

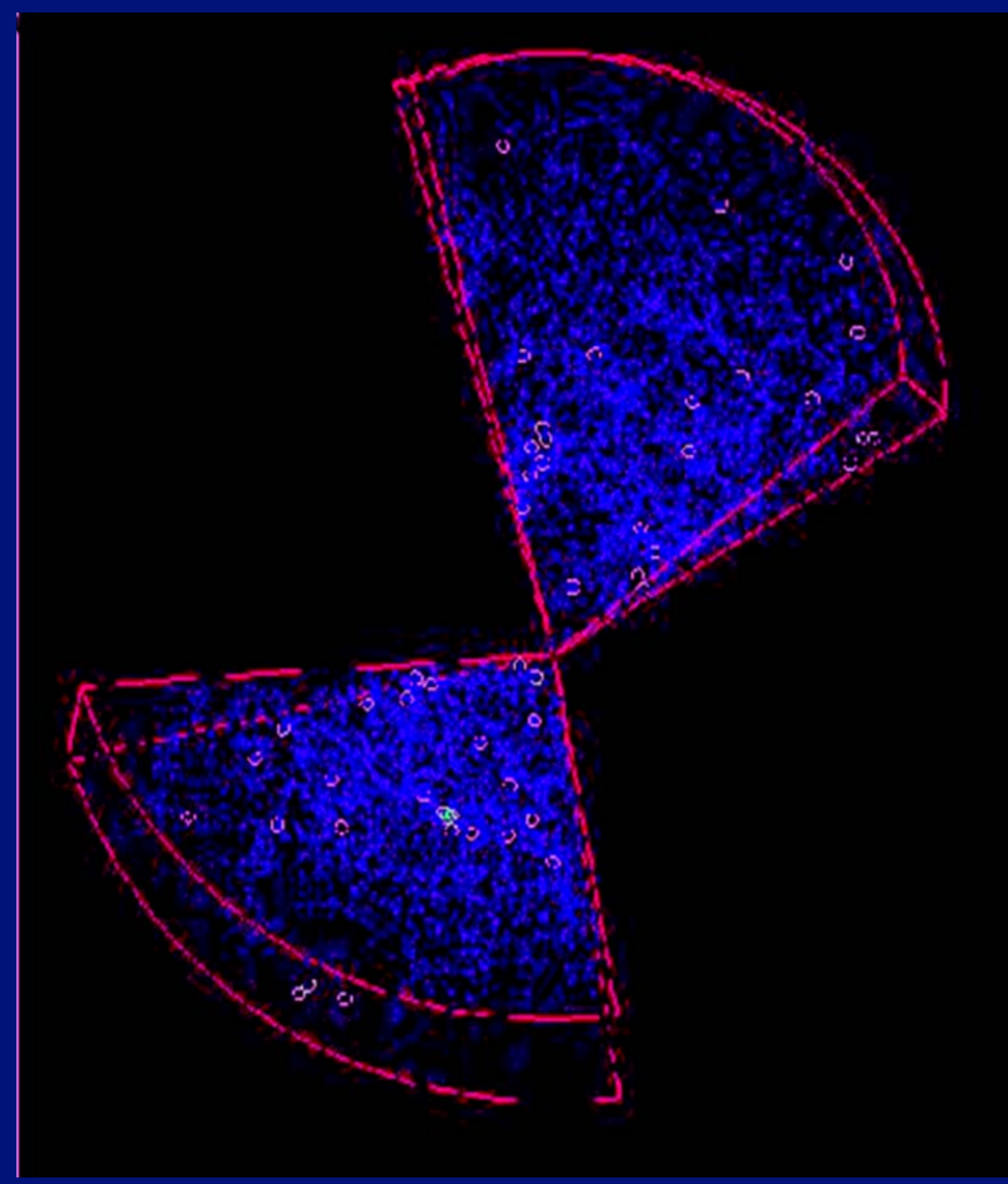
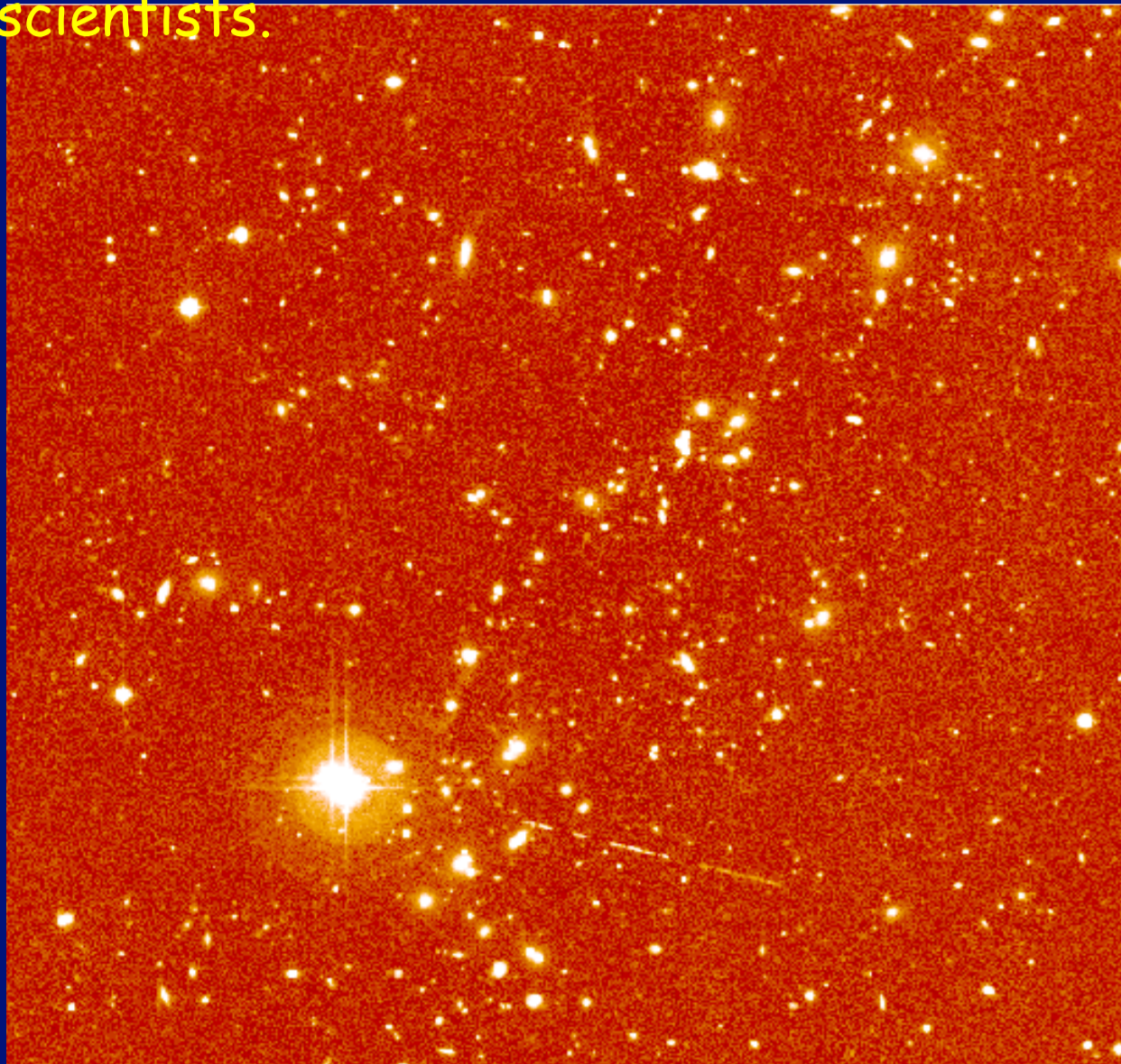
Formation of Clusters: A view from GMRT

❖ 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.

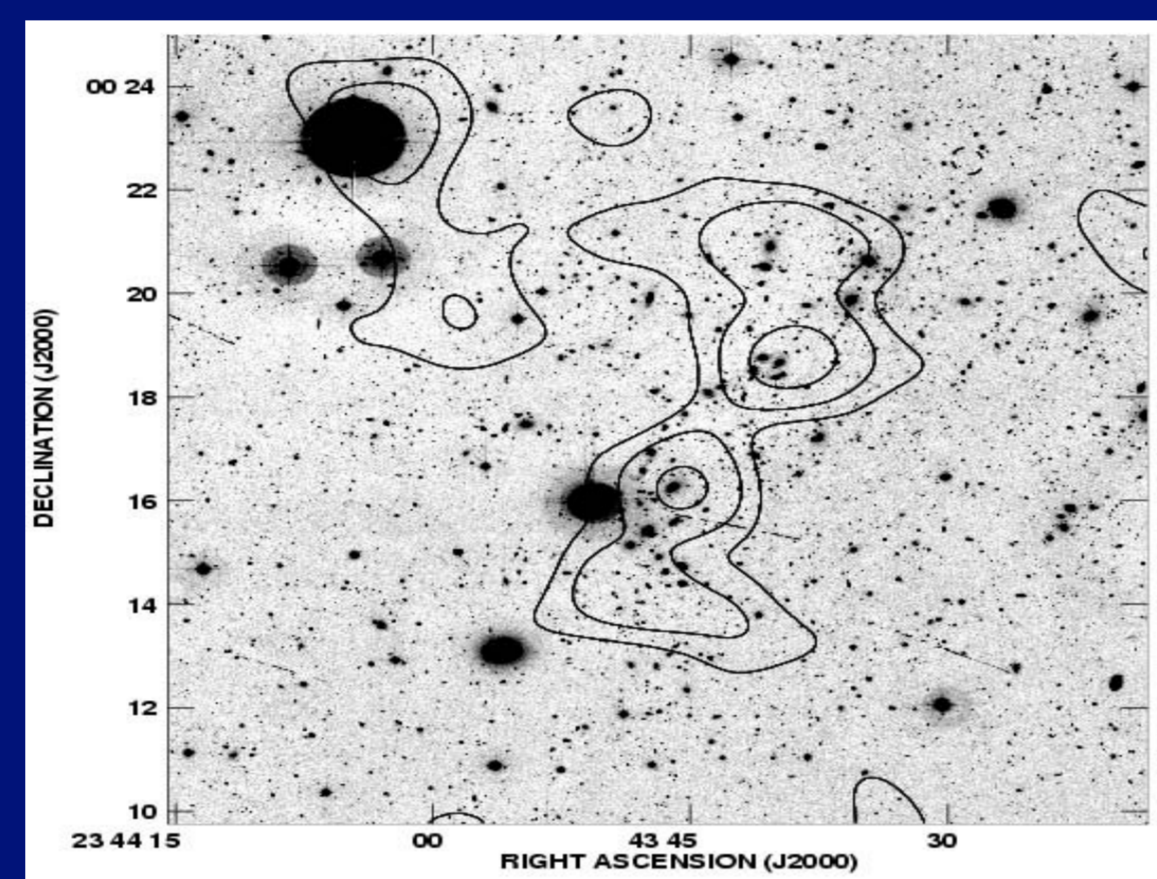


❖ During the merger process, very powerful shock waves are produced in the ionized Hydrogen gas between the galaxies.

❖ 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.

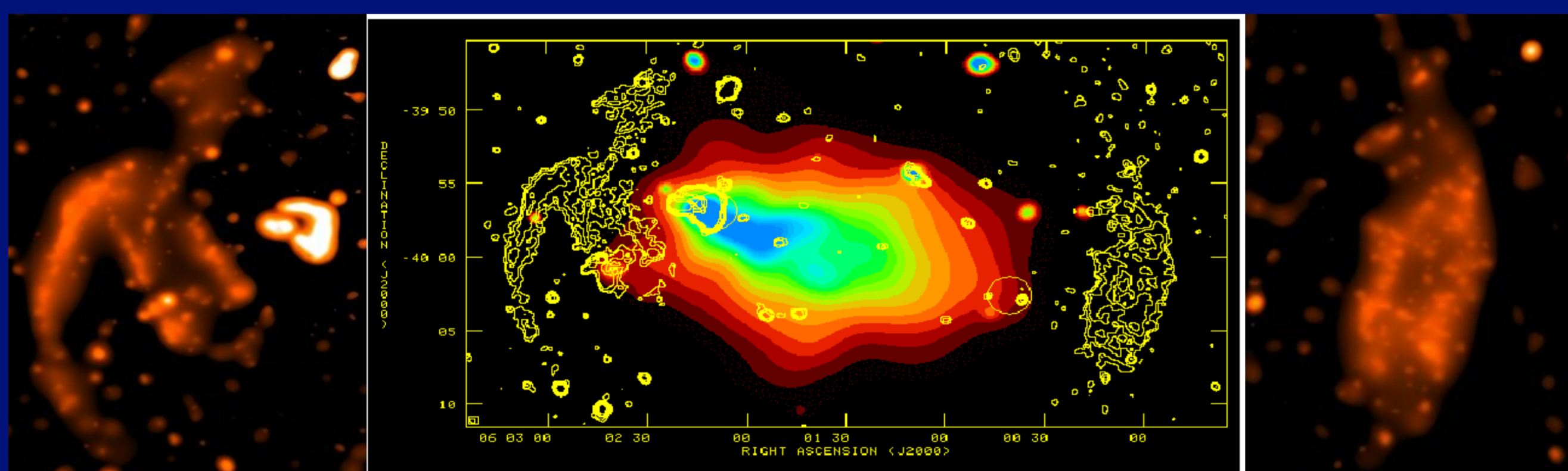
OPTICAL CCD PICTURE OF ZwCl2341.1+0000

❖ 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.

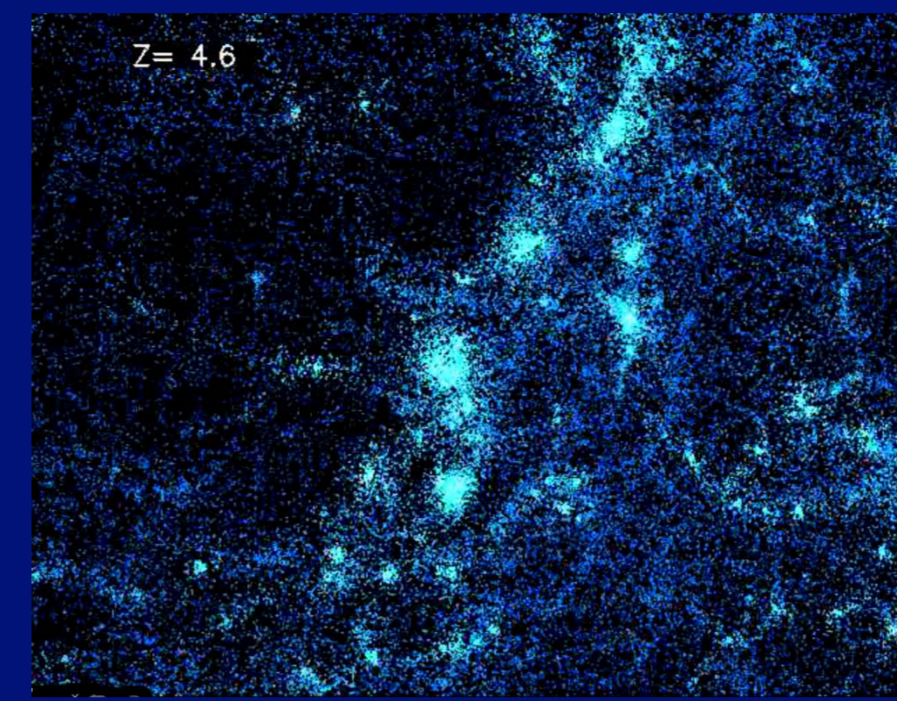
❖ The growth of small inhomogeneities via gravitational instability gives rise to many structures (e.g. galaxies, clusters).

❖ As the mass of the Universe is mostly dark matter, this structure formation is decided by dark matter gravity.

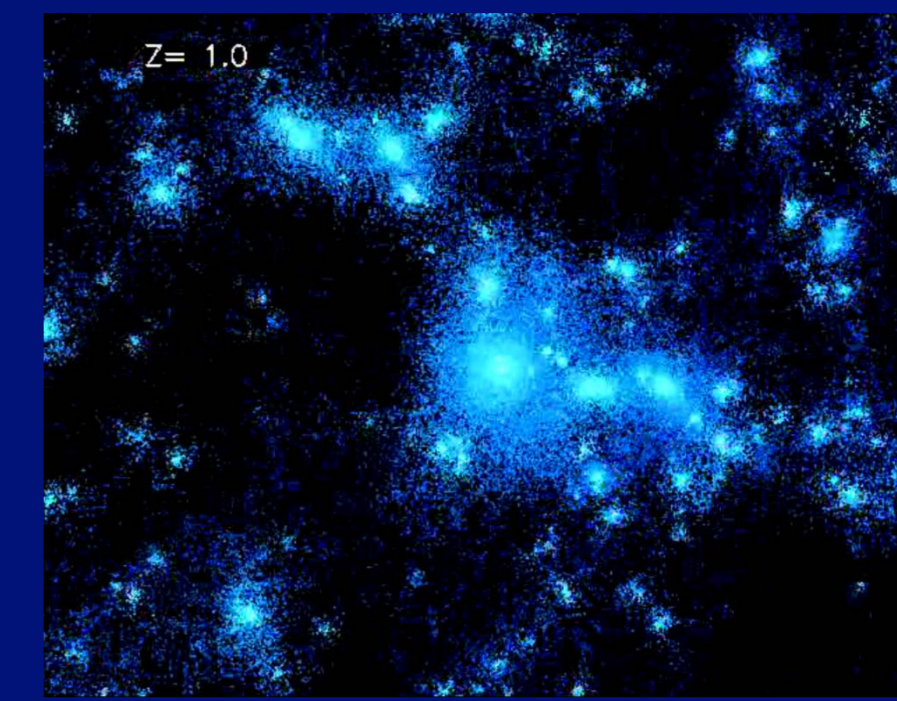
❖ **N-Body simulations** - Understanding structure formation via computers.

❖ We start with a near-uniform distribution of dark matter and they evolve via gravitational interaction.

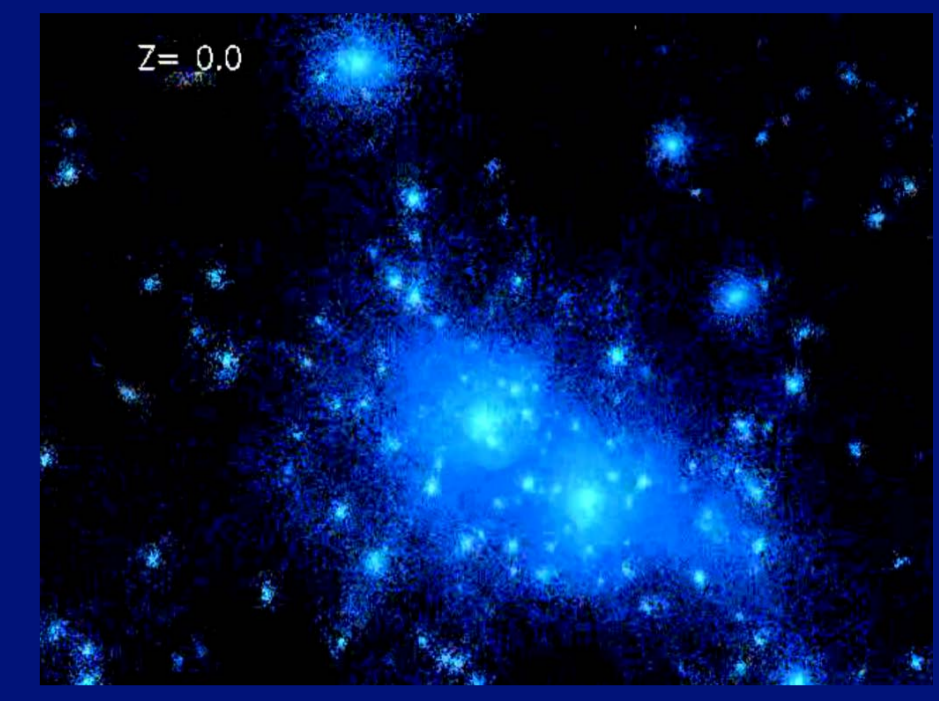
❖ We have run such simulations at IUCAA - see adjoining figures showing the growth of structures over time.



12 BILLION YEARS AGO



7 BILLION YEARS AGO



TODAY

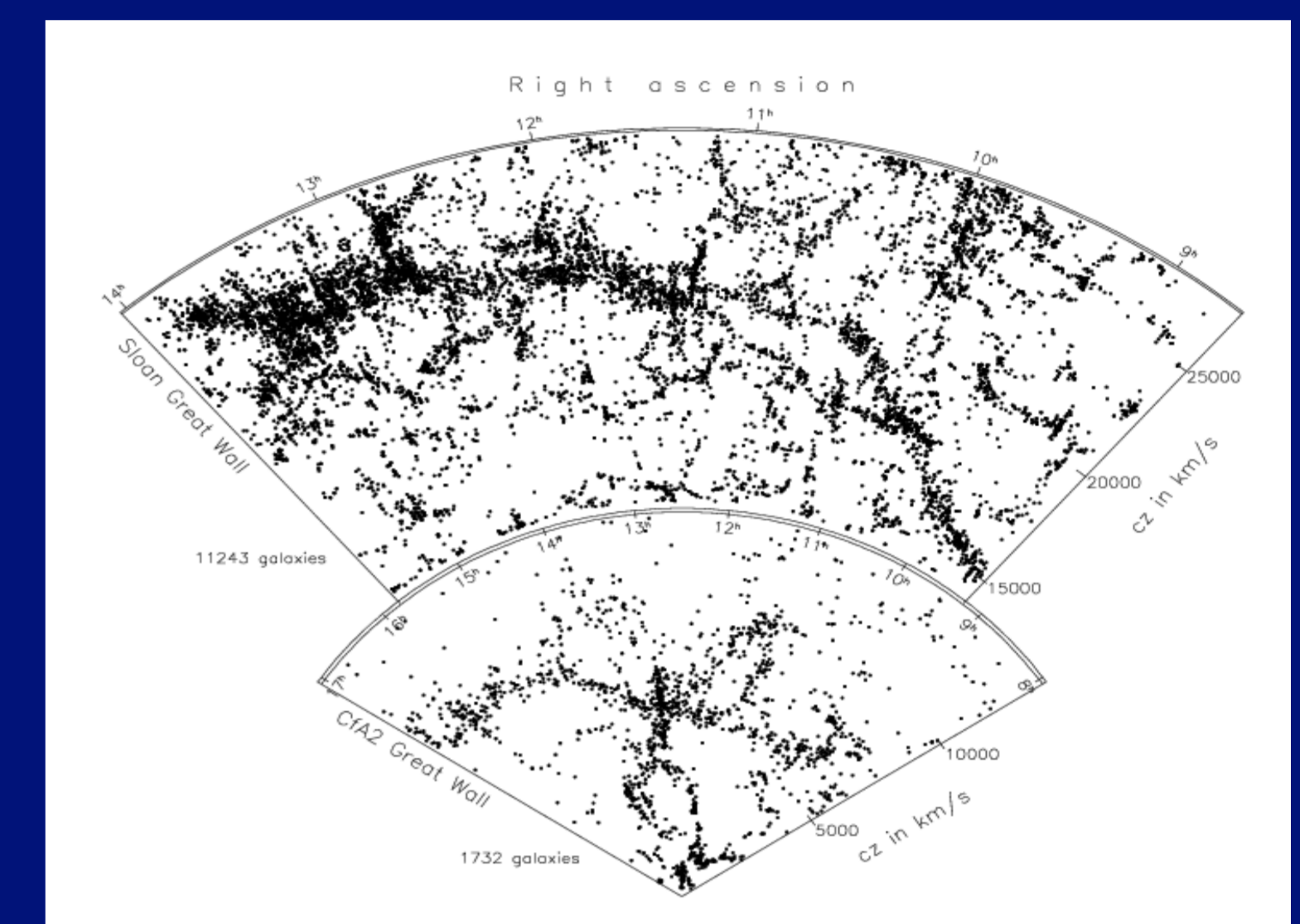
Quantifying the Large Scale Structure

❖ About 95% of the matter content in the Universe is dark. We saw above how dark matter evolves with time.

❖ The galaxies are made up of the rest of the visible matter, and they follow the dark matter during their formation and evolution.

❖ Astronomers have recently recorded 3-dimensional positions of 250000 galaxies.

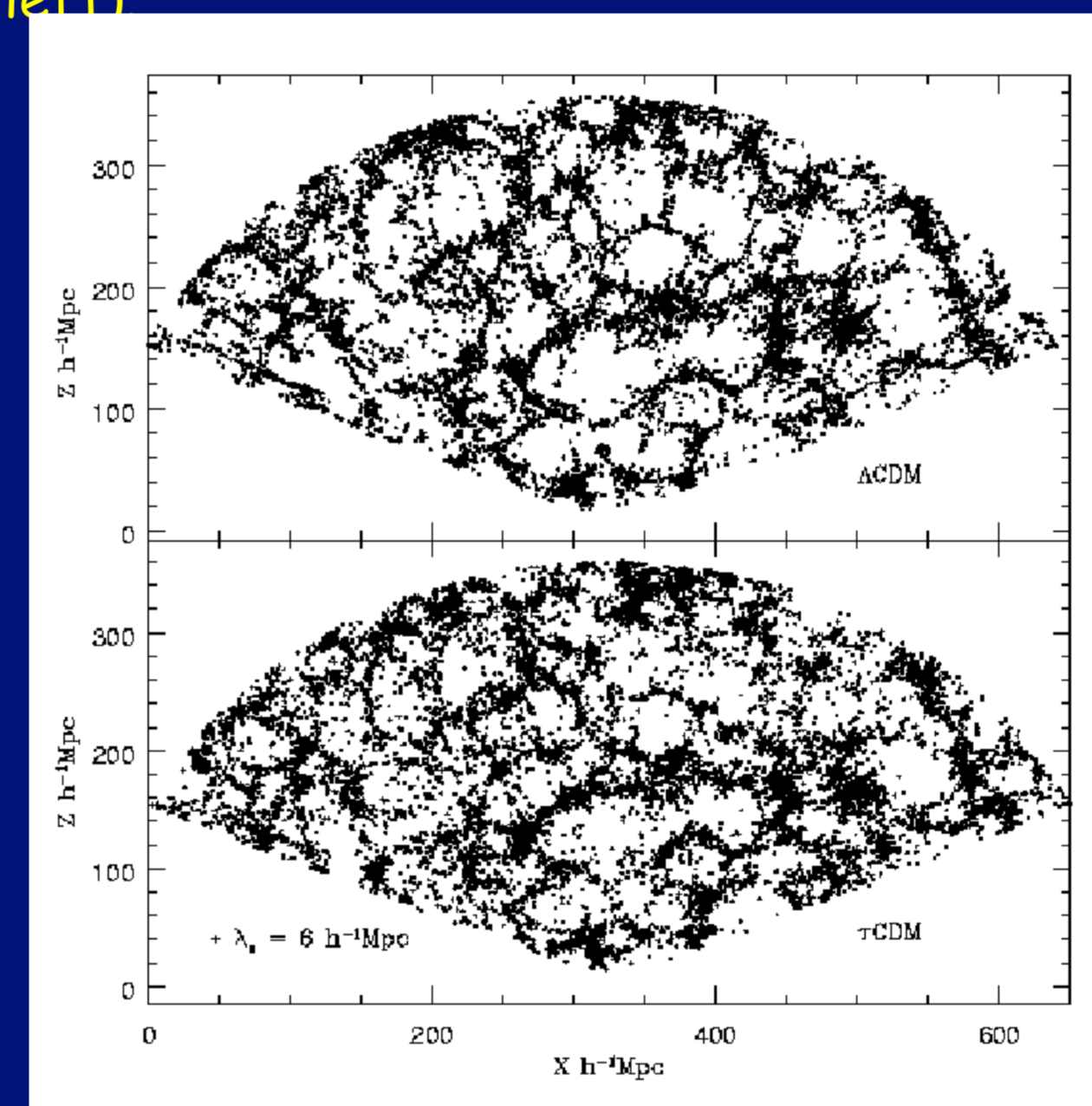
❖ The galaxies fall along filaments which interconnect, with clusters forming at the intersections. Most of the space in the Universe is empty - Voids. The large-scale structure is also dubbed as the **Cosmic Web**. (figure to the left)



The Sloan Great Wall is situated at $z \sim 0.8$ and its linear extent is $\sim 420h^{-1} \text{Mpc}$ which is twice larger than CfA great wall.

❖ At IUCAA we have developed a numerical tool **SURFGEN** which can measure the shapes and sizes of the filamentary superclusters and voids.

❖ SURFGEN can thus be used to compare theoretical predictions of various models with the observed large scale structure. See the figure above to see how SURFGEN determines a supercluster.

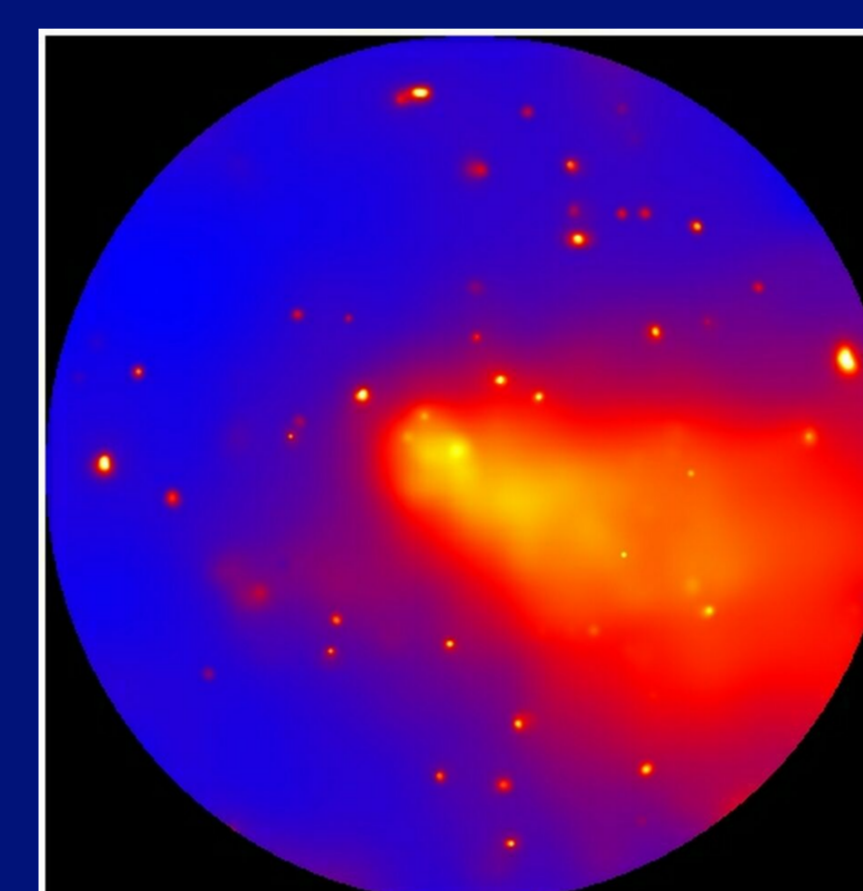
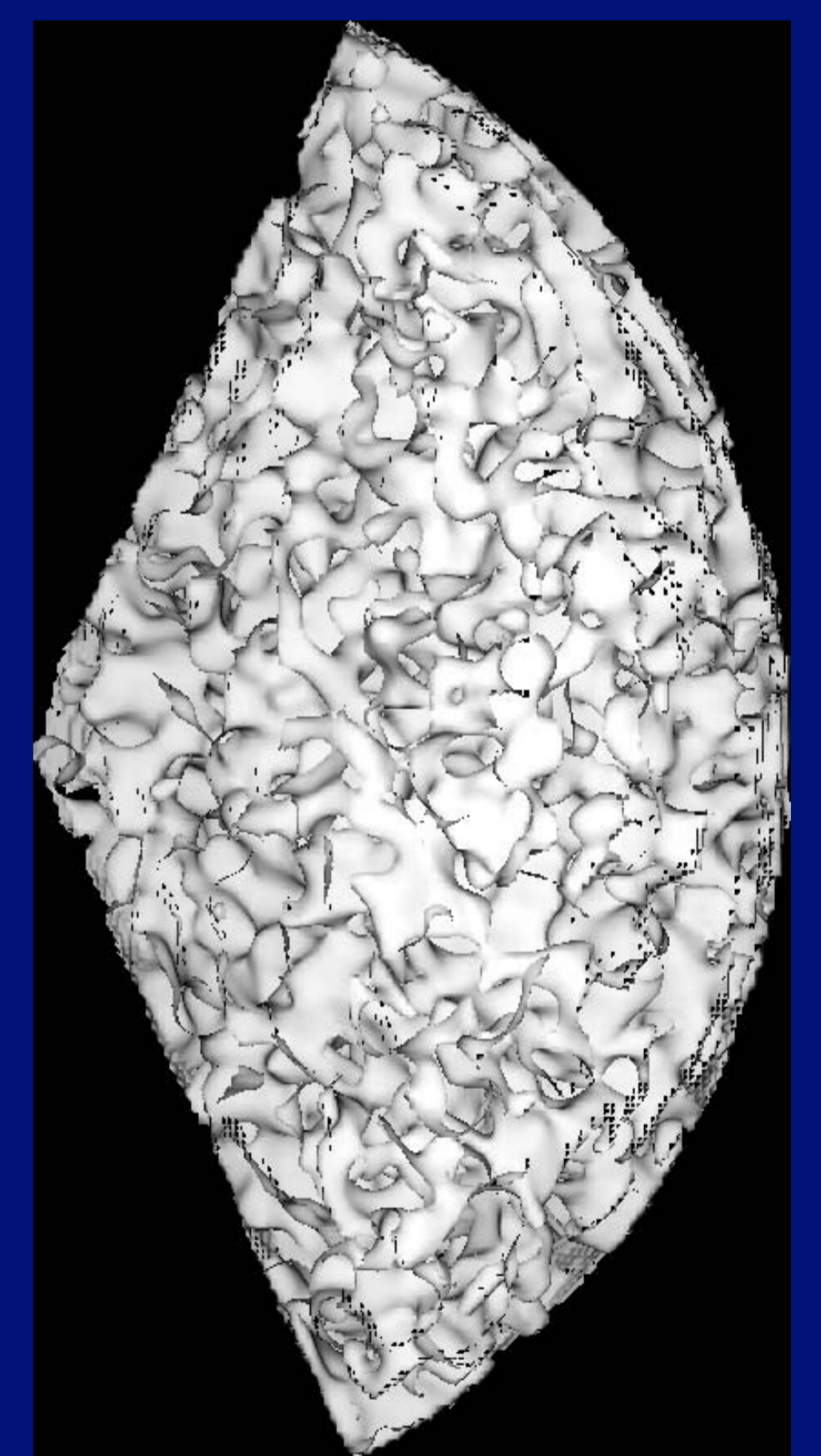


THIS FIGURE SHOWS HOW THE UNIVERSE MAY LOOK LIKE IF ONE OF TWO COSMOLOGICAL MODELS - LCDM OR TCDM - IS CORRECT. SURFGEN CAN HELP US COMPARE DIFFERENT MODELS. REFER TO THE DISCUSSION TO THE RIGHT FOR MORE DETAILS..

❖ The figure to the left shows large scale structure of the Universe in two cosmological models.

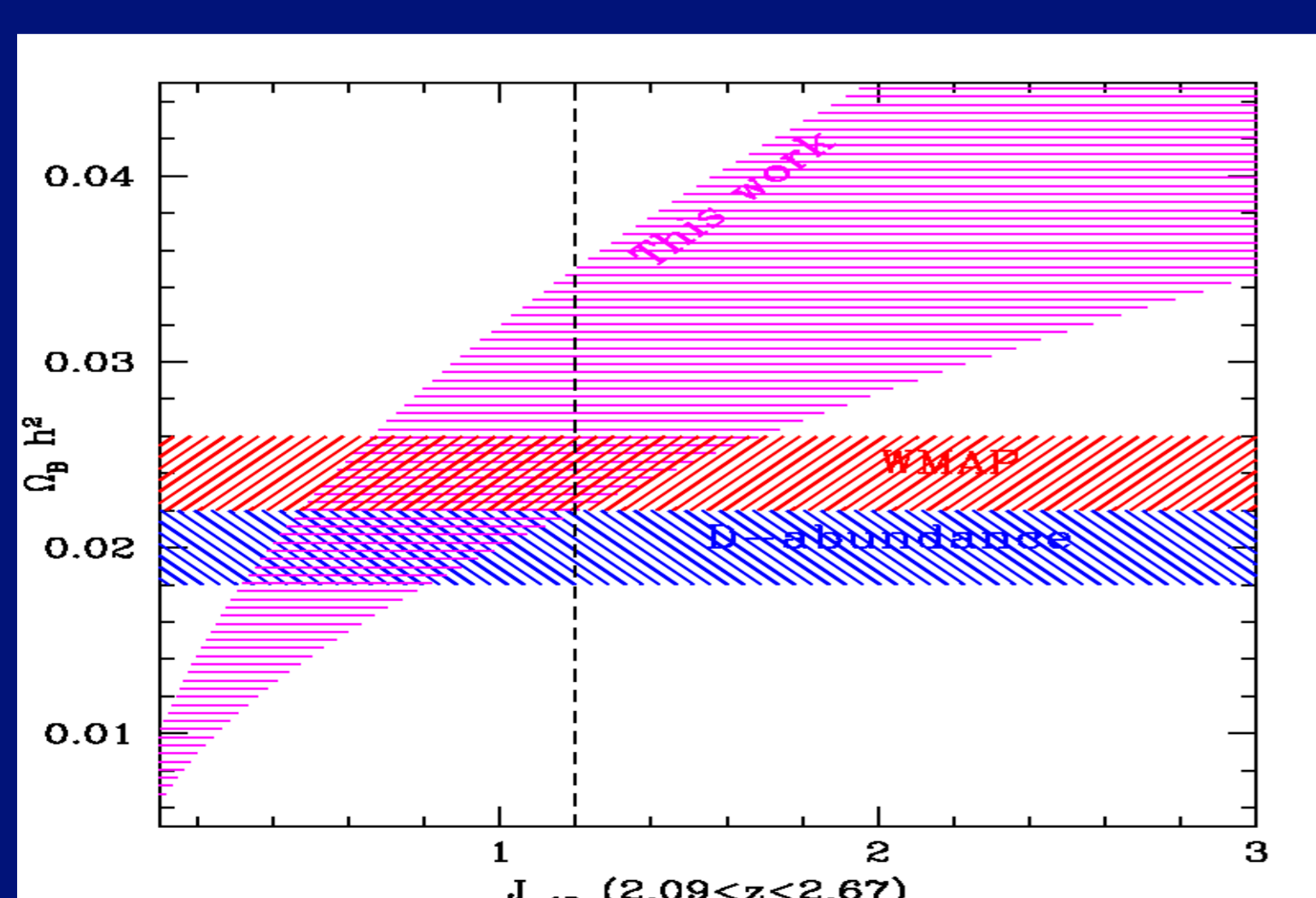
❖ Figure to the right shows contours plotted at constant density threshold, for clusters and superclusters.

❖ The correct theoretical model of the Universe should show superclusters as lengthy and thick as in the real Universe and huge voids - 150 million light years across.



XMM-Newton X-ray Map

Reionization and Study of Intergalactic Medium



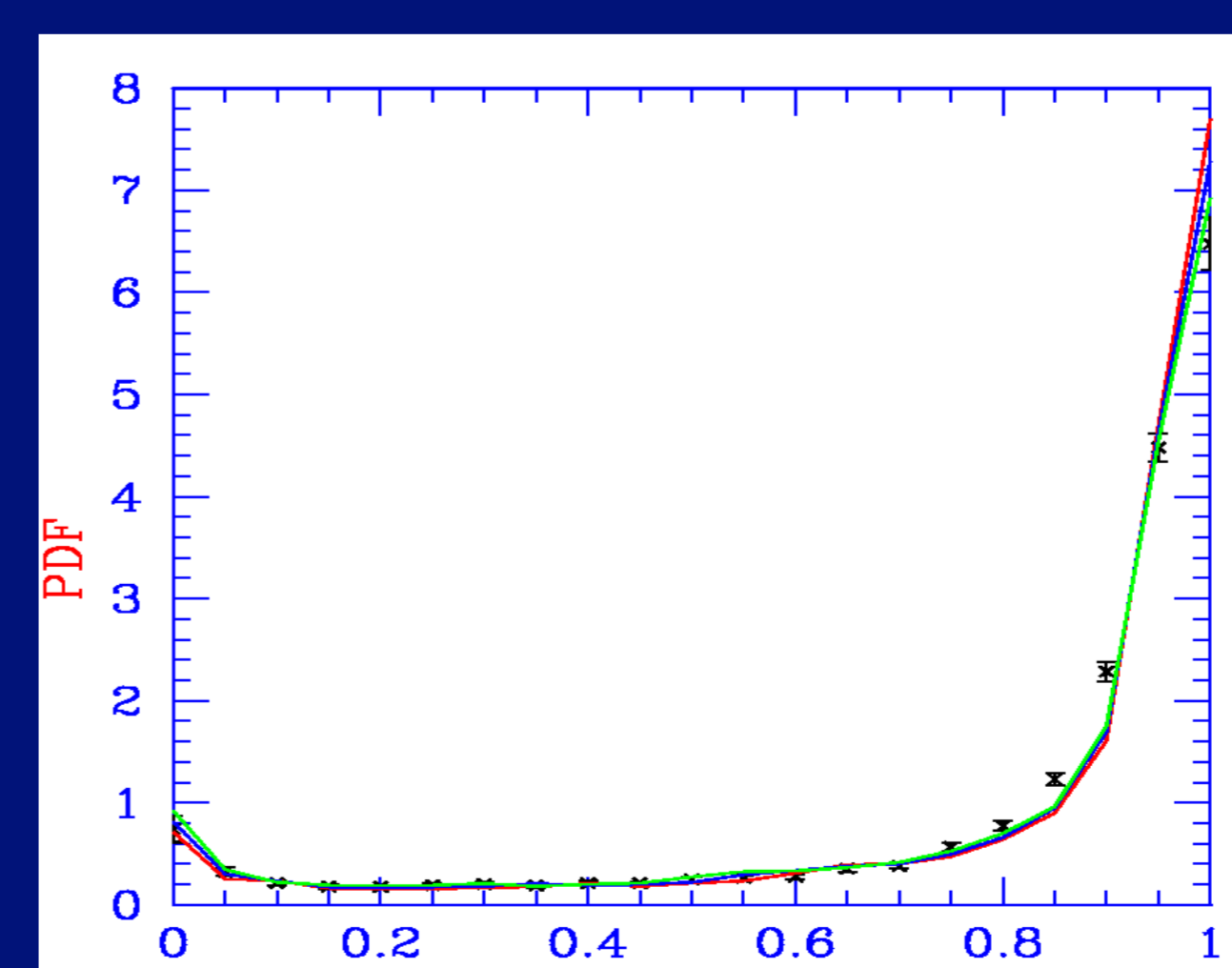
COMPARISON OF BOUNDS OBTAINED FROM IGM-STUDIES WITH THOSE FROM CMBR AND BIG BANG NUCLEOSYNTHESIS. X-AXIS STANDS FOR THE IONIZING FLUX WHILE Y-AXIS GIVES THE AMOUNT OF BARYONS (PROTONS, NEUTRONS AND ELECTRONS) IN THE UNIVERSE. WE SEE THAT IGM PREDICTIONS MATCH THE OTHER STUDIES IF THE IONIZING FLUX IS NOT VERY LARGE.

❖ The study of formation of galaxies and stars is difficult because in addition to gravity we have to study electromagnetic interaction between electrons and protons.

❖ Most studies of the formation of stars and galaxies involve the Universe when it was about a billion years old, when most of the material formed a diffuse ionized intergalactic medium (IGM). The IGM mainly contains ionized hydrogen and some helium.

❖ The ideal approach to understand the IGM is to model it semi analytically. At present, we are attempting to resolve some of the issues regarding the IGM, reionization and high redshift universe.

❖ We mainly concentrate on the quasi-linear regime of the IGM, where complicated phenomena like shock heating or star formation are not very effective.



COMPARISON OF SEMI ANALYTICAL MODELS WITH ACTUAL OBSERVATIONS. THE INDIVIDUAL POINTS (WITH SMALL ERROR BARS) REPRESENT THE DATA OBTAINED FROM SPECTRA OF DISTANT QUASARS. THE DIFFERENT LINES ARE THE MODEL PREDICTIONS.

❖ Observationally, the IGM manifests itself as an absorbing medium. Any light originating from a bright object like a quasar, while passing through the IGM, is absorbed, and the resulting absorption spectrum carries information about the IGM.

❖ The quasar absorption spectrum depends on parameters like the density of matter and the Hubble parameter. We compare the statistics of the absorption spectra obtained from our models with observations to constrain these parameters.

❖ Once we have constraints on the parameters from our model, we can compare these with the constraints obtained from Cosmic Microwave Background Radiation (CMBR) and Big-Bang Nucleosynthesis (BBN).