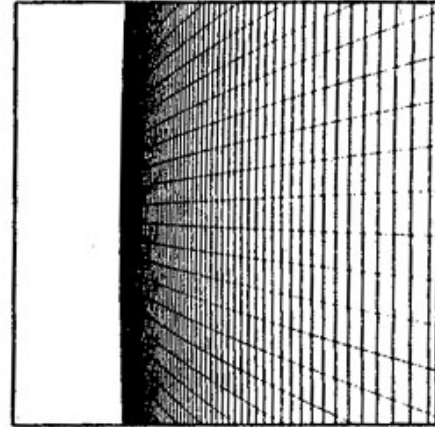
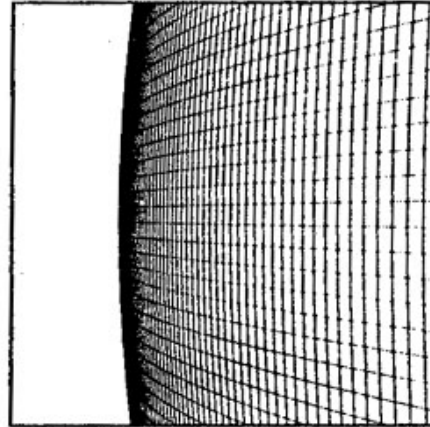
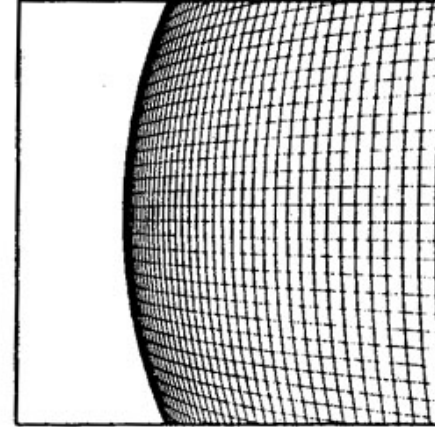
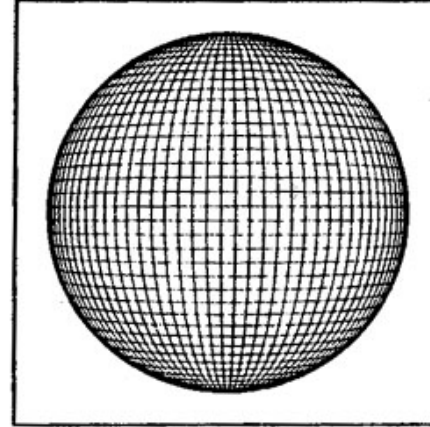
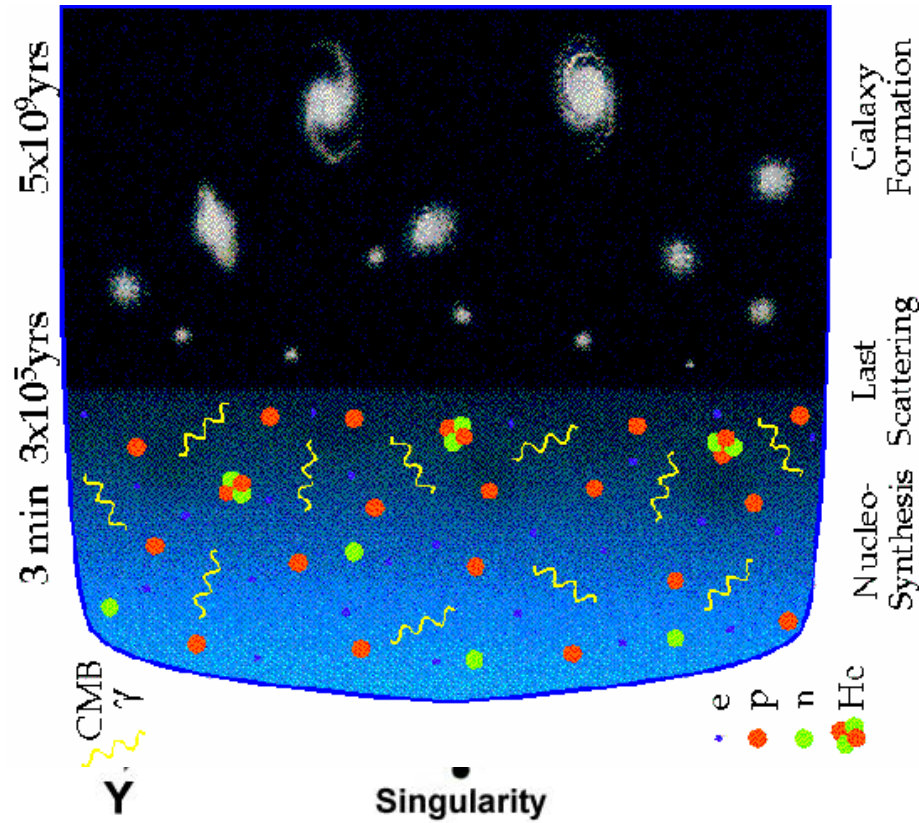


# MISC

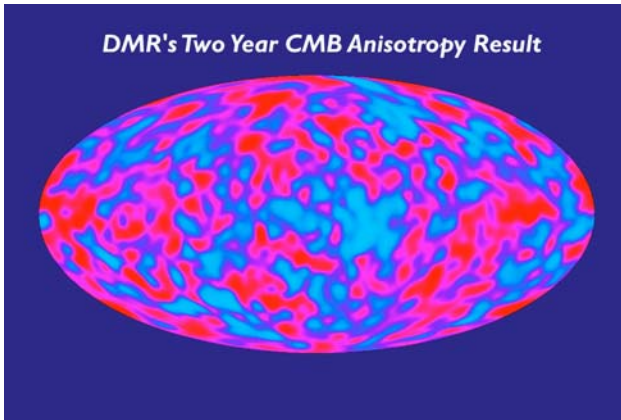
1. Homework 5 is distributed today – available as PDF on the class web site (it will be due next Friday, Feb 29, in class)
2. Today, we are covering material of [S 27-1, 27-2 \(Ch. 27\)](#) on fundamental forces and idea of inflation.

# The Early universe, fundamental forces and the idea of inflation



# The problems of the Big Bang

**Although quite successful in many respects, several worrisome puzzles and problems were identified by the late 1970s**

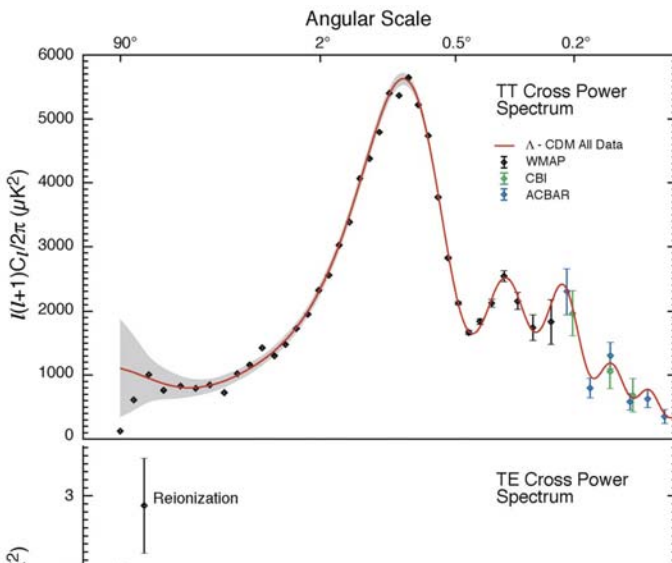


## □ The horizon problem.

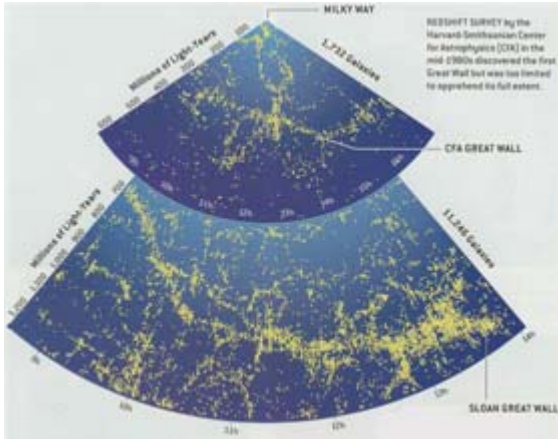
*Different parts of the Universe on the sky should be causally unconnected, but apparently exhibit the same properties*

## □ The flatness problem.

*The geometry of the Universe is close to flat ( $\Omega \sim 1$ ) and now we know this to be true to  $\sim 2\%$ . There is no special reason in the Big Bang for this. Cosmological parameters can be arbitrary...*



# The problems of the Big Bang



## □ The structure problem.

*Where did all the structures in otherwise homogeneous and isotropic universe come from?*

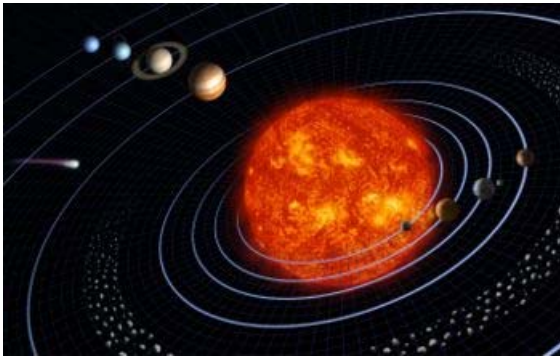
## □ The relic problem.

*The apparent absence of weird stuff, like magnetic monopoles and other very massive particles, predicted consistently by the Grand Unified Theories of particle physics*

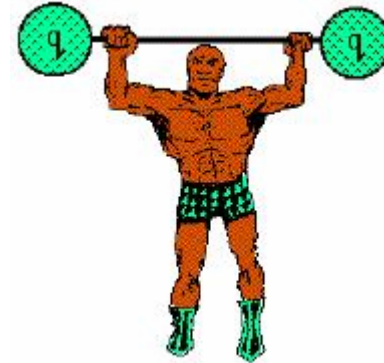
***In principle, all of this could be blamed on the initial conditions for the Big Bang, but the conditions had to be suspiciously and uncomfortably too finely tuned...***

# Fundamental forces

*the constituents of the Universe can be described in terms of a menagerie of particles and four fundamental forces*



gravity



Strong force

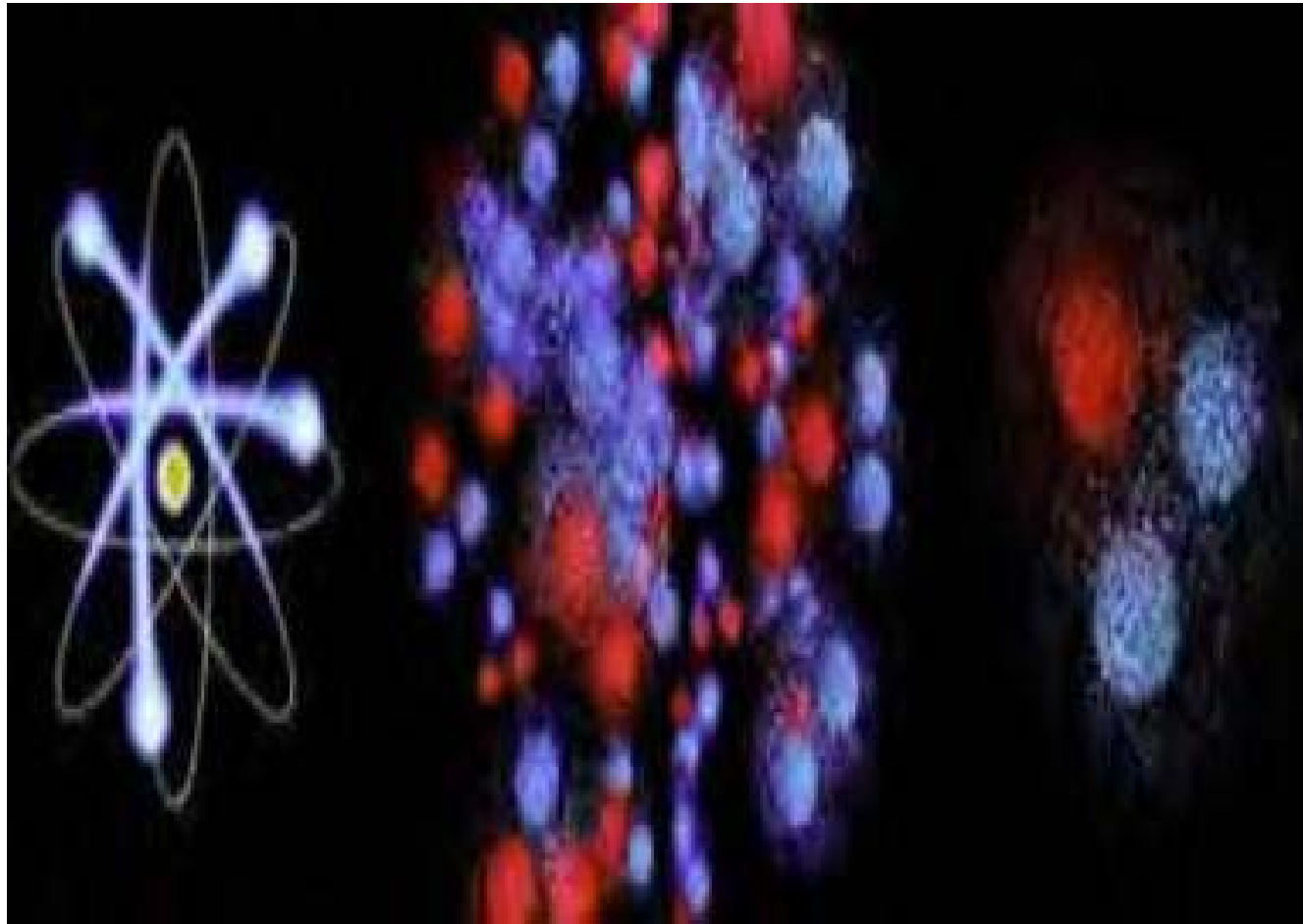
electromagnetic force



weak force

*Electromagnetic, strong, and weak forces are governing  
the structure and properties of atoms and atomic nuclei  
these three forces can all be described in a very similar way*

atom



proton or  
neutron

atomic nucleus

# The force between two charges



Charles-Augustin  
de Coulomb

$$|F| = k_C \frac{|q_1| |q_2|}{r^2}$$

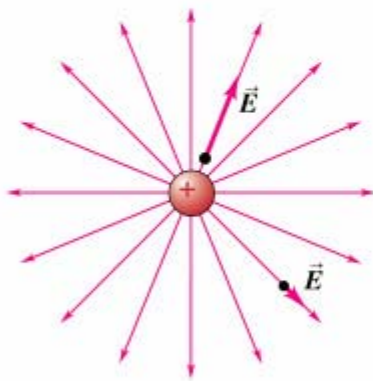
**Coulomb's law.**  
**Looks familiar?**

# Force field

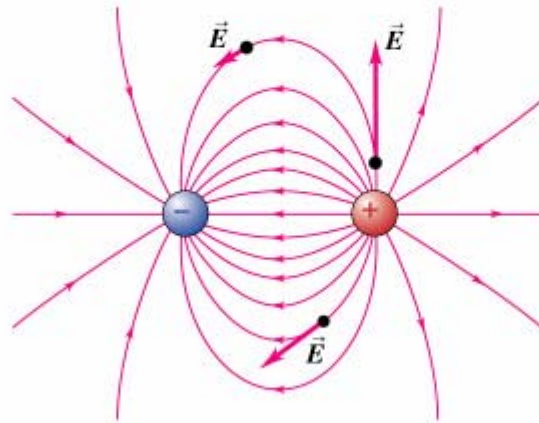


Michael Faraday

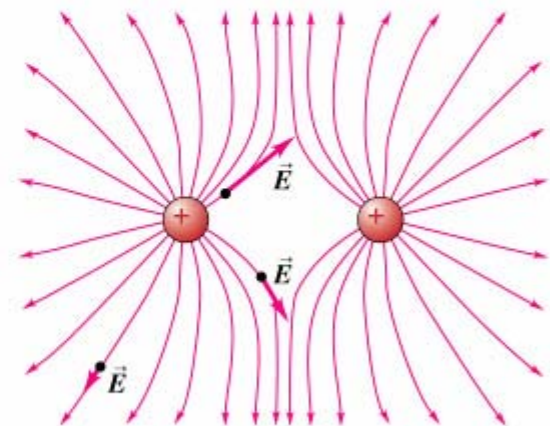
Michael Faraday introduced the concept of electric force field – a field that emanates from each electric charge into space. If another charge is placed in the field, it feels the electric force and the force fields of two particles interact. Force field is simply a mathematical concept used to describe what experiments indicated...



(a) A single positive charge (compare Figure 21.16)



(b) A positive charge and a negative charge of equal magnitude (an electric dipole)



(c) Two equal positive charges



Michael Faraday

# Connection of electric and magnetic forces

Michael Faraday used experiments to show that electricity and magnetism are connected.

For example, moving electric charges influenced magnets, and moving a magnet through a coil of wire generates electric current in the wire.

This was interpreted as an indication that electricity and magnetism are a manifestation of the same underlying electromagnetic force

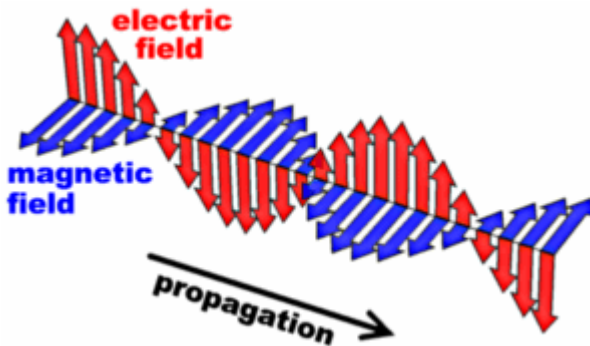
# Theory of Electromagnetism



James Clerk Maxwell

In 1864, James Clerk Maxwell came up with a set of differential equations that described the empirical data on the electric and magnetic forces/fields and their relation to each other

- equations described how perturbances in electric and magnetic fields propagate in space and time
- according to this theory, such perturbances or waves are propagating with the speed of light (this directly implies that light itself is an electromagnetic wave)
- at the same time, quantum mechanics developed in the beginning of the 20<sup>th</sup> century indicated that light and radiation in general came in discrete parcels, called quanta



Electro-magnetic radiation

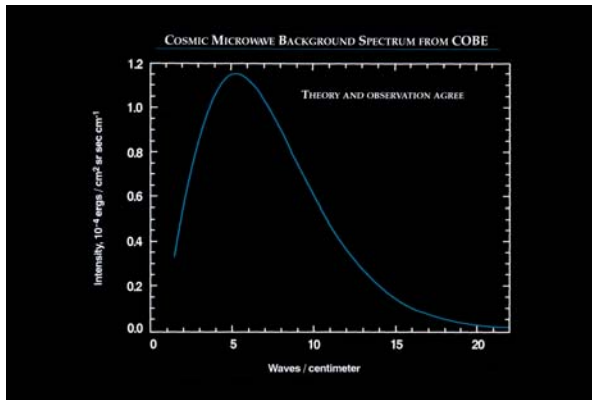
# Electromagnetic radiation and quantum mechanics



Max Planck

In late 19<sup>th</sup> century, Max Planck tried to explain the shape of the spectrum of the black body radiation observed in laboratory, and came up with an idea that electromagnetic waves come in discrete parcels of energy – quanta

*this proved to be a very fundamental paradigm shift and changed understanding of the laws governing microscopic physics profoundly. However, quantum mechanics developed before 1930 did not satisfy the revised view of space-time of special theory of relativity*



spectrum of black body radiation

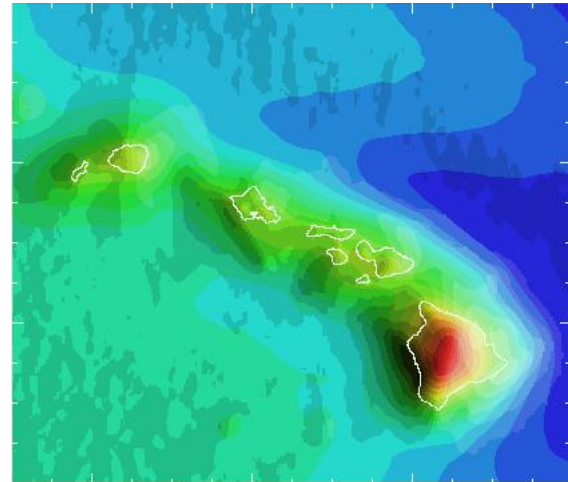
# quantum field theory

- Particles and forces between them can mathematically be described as fields – functions defined as a function of time and spatial coordinates.
- Forces are mediated by special particles (e.g., EM by photons) and propagate at the speed of light.



Paul Dirac

(derived the first version of the quantum field theory to describe quantum behavior of electron)



*Height of the Earth surface above the sea floor is a scalar function of position and time.*

# The idea of cosmic inflation



*Robert Dicke (1916-1997)*

- *Robert Dicke has popularized the Big Bang problems in the late 1970s among cosmologists and particle physicists in a series of talks and lectures*
- *Alan Guth, who worked on an independent problem, realized in 1979 that a rapid, exponential expansion (the cosmic inflation) in the early Universe can solve the problem of relics and the flatness of the Universe.*



*Alan Guth (MIT)*

*He even identified a suitable particle to drive the inflation, the Higgs boson which plays a role in many theories of spontaneous symmetry breaking (this however turned out not to work...)*

BV ⑤  
Dec 7, 1979

**SPECTACULAR REALIZATION:**

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

Let me first rederive the Dicke paradox. He relies on the empirical fact that the deceleration parameter today  $q_0$  is of order 1.

$$q_0 = -\ddot{R} \frac{R}{\dot{R}^2}$$

Use the eqn of motion

$$3\dot{R}^2 = -4\pi G(\rho + 3p)R$$
$$\dot{R}^2 + k = \frac{8\pi G}{3}\rho R^2.$$

so

~~$$q_0 = \frac{\frac{1}{2}(1 + 3p/\rho)}{1 - \frac{3kM_p^2}{8\pi G R^2}}$$~~

$$\frac{k}{R^2} = \frac{8\pi p}{3M_p^2} - H^2 \quad G = \frac{1}{M_p^2}, \quad H = \frac{\dot{R}}{R}$$

$$q_0 = \frac{4\pi}{3M_p^2}(\rho + 3p) \frac{1}{H^2}$$

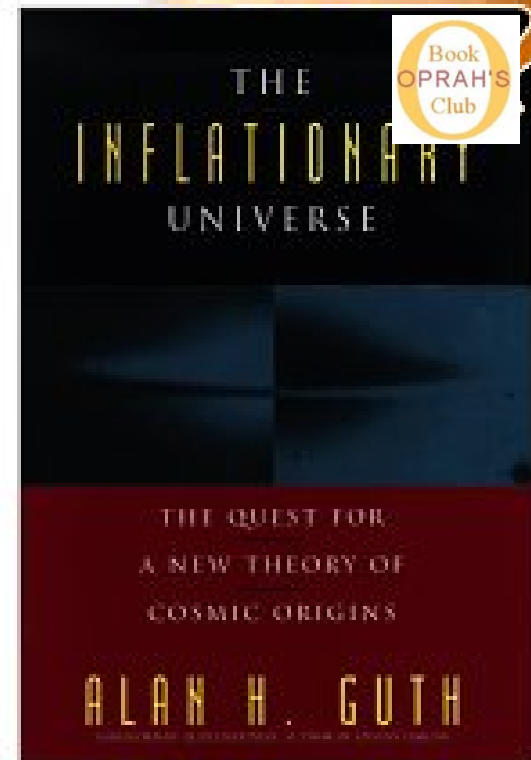
$$\frac{k}{R^2} = \frac{H^2}{(1 + \frac{3p}{\rho})} \left[ 2q_0 - 1 - \frac{3p}{\rho} \right]$$

Using the above eq., the fact that  $\frac{3p}{\rho} \approx 0$  for today's universe, and the fact that  $q_0 \sim 1$ , one has

A page from Alan Guth's log book from Dec 7, 1979

with the "spectacular realization" that exponential expansion of the early Universe can solve the flatness problem

**SEARCH INSIDE!**<sup>TM</sup>



# The idea of cosmic inflation



*Andrei Linde*

*It turned out that this idea was not born in a vacuum, similar idea has been developed by Andrei Linde and David Kirzhnits, and by Alexey Starobinsky in Moscow since mid-70s*

*However, it was Guth who formulated the first complete and coherent model of cosmic inflation in 1979-1980 and explained why it was so very important.*



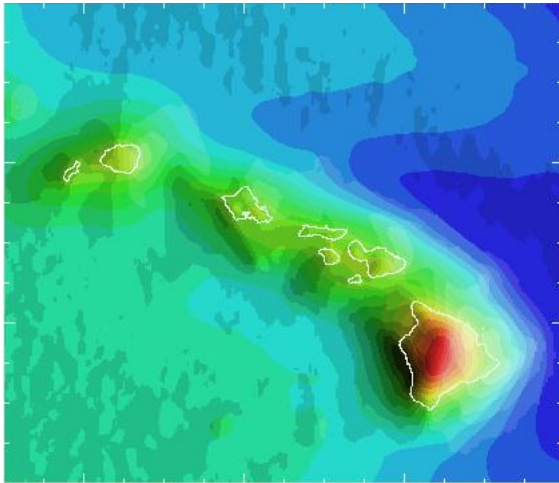
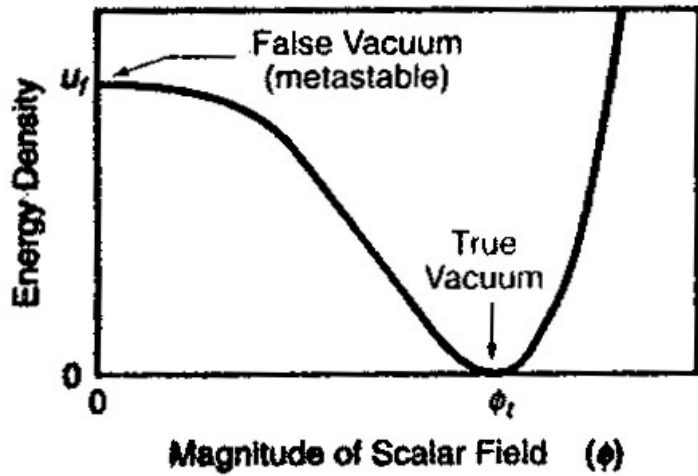
*David Kirzhnits (1926-1998)*



*Alexey Starobinsky*

# Cosmic inflation: details

**The original Guth's model used the Higgs boson to drive the inflation in the early universe**



Height of the Earth surface above the sea floor is a scalar function of position and time.

- ❑ The Higgs particle is characterized by a potential, which describes the energy density of the field as a function of the scalar field value  $\phi(x,t)$
- ❑ Guth postulated that the Universe could have started with unstable, non-zero field energy (false vacuum), which then evolved towards the zero energy state (true vacuum)
- ❑ While in the false vacuum state, the energy density of the field is  $>0$ , it dominates the energy density of the Universe, and can drive inflation

# The basic idea is simple

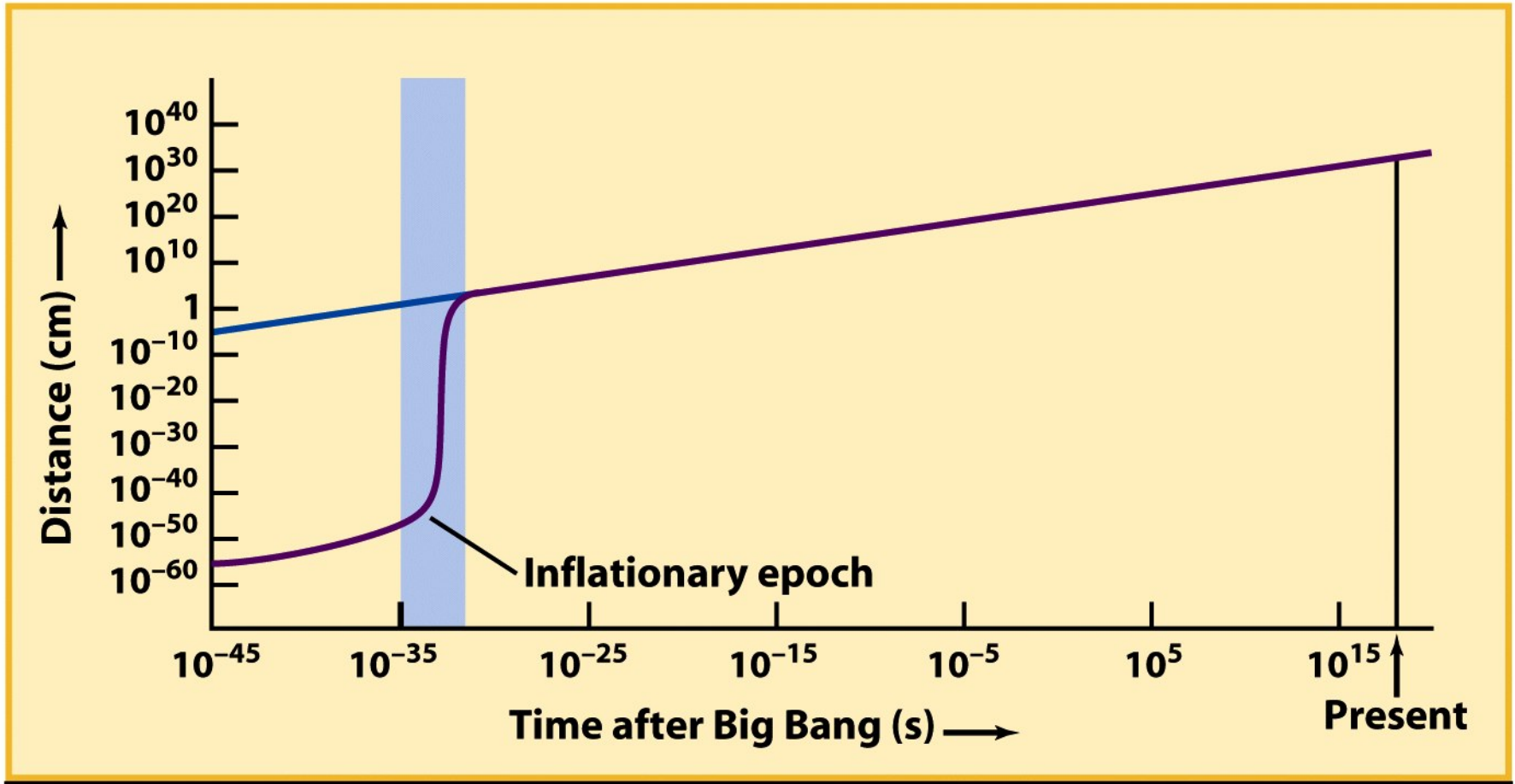
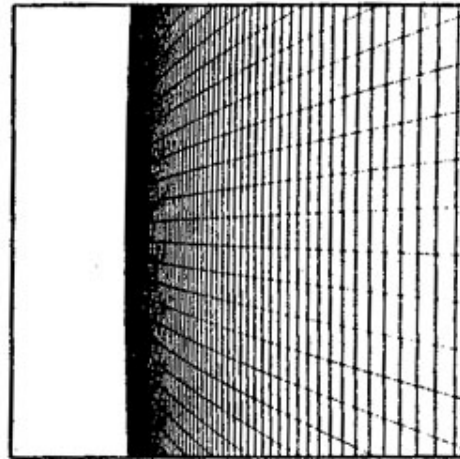
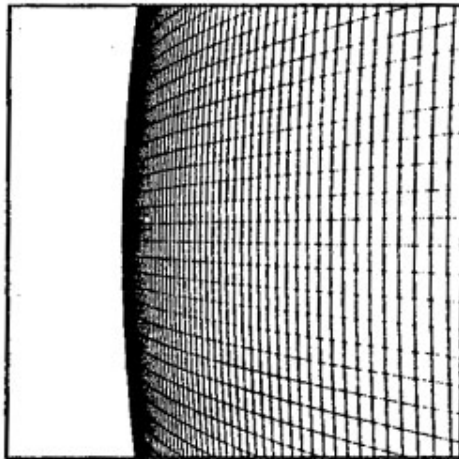
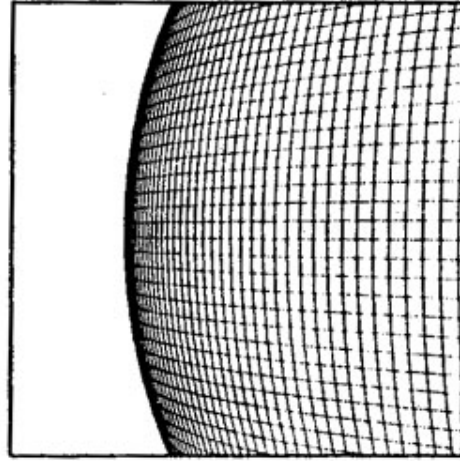
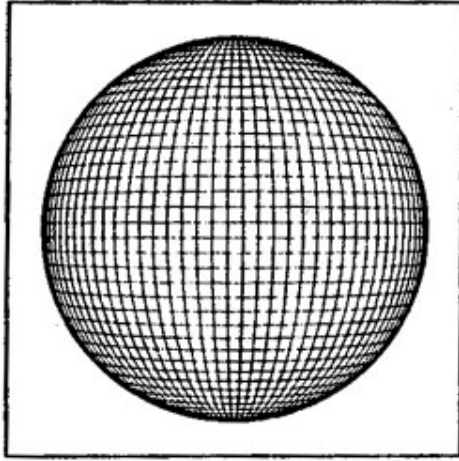


Figure 27-2  
*Universe, Eighth Edition*  
© 2008 W. H. Freeman and Company

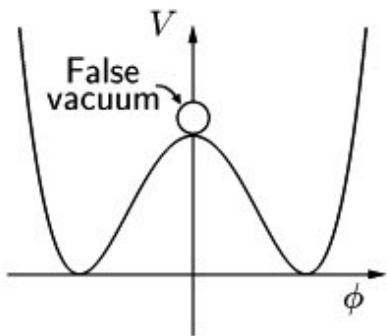
Rapid expansion "stretches" space  
making it locally flat



# "New and chaotic inflation"

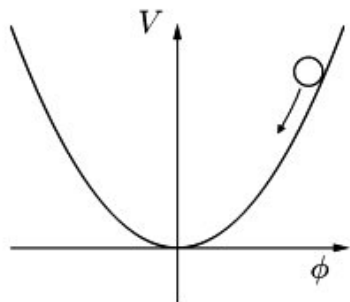
## Aka "Slow-roll inflation"

**Was proposed independently by Andrei Linde and by Andreas Albrecht and Paul Steinhardt**



New Inflation

Linde; Albrecht & Steinhardt  
(1982)



Chaotic Inflation

Linde (1983)

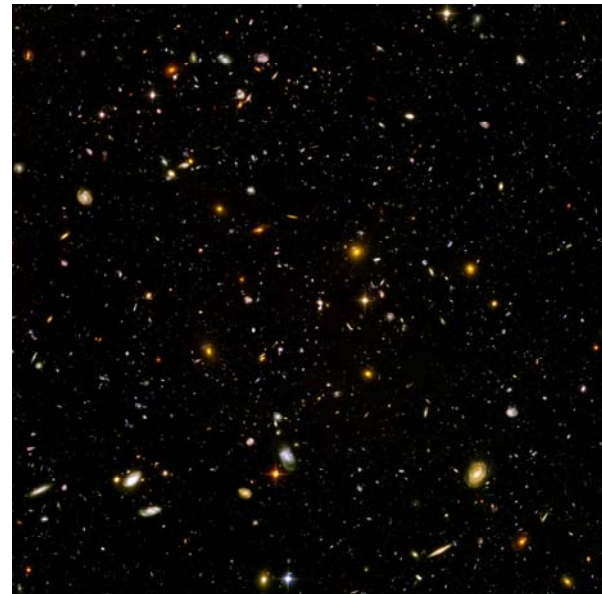
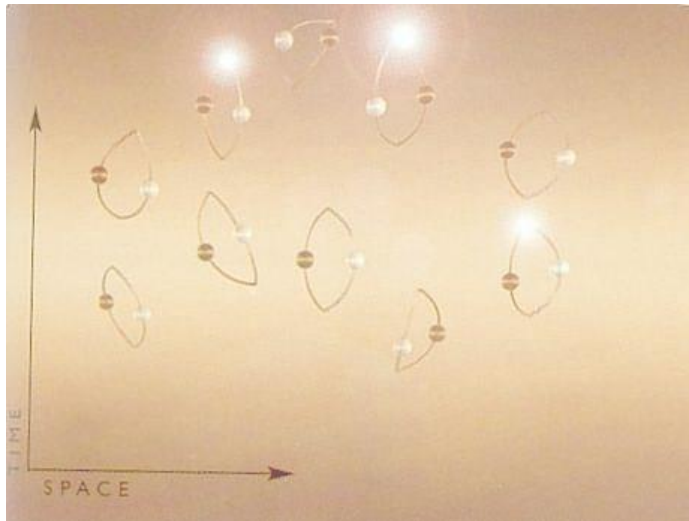
- *New/chaotic inflation substitutes Higgs potential by a different potential due to unknown particle, the inflaton, which has slowly decreasing potential near  $\phi=0$*
- *This slow-decrease of  $V(\phi)$  means that the expansion is quasi-exponential and actually slows down as the field moves to the true vacuum, alleviating the graceful exit problem*

# Inflation and the quantum origin of structures in the universe

*Exponential expansion of the Universe magnifies quantum fluctuations existing on very small scales to much larger size*

*large enough to seed formation of galaxies and all of the structures in the Universe...*

*Inflation thus provides an ultimate link between the smallest quantum scales and the largest structures in the Universe*



# Cosmic Inflation

*Obviously leads to many interesting and striking implications...*

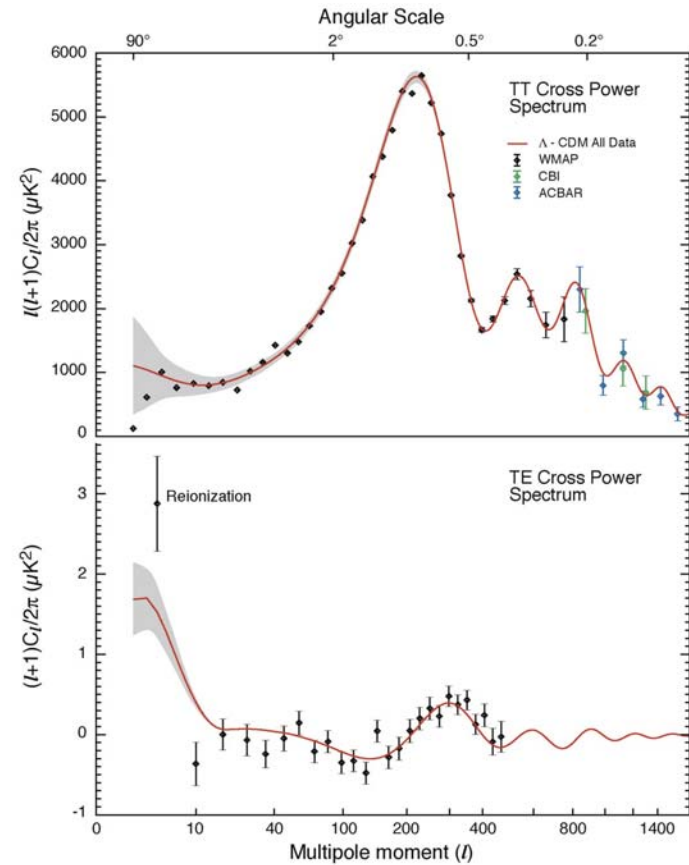
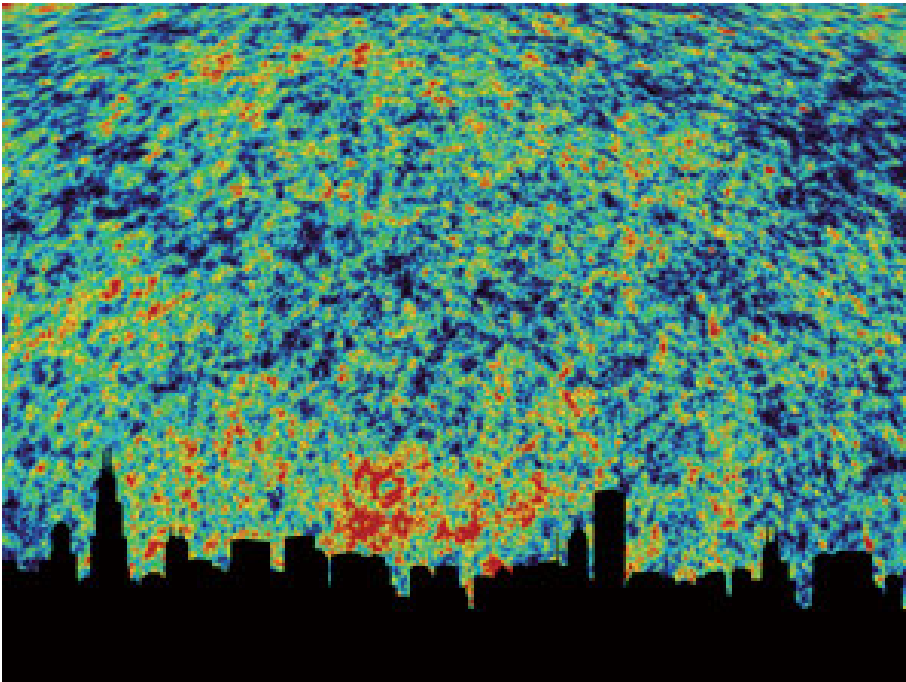
*No favored model exists yet, and observations are consistent with the inflation but do not yet firmly confirm or disprove it (this can happen in the next 5-20 years with improved measurements of the CMB anisotropies)*

*As a basic idea explaining the flatness of space, the relic problem, and the causality problem inflation remains very attractive and important*

# Tests of inflation

"I really never thought that anybody would ever actually measure these things... I thought we were just calculating for the fun of it." – Alan Guth

Each specific inflation model makes predictions for the form of the spectrum of primordial perturbations which can be tested by observations of the CMB anisotropies and large-scale structure



## Connections: Quarks to the Cosmos

The image features a central funnel-like structure that tapers from left to right. The left side of the funnel is filled with a dense, intricate network of glowing orange, yellow, and purple filaments, representing the microscopic world of quarks and elementary particles. The right side of the funnel opens up into a vast, dark space filled with numerous galaxies, including spiral and elliptical types, representing the macroscopic universe. The overall color palette transitions from warm, bright colors on the left to cooler, darker blues and purples on the right.

Amazingly, studying microscopic physics of elementary particles and evolution of the universe as a whole came to a very strong connection...