Misc

1. Today we will talk about early stages in the evolution of the Universe (continuation from monday lecture).
Reading: S 27-2, 27-3, 27-4.

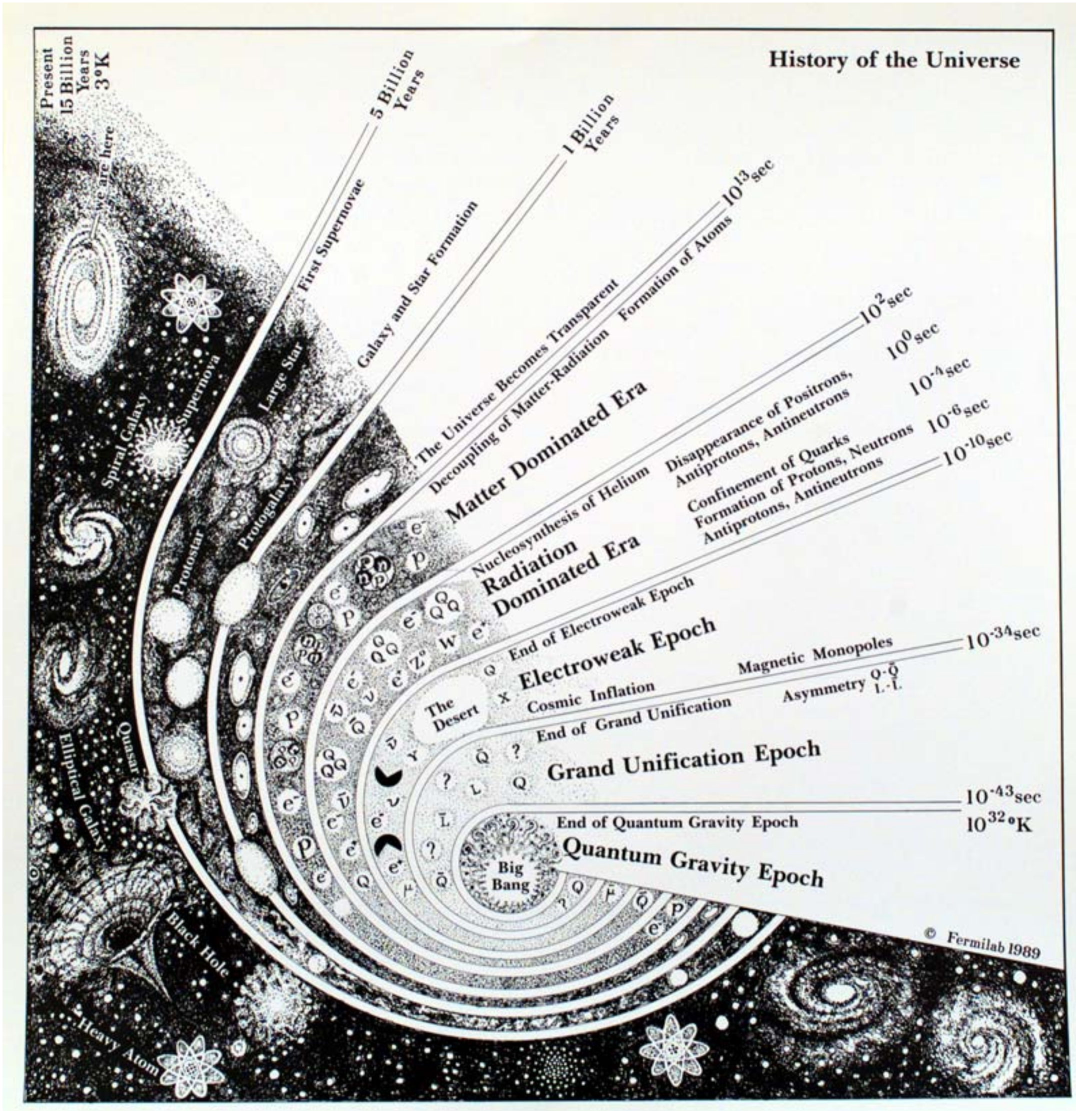
2. HW 5 solutions are on the class website.

3. The last HW7 will be distributed on Friday. HW6 is due on Friday in class.

4. Labs – next week make-up lab week and we will continue CMB lab for those who have not had a chance to get measurements Monday through Wednesday.

5. Final Exam – Monday, March 17 (here in KPTC 106) – 1:30-3:30PM.

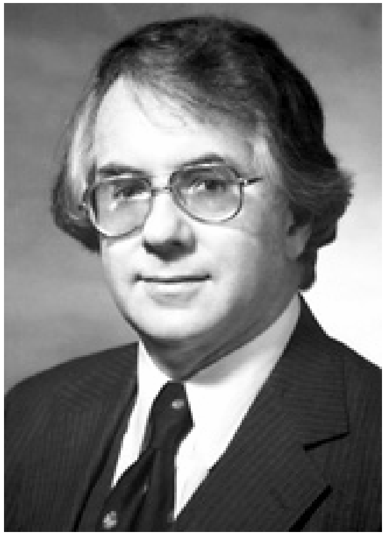
Physical processes in the early Universe (continued)



Unification of electromagnetic and weak forces

- In 1960s, Glashow, Salam, and Weinberg came up with a theory which explained both EM and weak force as a manifestation of a single unified force
- This worked if one assumed that quarks and leptons have negligible mass, which would be true if all of their energy was in the form of energy of their motions and their rest mass is not important.
- This is true if particles have a lot of kinetic energy of motions and move with velocities close to the speed of light

Steven Weinberg

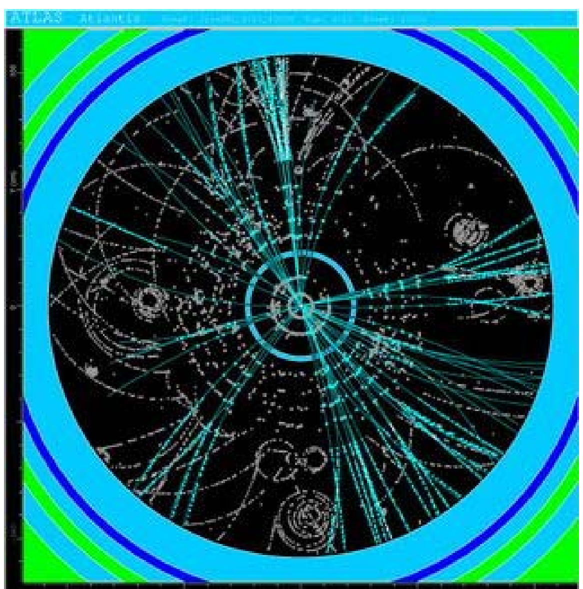


Sheldon Glashow

Abdus Salam

Unification of electromagnetic and weak forces

- The electroweak theory *predicted* that two new particles – W and Z gauge bosons, mediated interactions of the new unified force.
- These particles were later discovered in the CERN laboratory experiments in 1979
- Electroweak theory also predicts existence of a neutral particle, the Higgs boson, that is responsible for the symmetry breaking (separation of the two forces) and has mass of order 120-1000 GeV.



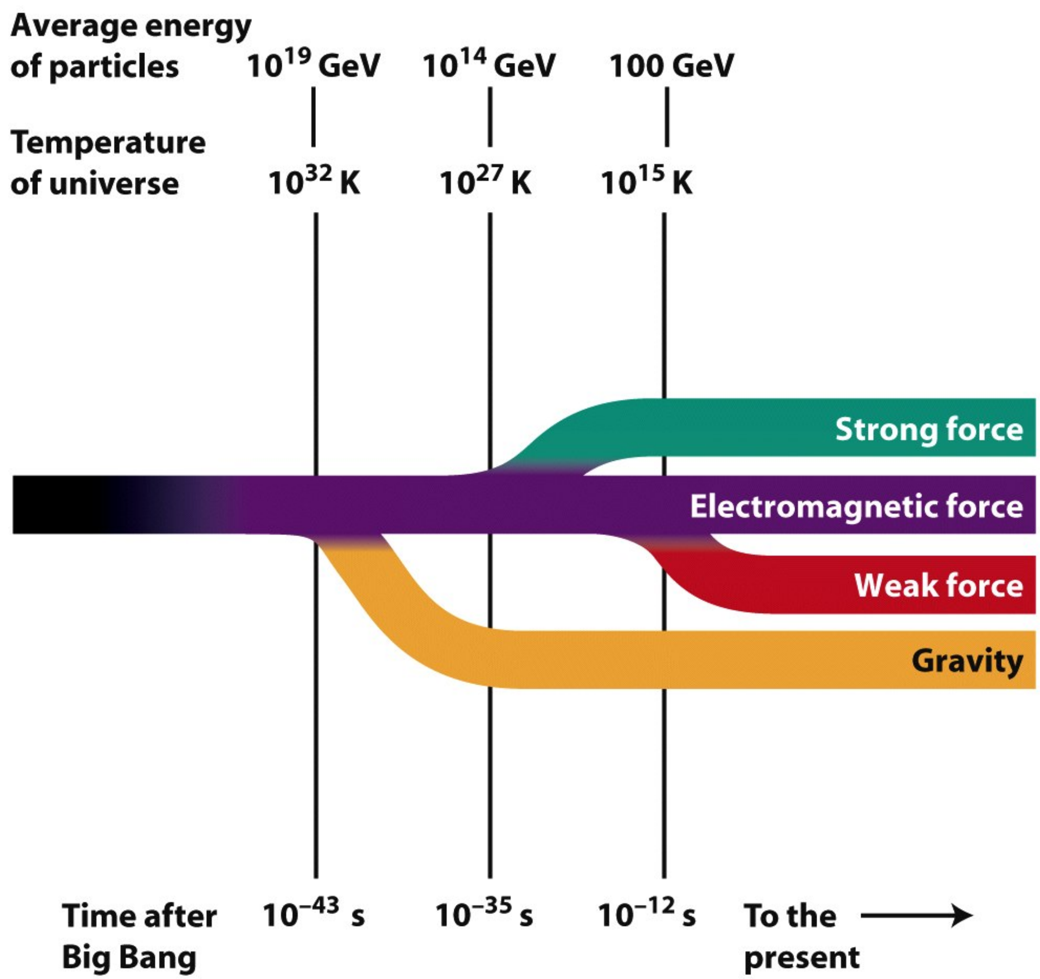
Aerial view of the CERN laboratory

Unification of electromagnetic, weak and strong forces: Grand Unification Theories (GUTs)

- In 1970s, Glashow, Georgi, Pati, and Salam proposed a class of theories, the Grand Unification Theories (GUTs), that predict that EM, weak and strong force become indistinguishable (unified) at energies $>10^{14}$ GeV
- Physicists also suspect that all four fundamental forces become indistinguishable at energies $> 10^{19}$ GeV – Theories of Everything (TOEs).

Early universe and unification of forces

energy and temperature are related
by the Boltzmann constant:
$E = kT$; where $k = 10^{-13}$ GeV/K



How the four forces behave at different energies and temperatures

Figure 27-6a

Unification of electromagnetic, weak and strong forces: Grand Unification Theories (GUTs)

- These theories are not yet verified experimentally, because humans cannot reach such large energies with the current technology and resources – the largest modern accelerators can achieve energies of order 10 TeV (10^4 GeV).
- Nevertheless, some aspects of these theories and the validity of the electroweak unification can be tested with the Tevatron at Fermilab and the new Large Hadron Collider (LHC) on the border of Switzerland and France.

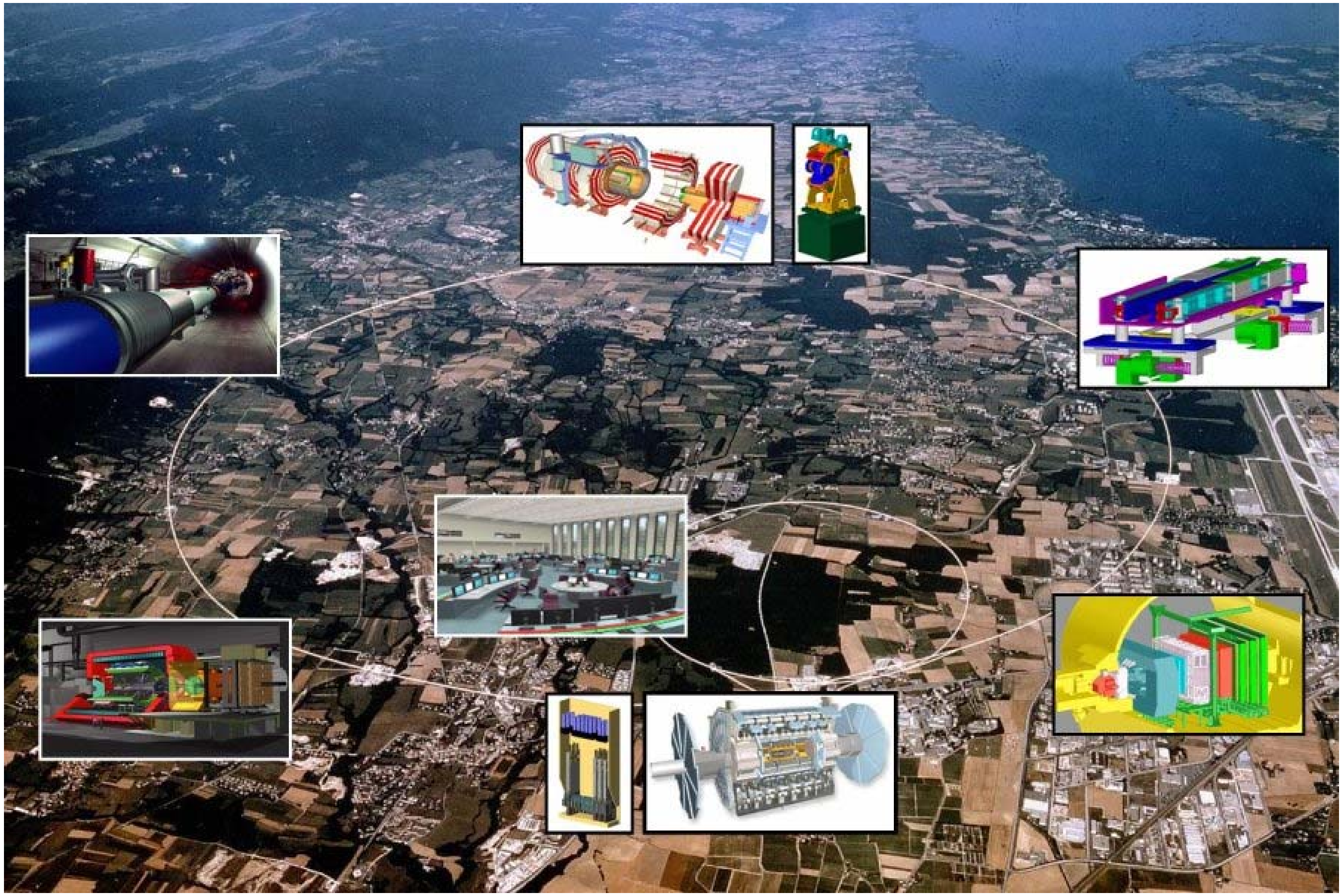
Fermilab's Tevatron
in Batavia, near Chicago

The Tevatron accelerates protons and anti-protons in a 4 mile ring to energies of up to 1 TeV (1000 GeV)

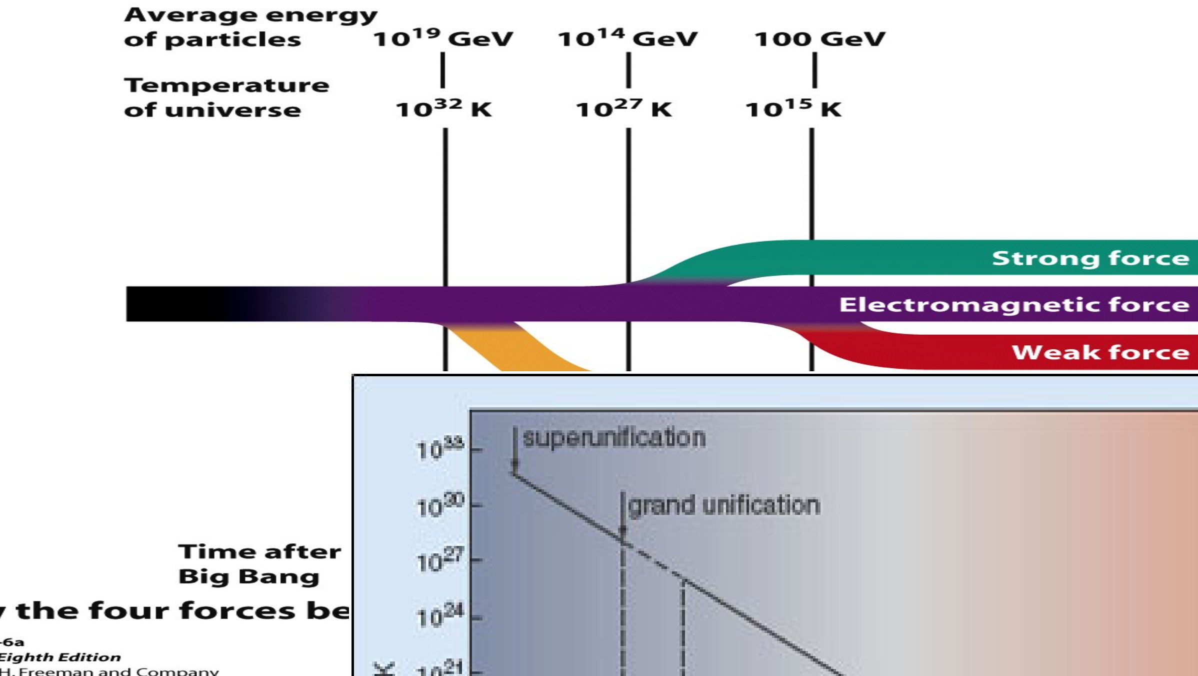
Large Hadron Collider (LHC) on the border of France and Switzerland

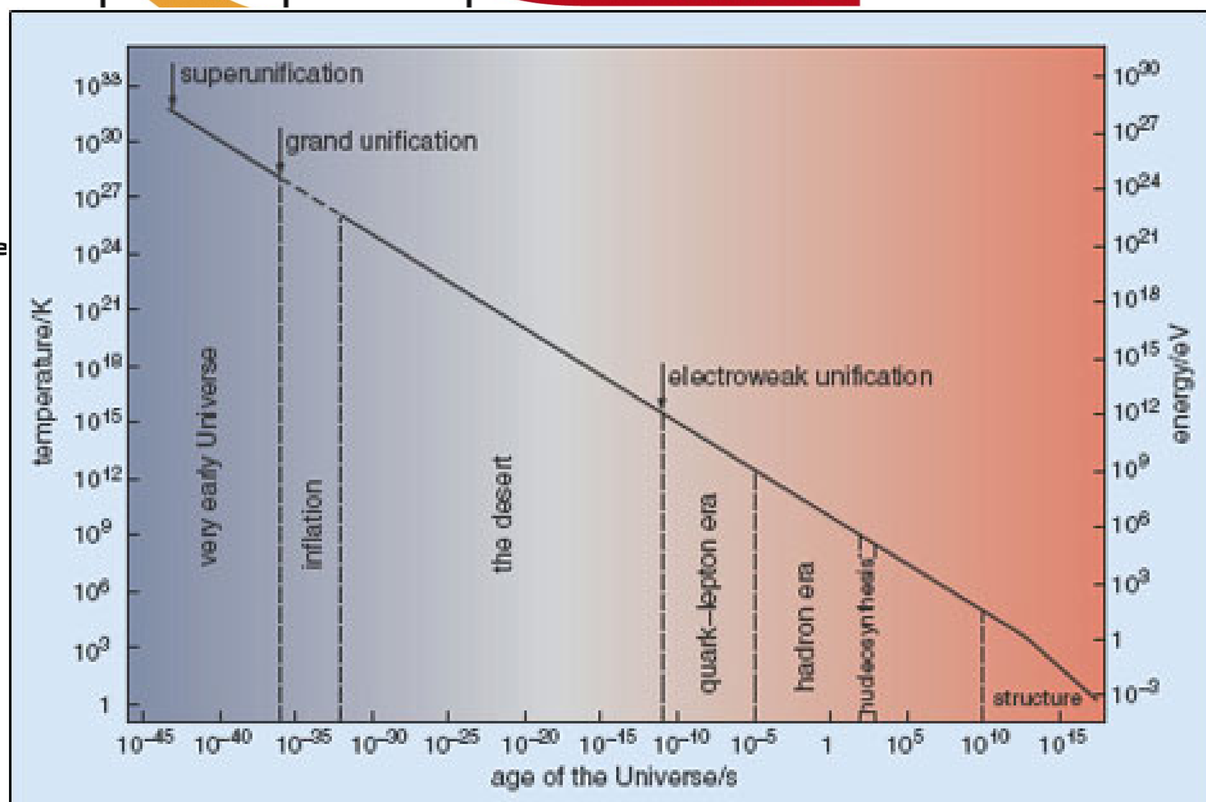
The LHC can accelerate protons in a ring of 16.5 mile radius
to energies of up to 7 TeV.

It will start operation in 2008 – physicists expect it to detect the Higgs boson among other things (such as sypersymmetric partners of normal particles)



High-energy physics and early stages in the evolution of the Universe

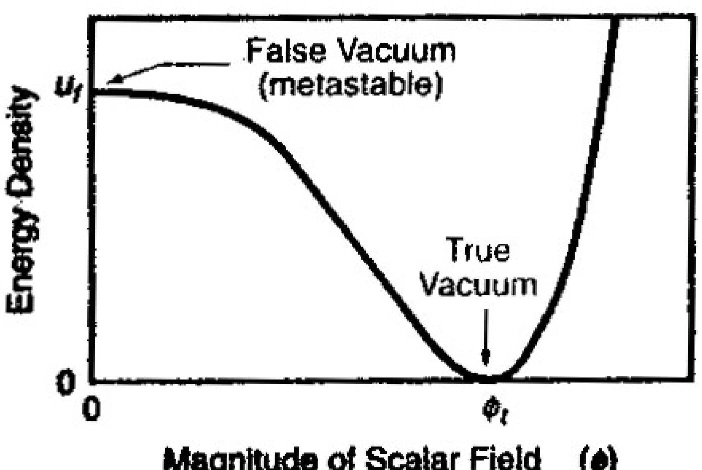




Cosmic inflation

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

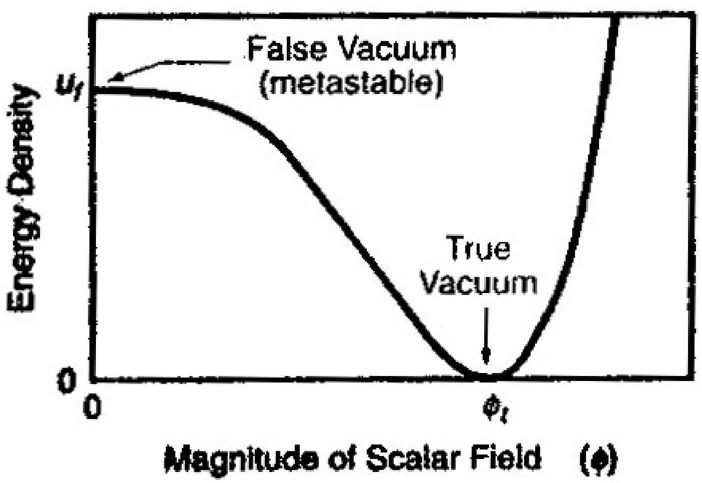
Alan Guth (MIT)

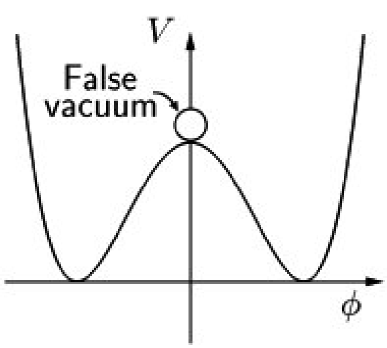


- *The Higgs particle is characterized by a potential, which describes the energy density of the field as a function of the scalar field value $\phi(x,t)$*
- *Guth postulated that the Universe could have started with unstable, non-zero field energy (false vacuum), which then evolved towards the zero 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*

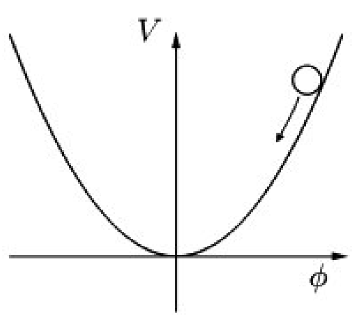
Cosmic inflation: details

It was, however, quickly realized that this original model does not work…





New Inflation
Linde; Albrecht & Steinhardt
(1982)

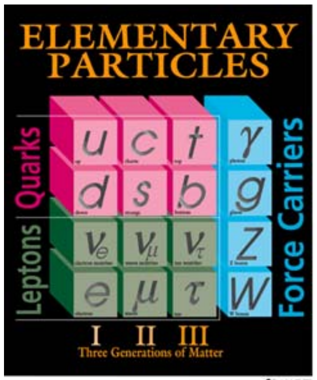


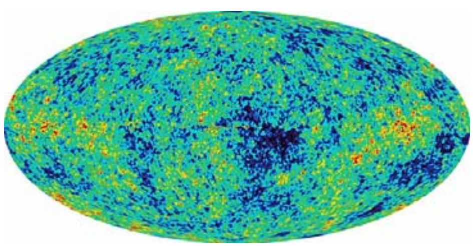
Chaotic Inflation
Linde (1983)

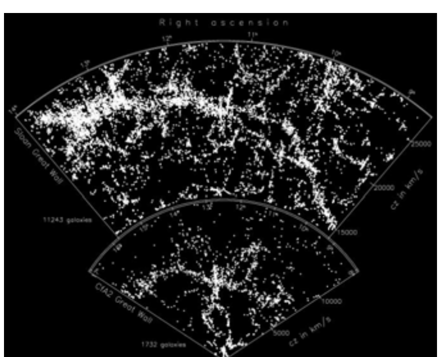
- *Inflation continues until the field reaches the true vacuum $V(\phi)=0$, which follows the symmetry breaking of the force unification, and the field remains there indefinitely (i.e., no more inflation in the future).*
- *However, it turned out that for the Higgs field, the transition from the false to true vacuum was way too long and inflation continued too long. (the so-called graceful exit problem). This is because <u>the potential of the Higgs boson is too flat</u> near $\phi=0$. Cosmologists introduce different hypothetical fields,the inflaton to drive inflation.*

Inflation can naturally explain two key facts about our Universe

(in addition to explaining the horizon, flatness, and other puzzles)

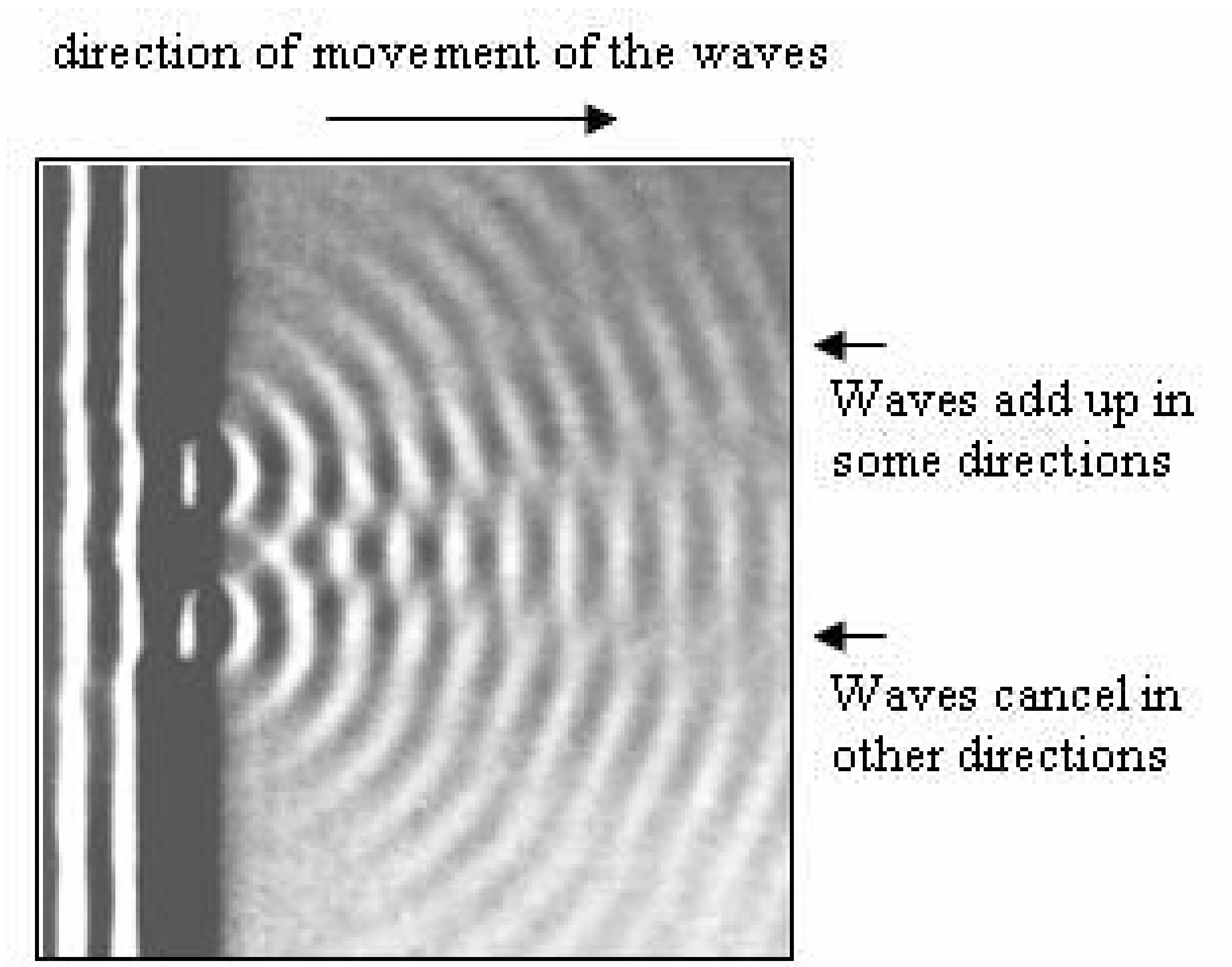






- *The origin of matter and particles in the Universe.*
- *The origin of inhomogeneities that led to formation of CMB temperature fluctuations, galaxies, clusters and superclusters.*
- *Both are related to the quantum nature of the microscopic physics and Heisenberg's uncertainty principle.*

two slit diffraction of a wave



Quantum weirdness: two slit diffraction of particles

Particles (e.g., electron) are “fuzzy” and propagate through two slits at the same time