A brief history of cosmological ideas

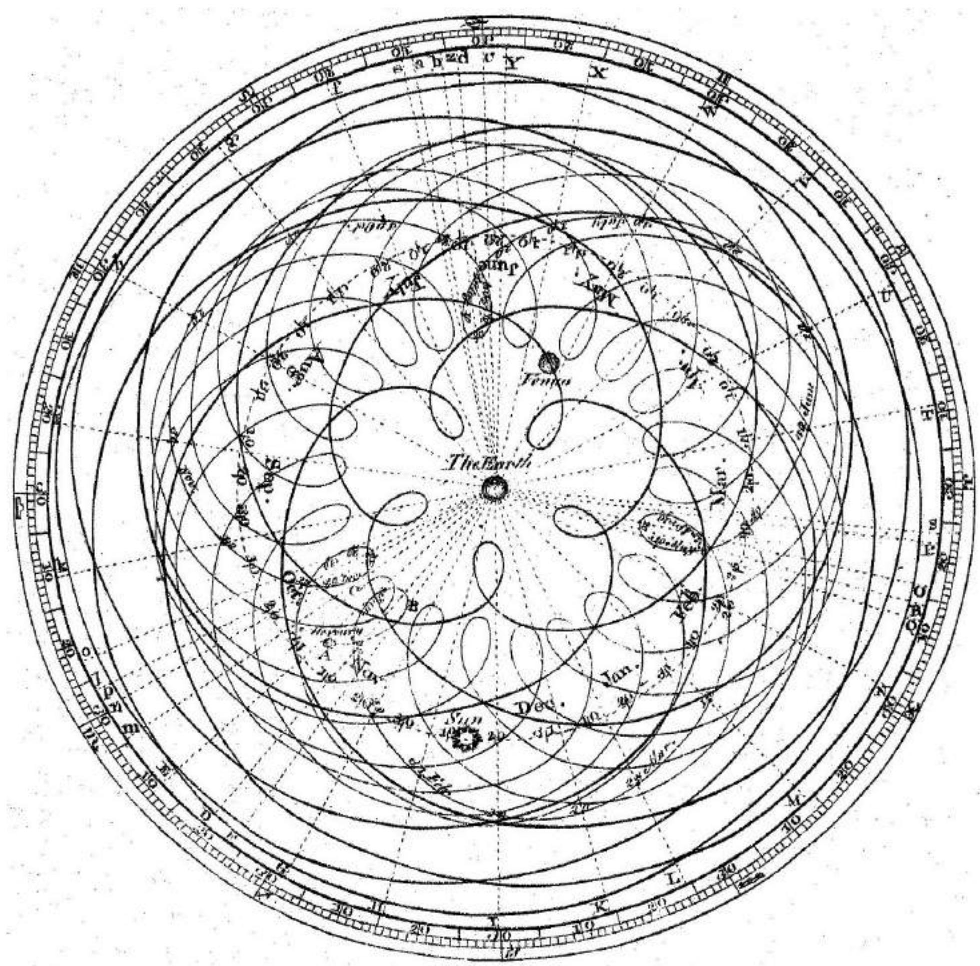
<u>Cosmology:</u> Science concerned with the origin and evolution of the universe, using the laws of physics.

<u>Cosmological principle:</u> Our place in the universe is not special
$\Rightarrow$ our laws of physics apply elsewhere.

Ancient Greeks

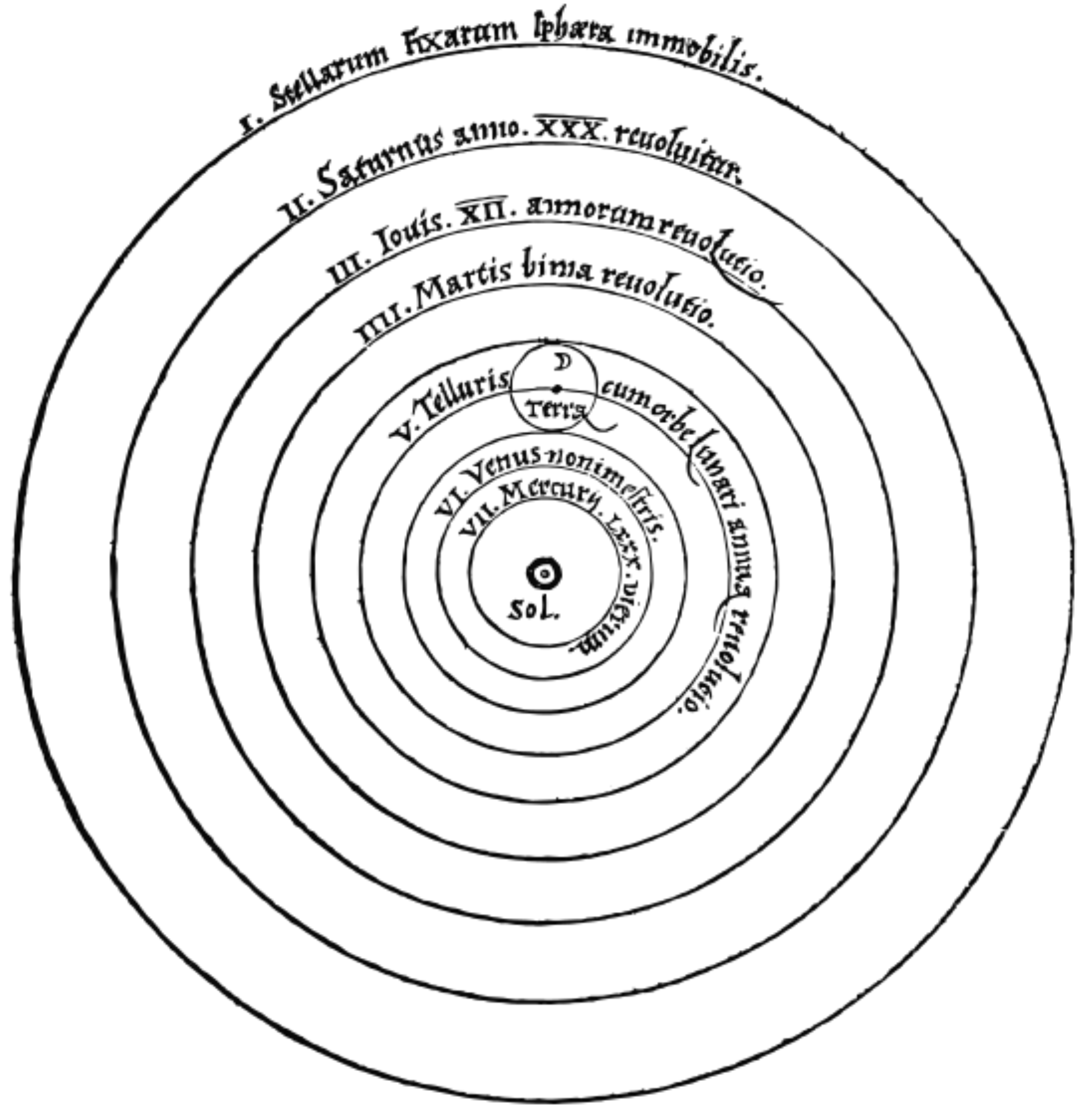
<u>Geocentric:</u> Earth at center of cosmos, circled by Moon, Sun, and planets.

Ptolemy's (90-168 AD) epicyclic model explained planetary motion



Copernicus (early 1500s)

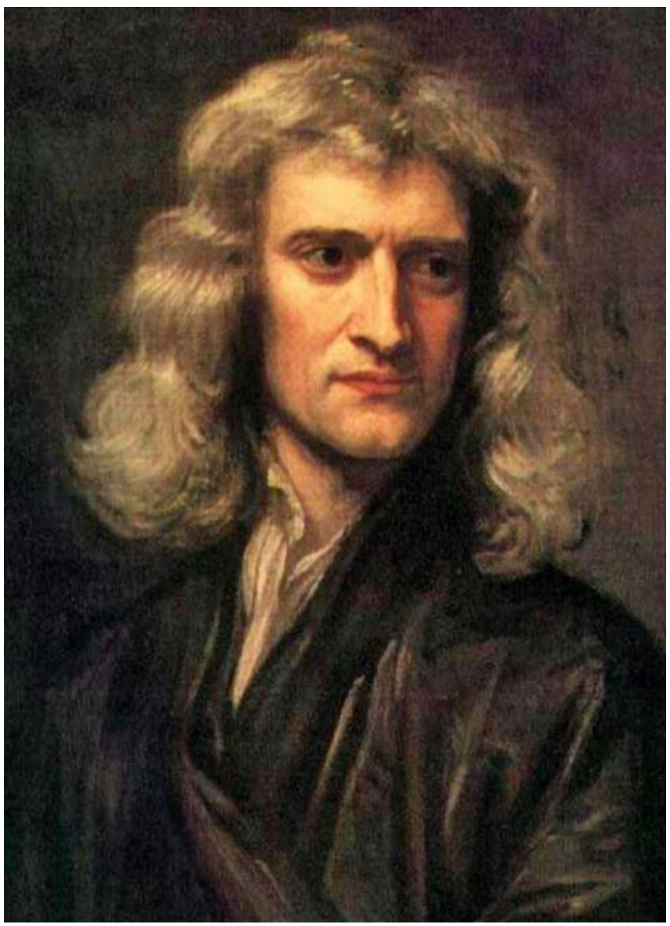
__Heliocentric:__ Earth and planets revolve around the Sun.

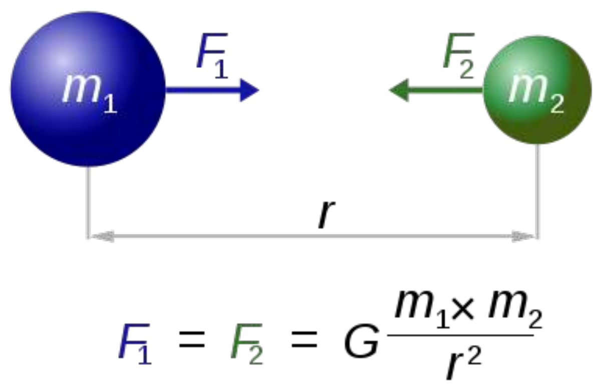


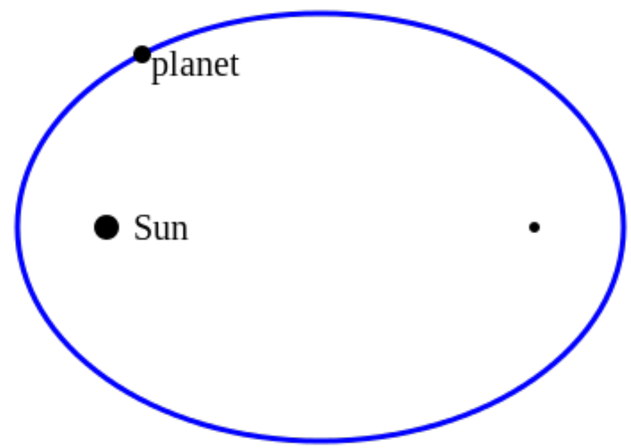
Newton (1600s)

<u>Physics:</u> Laws of motion and gravitation explain motion of planets around the Sun.

Realized that stars were 'suns' distributed roughly uniformly throughout the universe. Assumed that space was infinite. He knew this situation was unstable (stars attract each other so over-densities should grow).







Herschels (late 1700s)

William & Caroline (brother & sister) collaborated.

Made telescopes and astronomical measurements.

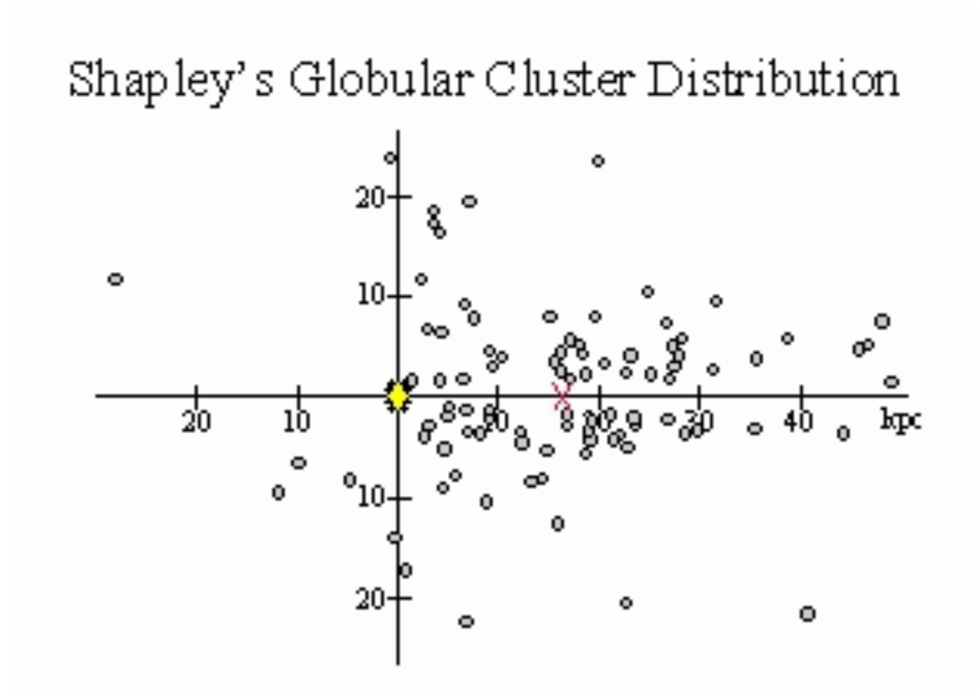
Found that stars are not evenly distributed but assembled in disk-shaped structure, the Milky Way galaxy.

Wrongly concluded that the Solar System is at the center of the Milky Way.

Shapley (early 1900s)

By measuring the distribution of globular clusters, inferred that the Sun is ~2/3 of radius away from center of the Milky Way.

Believed that the Galaxy was at the center of the universe.



Baade (1952)

Observed many galaxies.

Concluded that the Milky Way is a fairly typical galaxy.

⇒ consistent with cosmological principle

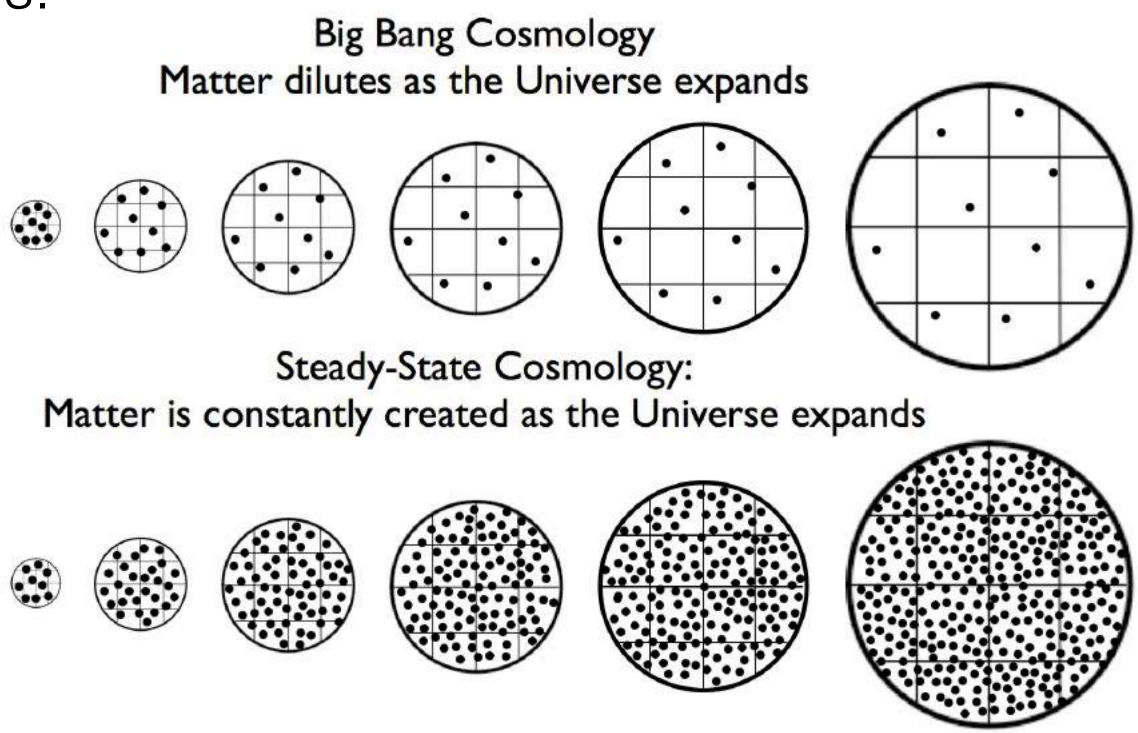
that we are not in a special location.

Note: Cosmological principle is not exact — holds better and better on larger length scales, e.g. in large regions of the universe containing millions of galaxies. Locally, the universe can be very inhomogeneous ('clumpy').

Big Bang cosmology

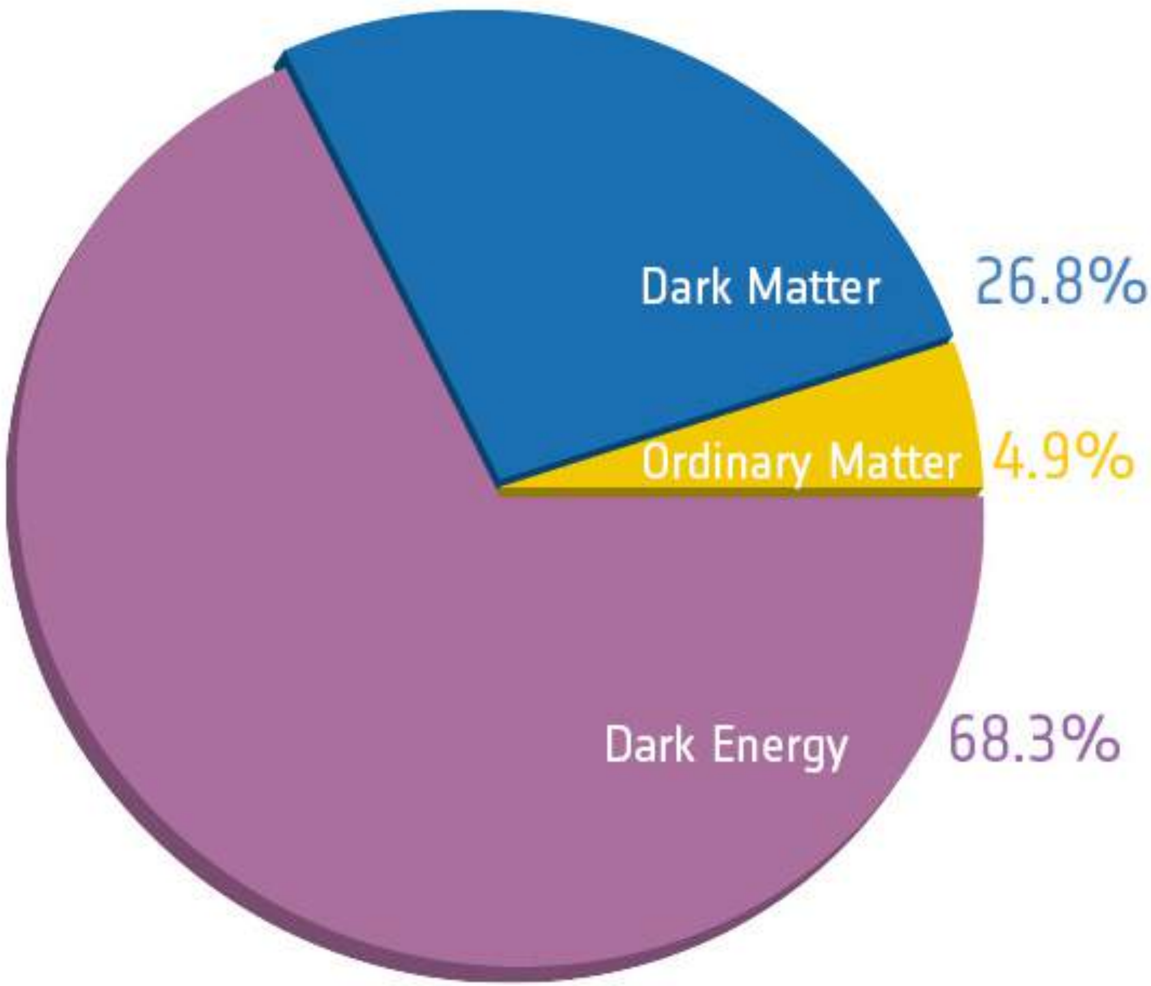
Current best description of the universe: the universe is expanding, and was much denser and hotter in the past.

Contrast with the steady state universe, advocated by several prominent astrophysicists in the mid 1950s (Bondi, Gold, Hoyle, …), but now discredited: universe does not evolve but rather has looked forever the same (no 'beginning'), with new material being created to fill gaps as the universe expands.



What we will cover in this course

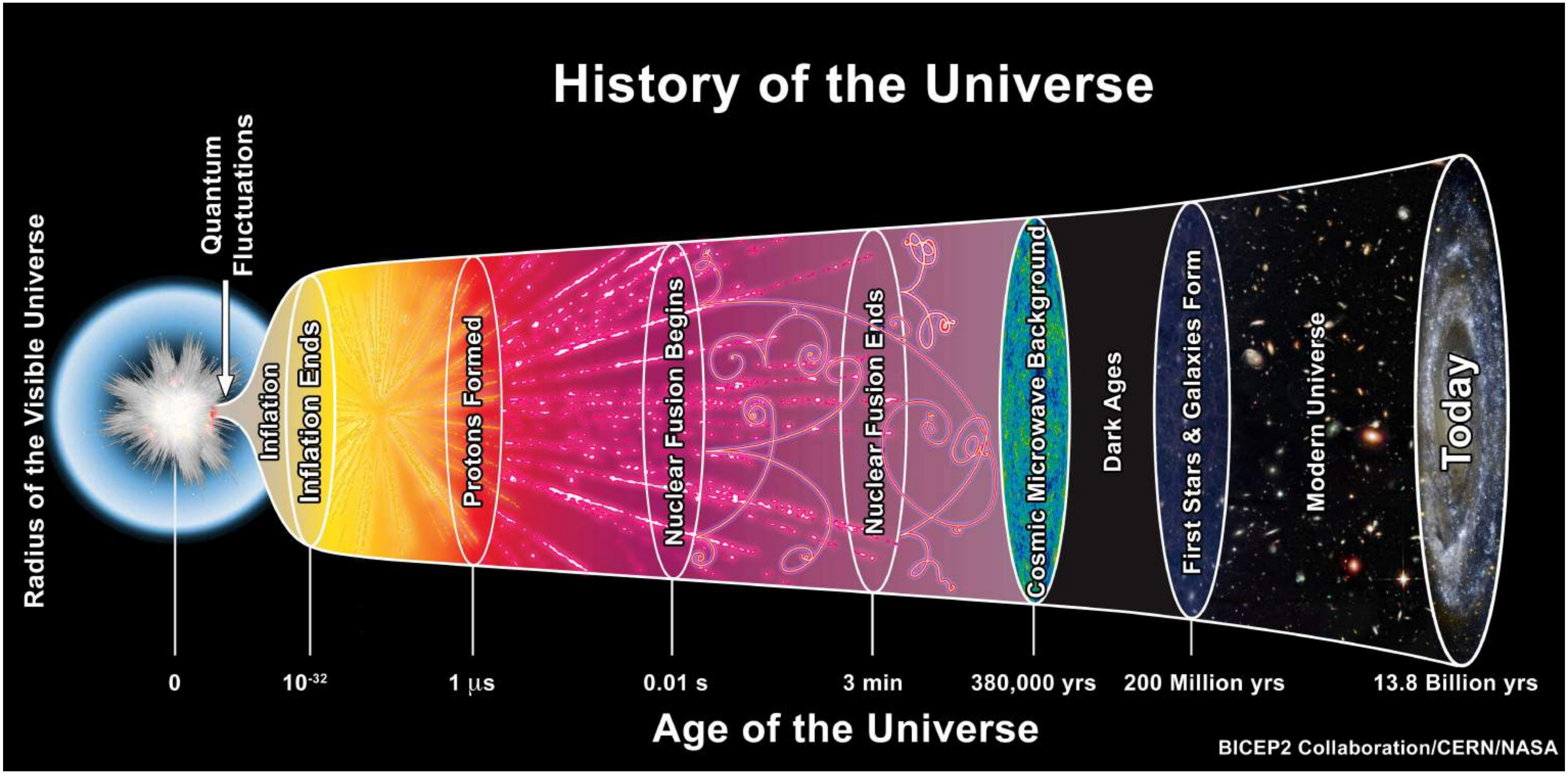
The standard "inflationary Λ cold dark matter (ΛCDM)" cosmological model (more precise name for best-fit Big Bang model)



- What is it?
- What are the different components?
- What is the empirical evidence (+some history)?
- What are the big open questions?
- How do to calculations in an expanding universe.

Planck 2013

Different epochs in the evolution of the universe

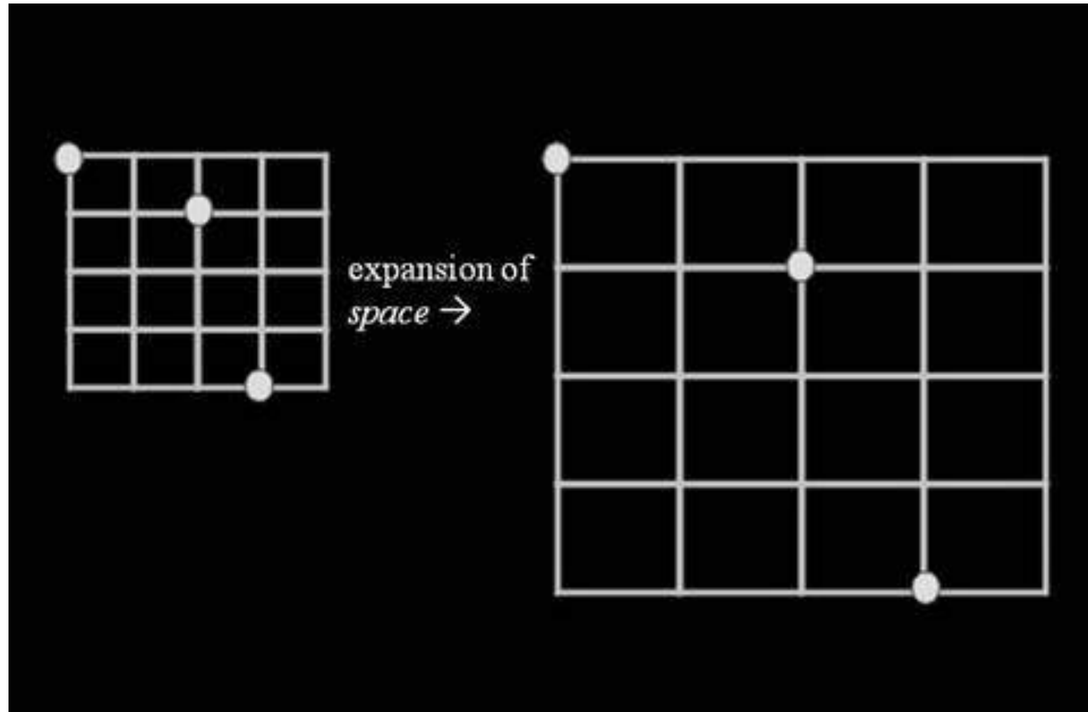


Eras of:
- radiation domination
- matter domination
- dark energy domination

Important phases in the early universe:
- cosmic microwave background
- Big Bang nucleosynthesis
- inflation

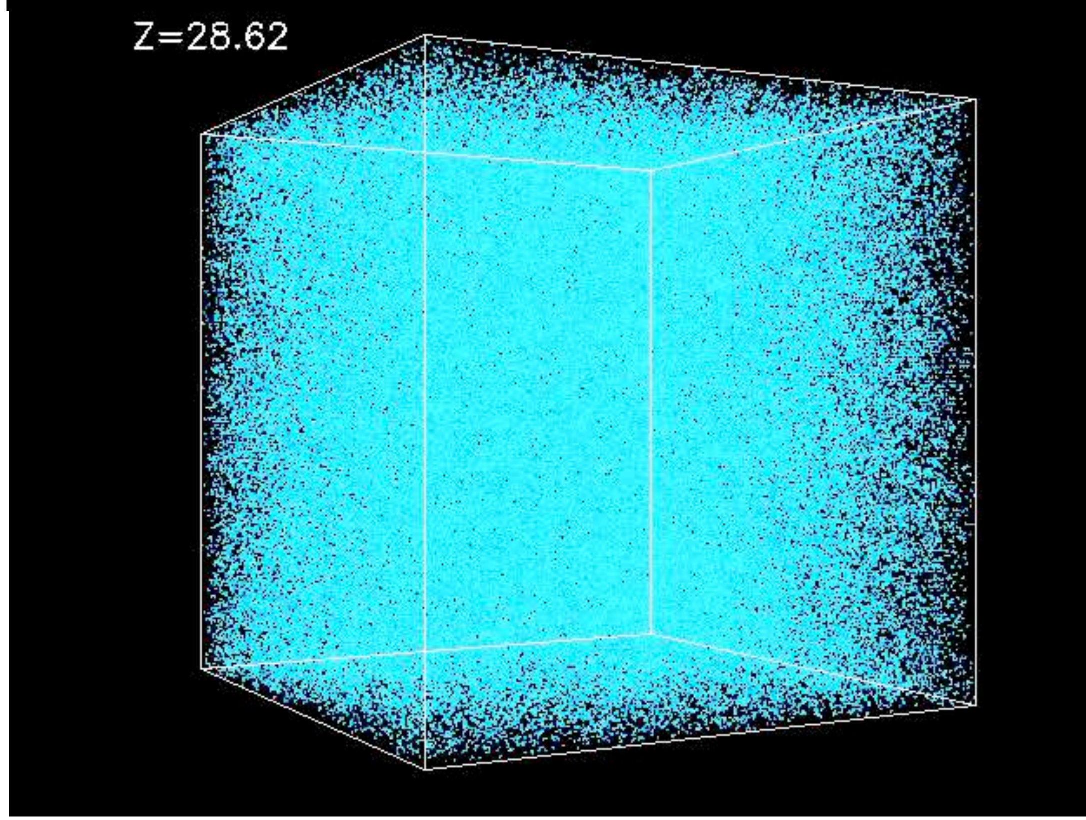
The smooth universe vs. the lumpy universe

When averaged over very large scales, the universe can be approximated as smooth — relevant picture for describing expansion and overall evolution



On smaller scales, gravity amplifies density perturbations and the universe becomes highly inhomogeneous — view relevant for studying the formation of large-scale structure and galaxies

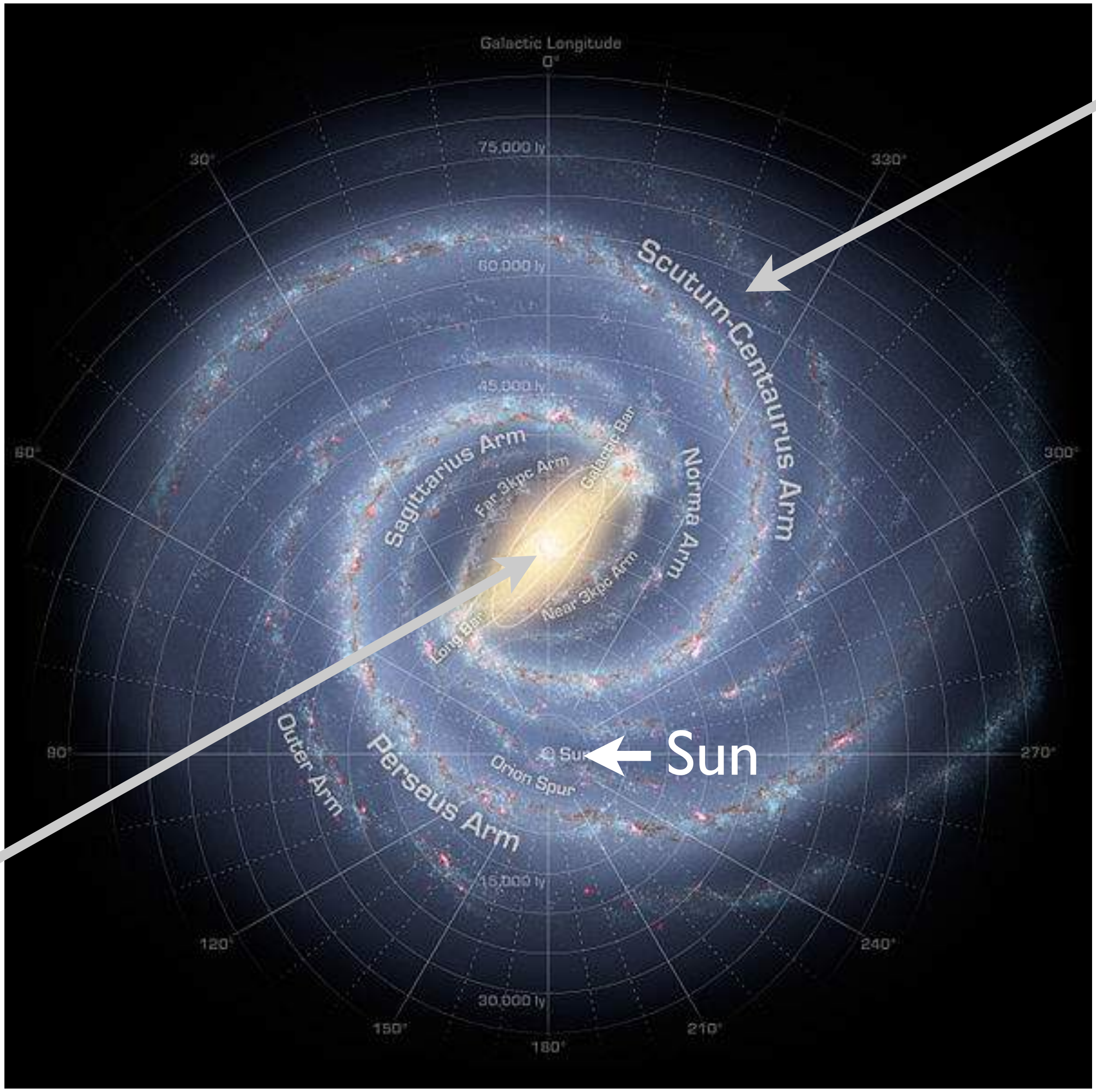
Dark matter in ΛCDM simulation



Galaxies and their spatial distribution

What is a galaxy? The Milky Way

disk of stars,
dust, and gas
$\sim 10^{11}$ stars



4×10^{6} M_{sun}
black hole

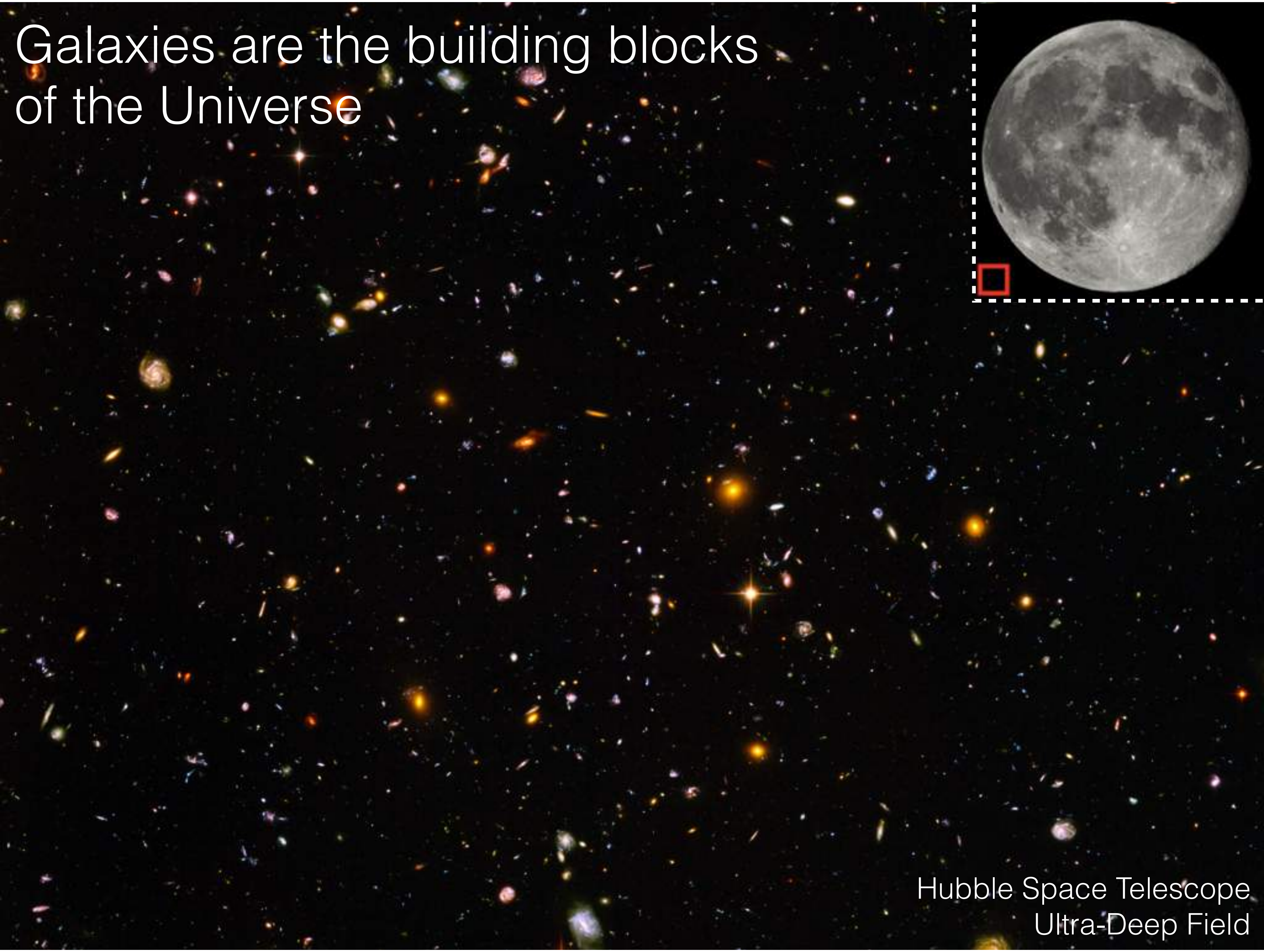
8 kpc
1 pc≈3 lyr

rotation period
at R_{sun}~200 Myr

Gravity turns gas into stars

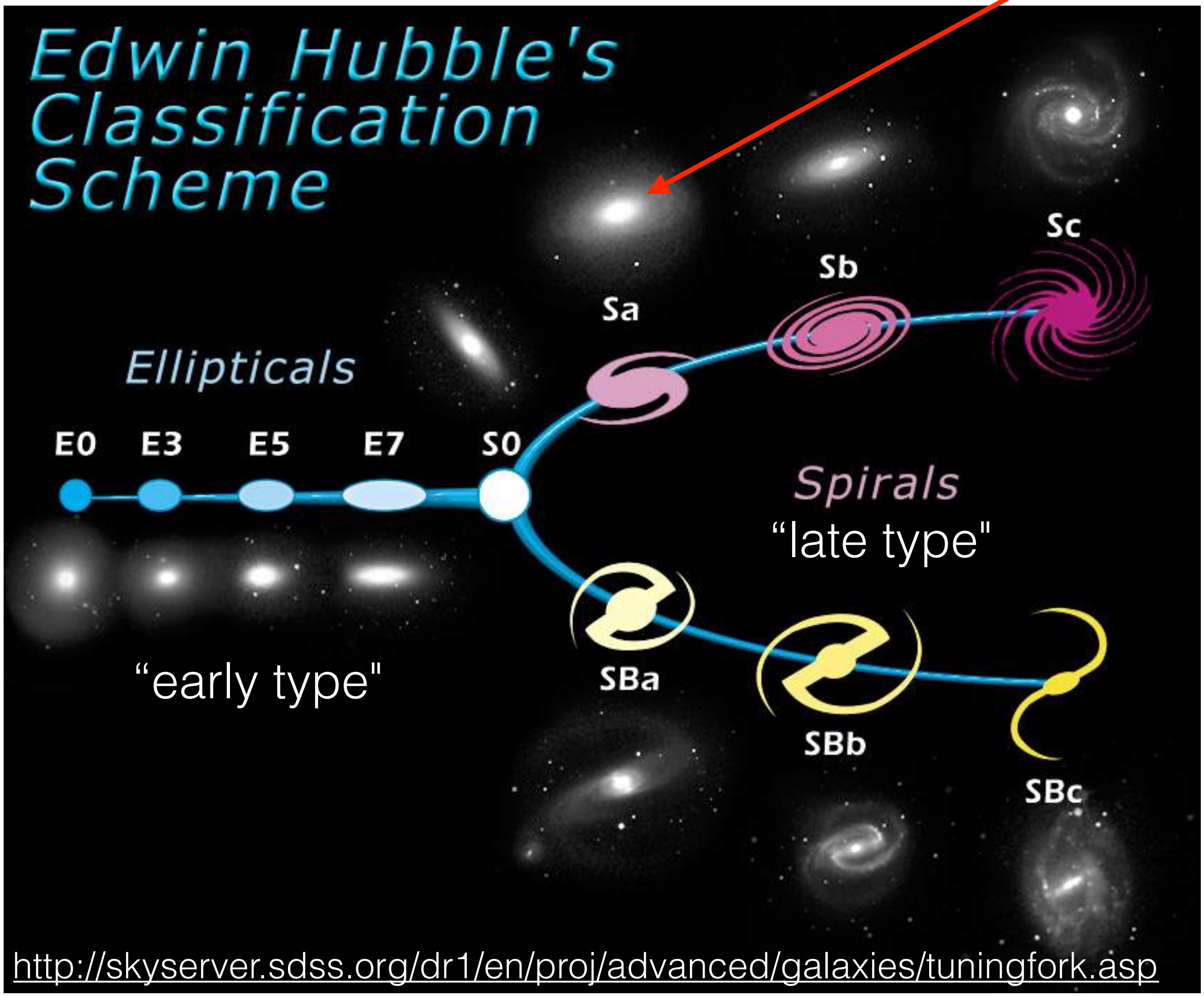
(all in a halo of dark matter)

Galaxies are the building blocks of the Universe



Hubble's morphological classes

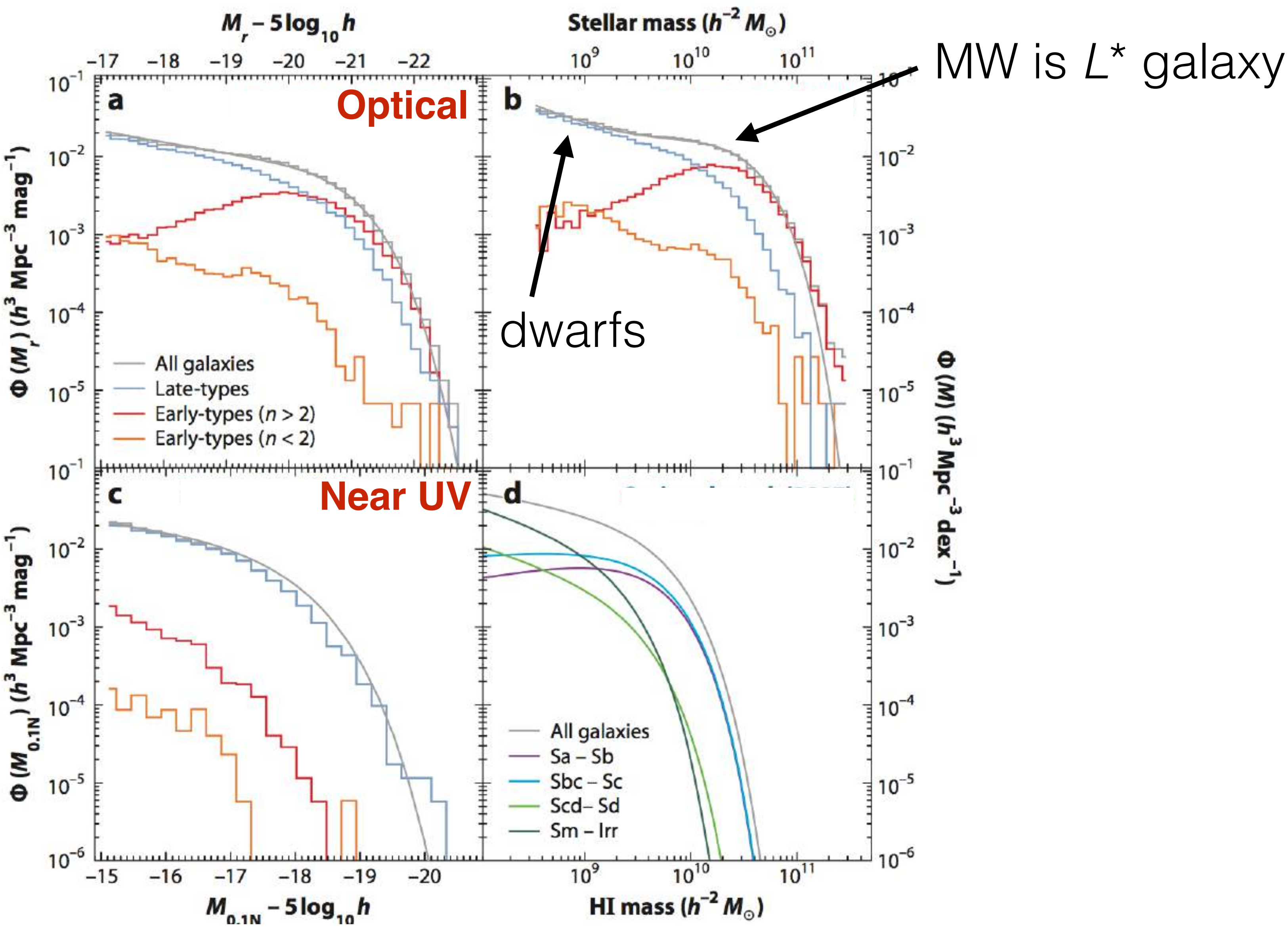
bulge or spheroidal component



barred

Not a time or physical sequence

Luminosity and mass functions

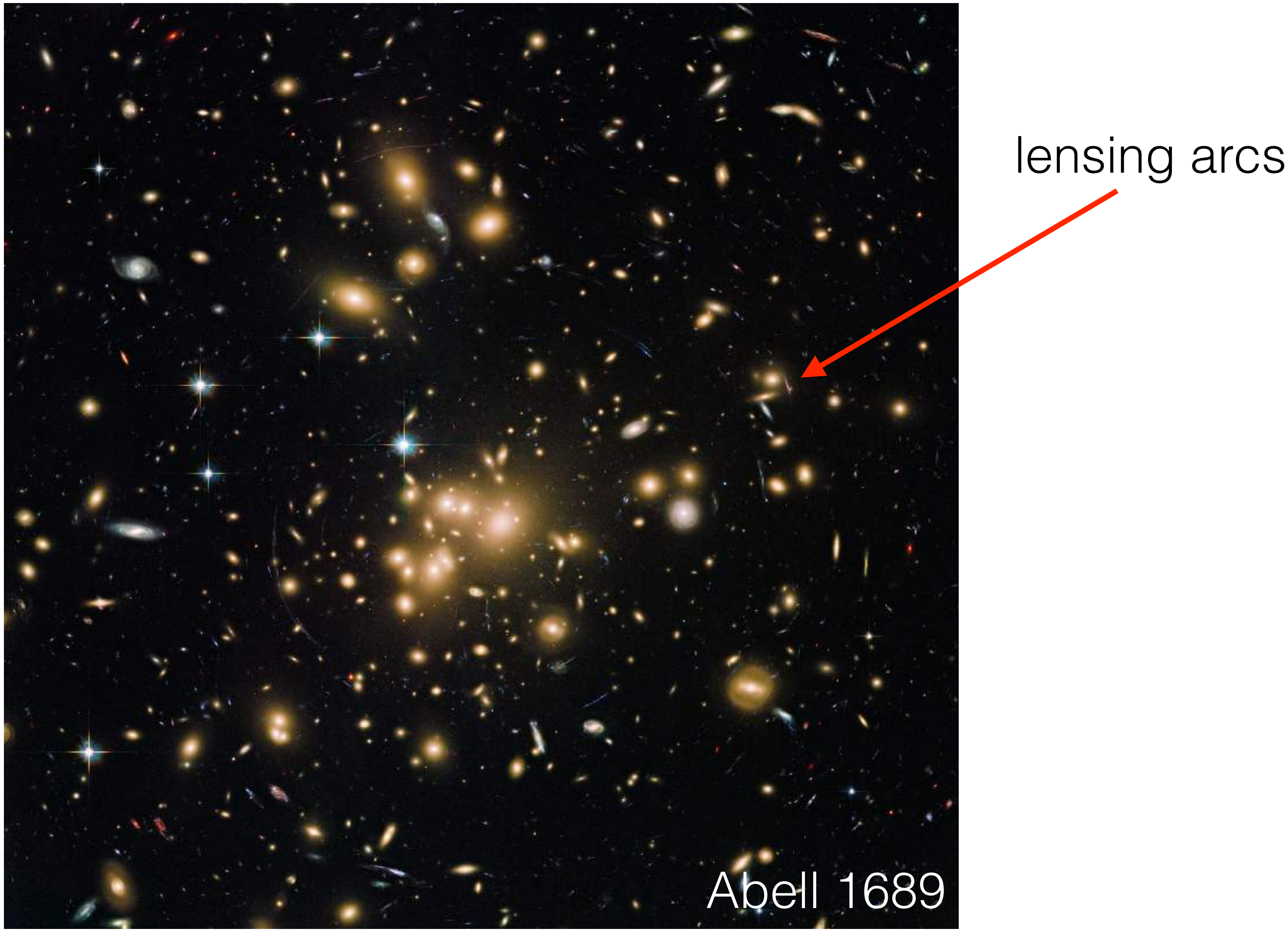


Schechter fits: $\Phi(L)dL = \frac{dL}{L_*}\exp(-L/L_*)\left[\phi_{*,1}\left(\frac{L}{L_*}\right)^{\alpha_1} + \phi_{*,2}\left(\frac{L}{L_*}\right)^{\alpha_2}\right]$

$M = -2.5\log_{10} L + const.$

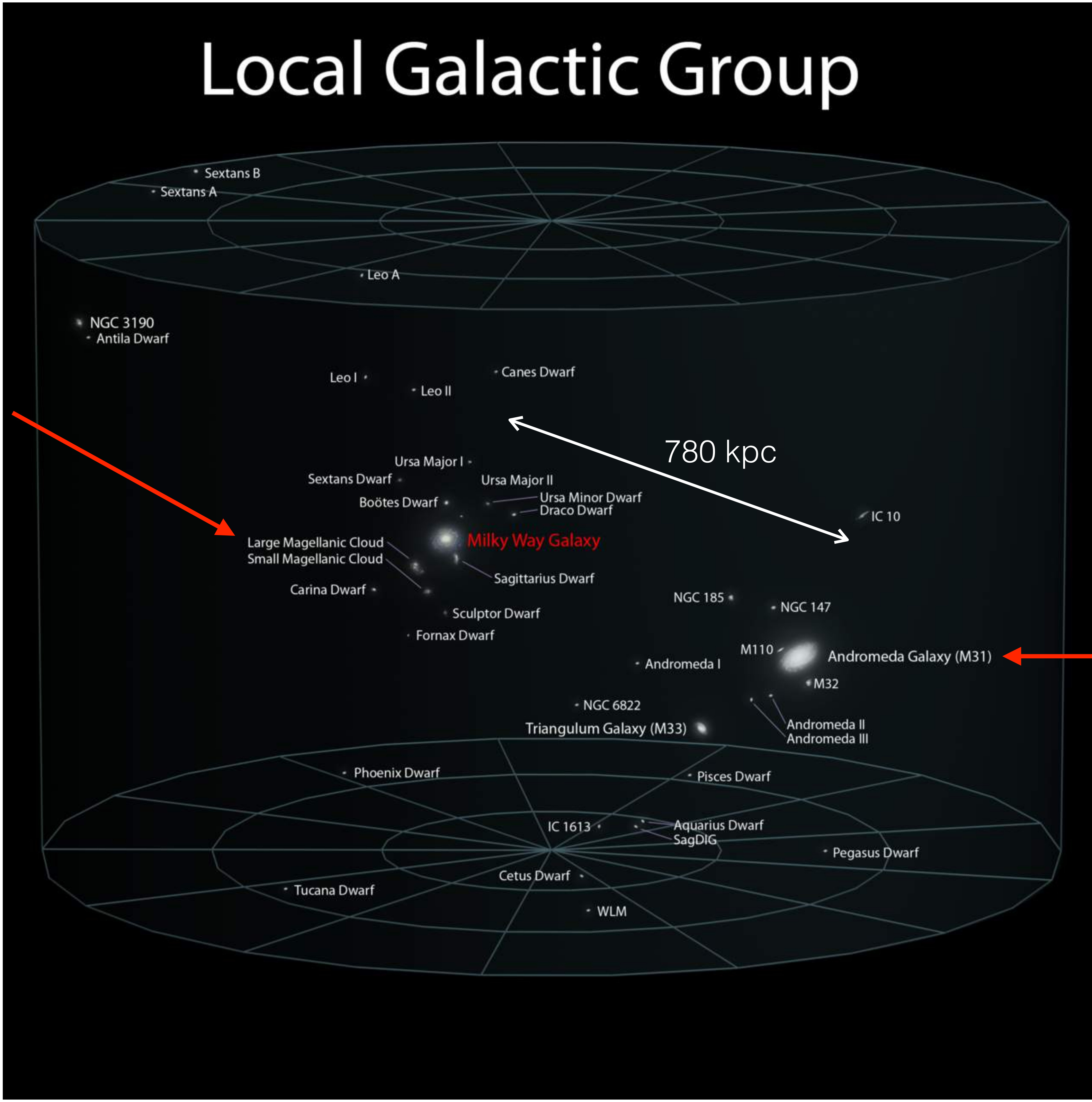
Local galaxies from SDSS; Blanton & Moustakas 08

Galaxy clusters



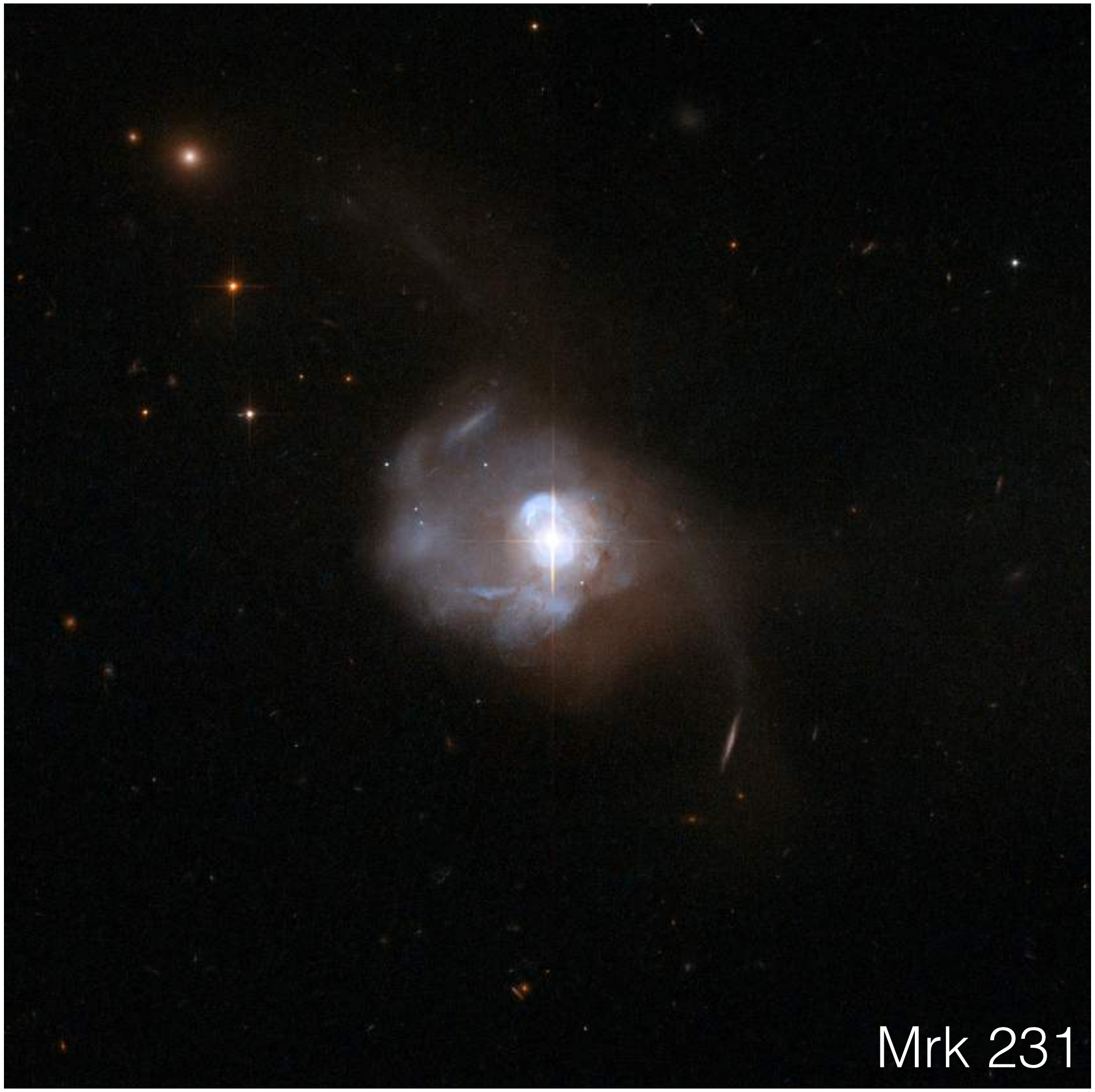
- most massive gravitational bound objects in the Universe
- contain up to thousands of galaxies
- most baryons intracluster gas, T~10^7-10^8 K gas
- smaller collections of bound galaxies are called 'groups'

well-
studied
MW
satellites



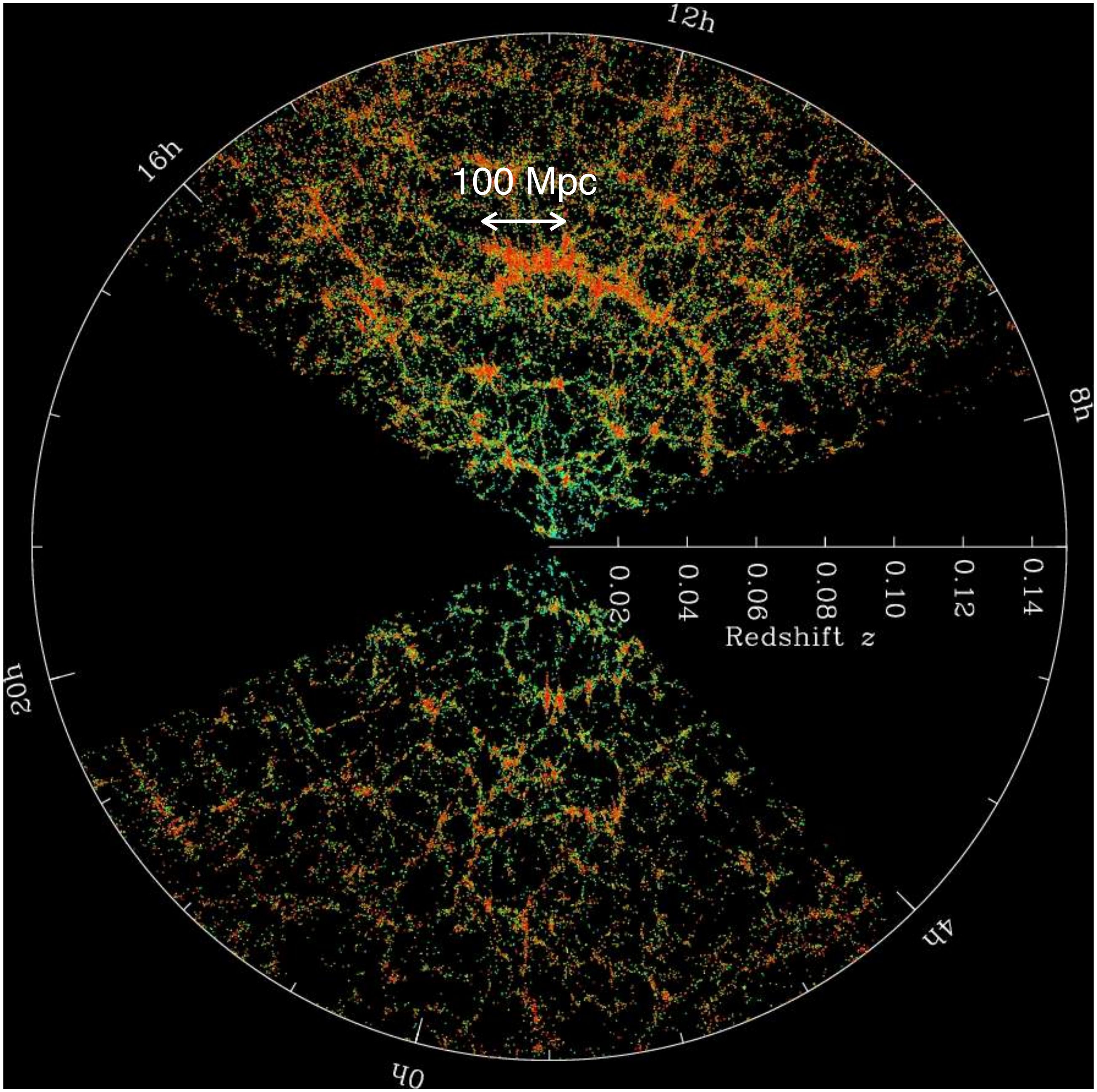
most
massive

Active galactic nuclei



- accreting nuclear black holes visible as AGN
- the most luminous AGN are called quasars (can outshine entire host galaxy)
- in local Universe, quasars are associated with galaxy mergers

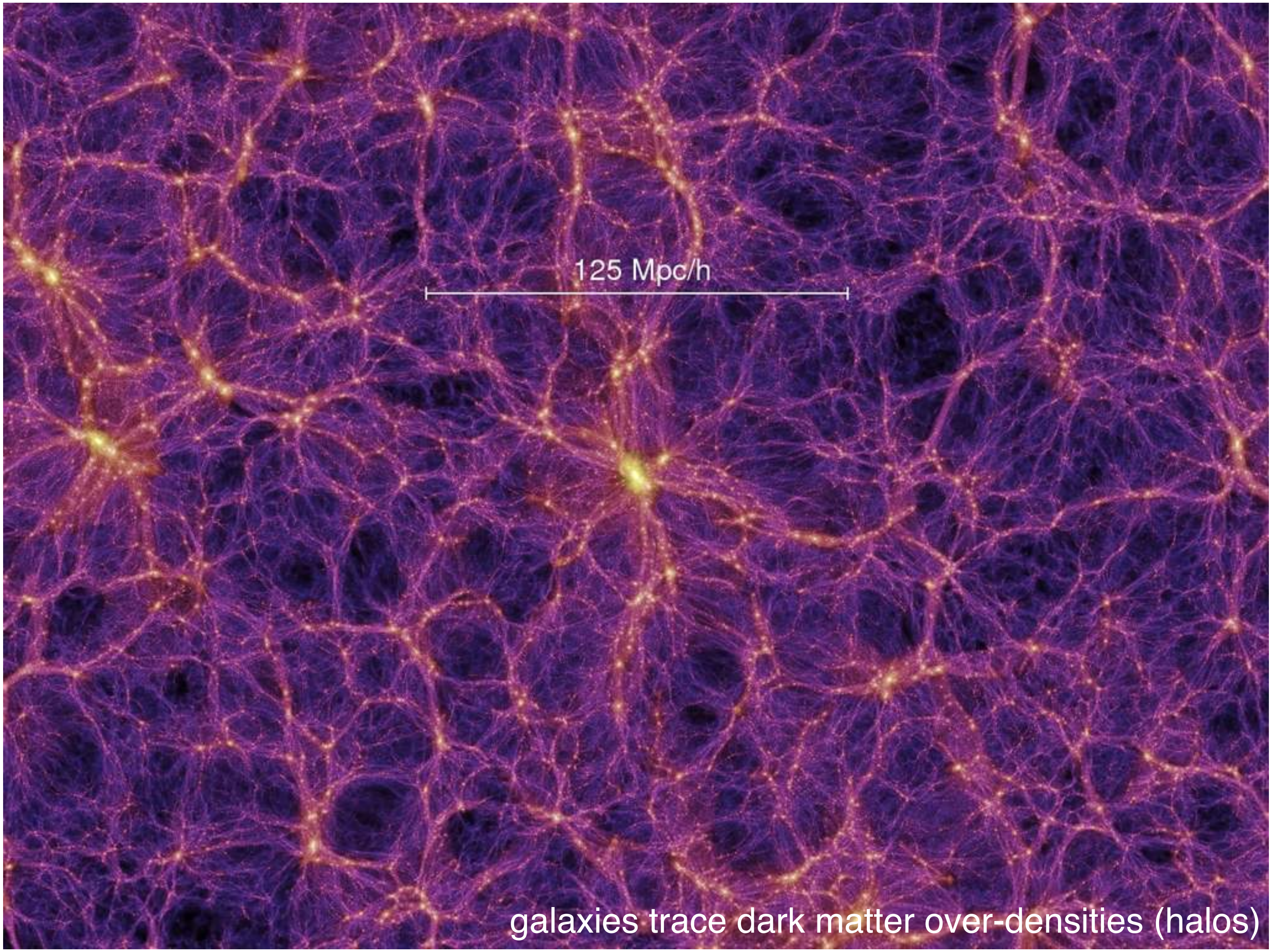
Map of large-scale structure traced by galaxies



Sloan Digital Sky Survey

- in cosmology, detailed structure of galaxies is often irrelevant — thought of as point-like
- galaxies cluster on small scales, smoothly distributed on very large scales
- largest structures (voids and super-clusters) ~100 Mpc

Preview: Galaxy clustering is the result of gravitational instability amplifying tiny density fluctuations seeded by 'inflation'



Millennium simulation showing the dark matter distribution at the present time (Springel 2005)

Discovery of the cosmic microwave background

Bell Labs work on early communication satellites

- 1964: Arno Penzias and Robert Wilson experimenting with super-sensitive 6-m horn antenna built to detect radio waves bouncing off Echo balloon satellites
- after working hard to eliminate undesirable sources of noises (including pigeon droppings), could not get rid of background noise with temperature ~3 K, apparently uniform on the sky

Echo 2 satellite, lifted to ~1,000 km orbit

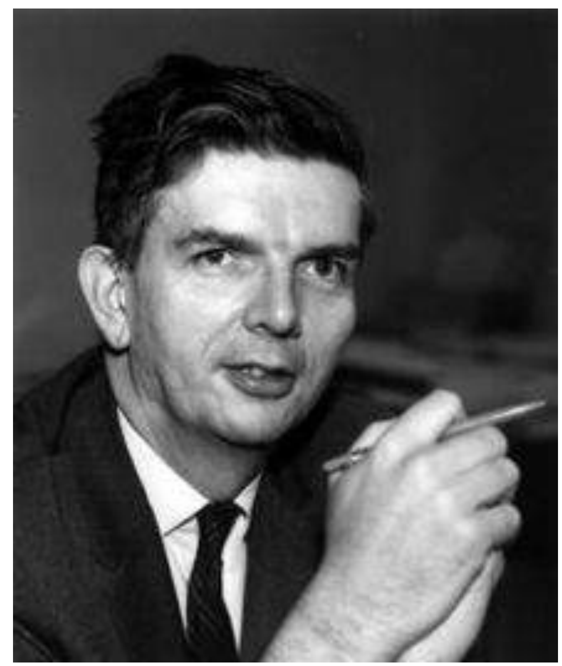
Penzias & Wilson with antenna in Holmdel, NJ

Princeton work on early Universe

- Just 60 km away, Robert Dicke, Jim Peebles, and David Wilkinson at Princeton University were preparing to search for microwave radiation left over from the Big Bang
- Microwave radiation had been predicted in the context of the Big Bang model by George Gamow, Dicke and Peebles
- Penzias heard of the Princeton cosmology work and contacted Dicke

Gamow

Peebles



Dicke

Peebles' prediction of the CMB

THE BLACK-BODY RADIATION CONTENT OF THE UNIVERSE AND THE FORMATION OF GALAXIES*

P. J. E. PEEBLES
Palmer Physical Laboratory, Princeton University, Princeton, N J.
Received March 8, 1965; revised June 1, 1965

ABSTRACT

A critical factor in the formation of galaxies may be the presence of a black-body radiation content of the Universe. An important property of this radiation is that it would serve to prevent the formation of gravitationally bound systems, whether galaxies or stars, until the Universe has expanded to a critical epoch. There is good reason to expect the presence of black-body radiation in an evolutionary cosmology, and it may be possible to observe such radiation directly.

Two coordinated discovery papers in ApJ

A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE
AT 4080 Mc/s

Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and free from seasonal variations (July, 1964–April, 1965). A possible explanation for the observed excess noise temperature is the one given by Dicke, Peebles, Roll, and Wilkinson (1965) in a companion letter in this issue.

. . .

A. A. Penzias
R. W. Wilson

May 13, 1965
Bell Telephone Laboratories, Inc
Crawford Hill, Holmdel, New Jersey

1978 Nobel Prize in Physics

COSMIC BLACK-BODY RADIATION*

One of the basic problems of cosmology is the singularity characteristic of the familiar cosmological solutions of Einstein's field equations. Also puzzling is the presence of matter in excess over antimatter in the universe, for baryons and leptons are thought to be conserved. Thus, in the framework of conventional theory we cannot understand the origin of matter or of the universe. We can distinguish three main attempts to deal with these problems.

. . .

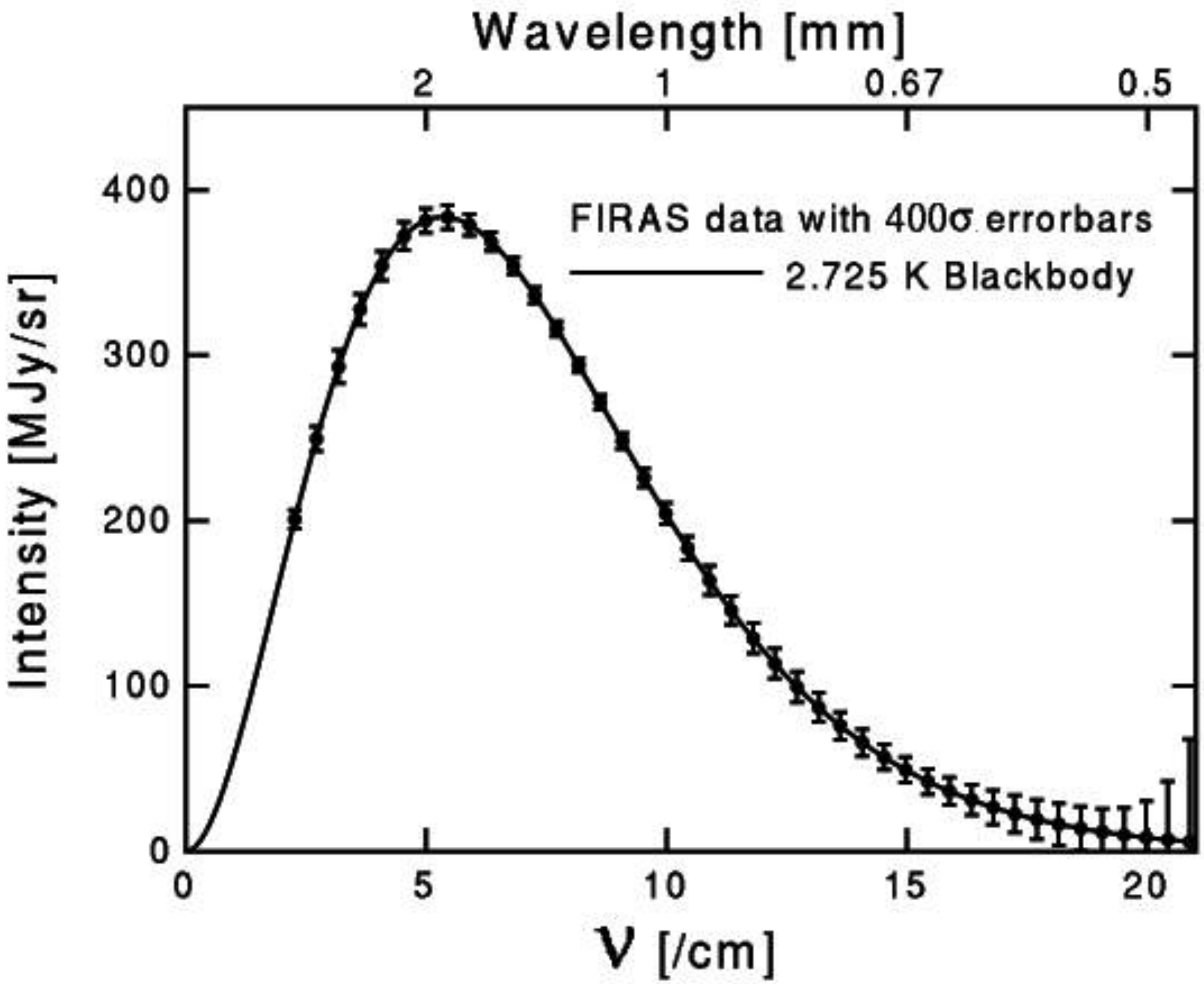
While we have not yet obtained results with our instrument, we recently learned that Penzias and Wilson (1965) of the Bell Telephone Laboratories have observed background radiation at 7.3-cm wavelength. In attempting to eliminate (or account for) every contribution to the noise seen at the output of their receiver, they ended with a residual of $3.5° \pm 1° K$. Apparently this could only be due to radiation of unknown origin entering the antenna.

. . .

R. H. Dicke
P. J. E. Peebles
P. G. Roll
D. T. Wilkinson

May 7, 1965
Palmer Physical Laboratory
Princeton, New Jersey

Perfect black body spectrum of the CMB



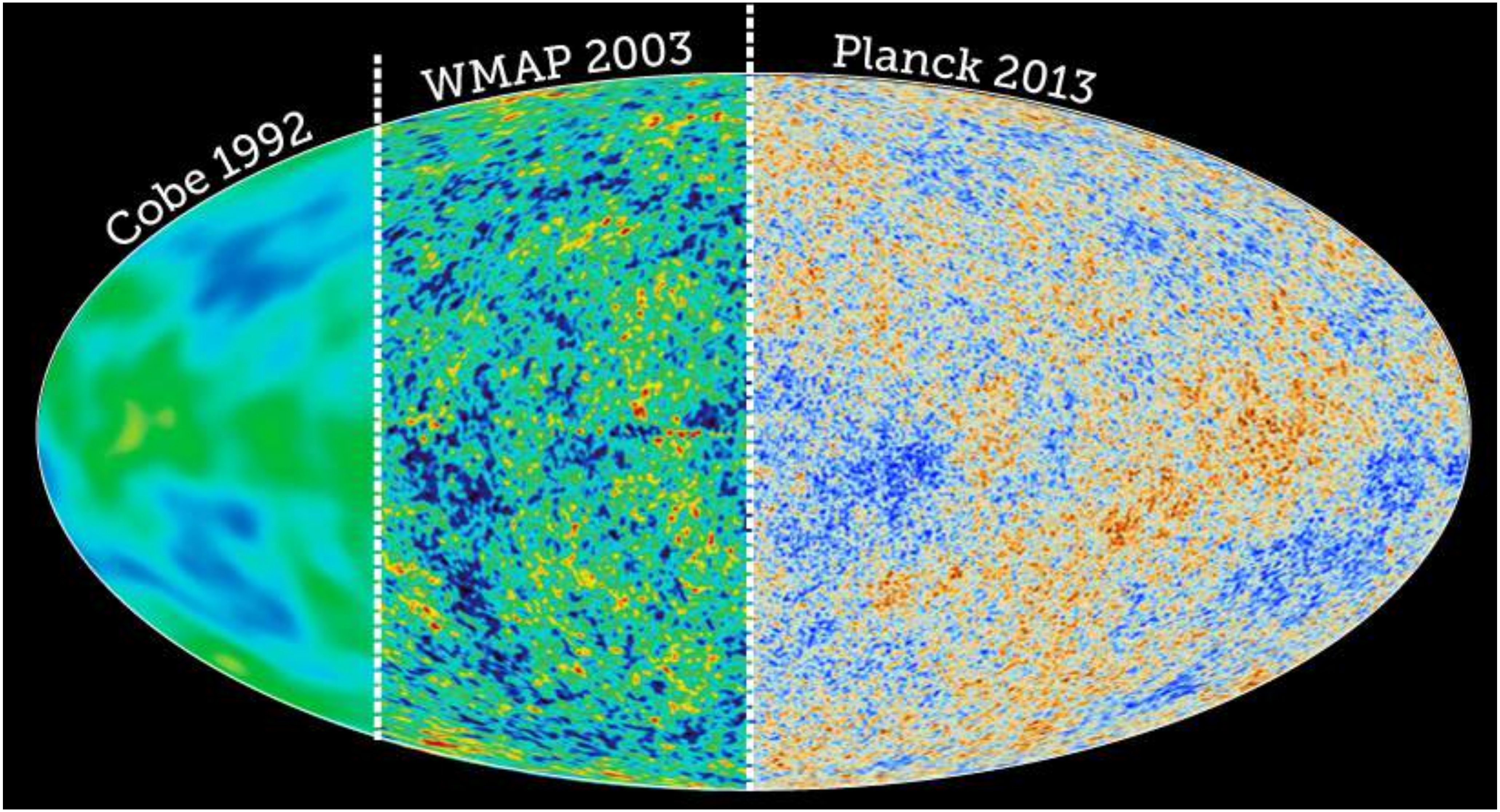
Far Infrared Absolute Spectrophotometer (FIRAS)

aboard the

Cosmic Background Explorer (COBE) satellite

Mather+94, Fixen+96

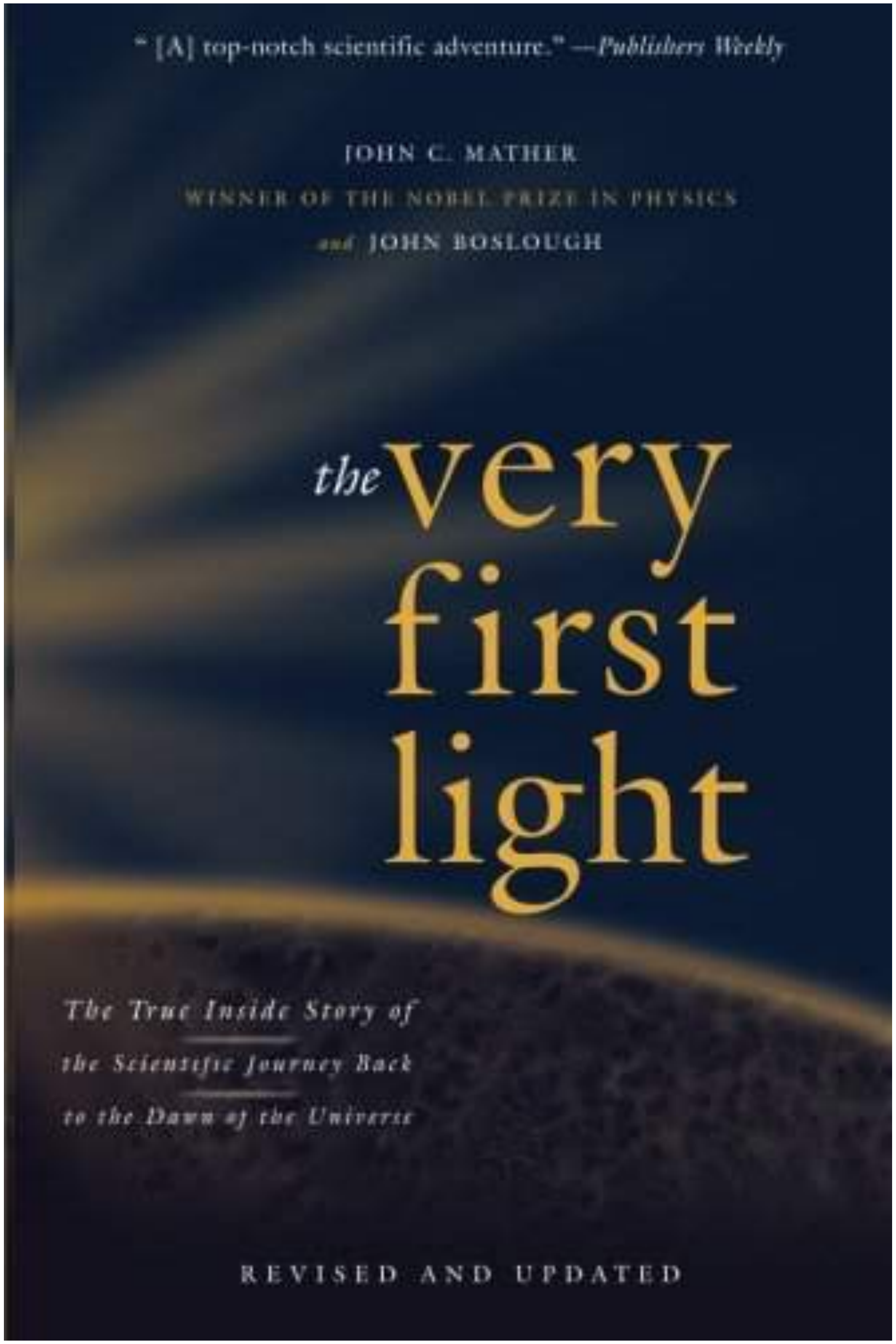
Fluctuations (anisotropies) in CMB



map of density fluctuations ~400,000 yr after Big Bang — contrast enhanced by 10^5

⇒ uniformity on large scales is strong evidence for cosmological principle

For more on the history of the CMB:



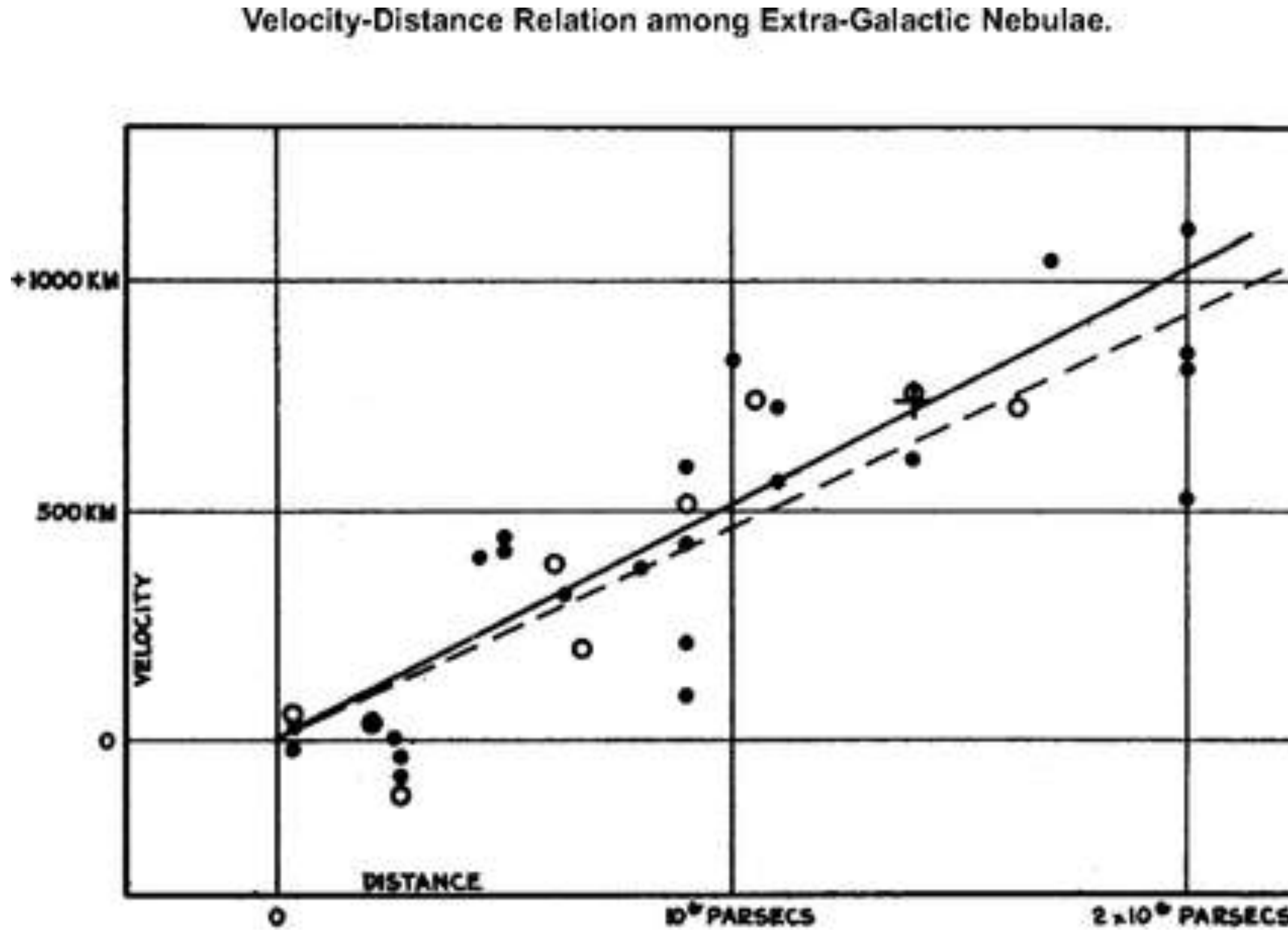
John Mather and George Smoot

shared 2006 Nobel Prize in Physics

for work on COBE

Hubble's Law

Hubble's original 1929 diagram



Distances determined using stars of known luminosity, including Cepheids

Note: velocity units should be km/s