Ay 21 - Galaxies and Cosmology

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Winter 2024

Caltech

Cosmology* as a Science

- A study of the universe as a whole, its global geometry, dynamics, history, fate, and its major constituents - galaxies and large-scale structures, their formation and evolution
- A basic assumption: the physical laws are the same at all times and everywhere
  - Some aspects of this are testable
  - But a new and unexpected physics can show up, e.g., dark matter, dark energy
- Only one object of study, and all we can do is look at the surface of the past light cone
- Observations tend to be difficult, and subject to biases and selection effects

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* From Greek *kosmos* = order; see also *cosmetology* …

The Evolution of the Cosmological Thought

… From magical and arbitrary to rational and scientific

Folklore to theology to philosophy to physics

… Away from anthropocentric/anthropomorphic

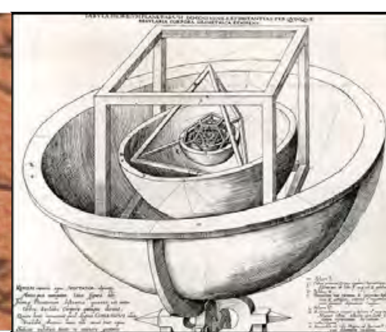
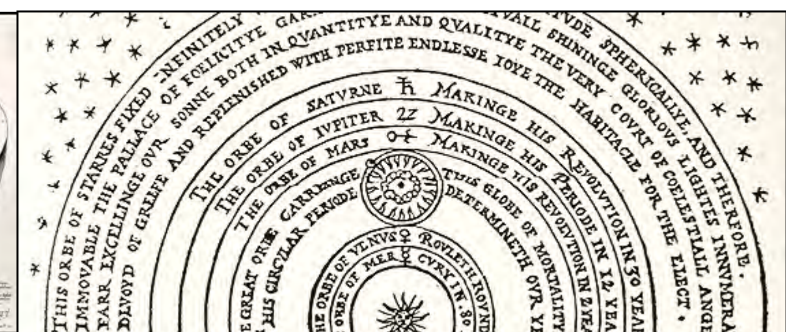
The Copernican revolution

… From final and static to evolving and open-ended

The Darwinian revolution

… From absolute certainty to an ever expanding sphere of knowledge and a boundary of unknown

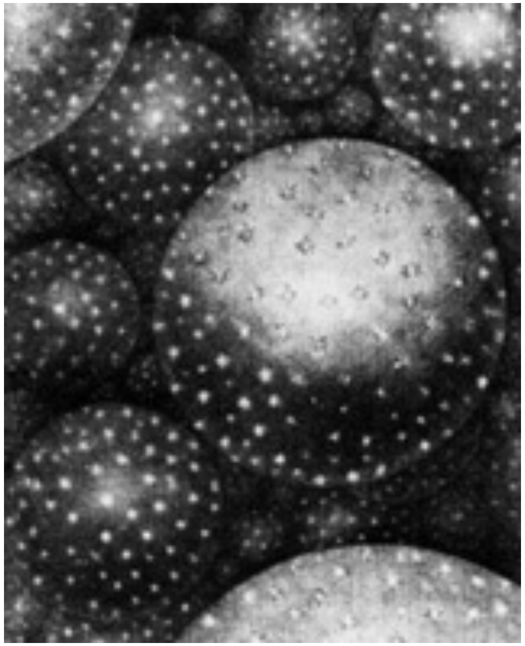
Cosmology today is a branch of physics

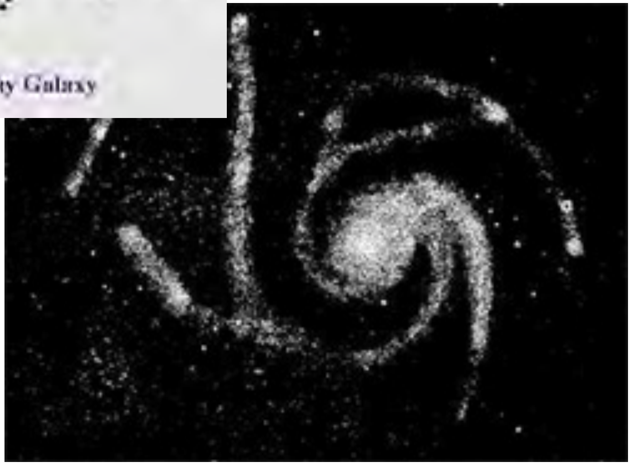




The Discovery of Galaxies

18th Century:

- The first catalogs of "nebulae": Charles Messier, William Herschel
- The pioneers of "island universes": Thomas Wright, Immanuel Kant





19th and Early 20th Centuries:

- More catalogs, first spectra, but no physical understanding

The Shapley-Curtis Debate
on the nature of faint nebulae (= galaxies)

At the meeting of the National Academy of Sciences in Washington on 26 April 1920, Harlow Shapley of Mount Wilson and Heber D. Curtis of Lick Observatory gave talks under the title "The Scale of the Universe"

☚ Shapley argued that the nebulae are parts of our own Galaxy, the only one

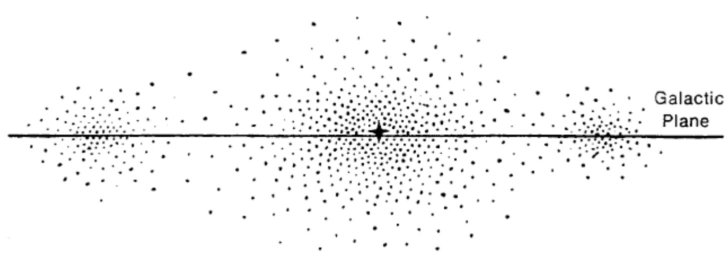


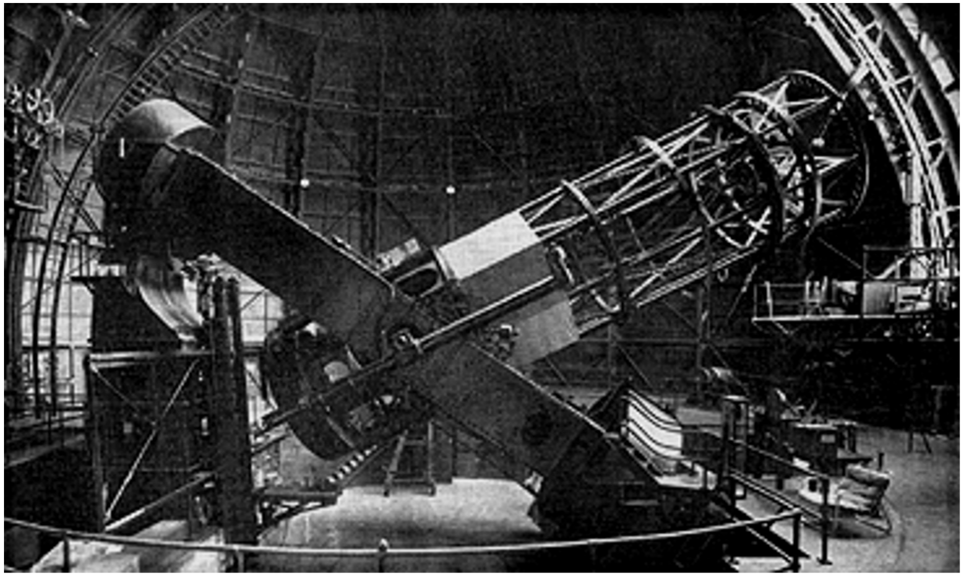
FIG. 3—Arthur Eddington's (1912) galaxy placed the Sun's position 60 LY above the center of the galactic plane.

Curtis ☛
thought that these are other galaxies, just like ours

The Resolution: Nebulae are Extragalactic

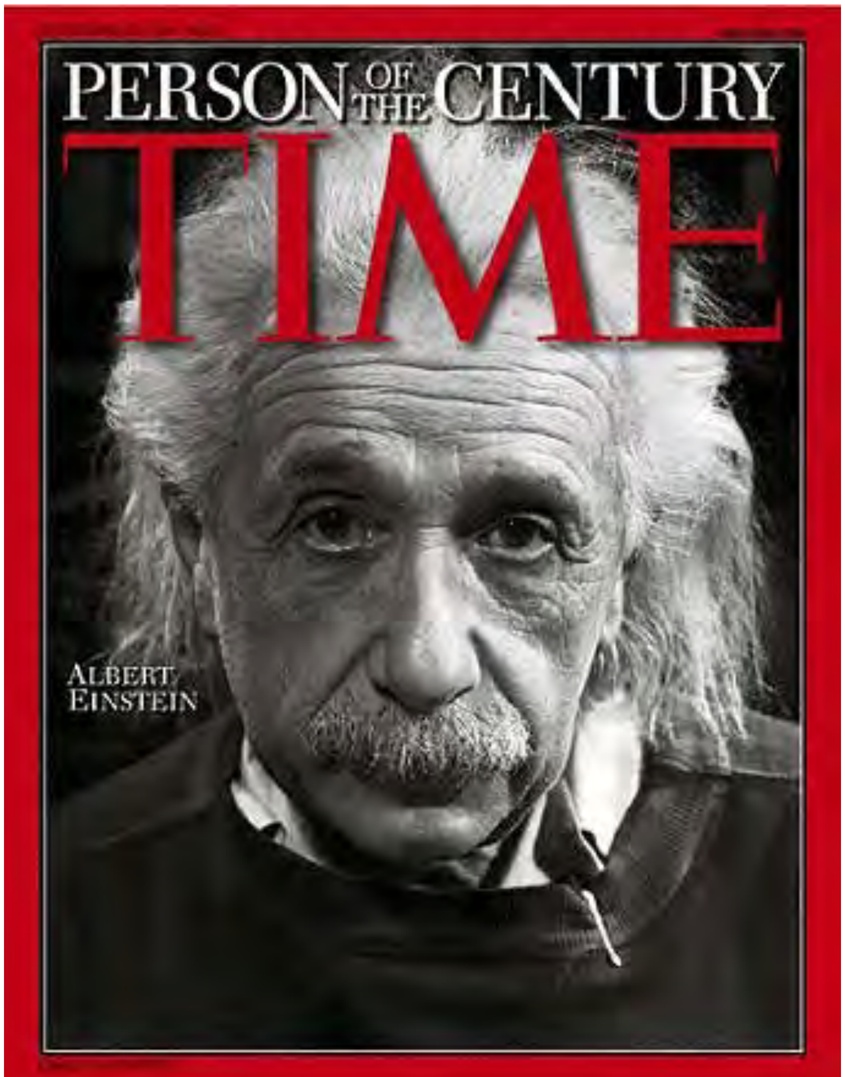
- In 1923 Hubble resolved Cepheids in M31 (Andromeda)
- A profound shift in the understanding of the scale of the universe

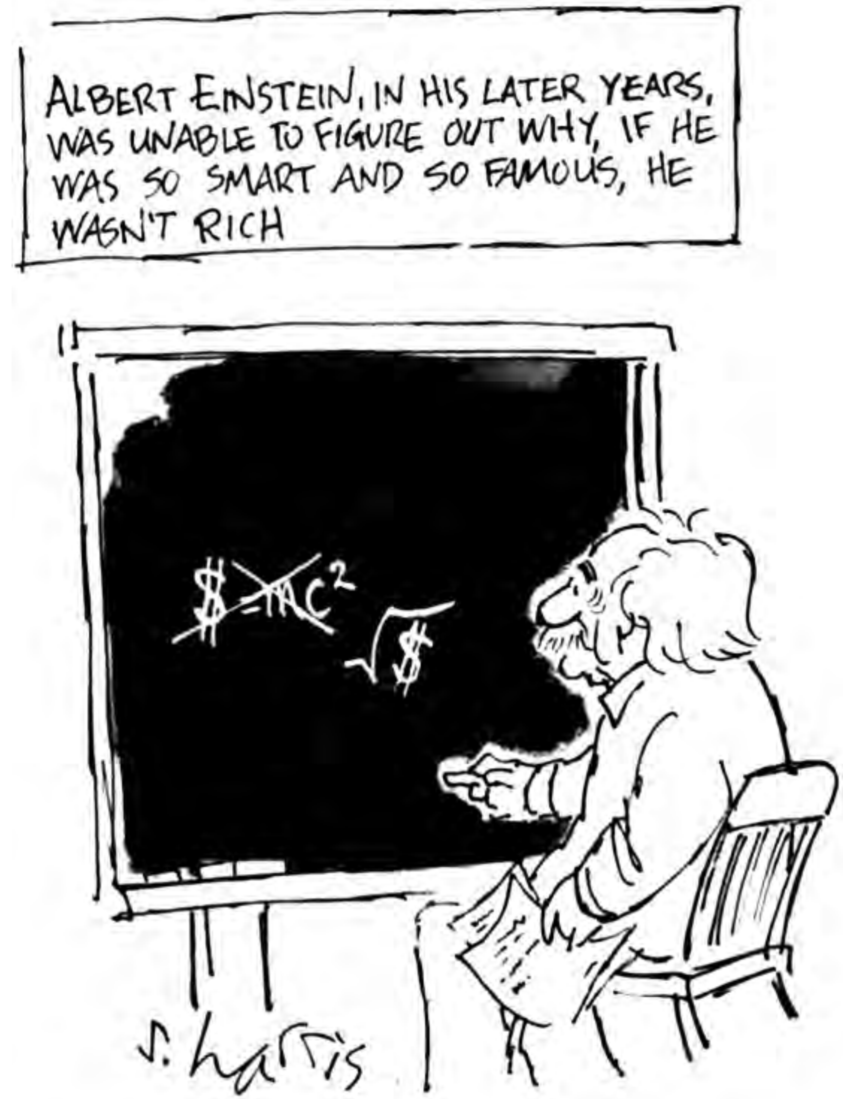
Edwin Hubble



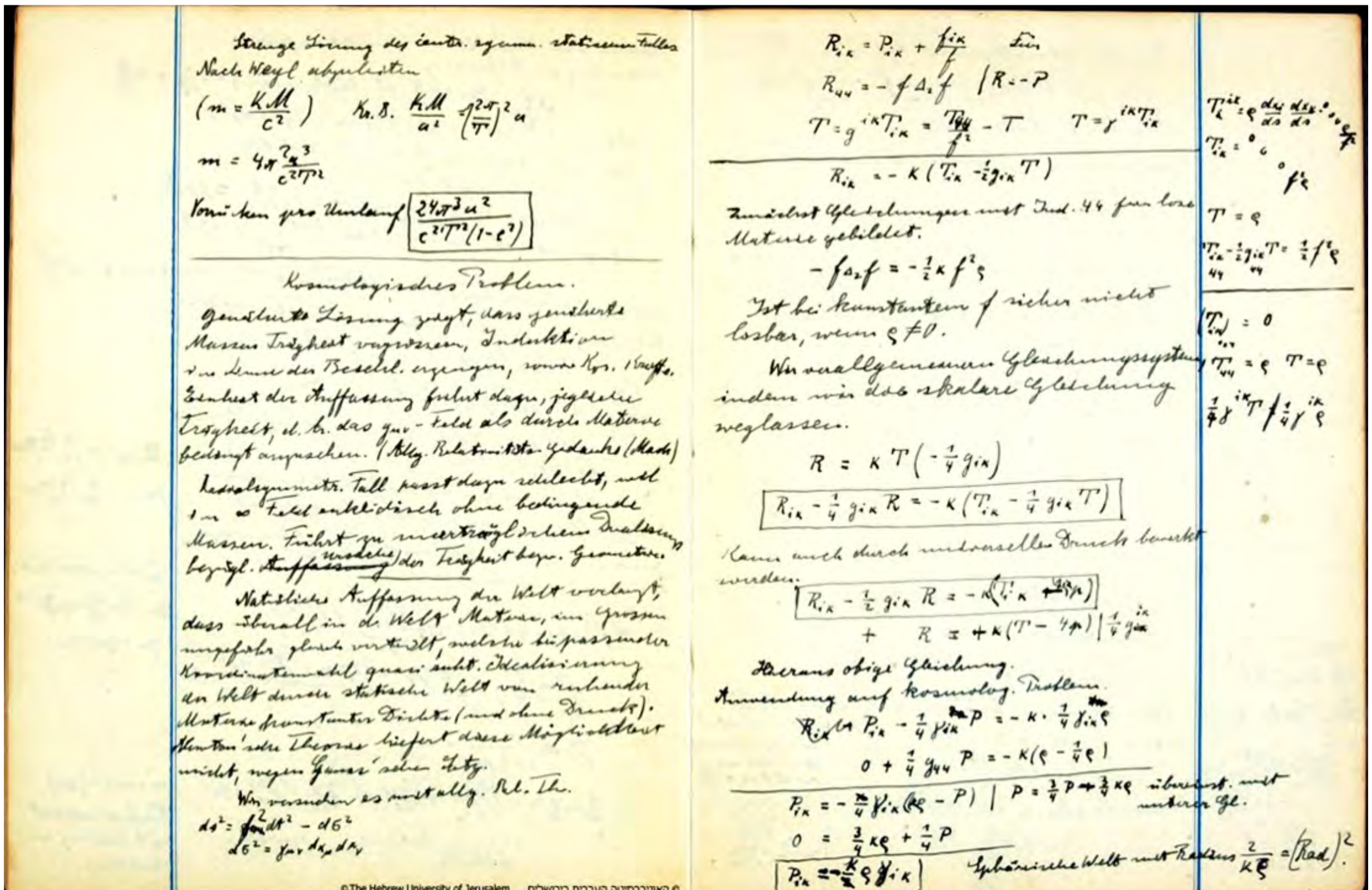
The Mt. Wilson 100-inch

Theoretical Basis of Modern Cosmology: The General Theory of Relativity (1915)





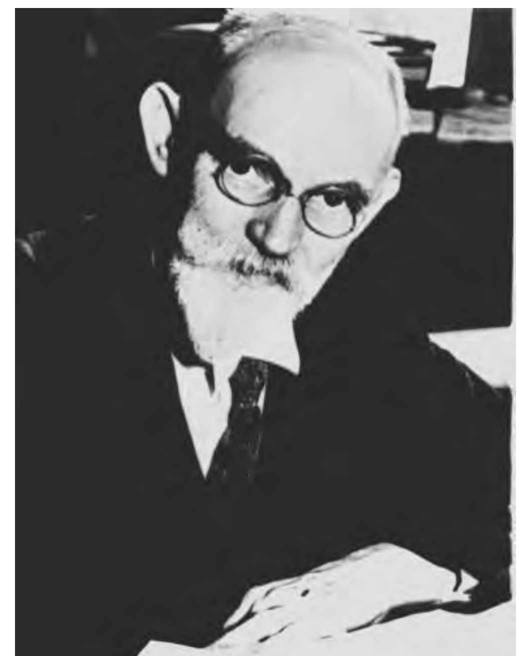
Einstein's lecture notes for a course he taught on GR in 1919. The final topic of the course was cosmology, which he had begun to investigate only two years earlier. Here he describes his methods in constructing the first mathematical model of cosmology in GR. This universe contains non-relativistic matter, stars and nebulae in agreement with the contemporary observations, but is spatially finite.



(From R. Caldwell)

The Early Cosmological Models

Einstein in 1917 constructed the first relativistic cosmological models. Thinking that the universe is static, he introduced the cosmological constant term to balance the force of gravity. This model was unstable, and he failed to predict the expansion of the universe, later calling this the biggest mistake of his career.



Willem De Sitter in 1917 also developed a similar model, but also obtained solutions of Einstein equations for a nearly empty, ***expanding*** universe.

In 1932, Einstein & De Sitter jointly developed another, simple cosmological model which bears their names.

Discovery of the Expanding Universe

Vesto Melvin Slipher
(1917)

Knut Lundmark
(1924)

And also Carl Wirtz (1923)

TABLE I.

RADIAL VELOCITIES OF TWENTY-FIVE SPIRAL NEBULÆ.

Nebula.	Vel.	Nebula.	Vel.
N.G.C. 221	− 300 km.	N.G.C. 4526	+ 580 km.
224	− 300	4565	+1100
598	− 260	4594	+1100
1023	+ 300	4649	+1090
1068	+1100	4736	+ 290
2683	+ 400	4826	+ 150
3031	− 30	5005	+ 900
3115	+ 600	5055	+ 450
3379	+ 780	5194	+ 270
3521	+ 730	5236	+ 500
3623	+ 800	5866	+ 650
3627	+ 650	7331	+ 500
4258	+ 500		

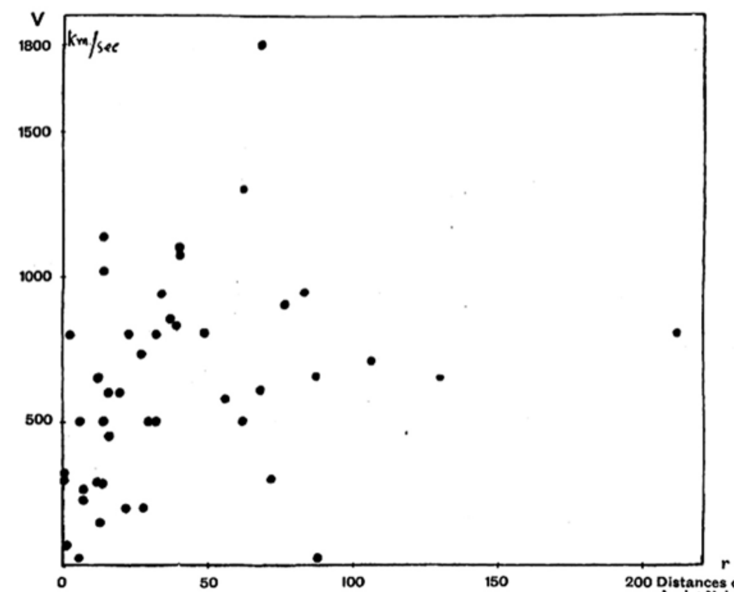
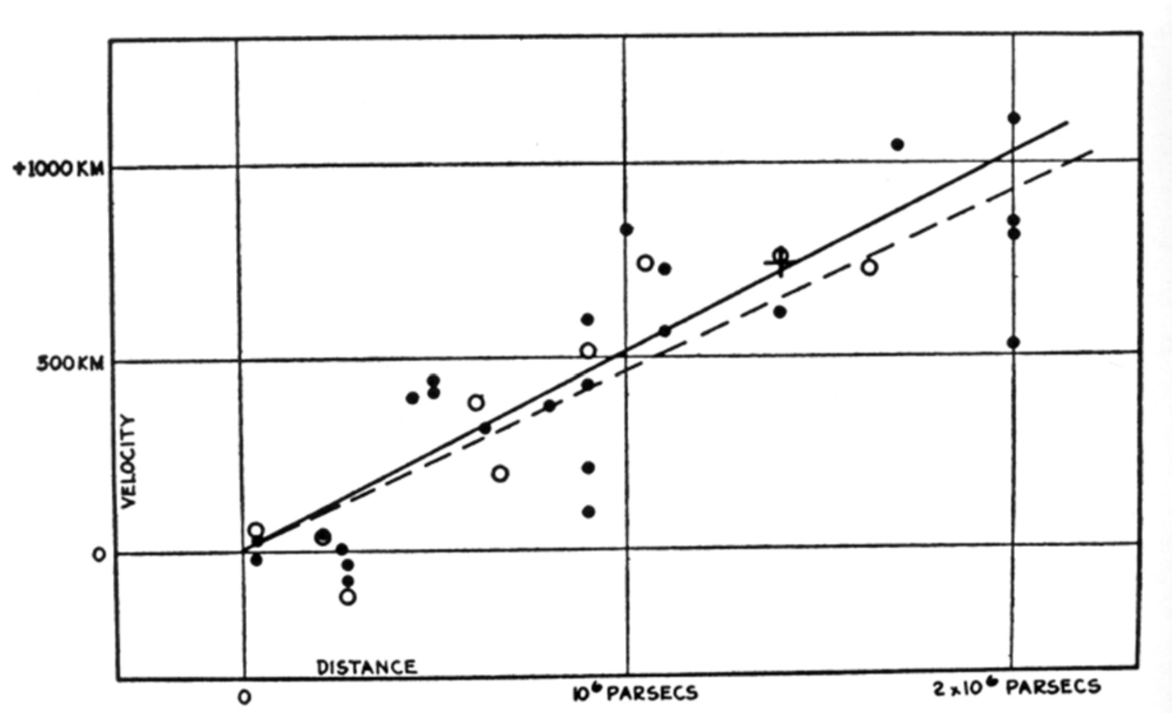


FIG. 5.—Relation between the relative distances (the unit is the distance of the Andromeda nebula) and the measured radial velocities of spiral nebulæ.

Discovery of the Expanding Universe

Edwin Hubble (1929)

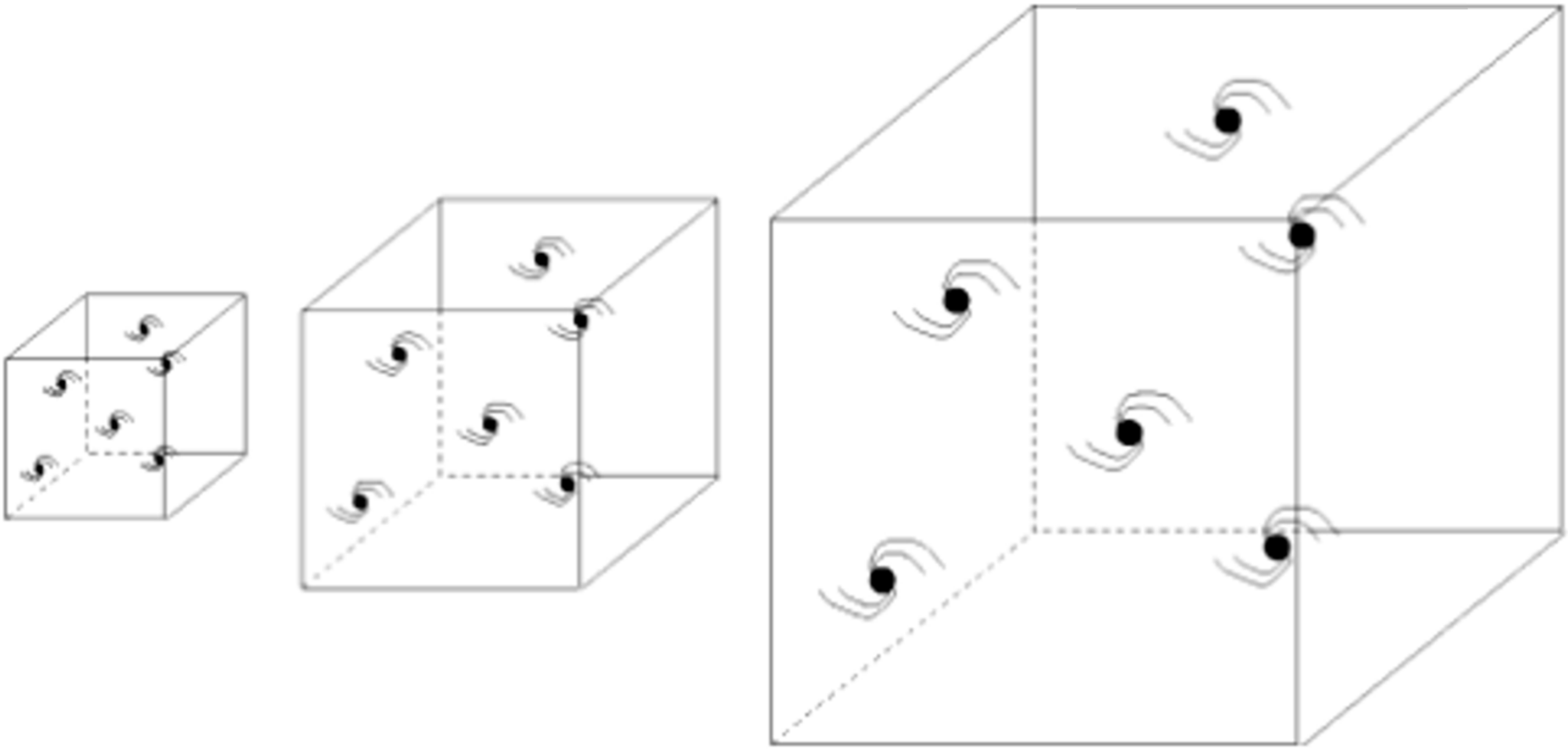


The Hubble diagram (1936)

However, Georges Lemaître came up with the same conclusion around the same time, probably independently.

The expansion of the universe was then called "the De Sitter effect"

Expansion of the Universe



The space itself expands, and carries galaxies apart

In a homogeneous, isotropic universe, there is no preferred center

Friedmann and Lemaître Models

⇦ **Alexander Friedmann**

In 1922 developed the GR-based, expanding universe model. It was not taken very seriously at the time, since the expansion of the universe has not yet been established.

Georges Lemaître ⇨

In 1927 independently developed cosmological models like Friedmann's. In 1933, he "ran the film backwards" to a hot, dense, early state of the universe he called "the cosmic egg". This early prediction of the Big Bang was largely ignored.

Development of Relativistic Cosmology


Edward Milne


Arthur Eddington


Howard Robertson


Geoffrey Walker

- E. Milne in 1933 developed “kinematical relativity”, and a cosmological model based on the special relativity
- A. S. Eddington promoted and developed relativistic models, and began the interface of quantum theory and cosmology
- H. Robertson and G. Walker in 1930’s developed a sounder mathematical basis for GR cosmology and the eponymous metric

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

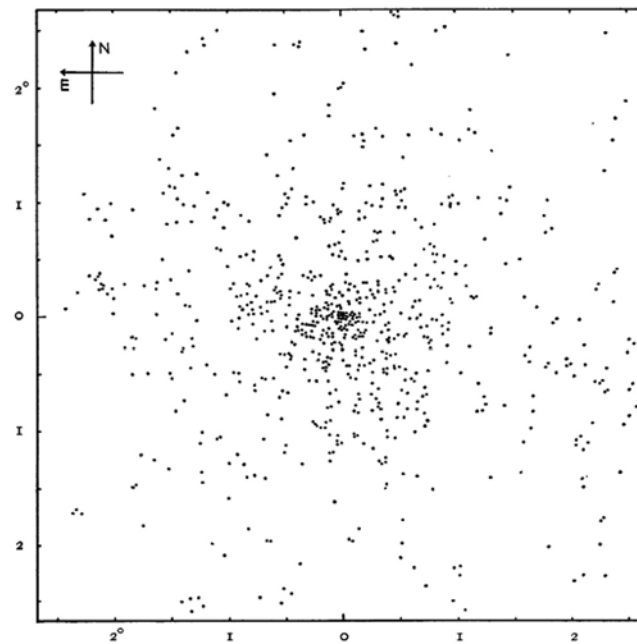
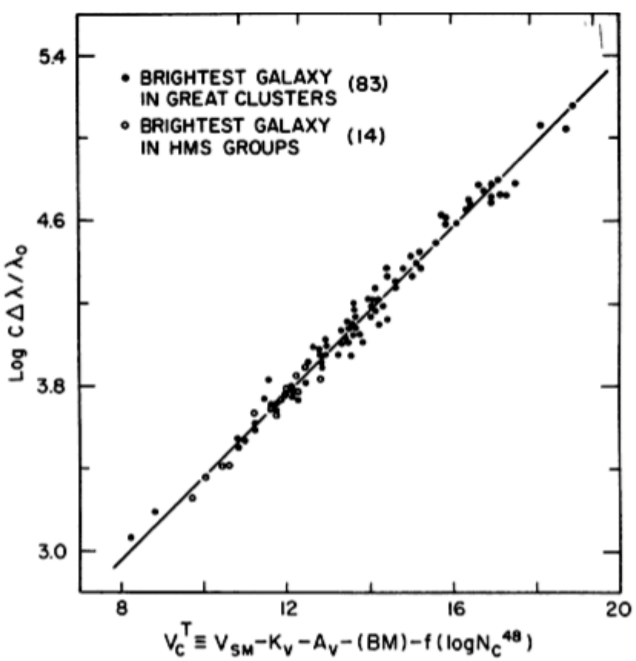


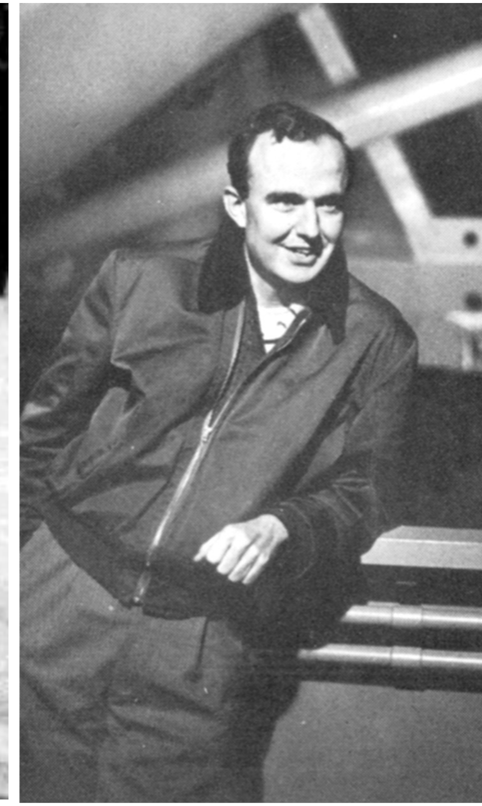
FIG. 3.—The Coma cluster of nebulae

- 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" [H_0 and q_0]
- Hubble diagram of the brightest cluster ellipticals as the primary tool
- Doomed by galaxy evolution



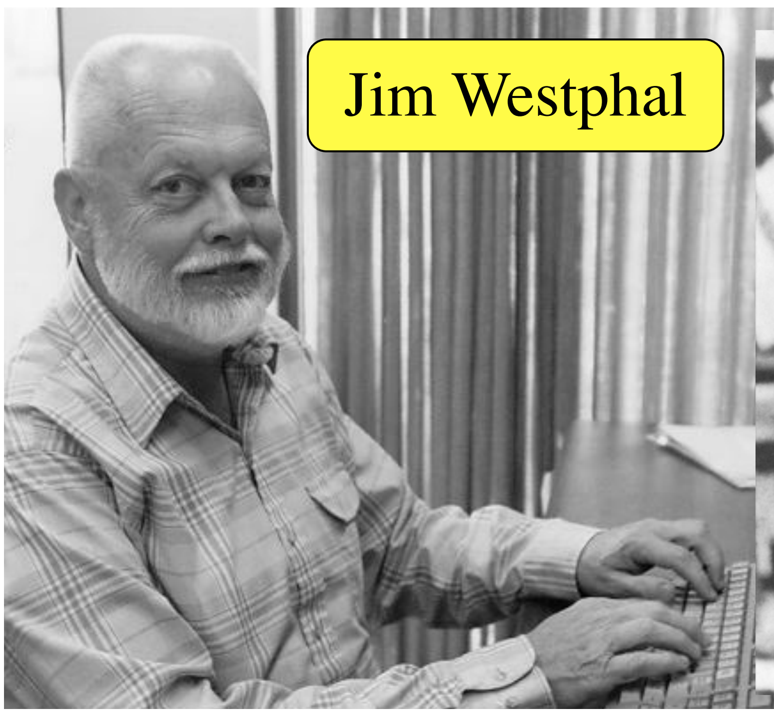


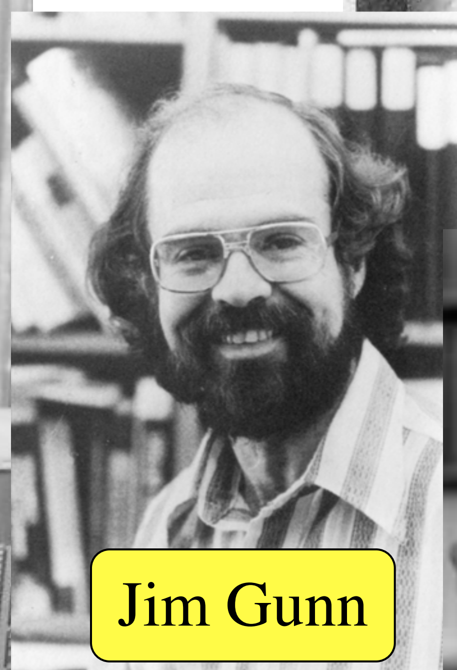
THE ABILITY OF THE 200-INCH TELESCOPE TO DISCRIMINATE BETWEEN SELECTED WORLD MODELS

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





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 - "αβγ" theory), even though the synthesis stopped at He…

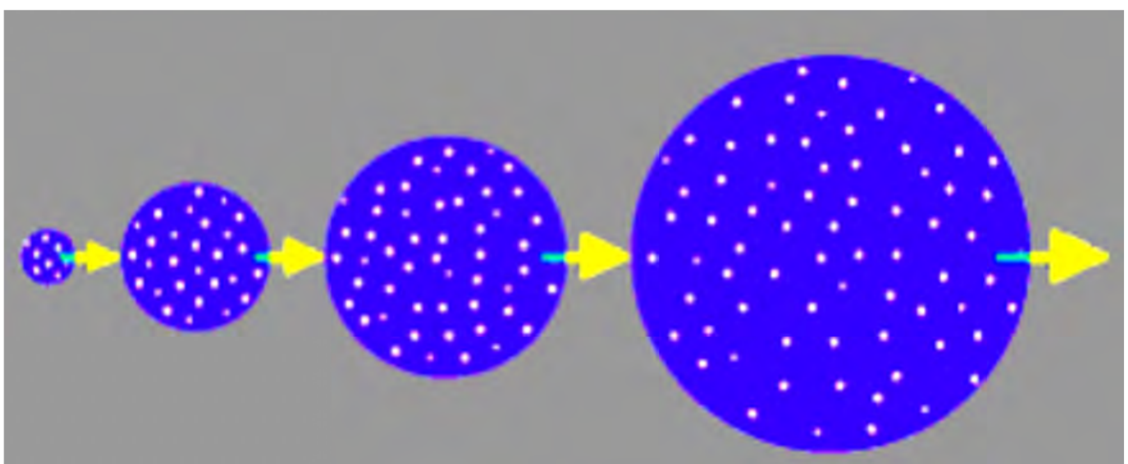
They also predicted that **the afterglow of this hot stage will be now present in the universe as a thermal background with T ~ 5 K**

The Steady State Cosmology (1948)

Thomas Gold, Hemann Bondi, Fred Hoyle

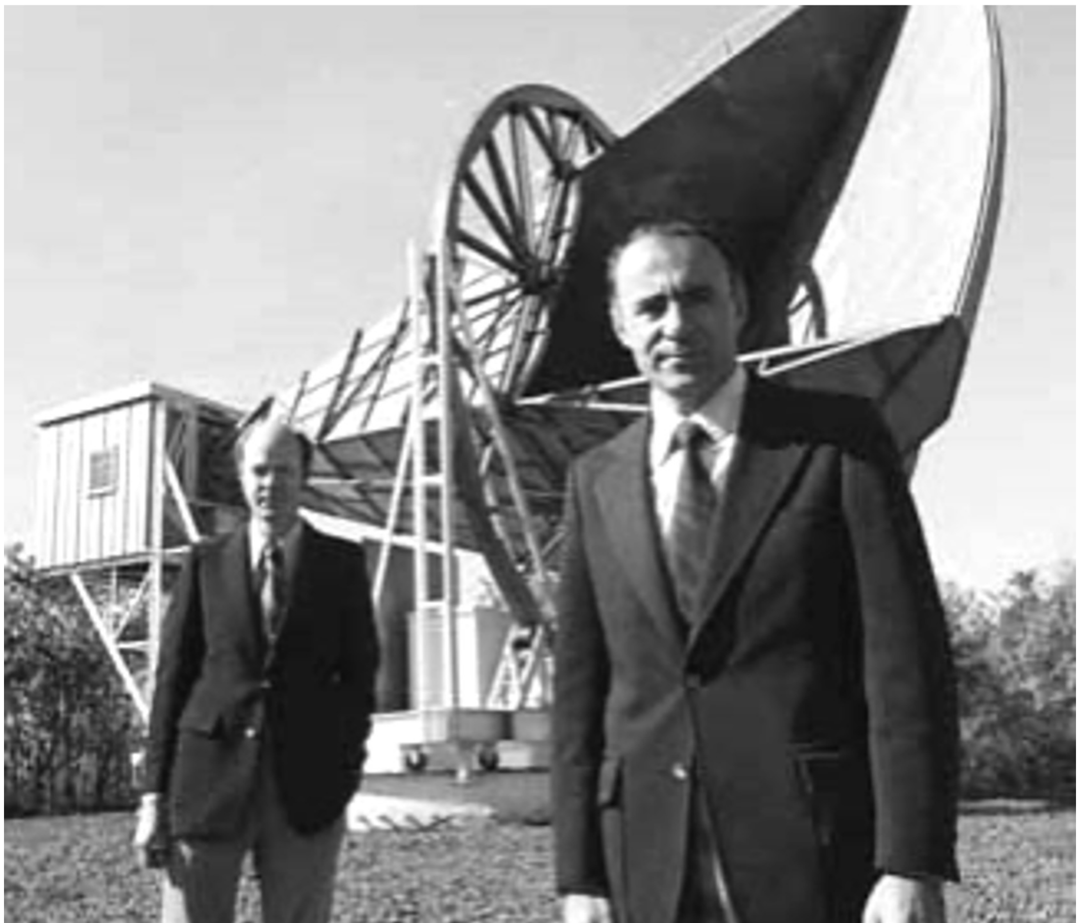
Proposed as an alternative to the Big Bang

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

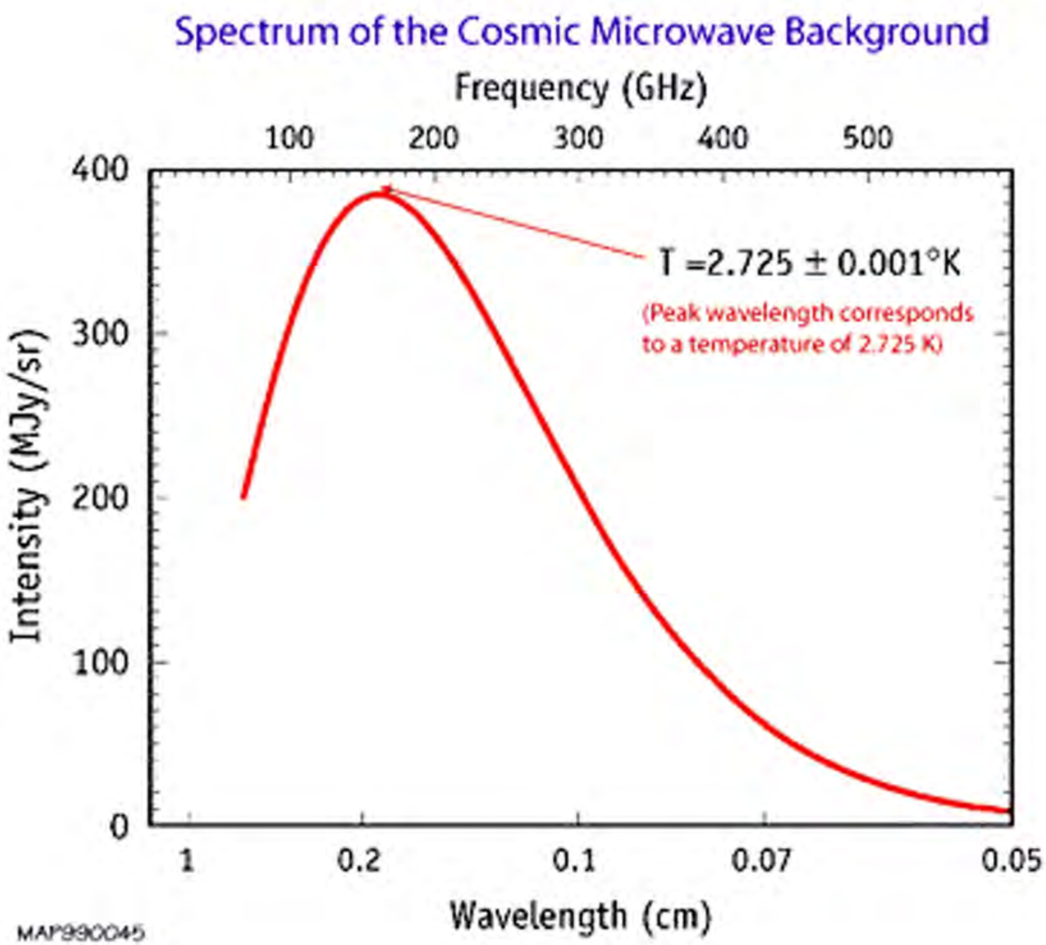
Discovery of the Cosmic Microwave Background (CMBR): A Direct Evidence for the Big Bang



Arno Penzias &
Robert Wilson (1965)

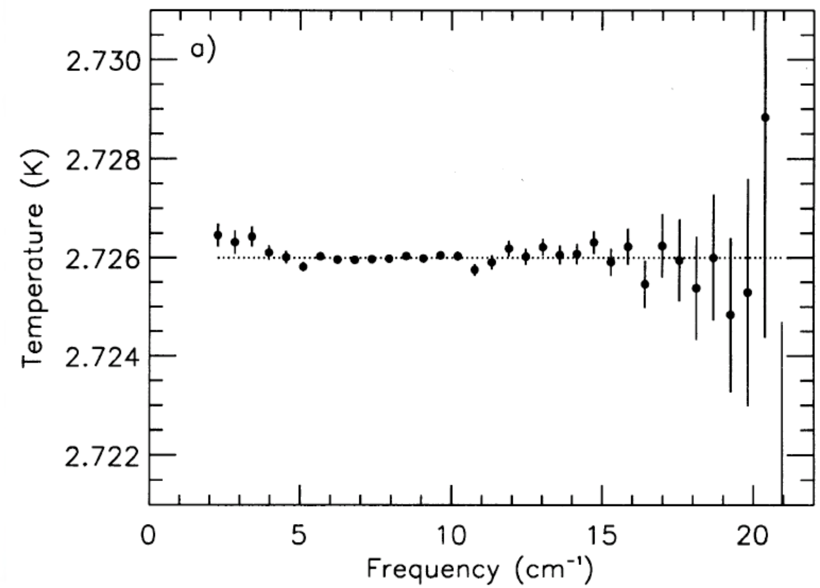
Nobel Prize, 1978

The CMBR Spectrum: A Nearly Perfect Blackbody



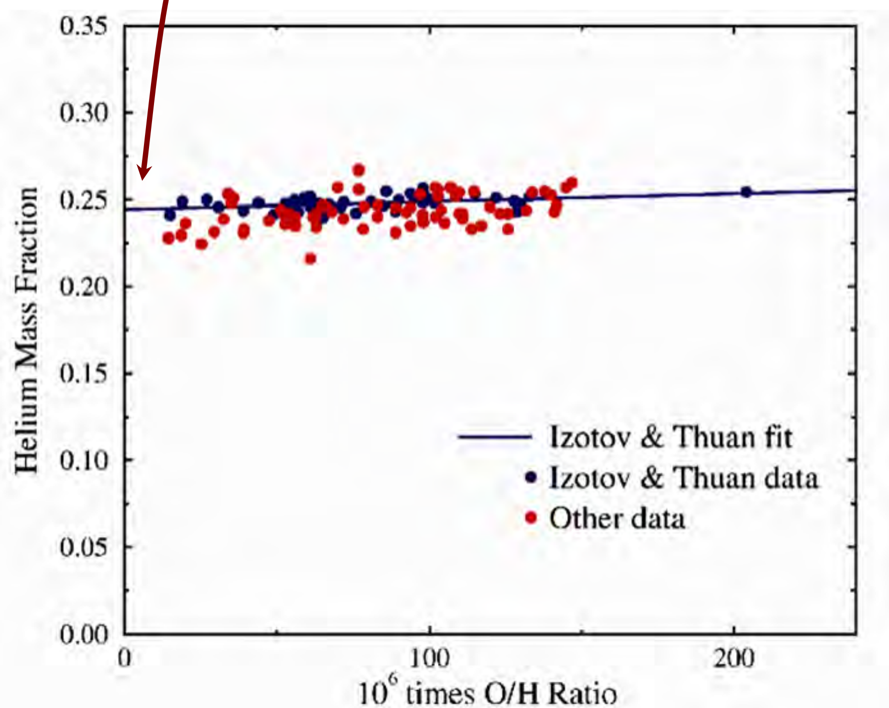
COBE, WMAP missions

Residuals

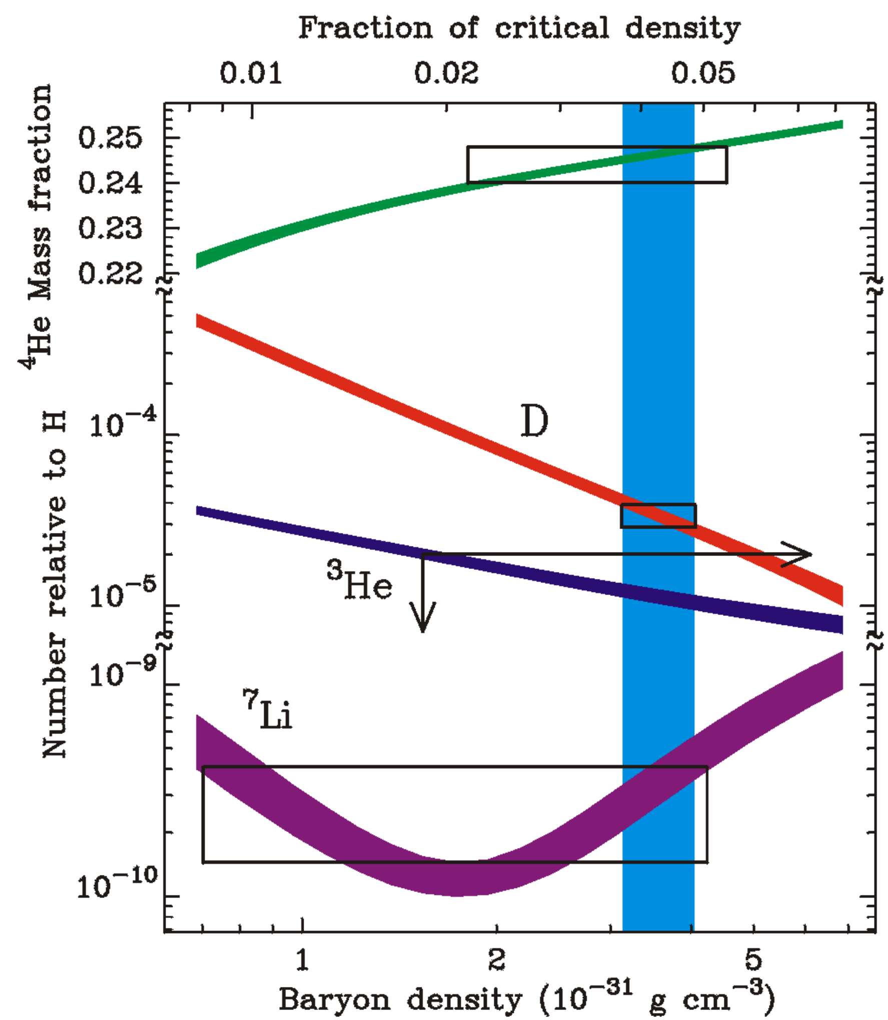


Big Bang Nucleosynthesis Predicts Correct Abundances of Light Elements

Intercept gives the primordial He abundance



Oxygen produced in stars →

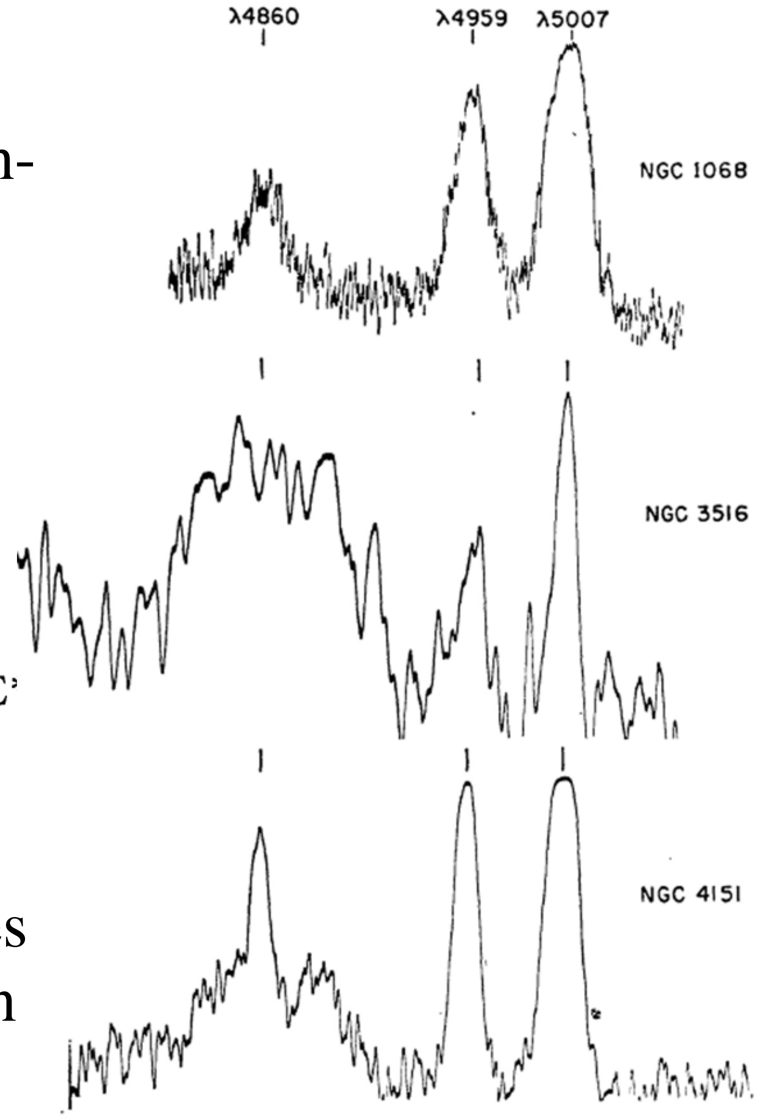


Discovery of Active Galactic Nuclei: Carl Seyfert (1943)

Broad and high-ionization emission lines, bright and compact nuclei…

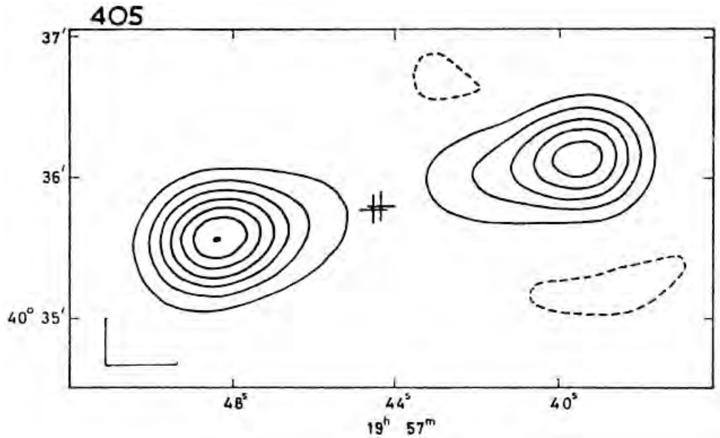
NUCLEAR EMISSION IN SPIRAL NEBULAE*

CARL K. SEYFERT†



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

Discovery of Powerful Radio Galaxies



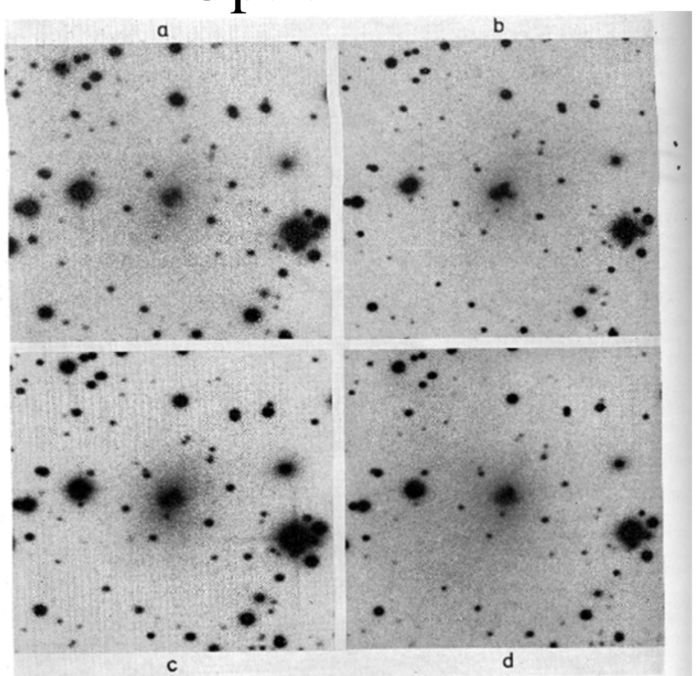
⬅ Cygnus A = 3C405, early radio map

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

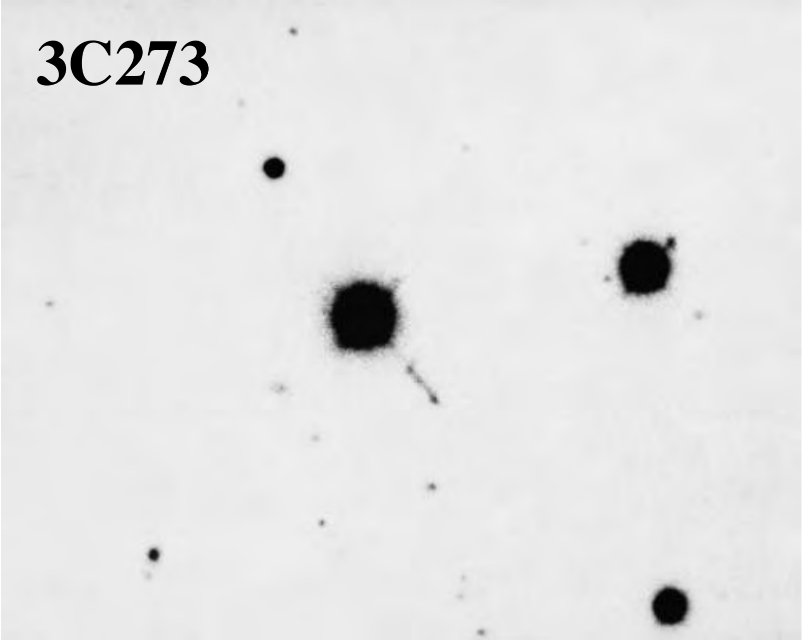
Optical ID



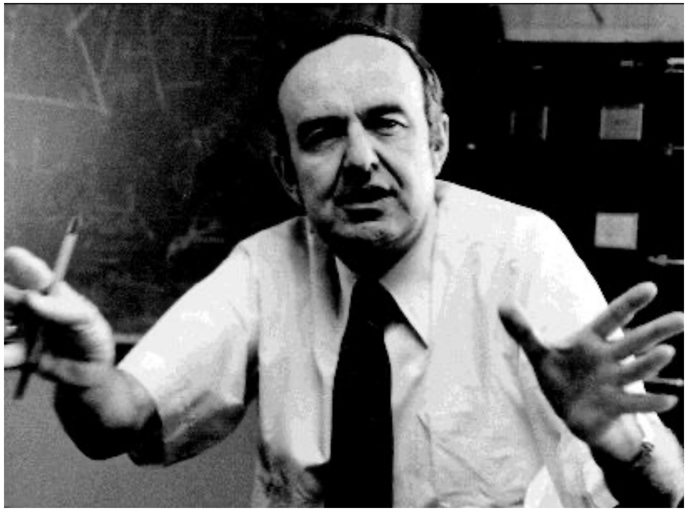
Walter Baade

Rudolph Minkowski

Discovery of Quasars (1963)

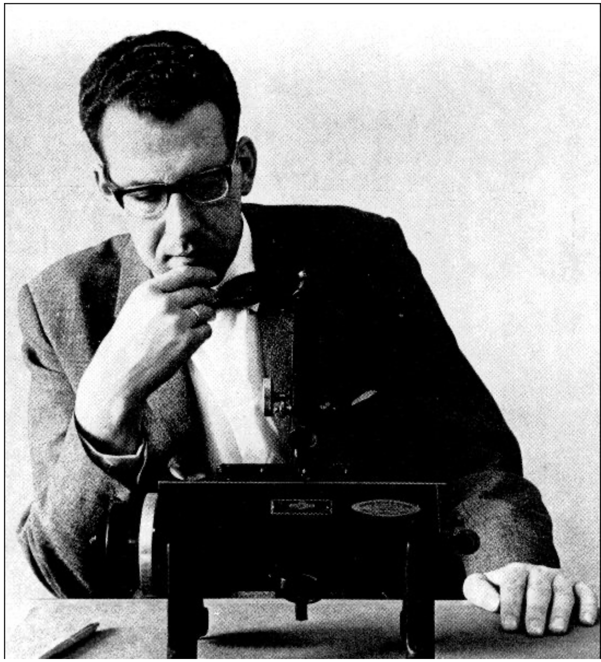


Cyril Hazard ➡ got the precise radio position

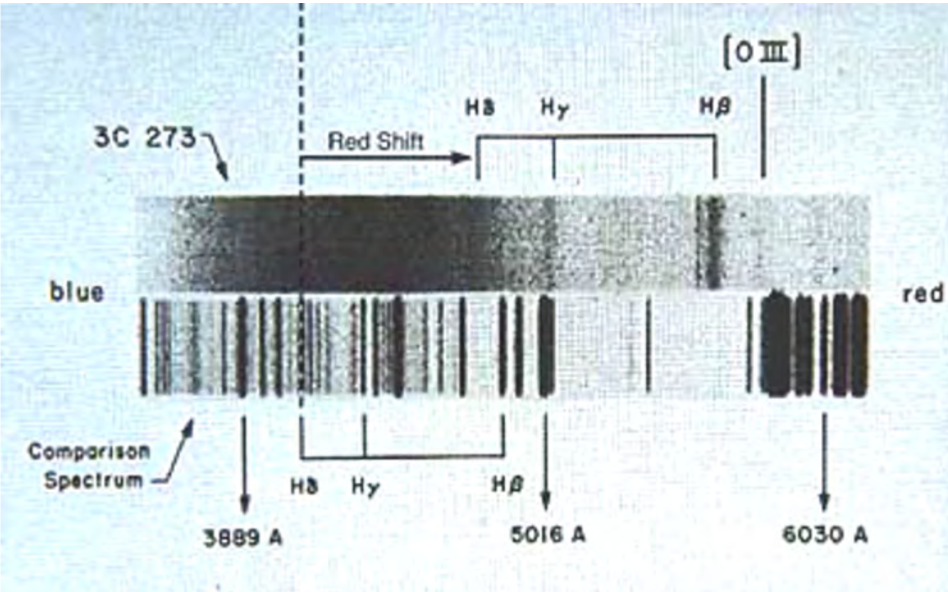


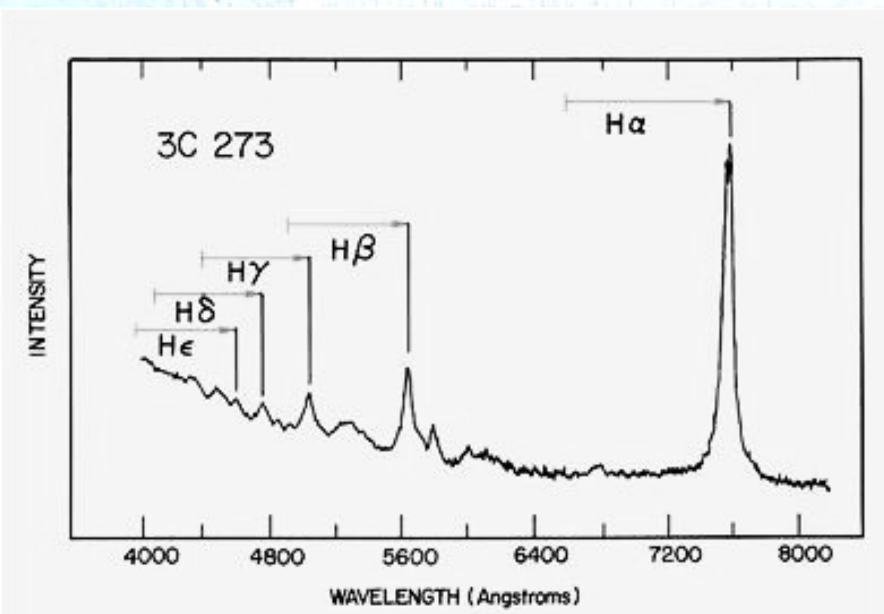
⬅ Allan Sandage got the optical ID

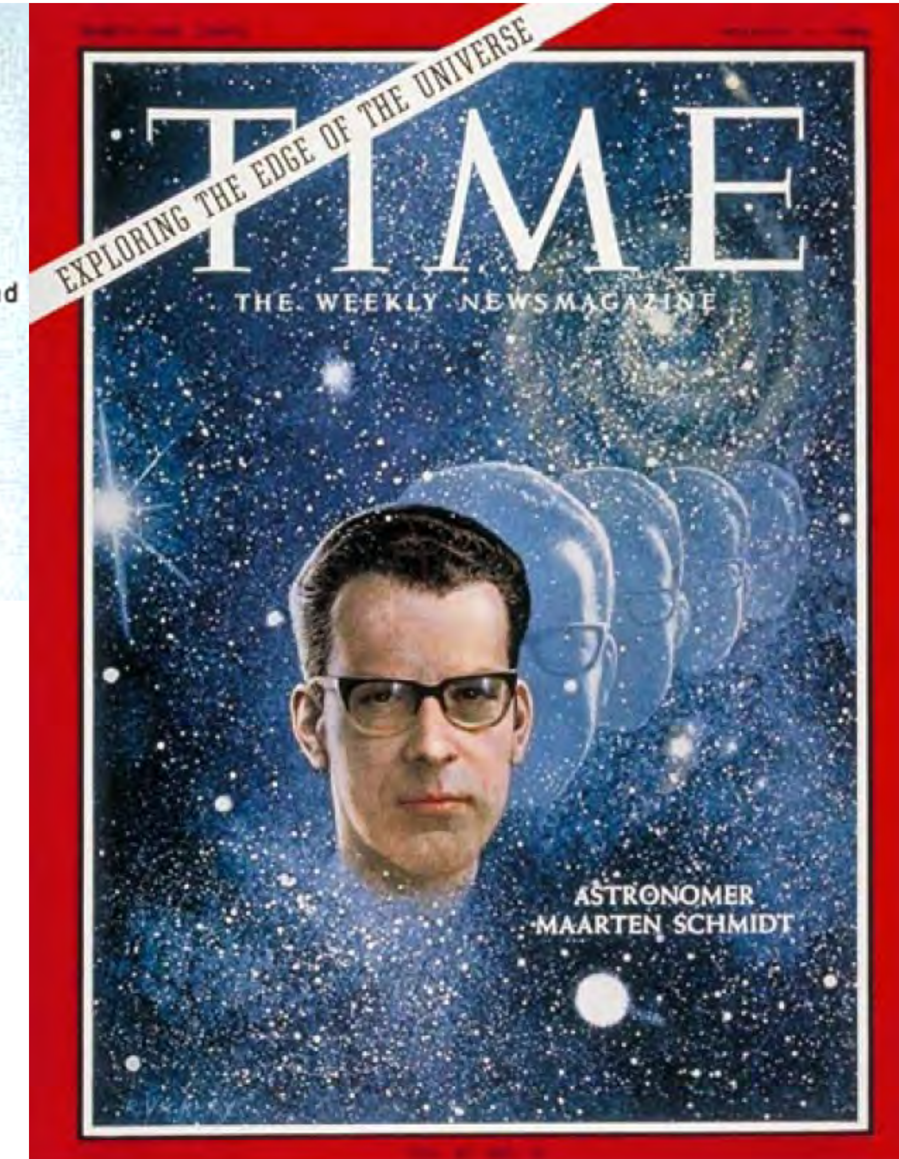
Maarten Schmidt ➡ figured out the spectrum and the redshift



Discovery of Quasars (1963)







Discovery of the Large Scale Structure

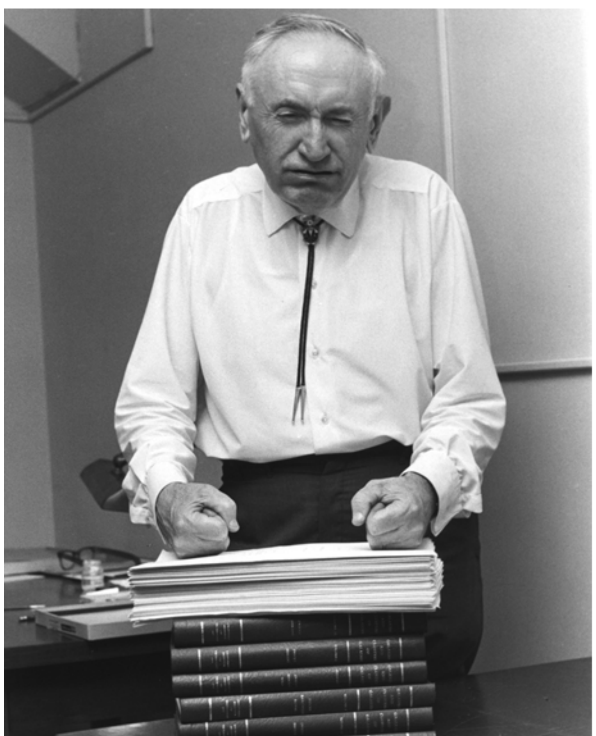
Universe was assumed to be homogeneous on scales larger than galaxies, until …

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



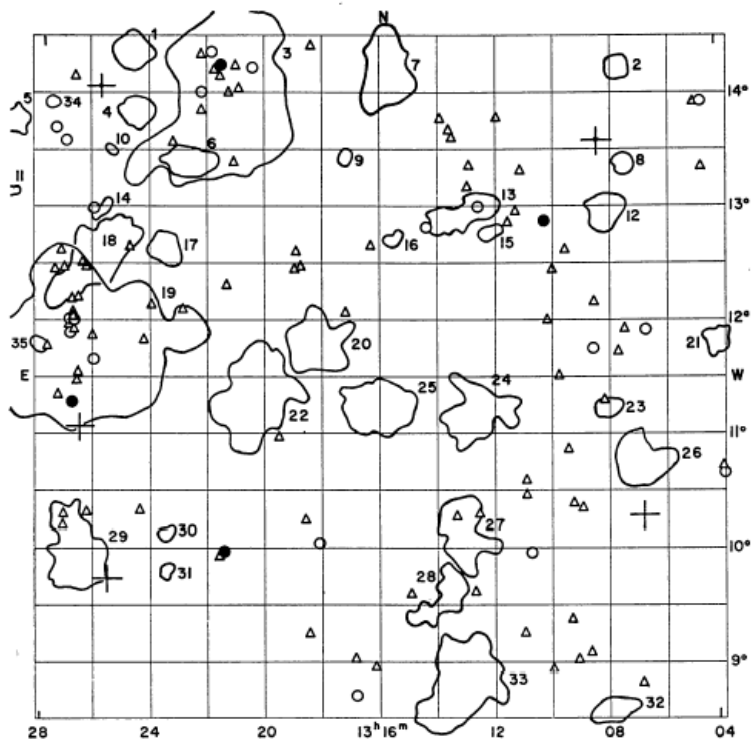
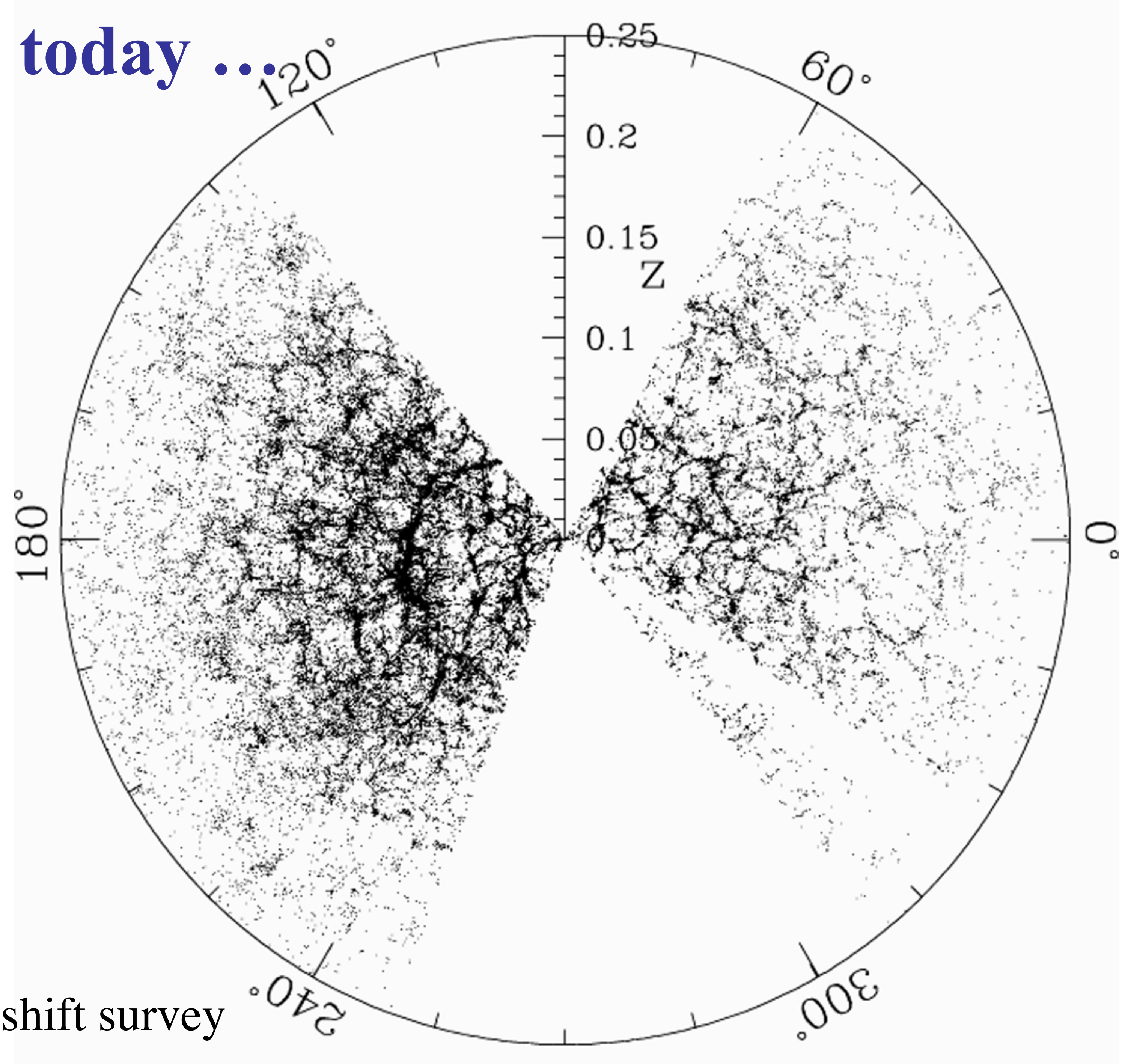


FIGURE 4

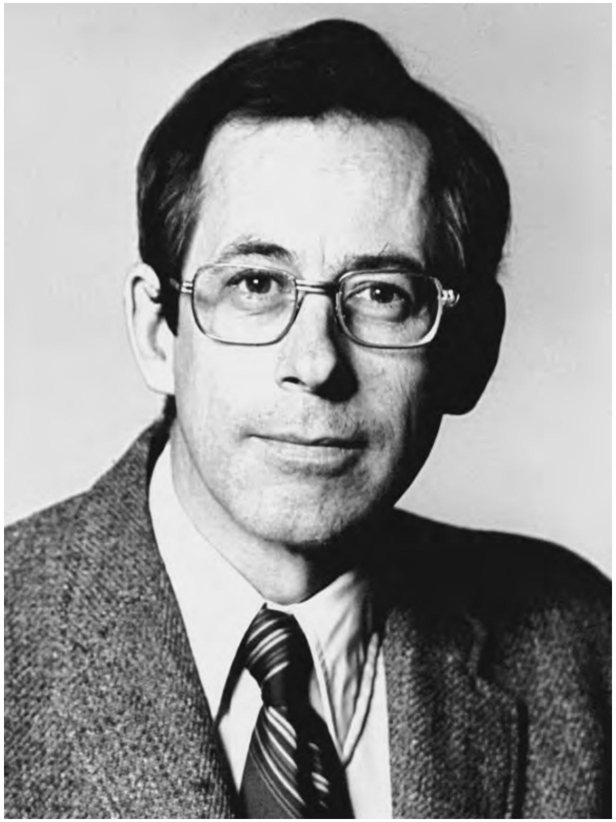
Zwicky's map of the overdensities in galaxy counts

… and today …

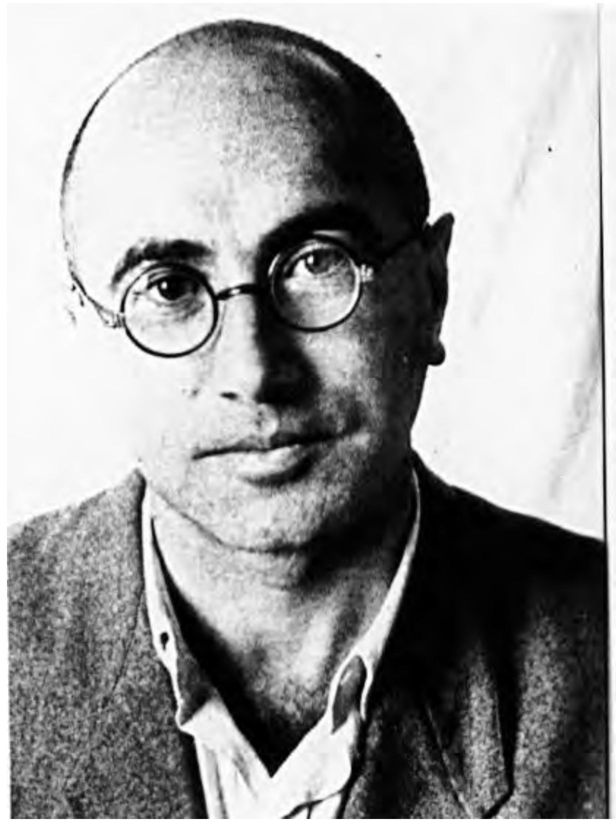


SDSS redshift survey

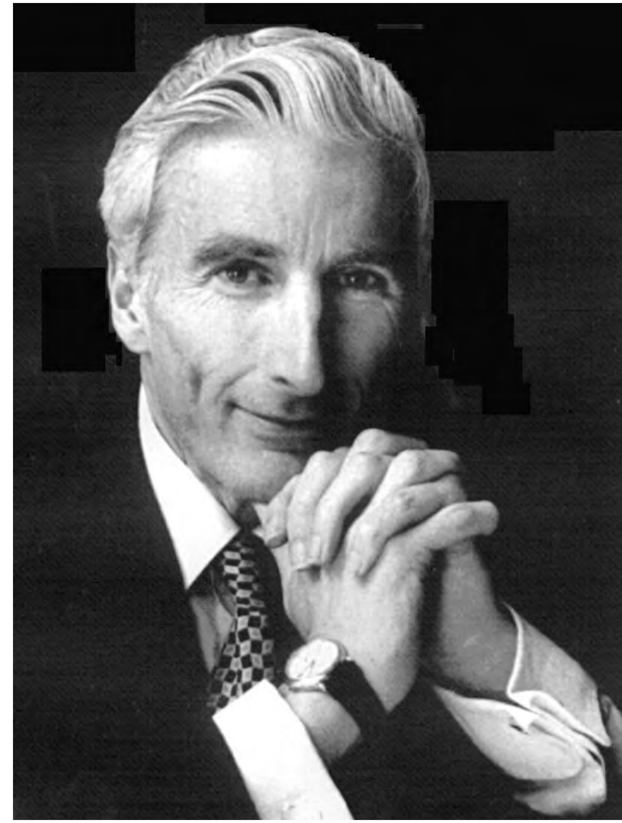
Development of Theoretical Models of Galaxy and Structure Formation: 1970's - 1990's



Jim Peebles



Yakov Zel'dovich

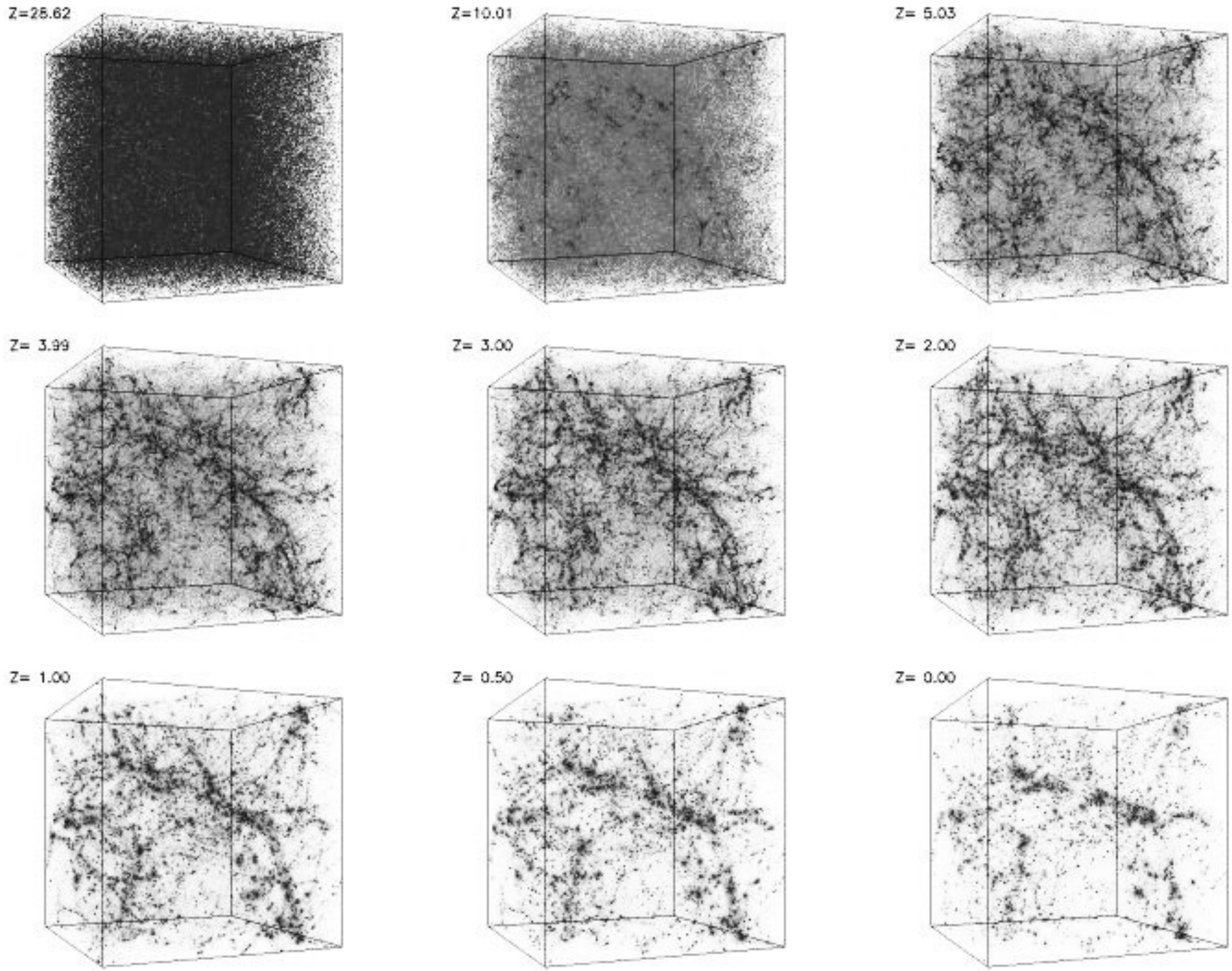


Martin Rees

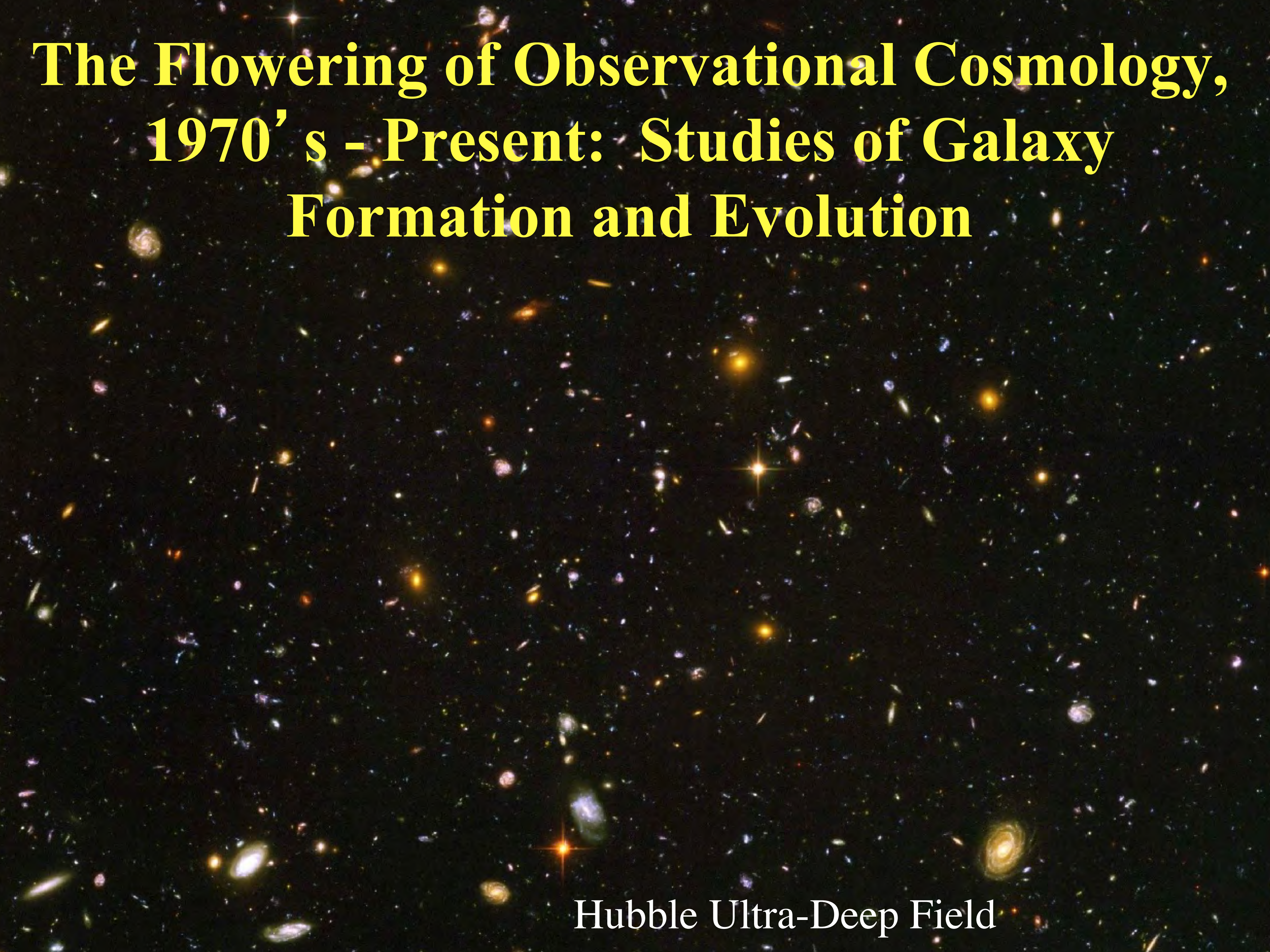
They established that the **dark matter** played a crucial role in these processes

Numerical Simulations of Structure and Galaxy Formation: 1970’s - Present

A “cosmic cube” simulation by A. Kravtsov



The Flowering of Observational Cosmology, 1970's - Present: Studies of Galaxy Formation and Evolution



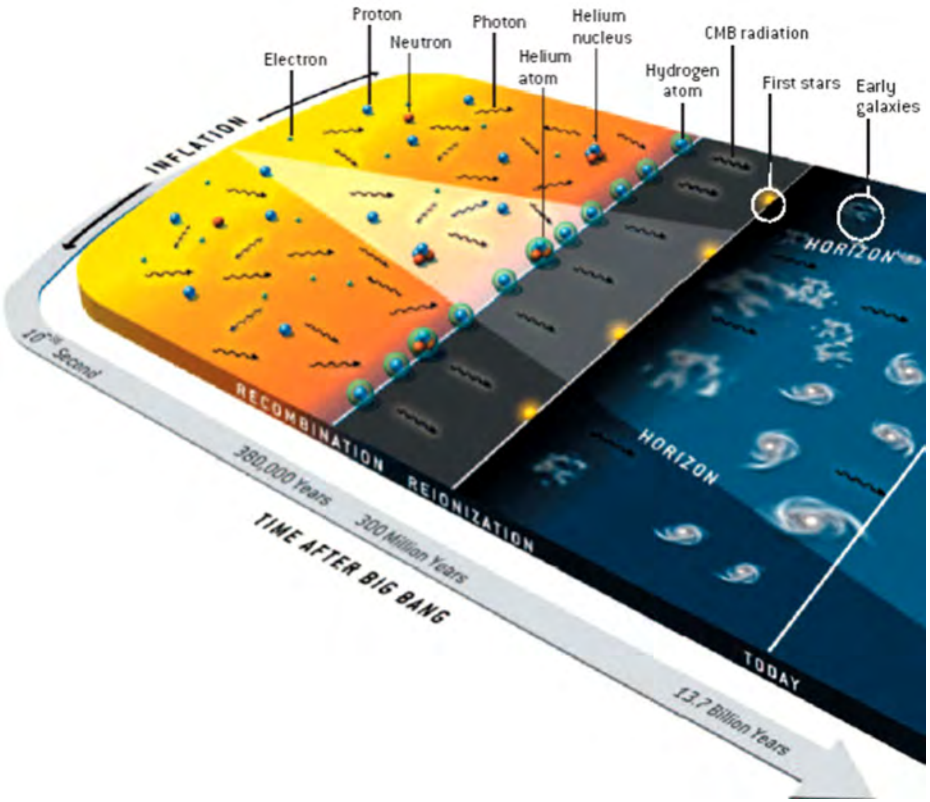
Hubble Ultra-Deep Field

Inflation: A Key Theoretical Idea

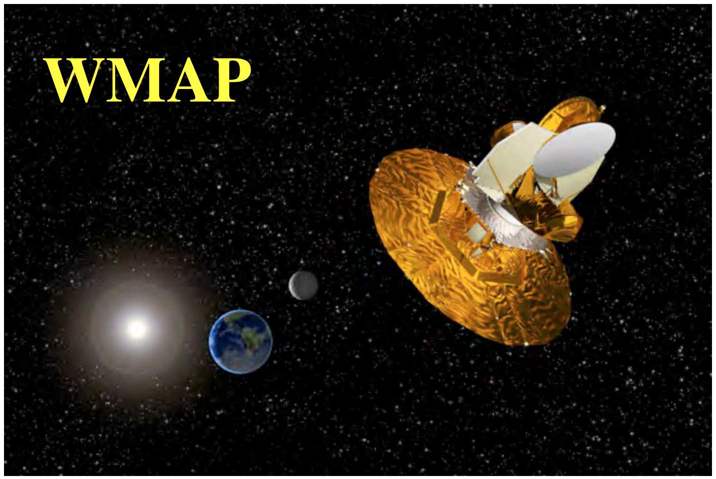
- Alan Guth (1980); precursors: D. Kazanas, A. Starobinsky
- Explains a number of fundamental cosmological problems: flatness, horizon, origin of structure, absence of topological defects…
- Chaotic inflation: Andrei Linde - is our universe just a bubble in a *much* larger megaverse?

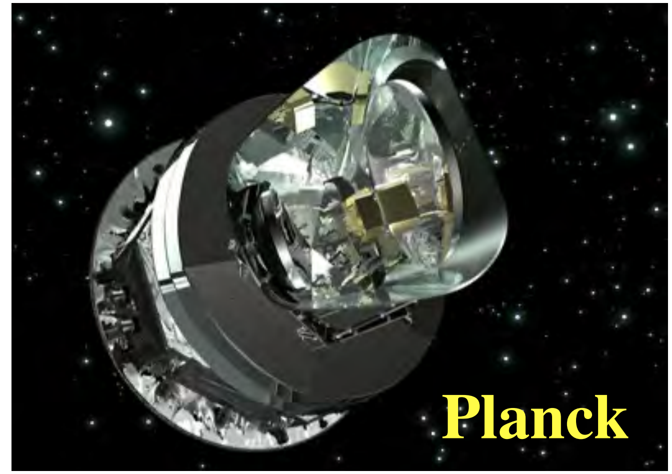

A. Guth


A. Linde

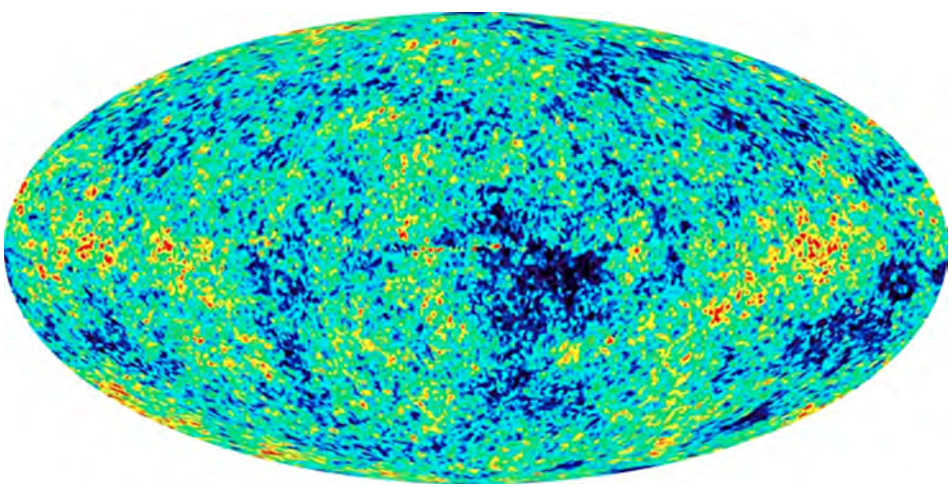


Precision Cosmology From CMB (~1998 – Present)

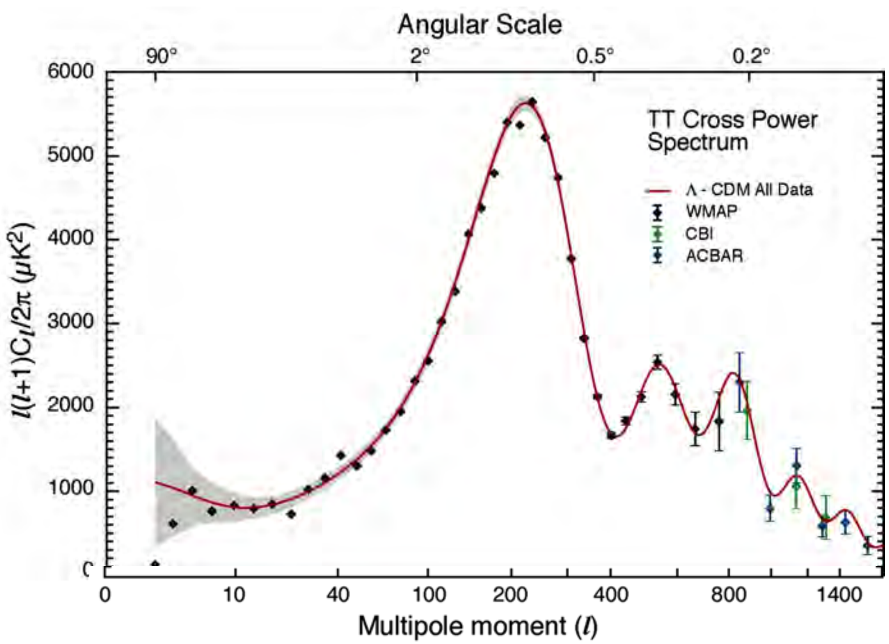




Temperature Fluctuations



Angular Power Spectrum



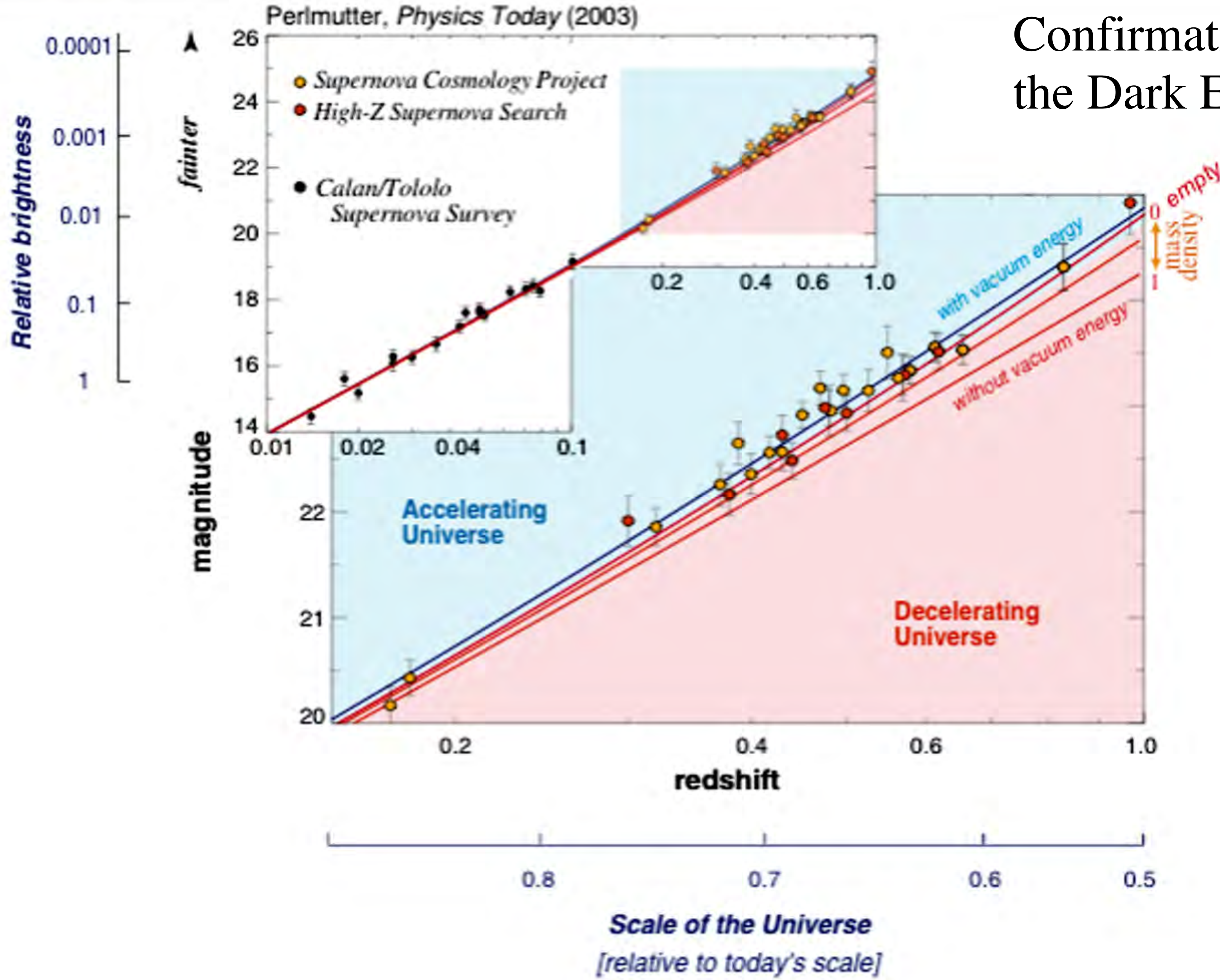
Precision Cosmology From CMB

Planck Collaboration (2018)

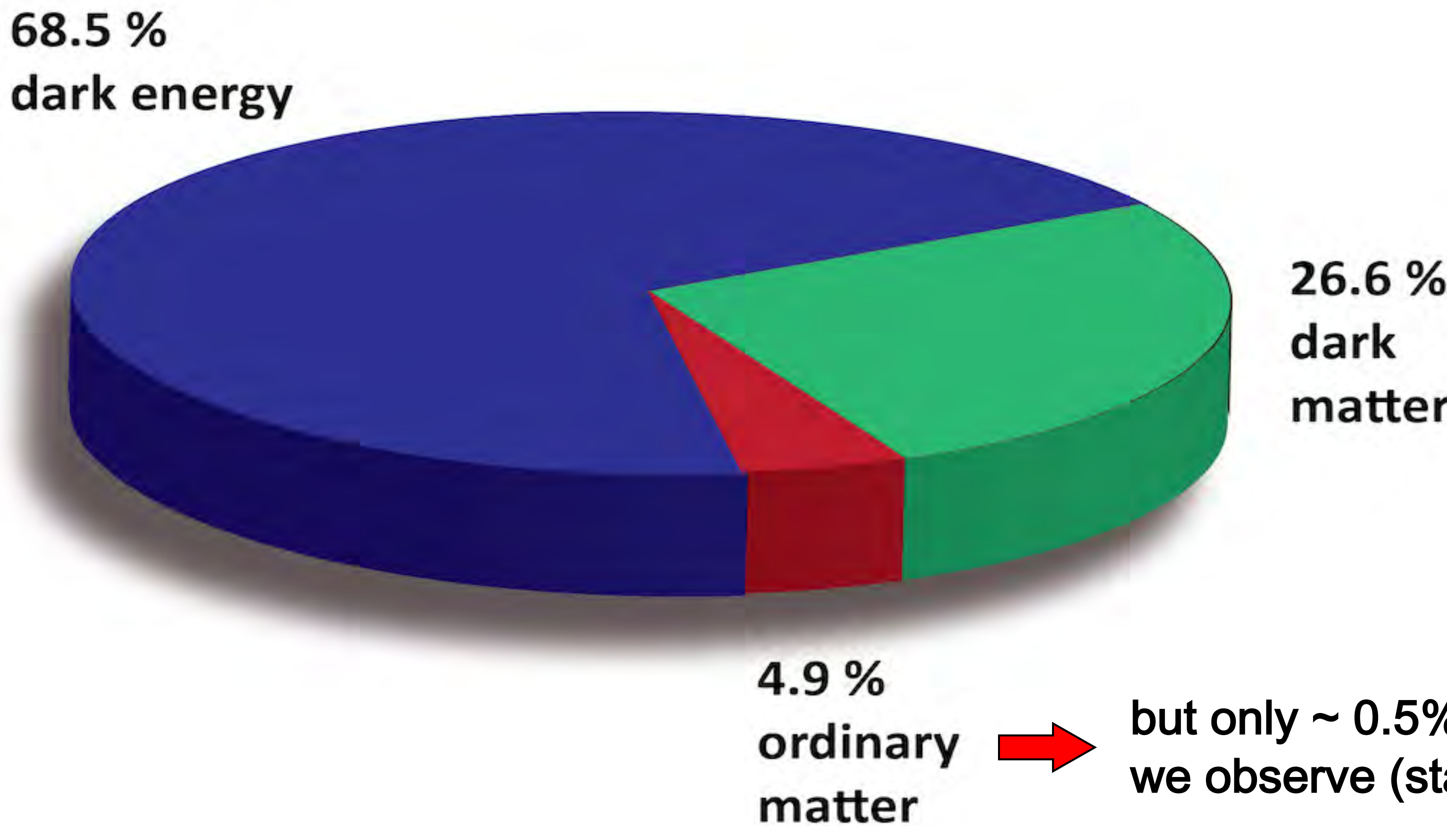
Parameter	Plik best fit	Plik [1]	CamSpec [2]	Combined
$\Omega_b h^2$	0.022383	0.02237 ± 0.00015	0.02229 ± 0.00015	0.02233 ± 0.00015
$\Omega_c h^2$	0.12011	0.1200 ± 0.0012	0.1197 ± 0.0012	0.1198 ± 0.0012
$100\theta_{MC}$	1.040909	1.04092 ± 0.00031	1.04087 ± 0.00031	1.04089 ± 0.00031
τ	0.0543	0.0544 ± 0.0073	$0.0536^{+0.0069}_{-0.0077}$	0.0540 ± 0.0074
$\ln(10^{10} A_s)$	3.0448	3.044 ± 0.014	3.041 ± 0.015	3.043 ± 0.014
n_s	0.96605	0.9649 ± 0.0042	0.9656 ± 0.0042	0.9652 ± 0.0042
$\Omega_m h^2$	0.14314	0.1430 ± 0.0011	0.1426 ± 0.0011	0.1428 ± 0.0011
H_0 [$\mathrm{km\,s^{-1}\,Mpc^{-1}}$] .	67.32	67.36 ± 0.54	67.39 ± 0.54	67.37 ± 0.54
Ω_m	0.3158	0.3153 ± 0.0073	0.3142 ± 0.0074	0.3147 ± 0.0074
Age [Gyr]	13.7971	13.797 ± 0.023	13.805 ± 0.023	13.801 ± 0.024
σ_8	0.8120	0.8111 ± 0.0060	0.8091 ± 0.0060	0.8101 ± 0.0061
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$	0.8331	0.832 ± 0.013	0.828 ± 0.013	0.830 ± 0.013
z_{re}	7.68	7.67 ± 0.73	7.61 ± 0.75	7.64 ± 0.74
$100\theta_*$	1.041085	1.04110 ± 0.00031	1.04106 ± 0.00031	1.04108 ± 0.00031
r_{drag} [Mpc]	147.049	147.09 ± 0.26	147.26 ± 0.28	147.18 ± 0.29

Supernova Hubble Diagram

Confirmation of the Dark Energy



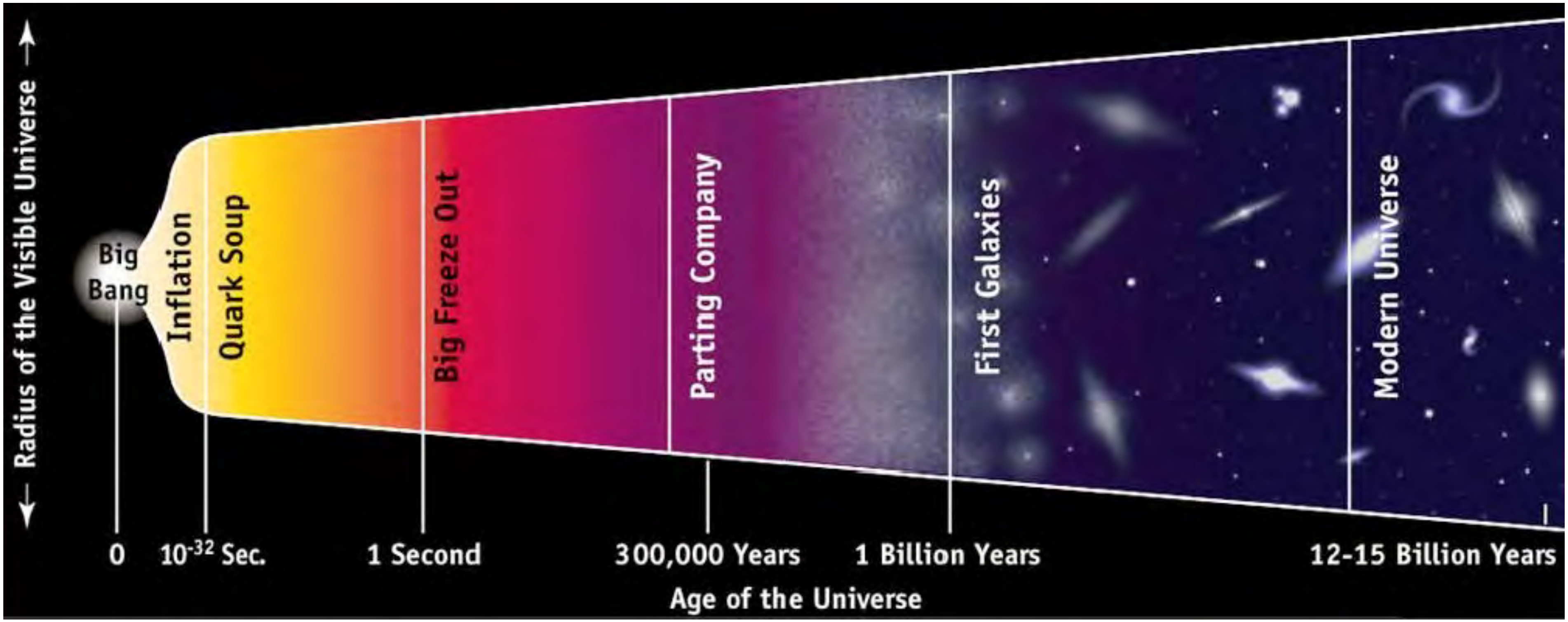
The Composition of the Universe



but only ~ 0.5% is the stuff we observe (stars and gas)

- A picture consistent with many different observations, in a Concordance Cosmology
- The nature of the Dark Matter and Dark Energy are among the most outstanding problems of science today

The Cosmic Timeline



Fairly well understood

The current frontier

Physics reasonably well understood

Highly speculative physics

The Key Concepts

- The theoretical basis of modern cosmology is the General Theory of Relativity, since gravity is the only important interaction at large scales
- The observational basis of modern cosmology starts with the recognition of the nature of galaxies and the discovery of the expanding universe in the 1920s
- The formation and evolution of galaxies and the large-scale structure are among the key topics of study in cosmology
- We have a fairly good understanding of the overall history of the universe, from the early Big Bang until today
- The nature of the dark matter (DM) and the dark energy (DE) are among the outstanding challenges of fundamental physics