Cosmology - The Story of our Universe

Lecture 2

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What is Cosmology?

- Study of our Universe today – galaxies, clusters, superclusters

- Understanding the past history and future evolution of our Universe

PAST ← PRESENT → FUTURE

- Observational Astronomy and Theory of General Relativity has given us today an understanding of the Cosmos

Course Outline

I. Overview of what we know about our Universe

II. Laws governing the evolution of the Universe

III. Constituents of our Universe
(radiation, matter incl. dark matter, dark energy)

IV. Formation of Structure

V. Physics of the very early Universe ($t < 10^{-6}$ s)
Interface with Particle Physics

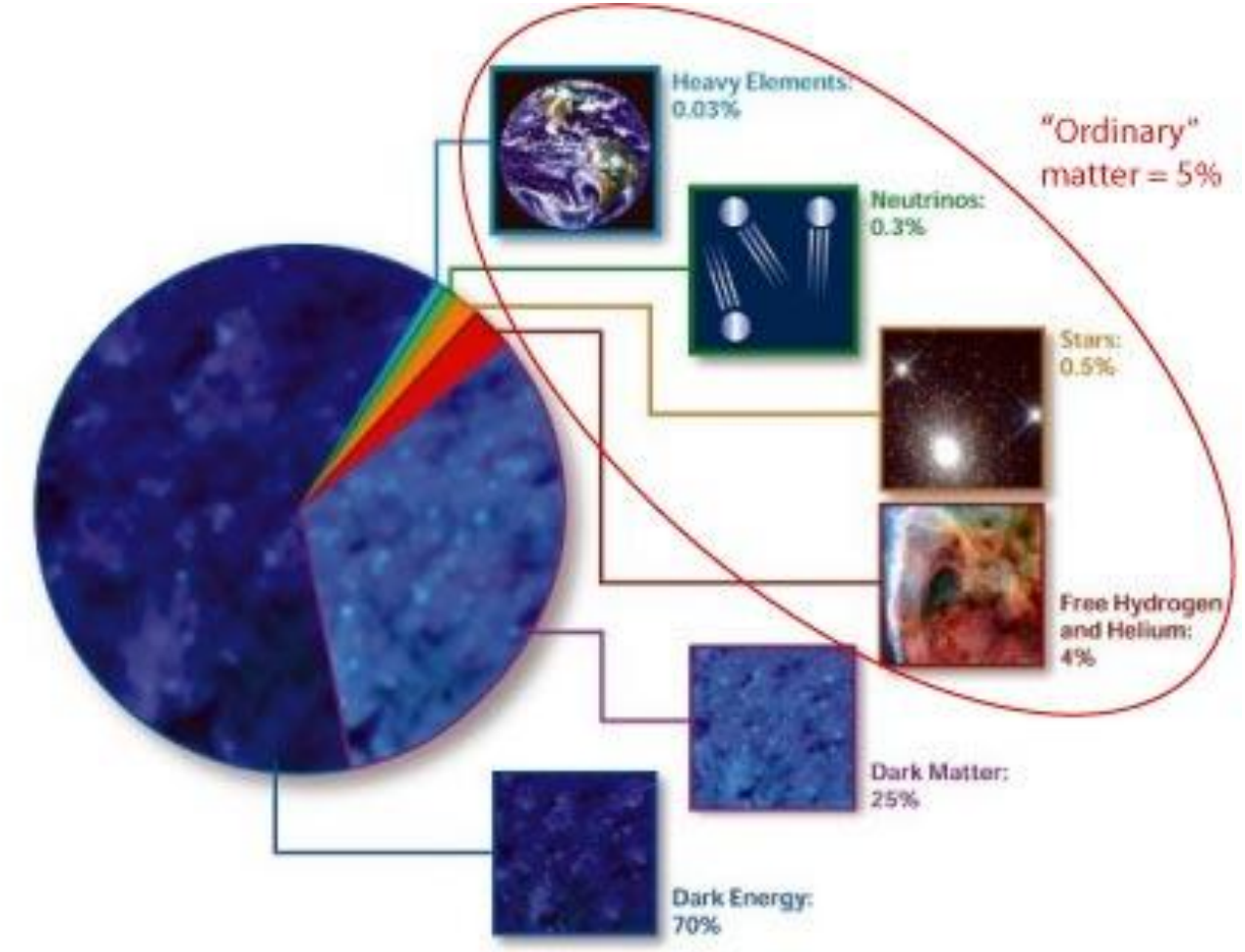
PRESENT

- Stars with planets
- Galaxies
- Clusters of Galaxies
- Superclusters
- Voids

Composition of our Universe

- Photons and neutrinos – negligible
- Protons, neutrons and electrons – 5%
- Dark Matter – 25%
- Dark Energy – 70%

Composition of our Universe



Composition of the Universe

Expansion of the Universe

- All distant galaxies are moving away from each other (Hubble 1929)

- Not because of intrinsic velocities but because space is expanding

The Past

- Go back in time, all material that is in all galaxies around us was in a smaller and smaller region

INITIAL STATE (14 billion years ago)

- At the earliest instant, density/energy very high
- Expansion rate very high

THE BIG BANG

After the Big Bang

- First second – hot primordial soup of electrons, protons, neutrons, dark matter
- 1 s – 3 min – light nuclei (helium, lithium, ..)
- 400,000 years – Atoms form
- 300 million years – First stars form
- 1 billion years – First galaxies form
- 9 billion years – Universe is accelerating
- Solar system formed
- 14 billion years – Today

The Future

- Universe keep expanding
- May continue to accelerate or may not

  Different scenarios

Summary

- We live in an expanding Universe
- Initial condition was a very dense, energetic, fast expanding state – The Big Bang
- Today Universe of stars and galaxies, clusters and voids - structure
- Accelerated expansion today. Unsure about future

Books on Cosmology

- The First Three Minutes by S. Weinberg

- The Big and the Small vII by G. Venkataraman

- Also see Cosmology and Relativity Tutorials on Ned Wright's (UCLA) homepage
  http://www.astro.ucla.edu/~wright/intro.html ,
  and on John Baez's (UCR) webpages
  http://math.ucr.edu/home/baez/gr/ and
  http://math.ucr.edu/home/baez/physics/

THE UNIVERSE

BY MICHAEL S. TURNER

Cosmologists are closing in on the ultimate processes that created and shaped the universe

Scientific American, Sept. 2009, 36-43

Send email to raghavan@prl.res.in

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Evolution: Past and Future

- Theory of General Relativity
- Observations

Important observations in the study of Cosmology

Observations

- Early 20th c. debate

  Is the Milky Way the entire Universe or one of many island universes (galaxy) ?

- Shapley-Curtis `The Great Debate' 1920

  National Academy of Sciences, Washington DC

Supporting observations for both sides regarding spiral nebulae

Observations

- Early 20th c. debate

  Is the Milky Way the entire Universe or one of many island universes (galaxy) ?

- Shapley-Curtis `The Great Debate' 1920

  National Academy of Sciences, Washington DC

Resolved in the 1920s by Edwin Hubble –

Spiral nebulae are too distant to be in our galaxy

Observations

- Distant galaxies are moving away from us

  Vesto Slipher 1912 (redshift)

- At a speed proportional to their distance from us

  Edwin Hubble 1929 (and Milton Humason*)

Edwin Hubble

* School dropout, muleskinner and janitor, astronomer

All distant galaxies are moving away from us at a speed proportional to their distance -- Hubble's Law: $v = H d$ [Lemaitre 1927]

Galaxies are moving away from each other
Universe is expanding.

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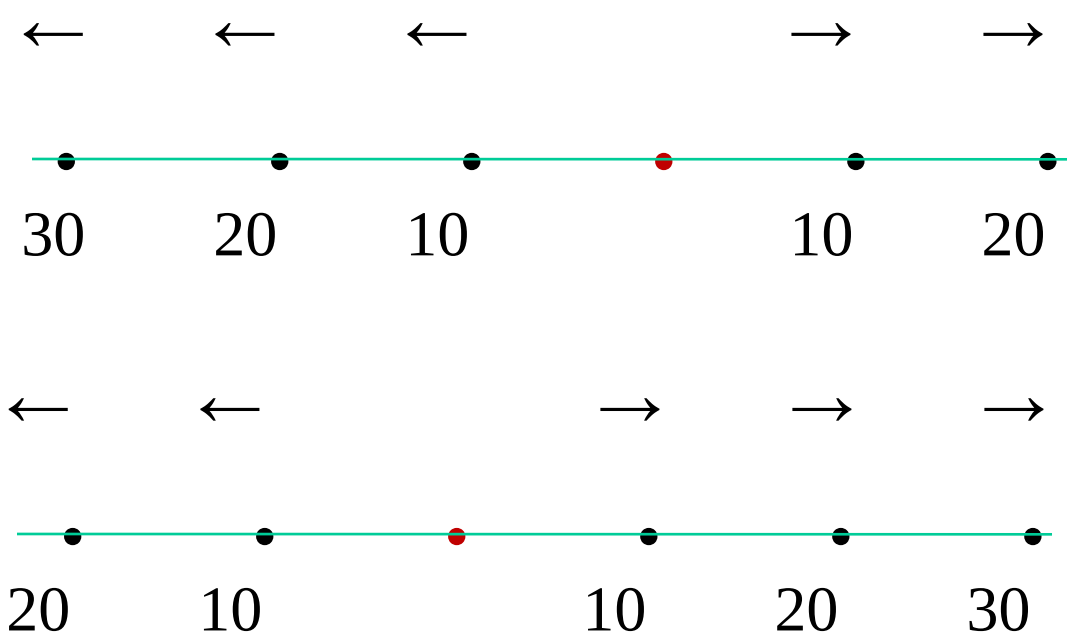

Galaxies are moving away from each other
Universe is expanding.

Cosmological Principle

- Universe appears the same for each galaxy
- Our galaxy is not special in the Universe

- Similar to the Copernican Principle for the Solar System – We are not at the centre of the solar system

The Theory

- Einstein's Theory of General Relativity (1907-1915)

  Theory of Gravity

  Supersedes Newton's Theory of Gravity (1684)

  Valid for very massive objects, high velocities, gravity of the universe

The Theory of General Relativity

- Mass (or energy) curves space
- Objects moving in this space change their motion because of the curvature of space
- Gravitational field replaced by modification of space

Gravity = Accelerating frame

- You are in a rocket far from any massive body.
  Rocket accelerates at +9.8 m/s^2.
  Drop a ball. It falls to the floor of the rocket with acceleration 9.8 m/s^2.

- You are in the rocket at rest on the Earth.
  Drop a ball. It falls to the floor of the rocket with acceleration 9.8 m/s^2.

Gravity = Accelerating frame

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- You are in the rocket at rest on the Earth.
  Drop a ball. It falls to the floor of the rocket with acceleration 9.8 m/s^2.

Suppose the rocket is sealed with no windows.
Would you be able to tell the difference?

Gravity = Accelerating frame

- http://www.physics.nyu.edu/~ts2/Animation/general_relativity.html

Gravity = Accelerating frame

- You are in a rocket far from any massive body.
  Rocket is moving at a constant velocity.
  Release a ball. It remains at rest relative to you.

- You are in the rocket falling freely towards the Earth.
  Release a ball. It remains at rest relative to you.
  (As in a spacecraft with engines off)

Suppose the rocket is sealed with no windows.
Would you be able to tell the difference?

Principle of Equivalence

- A linearly accelerated frame is locally equivalent to a frame at rest in a gravitational field.

- Uniform motion in the absence of a gravitational field is locally equivalent to free fall in a gravitational field.

Space(time) is curved

- Do away with the gravitational field
- But we do not have rockets accelerating us.

  Then how explain ball falling to Earth, or Earth going around the Sun?
- Space is curved due to the presence of massive bodies which affects the motion of other bodies.

Space(time) is curved

- Space is curved due to the presence of massive bodies which affects the motion of other bodies.

- Since this curvature is a property of the space, that is why different masses will fall at the same rate to the Earth (Galileo experiment).

- [Recall acceleration due to electric field = qE/m. Depends on particle – not due to space.]

Are these ideas correct?

Predicted differences from Newtonian gravity

- Close to a massive object (star)
- At relativistic speeds (v ~ c)
- Applied to the Universe

Precession of the perihelion of Mercury

- Planet around the Sun in an elliptical orbit with the Sun at a focus (Kepler's First Law)
- Perihelion (point of closest approach) is fixed
- Precession of the perihelion of Mercury

Precession of the perihelion of Mercury

- http://en.wikipedia.org/wiki/Kepler_problem_in_general_relativity
- Other planets, oblateness of the Sun (minor)
- Not agree with Newtonian analysis

  1859 Le Verrier (observations of transits of Mercury over the Sun's disk from 1697 to 1848)

Precession of the perihelion of Mercury

- Not agree with Newtonian analysis

  1859 Le Verrier (observations of transits of Mercury over the Sun's disk from 1697 to 1848)

- Discrepancy decreased in Einstein's analysis 1915

Precession of the perihelion of Mercury

- Einstein had to make some approximation to describe the gravity, or curvature of space, around the Sun
- Karl Schwarzchild gave the exact solution around a spherical star 1916
- First exact solution of eqns of General Relativity
- Valid for black holes: Event horizon is given by the Schwarzschild radius

Precession of the perihelion of Mercury

- Karl Schwarzchild wrote his paper while fighting on the Russian front during WWI
- “As you see, the war treated me kindly enough, in spite of the heavy gunfire, to allow me to get away from it all and take this walk in the land of your ideas.”

  – letter to Einstein, December 22, 1915
- Died shortly thereafter (1916)

Schwarzchild solution

- Relevant for neutron stars and black holes
- Minor correction for gravity of the Earth

- But other GR effects are relevant near the Earth – GPS have to include GR corrections

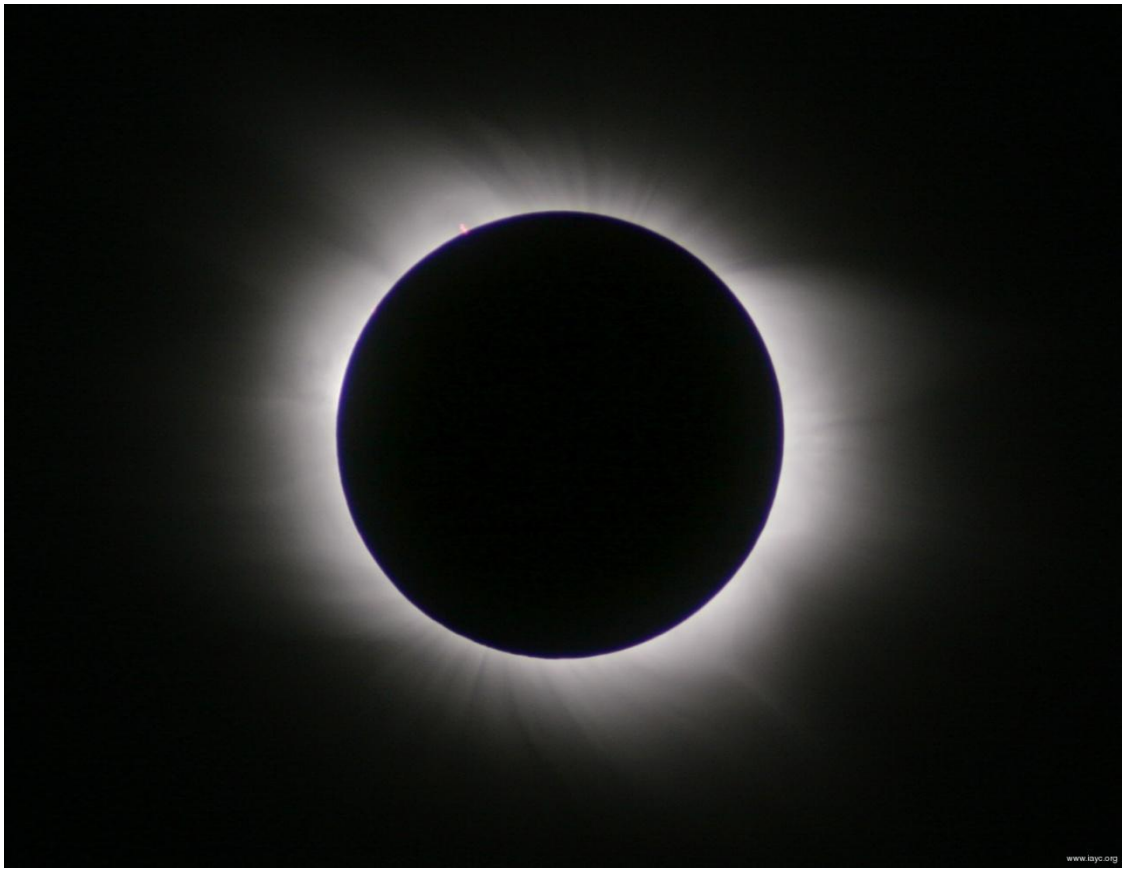
Gravitational Bending of Light

- Space is curved due to the presence of massive bodies
- Property of space – affects all objects in this space
- Also affects light Einstein 1911, 1915

Gravitational Bending of Light

- Expedition was sent to measure gravitational bending of the light from stars near the sun during a solar eclipse

- Total solar eclipse August 21, 1914 in Russia (region of greatest eclipse)



Dodelson-2007

1914 was not a good year to start a scientific expedition in Europe !

Dodelson-2007

- The astronomers were captured by Russian soldiers (and released a month later).
- Good thing. In the following years, Einstein revised his calculation.
- Confirmed by solar eclipse expeditions led by Eddington in 1919 to islands of Sao Tome and Principe on west coast of Africa (and Brazil-telescope issues)

The Theory of General Relativity

- Einstein's Theory of General Relativity (1915)

  Theory of Gravity, Valid for very massive objects, high velocities, gravity of the universe

- Star, Bending of Light. Now the Universe

- “As to relativity, I must confess that I would rather have a subject in which there would be a half dozen members of the Academy competent enough to understand at least a few words of what the speakers were saying if we had a symposium upon it. I pray to God that the progress of science will send relativity to some region of space beyond the fourth dimension, from whence it may never return to plague us.”

  Abott (Sec., Natl. Academy of Sciences) to

  Hale (Director, Mount Wilson Obs.) 1920

- “That fellow Einstein suits his convenience. Every year he retracts what he wrote the year before.”

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  Albert Einstein 1915

Our Universe

- Einstein 1917
- Universe is isotropic and homogeneous
- Mathematical simplicity
- Valid on very large scales -- isotropy of CMBR, radio sources, galaxy surveys
- Cosmological Principle

Our Universe

- $d_{AB}(t_2) = d_{AB}(t_1)\, R(t_2)/R(t_1)$

R is the scale factor, function of t only, not position, or direction [isotropic, homog]

$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G}{3}\rho - \frac{k}{R^2}$$

k = -1, 0, +1; ρ is the energy density

G is Newton's gravitational constant

k = -1, 0 Universe expand or contract

Our Universe

$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G}{3}\rho - \frac{k}{R^2}$$

k = -1, 0 Universe expand or contract

Einstein (1917) did not like this. So set k=1

Our Universe

$$\frac{\ddot{R}}{R} = -\frac{4\pi G}{3}(\rho + 3p)$$

p is the pressure ~ 0 for non-relativistic matter

Universe is not static. Collapse

Einstein introduce another term in the Einstein's equation – cosmological constant Λ

Our Universe

$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G}{3}\rho - \frac{1}{R^2} + \frac{\Lambda}{3}$$

$$\frac{\ddot{R}}{R} = -\frac{4\pi G}{3}\rho + \frac{\Lambda}{3}$$

If $\Lambda = 4\pi G\rho$ $R = 1/(4\pi G\rho)^{\frac{1}{2}}$

the Universe is static. Λ provides a positive acceleration. All is well.

Our Universe

$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G}{3}\rho - \frac{1}{R^2} + \frac{\Lambda}{3}$$

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If $\Lambda = 4\pi G\rho$ $R = 1/(4\pi G\rho)^{\frac{1}{2}}$

the Universe is static. Λ provides a positive acceleration. All is well. But …

But the Universe is expanding!

- Distant galaxies are moving away from us at a speed proportional to their distance from us:

  Edwin Hubble and Milton Humason 1929

Edwin Hubble

Einstein called introducing the cosmological constant his `biggest blunder’.

The Theory of General Relativity

- Static universe 1917 Einstein -- discarded
- Friedmann (1922) and Lemaitre (1927) expanding univ
- Hubble's discovery of expanding universe 1929
- Lemaitre 1931 Initial state – dense, energetic, fast exp

Friedmann-Lemaitre-Robertson-Walker Model

- Expanding Universe with radiation and matter
- Universe today dominated by non-relativistic matter
- Big Bang initial state with high energy relativistic matter (radiation)
- Expanding but decelerating

The Return of Λ

- 1998 discovery of the accelerating Universe
- Reintroduce Λ. Our Universe is dominated by Λ (or dark energy) today
- Accelerating

Our Universe

$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G}{3}\rho + \frac{\Lambda}{3}$$

$k/R^2 \sim 0$

$$\frac{\ddot{R}}{R} = -\frac{4\pi G}{3}\rho + \frac{\Lambda}{3}$$

Λ provides a positive acceleration.
Like a contribution to ρ. So Dark Energy.

Equations of evolution

Our Universe

- Using the Friedmann-Lemaitre (+ Robertson-Walker) solutions of the equations of General Relativity can explain the past history and possible future of our Universe, given observational inputs

History of our Universe

- First second – hot primordial soup
- 1 s – 3 min – light nuclei (helium, lithium, ..)
- 77,000 years – Univ becomes matter dominated

History of our Universe

- 77,000 years – Univ becomes matter dominated
- 400,000 years – Atoms form
- 300 million years – First stars form
- 1 billion years – First galaxies form
- 9 billion years – Universe is accelerating, Λ dom
- 14 billion years – Today

Our Universe – Big Bang Cosmology

- Using the Friedmann-Lemaitre (+ Robertson-Walker) solutions of the equations of General Relativity can explain the past history and possible future of our Universe, given observational inputs
- Correctly predicted light element abundances
- Correctly predicted the existence of the cosmic microwave background radiation

Principle of Equivalence

- Applies for all phenomena
- Consider a light ray moving perpendicular to an accelerating rocket in space.

  In the rocket frame it will enter and exit at different heights – exit point will be lower.
- By the principle of equivalence, the same observation is made by an observer in a rocket at rest in a gravitational field.
- Therefore light must bend in the gravitational field.