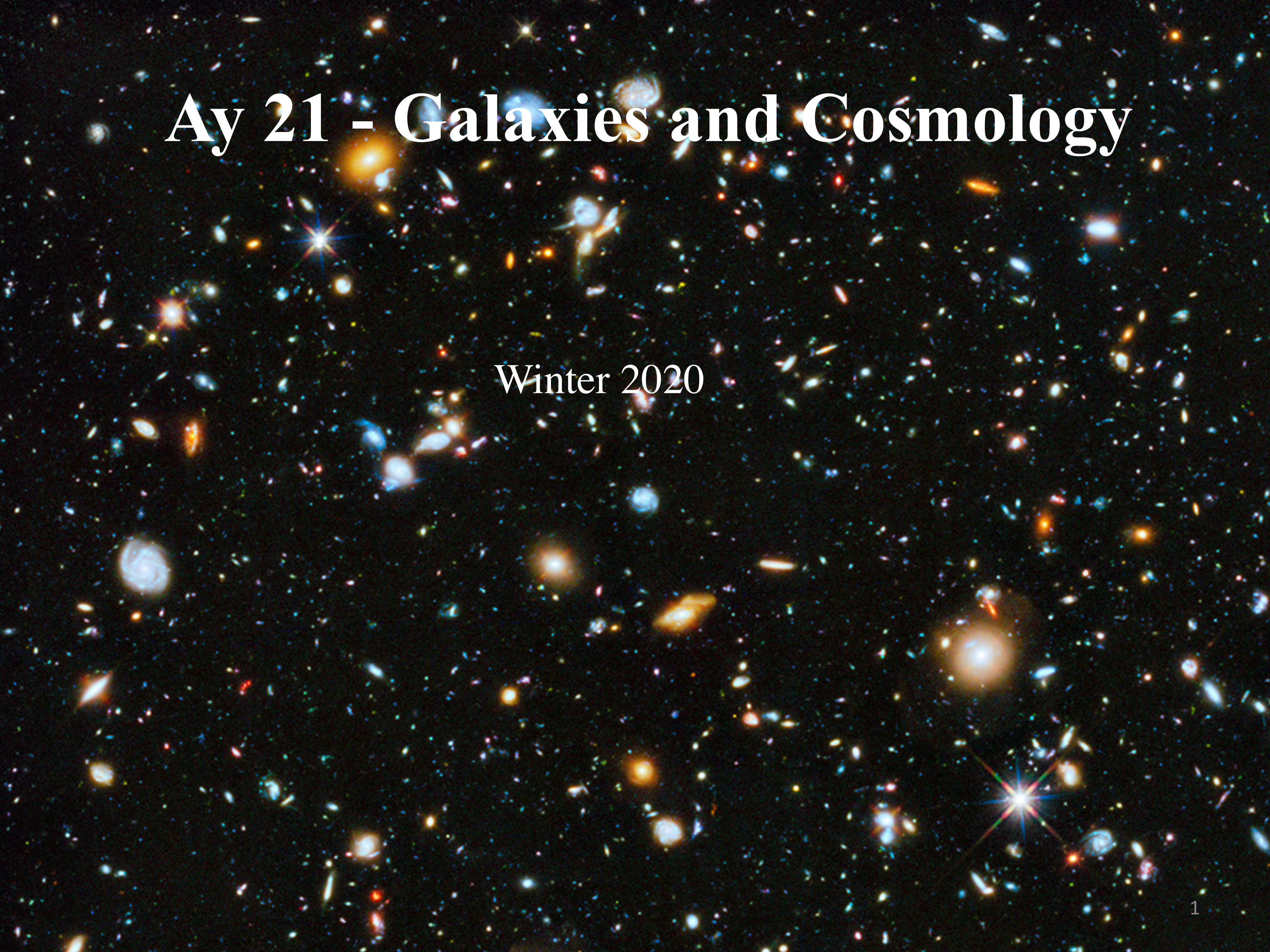
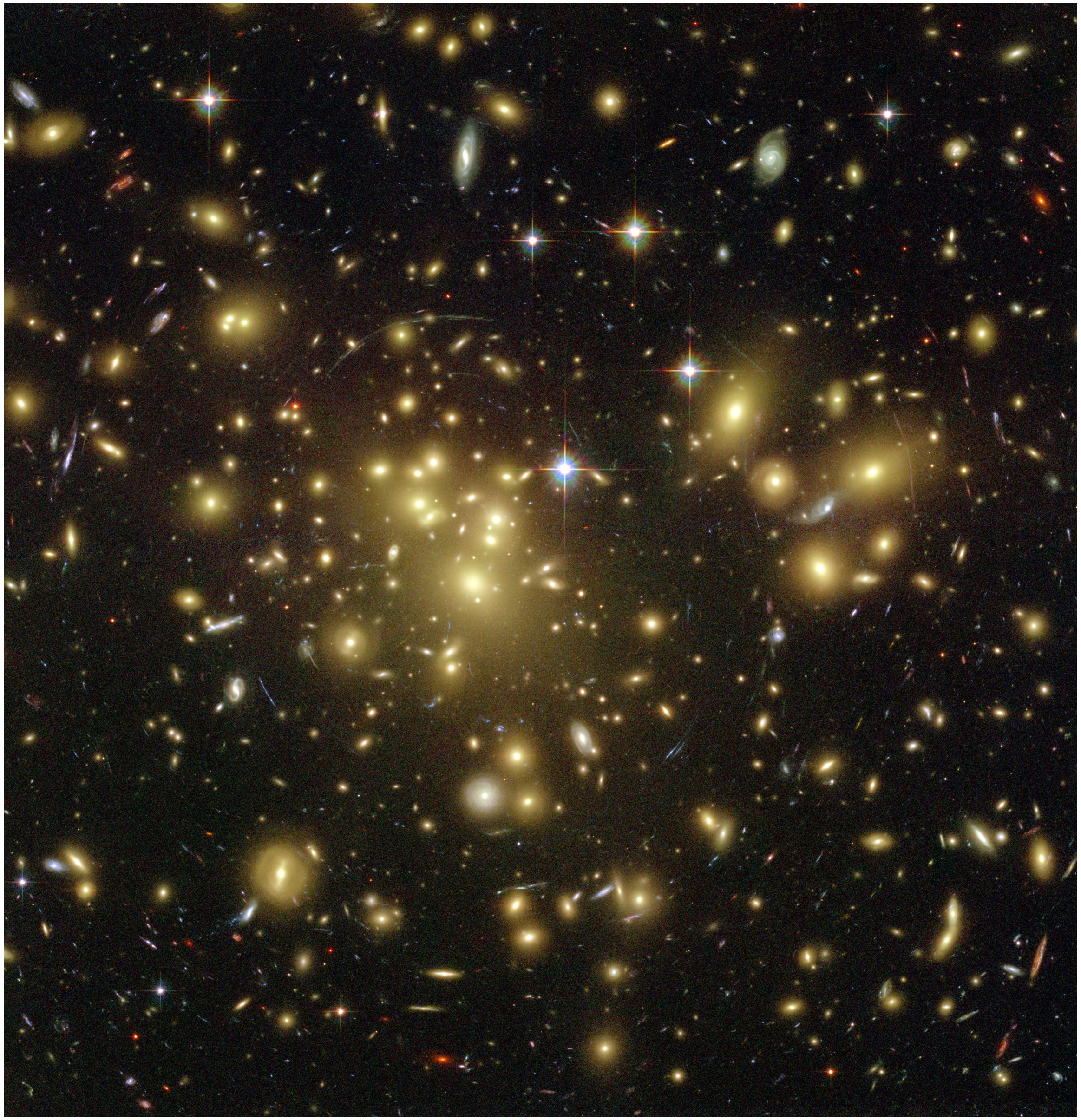
Ay 21 - Galaxies and Cosmology

Winter 2020



“Big Questions”



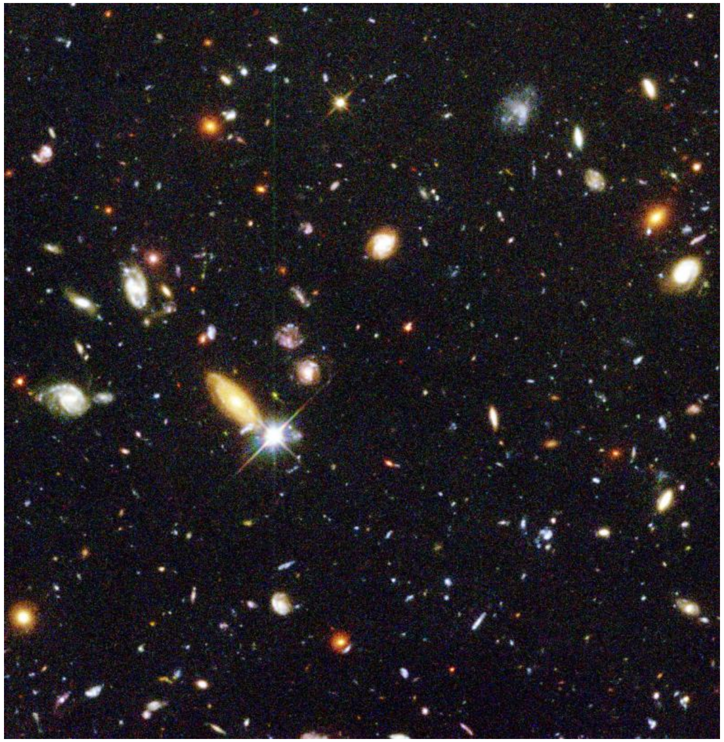
What is dark matter?

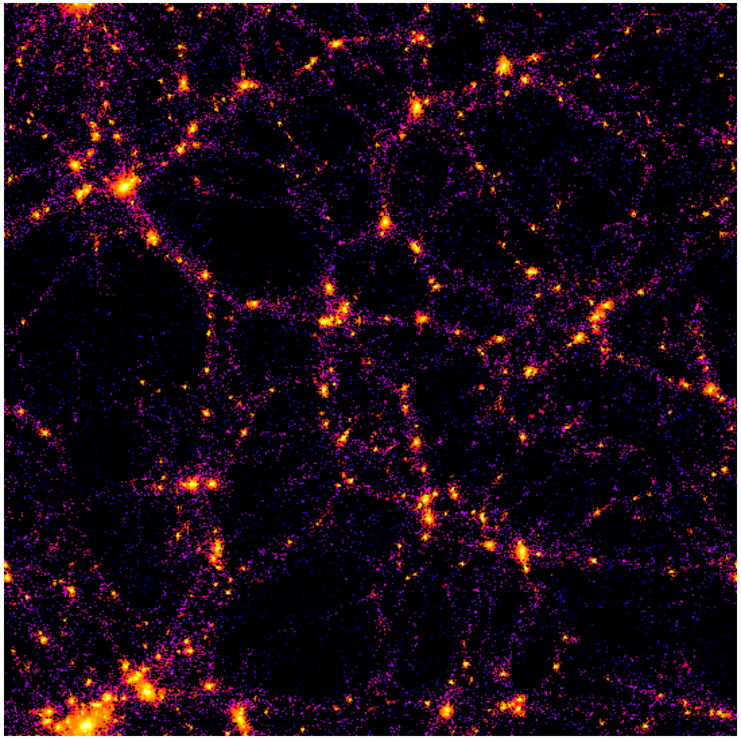
How much of it is there?

How is it distributed, and how do we know it’s there?

"Big Questions" in Astronomy and Astrophysics:

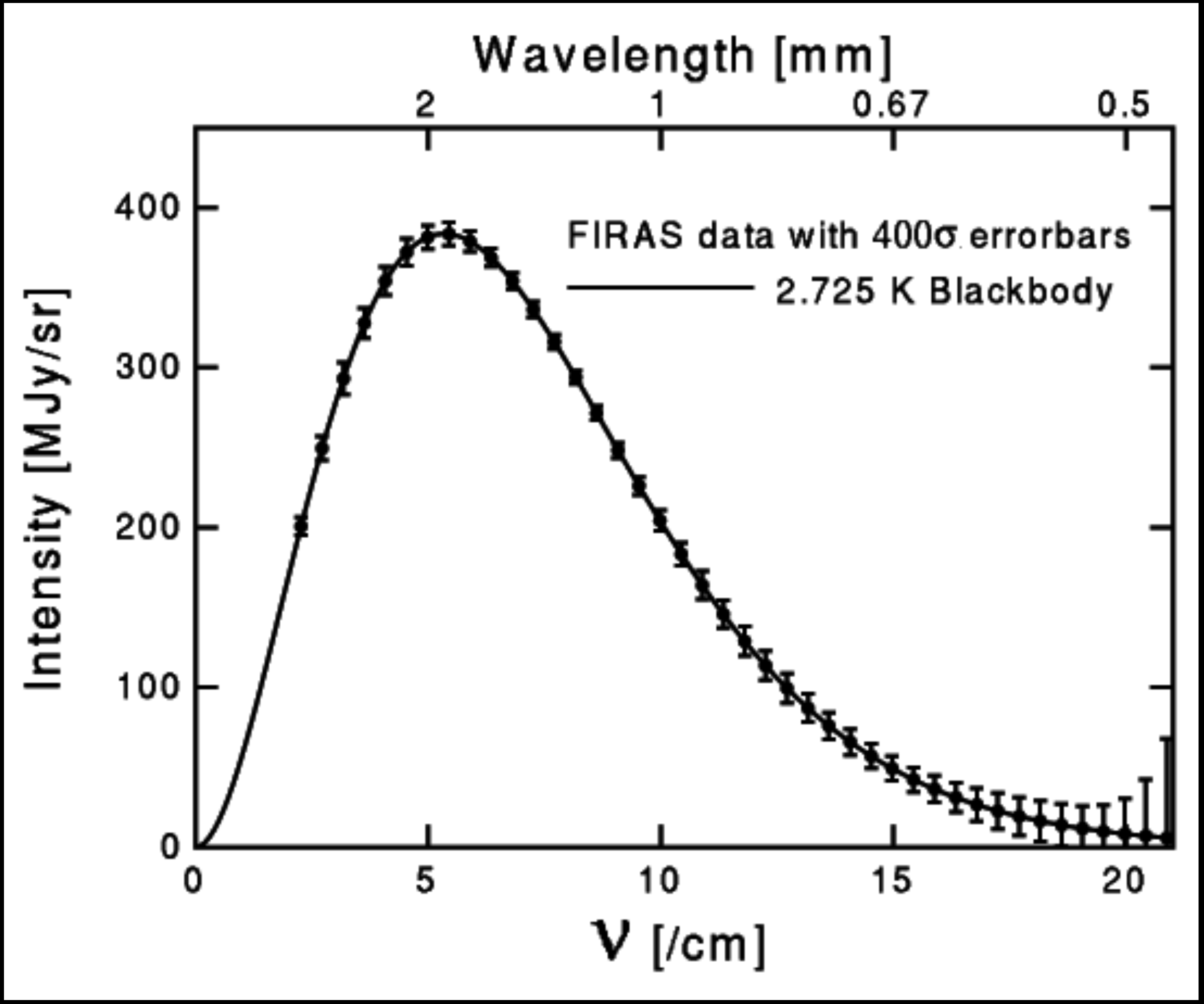
How did structure emerge? Why are galaxies the way they are? When did most of the stars in the Universe form?



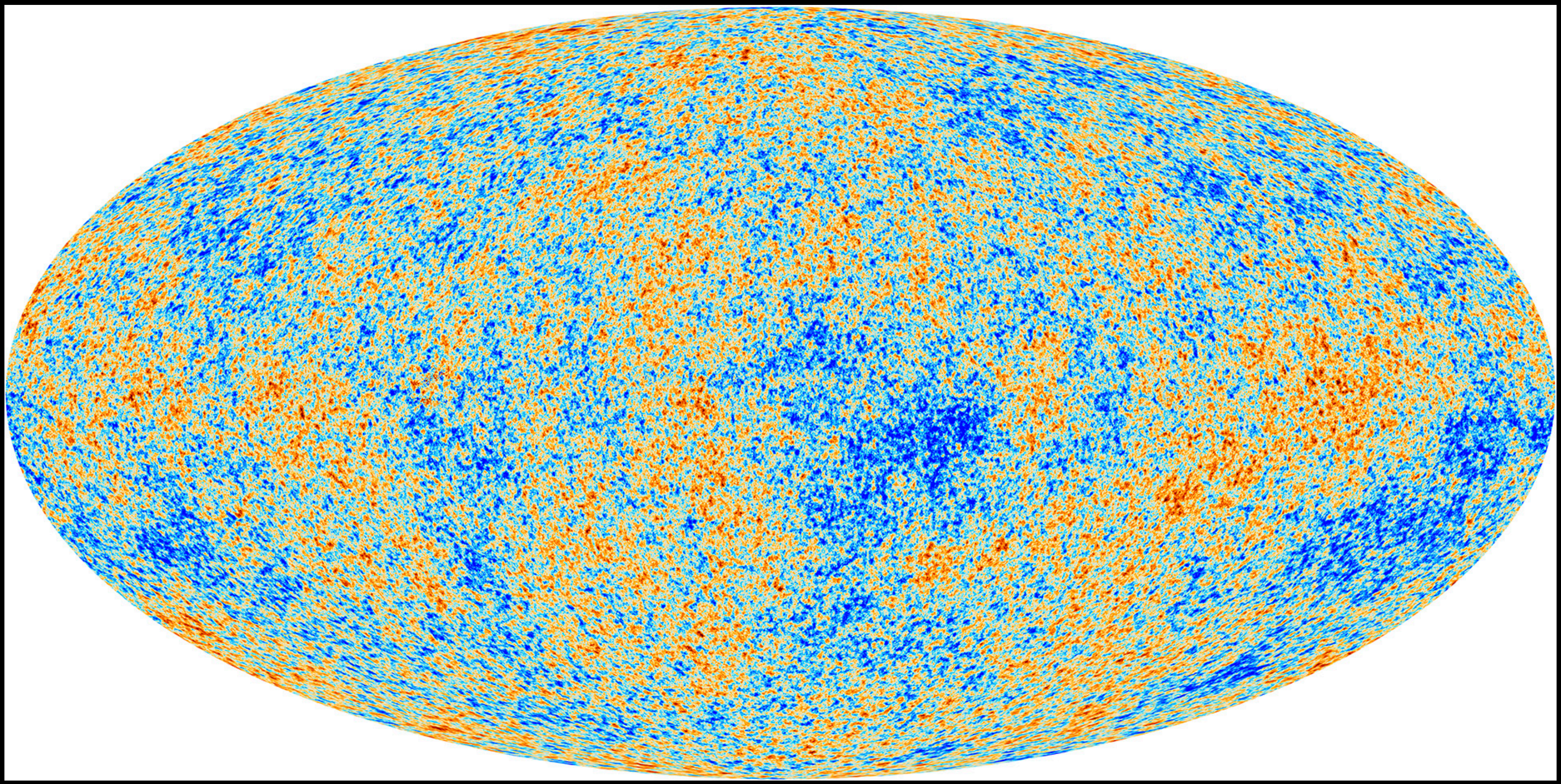


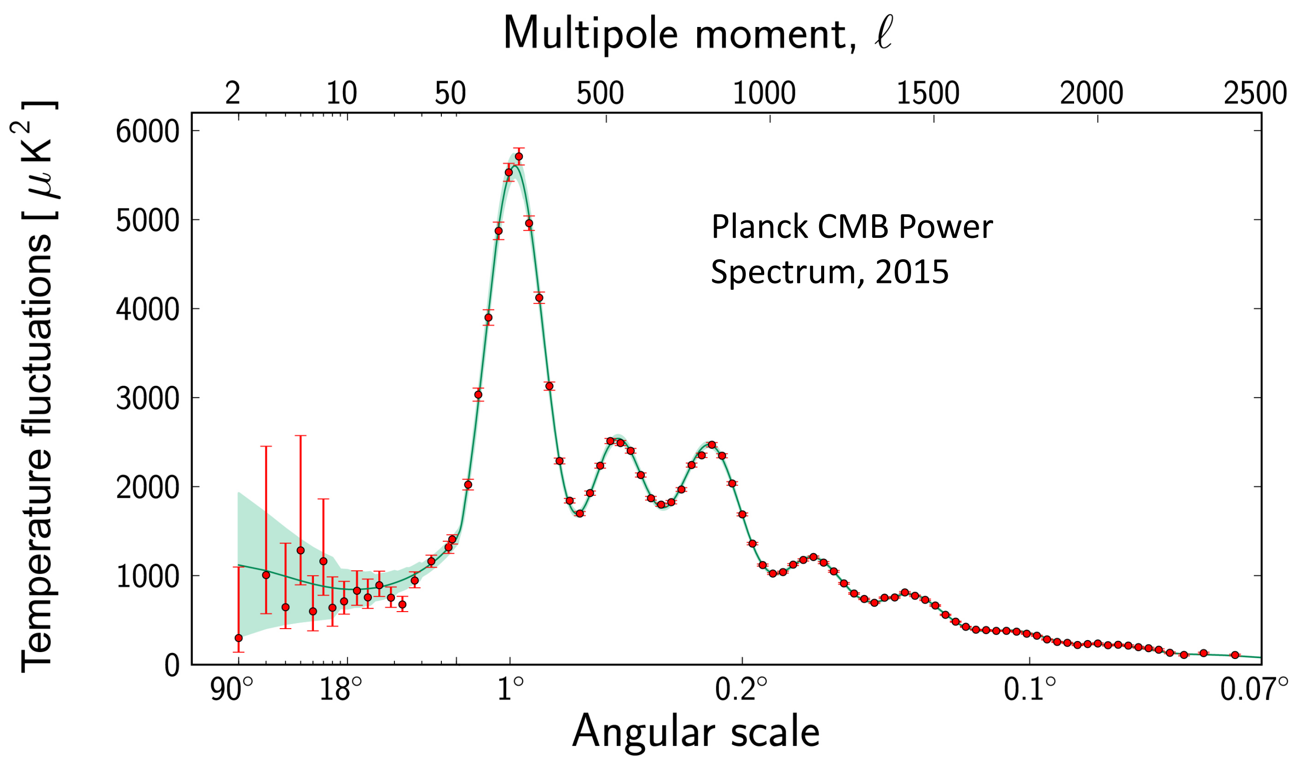
The History of Galaxy Formation

COBE FIRAS experiment: CMB is an almost perfect blackbody (1990)

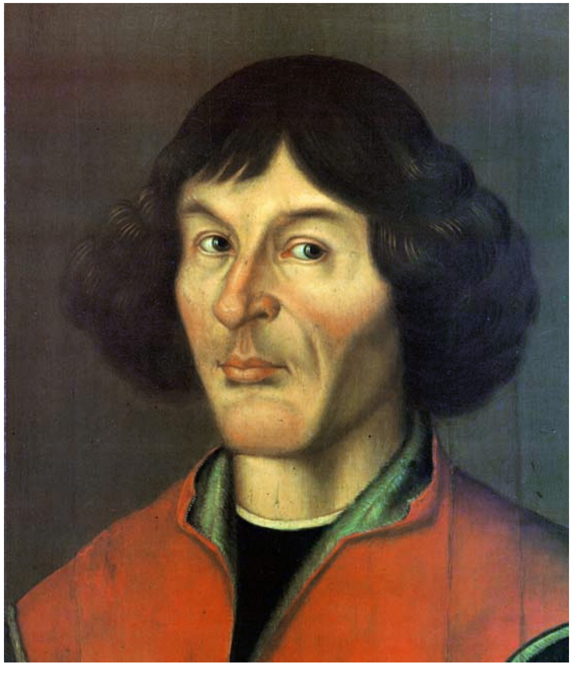


Planck 2015 temperature map




Multipole moment, ℓ
2
10
50
500
1000
1500
2000
2500
Temperature fluctuations [μK2]
6000
5000
4000
3000
2000
1000
0
Planck CMB Power
Spectrum, 2015
90°
18°
1°
0.2°
0.1°
0.07°
Angular scale

Copernicus (1550)

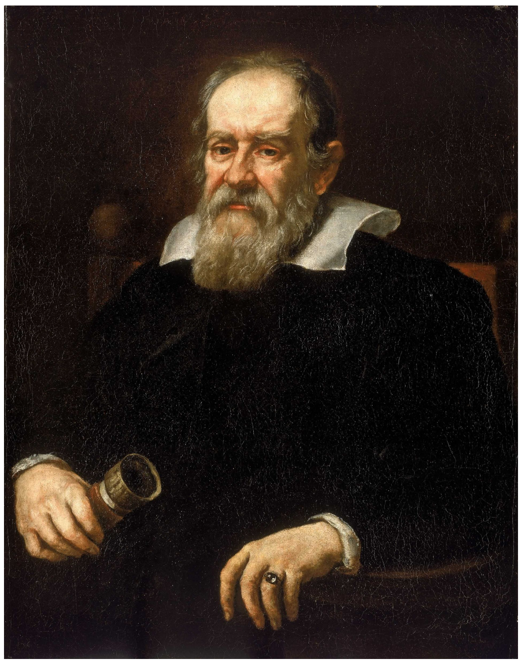


First adaptation of a non-earth-centered cosmology (his was heliocentric)

Kepler (1600)

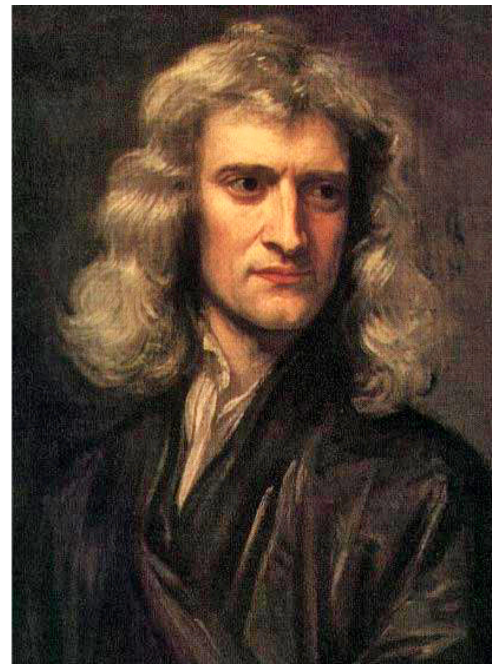
Saw mathematical regularity in the sky, but invoked mysticism to explain it.

Galileo (1625)



First systematic observations with a telescope.

Newton (1700)



Proposed that one can model the universe based on terrestrial physics

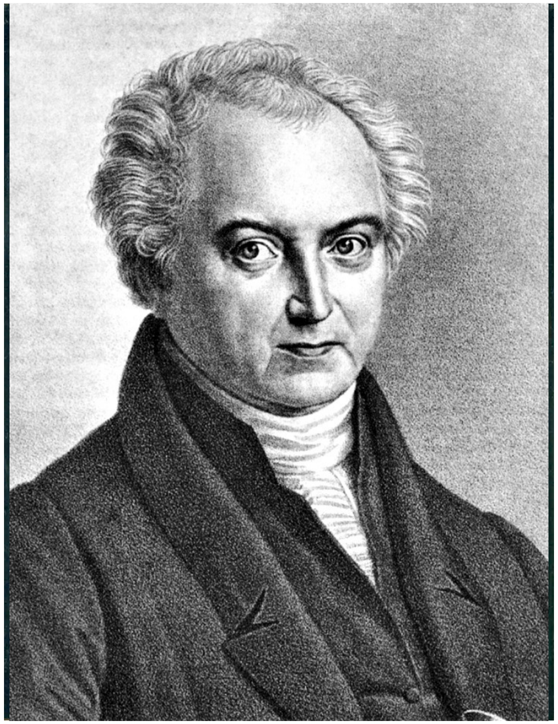
Kant (1750)

Idea of "island universes"—philosophical rather than physical

Herschel (1800)

Discovery of "nebulae"; suggested perhaps our Galaxy might resemble these these if viewed from afar (later rejected this notion because of confusion with other "nebulae")

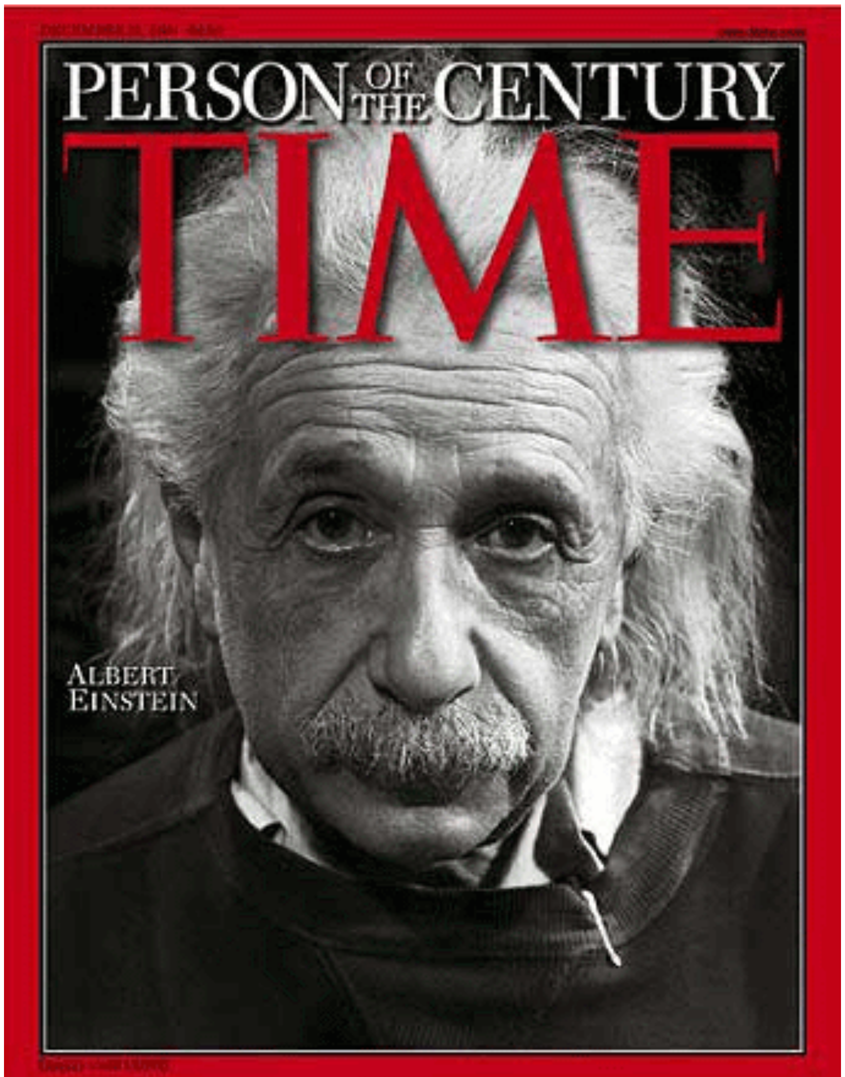
Olber (1826)

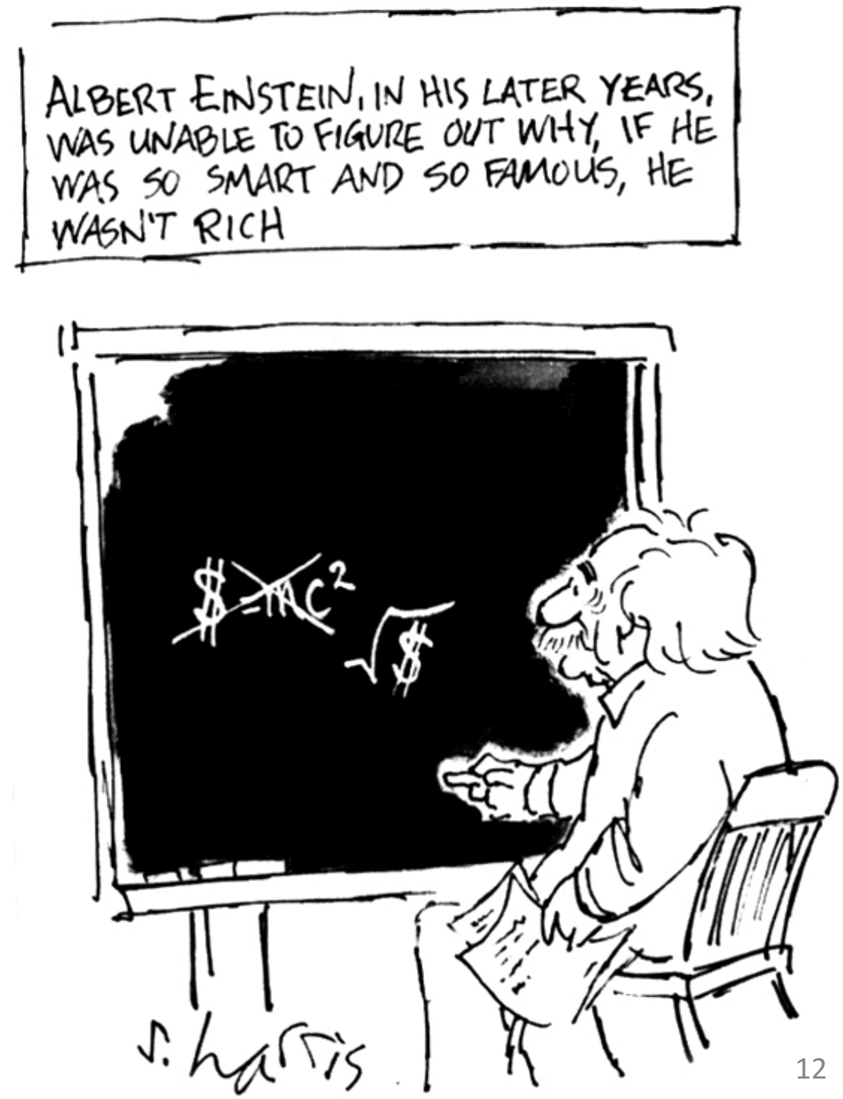


Suggested that the universe cannot be infinite and static by simple reasoning. Has a paradox named after him.

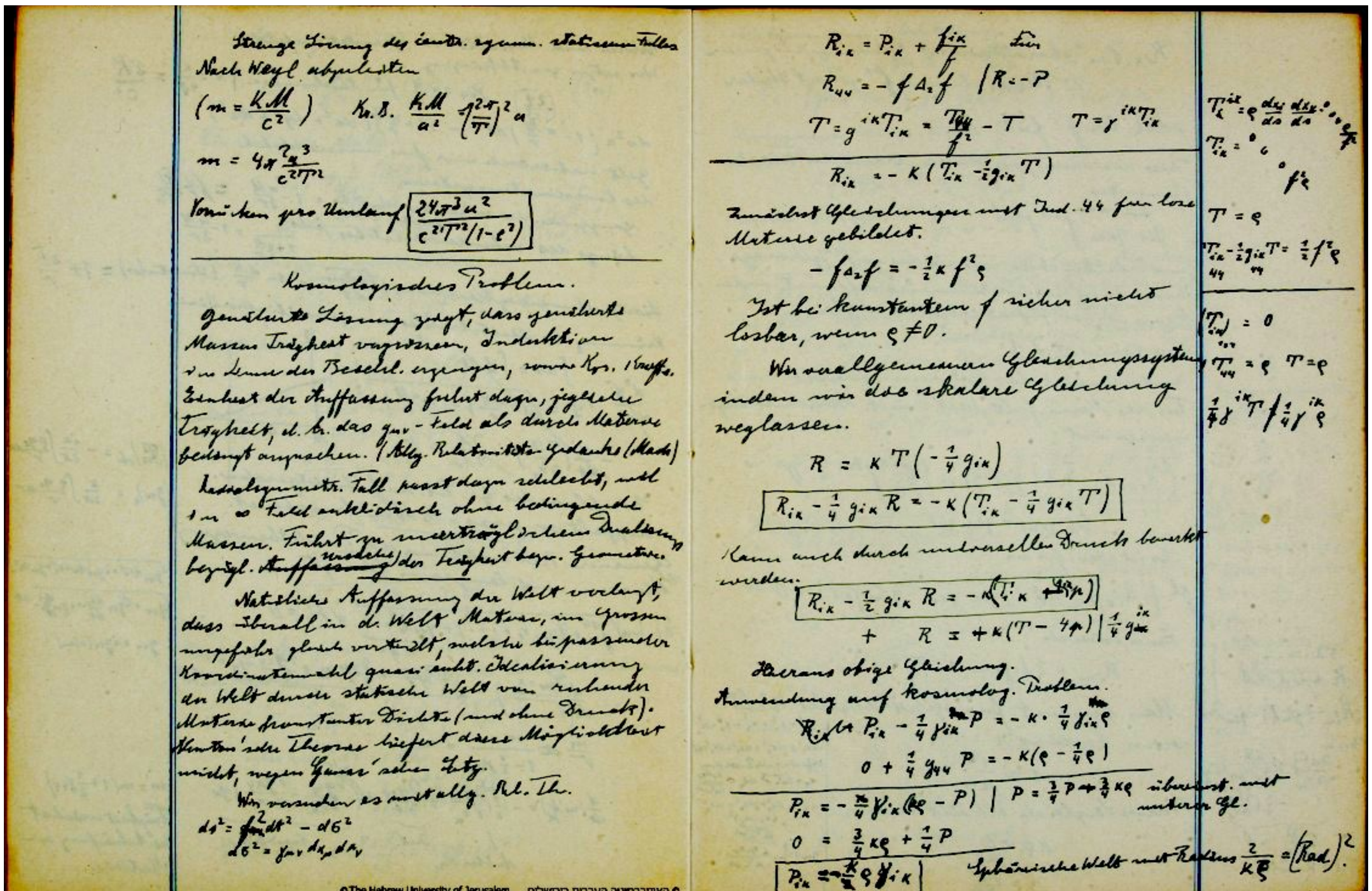
Progress slowed on cosmology at this point, until well into the 20th century…

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 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

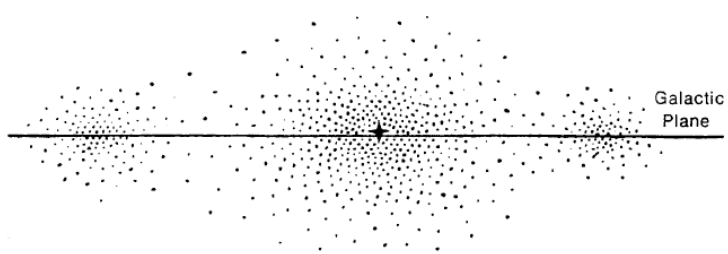
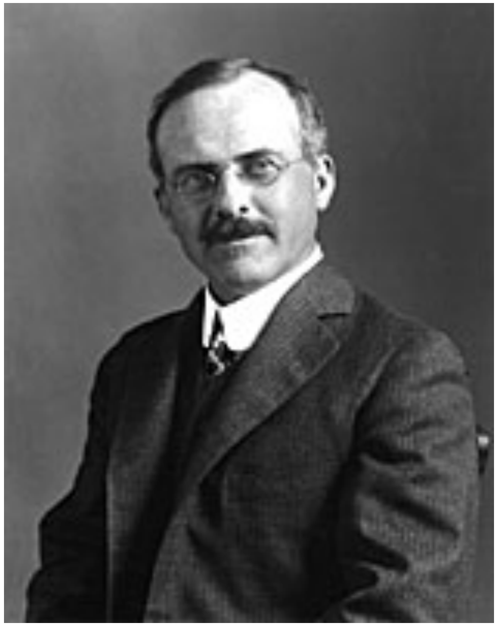


FIG. 3—Arthur Eddington's (1912) galaxy placed the Sun's position 60 LY above the center of the galactic plane.

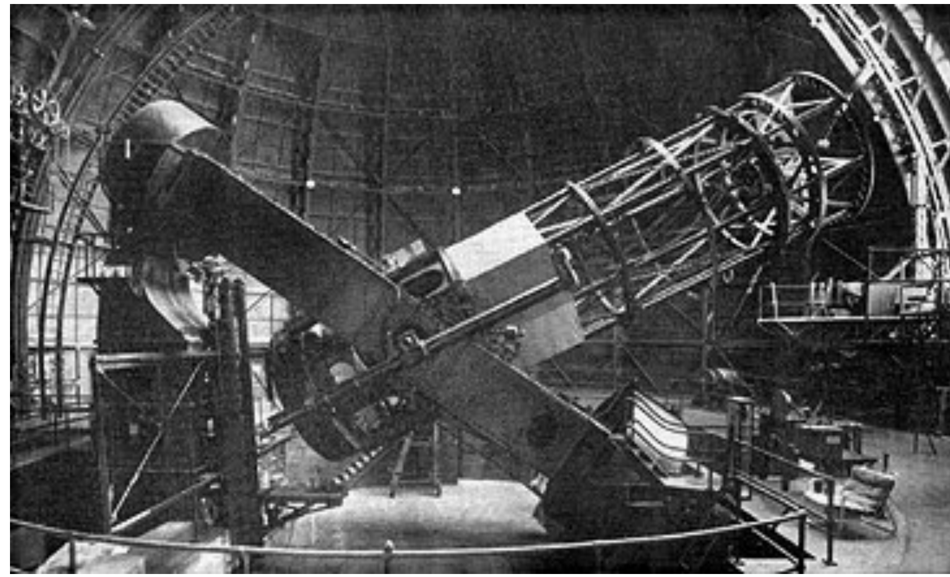
Curtis ☛ thought that these are other galaxies, just like ours



The Resolution: Nebulae are Extragalactic

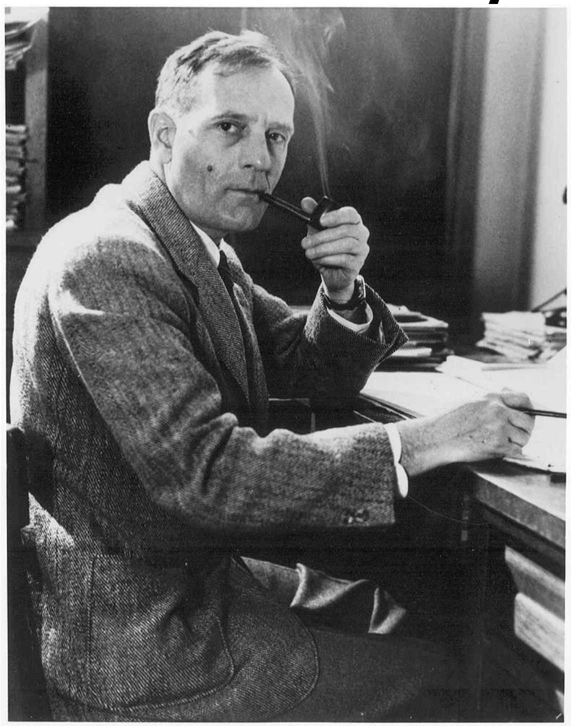
- In 1923 Hubble resolved Cepheids in M31 (Andromeda)
- A profound shift in the understanding of the scale of the universe

Edwin Hubble

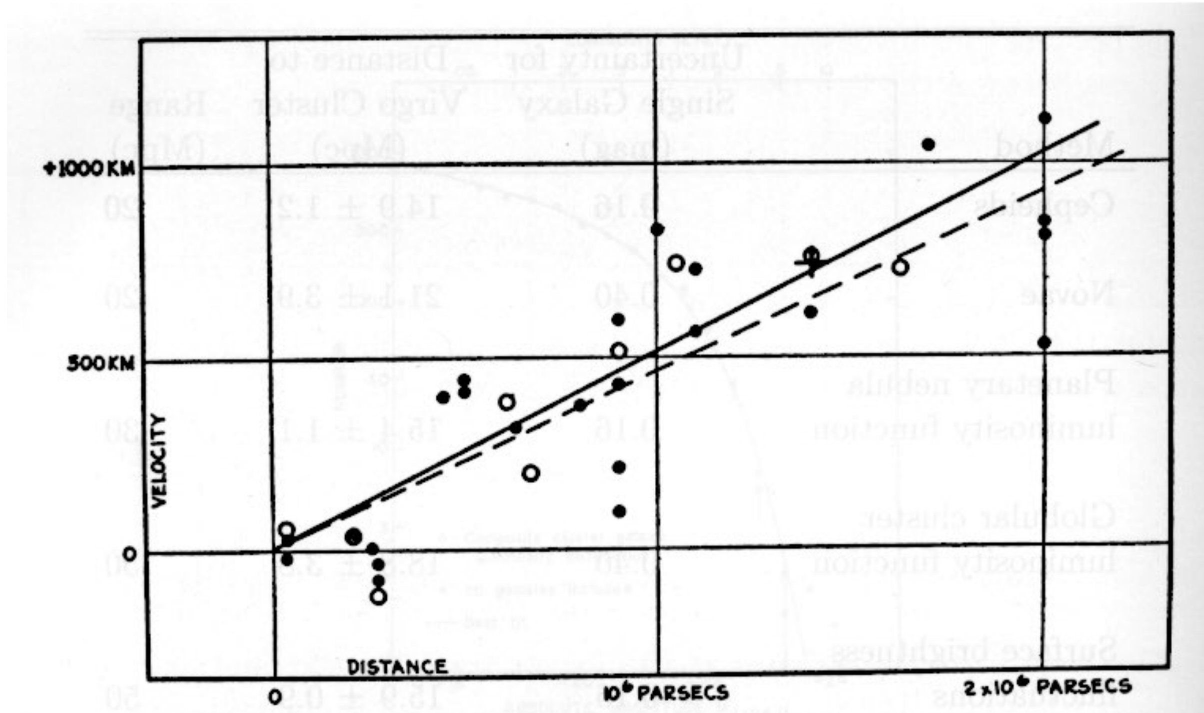


The Mt. Wilson 100-inch

Discovery of the Expanding Universe



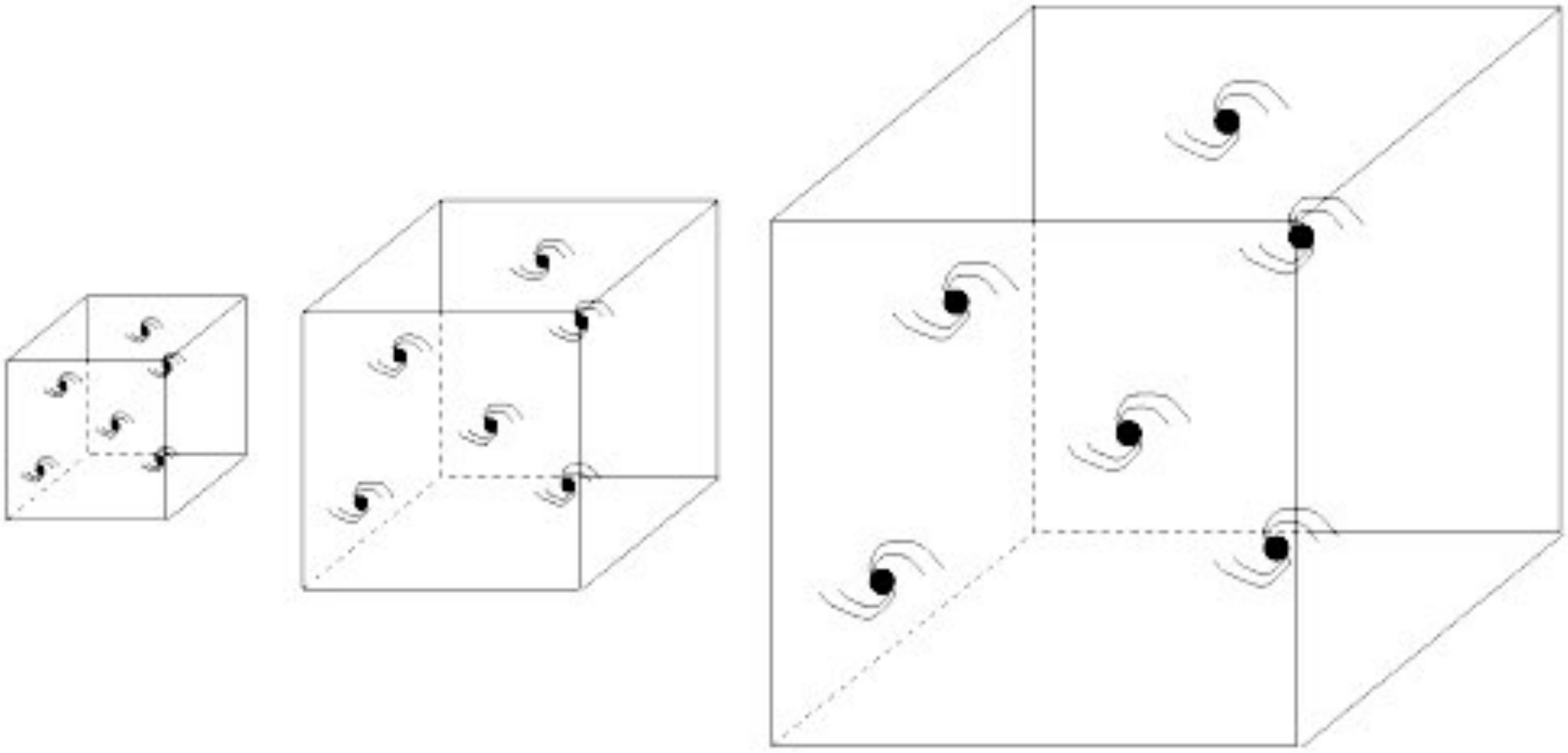
Edwin Hubble (1929)



The Hubble diagram (1936)

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

Expansion of the Universe



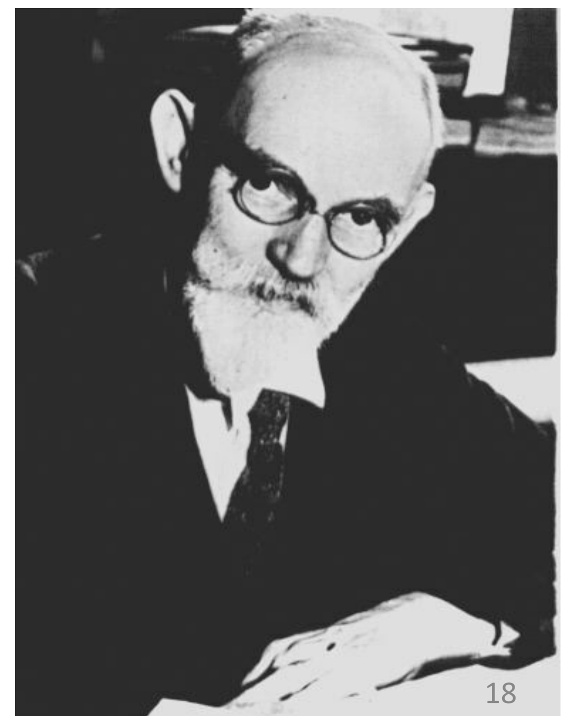
The space itself expands, and carries galaxies apart

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

Early Cosmological Models

Einstein in 1917 constructed the first relativistic cosmological models. Thinking that the universe *must be* static (on philosophical grounds), he introduced the cosmological constant term to balance the force of gravity. This model was unstable.

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 both their names.

The Friedmann and Lemaitre 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 had not yet been established.

Georges Lemaitre ⇨

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

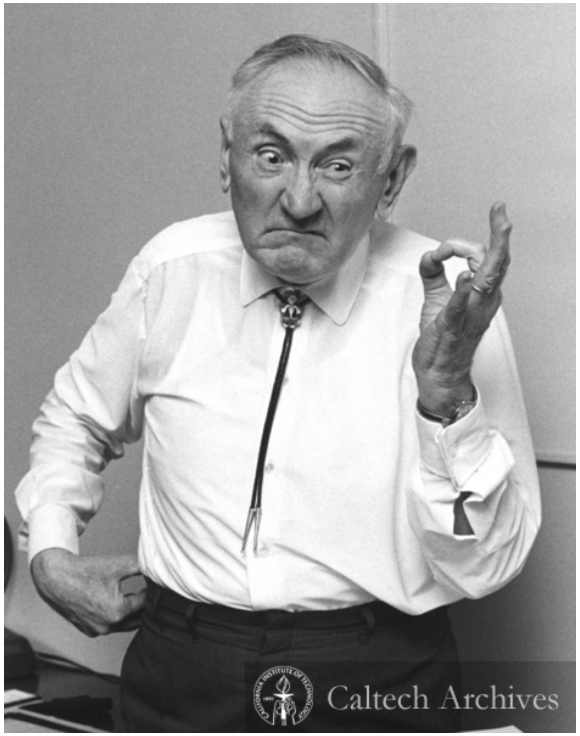
Arthur Eddington

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 Dark Matter



- Fritz Zwicky (1933): from application of the virial theorem to the Coma Cluster, deduced that it contains ~ 400 times more mass than can be attributed to visible stars

- Largely ignored until 1970's, when flat galaxy rotation curves (e.g., Vera Rubin) made the existence of DM unambiguous
- DM now plays a dominant role in models of structure formation
- The nature of DM is now one of the outstanding problems of physics

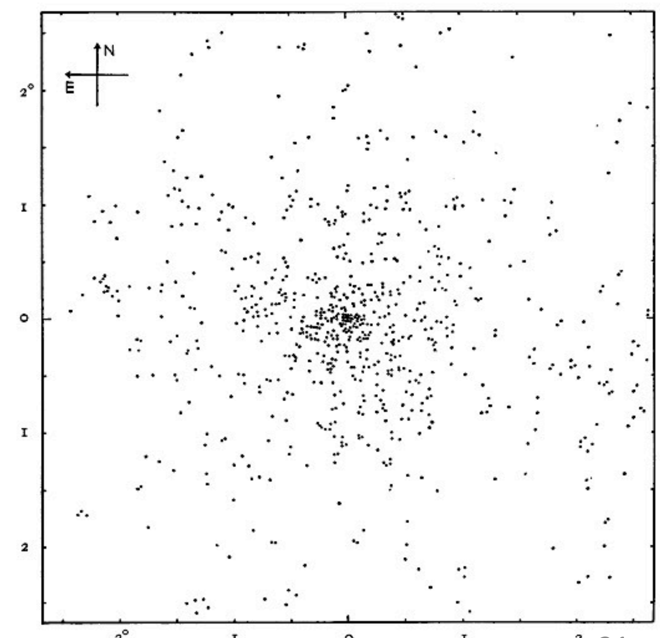


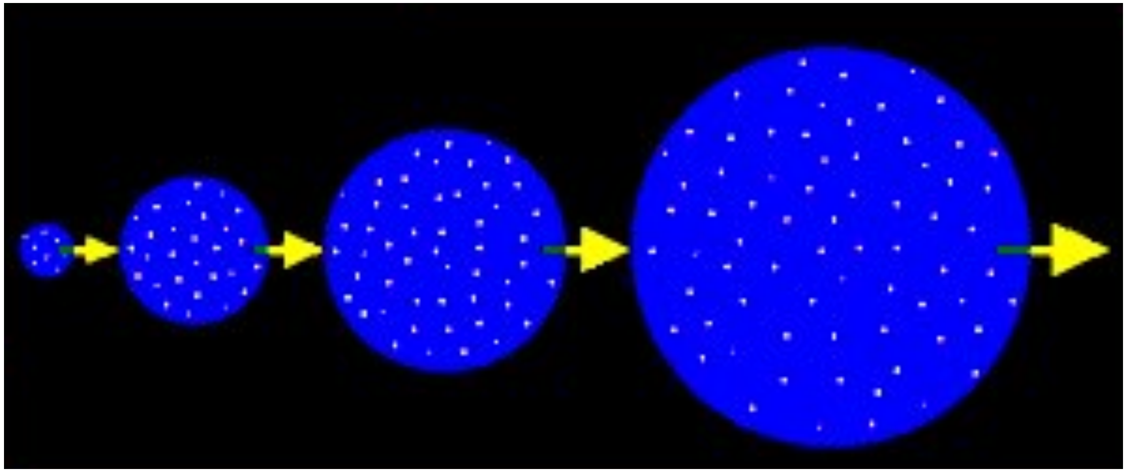
FIG. 3.—The Coma cluster of nebulae

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 Cosmic Nucleosynthesis and the Cosmic Microwave Background

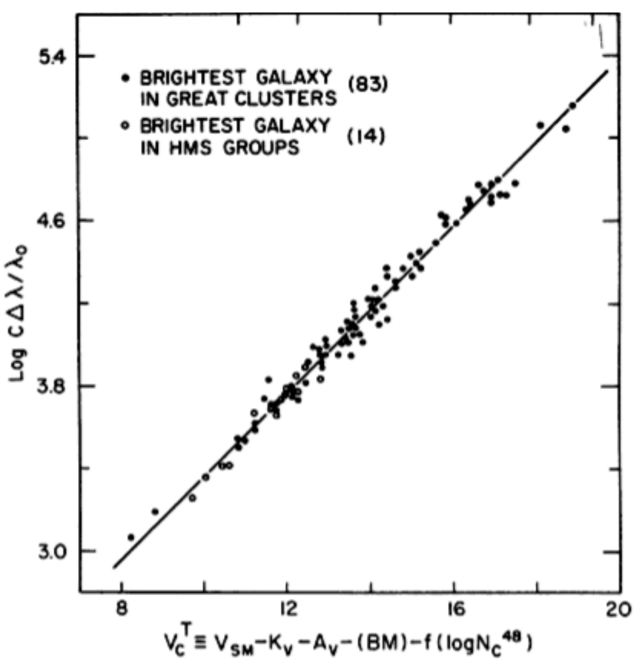
Ralph Alpher   George Gamow   Robert Herman

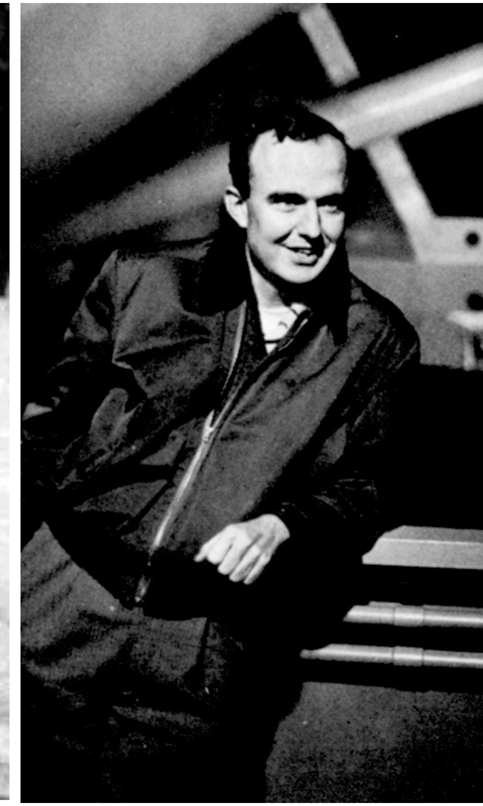
Gamow et al. in 1948 also "ran the film backwards" and figured primordial nucleosynthesis in the early universe (Alpher, Bethe, & Gamow - "αβγ" theory), even though the synthesis stopped at He…

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 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



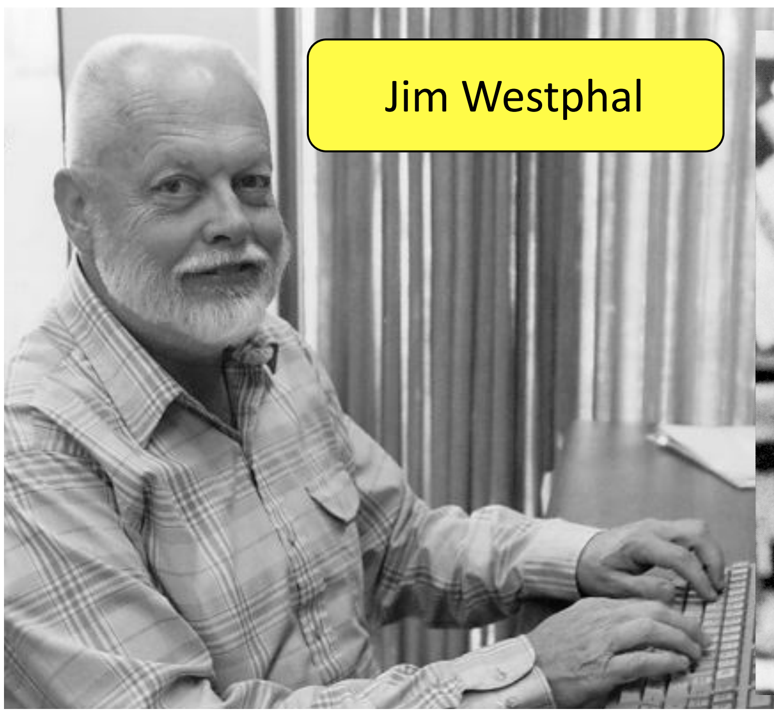


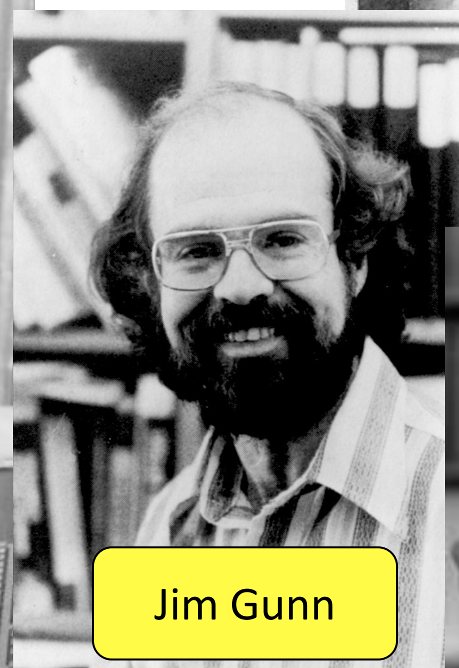
THE ABILITY OF THE 200-INCH TELESCOPE TO DISCRIMINATE BETWEEN SELECTED WORLD MODELS

ALLAN SANDAGE
Mount Wilson and Palomar Observatories

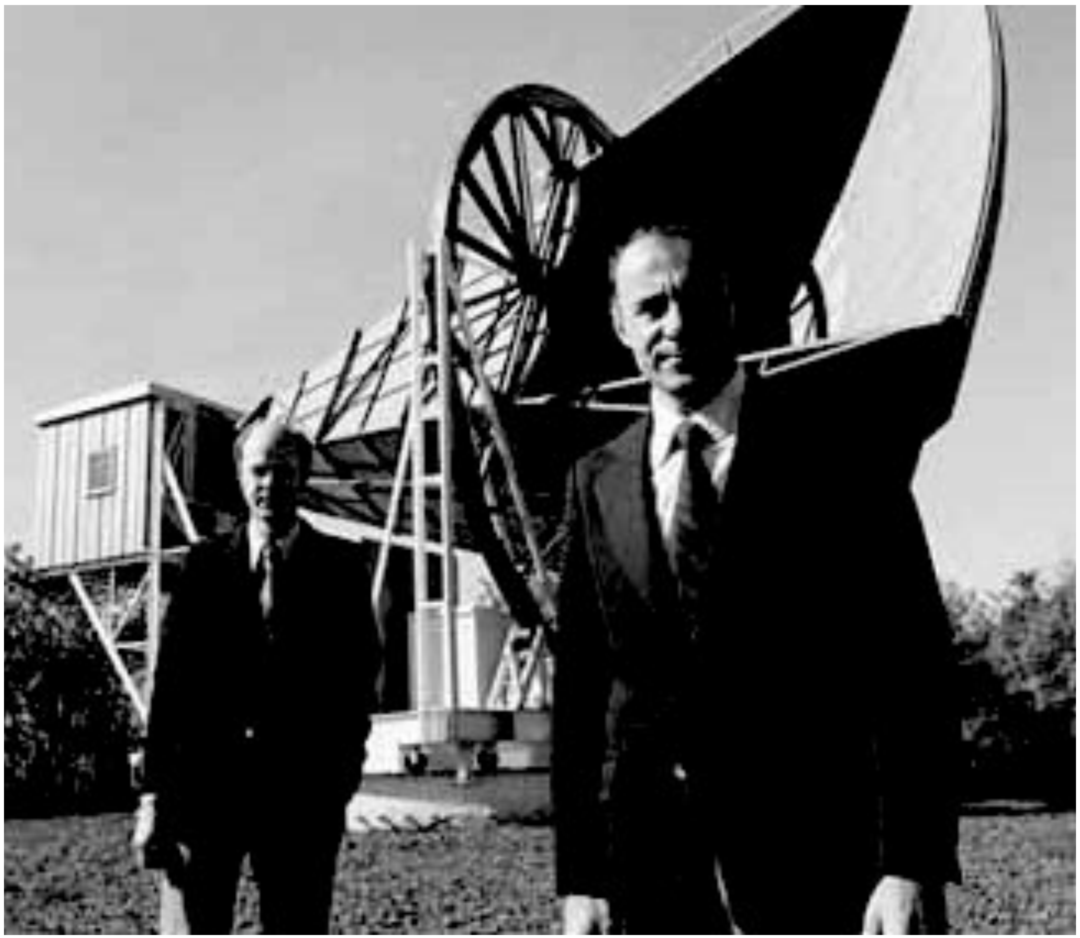
Observational Cosmology At Palomar: 1970's - 1980's

- 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





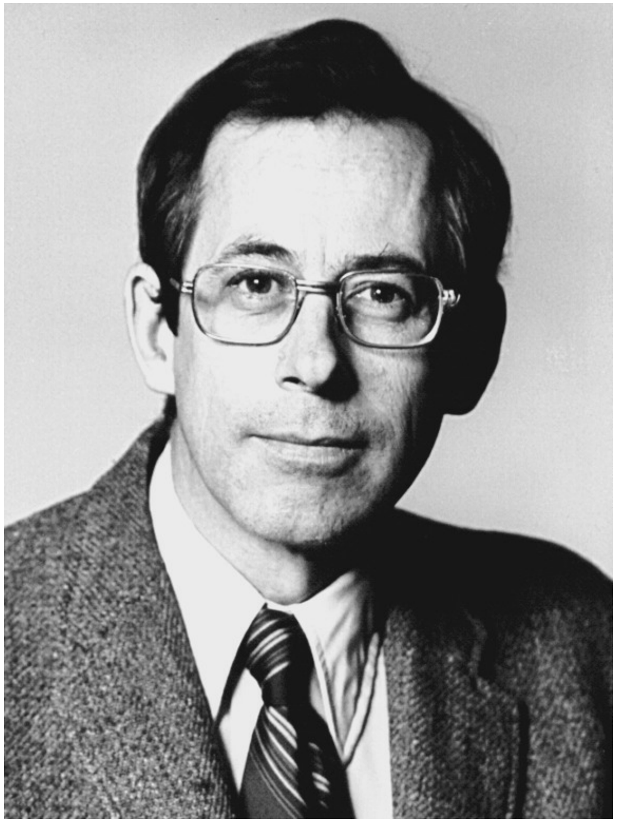
Discovery of the Cosmic Microwave Background (CMBR): Direct Evidence for the Big Bang



Arno Penzias & Robert Wilson (1965)

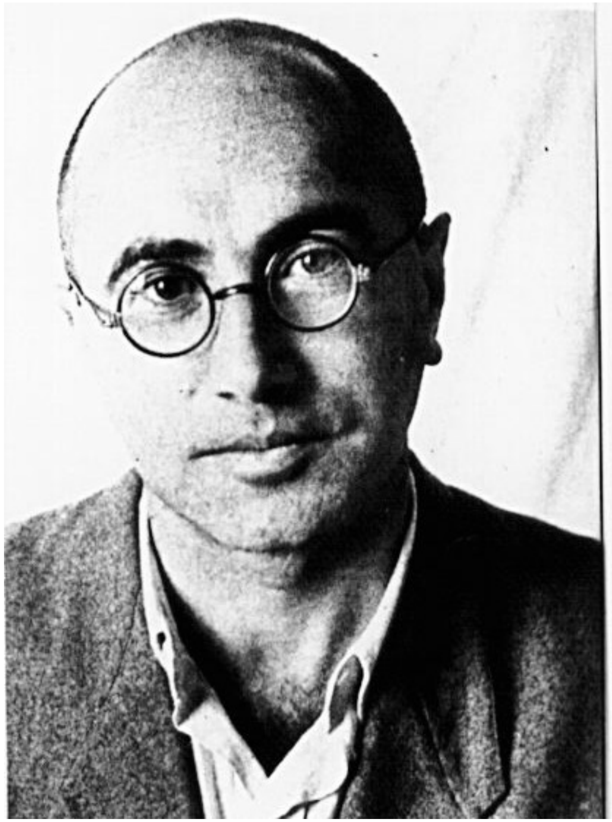
Nobel Prize, 1978

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

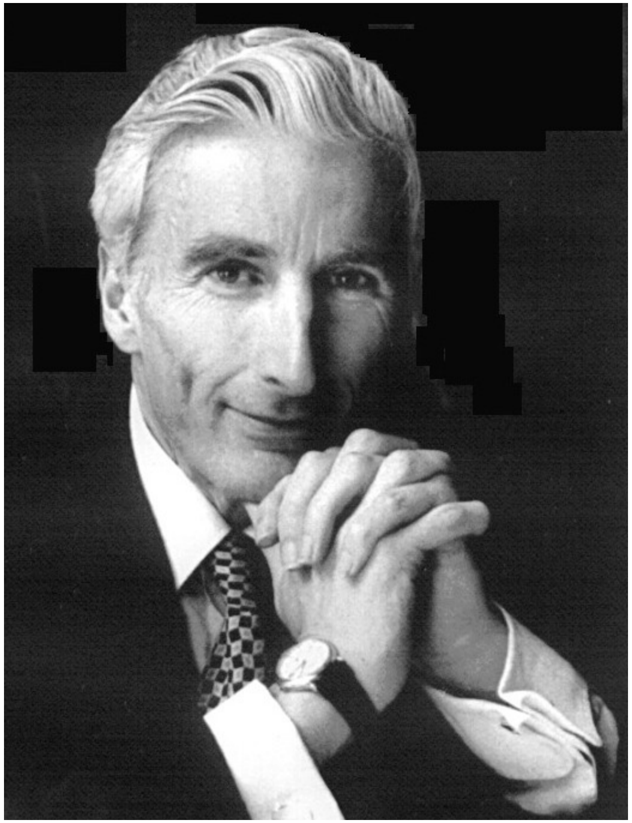


Jim Peebles

2020 Nobel Prize in Physics



Yakov Zel'dovich



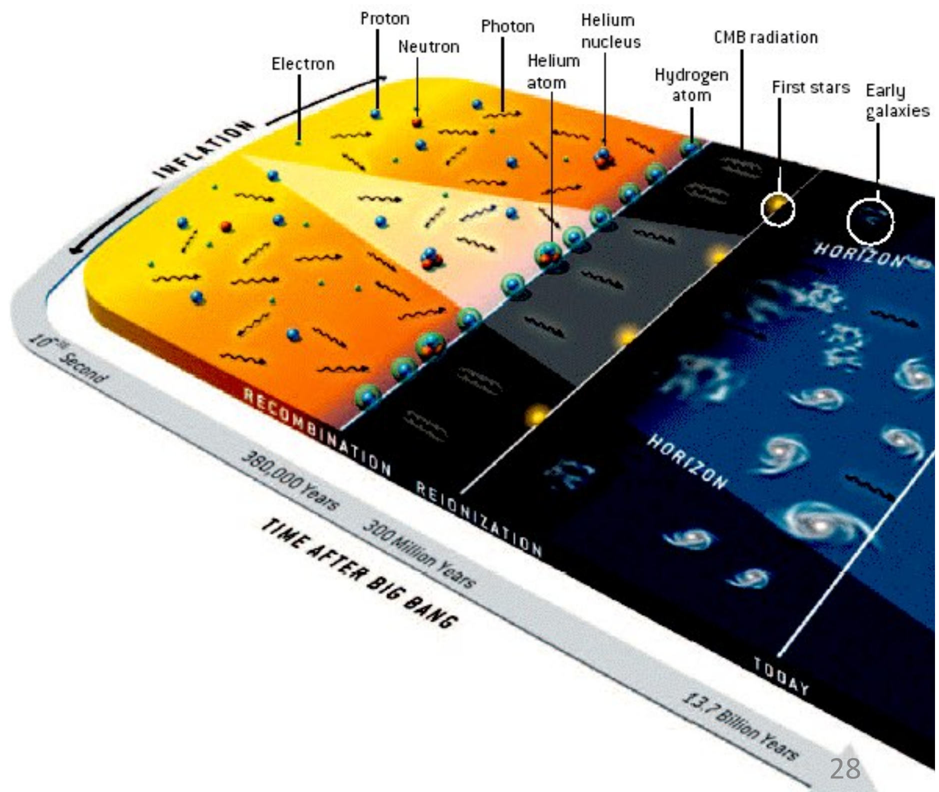
Martin Rees

Inflation: A Key Theoretical Idea

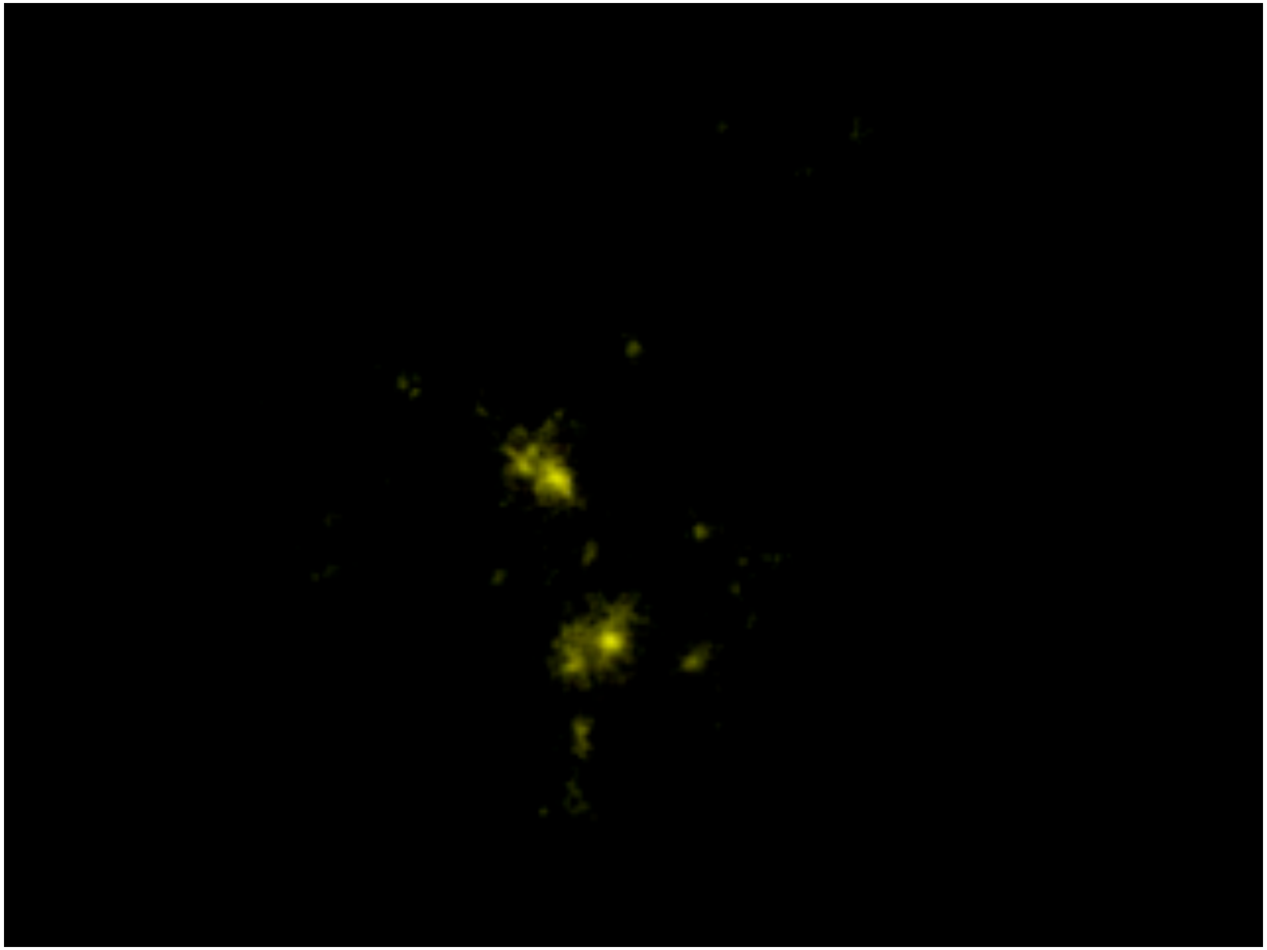
- Alan Guth (1980); precursors: D. Kazanas, A. Starobinsky
- Explains a number of fundamental cosmological problems: flatness, horizon, origin of structure, absence of topological defects…
- Chaotic inflation: Andrei Linde - is our universe just a bubble in a *much* larger megaverse?

A. Guth

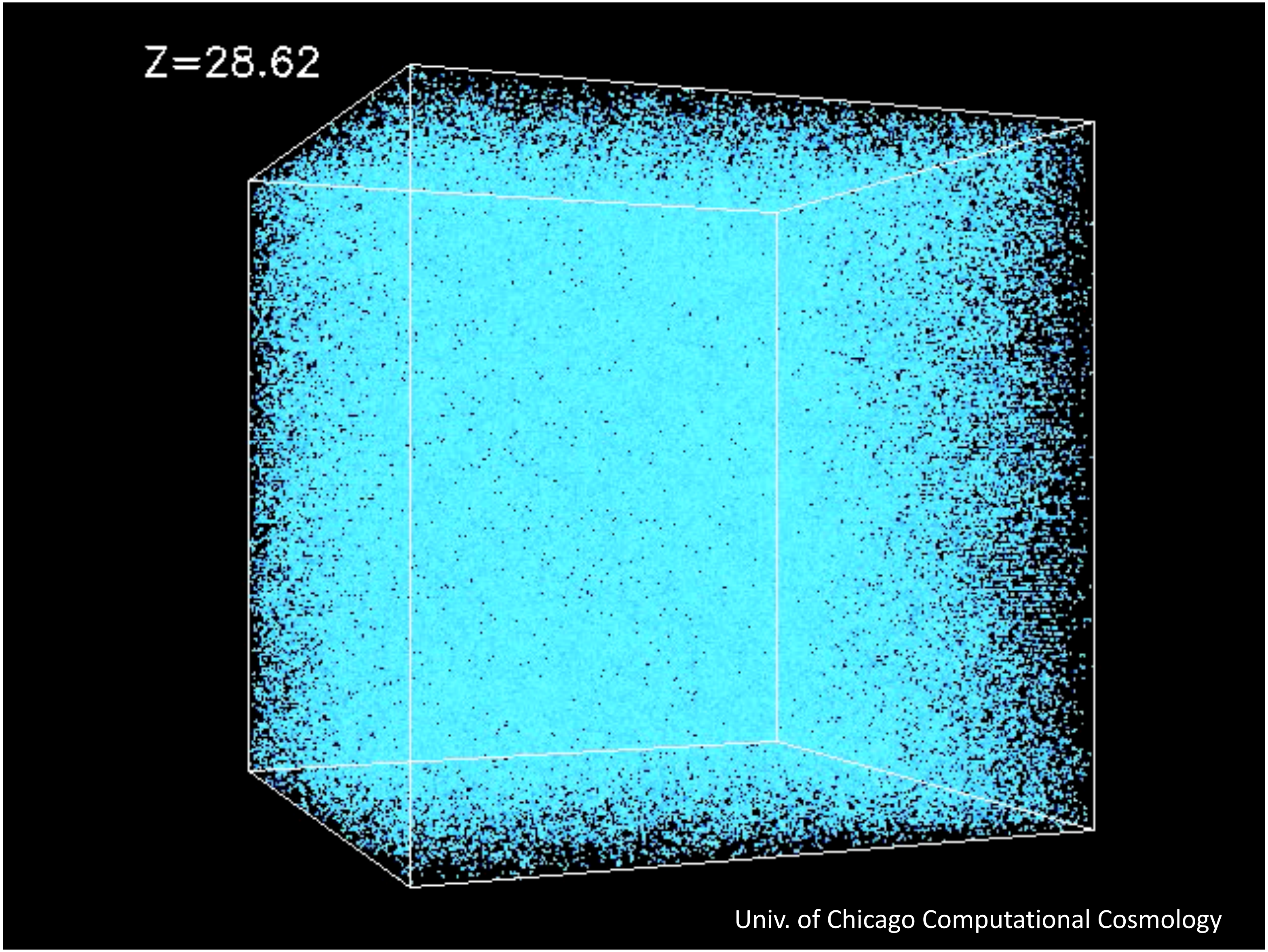
A. Linde



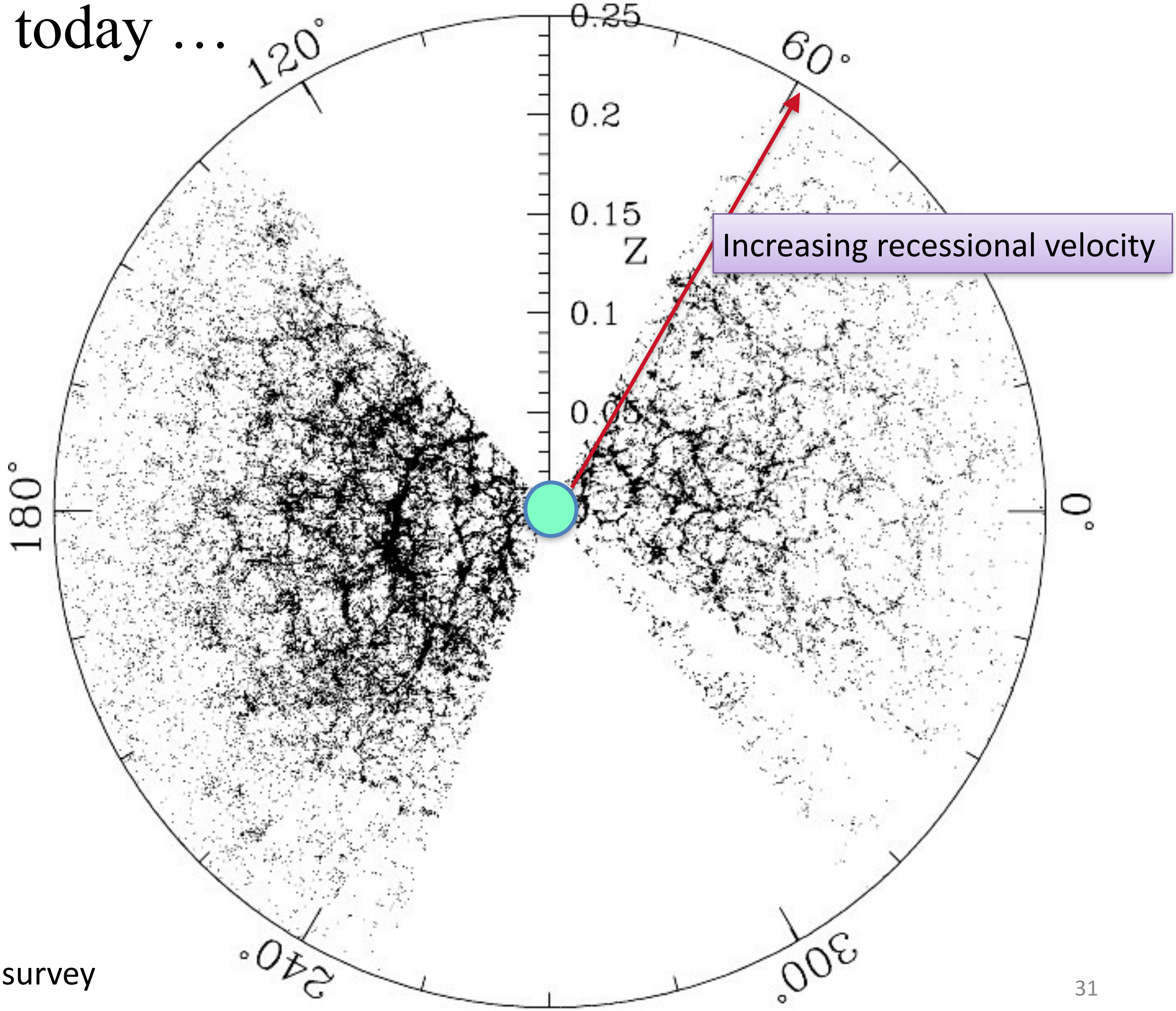
Gravitational Instability



Growth of Large Scale Structure: The Universe in a Computer

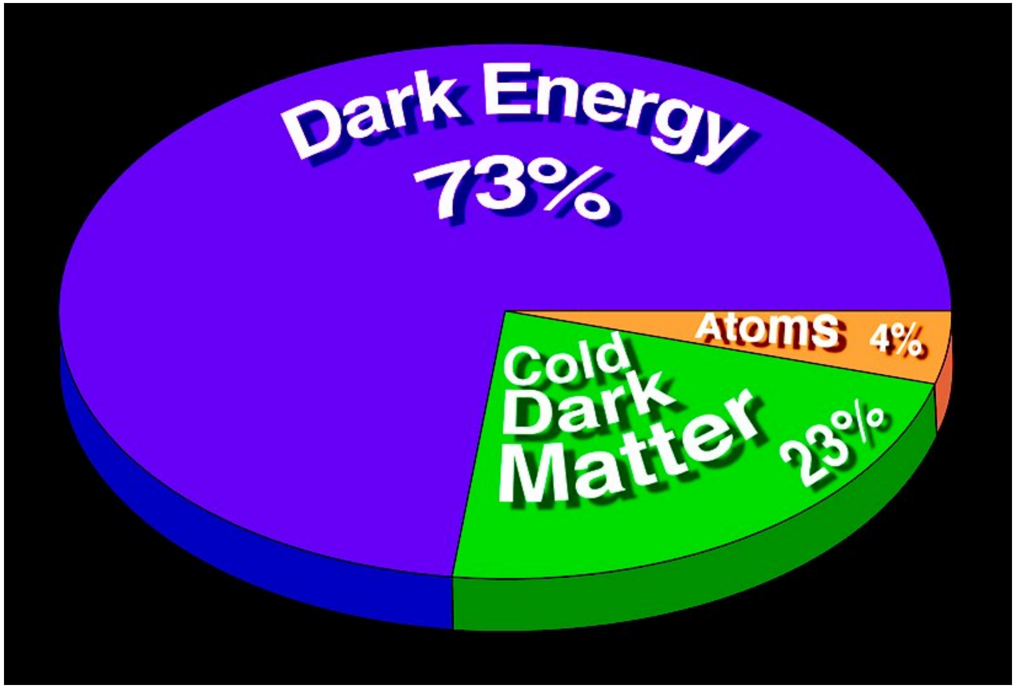


… and today …



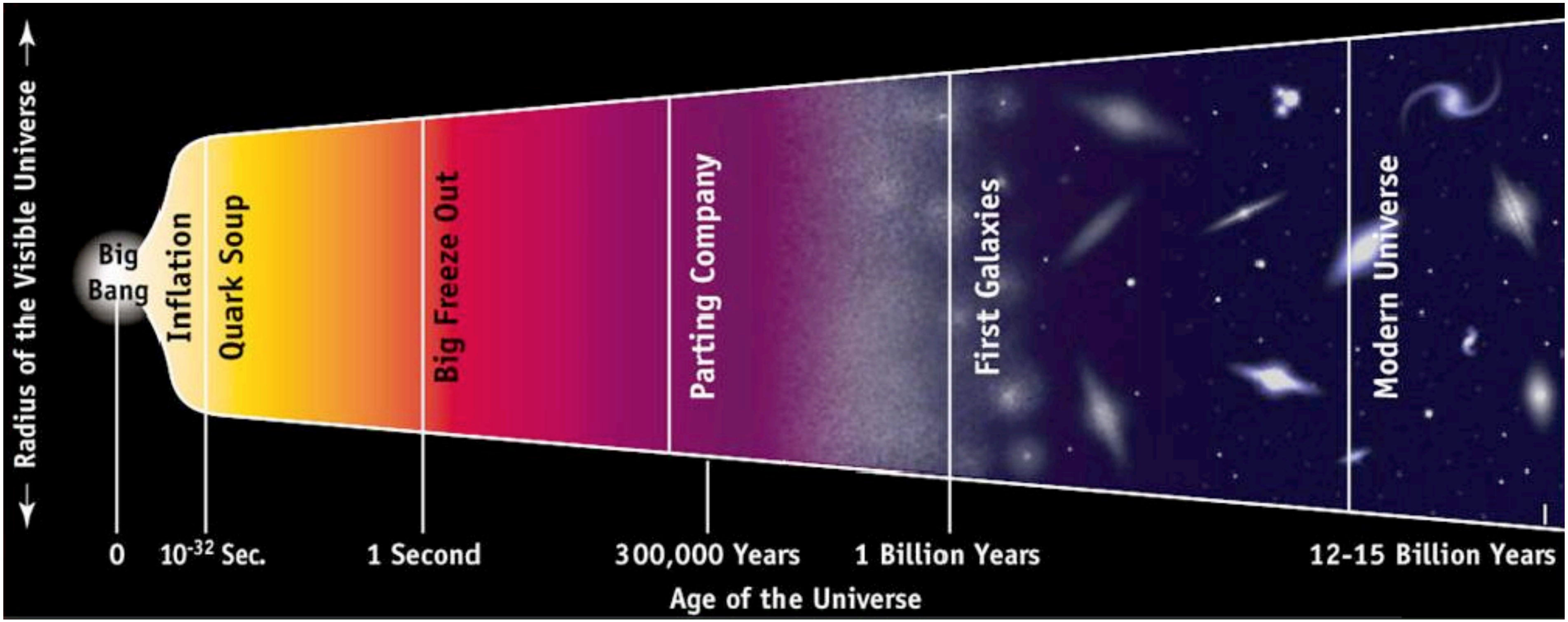
SDSS redshift survey

The Composition of the Universe



- A picture consistent with many different observations, not just SNe and CMBR: Concordance Cosmology
- The nature of Dark Matter and Dark Energy are among the most outstanding problems in science today

The Cosmic Timeline



Fairly well understood

The current frontier

Physics reasonably well understood

Highly speculative physics