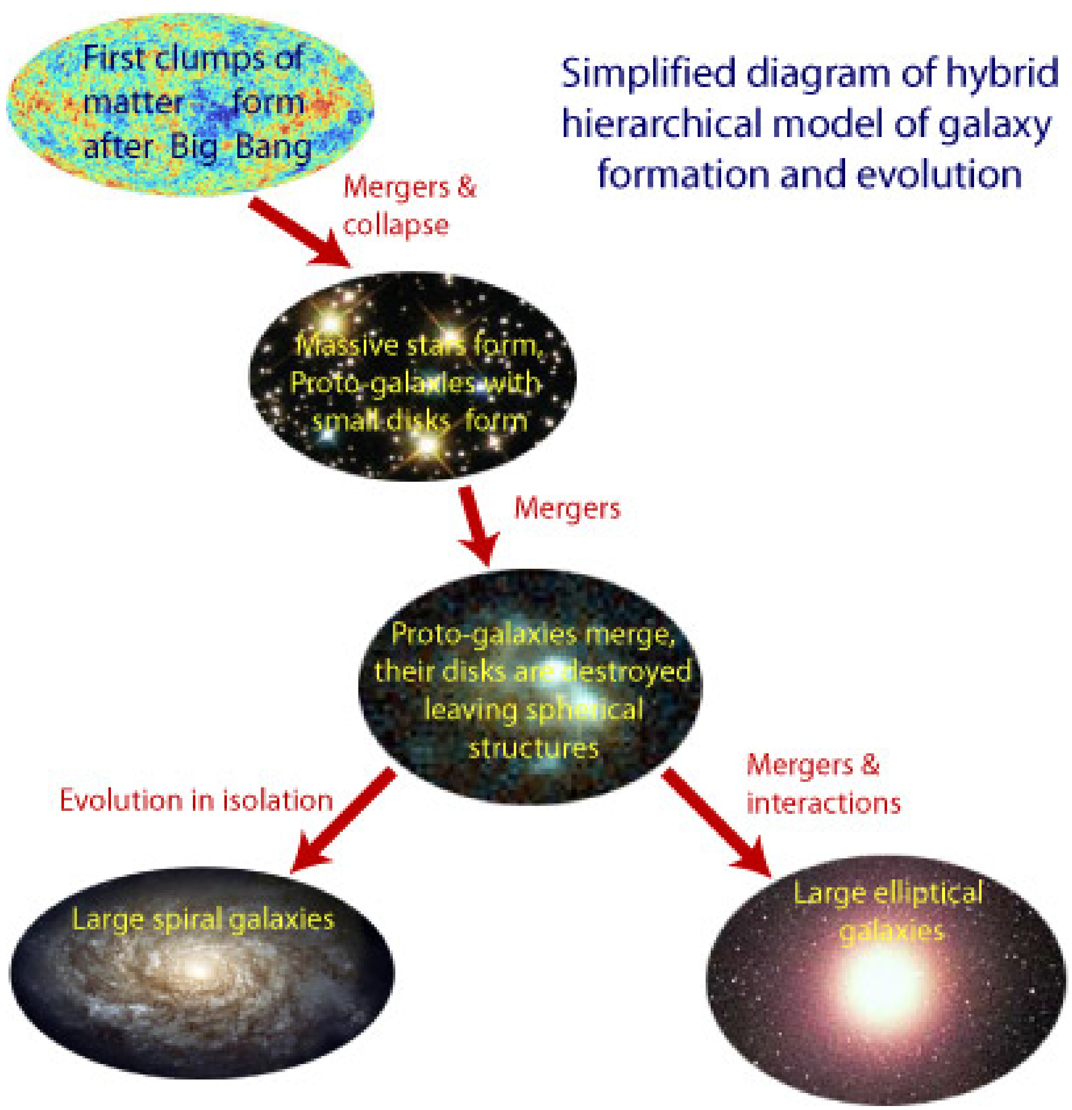
Astronomy & Astrophysics : An Introductory Survey

A lecture series by Prof. G. Srinivasan

A 'Golden Jubilee Celebration' Event of the Astronomical Society of India

Lecture 36 : The Evolution of the Universe

In the early universe, various elementary particles and radiation were in thermal equilibrium, everything at the same temperature. The universe was opaque. At an age of roughly 350,000 years, electron scattering off photons became inefficient and the universe became transparent. Matter and radiation decoupled from one another; radiation 'cooled as the universe expanded, but still maintained a Black Body spectrum. This 'relic radiation was discovered in 1964. The 'cosmic background radiation was incredibly isotropic, as one would expect of black body radiation. This posed a major question, "How did the galaxies and clusters of galaxies form from this primordial soup. The vital clue came in the early 1990s. Since then, there have been attempts to explain the origin of the 'large scale architecture of the universe. In this lecture, I describe our present understanding of the origin of structures in the universe.



[Picture Credit: ATNF - Adapted from a diagram by J. Stanger. Background images from AAO, NASA (WMAP and HST).]

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[Supplementary Material : Dr. Sushan Konar]

Suggested Problems

1. Intergalactic Thomson Scattering :
   (a) The baryon density today is $\rho_{b,0} = \Omega_{b,0}\, \rho_{\rm crit} = 3\Omega_b H_9^2/8\pi G$. For these baryons, X is the mass fraction of Hydrogen and Y is that of Helium (ignore the rest). Estimate the current electron number density if $X = 0.75$.
   (b) Optical depth due to Thomson scattering is defined as $d\tau = n_e \sigma_T\, ds$ where n_e is the electron density, and σ_T is the Thomson scattering cross section. Here the distance is the proper distance traveled by photons: $ds = cdt$. Find the total optical depth for sources at $z = 5$.
   Obtain the time (after Big Bang) corresponding to the optical depth (of the reionised material) of 0.08, the current best limit from the WMAP satellite.
   (c) The CMBR is emitted at $z \sim 1100$. Had the IGM been ionized back too far back in time, the optical depth would have been to high, the scattering washing out all the CMBR fluctuations. What conclusion can we draw about the epoch of reionisation from the fact that we do observe the fluctuations today.

2. A rough reproduction of the reasoning that led Alpher and Gamow to predict the existence and temperature of the CMBR in 1948, 17 years before its discovery. Assume, that deuterium begins to form when the universe's temperature drops to $T = 10^9$K (at higher temperatures it is photodissociated).
   (a) Calculate the age of the universe when $T = 10^9$K. Show that if we waited much longer than this, most of the neutrons from which deuterium is formed will have decayed.
   (b) Require that neutron capture be efficient enough to form light elements but not so efficient as to leave no deuterium, i.e. $< \sigma v > n_b t \sim 1$, where n_b is the baryon density. Using $< \sigma v >= 5 \times 10^{-20}$cm^{3}s^{-1} at 10^9K, and the age of the universe obtained in the problem above, estimate the required baryon density n_b when $T = 10^9$K.
   (c) Assuming the present-day baryon number density gives $\Omega_{b,0} = 0.045$, what is the scale factor $(1/(1+z))$ at $T = 10^9$K?
   (d) What is (roughly) the resulting predicted temperature of the background radiation today day?

3. Supernova 'Velma', at a redshift of $z = 1.05$ was discovered in 1999 by the High-z SN team. Suppose there existed Velman cosmologist who were observing the CMBR when the light we now see from the supernova was emitted. Given that the CMBR is black-body radiation, with a present day mean temperature of $T_0 = 2.73$K, explain why the Velman cosmologists would have measured the mean temperature of the CMBR to be $T_V = 5.6$K.
   Approximately what value of the redshift of the CMBR would the Velman cosmologists have measured at that time (Take the current redshift of the CMBR to be $\sim$1000.

4. The redshift of recombination depends entirely on just one parameter: η, the baryon-to-photon ratio. It is interesting to investigate how any uncertainty in the baryon-to-photon ratio affects the redshift of reionisation (when the ionization fraction, X = 0.5). Take two cases: $\eta = 4 \times 10^{10}$ and $\eta = 8 \times 10^{10}$ and determine the temperature (and therefore the redshift) of recombination. Note that it may be useful to plot X as a function of T(z).

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