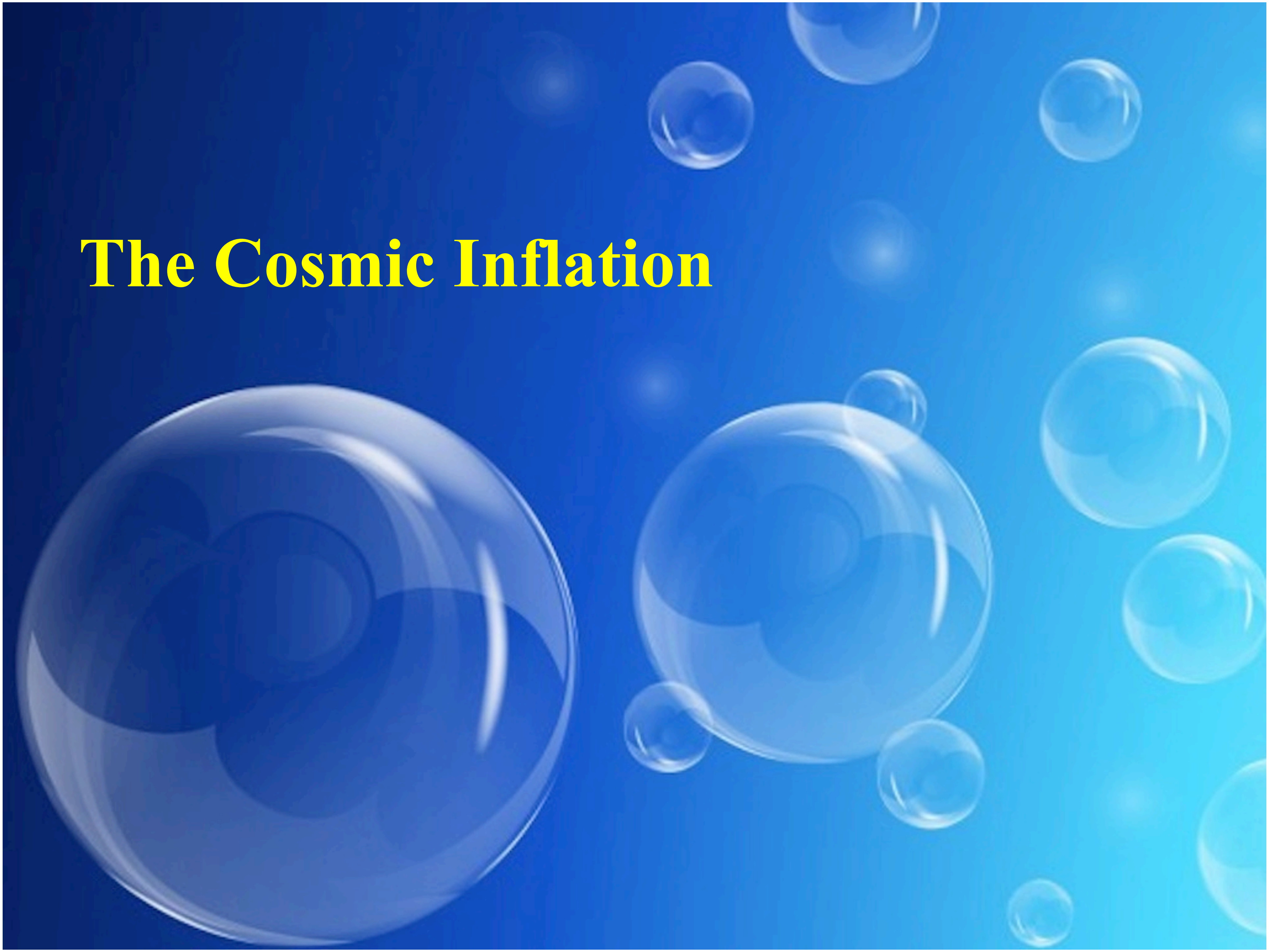

The Cosmic Inflation

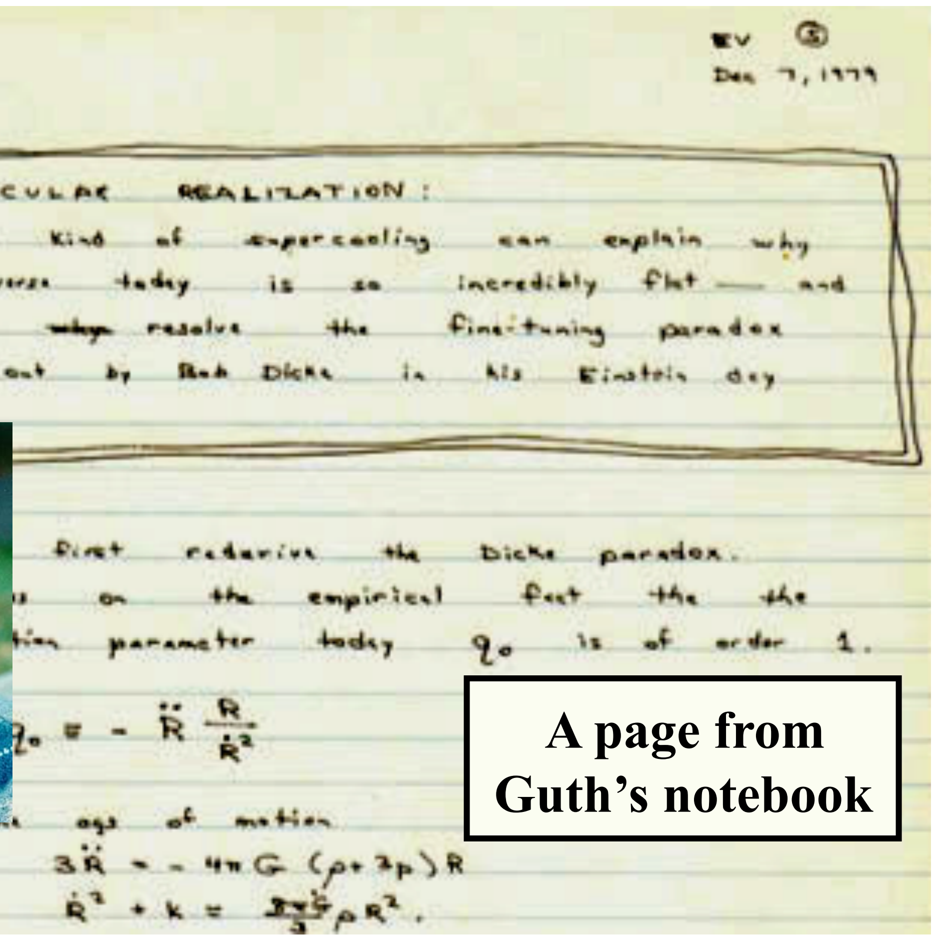
The Idea of Inflation

- Alan Guth (1980); precursors: D. Kazanas, A. Starobinsky
- Explains a number of fundamental cosmological problems: flatness, horizon, origin of structure, absence of topological defects…
- Develped further by P. Steinhardt, A. Albrecht, A. Linde, and many others

A. Guth

A. Starobinsky

A. Linde



Dec. 7, 1979

SPECTACULAR REALIZATION: This kind of supercooling can explain why the universe today is so incredibly flat — and therefore resolve the fine-tuning paradox pointed out by Bob Dicke in his Einstein day lectures.

A page from Guth's notebook

The Inflationary Scenario

It solves ***3 key problems*** of the Big Bang cosmology:

1. **The flatness problem**: why is the universe so close to being flat today?
2. **The horizon problem**: how comes the CMBR is so uniform?
3. **The monopole problem**: where are the copious amounts of magnetic monopoles predicted to exist in the BB cosmology?

… It also *accounts naturally for the observed power spectrum of the initial density perturbations*

... *It predicts* a similar, scale-invariant spectrum for the cosmic gravitational wave background

… And it implies a much, much(!) bigger universe than the observable one

The Flatness Problem

The expanding universe *evolves away* from $\Omega_{tot} = 1$:

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

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

This creates an *enormous fine-tuning problem*: the early universe must have been remarkably close to $\Omega_{tot} = 1$ in order to have $\Omega_{tot} \sim 1$ today !

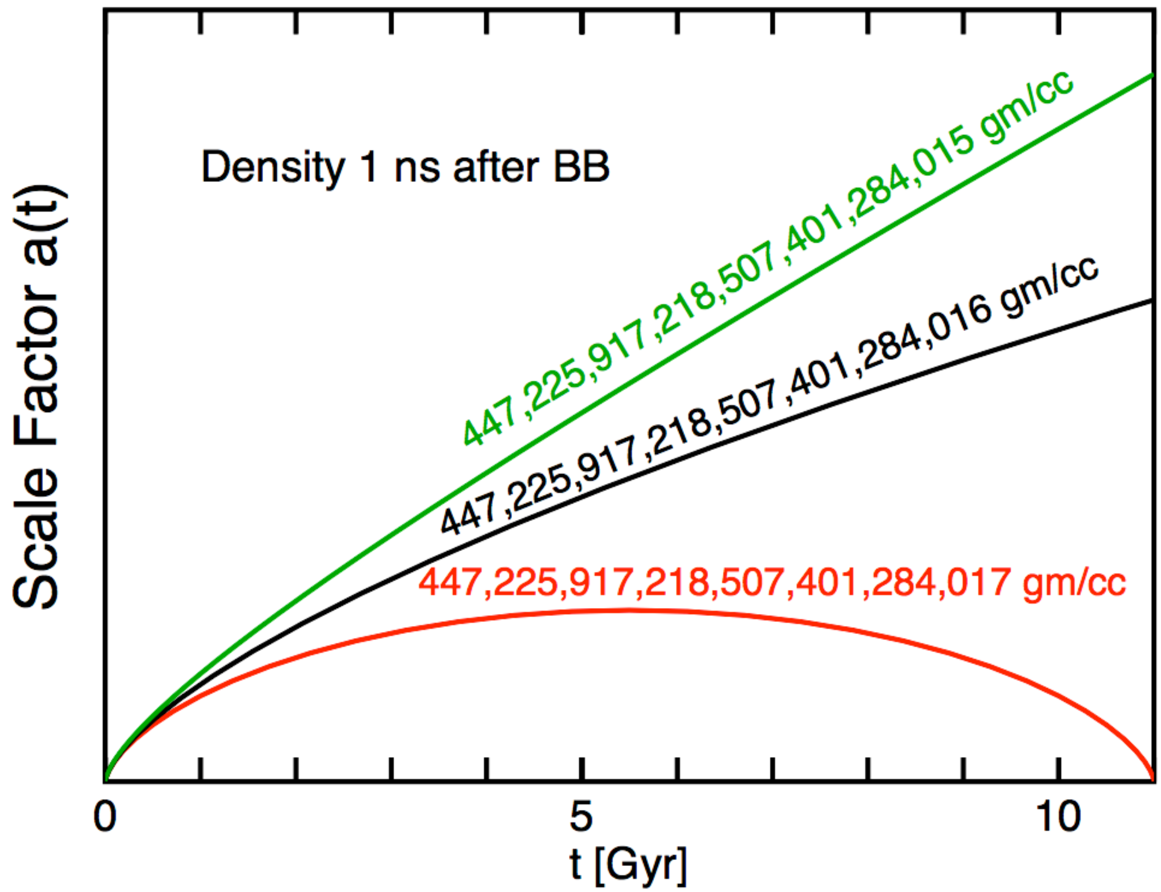


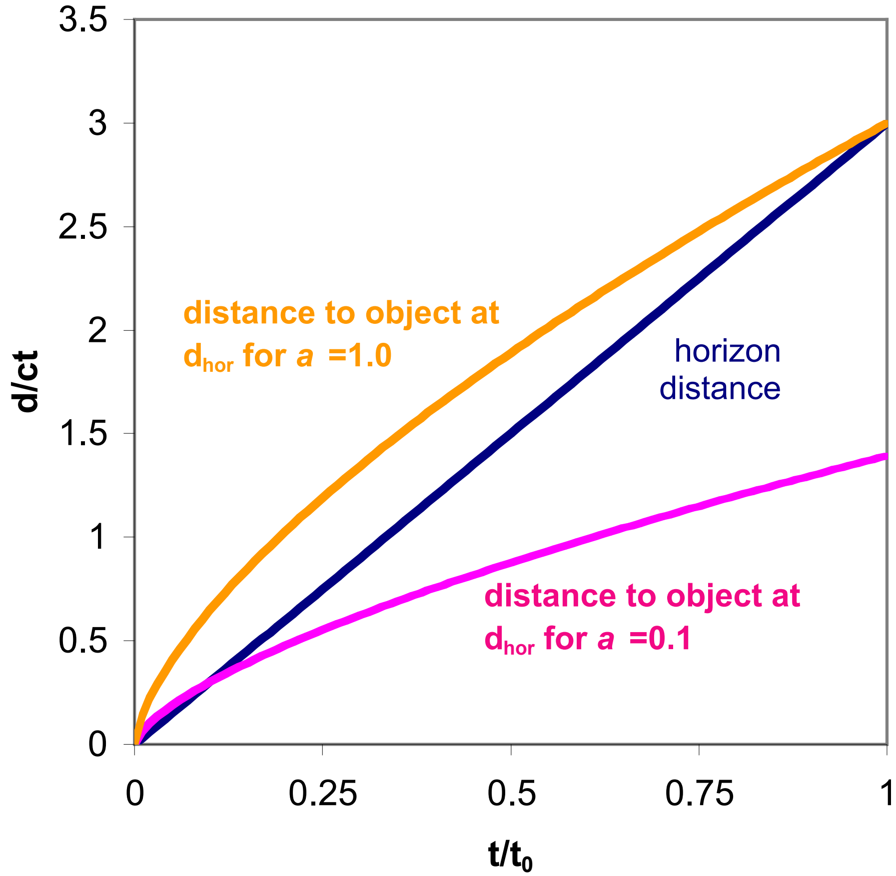
Fig. 11.— Scale factor *vs.* time for open, critical and closed Universes with density at 1 nanosecond after the Big Bang indicated.

(from N. Wright)

The Horizon Problem

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, so new" objects are constantly coming into view



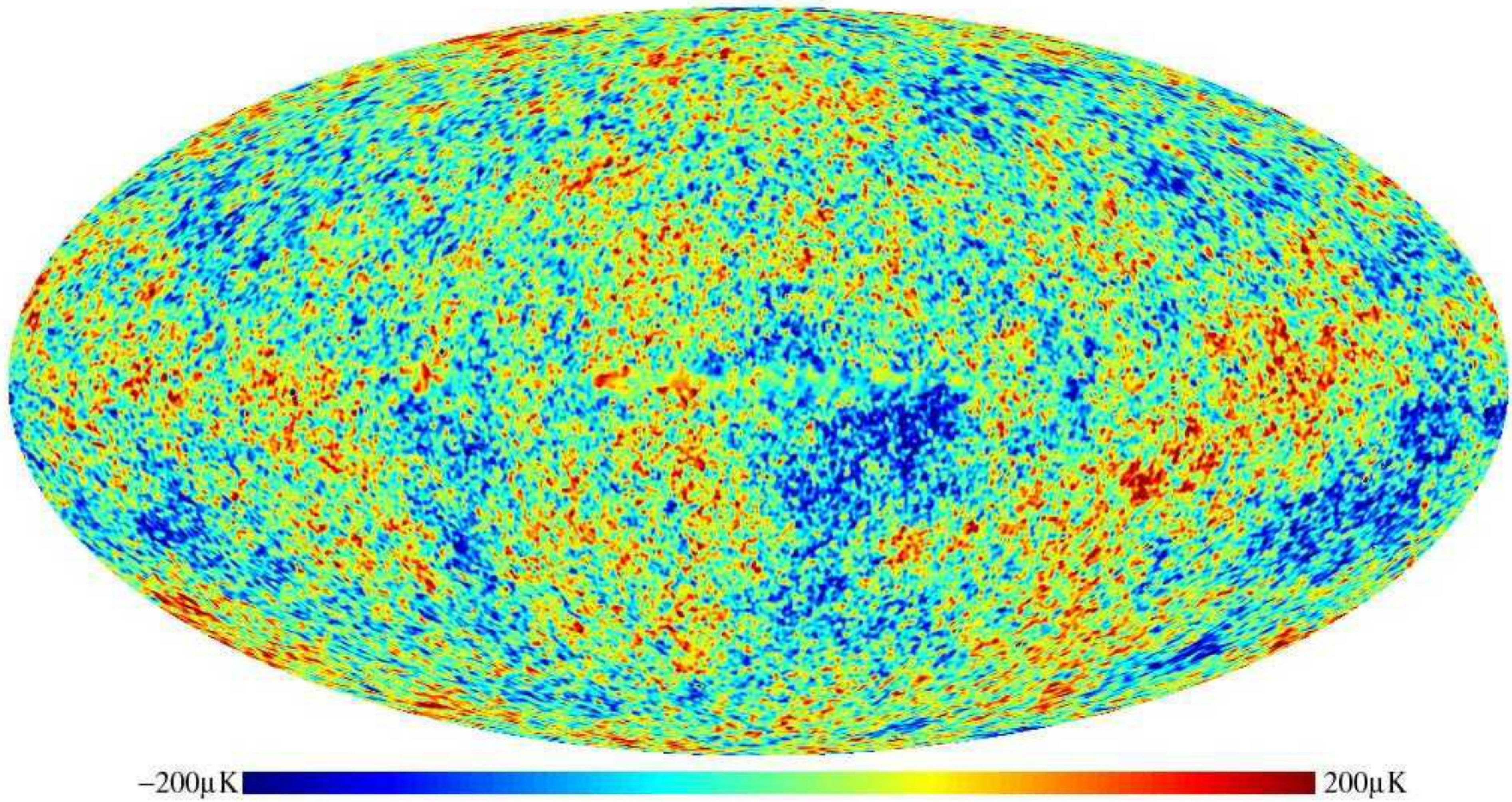
Consider CMBR:

- It decouples at $1+z \sim 1000$
- i.e., $t_{CMB} = t_0/10^{4.5}$
- Then $d_H(t_{CMB}) = 3ct_0/10^{4.5}$
- 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 ~ 2°

→ Patches of CMB sky > 2° apart should not be causally connected!

CMBR is Uniform to $\Delta T/T \sim 10^{-6}$

Yet the projected size of the particle horizon at the decoupling was $\sim 2°$ - these regions were causally disconnected - so how come?



The Monopole Problem

- Magnetic monopoles are believed to be an inevitable consequence of Grand Unification Theories (GUTs)
  - Point-like topological defects arising during the phase transition when the strong and the electroweak forces decouple
- Expect enormous numbers of them
  - Mass $\sim 10^{16}$ m_p ; dominate all other matter density by a factor of $\sim 10^{12}$ and thus close the universe and drive it to a Big Crunch a long time ago …
- Not observed! So, where are they?

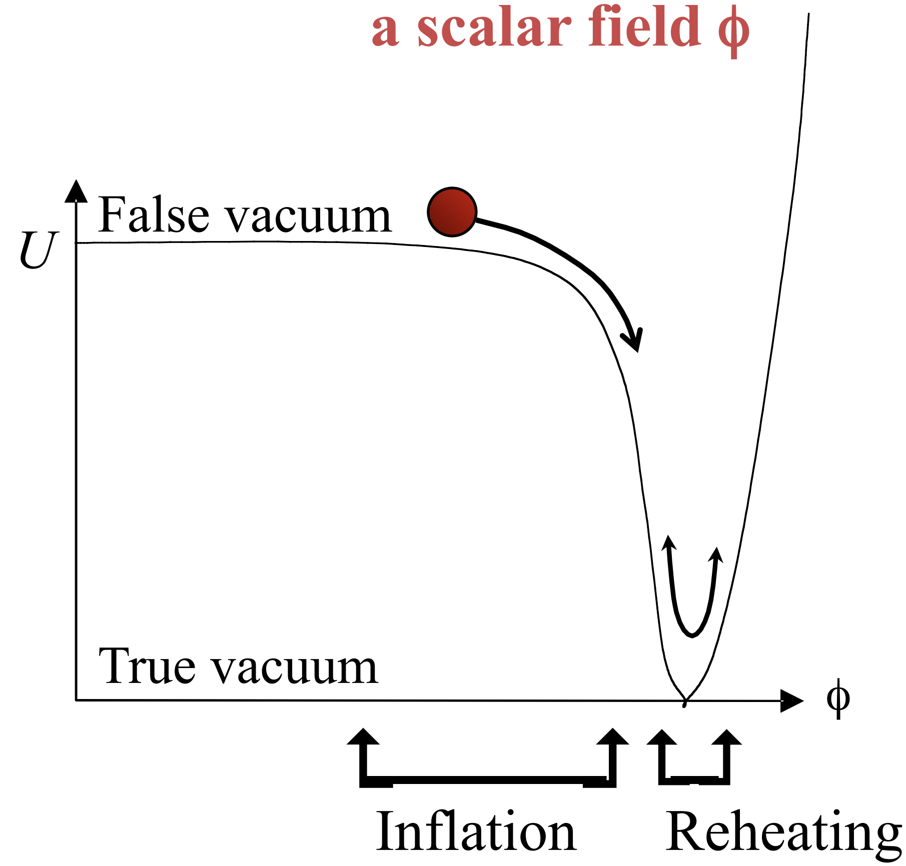
Inflationary Universe Scenario

- If there is a Theory of Everything (TOE) that unifies all four forces it will break spontaneously at the Planck time ($t \sim 10^{-43}$ sec) into the gravitation and a unified version of the magnetic, electroweak, and strong forces – a Grand Unified Theory (GUT)
- The GUT will hold until $T \sim 10^{28}$ K, or $t \sim 10^{-34}$ sec. At this point the universe entered a period of ***"false vacuum":*** the energy level higher than the lowest, "ground" state
- Symmetry breaking in GUT theories is associated with massive Higgs bosons, which are quanta of a scalar field that has an associated potential which describes the energy of the field
- The false vacuum is a metastable state, with it's vacuum energy acting as a "negative pressure" causing the universe to expand exponentially as it "rolls down the scalar field"

Inflation With a Scalar Field

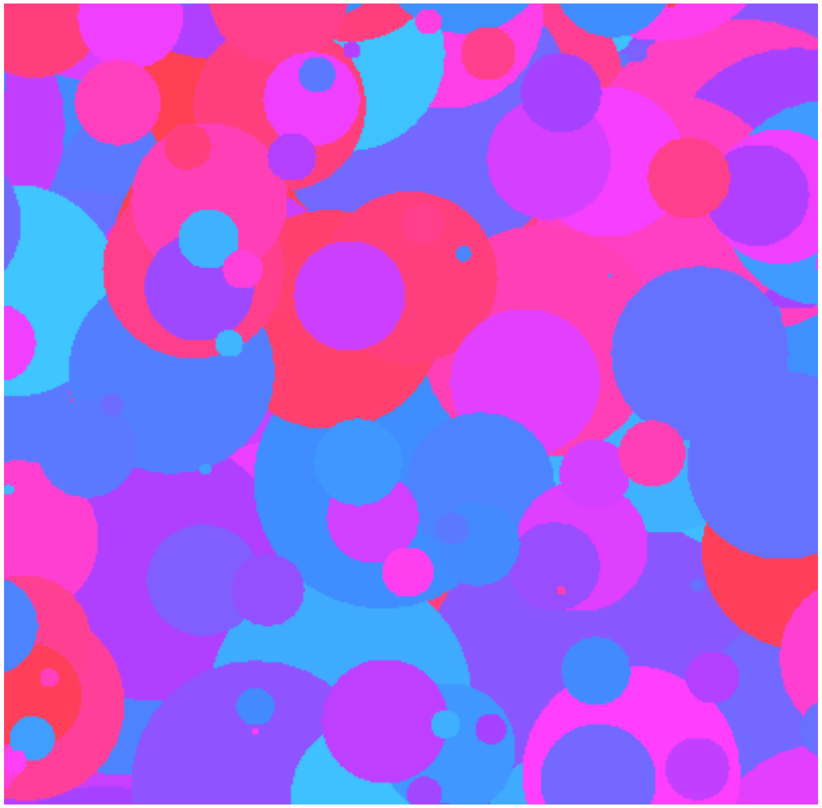
- Need potential *U* with broad nearly flat plateau near $\phi = 0$
- This is the metastable **false vacuum**
- Inflation occurs as ϕ moves slowly away from 0
- It stops at drop to minimum U - the **true vacuum**
- Decay of inflaton field ϕ at this point **reheats** universe, producing photons, quarks, etc. - ***all of the matter/energy content of the universe is created in this process***
- This is equivalent to latent heat of a phase transition

Potential U(ϕ) of a scalar field ϕ



The Inflation as a Phase Transition

The universe undergoes a phase transition from a state of a false vacuum, to a ground state; this releases enormous amounts of energy ("latent heat") which drives an exponential expansion



Regions of non-inflating universe are created through the nucleation of bubbles of true vacuum. When two such bubbles collide, the vast energy of the bubble walls is converted into the particles. This process is called reheating

The Cosmic Inflation

Recall that the energy density of the physical vacuum is described as the ***cosmological constant***. If this is the dominant density term, the Friedmann Eqn. is:

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{\Lambda_i}{3}$$

The solution is obviously:

$$a(t) \propto e^{H_i t}$$

In the model where the GUT phase transition drives the inflation, the net expansion factor is:

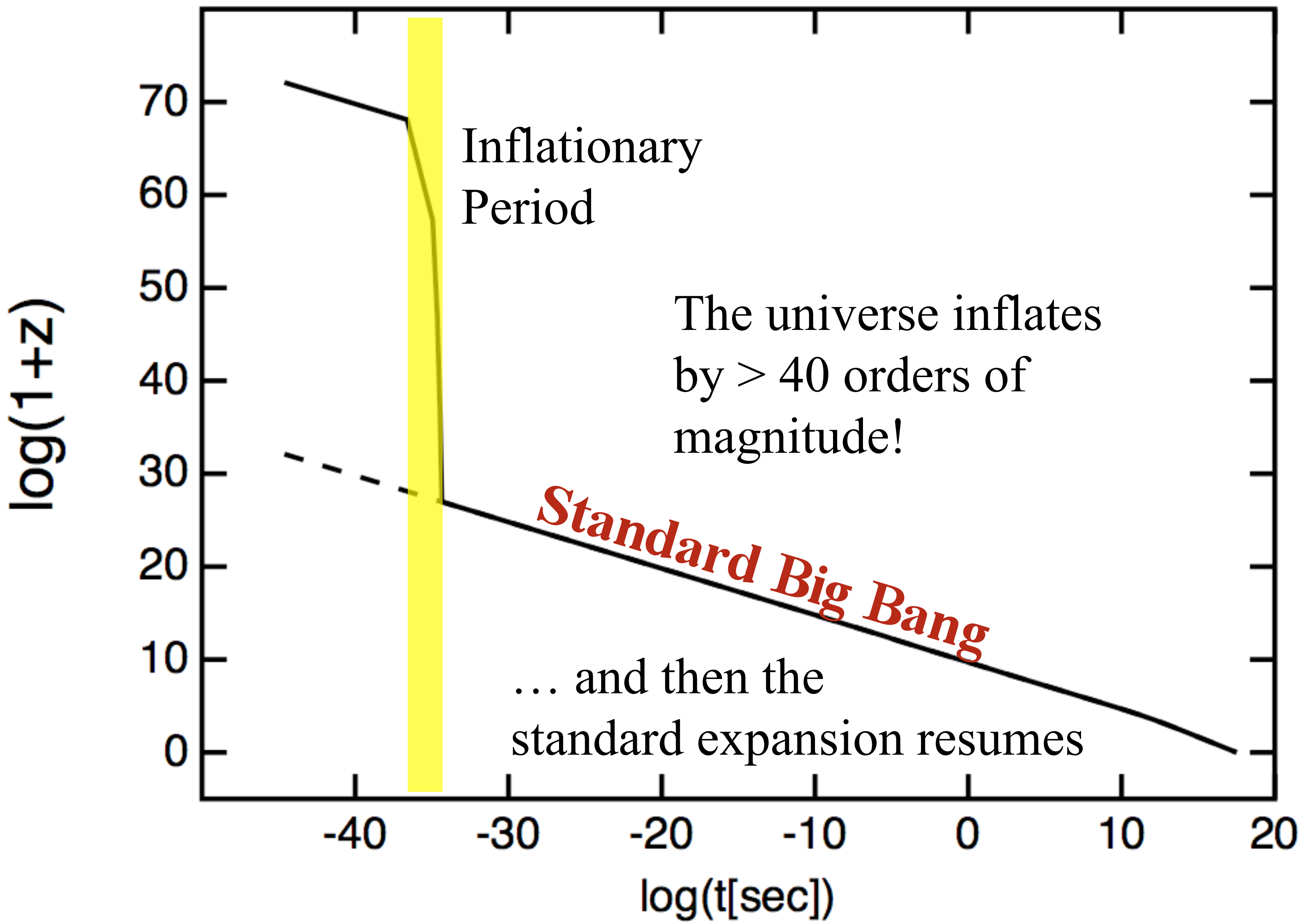
$$\frac{a(t_f)}{a(t_i)} \sim e^{100} \sim 10^{43}$$

The density parameter evolves as: $|1 - \Omega(t)| \propto e^{-2H_i t}$

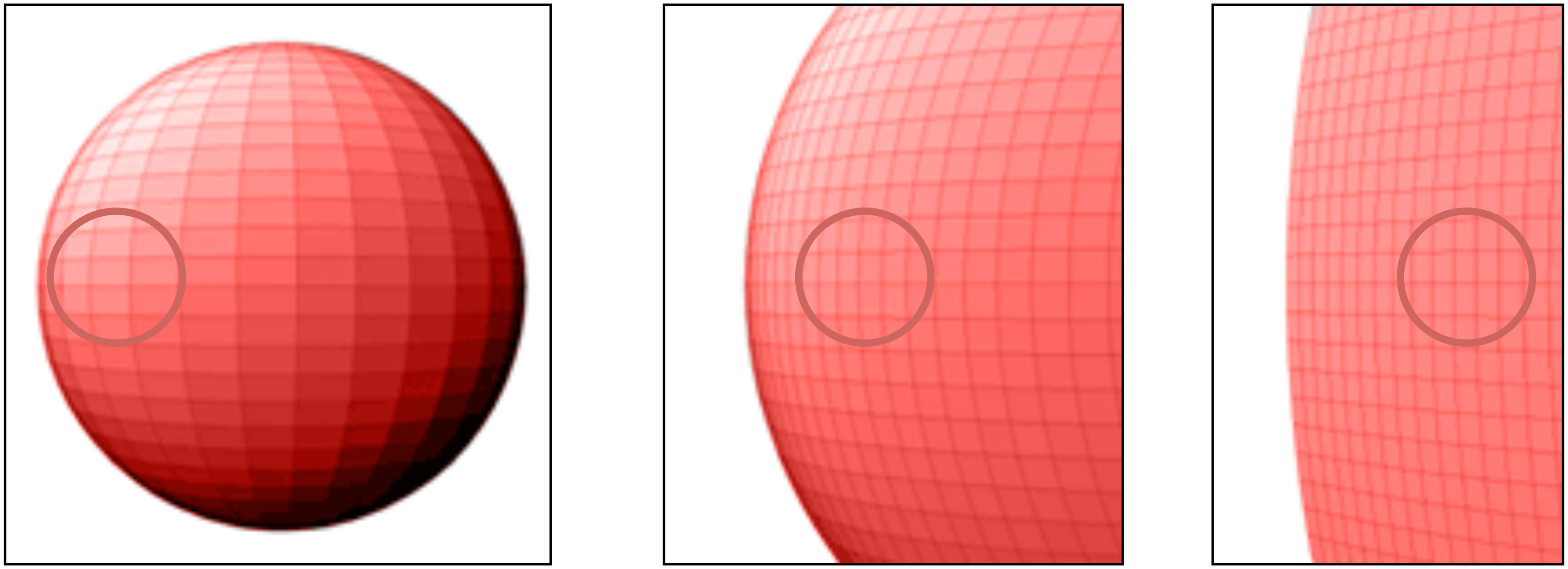
Thus:

$$|1 - \Omega(t_f)| \sim e^{-2N} \sim e^{-200} \sim 10^{-87}$$

The Inflationary Scenario



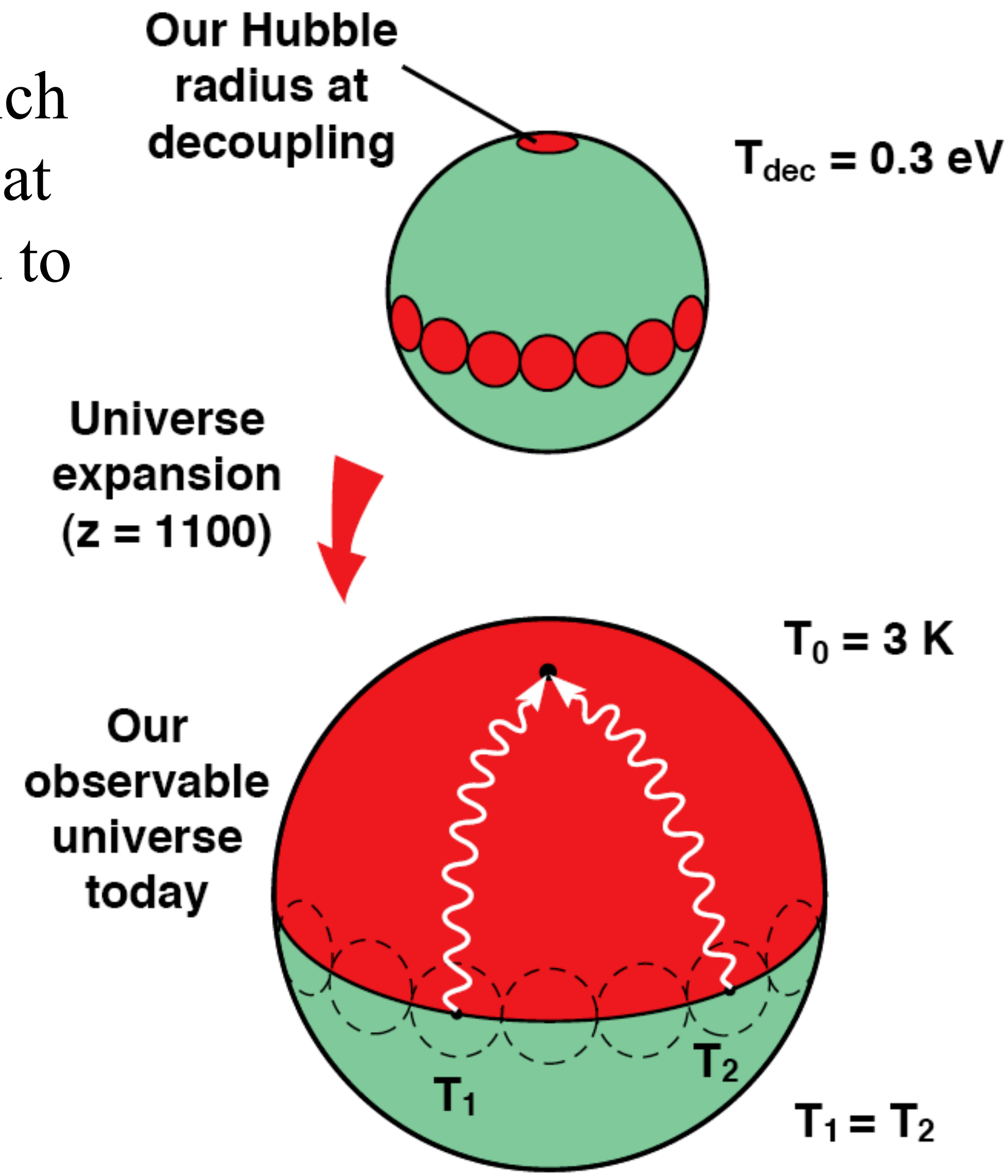
Inflation Solves the Flatness Problem



As the universe inflates, the local curvature effects become negligible in comparison to the vastly increased "global" radius of curvature: the universe becomes extremely close to flat locally (which is the observable region now). Thus, at the end of the inflation, $\Omega = 1 \pm \varepsilon$

Inflation Solves the Horizon Problem

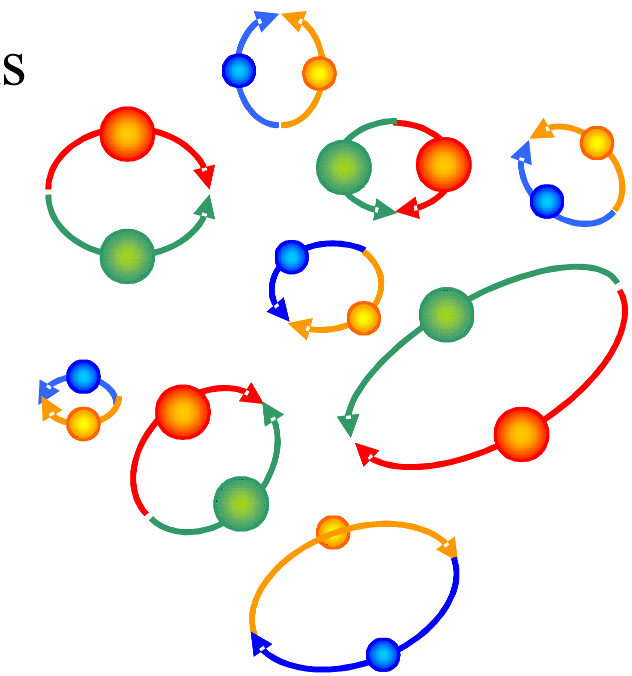
Regions of the universe which were causally disconnected at the end of the inflation used to be connected before the inflation - and thus in a thermal equilibrium



Note that the *inflationary expansion is superluminal*: the space can expand much faster than ***c***

Inflation and Structure Formation

- Uncertainty Principle means that in quantum mechanics vacuum constantly produces temporary particle-antiparticle pairs
  - This creates minute density fluctuations
  - Inflation blows these up to macroscopic size
  - They become the seeds for structure formation



- Expect the mass spectrum of these density fluctuations to be approximately scale invariant
  - This is indeed as observed!
  - Not a "proof" of inflation, but a welcome consistency test


Next:
The Very Early Universe