20th century cosmology

- **1920s – 1990s (from Friedmann to Freedman)**
  - **theoretical technology available, but no data**
  - **20th century: birth of observational cosmology**
    - Hubble's law ~1930
    - Development of astrophysics 1940s – 1950s
    - Discovery of the CMB 1965
    - Inflation 1981
    - CMB anisotropies: COBE ~1990

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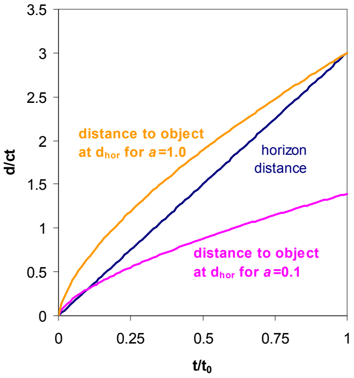
    - Inflation 1981
      - addresses problem of large-scale isotropy of Universe
      - first application of modern particle physics to cosmology

Outstanding Problems

- **Why is the CMB so isotropic?**
  - **consider matter-only universe:**
    - horizon distance $d_H(t) = 3ct$
    - scale factor $a(t) = (t/t_0)^{2/3}$
    - therefore horizon expands faster than the universe
      - "new" objects constantly coming into view
  - **CMB decouples at $1+z \sim 1000$**
    - i.e. $t_{CMB} = t_0/10^{4.5}$
    - $d_H(t_{CMB}) = 3ct_0/10^{4.5}$
    - now this has expanded by a factor of 1000 to $3ct_0/10^{1.5}$
    - but horizon distance now is $3ct_0$
    - so angle subtended on sky by one CMB horizon distance is only $10^{-1.5}$ rad ~ 2°
  - **patches of CMB sky >2° apart should not be causally connected**



Outstanding Problems

- **Why is universe so flat?**
  - **a multi-component universe satisfies**

$$1-\Omega(t) = -\frac{kc^2}{H(t)^2 a(t)^2 R_0^2} = \frac{H_0^2(1-\Omega_0)}{H(t)^2 a(t)^2}$$

and, neglecting Λ,

$$\left(\frac{H(t)}{H_0}\right)^2 = \frac{\Omega_{r0}}{a^4} + \frac{\Omega_{m0}}{a^3}$$

  - **therefore**
    - during radiation dominated era $|1 - \Omega(t)| \propto a^2$
    - during matter dominated era $|1 - \Omega(t)| \propto a$
    - if $|1 - \Omega_0| < 0.06$ (WMAP), then at CMB emission $|1 - \Omega| < 0.00006$
  - **we have a fine tuning problem!**

Outstanding Problems

- **The monopole problem**
  - **big issue in early 1980s**
    - Grand Unified Theories of particle physics → at high energies the strong, electromagnetic and weak forces are unified
    - the symmetry between strong and electroweak forces ‘breaks’ at an energy of ~10^{15} GeV ($T \sim 10^{28}$ K, $t \sim 10^{-36}$ s)
      - this is a phase transition similar to freezing
      - expect to form ‘topological defects’ (like defects in crystals)
      - point defects act as magnetic monopoles and have mass ~10^{15} GeV/c^2 (10^{-12} kg)
      - expect one per horizon volume at $t \sim 10^{-36}$ s, i.e. a number density of 10^{82} m^{-3} at 10^{-36} s
      - result: universe today completely dominated by monopoles (not!)

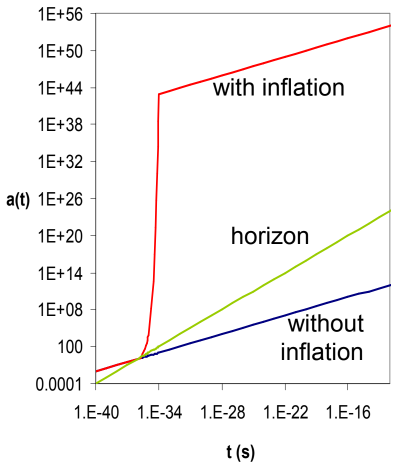
Inflation

- **All three problems are solved if Universe expands *very* rapidly at some time t_{inf} where $10^{-36}\,\mathrm{s} < t_{\mathrm{inf}} \ll t_{\mathrm{BBN}}$**
  - **monopole concentration diluted by expansion factor**
  - **increase radius of curvature**
  - **visible universe expands from causally connected region**
- **this is *inflation***

Alan Guth and
Andrei Linde, 1981

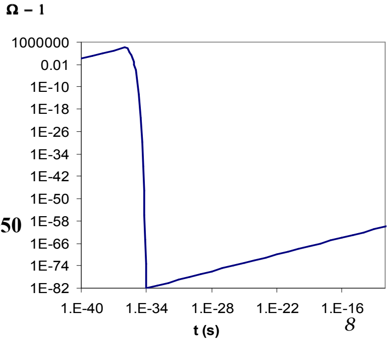
Inflation and the horizon

- **Assume large positive cosmological constant Λ acting from t_{inf} to t_{end}**
- **then for $t_{\text{inf}} < t < t_{\text{end}}$ $a(t) = a(t_{\text{inf}}) \exp[H_i(t - t_{\text{inf}})]$**
  - **$H_i = (⅓\,\Lambda)^{1/2}$**
  - **if Λ large a can increase by many orders of magnitude in a very short time**
- **Exponential inflation is the usual assumption but a power law $a = a_{\text{inf}}(t/t_{\text{inf}})^n$ works if $n > 1$**



Inflation and flatness

- **We had** $1-\Omega(t) = -\dfrac{kc^2}{H(t)^2 a(t)^2 R_0^2} = \dfrac{H_0^2(1-\Omega_0)}{H(t)^2 a(t)^2}$
  - **for matter-dominated universe $1 - \Omega \propto a$**
  - **for cosmological constant H is constant, so $1 - \Omega \propto a^{-2}$**
- **Assume at start of inflation $|1 - \Omega| \sim 1$**
- **Now $|1 - \Omega| \sim 0.06$**
  - **at matter-radiation equality $|1 - \Omega| \sim 2\times10^{-5}$, $t \sim 50000$ yr**
  - **at end of inflation $|1 - \Omega| \sim 10^{-50}$**
  - **so need to inflate by $10^{25} = e^{58}$**



What powers inflation?

- **We need $H_{\mathrm{inf}}(t_{\mathrm{end}} - t_{\mathrm{inf}}) \geq 58$**
  - **if $t_{\mathrm{end}} \sim 10^{-34}$ s and $t_{\mathrm{inf}} \sim 10^{-36}$ s, $H_{\mathrm{inf}} \sim 6 \times 10^{35}\ \mathrm{s}^{-1}$**
  - **this implies $\Lambda \sim 10^{72}\ \mathrm{s}^{-2}$**
  - **energy density $\varepsilon_{\Lambda} \sim 6 \times 10^{97}\ \mathrm{J\ m}^{-3} \sim 4 \times 10^{104}\ \mathrm{TeV\ m}^{-3}$**
    - cf. current value of $\Lambda \sim 10^{-35}\ \mathrm{s}^{-2}$, $\varepsilon_{\Lambda} \sim 10^{-9}\ \mathrm{J\ m}^{-3} \sim 0.004\ \mathrm{TeV\ m}^{-3}$
- **We also need an equation of state with negative pressure**
  - $\frac{\ddot{a}}{a} = -\frac{4\pi G}{3c^2}(\varepsilon + 3P)$ → **accelerating expansion needs $P < 0$**
    - cosmological constant Λ has $\varepsilon = -P$

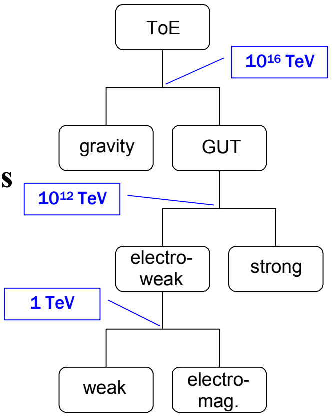
Inflation and particle physics

- **At very high energies particle physicists expect that all forces will become unified**
  - **this introduces new particles**
  - **some take the form of scalar fields φ with equation of state**

$$\varepsilon_{\varphi} = \frac{1}{2\hbar c^3}\dot{\varphi}^2 + U(\varphi)$$

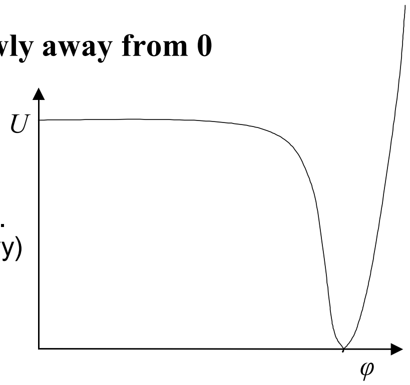
$$P_{\varphi} = \frac{1}{2\hbar c^3}\dot{\varphi}^2 - U(\varphi)$$

  - **if $\dot{\varphi}^2 << 2\hbar c^3 U(\varphi)$ this looks like Λ**



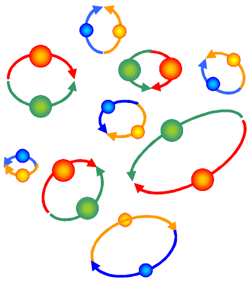
Inflation with scalar field

- **Need potential *U* with broad nearly flat plateau near $\varphi = 0$**
  - **metastable false vacuum**
  - **inflation as φ moves very slowly away from 0**
  - **stops at drop to minimum (true vacuum)**
    - decay of inflaton field at this point reheats universe, producing photons, quarks etc. (but not monopoles – too heavy)
    - equivalent to latent heat of a phase transition



Inflation and structure

- **Uncertainty Principle means that in quantum mechanics vacuum constantly produces temporary particle-antiparticle pairs**
  - **minute density fluctuations**
  - **inflation blows these up to macroscopic size**
  - **seeds for structure formation**
- **Expect spectrum of fluctuations to be approximately scale invariant**
  - **possible test of inflation idea?**



Inflation: summary

- **Inflation scenario predicts**
  - **universe should be very close to flat**
  - **CMB should be isotropic, with small scale invariant perturbations**
  - **monopole number density unobservably low**
- **Inflation scenario does not predict**
  - **current near-equality of Ω_m and Ω_Λ**
  - **matter-antimatter asymmetry**
- **Underlying particle physics very difficult to test**
  - **energy scale is much too high for accelerators**

State of Play, ~1995

- **General features of "Standard Cosmological Model" reasonably well established**
  - **"Smoking gun" is blackbody spectrum of CMB**
  - **Inflation required to explain observed isotropy and flatness**
- **Exact values of parameters not well established at all**
  - **H_0 uncertain to a factor of 2**
  - **Ω uncertain to a factor of 5 or so**
  - **individual contributions to Ω unclear, apart from baryons (defined by nucleosynthesis)**
- **Further progress requires better data**
  - **forthcoming in the next decade…**