Cosmology - The Story of our Universe

Lecture 4

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Composition of our Universe

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

Composition of our Universe

- Cosmic Microwave Background Radiation

Accidental discovery of the theoretically predicted CMBR – confirmed Big Bang theory

Blackbody spectrum

Very uniform with slight variations in the temp

Composition of our Universe

- Protons, neutrons and electrons – 5%

Abundances of light elements (D, He, Li) calculated in the Big Bang theory

Observations of abundances were consistent with the theoretical calculations

Another confirmation of the Big Bang theory

Composition of our Universe

- Dark Matter – 25%

Velocity as a function of distance of stars outside the bulge of a galaxy indicate additional matter than what is seen

We do not know what kind of particle makes up the dark matter

Composition of our Universe

- Dark Energy – 70%

The dimming of light of distant supernovae indicates that our Universe is accelerating.

We do not know whether this is due a Cosmological Constant in the evolution equations or due to some unknown new constituent of the Universe.

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

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Structure

- Stars with Planets, Galaxies, Clusters, Superclusters and Voids

- How do these form ?

- Bottom up – smaller structures form first and then larger, starting from galaxies

  Stars with planets form within galaxies (local conditions)

Galaxies

- First start as proto-galaxies 100 – 250 m yrs after the Big Bang –

  i) large gas clouds of H and He (even today the Universe is ~ 75% H and ~ 25% He), and

  ii) dark matter

- 30-100 lt years big
- LM and DM uniformly distributed
- The first stars form in these proto-galaxies

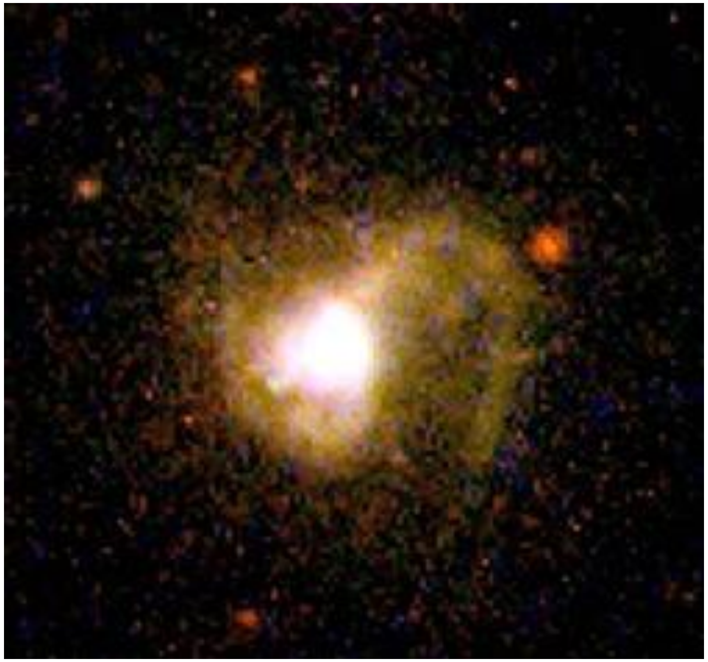
Proto-Galaxies

t = 2 billion years

Galaxies

- 1 billion years after the Big Bang these star forming proto-galaxies merge to form galaxies

Proto-Galaxies → Galaxies



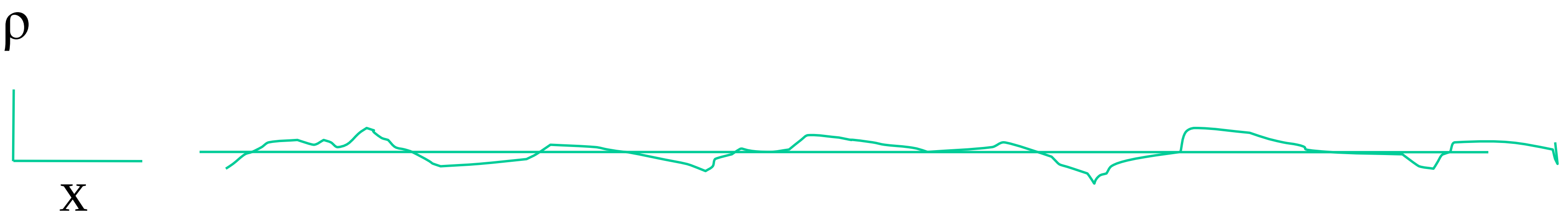
POX189 – forming into a spiral galaxy in the last 100 m years

Galaxies

- How did the proto-galaxies form ?
- How do stars form in the proto-galaxies ?

How did the Proto-Galaxies form ?

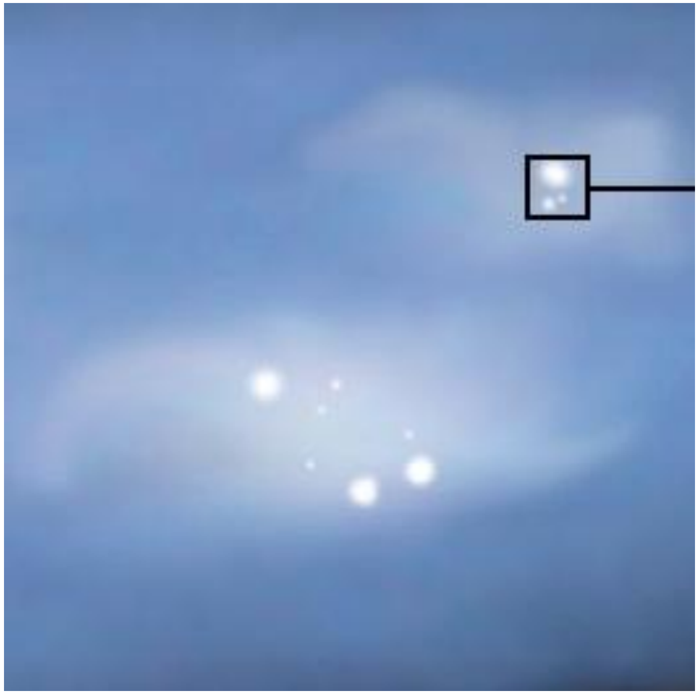
- Uniform density with some inhomgeneity, i.e., spatial variation in density of matter (baryonic (n,p,e) and dark matter)



- Clumping leads to formation of proto-galaxies

How do the first stars form ?

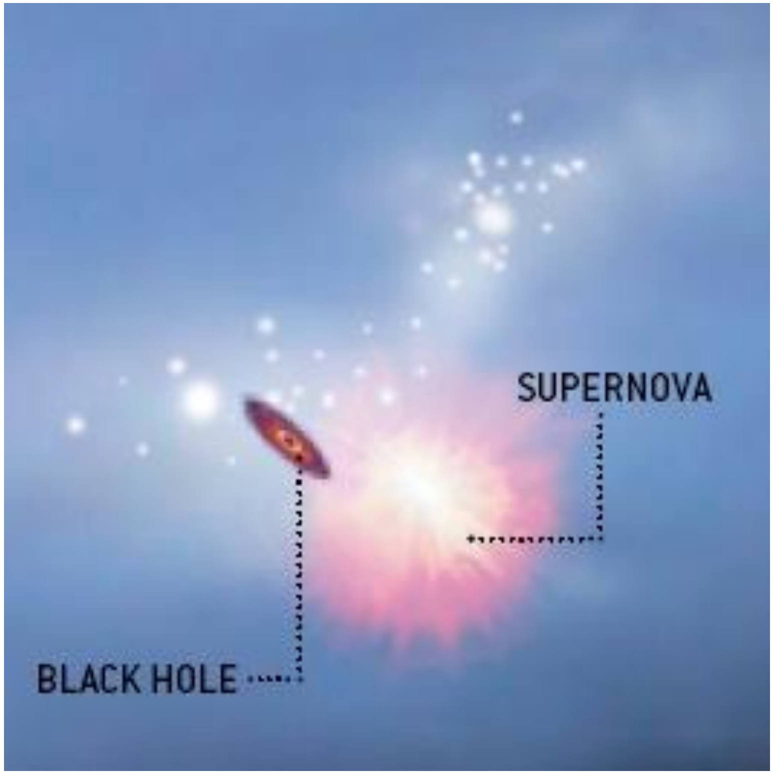
- Density inhomogeneity in the gas followed by clumping leads to formation of proto-galaxies



- These first stars are largely made of H and He
- Larger and more massive than later stars

How do the first stars form ?

- Create heavier elements through fusion

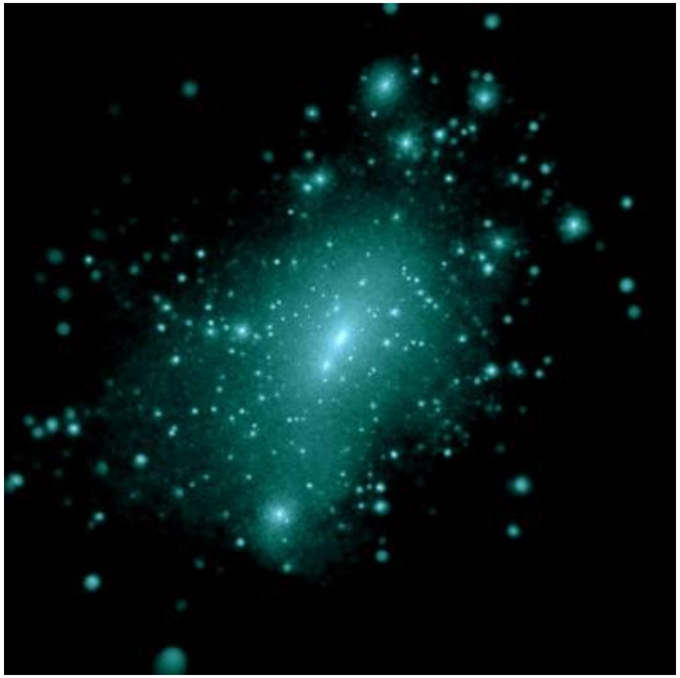


- Collapse followed by supernova explosion; heavier elements recycled in the next gen of stars

Larger Galaxies

- Galaxies form by the merger of the proto-galaxies
- Larger galaxies form by the merger of smaller galaxies and galaxy collisions

Smaller Galaxies → Larger Galaxies



Simulation – large galaxy surrounded by smaller dwarf galaxies (dark matter)

Galactic Collisions

Mice Galaxies – colliding spiral galaxies

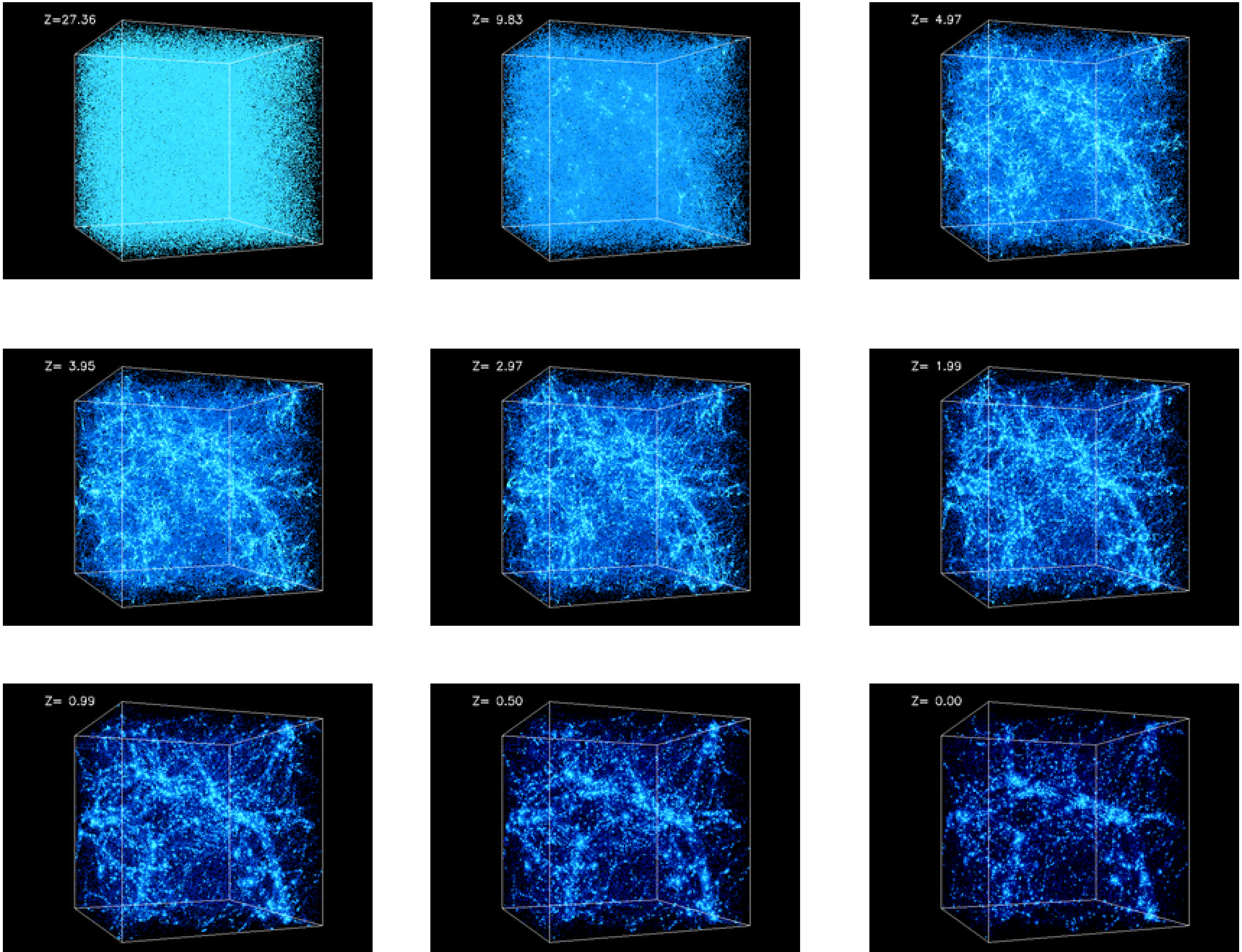
Galactic Collisions

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

Structure

- Galaxies form by the merger of the proto-galaxies, merger of smaller galaxies, collisions
- Clusters form because of initial inhomogeneities on larger scales
- Superclusters form because of initial inhomogeneities on even larger scales
- No larger structures because of the accelerating Universe

100
m yr



Today 13.7 b yr

What we know about Structure Formation

- The level of the initial inhomogeneity on different scales is approximately the same (assumption – observations justify)

  At initial time, average over regions of a particular size and see variation in energy density between the regions. The percentage of variation does not change if change size of regions

What we know about Structure Formation

- Clumping is in baryonic (n,p,e) matter as well as dark matter (gravity affects all matter)
- Clumping in dark matter starts when our Universe becomes matter dominated (77,000 yr)
- Clumping in baryonic matter starts when neutral atoms form (400,000 yr); enhanced by dark matter clumping

History of our Universe

- 77,000 years – Univ becomes matter dominated
  Dark matter clumps

- 400,000 years – Atoms form
  Baryonic matter clumps

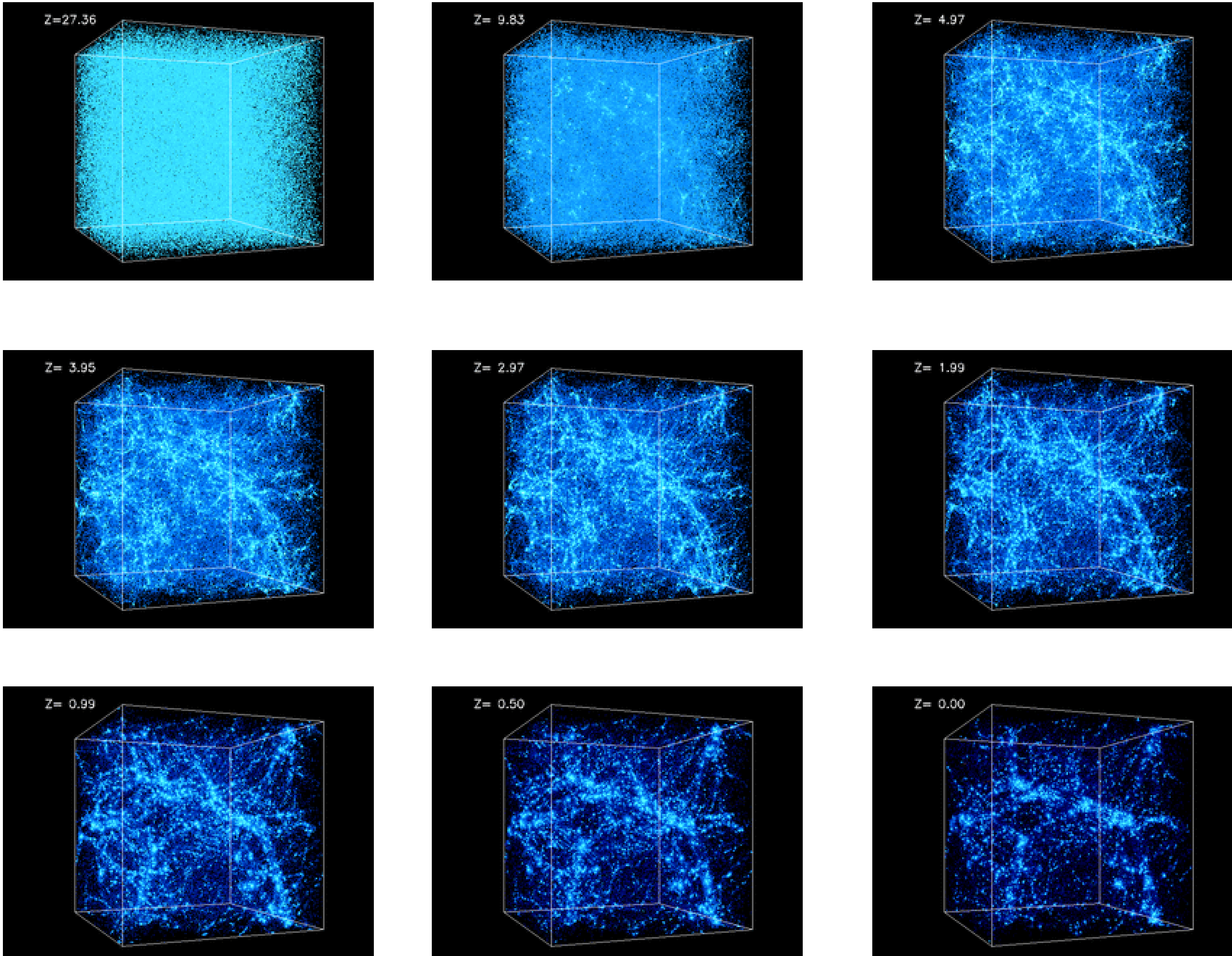
- 14 billion years – Today

Structure

- Can measure the level of the inhomogeneity on different scales – galaxy, cluster, supercluster – today

- If clumping in dark matter starts when our Universe is 77,000 yr old and our Universe is 14 billion years old today then to get the level of structure seen today one needs an initial inhomogeneity of order 10^{-5} on different scales, i.e., if average over regions of size L then the variation in energy density between the regions should ~ 10^{-5} ρ_{av} , or $\frac{\delta\rho}{\rho} \sim 10^{-5}$, or 0.001 %

100
m yr



Today 13.7 b yr

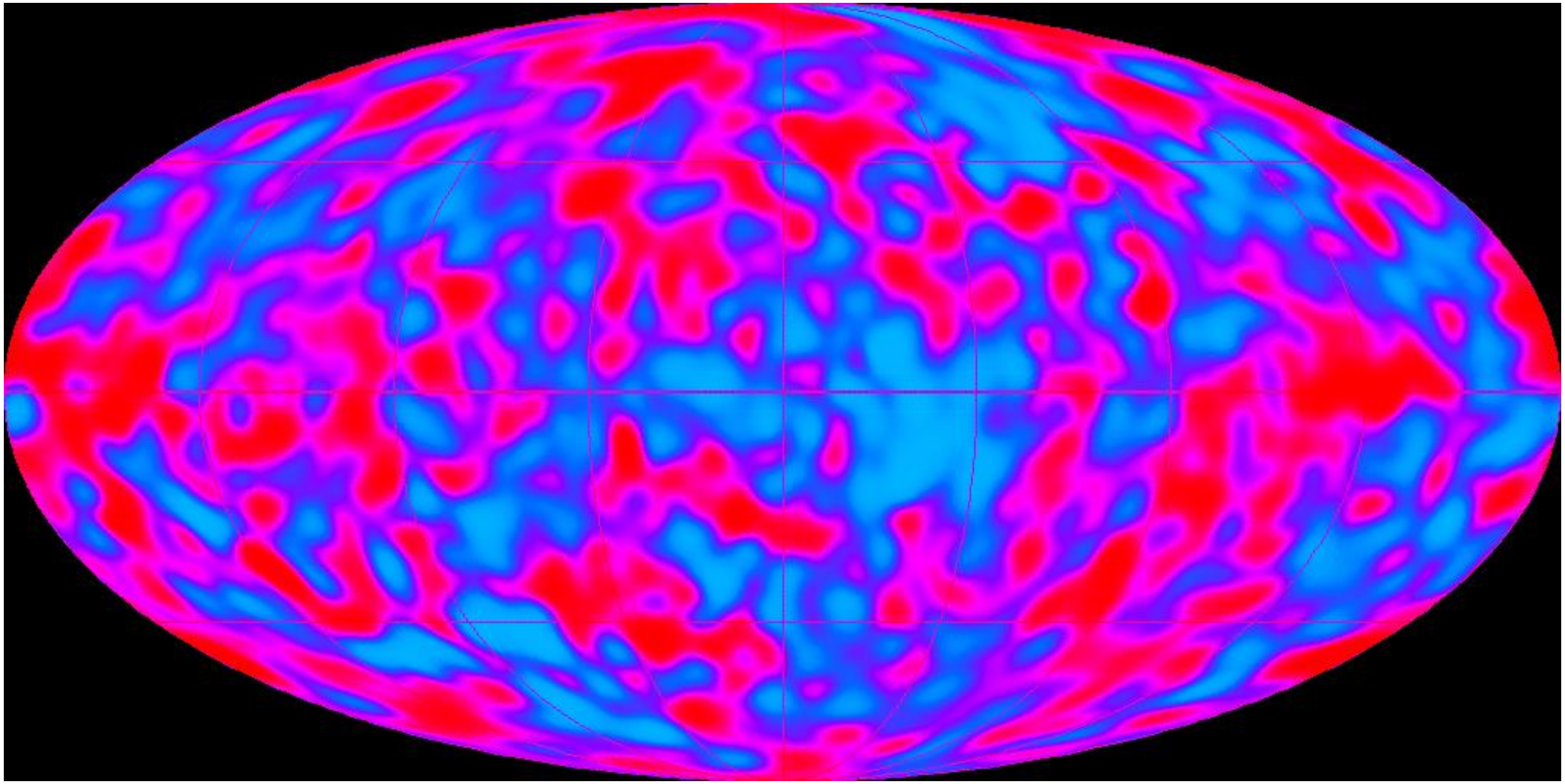
Initial Inhomogeneity

- Initial inhomogeneity in energy density generated between 10^{-34} s and 10^{-12} s after the Big Bang (during a brief period of accelerated expansion called inflation)

- **The inhomogeneity was both in matter and in radiation**

- **Therefore expect variation in the Cosmic Microwave Background Radiation temperature ~ 10^{-5}**

CMBR Anisotropy ~ 10^{-5}



-150μK – +150 μK

COBE CMBR Temperature = 2.725 ± 0.00003 K

(Spatial variation in temperature on angular scales 10° – 60° ↑)

COBE

- If the **Co**smic **B**ackground **E**xplorer had detected a spatial variation in temperature that was less than 10^{-5} it would have implied that our understanding of structure formation in the Universe was incorrect !

Stars and Planets – Our Solar System

Stars and Planets

- Formation of stars and planets due to clumping of inhomogeneous gas in galaxy + local triggers
- First stars H and He
- Stellar nucleosynthesis creates heavier elements
- Supernova explosions expel these into surroundings

Supernova 1054 AD in Milky Way

Crab Nebula
(Neutron star
at the centre)

- Next generation of stars from collapse of enriched gas

Stars and Planets

- Formation of stars along with planets
- About 490 exo-planets discovered
- Can not see the planets (only 10 directly IR)
- But from variations in the star’s radial velocity, and decrease in luminosity of the star during planet’s transit
- PRL Advanced Radial-velocity All-sky Search (PARAS) at the Mt. Abu Observatory

Our Solar System

- From collapse of small region of gas (1 parsec) in a giant cloud of gas and dust (20 parsec) about 4.6 b years ago [1 parsec ~ 3 lt-yr]

Horsehead Nebula (dark due to dust)

Our Solar System

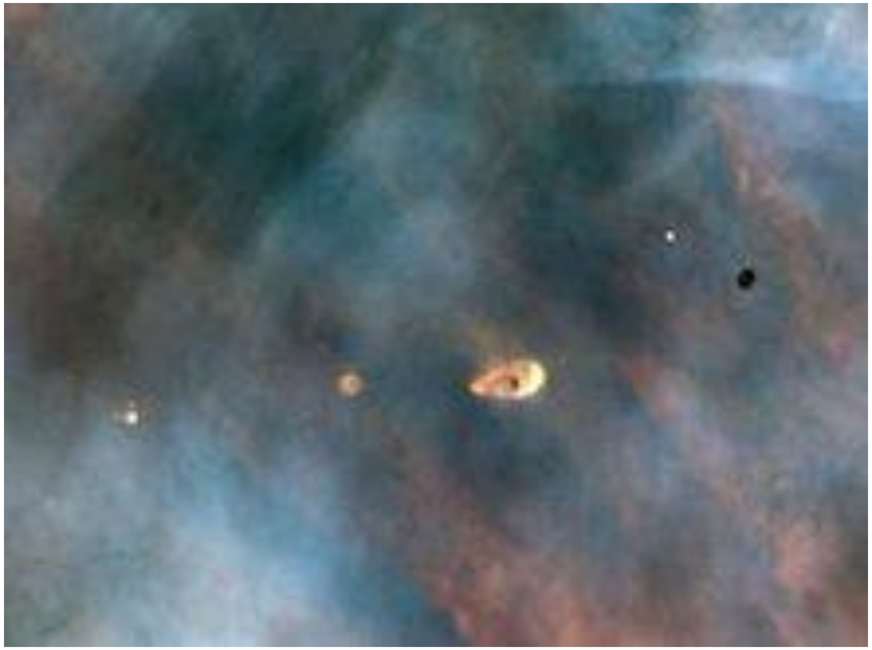
- Pre-solar nebula (giant molecular cloud of gas and dust)

  98% H, He, Li from primordial nucleosynthesis
  (1 s – 3 minutes after the Big Bang)

  2% heavier elements synthesised in stellar nucleosynthesis

- 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.

Our Solar System

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- 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

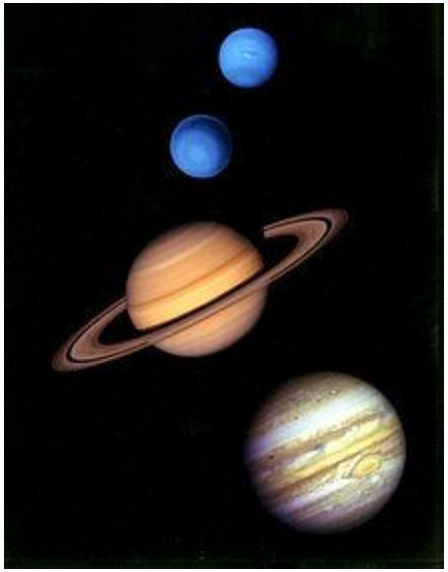
Terrestrial planets

Mercury, Venus, Earth and Mars (and Ceres)

- Dust grains in orbit, clump, collide, clump more and form planetesimals (10 km) [100,000 yr]
- Further collisions and mergers creates 50-100 Moon-Mars sized planetary embryos → 4 planets

< 100 mill y

Jovian planets



Jupiter, Saturn, Uranus and Neptune (not to scale)

- Heavier than terrestrial, 99% of solar system – sun
- Lighter elements–heavier pulled towards sun, gas,ice
- All have rings, have many moons [Jupiter 63, Saturn 62, Uranus 27, Neptune 13], some > Mercury

Asteroid belt

951 Gaspra ~ 18 km x 10 km x 9 km

- Between Mars and Jupiter, largest is about 1000 km
- Planetesimals → 20-30 planetary embryos
- Orbits disturbed by Jupiter and Saturn, collide and shatter

Our Solar System

- When asteroids leave their orbit some come towards the Earth
- Burn up in the Earth’s atmosphere – shooting star, meteors
- Some hit the Earth – meteorites

Formation of our Moon, killed the dinosaurs, craters

Meteorite Crater, Arizona

Lonar Lake, Maharashtra

Our Solar System

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Study them to understand our Solar System

Is there life out there ?

- Nothing special about our Earth or our Solar System or our Galaxy
- Life forms may be different from ours
- May be intelligent life forms

- SETI – Search for Extra-Terrestrial Intelligence

- http://setiathome.ssl.berkeley.edu/

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Test

Tuesday, Sept. 7, 5:00 – 7:00 pm

- Go over the lectures – uploaded
- Read the articles I sent

No need to memorise anything, Exam is fun !