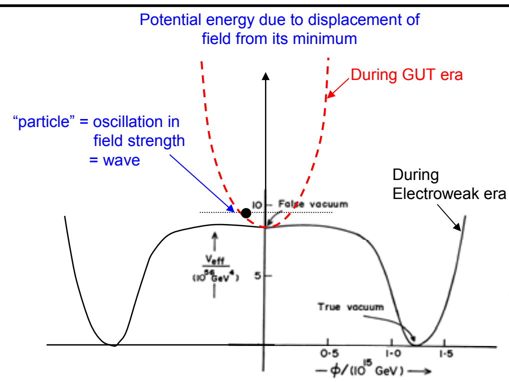
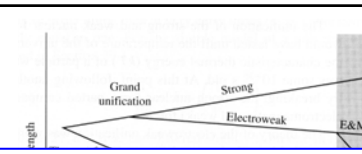


Figure 4 The Coleman-Weinberg potential that was used in the first major revision of the inflationary model.

Strength of scalar field ➔





"So we will drop any pretensions of connecting the generic scalar field which drives inflation to known physics. Making this connection is left as a homework problem for a future Nobel laureate."
from Dodelson, "Modern Cosmology", 2003.

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

From "Inflation for ~~Dummies~~ Astronomers"

Potential Energy ➔

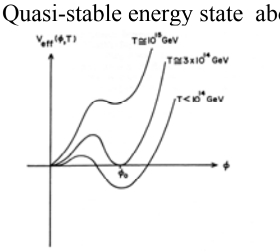


Figure 3 The potential energy of the Higgs field ϕ at various temperatures in the original model proposed by Guth.

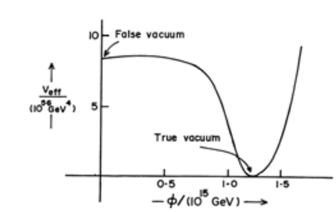


Figure 4 The Coleman-Weinberg potential that was used in the first major revision of the inflationary model.

Strength of scalar field ➔

False Vacuum ➔ Inflation

[CO Fig 30.4]

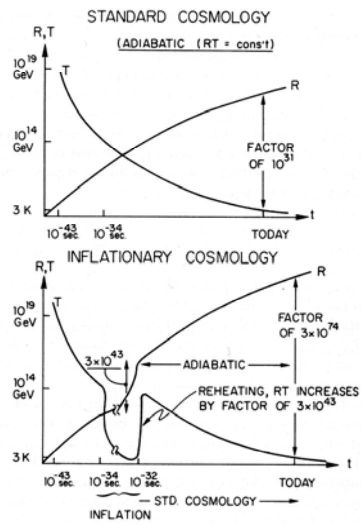
- Fixed energy density.
- Same effect as *large* value of cosmological constant.

$$\left[\left(\frac{1}{R}\frac{dR}{dt}\right)^2 - \frac{1}{3}\Lambda c^2\right]R^2 = -kc^2 = 0$$

$$R(t) = R_i\, e^{(t-t_i)\sqrt{\frac{\Lambda c^2}{3}}}$$

~0

- Exponential expansion until universe falls into true lowest energy state.



Vacuum Energy ≠ Λ

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

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

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

Reheating

[CO Fig 30.4]

- Then, *reheating*.
  - Vacuum energy density (latent heat) gets converted back to radiation energy.
- Current energy density of CMB radiation (T = 2.725K) :

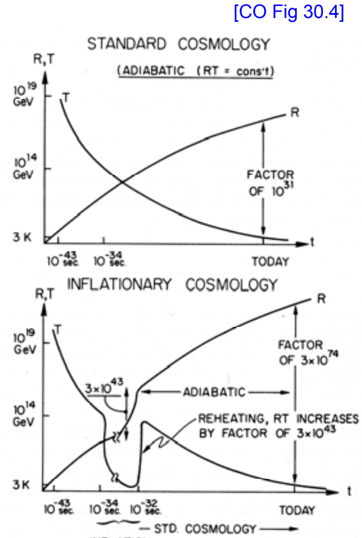
  $u = aT^4 = 4\times10^{-14}$ J m^{-3}

- GUT epoch ended when T ~ 10^{28}K

  u ~ 8×10^{96} J m^{-3}

same

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



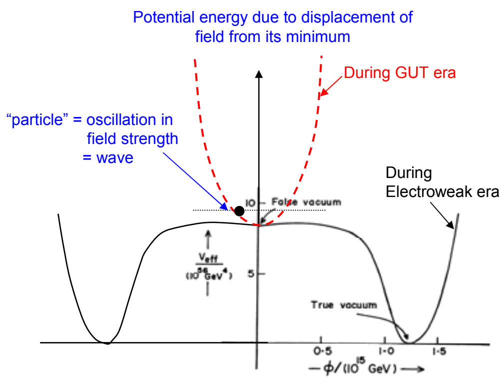
Vacuum Energy ≠ Λ

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

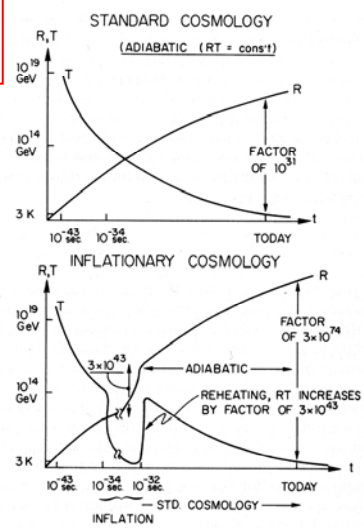
vs. Observed $u_\Lambda = 6 \times 10^{-10}$ J m^{-3}

Important note: bottom paragraph on [CO pg. 1241] says regions of zero pressure expand into regions of negative pressure.
WRONG!

- Then, *reheating*.
  - Vacuum energy density (latent heat) gets converted back to radiation energy.



[CO Fig 30.4]



An expanding, cooling universe.

TABLE 30.2 Eras and Events in the Early Universe. The values are approximate.

Era or Event	Time	Temperature (kT)
Planck era	$< 5\times10^{-44}$ s	$> 10^{19}$ GeV
Planck transition	5×10^{-44} s	10^{19} GeV
Grand unification era	5×10^{-44} s to 10^{-36} s	10^{19} GeV to 10^{15} GeV
Inflation	10^{-36} s to 10^{-34} s	10^{15} GeV
Electroweak era	10^{-34} s to 10^{-11} s	10^{15} GeV to 100 GeV
Electroweak transition	10^{-11} s	100 GeV
Quark era	10^{-11} s to 10^{-5} s	100 GeV to 200 MeV
Quark–hadron transition	10^{-5} s	200 MeV
Neutrino decoupling	0.1 s	3 MeV
Electron–positron annihilation	1.3 s	1 MeV
Big-bang Nucleosynthesis	3 min	
Decoupling	379,000 yr	