Our UNIVERSE: where it all came from....
QUESTIONS OF THE DAY....

- How did the Universe start?
- How did the Universe evolve up to the present day?
- What is the fate of our Universe?
The theory of general relativity provides the framework to study the large-scale structure of the Universe.

- Gravity is the only force that is long-ranged enough to influence object scales much larger than typical interstellar distances.

- There is a lot of matter in the Universe to serve as gravity’s source.
The Universe is homogeneous and isotropic on large scales

[Image from “The Physical Universe” by F. Shu]
Solutions to Einsteins’ field equations for an homogeneous and isotropic Universe

[Image from “The Cosmic Perspective” by Bennett et al.]
All solutions are TIME-DEPENDENT, i.e. they describe an EVOLVING Universe.

Einstein introduces a “fudge factor” in his equations to “counteract” the effect of gravity and make the Universe static.

Einstein does not like these time-dependent solutions.
1929: the truth is revealed..... Edwin Hubble discovers that the Universe is expanding

- Distant galaxies are always seen to have redshifted spectra
- The magnitude of the Doppler shift is proportional to the distance of the galaxy

[Image of E. Hubble from the Caltech Archives]
The more distant two points are on the balloon, the fastest they will appear to move away from each other.
Einstein gives up.....

He admits that the cosmological constant has been the biggest blunder of his career

... well... maybe not quite....
HOW DID THE UNIVERSE BEGIN?

BIG BANG THEORY describes earliest moments of Universe

Beginning of Universe = beginning of TIME
Image from “The Cosmic Perspective” by Bennett et al.
Planck Era: $t < 10^{-43}$ sec
- Universe extremely small, dense and hot
- All 4 forces are unified
- Need a theory of gravity and quantum mechanics for understanding this phase

GUT Era: $10^{-43} < t < 10^{-38}$ sec
- Gravity separates

Electroweak Era: $10^{-38} < t < 10^{-10}$ sec
- Electromagnetic and weak forces separate

[Image from “The Cosmic Perspective” by Bennett et al.]
Particle Era: $10^{-10} < t < 0.001$ sec ($T \approx 10^{12}$ K)

- Continuous process of creation and annihilation of elementary particles and antiparticles (electrons, neutrinos, quarks)

Matter-antimatter symmetry breaks

Era of Nucleosynthesis: $(0.001 \text{ sec} < t < 3 \text{ min})$

$(10^{12} \text{ K} < T < 10^9 \text{ K})$

- Quarks combine to form protons and neutrons
Era of Nuclei: $3 \text{min} < t < 380,000 \text{yr}$
$10^9 \text{K} < T < 3000 \text{ K}$

- Protons and neutrons combine to form nuclei

Era of atoms: $380,000 < t < 1 \text{ billion years}$

- Nuclei and electrons combine to form atoms
- Stars begin to form

Era of galaxies: $1 \text{ billion years} < t < \text{today}$

- Galaxies form
One obvious question….

How do we know that this is actually TRUE?

Big bang theory predicts (Gamow 1940):

- We should be able to see the “remnant” of the radiation from the early, hot, Universe
- The radiation should appear isotropic on the sky
1965: Penzias & Wilson discover the cosmic background radiation, relic of the Big Bang
Electrons recombine with protons and neutrons to form atoms: photons are free to “get away”

Lots of collisions between photons and electrons: photons are “trapped”

Where the cosmic microwave background comes from
The sky “seen” by WMAP in the microwave band

Isotropic to a few parts in $10^5$ K
Does the Big Bang Theory explain everything?

NO!

Biggest unanswered questions:

- **“Flatness” problem:** why is the density in the Universe almost critical?
- **“Horizon” problem:** why is the large scale of the Universe so smooth?
Mid-80s: Alan Guth formulates the THEORY OF INFLATION to solve these problems
THE THEORY OF INFLATION

Inflation

under inflationary cosmology, the Universe underwent a phase change at the GUT era and expanded faster than the speed of light (the spacetime itself expanded, so there is no violation of special relativity)
The enormous inflation “stretches out” the curvature of space, making it flat.

Solution to the “flatness” problem

[Image from “The Cosmic Perspective” by Bennett et al.]
Regions (that could not have communicated without Inflation) were in contact before Inflation started.
Big Bang Theory + Inflation provide a pretty good (although still not complete) picture of the early moments of the Universe.

What comes next?

STRUCTURE FORMATION

Being now days studied with computer simulations...
Formation of structure

- Universe expands from left to right
- Matter collapses into filaments and clusters
- Simulations show similar features compared to observations

[Image from http://cosmicweb.uchicago.edu/filaments.html]
Example of “structure” today….

The spiral galaxy NGC 1232, about 100 million light years away.

[Image: ESO/VLT]
The MILKY WAY
WHAT IS THE FATE OF OUR UNIVERSE?

Observations suggest presence of repulsive force ("dark energy" or "cosmological constant")
Not everything that can be counted counts, and not everything that counts can be counted.

- Albert Einstein