Cosmology - The Story of our Universe

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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

Cosmology - The Story of our Universe

- How old is the Universe? Existed forever or does it have a beginning? Will it exist forever, or have an end?
- What governs the motion of the stars?

Curiosity led to the development of science – astronomy and mathematics – in all societies

- Position and motion of stars and planets in the sky

  Calendar, navigation

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- Telescope 17th c. Galileo

  Kepler's laws of Planetary Motion

  Newton's law of Gravitation – universal 17th c.

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- Einstein's theory of Gravity – General Relativity

  Application to the Universe early 20th c.

What is the Theory of General Relativity ?

- It is a theory of gravity (1907-1915)

- Attraction between massive objects, i.e. the gravitational force, replaced by modification of space

- Mass (or energy) of matter modifies space
- Objects moving in this space change their motion because of the modification of space

Space ? Modify ?

- Space is the region in which all matter exists and physical phenomena occur

- Upto 20^{th} c., space is unaffected by matter in it and physical phenomena

- Early 20^{th} c. General Relativity: Space is affected -- Radical idea

The Theory of General Relativity

- Invoke GR very close to a massive object (star/Earth-accuracy GPS), v ~ c, Universe
- Reduces to Newtonian gravity otherwise

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- Study of our Universe today – galaxies, clusters, superclusters – Telescopes and satellite based instruments

- Understanding the past history and future evolution of our Universe – General Relativity

PAST ← PRESENT → FUTURE

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- Newton's laws of motion tell us the future motion given x_0 and v_0, or the past motion given x_f and v_f

- Parameters of the Universe today. Can use Einstein's eqns from General Relativity to study future and past of the Universe

Outline

- PRESENT
  (Structure, Dynamics and Composition)

- PAST

- FUTURE ?

PRESENT

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

Stars and Planets

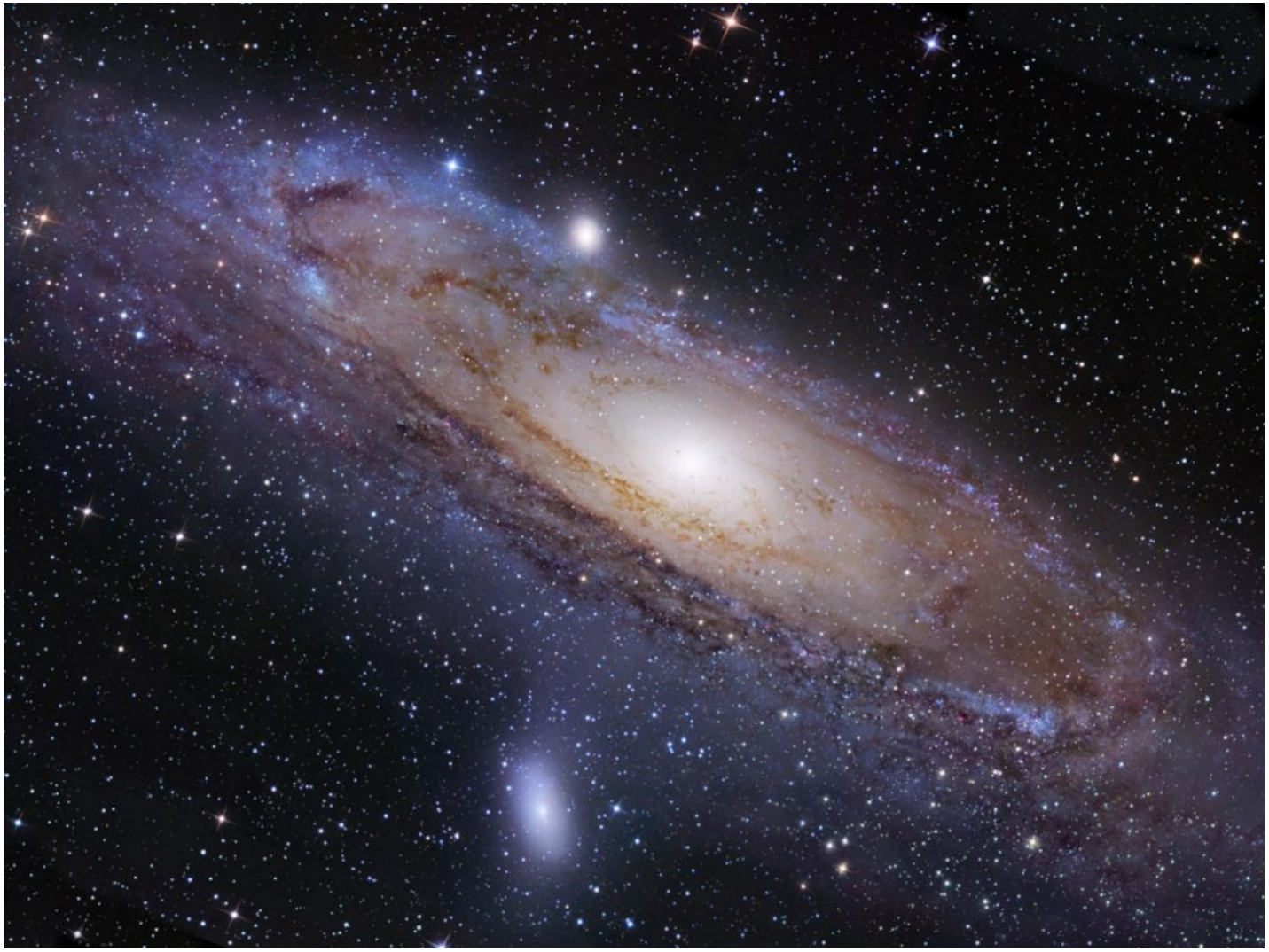
- Billions of stars like our Sun in a galaxy
- Can have planets – ~4200 discovered so far around others stars
- Discovered by decrease in intensity as planets passes in front of it
- Or, by wobbling of star towards or away from us due to motion about centre of mass of two body system – red/blueshift of starlight

Galaxies

- Spherical, elliptical, spiral, irregular

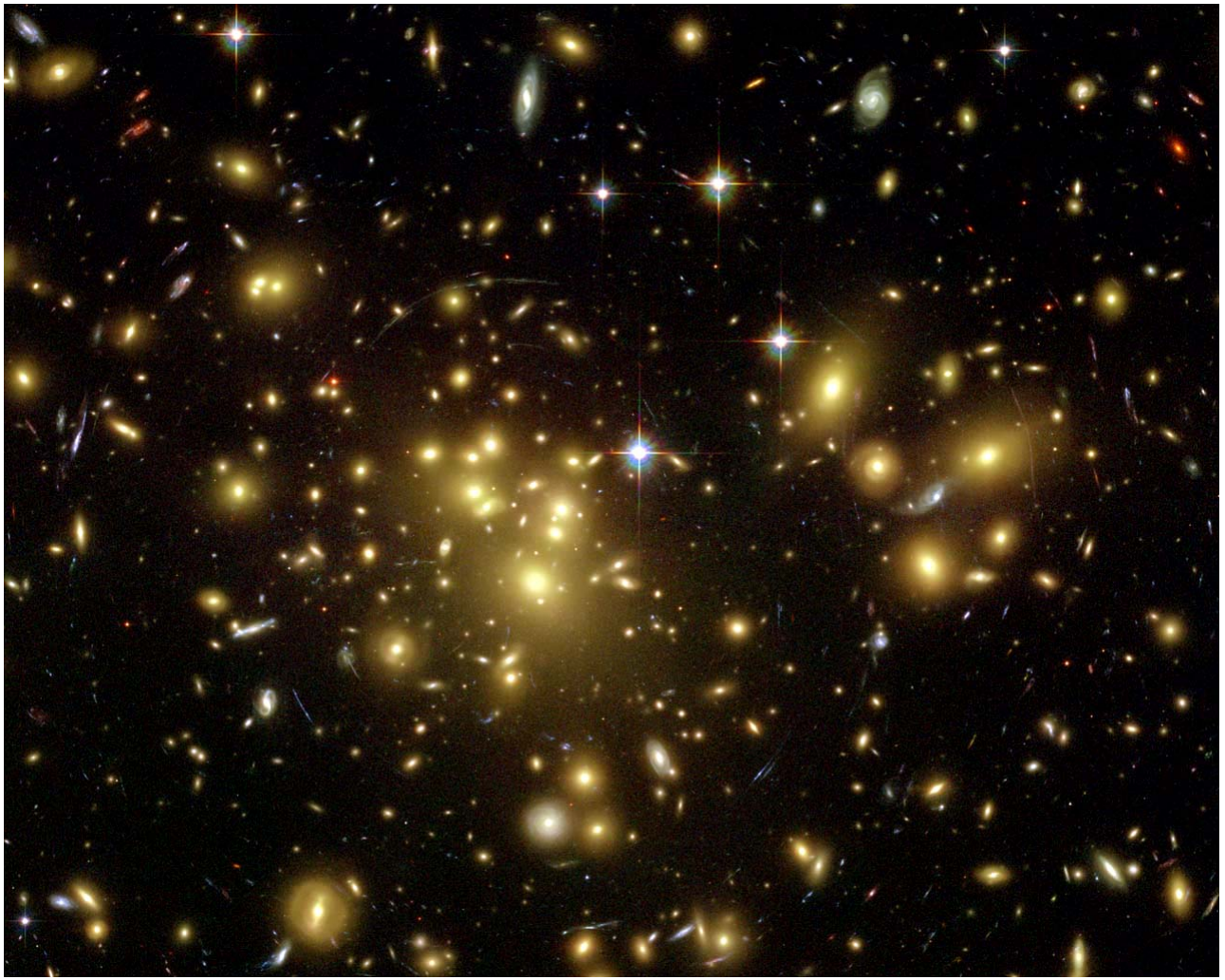
NGC 7331

Milky Way twin



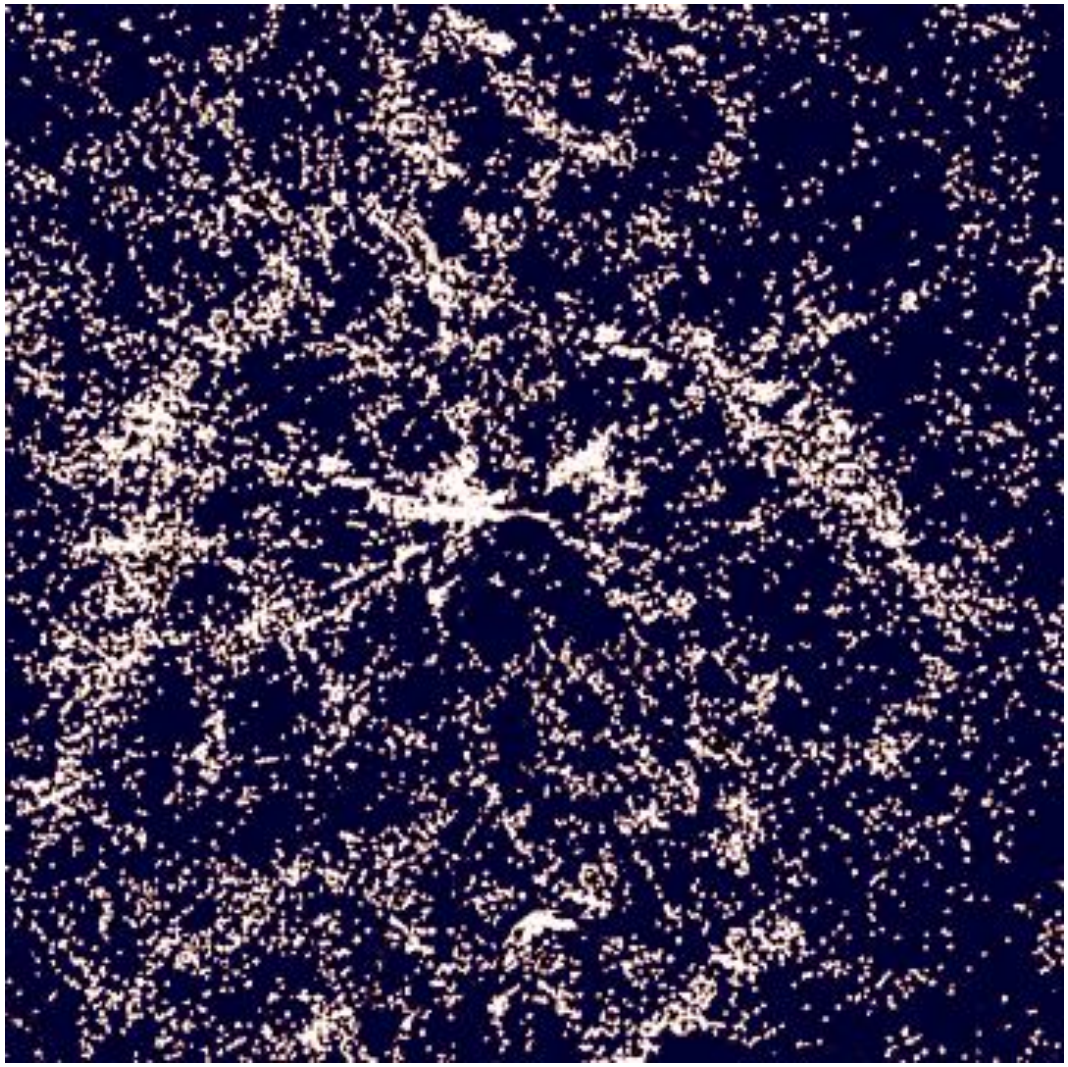
Andromeda Galaxy Nearest large galaxy
4.5 b y

Galaxy Cluster



Abell 1689

Superclusters - Filaments, Sheets and Voids



Present

- Structure: Galaxies, Clusters, Superclusters
- Is the Universe static?

Present

- Structure: Galaxies, Clusters, Superclusters

- Is the Universe static?
- (Einstein presumed it was when he first applied his Theory of General Relativity to the Universe in 1917)

Is the Universe static?

- Distant galaxies are moving away from us

  Vesto Slipher 1912 (redshift)

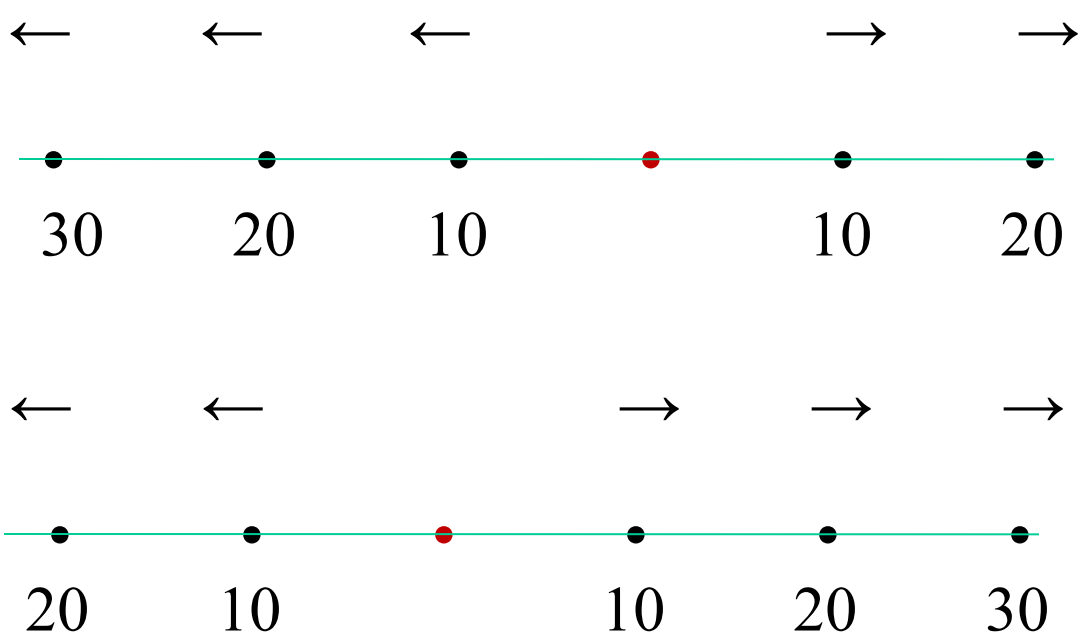
- At a speed proportional to their distance from us

  Edwin Hubble 1929 (and Milton Humason*)

Edwin Hubble

* School dropout, muleskinner and janitor, astronomer

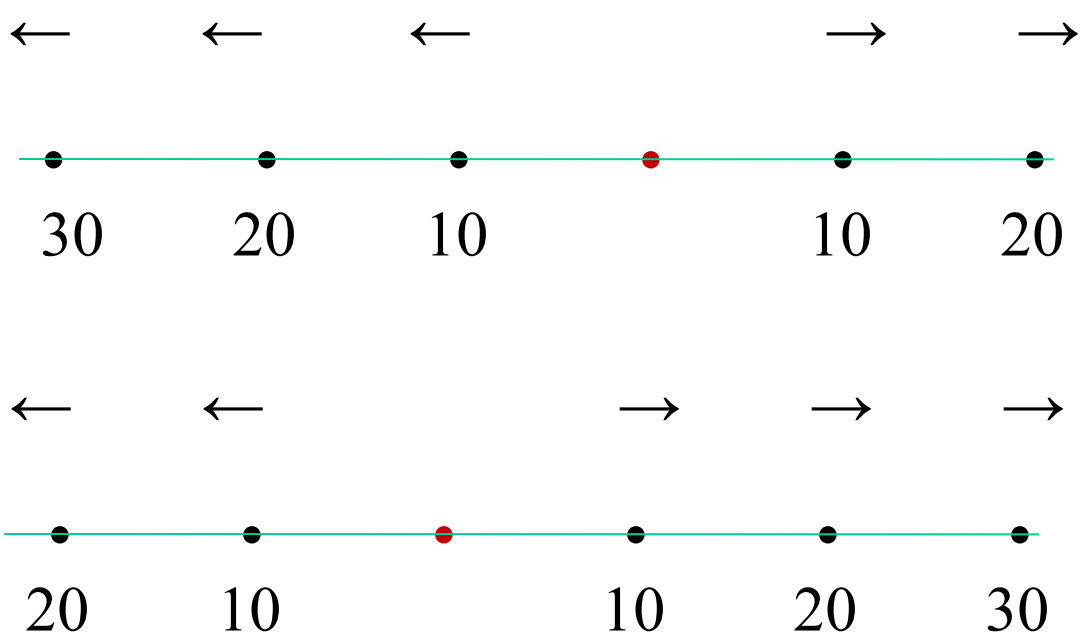
All distant galaxies are moving away from us at a speed proportional to their distance -- Hubble's Law: $v = H\,d$ [Lemaitre 1927]



Galaxies are moving away from each other

Universe is expanding. (Not static)

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. (Einstein error)

Is the Universe static? NO

- All distant galaxies are moving away from each other

- Locally bound systems – solar system, galaxies are not affected by the overall expansion of the Universe

What determines the expansion?

- Not because of intrinsic velocities but because space is expanding

General Relativity (gravity–> dynamic space)

Rate of expansion $\propto$ (ave. mass/energy density)$^{1/2}$

Evolution and expansion also depends on the composition of the Universe (rel or non-rel, ..)

Expansion of Space

- What is space expanding into?

  Consider an infinite Universe

- Conservation of energy

Present

- Structure: Galaxies, Clusters, Superclusters
- Is the Universe static ? No
- What is the Universe made up of ?

Background radiation (rel. part. v~ c)

- Ignore radiation from stars and galaxies
- Background of photons in the microwave – Cosmic Microwave Background (2.725 K)
- Cosmic Neutrino Background (undetected)

  (light m < one-millionth electron mass, neutral, also from nuclear reactions in sun/reactors)

Luminous matter

Protons, neutrons, electrons (interactions produce light)

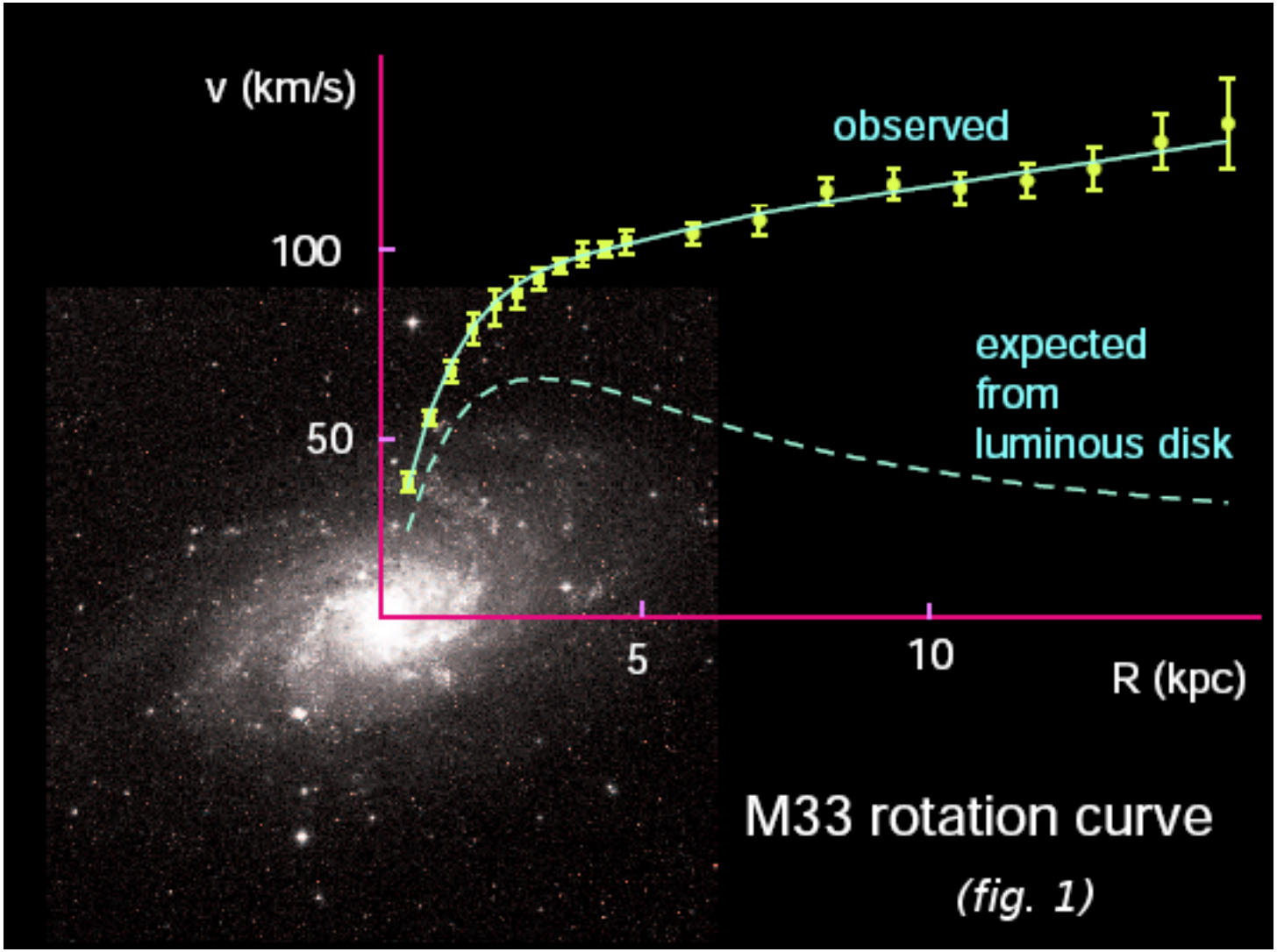
Dark matter

Dark matter ~ 10 Luminous matter

Dark Matter

- Velocity rotation curves of galaxies

Expect v ~ $1/r^{1/2}$ because $m\frac{v^2}{r} = G\frac{Mm}{r^2}$ and M is const.
But ….


v (km/s)
100
50
observed
expected
from
luminous disk
5
10
R (kpc)
M33 rotation curve
(fig. 1)

- Take v ~ constant. How can this be explained ?

$$m\frac{v^2}{r} = G\frac{Mm}{r^2}$$

- If M(r) = A r, then v ~ constant
- But if M(r) = A r then as r increases, M increases i.e. there is matter outside the central luminous bulge which we can not see.

- This non-luminous matter (does not emit or scatter light) is called Dark Matter

Dark Energy

- Observations indicate that the expansion rate of the Universe was decreasing for the first 9 billion years after the Big Bang and has been increasing for the last 5 billion years
- The earlier period of deceleration is understood. But we do not know what is causing this acceleration

Dark Energy

- Can be explained by modifying Einstein's equations in General Relativity ,

  or

  by including some new field that pervades the Universe and causes space to expand faster with time (Quintessence)

- Referred to as Dark Energy

Composition of our Universe

- Background photons and neutrinos
- Protons, neutrons and electrons
- Dark Matter
- Dark Energy

- Quantify: Averaged over the Universe, how much contribute to the energy density

(kinetic energy + potential energy + mass energy)

Composition of our Universe

- Photons and neutrinos – negligible

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  (DM/LM in galaxies ~ 10, overall ~ 5)

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  (DM/LM in galaxies ~ 10, overall ~ 5)
- Dark Energy – 70%

Outline

- PRESENT Astronomical Observations
  Structure, Dynamics and Composition

- PAST

- FUTURE ?

Questions ?

- Was the Universe always like the present?

- Will the Universe continue to be like the present?

  All distant galaxies are moving away from each other (spectra redshifted) –

  Universe 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 b years ago)

- At the earliest instant, density very high
- All matter breaks down to elementary particles at high energies

  All matter moving out very fast

The Past

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

INITIAL STATE

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

THE BIG BANG

THE BIG BANG

- Not an explosion of concentrated matter in space

- An initial state of rapid expansion of space (filled with matter) everywhere

Coined by an opponent of the model

After the Big Bang

- First second – hot primordial plasma 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
  (also cyclic Universe models)

- May continue to accelerate or may not

  Different expanding scenarios

The Future

Universe keep expanding

- All distant galaxies move away but galaxies retain their structure for a long time (100 trillion years) before stars run out of fuel

- Galaxies move apart, Stars move apart, Stars break up, Universe filled with dilute gas, dark and cold (50 b y)

[Solar system destroyed long before that (7.5b y)
Sun heat up in 1b y]

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

Outstanding Issues

- Why the Big Bang ? Quantum Gravity
- What is the Dark Matter ? LHC
- Can not make a definitive prediction of the future as some parameters are not measured yet. Observations may tell us more about the nature of Dark Energy

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/

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Extra Slides

Our Solar System

- Pre-solar nebula (giant molecular cloud of gas and dust)

- Solar system formation triggered by a supernova explosion nearby causes region to collapse and form a spinning protoplanetary disc with a hot dense protostar (not start H fusion) [< mill. yr]

Our Solar System

Protoplanetary disc in the Orion Nebula

Our Solar System

- Protostar gravitationally collapse and pressure and density and temperature increases and fusion of H starts (50 million years). Today 4.5 billion years young.

- Planets – Terrestrial (Mercury, Venus, Earth and Mars)

  – Jovian (Jupiter and beyond)

  Terrestrial planets have heavy elements – largely composed of silicate rocks

  Jovian – not rocks, primarily gas or ice

Black Hole

- Formed by the collapse of very heavy stars
  -- collapsing object has mass > 3 M_{SUN}
- Centre is a point like region with extremely high mass density
- There is an associated distance proportional to the mass called the Schwarzschild radius
- Objects or light at distances less than this radius can not escape the black hole
- But beyond this radius gravitational effect is large but decreases with distance

Black Hole

- BH at centre of Milky Way = 4 million M_{SUN}
- Detect Black Holes by the rotational motion of stars around it (as for the BH in Milky Way)
- Or, by heated gas of companion star falling into the black hole (X-ray binary stars)
- And now, by GW
- Nearly every galaxy is believed to have a supermassive black hole ($M>10^5$ M_{SUN}) at their centres, formed by accretion, collisions with other stars/black holes, etc

Galactic Collisions

Mice Galaxies – colliding spiral galaxies

Galactic Collisions

Antennae Galaxies – colliding galaxies
Stars go through, gas collides, shock waves, star formation (Milky Way meets Andromeda)

Slides on Space and GR

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Flat Space

- Electron moving in free space. Unaffected by space. This bland, propertyless space assumed in old Physics (before GR) is called flat space (or, with time, Minkowski spacetime)

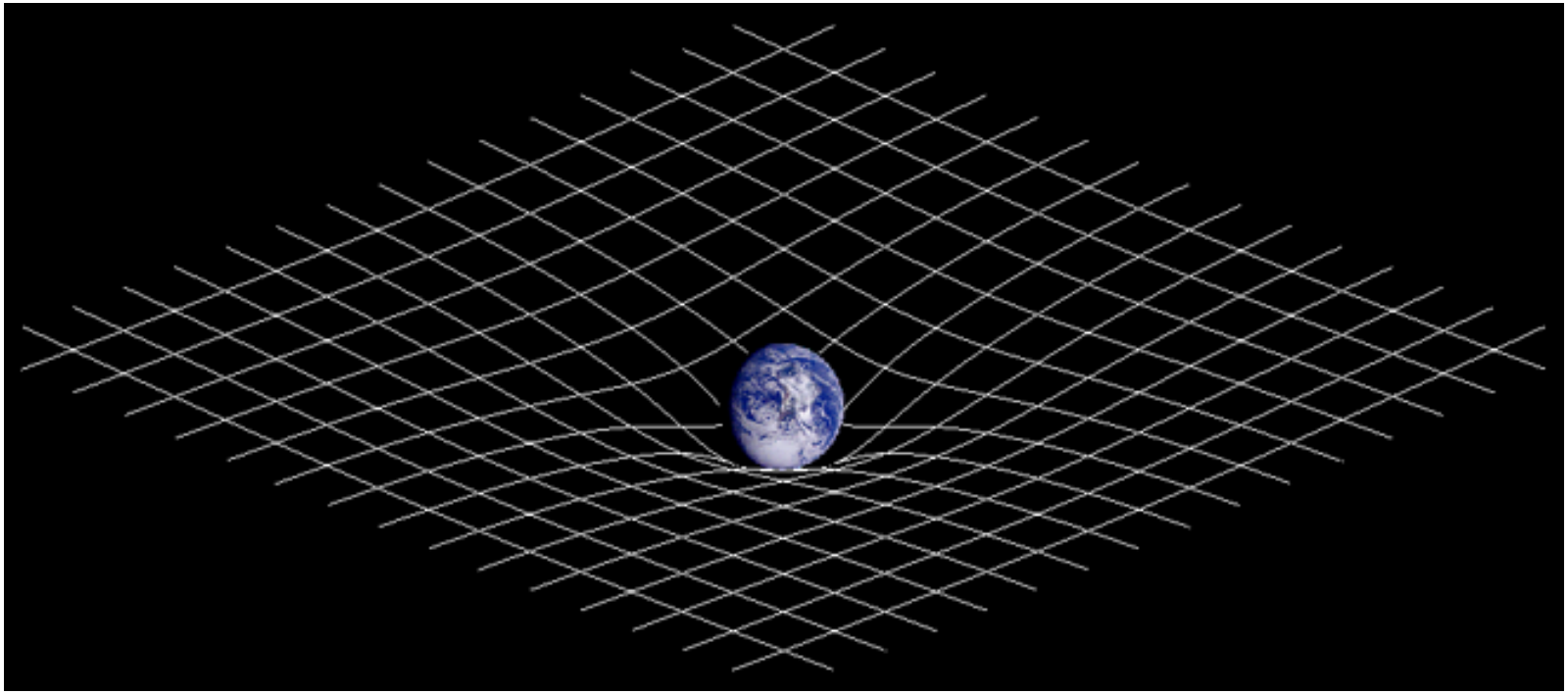
- Most scientific ideas are tested presuming this – atomic physics, collider experiments

Curved Space

- Put a star of mass M and consider electron moving past it
- GR: Space is modified outside M and motion of electron is affected
- In the presence of massive bodies space is curved

Curved Space

- In the presence of massive bodies space is curved



Gravity and curved space

- This curvature is a property of space. So at a point in space it affects motion of all bodies equally.

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  Recall acceleration due to gravitational field and due to electric field for a particle of mass m and charge q = GM/r^2, $(q/m)Q/r^2$. Latter also depends on particle – not due to space. So only gravity can be interp as due to mod of space which affects all bodies equally

Einstein's equations

- Space affected by matter

$$G_{\mu\nu} = 8\pi G_N T_{\mu\nu}$$

- rhs includes energy density, momentum and pressure of matter
- lhs is a function of the metric which describes properties of space
- G_N is Newton's gravitational constant