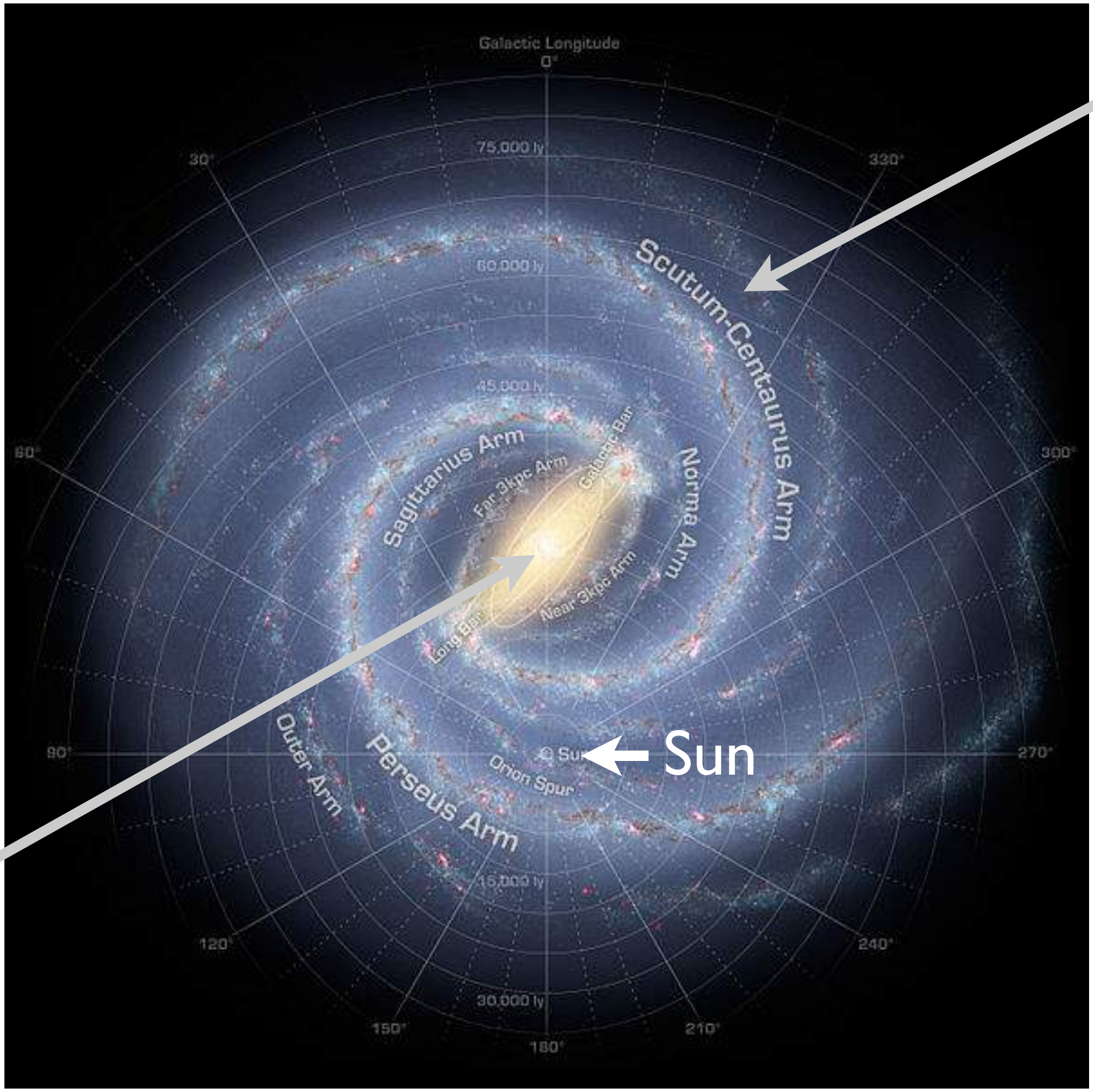
Observational overview of extragalactic astrophysics

What is a galaxy? The Milky Way

disk of stars,
dust, and gas
~10^{11} stars



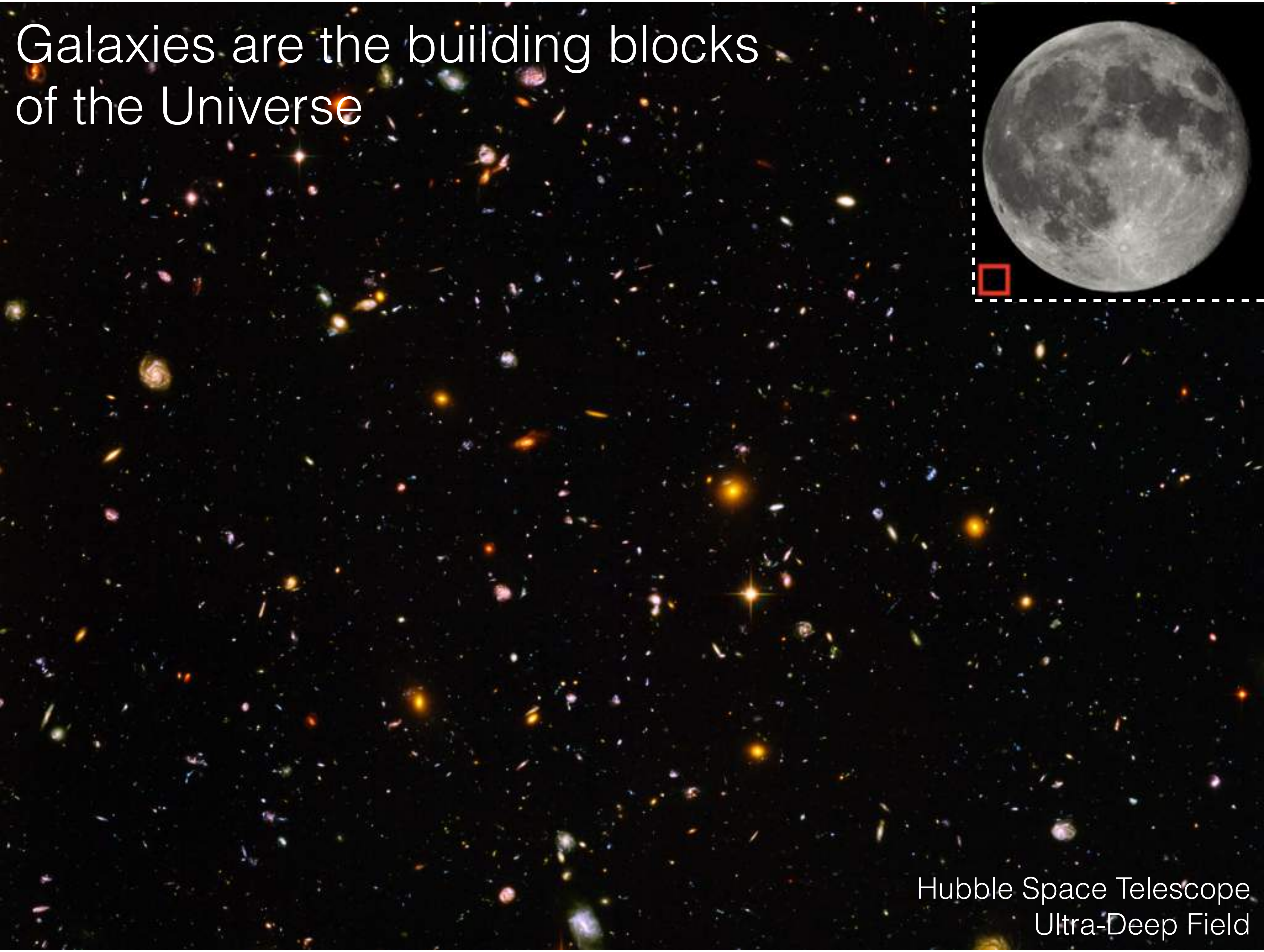
8 kpc
1 pc≈3 lyr

rotation period
at R_{sun}~200 Myr

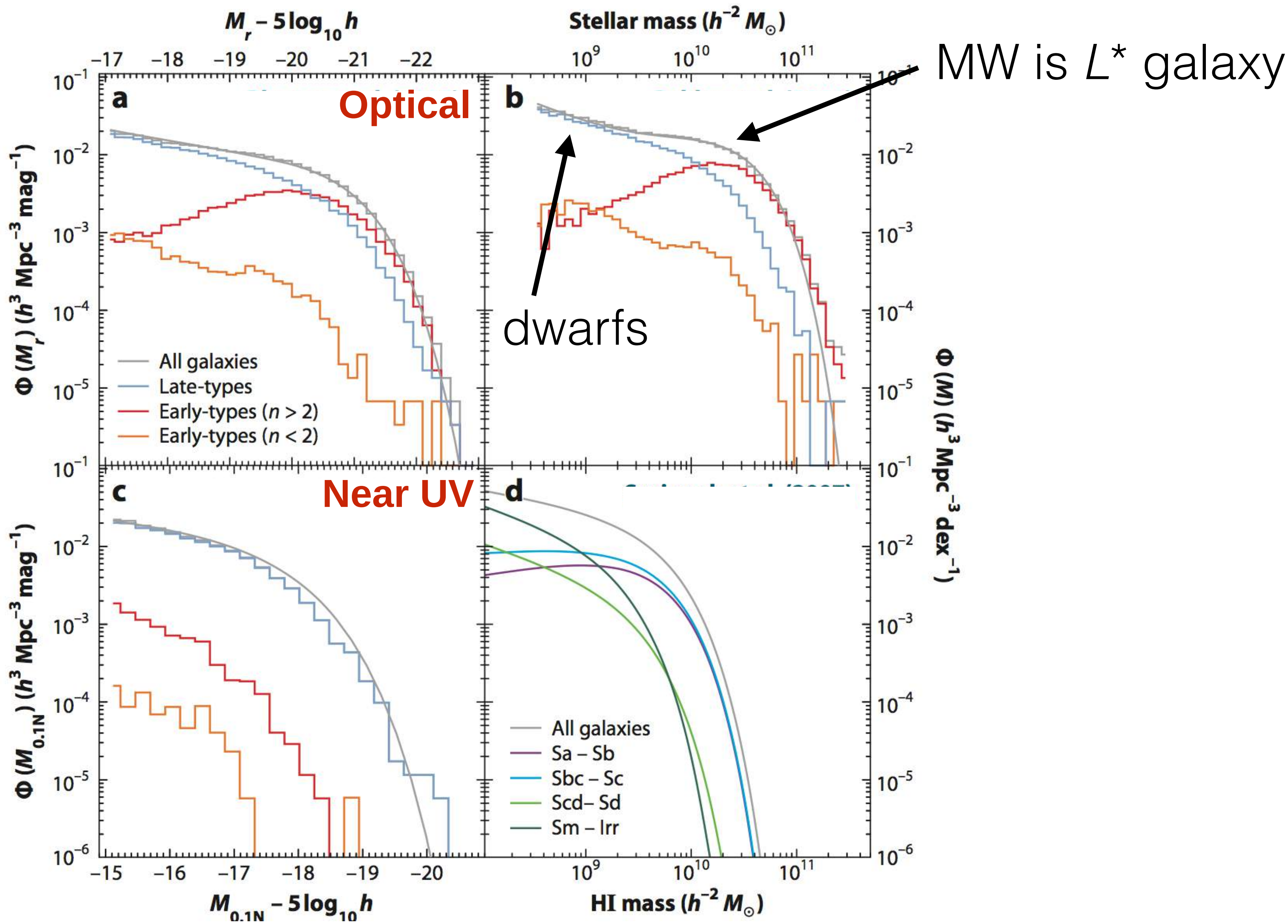
4×10^6 M_{sun}
black hole

Gravity turns gas into stars

(all in a halo of dark matter)


Galaxies are the building blocks
of the Universe
Hubble Space Telescope
Ultra-Deep Field

Luminosity and mass functions



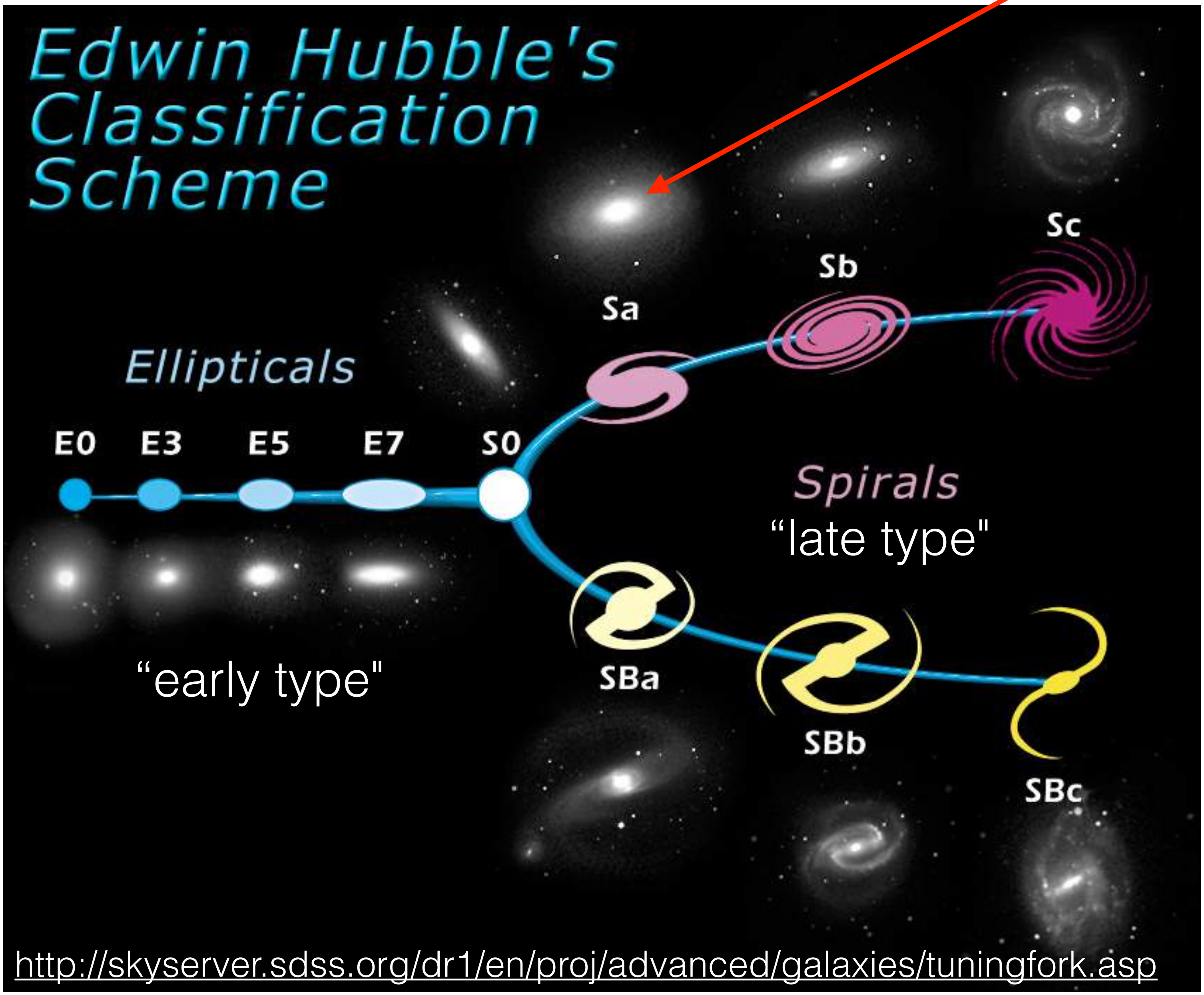
Schechter fits: $\Phi(L)dL = \frac{dL}{L_*}\exp(-L/L_*)\left[\phi_{*,1}\left(\frac{L}{L_*}\right)^{\alpha_1} + \phi_{*,2}\left(\frac{L}{L_*}\right)^{\alpha_2}\right]$

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

Local galaxies from SDSS; Blanton & Moustakas 08

Hubble's morphological classes

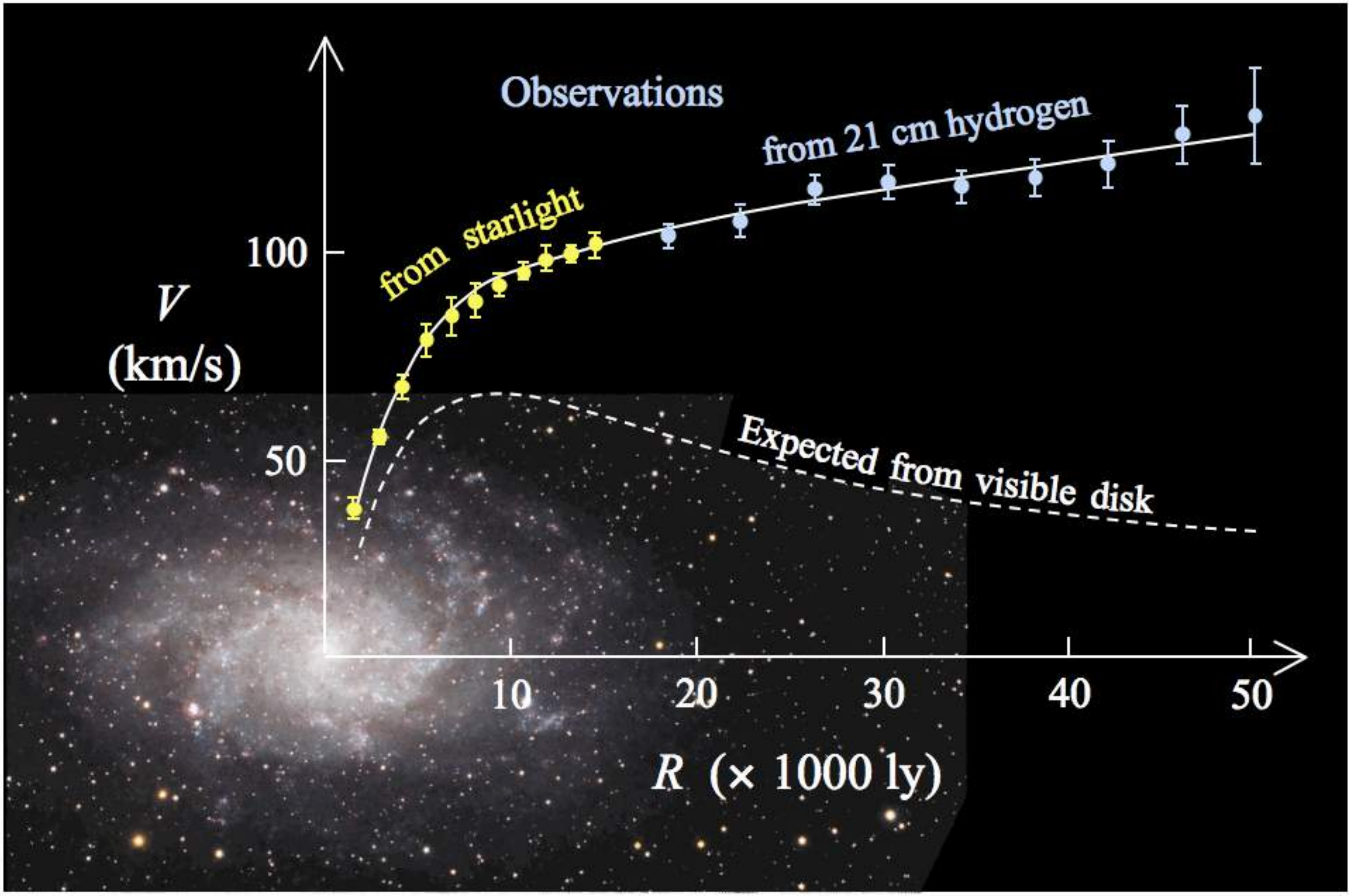
bulge or spheroidal component



barred

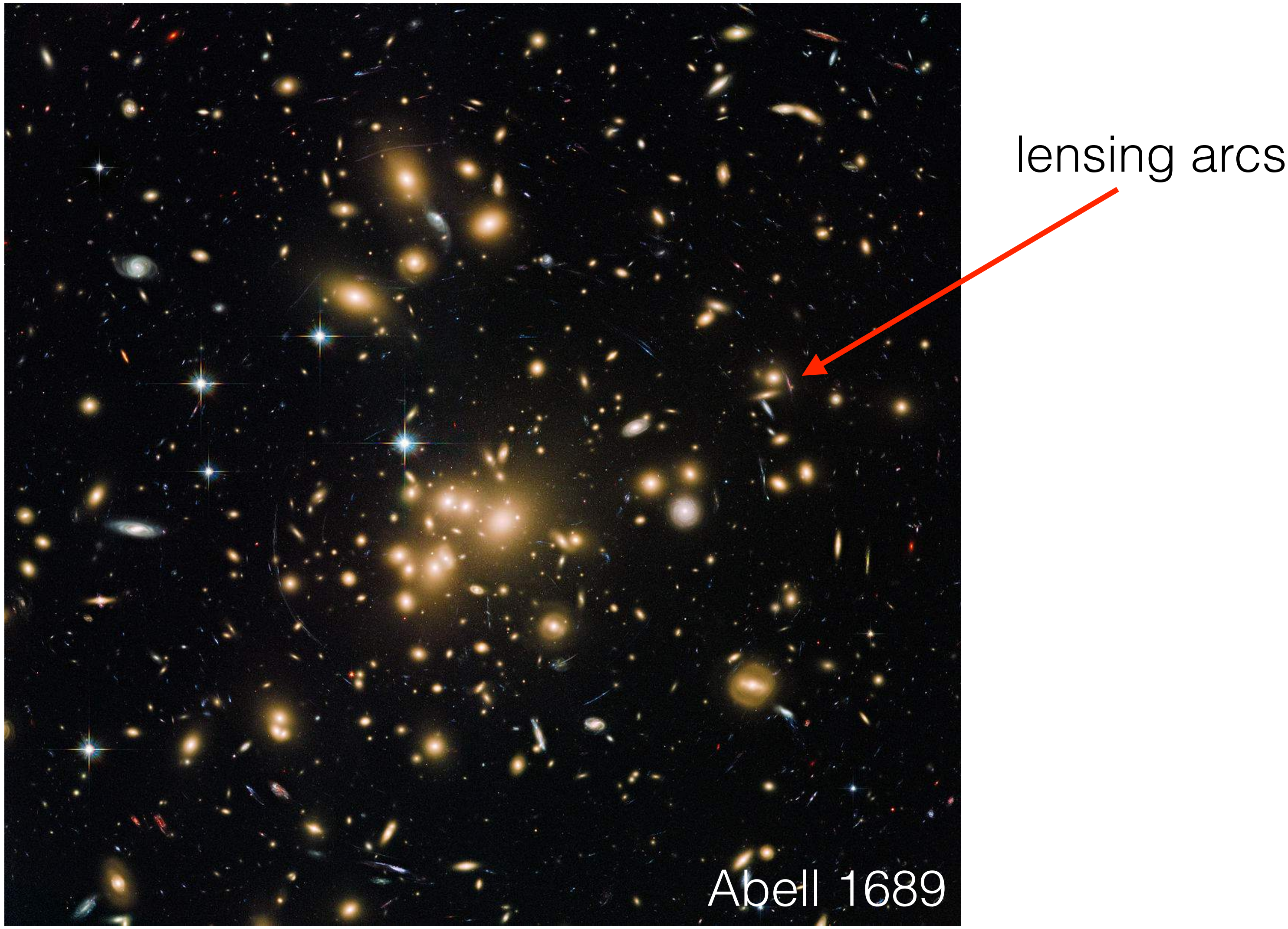
Not a time or physical sequence

Galaxy rotation curves: evidence for dark matter



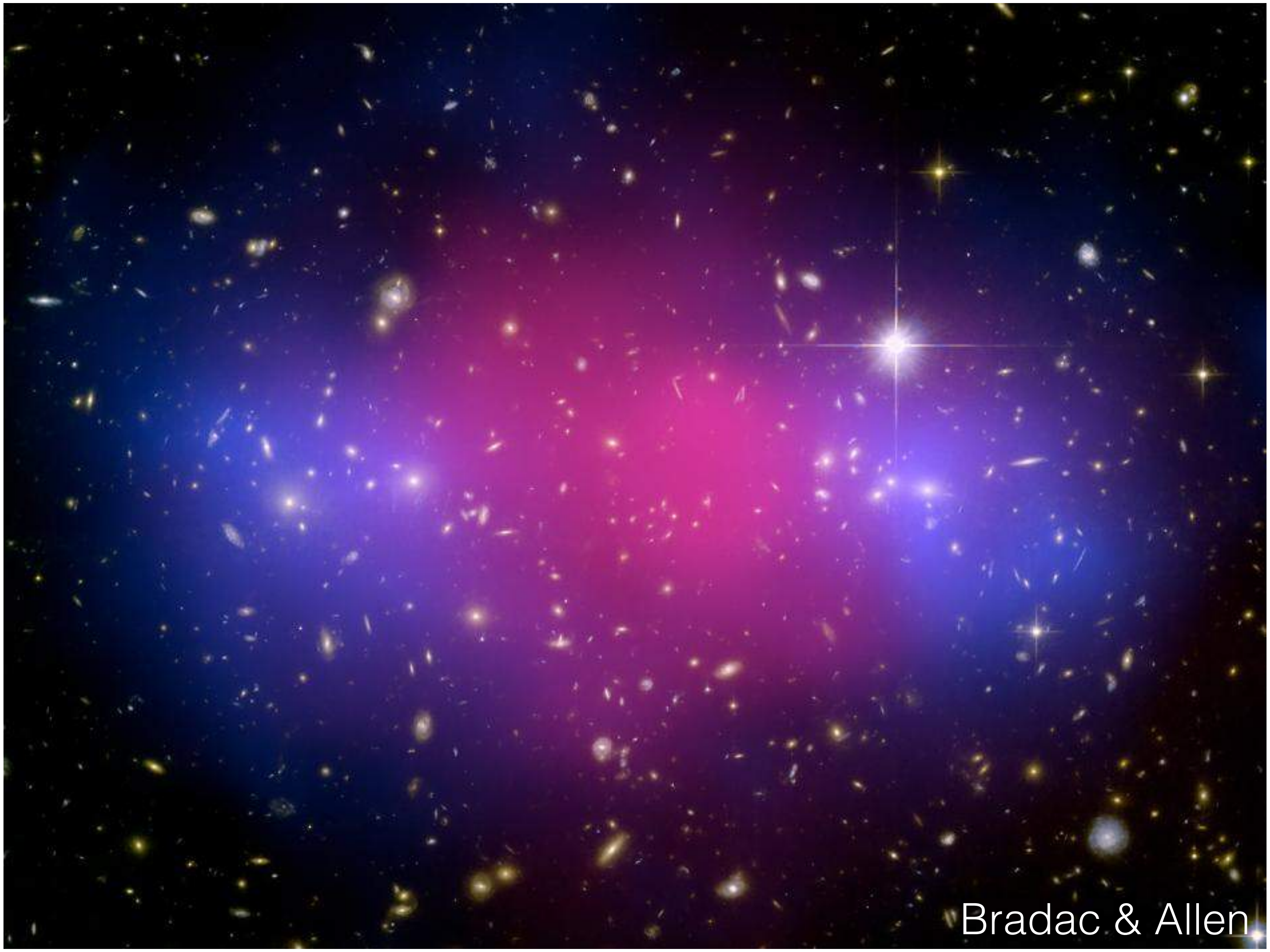
M33 rotation curve from http://en.wikipedia.org/wiki/Galaxy_rotation_curve

Galaxy clusters



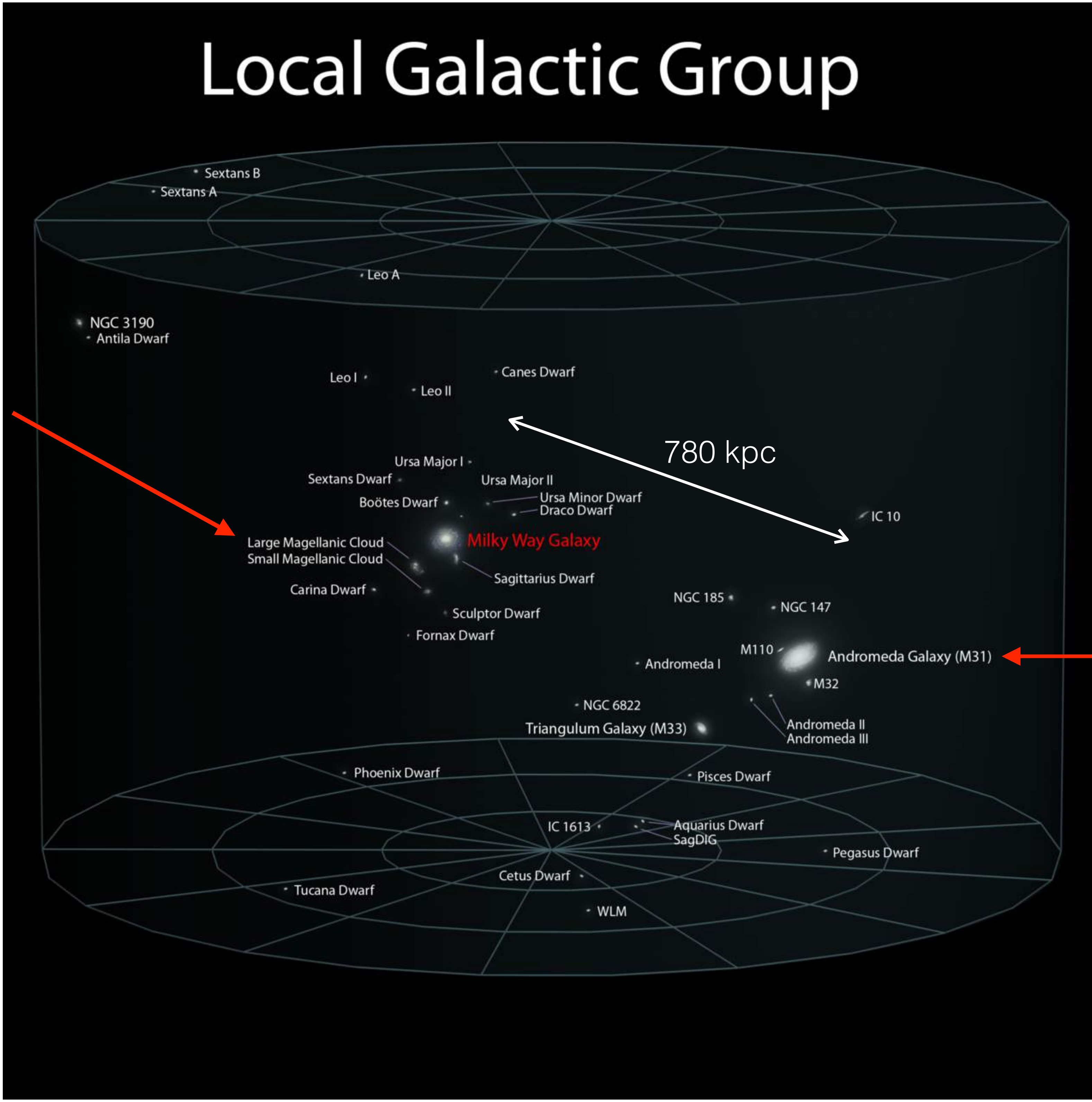
- most massive gravitational bound objects in the Universe
- contain up to thousands of galaxies
- most baryons intracluster gas, $T \sim 10^7$-10^8 K gas
- smaller collections of bound galaxies are called 'groups'

Bullet cluster: more evidence for dark matter



- two clusters that recently collided
- gravitational mass traced by weak lensing (blue)
- gas (collisional) stuck in middle

well-
studied
MW
satellites

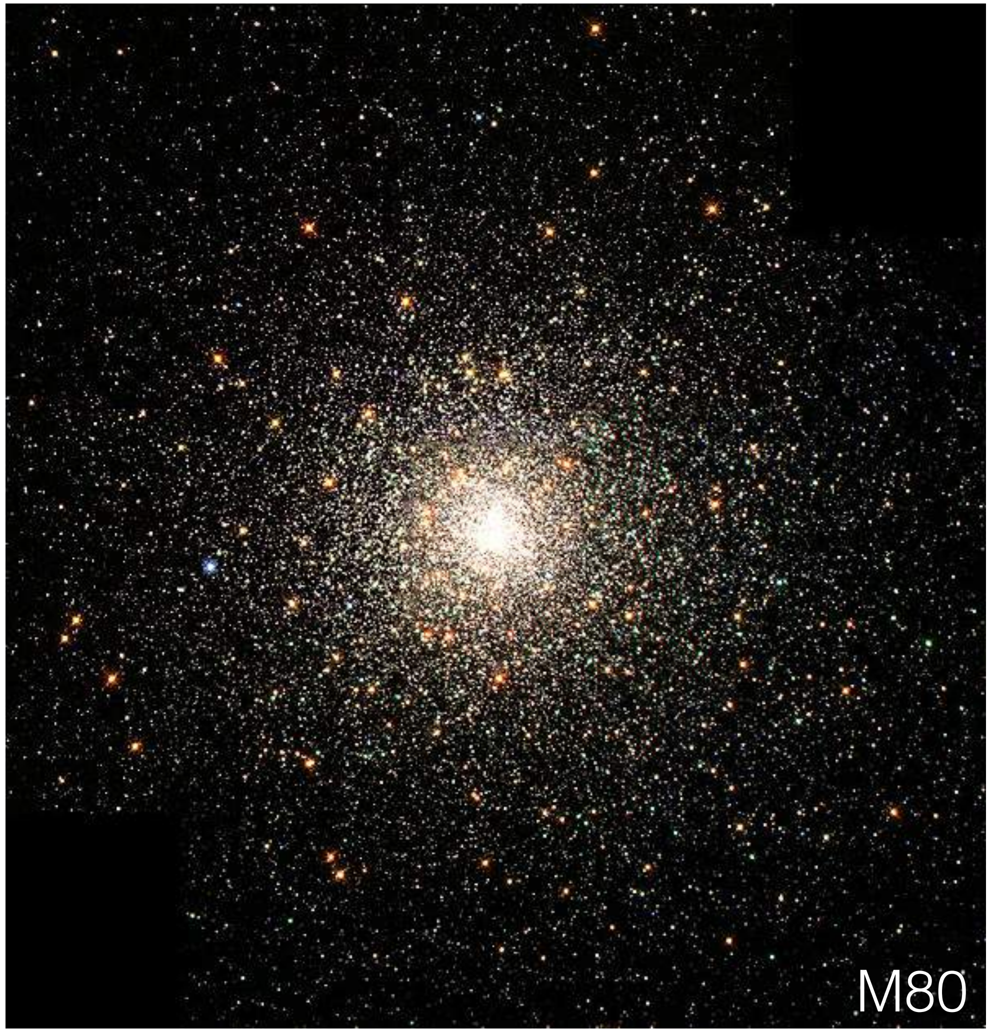


most
massive

Open clusters

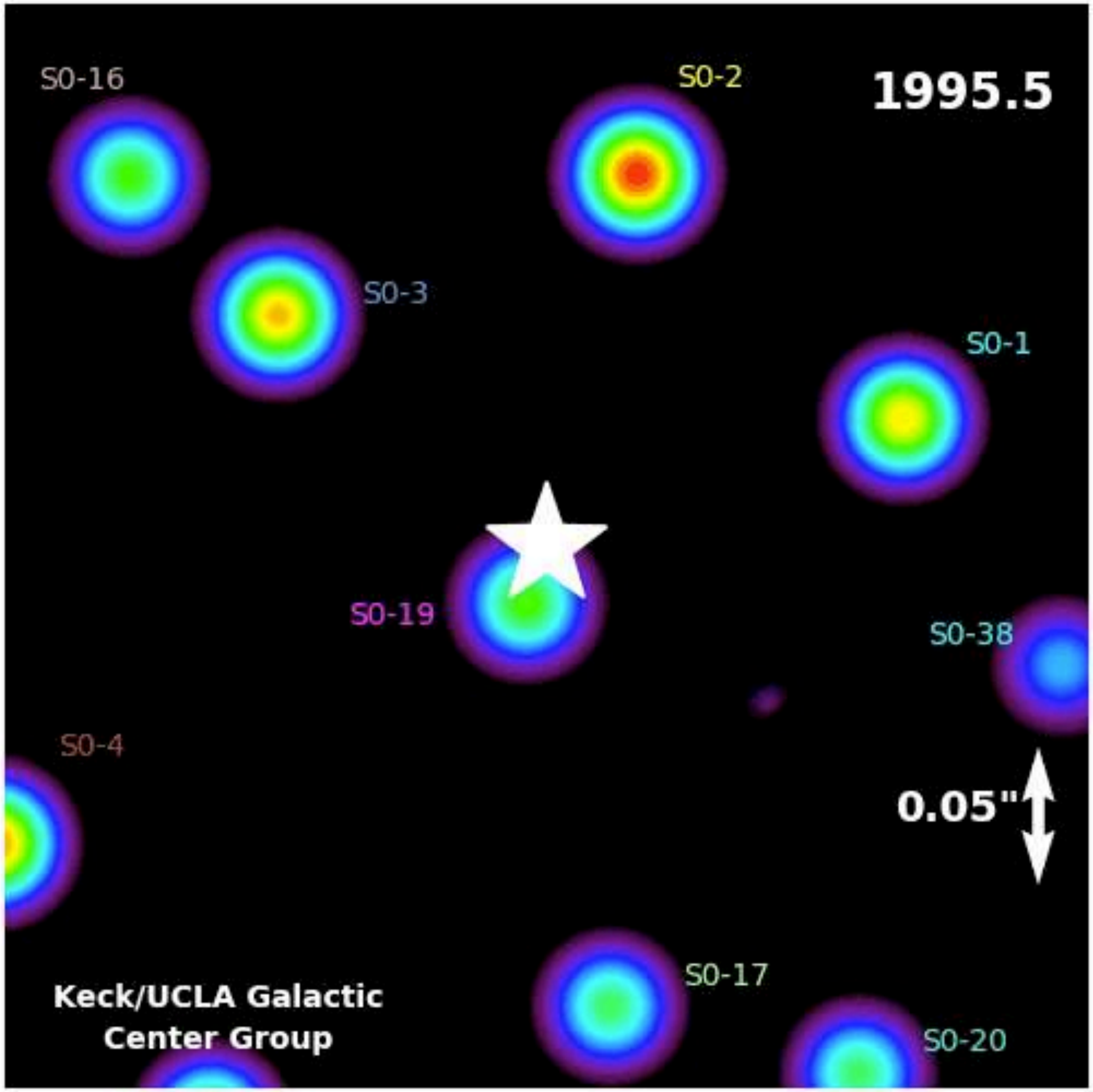
- ~10^2-10^4 stars, irregular
- most younger than 1 Gyr, in disk
- most stars probably formed in open clusters, which have since dissolved

Globular clusters



- ~10^4-10^6 stars, nearly spherical, in galaxy halos (in MW, ~5-30 kpc from center)
- little dust, gas, young stars, or dark matter
- central stellar density 10^4 M_{sun} pc^{-3} (compared to 0.05 M_{sun} pc^{-3} for solar neighborhood) ⟹ direct interactions between stars (collisional effects)

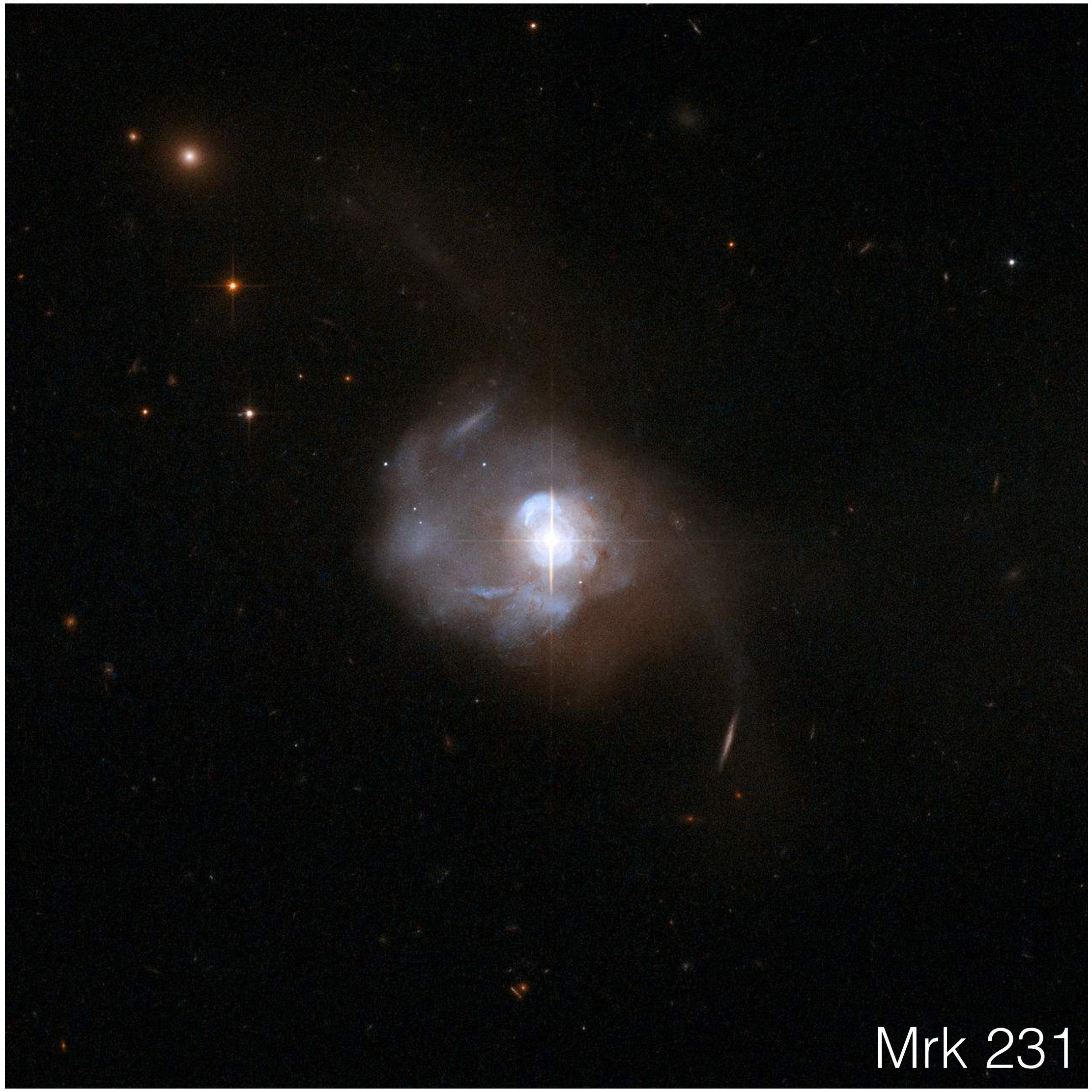
Nuclear black holes



10^{-4} pc

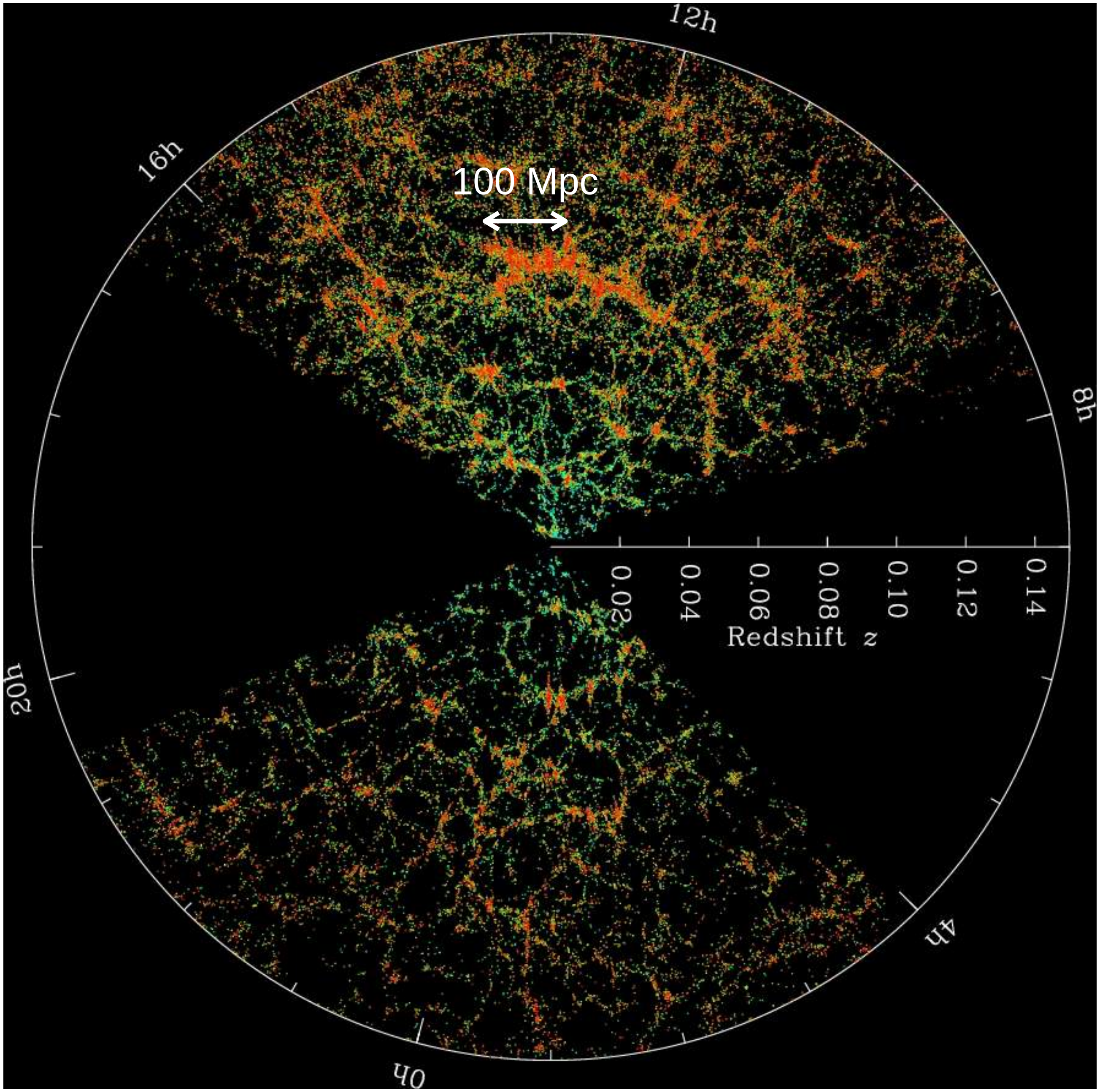
- all (massive) galaxies appear to have one
- in MW (Sgr A*), $M_{BH}=4\times10^6\ M_{sun}$, measured using individual stellar orbits

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

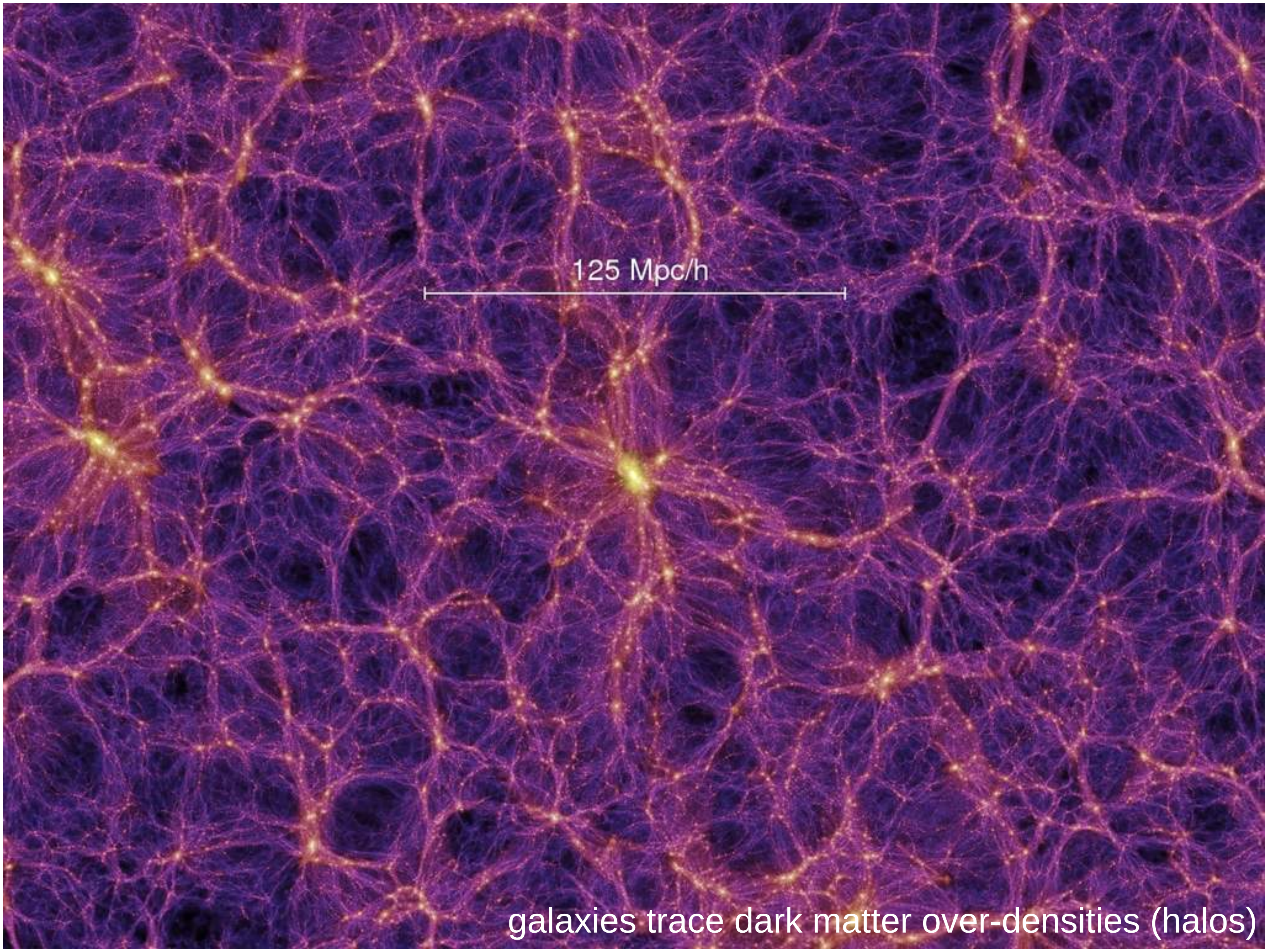
Map of large-scale structure traced by galaxies



- 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

Sloan Digital Sky Survey

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

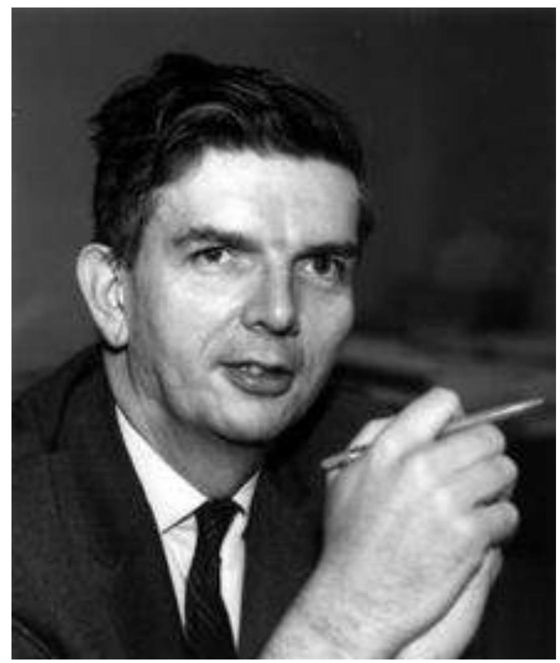
Penzias & Wilson with antenna in Holmdel, NJ

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.

. . .

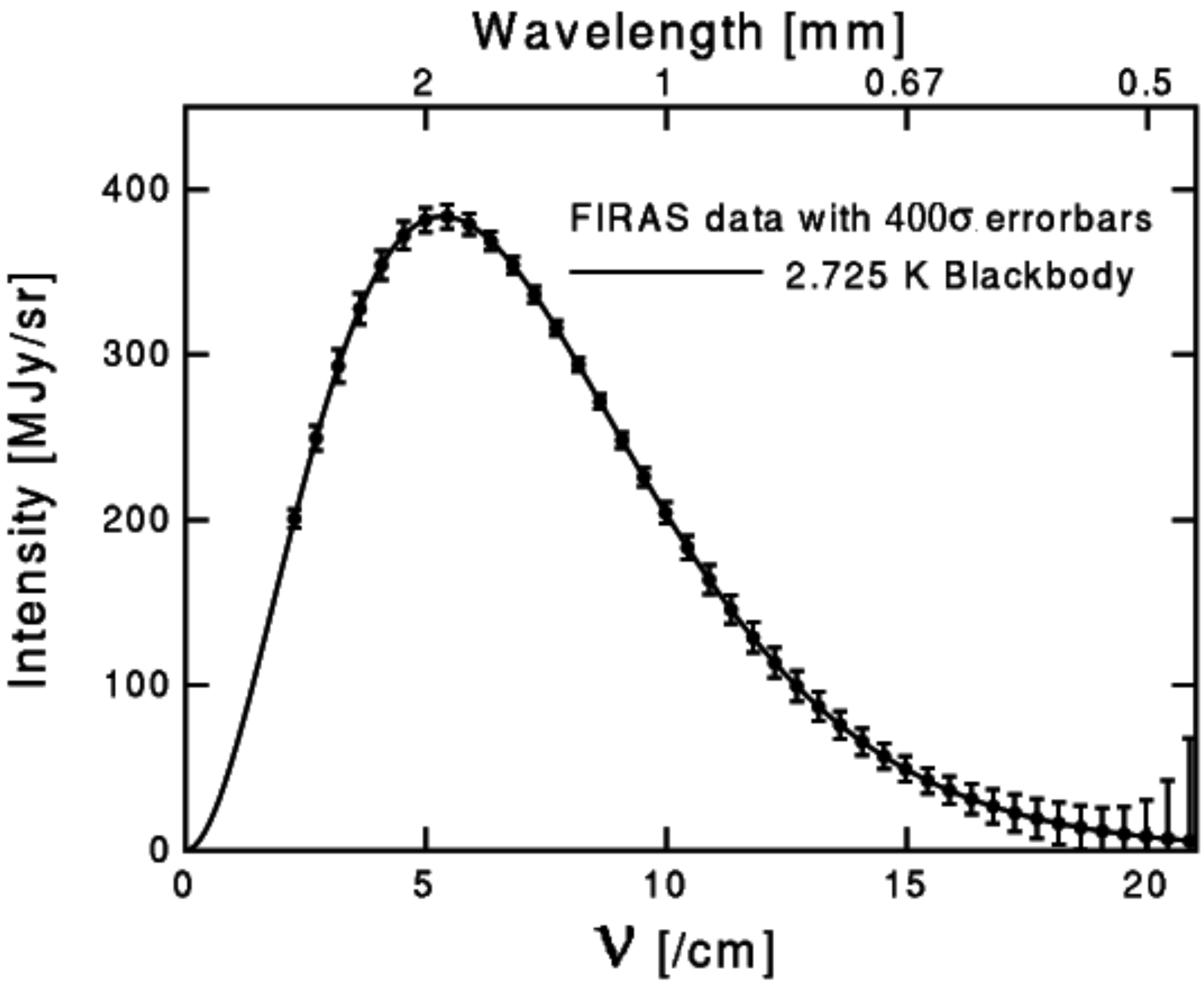
While we have not yet obtained results with our instrument, we recently learned that Penzias and Wilson (1965) of the Bell Telephone Laboratories have observed background radiation at 7.3-cm wavelength. In attempting to eliminate (or account for) every contribution to the noise seen at the output of 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



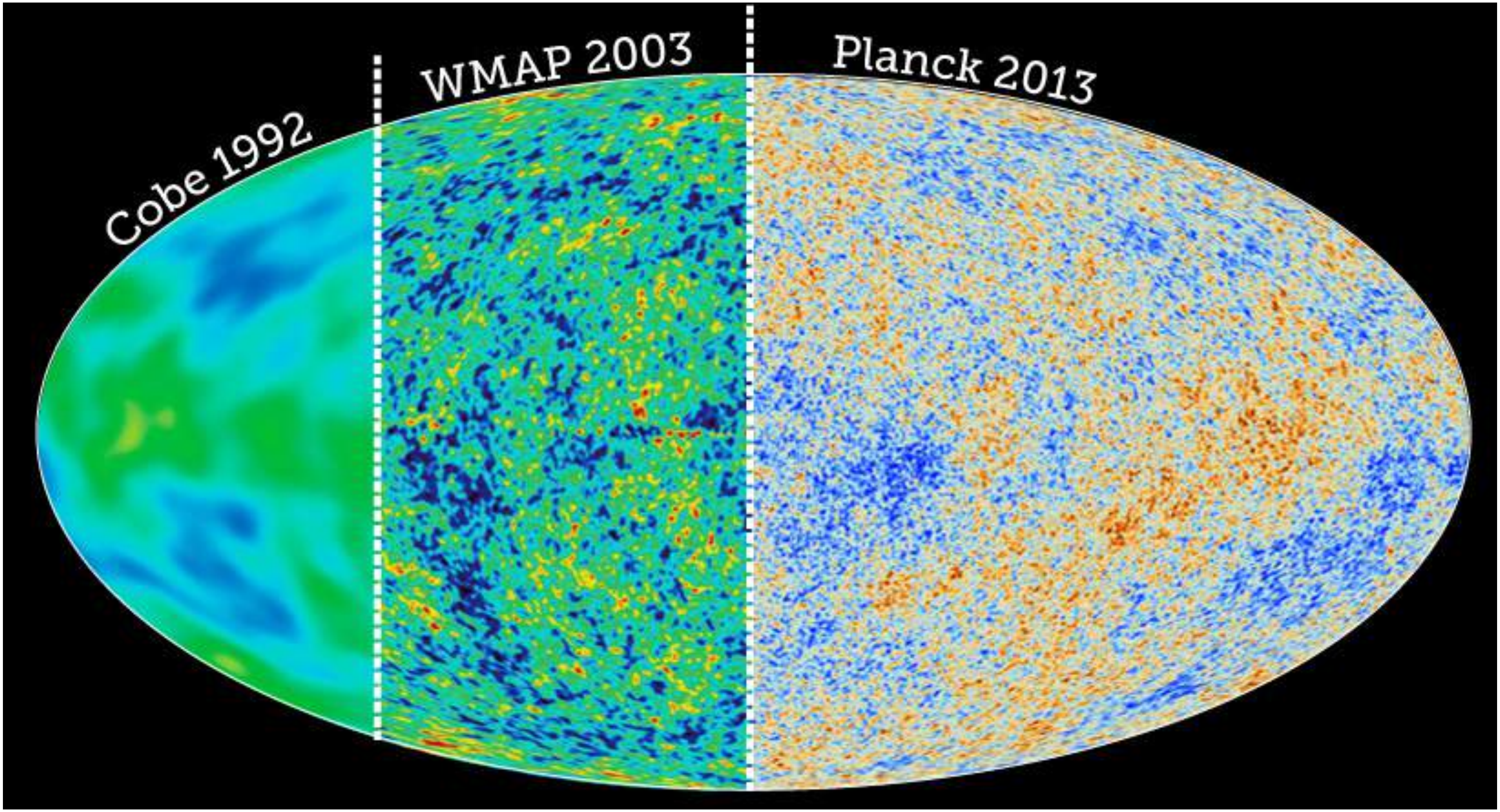
Far Infrared Absolute Spectrophotometer (FIRAS)

aboard the

Cosmic Background Explorer (COBE) satellite

Mather+94, Fixen+96

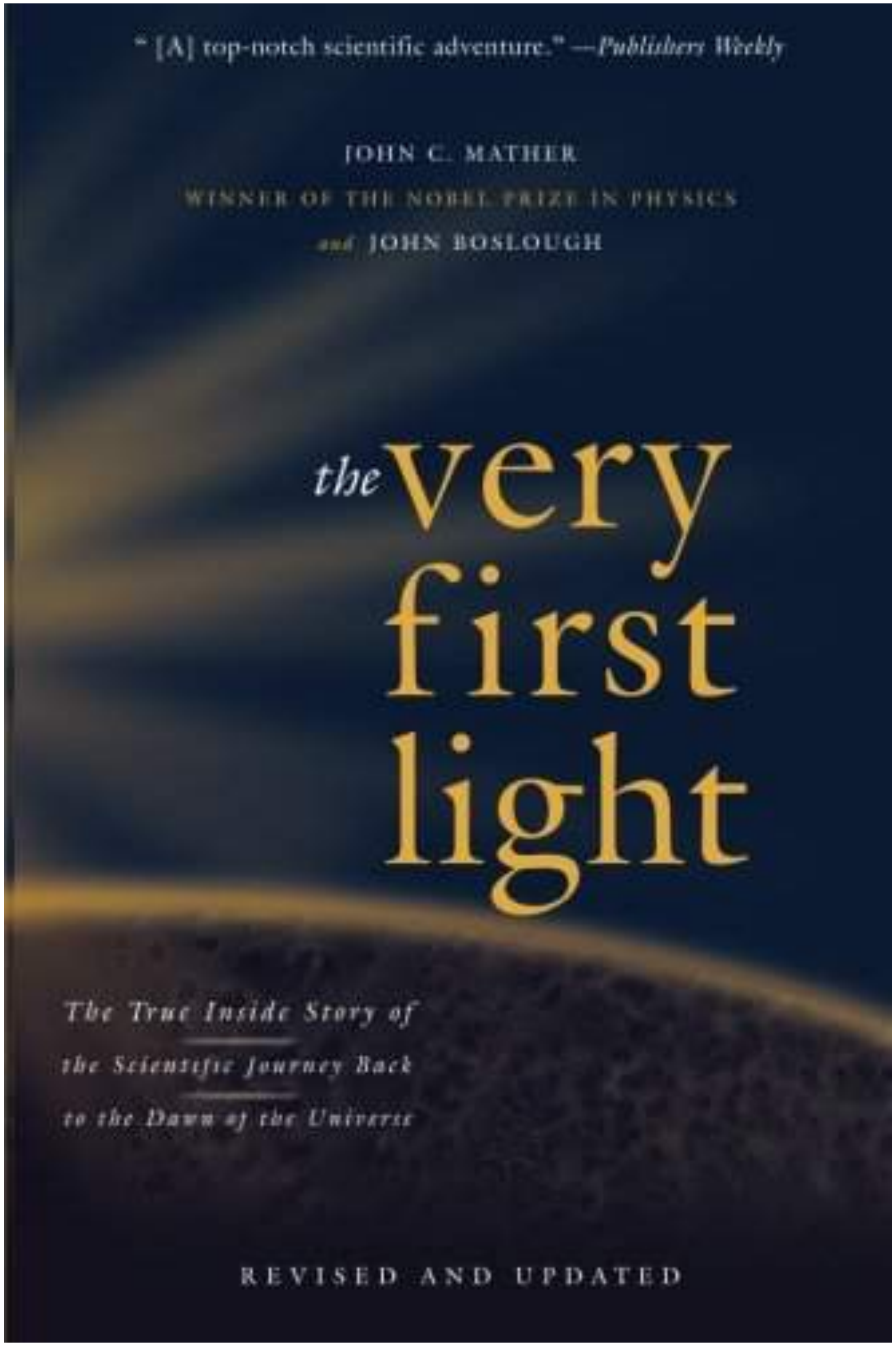
Fluctuations (anisotropies) in CMB



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

⇒ uniformity is strong evidence for cosmological principle

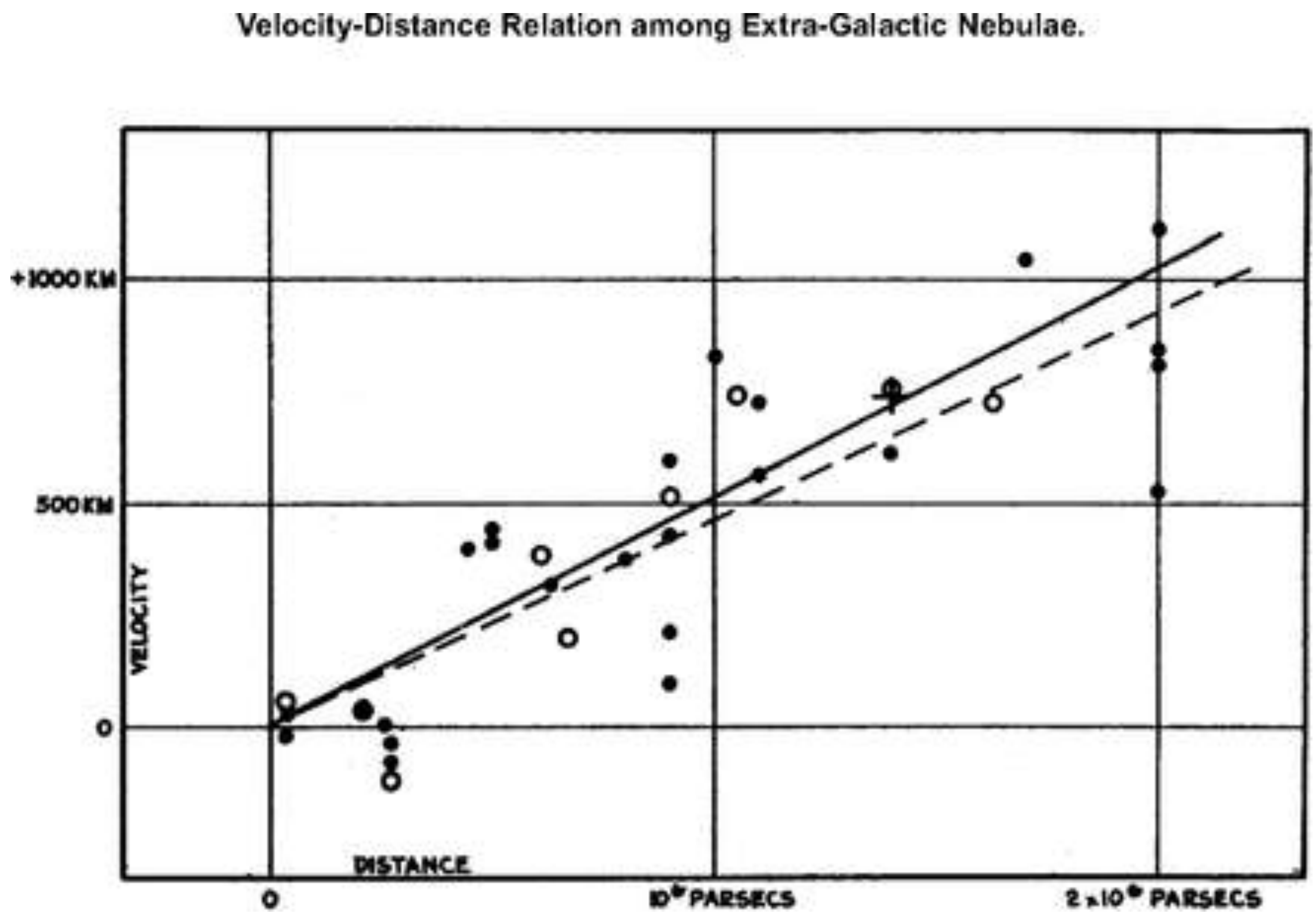
For more on the history of the CMB:



John Mather and George Smoot shared 2006 Nobel Prize in Physics for work on COBE

Hubble’s Law

Hubble’s original 1929 diagram



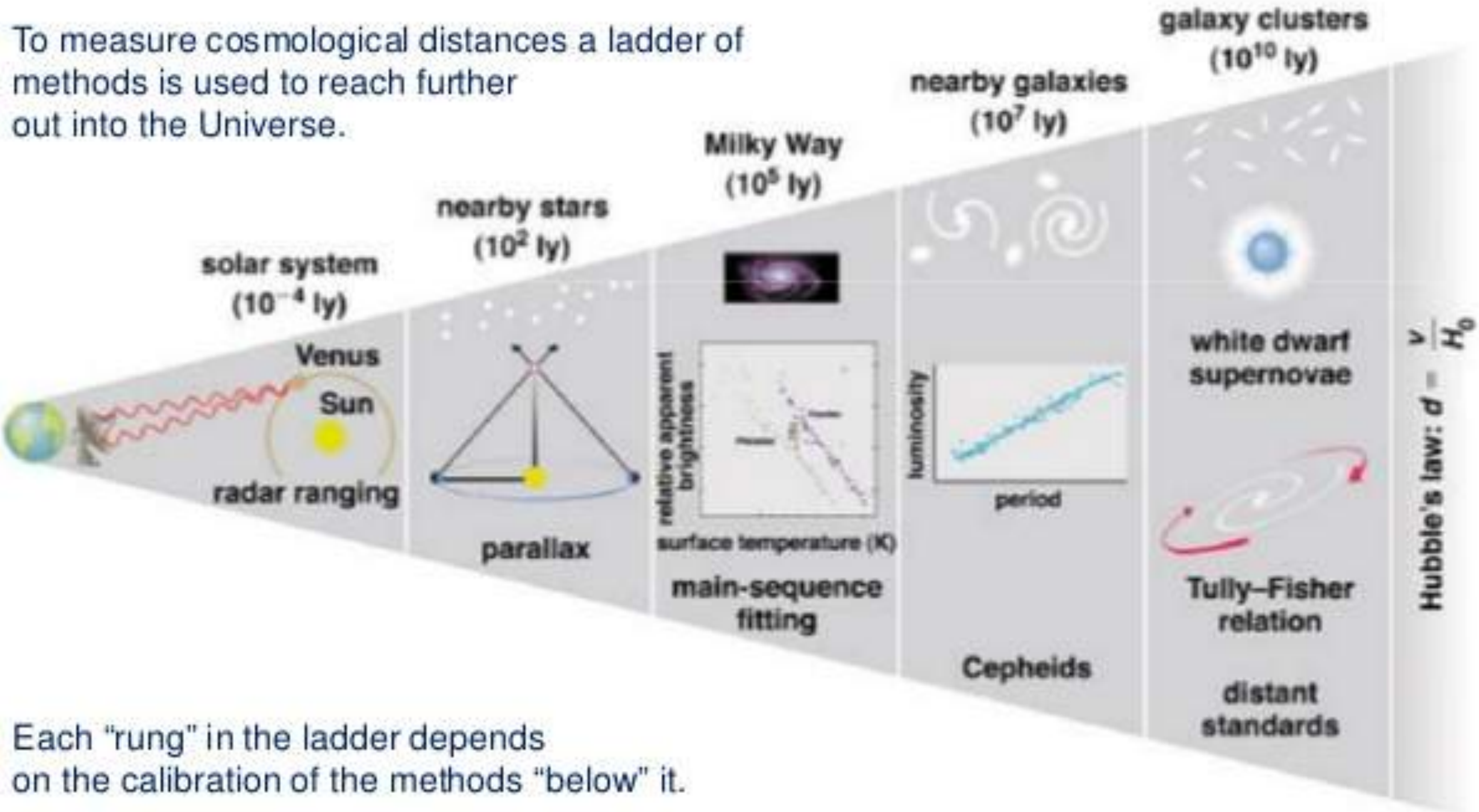
Distances determined using stars of known luminosity, including Cepheids

Note: velocity units should km/s

Size and Scale of the Universe

THE COSMIC LADDER

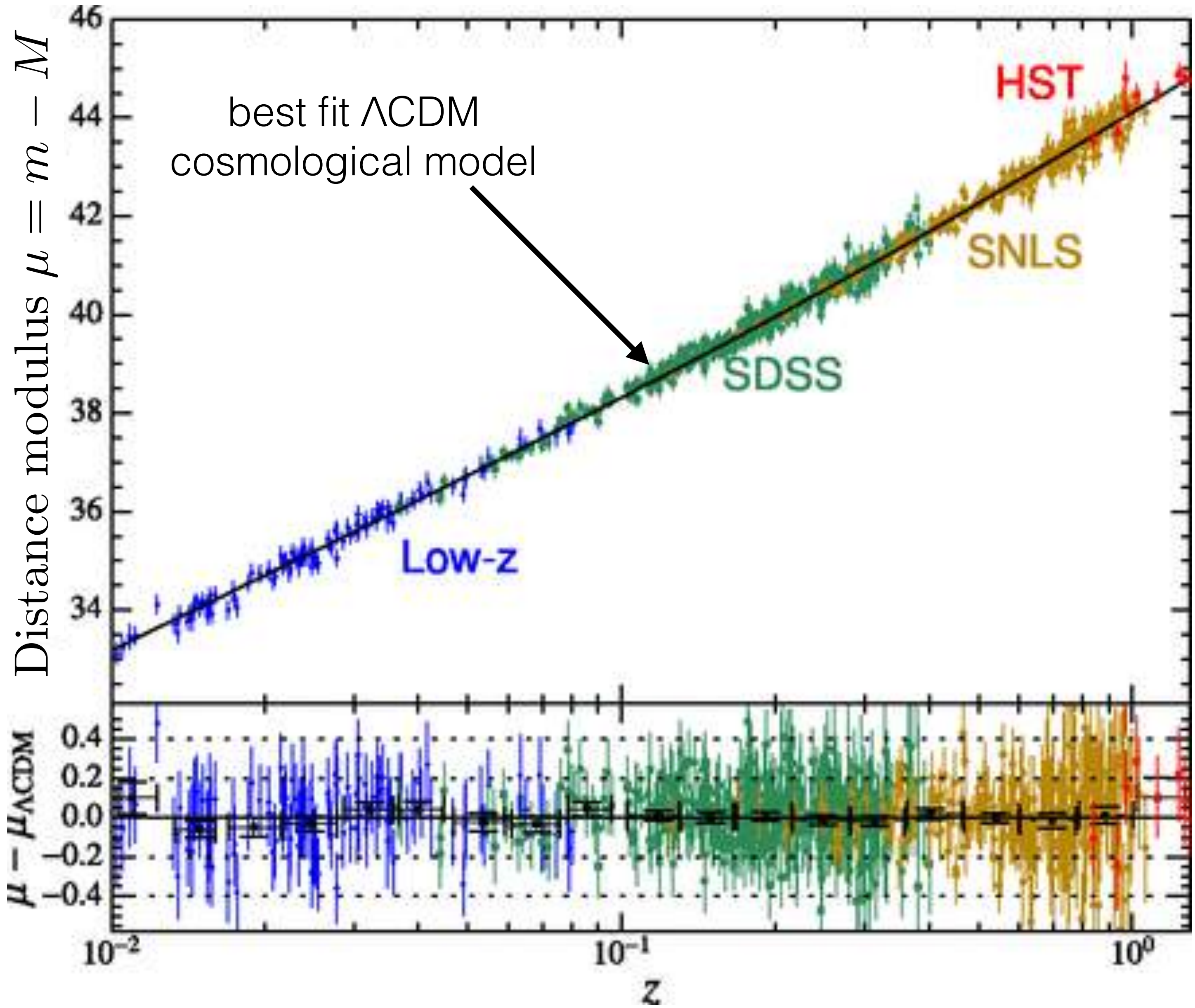
To measure cosmological distances a ladder of methods is used to reach further out into the Universe.



Each “rung” in the ladder depends on the calibration of the methods “below” it.

Image credit: Addison Wesley

Recent supernova Hubble diagram



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