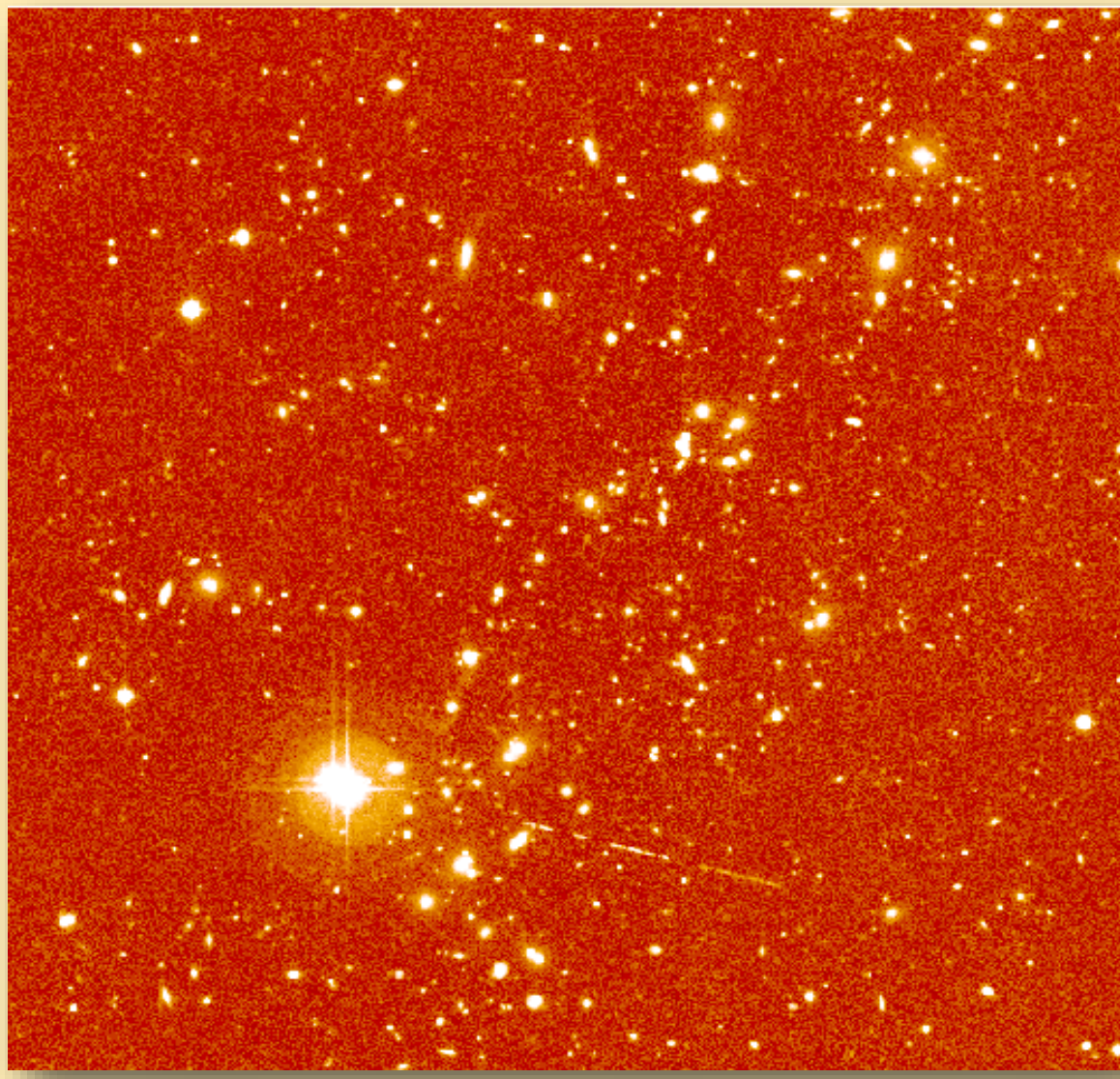
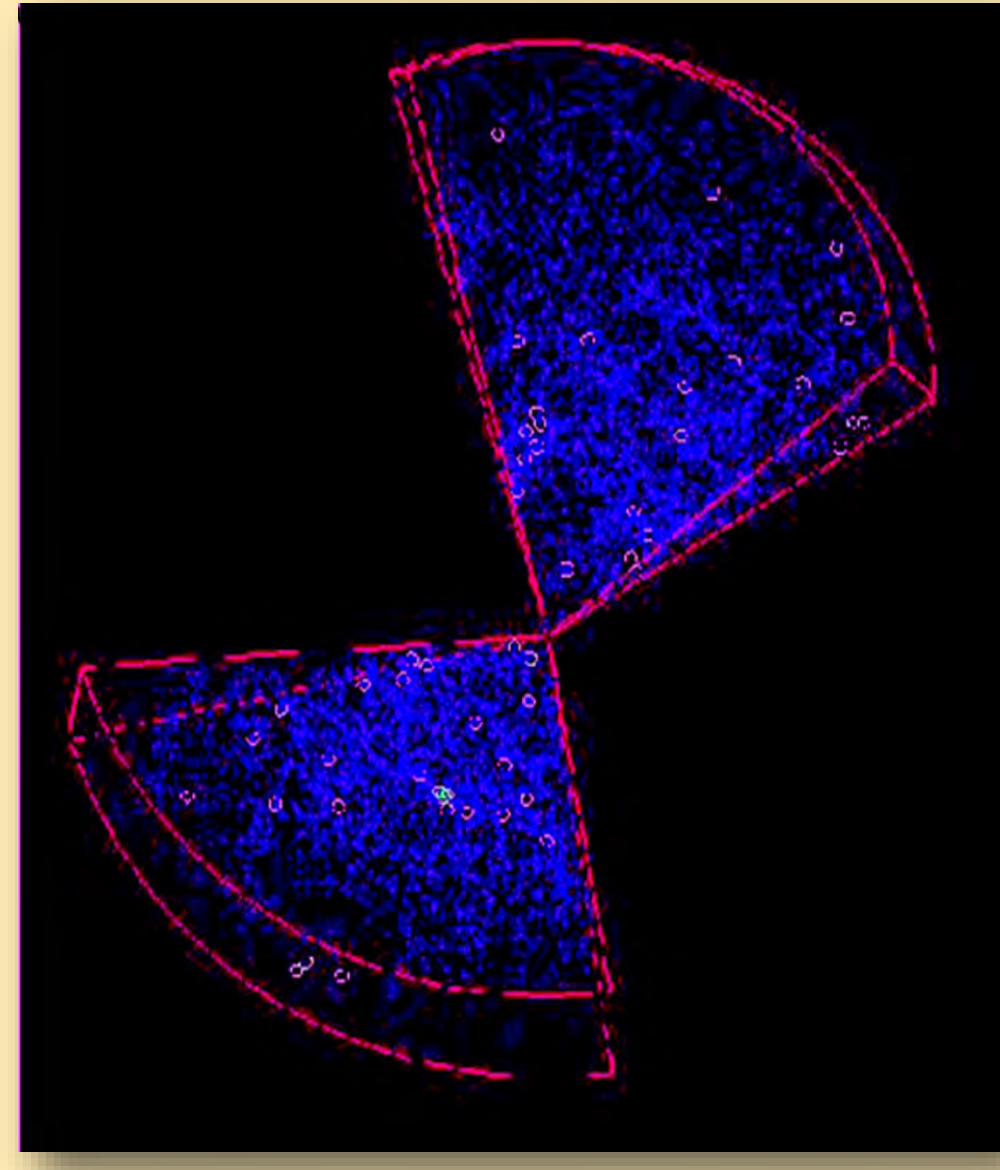


Formation of Clusters: A view from GMRT

Optical observations show that large clusters of galaxies are generally found at the densest regions of a foam like structure traced out by numerous galaxies. See the adjoining figure. How exactly do the clusters of galaxies form? It is believed that the smaller objects form first - **bottom-up scenario of structure formation**.

Thus, the galaxies form first at the centers of their respective dark matter halos, and they further merge together to form clusters.

The evidence of a forming cluster is found in a spectacular chain or filament structure containing hundreds of galaxies - ZwCl2341.1+0000, discovered recently by IUCAA scientists.



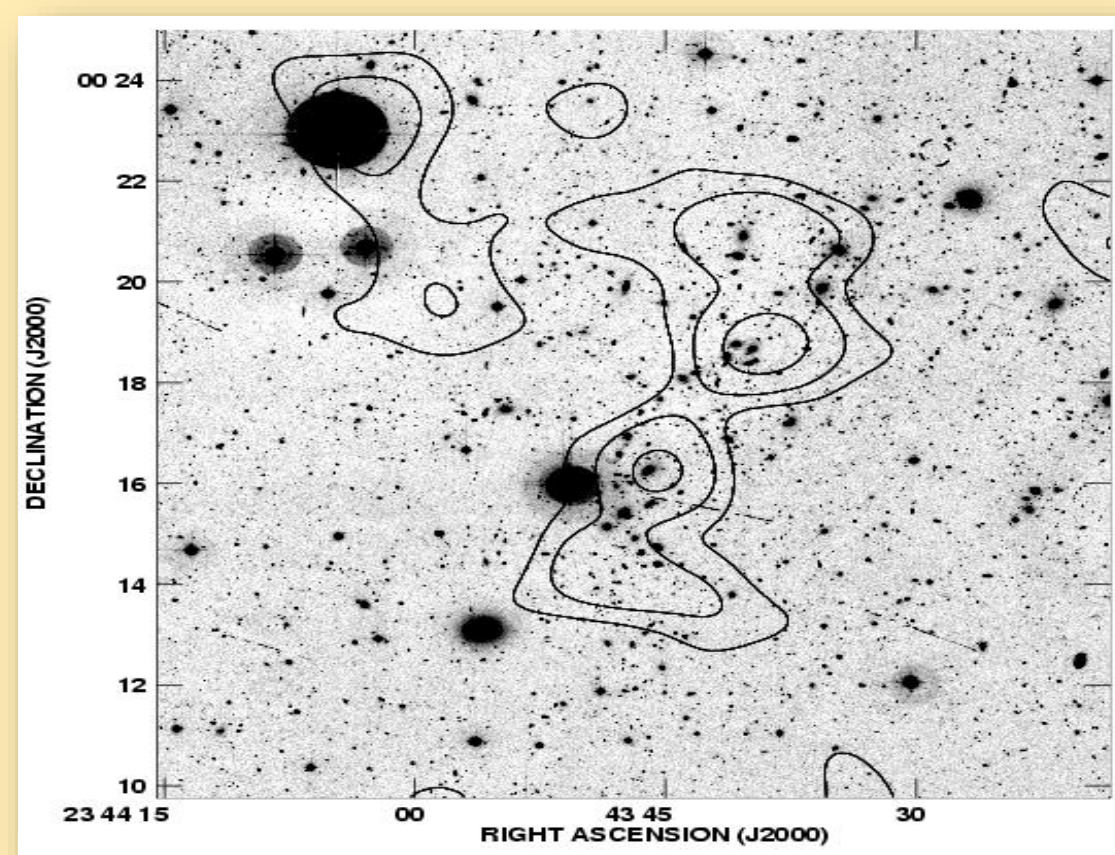
Optical CCD picture of ZwCl2341.1+0000

During the merger process, very powerful shock waves are produced in the ionized Hydrogen gas between the galaxies.

Radio astronomers at IUCAA in collaboration with scientists from Max Planck Institute for Astrophysics in Germany have found good evidence for existence of these shock waves in several forming clusters of galaxies.

The supercluster in the figure to the left is a vast collection of galaxies located about 4 billion light-years away.

The figure below shows that this large filament contains many visible galaxies and is filled with diffuse radio emission.



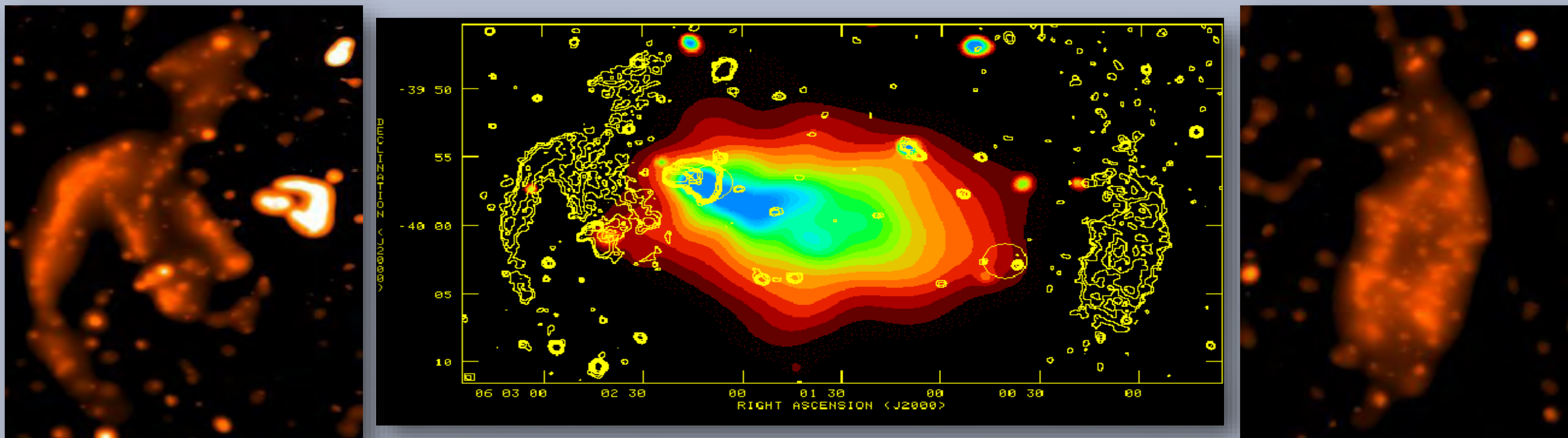
VLA radio (90cm) image contours superposed on optical CCD picture shown above

This radio emission is produced by **Synchrotron Radiation** - very energetic electrons moving in the magnetic field of the supercluster.

The electrons can get such high energy through powerful shock waves developing within the hot gas filling the supercluster volume.

This research shows that the process of formation of a cluster can be a very violent event giving rise to extremely high energy particles known as the **Cosmic Rays**.

IUCAA scientists discover the largest natural particle accelerator



IUCAA scientists have discovered giant, ring-like radio emitting sources around a cluster of galaxies called Abell 3376 which is more than 600 million light-years from Earth (see figure above).

Their discovery provides tantalizing new information about how such galaxy clusters are assembled, about magnetic fields in the vast spaces between galaxy clusters, and about the origin of cosmic rays, the mysterious ultra-high energy particles. The newly-discovered ring segments, some 6 million light-years across, surround a galaxy cluster called Abell 3376,

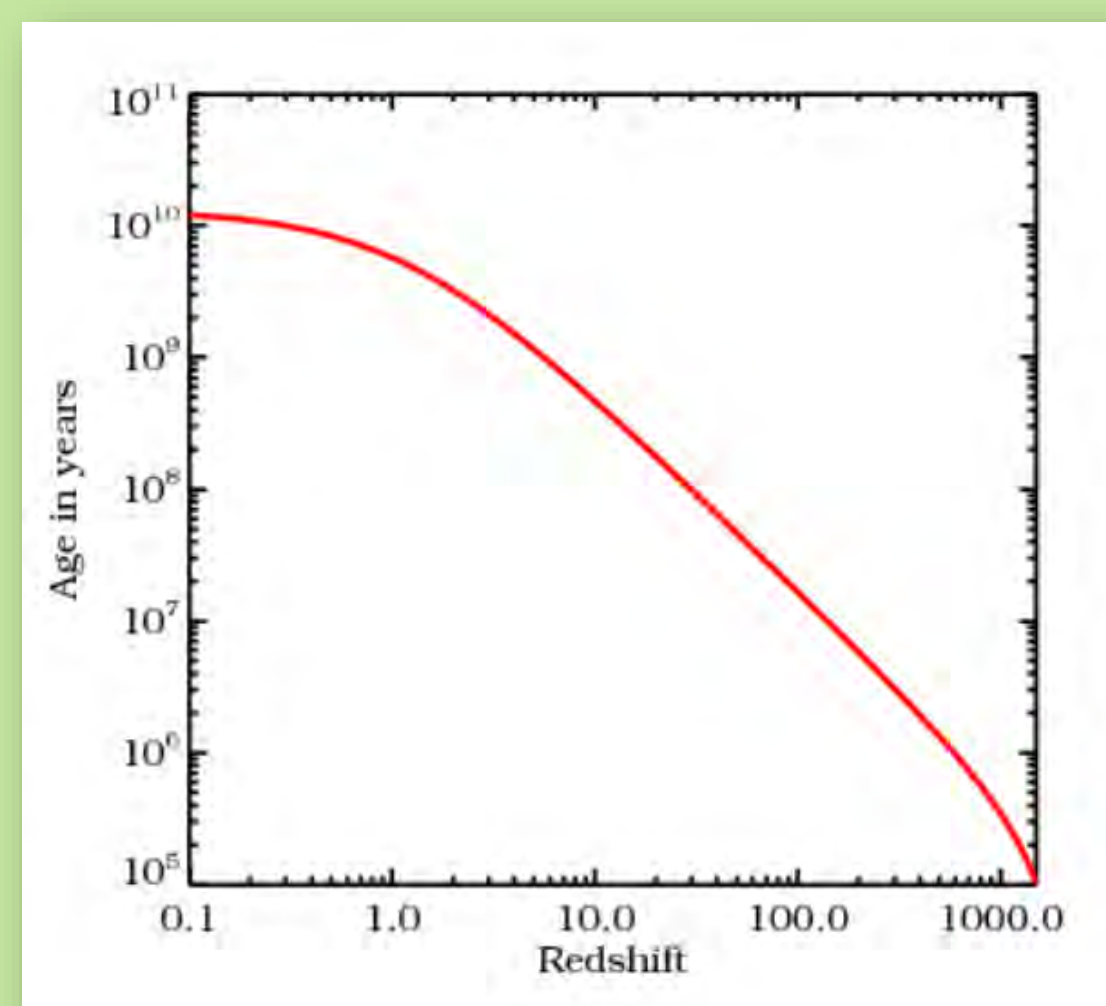
They were revealed because fast-moving electrons emitted radio waves as they spiraled around magnetic field lines in intergalactic space. The world's most sensitive radio telescope, the Very Large Array (VLA), was needed to map these feeble radio emitting ring structures. In X-ray they found a spectacular, "speeding bullet" shaped region of X-rays coming from gas heated to 60 million degrees Kelvin (see Figure beside).

IUCAA scientists calculate that in Abell 3376 the shock-waves are so powerful and so large that they will easily provide the right amount of "kick" to accelerate the cosmic rays (protons and atomic nuclei) to about 100 million times more energy than the highest energy achieved so far in any man-made particle accelerator.

Re-ionization Study of Intergalactic Medium

After big bang at redshift (z)=1100 electrons and protons combined to form hydrogen and helium. Then around $z \sim 30$ first stars are believed to be born. Radiation from these early stars with energy ($E > 13.6\text{eV}$) sufficient to remove electron of a hydrogen atom started separating the electron and proton. Such a separation is known as re-ionization of Hydrogen. From CMB and high redshift quasar observations scientists believe that the process of re-ionizing of almost all the hydrogen in the universe (1 out of 10000 hydrogen atom is not re-ionized) completed before $z=6$.

Similarly the re-ionization of helium, i.e. removing both the electron from it, is believed to be completed around $z=3$. It is because radiation of four times higher energy ($E > 54.4\text{eV}$) is needed to re-ionize Helium. Galaxies do not emit such energetic radiation but quasars do. The number of quasars around $z=3$ are believed to be sufficient to re-ionize the Helium but there were no direct observational evidences of that.



Redshift vs Age of the Universe in years

Galaxy Cluster Merger Simulation

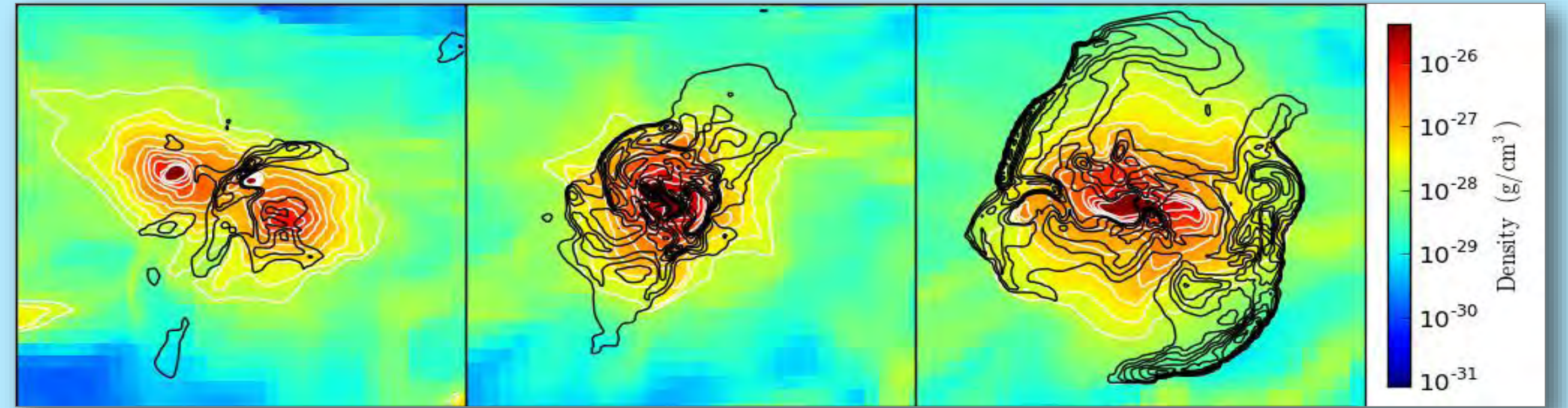
Galaxy clusters are known most massive and largest objects in the universe.

Within isotropic and homogeneous background, Large Scale Structures grow via gravitational instability from the initial density fluctuations.

Galaxies and clusters of galaxies formed due to hierarchical clustering of matters through accretion and violent mergers.

Dark Matter + hydrodynamic simulations – Best way to understand the structure formation is the cosmological simulations. IUCAA scientists are working on these hydrodynamic simulations.

Below is the time snapshots of a Galaxy Cluster merger event through which most of the clusters are formed. (Simulation is performed using IUCAA HPC facility and ENZO 2.1 hydrodynamic code.)

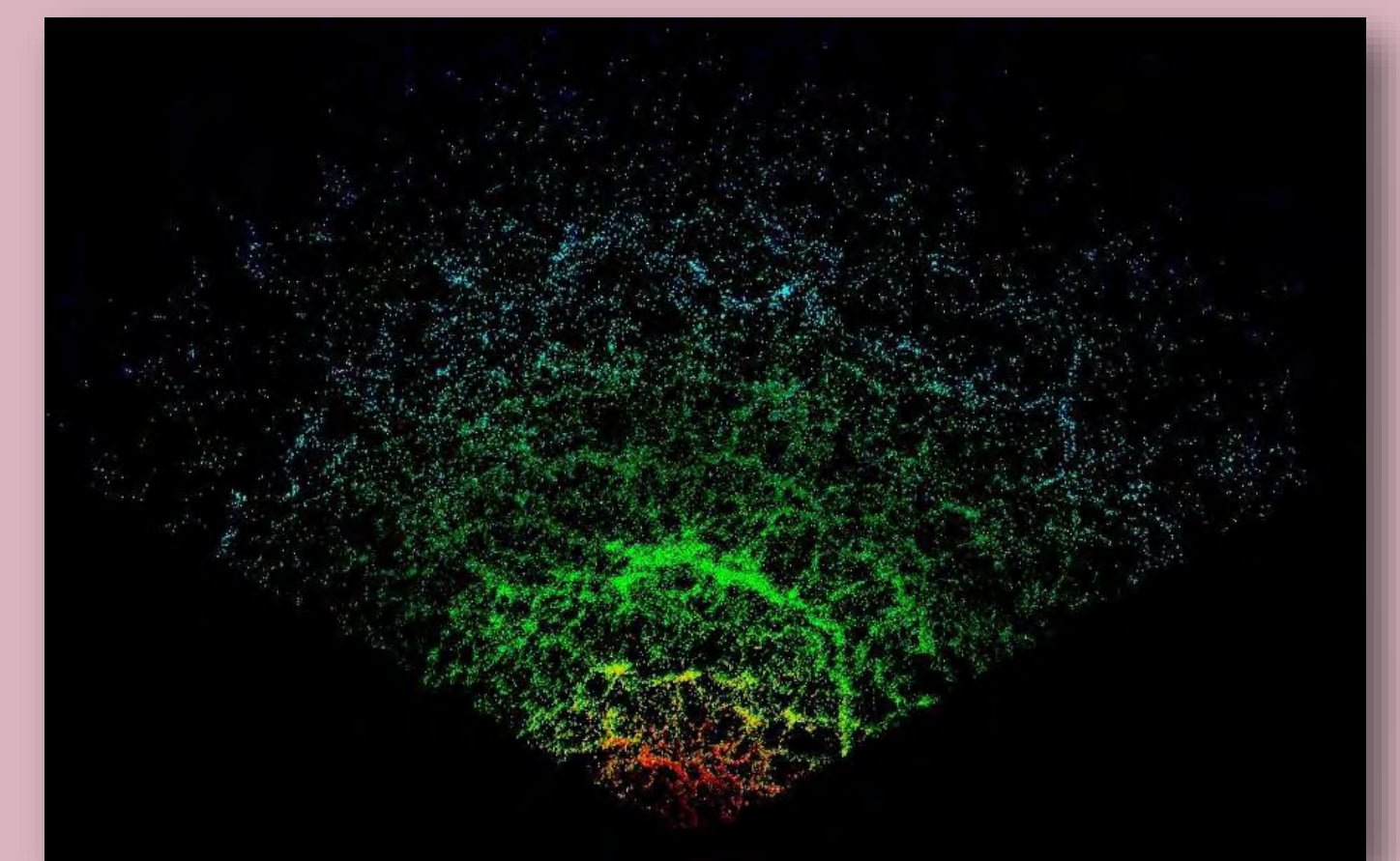


Each slice is 3 Mpc² and cut at the centre of mass on the merging plane. Density is colour coded and contour showing the temperature $\sim 10^7$ K (Panel 1: 3.0 Gpc, Panel 2: 2.7 Gpc, Panel 3: 2.4 Gpc away)

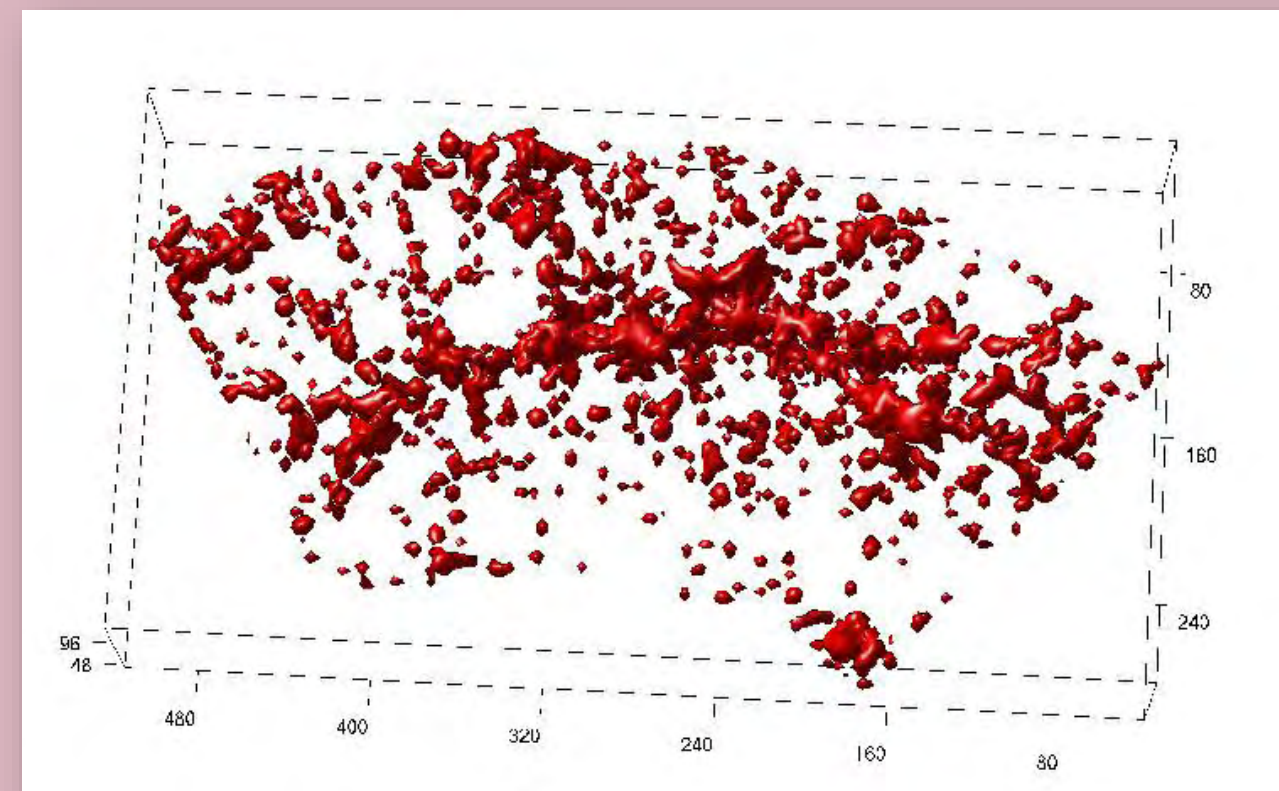
Quantifying the Large Scale Structure

The Large scale of the Universe mostly relies on the distribution of galaxies. The mapping of the three dimensional distribution of galaxies is known as **Galaxy Redshift survey**. The picture in right shows the projected distribution of galaxies from the Sloan Digital Sky Survey. The galaxies are distributed in a interconnected network of **filaments** encircling the voids. This complex pattern is known as **Cosmic Web**.

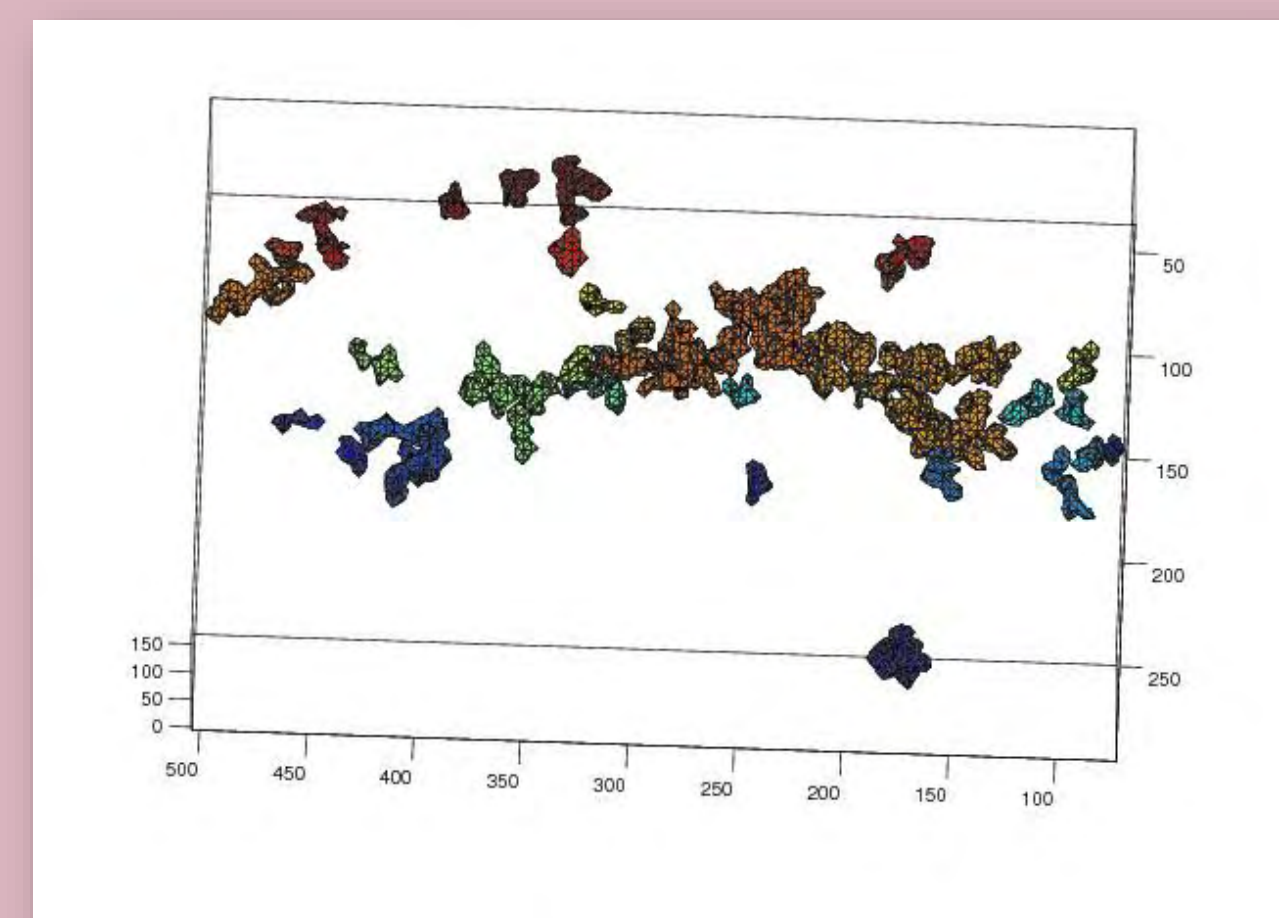
IUCAA scientists have developed a numerical tool **SURFGEN**, which is geometrical and Topological quantifier, to measure the shape and size of different structural element in the Cosmic Web. SURFGEN uses triangulated polyhedral surface computed using Marching Cube 33 algorithm.



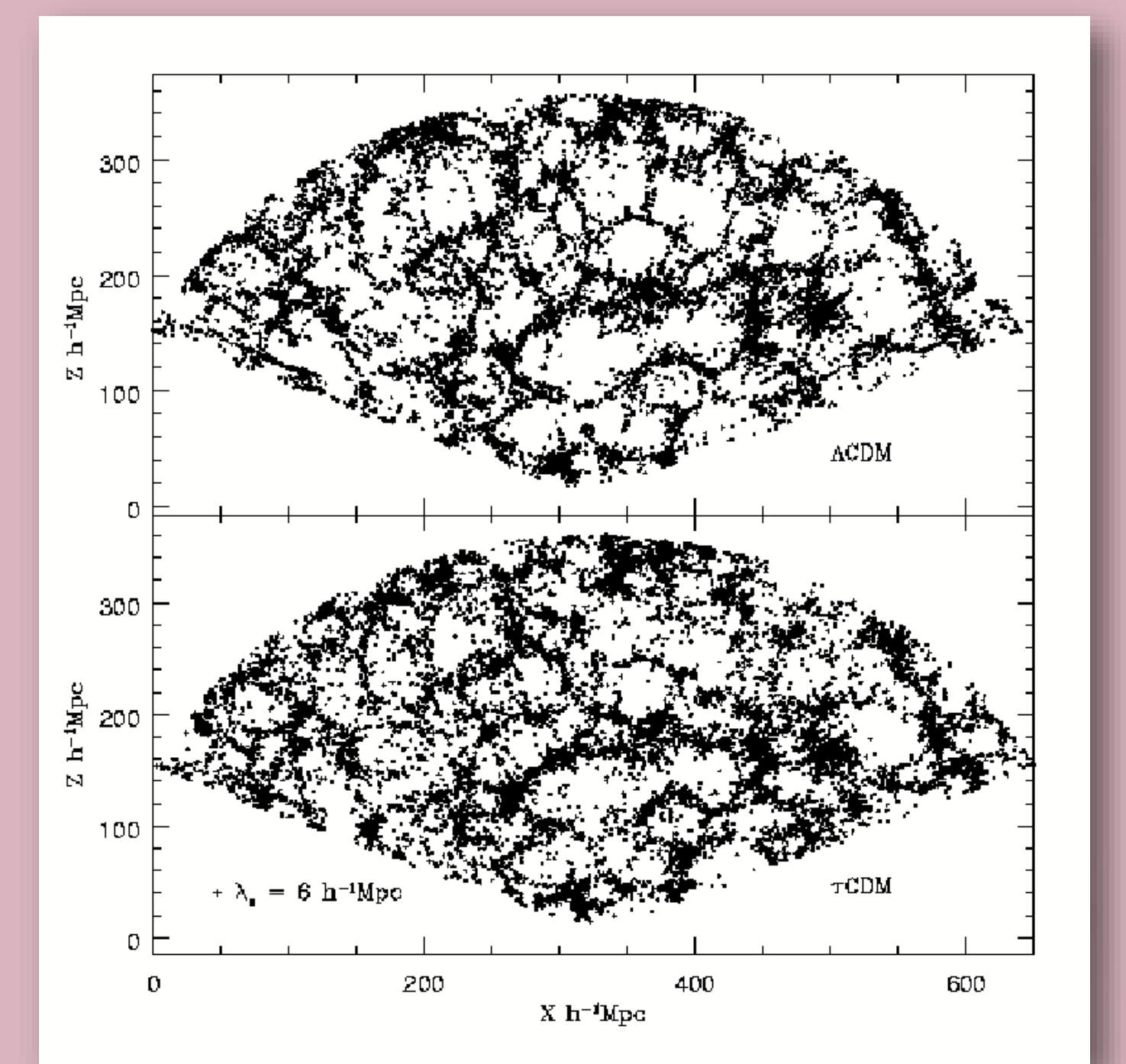
A map of the galaxy distribution in one slice of the sky, from the Sloan Digital Sky survey. We are at the center of the figure. Each point here represents a galaxies. The angular co-ordinate is given by the RA and the radial coordinate is given by redshift. The declination is suppressed.



This picture shows the 3D density of galaxy distribution in a volume limited subsample from SDSS.

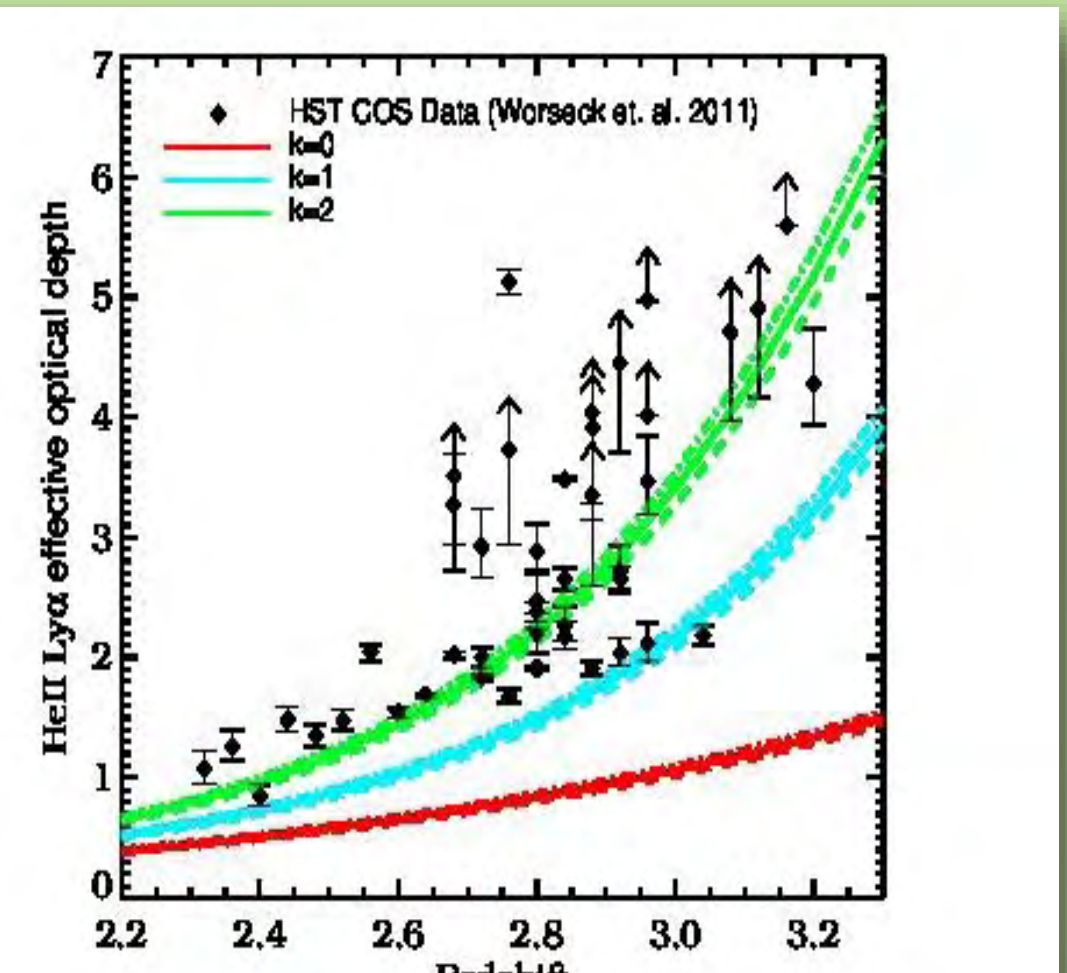


This figure shows different structures of the above figure quantified by SURFGEN. Different colour represents different connected structures.



This figure shows the galaxy distribution in two different models (LCDM and TCDM).

The formation of nonlinear structure in the universe is affected by the presence of Dark matter and Dark Energy. The size and shape of the super-clusters depends on the type of model we choose. **SURFGEN** is capable of discriminating between these different models of formation of non linear structures in the universe.



HeII Ly-alpha effective optical depth vs Redshift

Recent observation of five quasars from Cosmic Origin Spectrograph (COS), a new spectrograph installed on Hubble Space telescope (HST), favor the Helium re-ionization completing around $z=2.7$. It has been shown that the optical depth of Lyman alpha line of singly ionized helium is steeply increasing with redshift. It means that there is more neutral helium above $z=2.7$ and more ionized helium below $z=2.7$. While scientists in IUCAA show that the presence of galaxies which ionize more hydrogen can naturally explain these observations. The amount of hydrogen a galaxy can ionize is quantified by a parameter known as escape fraction (f_{esc}). Here, f_{esc} is denoted by a letter k ; higher values of k implies large f_{esc} . Scientists in IUCAA have shown that more f_{esc} indirectly suggests that there is more neutral helium in intergalactic clouds. Thus HST COS observation need not mean that Helium re-ionization is completed around $z=2.7$. Therefore the question of when exactly helium got re-ionized still remains to be answered.