History of Cosmology: Mid ~ 20th Century

Discovery of the Dark Matter



- Fritz Zwicky (1933): from application of the virial theorem to Coma Cluster, deduced that it contains ~ 400 times the amount of mass in visible stars
- Similar results obtained for Virgo Cluster by Sinclair Smith in 1936
- Largely ignored until 1970's, when flat galaxy rotation curves made the existence of DM unambiguous
- DM plays a key role in the models of structure formation
- The nature of the DM is now one of the outstanding problems of physics



The Hubble-Sandage Observational Cosmology Program at Palomar, 1950's - 1970's

- Cosmology as a "search for 2 numbers" [H₀ and q₀]
- Hubble diagram of the brightest cluster ellipticals as the primary tool
- Doomed by galaxy evolution





THE ABILITY OF THE 200-INCH TELESCOPE TO DISCRIMINATE BETWEEN SELECTED WORLD MODELS

ALLAN SANDAGE Mount Wilson and Palomar Observatories

Observational Cosmology At Palomar: 1970's -1980's

- Introduction of novel instrumentation, e.g., CCDs was a key development
- Still, classical tests like the Hubble diagram of galaxies were foiled, but many other advances were made



The Steady State Cosmology (1948)



Thomas Gold, Hemann Bondi, Fred Hoyle

Proposed as an alternative to the Big Bang

Based on the "Perfect" cosmological principle: the universe is homogeneous in time as well as in space



That means that new matter must be created as the universe expands

Predicting the Cosmic Nucleosynthesis and the CMBR

Ralph Alpher George Gamow Robert Herman



Gamow et al. in 1948 also "ran the film backwards" and figured primordial nucleosynthesis in the early universe (Alpher, Bethe, & Gamow - " $\alpha\beta\gamma$ " theory), even though the synthesis stopped at He...

They also predicted that the afterglow of this hot stage will be now present in the universe as a thermal background with $T \sim 5 \text{ K}$

Discovery of the Cosmic Microwave Background (CMBR): A Direct Evidence for the Big Bang



Arno Penzias & Robert Wilson (1965)

Nobel Prize, 1978



The CMBR Spectrum: A Nearly Perfect Blackbody



Big Bang Nucleosynthesis Predicts Correct Abundances of Light Elements



Discovery of Powerful Radio Galaxies



Optical ID



IDENTIFICATION OF THE RADIO SOURCES IN CASSIOPEIA, CYGNUS A, AND PUPPIS A

W. BAADE AND R. MINKOWSKI MOUNT WILSON AND PALOMAR OBSERVATORIES CARNEGIE INSTITUTION OF WASHINGTON CALIFORNIA INSTITUTE OF TECHNOLOGY *Received June 19, 1953*





Walter Baade



Rudolph Minkowski

The Discovery of Active Galactic Nuclei: Carl Seyfert (1943)



Broad and highionization emission lines, bright and compact nuclei...

NGC 1068 NGC 3516 NGC 4151 11. Mimi

NUCLEAR EMISSION IN SPIRAL NEBULAE'

CARL K. SEYFERT[†]

Unusal spectra of the Seyfert galaxies NGC 1068 and NGC 4151 have been noted even earlier

The Discovery of Quasars (1963)



Cyril Hazard ➡ got the precise radio position





Allan Sandagegot the optical ID

Maarten Schmidt ➡ figured out the spectrum and the redshift



The Discovery of Quasars (1963)



Discovery of the Large Scale Structure

Universe assumed to be homogeneous on galaxian scales, until ...

1930's: H. Shapley, F. Zwicky, and collab.

1950's: Donald Shane, Carl Wirtanen, others

1950's - 1970's: Gerard de Vaucouleurs, first redshift surveys

1970's - 1980's: CfA, Arecibo, and other redshift surveys





Discovery of the Large Scale Structure

Shane-Wirtanen galaxy counts, density map





G. De Vaucouleurs





Next: History of Cosmology: Modern Developments