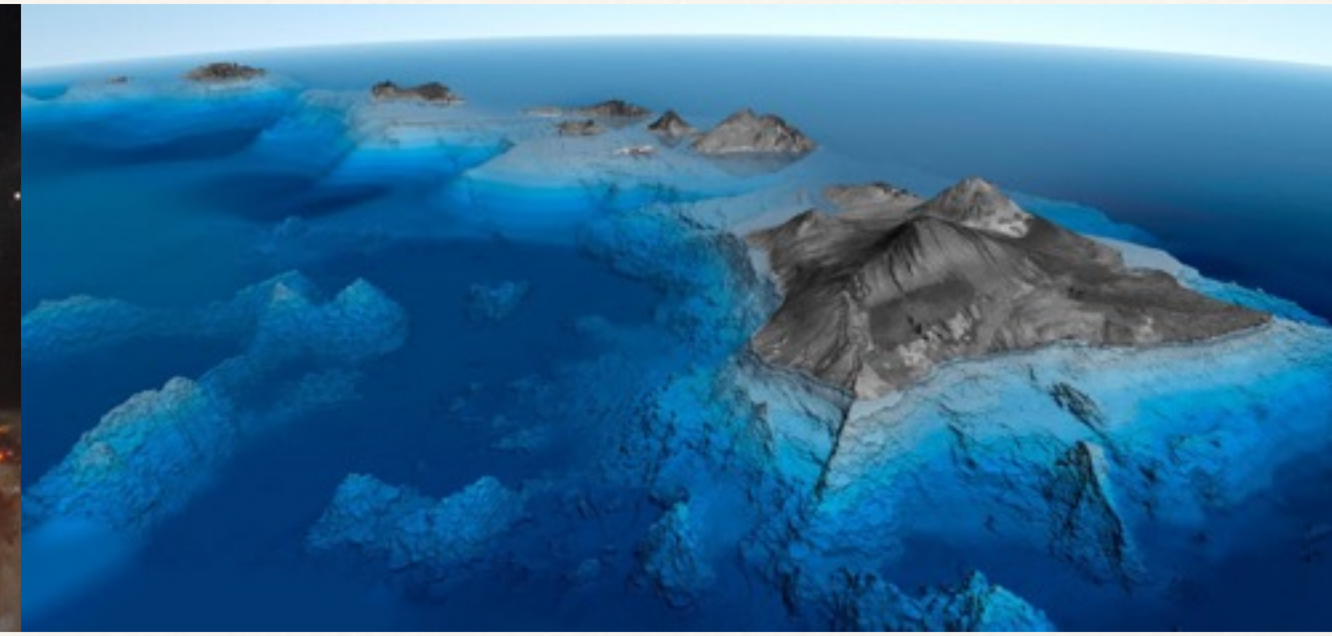


Getting to know the "island universes" out there.

Galaxies I

ASTR 555
Dr. Jon Holtzman

Course Overview

- An introduction to galaxies and extragalactic astronomy.
- Emphasis on making the connection between galaxy observations and fundamental galaxy properties.
- We will aim to cover:
  - the main techniques used for observing galaxies
  - the observed properties of galaxies
  - the basic building blocks that make up individual galaxies
  - our own Milky Way
- The companion class, ASTR 616 - Galaxies II, will build on this foundation to explore the underlying principles of galaxy formation, galaxy evolution, and cosmology.
- Class history
- Types of learning: Bloom's taxonomy

Course Logistics I

- **Canvas Course Webpage**
  - syllabus, schedule/readings, slides, assignments
- **Lectures**
  - Initial discussion on questions
  - Presentation of material, interspersed with short problem and/or discussion
- **Reading**
  - books: BM, EAC, MvdBW in reading room
  - issues with order of material

Course Logistics II

- Out-of-class Assignments (50%)
  - reading assignments
  - weekly summary / questions, as groups (10%)
    - main points of the week
    - most confusing point/question
    - complete as groups and submit by Friday 5:00pm
    - Credit will be awarded for being thoughtful and showing engagement with the material.
  - 4-5 journal article summaries, as individuals (15%)
  - 5 problem sets/coding exercises, as groups (25%)
- Exams
  - a Midterm (20%) and a Final Exam (30%)
  - complete as individuals!
- See syllabus for written summary of course logistics

Group work

- Group work
  - forces discussion of material, which usually fosters learning
  - for problems, should think about as individuals first, then meet to discuss
  - suggest regular meeting time(s) as possible, interaction via Slack (join and accept invitation!)
- Groups
  - A: Erick, Khagendra, Anna, Anokh
  - B: Daniel, Jessica, Victoria
  - C: Ezra, Sarah, Julio
  - D: Len, Asif, Annie, Kevin
- Attendance policy
- Logistics questions?

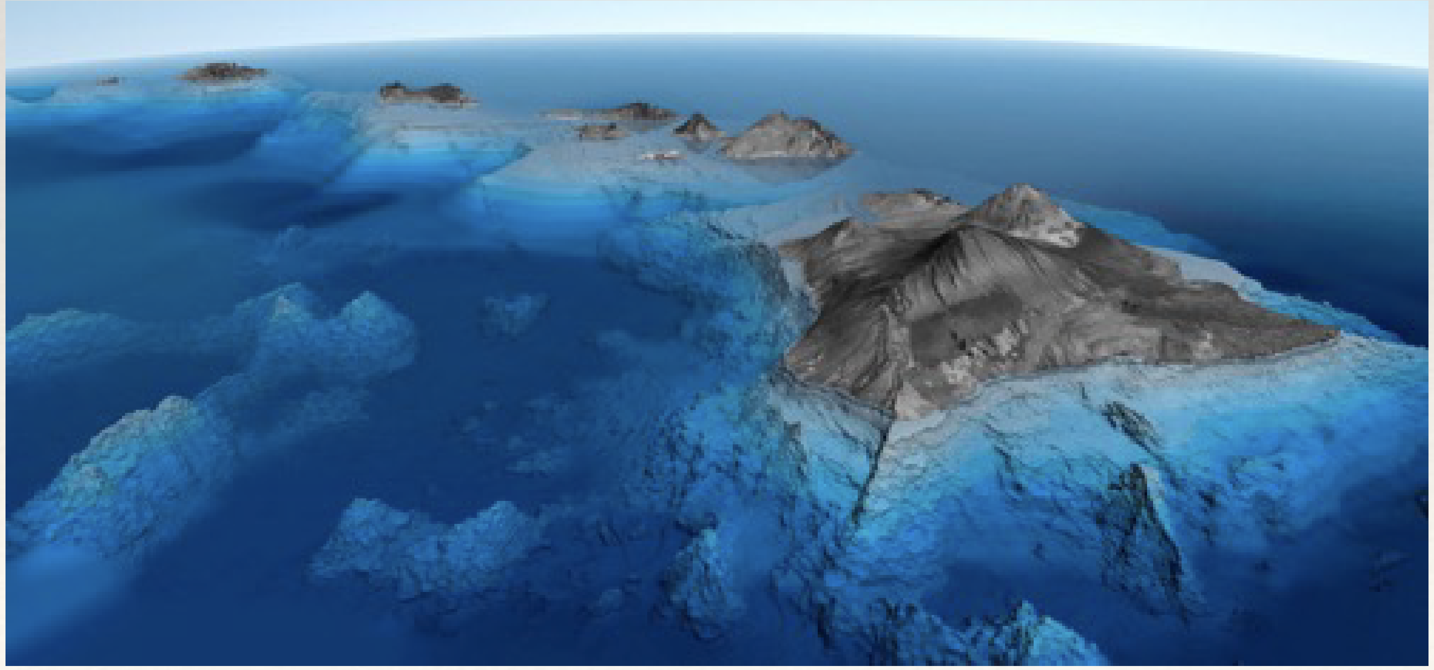
What are galaxies?

What are galaxies?

- Galaxies:
  - gravitationally bound collections of stars, gas, dust, dark matter, black holes
  - astronomical crossroads, the intersection of stellar physics, gas physics, cosmology
  - luminous tracers of large scale structure, act as cosmological probes
- Understanding galaxy formation/evolution is one of the current big problems in astronomy; and almost all other sub-fields can be regarded as important for understanding galaxies

Be ready to discuss

- Of all the revelations in extragalactic astronomy that we discuss, which do you think was the most shocking and revolutionary to the people of the time?
- In what respect(s) is this image appropriate and/or inappropriate to a course on galaxies?



A little history…

- Ancient times, pre-telescope
- By eye, can see the Milky Way, Andromeda, Large Magellanic Cloud (LMC), and Small Magellanic Cloud (SMC).

What is the Milky Way?

What are the clouds? (Latin: "nebulae")

Image: Mark Gee

The Milky Way is made of stars

- **1600s**
- 1610: Galileo Galilei:
  - "I have observed the nature and the material of the Milky Way… The galaxy is, in fact, nothing but a congeries of innumerable stars grouped together in clusters…" — *Siderius Nuncios*
- With telescopes, started to discover more fuzzy nebulae.

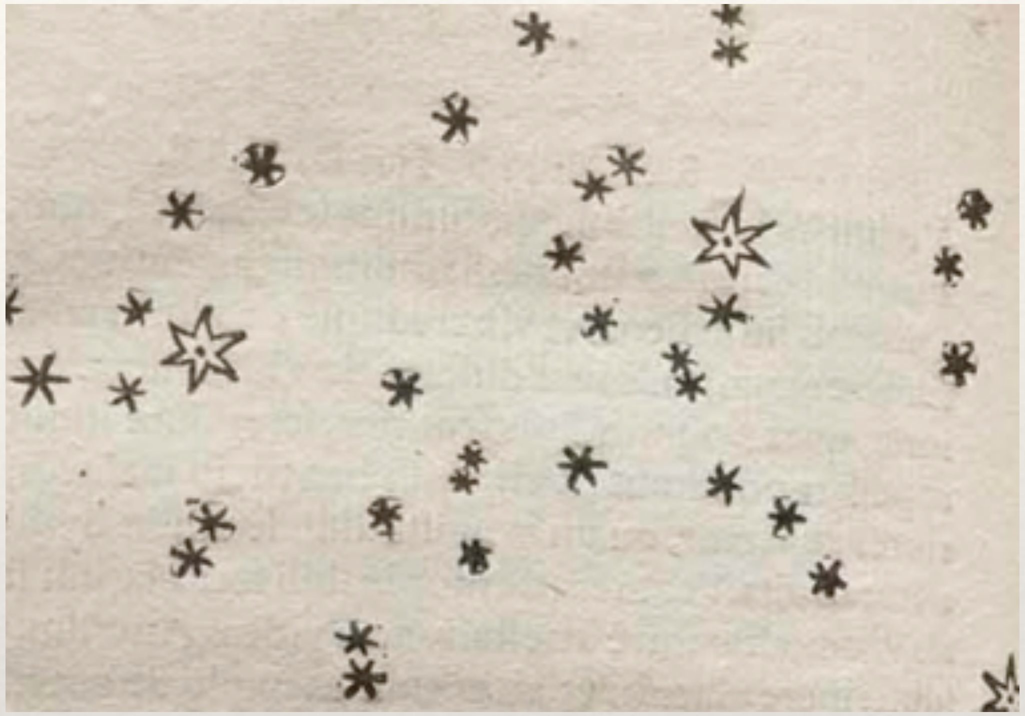
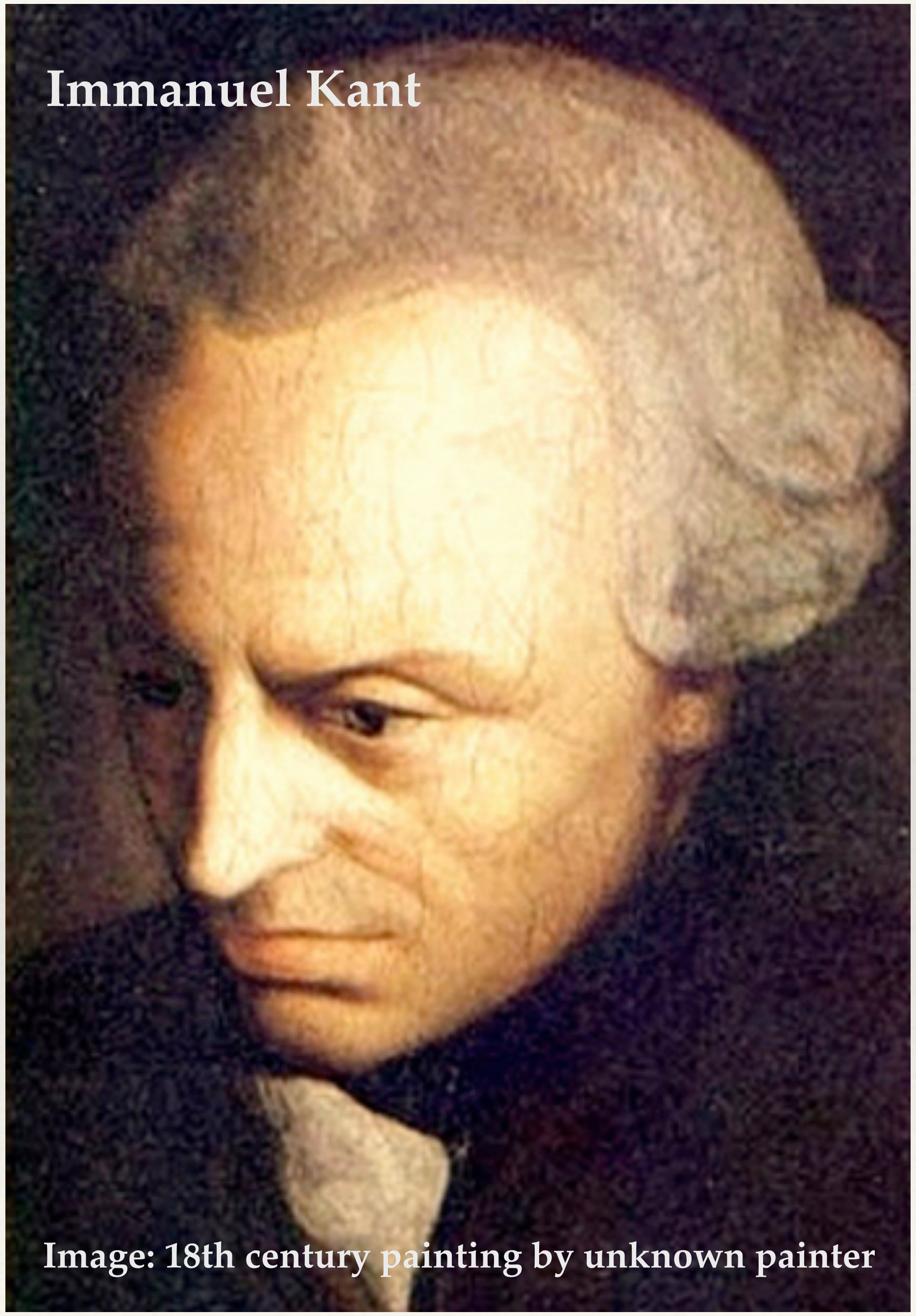


Image: Siderius Nuncius, Galileo Galilei, 1610

Image: Science Museum Group Collection

“Nebulae” vs. “Island Universes”

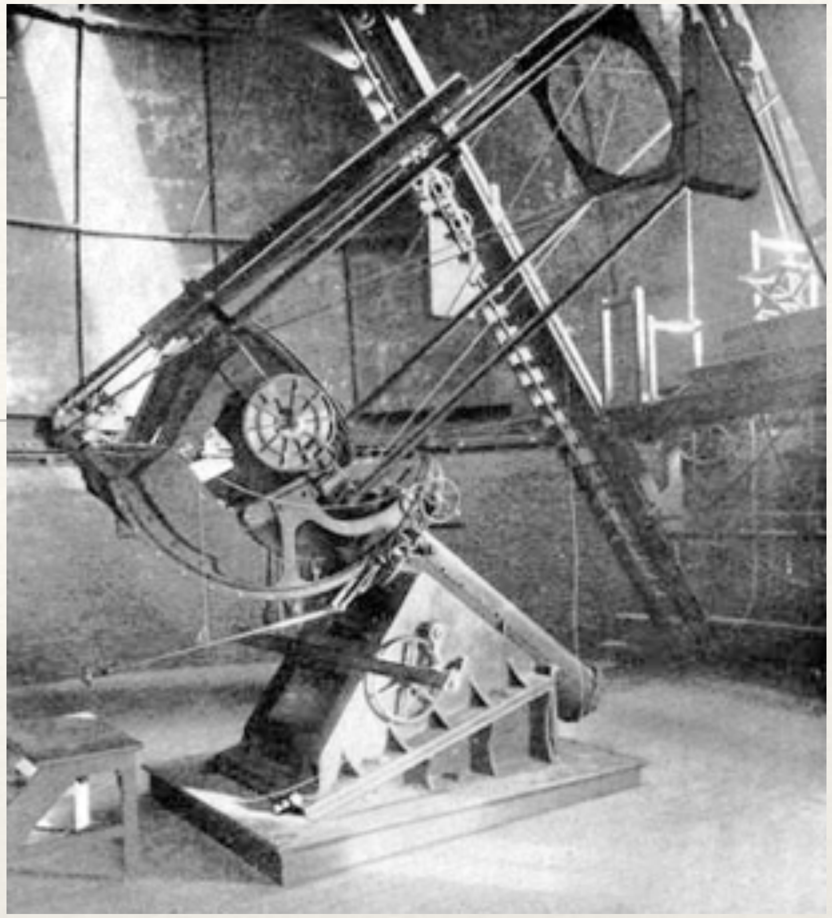
- **1700s**
- Immanuel Kant publishes treatise explaining planar structure of Solar System
- Structure of the Milky Way could arise in a similar way, on a much larger scale
- Some of the fuzzy “nebulae” might be complete “island universes”



Finding more nebulae…

- **1700-1900s**
- With telescopes, many more nebulae observed, initially not distinguished from Galactic nebulae (several types!). Herschel's General Catalog
- Dreyer: New General Catalog (NGC) and Index Catalog (IC), ~12000 objects. Example NGC objects?

Herschel 20 Foot Reflector (c. 1783)



Crossley Reflector (c. 1900), Lick Observatory.

Charles Messier

Painting by Nicolas Anseaume, 1771

William Herschel

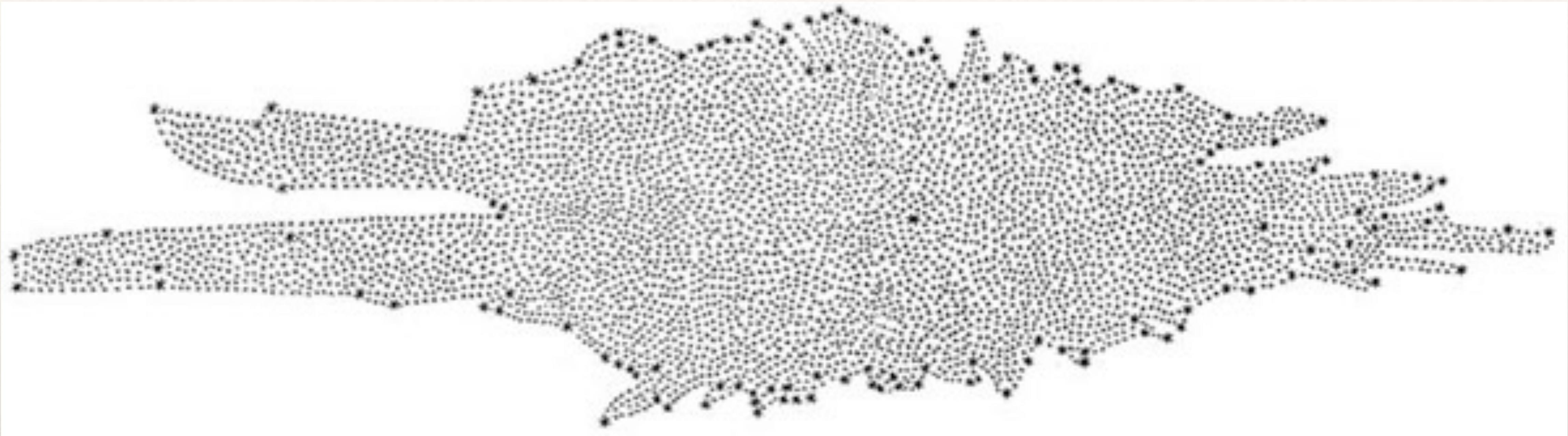
Painting by Lemuel Francis Abbott, 1785

Caroline Herschel

Painting by Melchior Gommar Tieleman

How big is the Milky Way?

Herschel's Map of the Milky Way (1785)



- The Herschels used star counts to measure the size of the Milky Way, assuming:
  - Stars are uniformly distributed throughout the Milky Way with none outside
  - The telescope used can detect all stars within the Milky Way

How bad are each of these assumptions?
How <u>specifically</u> will they bias the results?

How big is the Milky Way?

- **1900s-1920s**
- Jacobus Kapteyn carries out detailed study of the Milky Way:
  - a thick disk ~10-17 kpc across with Sun near center, and decreasing density with distance
- Finds some evidence for reddening, but concludes absorption not that important (because he assumed source was Rayleigh scattering)

Jacobus Cornelius Kapteyn
1851-1922

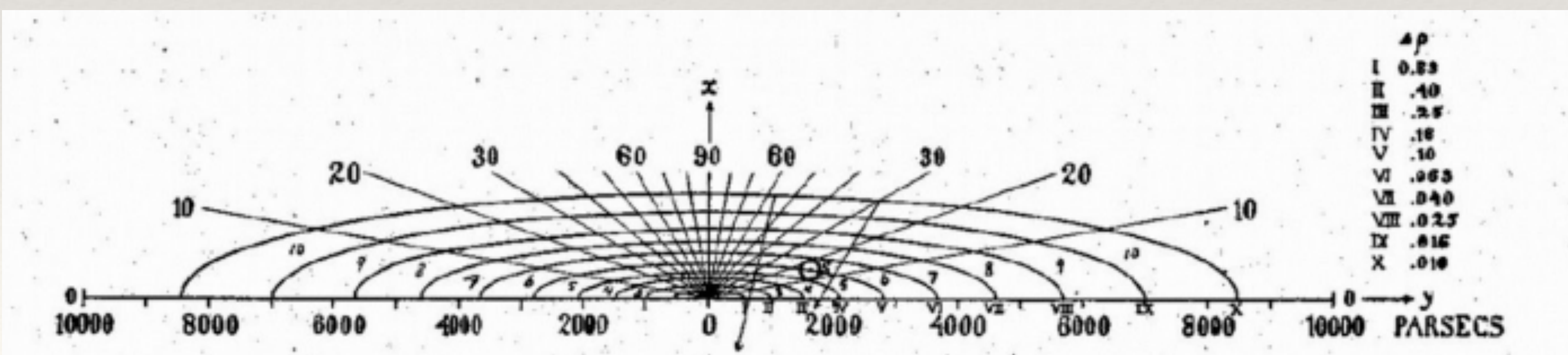


FIG. I

Kapteyn 1922, ApJ, 55, 302

Getting distances…

- **1910s-1920s**
- 1912: Henrietta Leavitt discovers Period-Luminosity relation for Cepheid variable stars:
    - ***"…there is a simple relation between the brightness of the variables and their periods…"***
- 1918: Harlow Shapley measures distances of globular clusters:
    - Milky Way is big (~100 kpc) with Sun far (~15 kpc) from center!

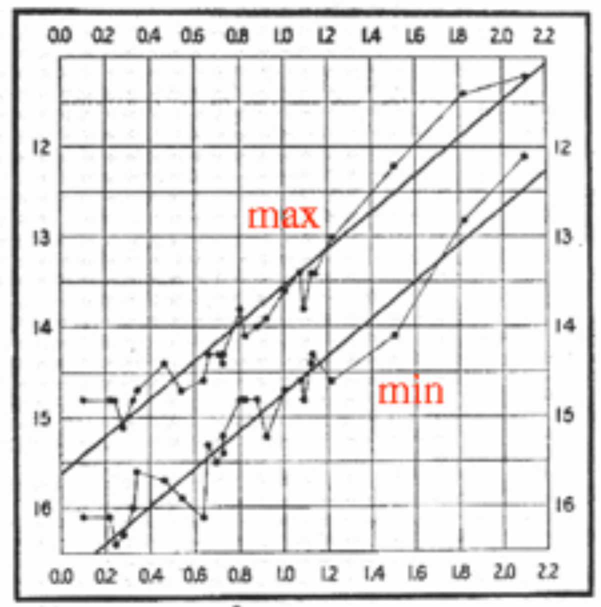
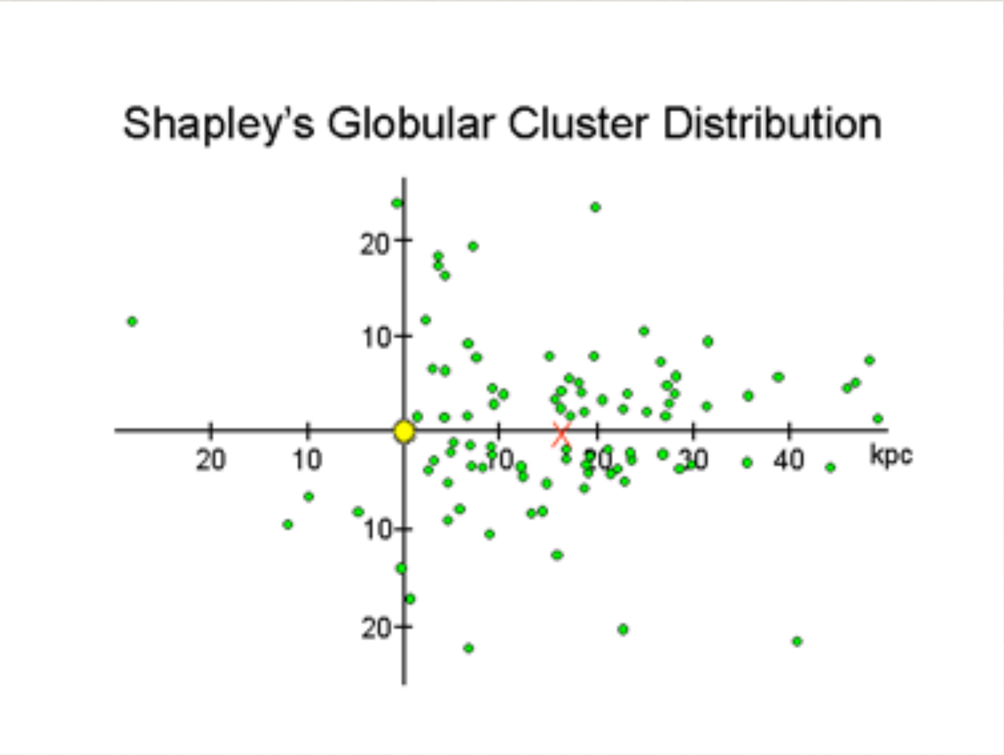


FIG. 2.

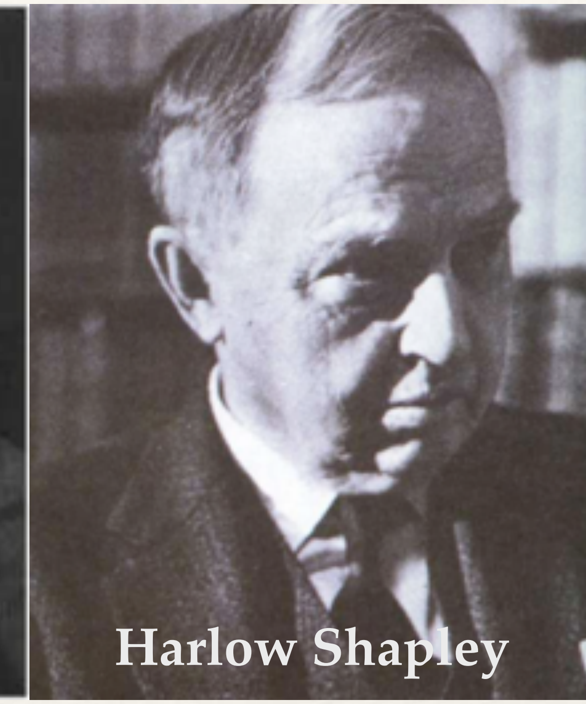
Pickering 1912, Harvard College Observatory Circular, 173, 1

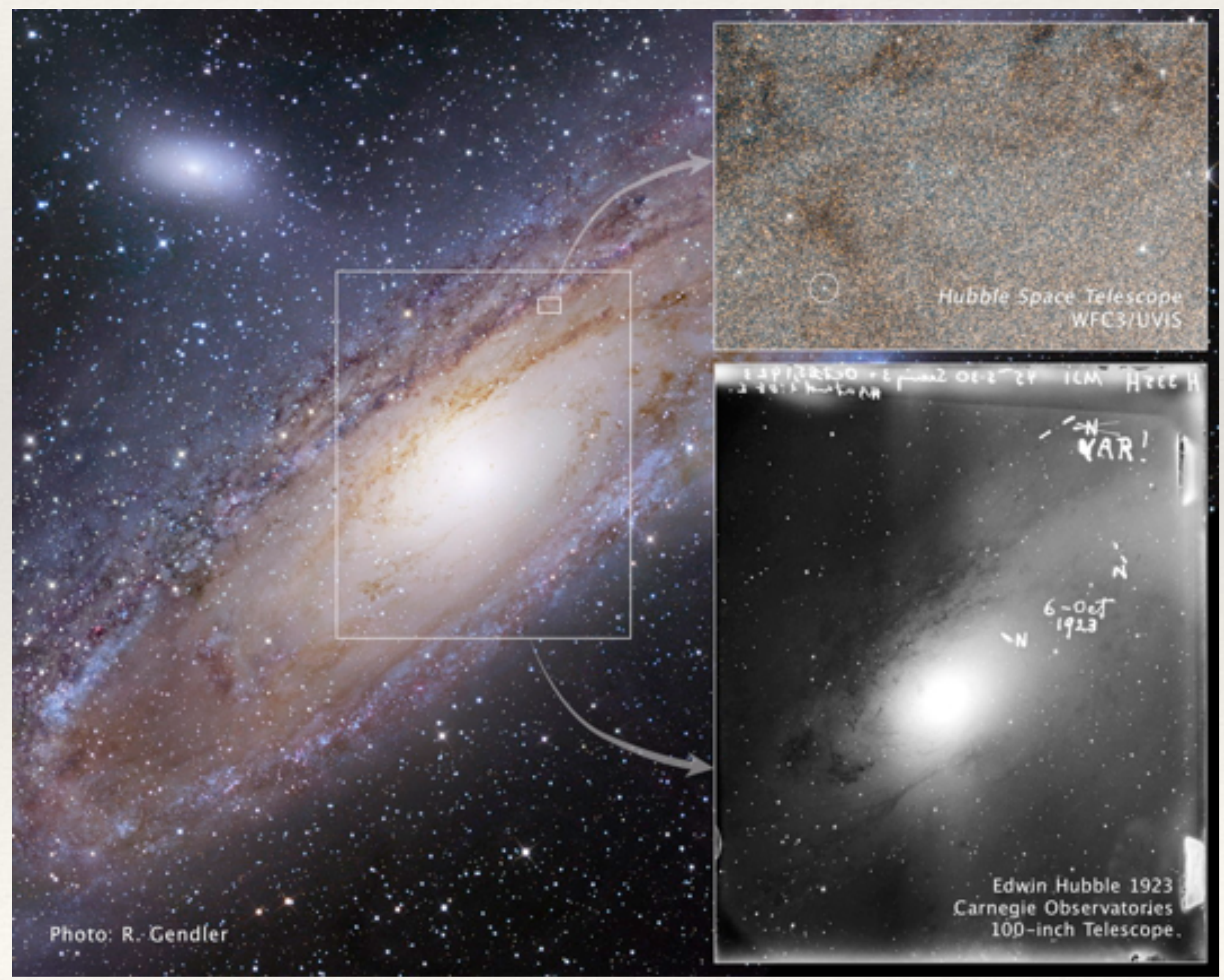

Henrietta Swan Leavitt
1868-1921



The “Great Debate”

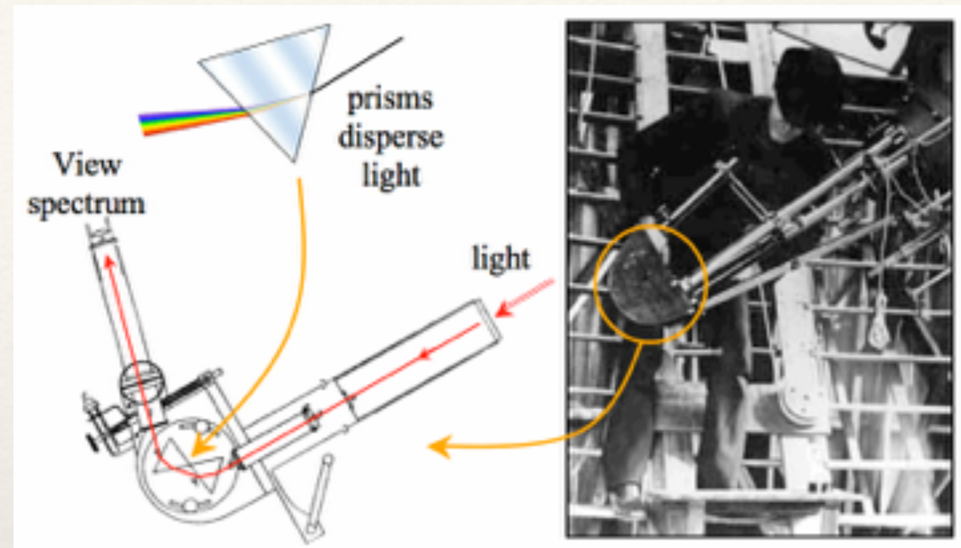
- **1920s-1930s**
- 1920: Public “debate” between Herber Curtis and Harlow Shapley:
  - "Are Spiral Nebulae Island Universes?” (and how big is the Milky Way?)
- 1923: Edwin Hubble finds Cepheids in M31 and calculates the distance.
  - “Here is the letter that destroyed my universese.” — Harlow Shapley





The universe is expanding…

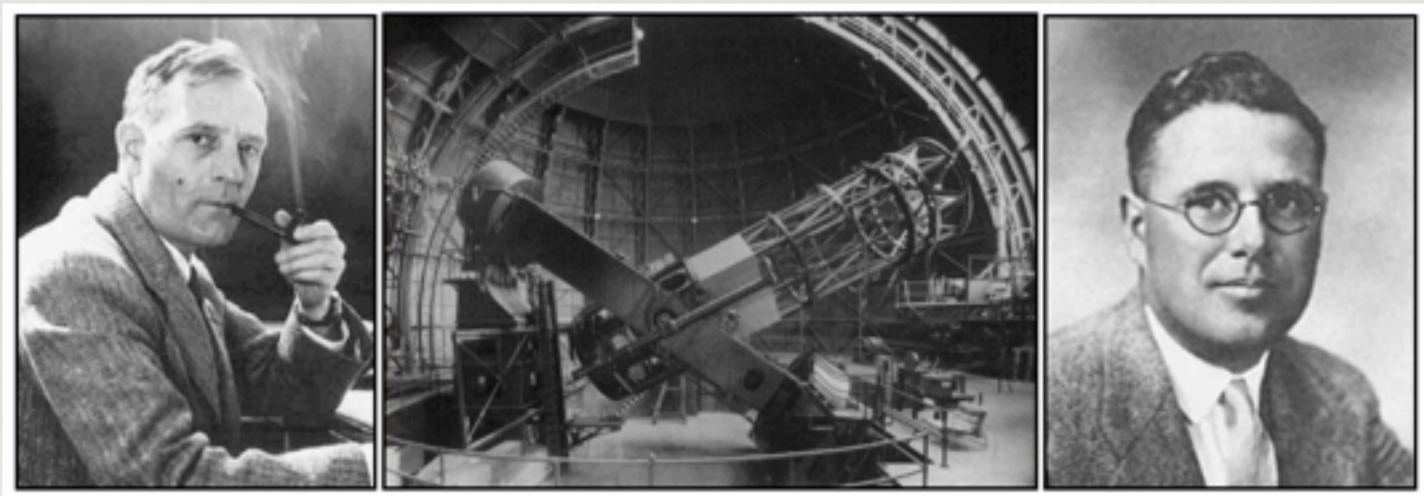
- **1920s-1930s**
- 1914: Vesto Slipher had painstakingly measured redshifts of galaxies
- 1927: George Lemaître publishes expanding universe theory in an obscure journal, largely overlooked
- 1929: Edwin Hubble and Milton Humason measure distances to galaxies:
  - Redshift-distance relation (Hubble-LeMaitre Law).
  - Universe expanding



A two-prism spectrograph

Vesto Slipher & spectrograph


George Lemaître

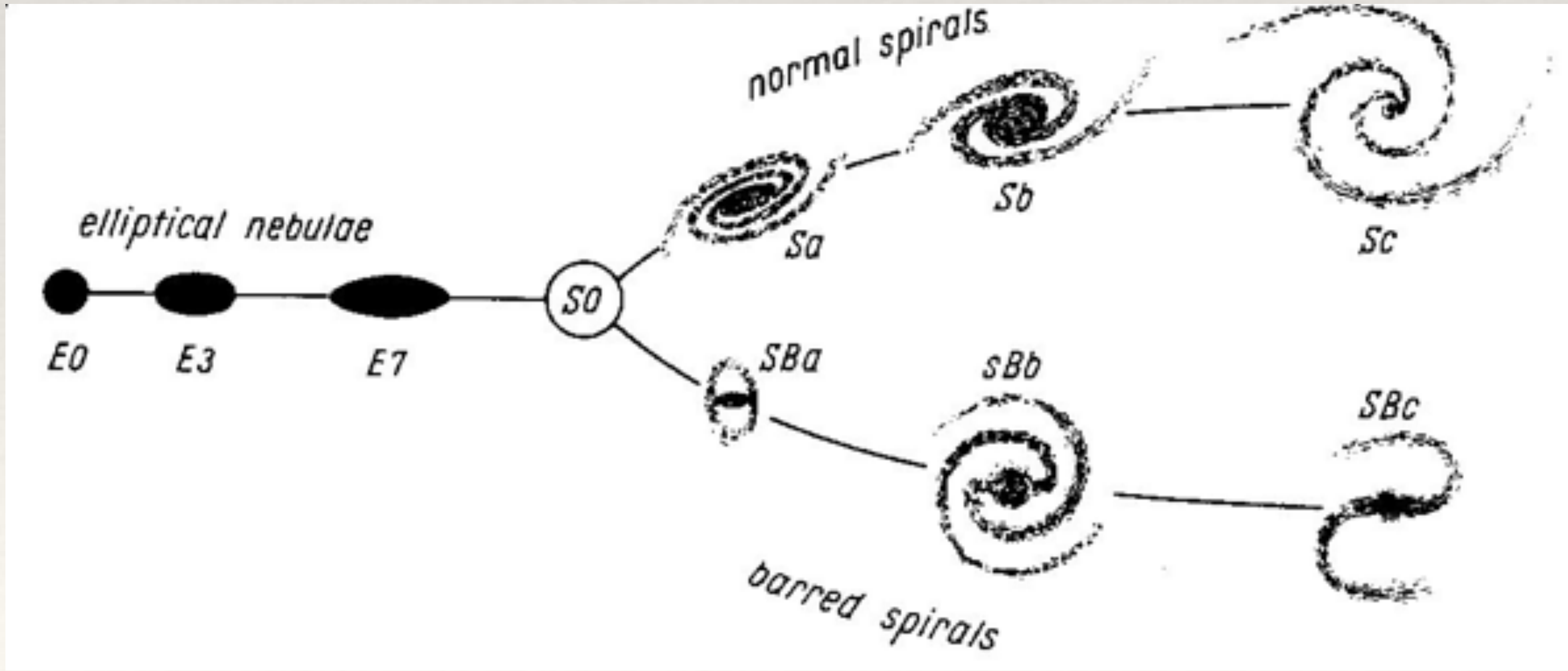

Edwin Hubble
1889 – 1953

100 inch Mt Wilson Telescope

Milton Humason
1891 – 1972

Galaxy Classification

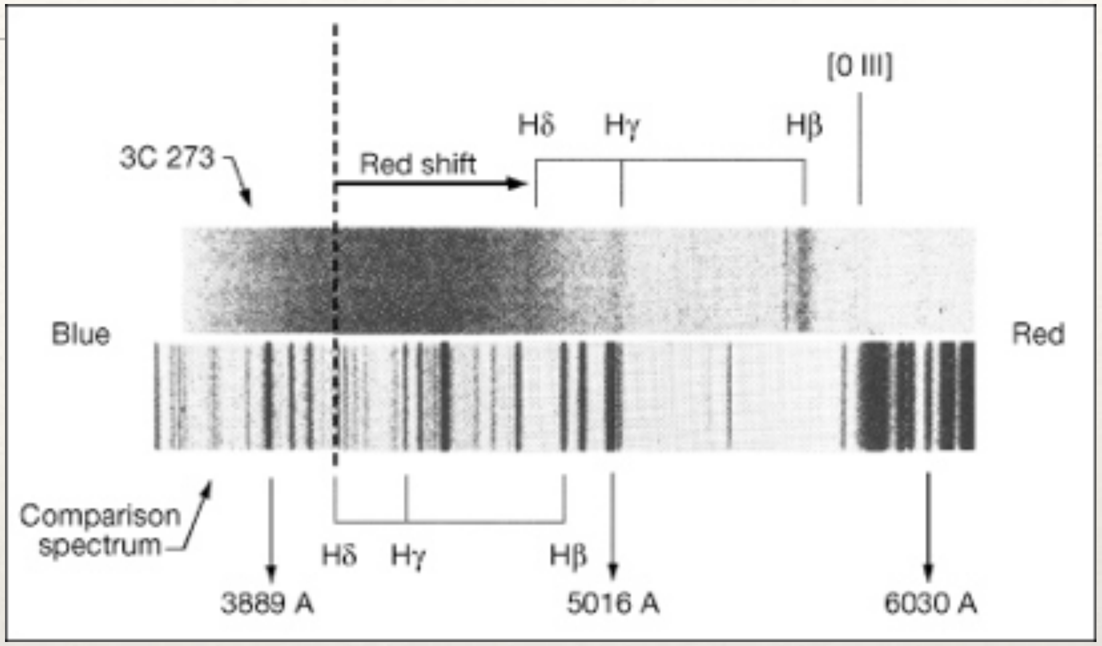
- **1930s-1950s**
- 1936: Edwin Hubble: publishes a galaxy classification system (Hubble tuning fork)
  - A sequence from "simple" to "complex", so used the terms "early" (elliptical) to "late" (spiral) in analogy to nomenclature used for stars.
  - Some debate about whether he was (incorrectly) implying an evolutionary trajectory.
- Classification system refined by others, with most modern types of galaxies recognized by 1940-50.



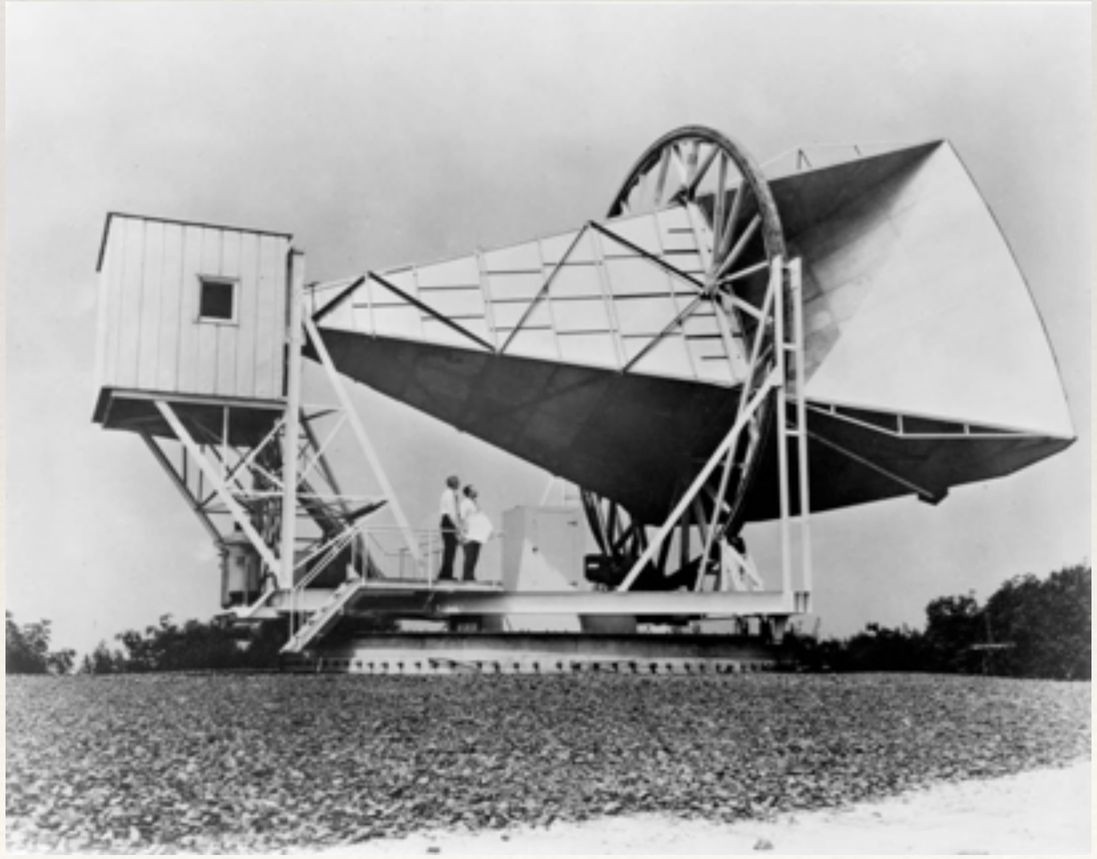
Hubble, E. 1936, The Realm of the Nebulae, Yale Univ. Press, Yale.

The cosmological context…

- **1960s-1970s**
- 1962: Eggen, Lynden-Bell, & Sandage propose Milky Way formed in a "monolithic collapse".
- 1963: Maartin Schmidt discovers quasars.
- 1965: Arno Penzias & Robert Wilson discover Cosmic Microwave Background (CMB), providing strong support for hot Big Bang model.
- 1972: Leonard Searle & Wal Sargent measure 24% He baseline, consistent with Big Bang nucleosynthesis predictions.



Schmidt 1963

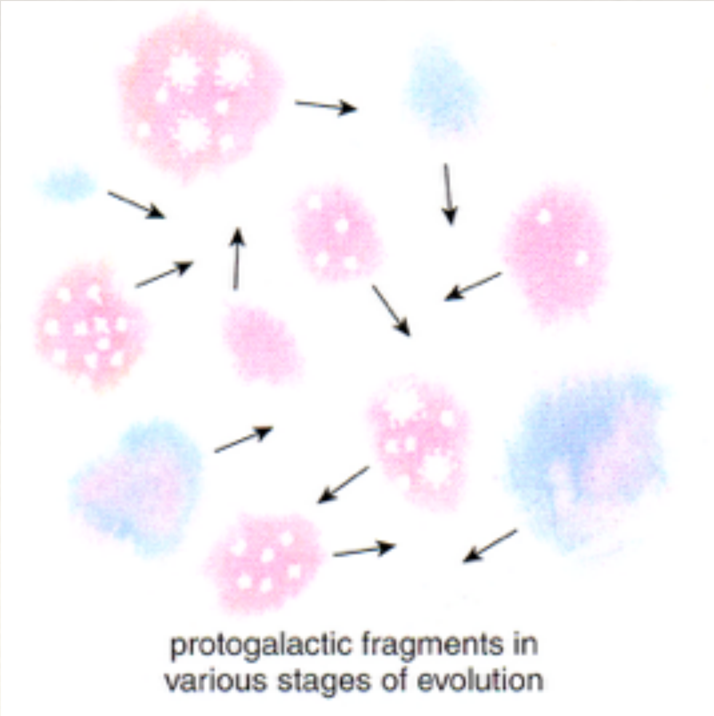


Penzias & Wilson

Galaxies evolve and merge!

- **1970s-1980s**
- 1967: Allan Sandage uses elliptical galaxies as standard candles:
  - Argues Universe will end in a Big Crunch
- 1968: Beatrice Tinsley's PhD thesis argues galaxies evolve as a result of stellar evolution:
  - No, Universe will expand forever!
  - Jump-starts field of evolutionary population synthesis models of galaxies
- 1978: Len Searle & Robert Zinn find Milky Way globular clusters have range of abundances/ages:
  - Milky Way halo built up by accretion of fragments

Beatrice Tinsley



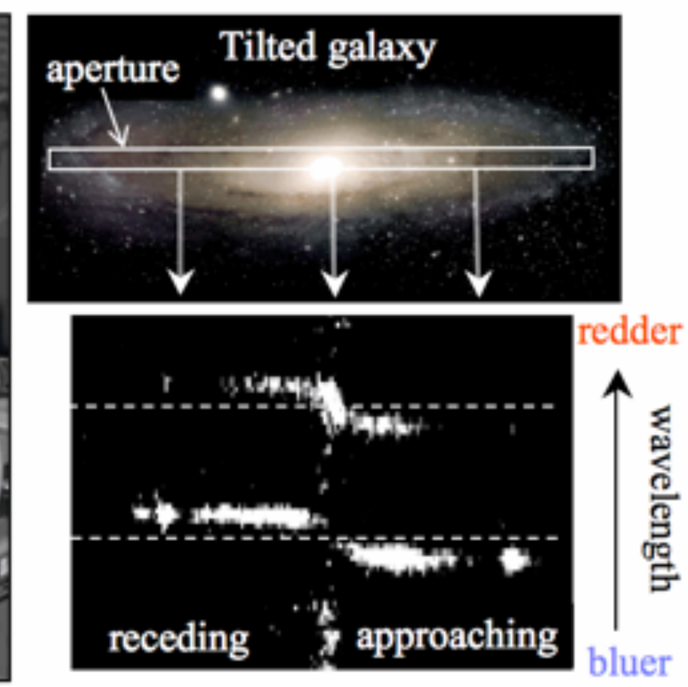
Galaxies have dark matter…

- **1970s-1980s**
- 1930s: Fritz Zwicky had measured galaxy velocities in the Coma cluster:
  - “Dark matter” needed if clusters were bound — no one paid much attention!
- 1970s: Vera Rubin infers dark matter from spiral rotation curves.
- 1973: Peebles & Ostriker N-body simulations indicated Milky Way must contain dark matter in order to be stable.

Fritz Zwicky

Coma Cluster (NASA, JPL)

Vera Rubin measuring galaxy rotation curves (~1970)

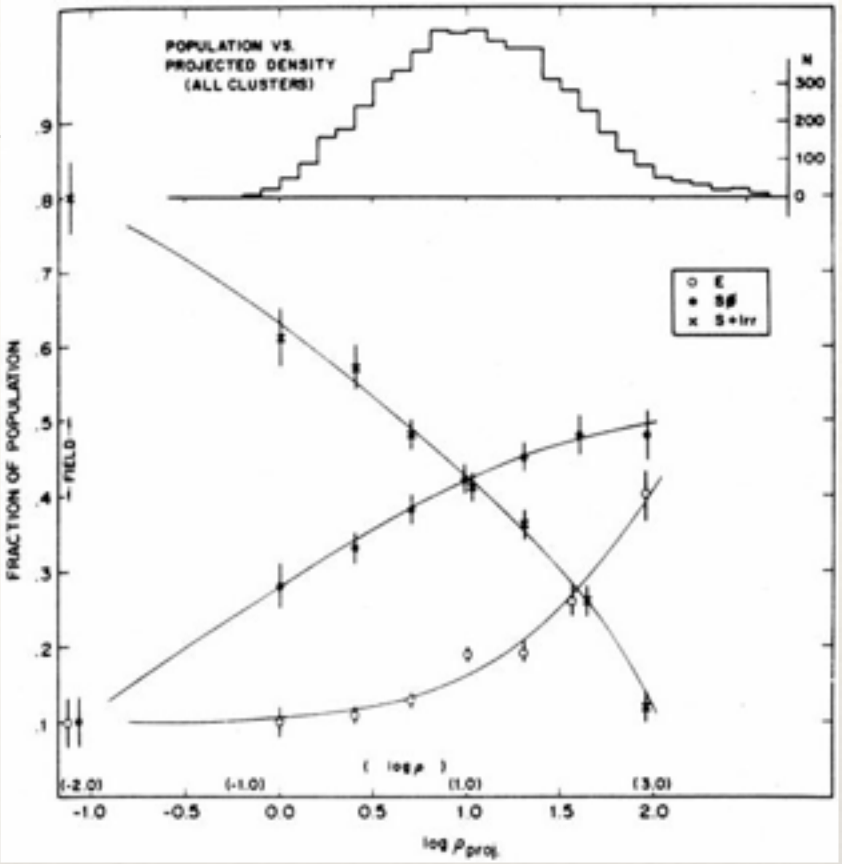


Resulting spectrum of light within aperture

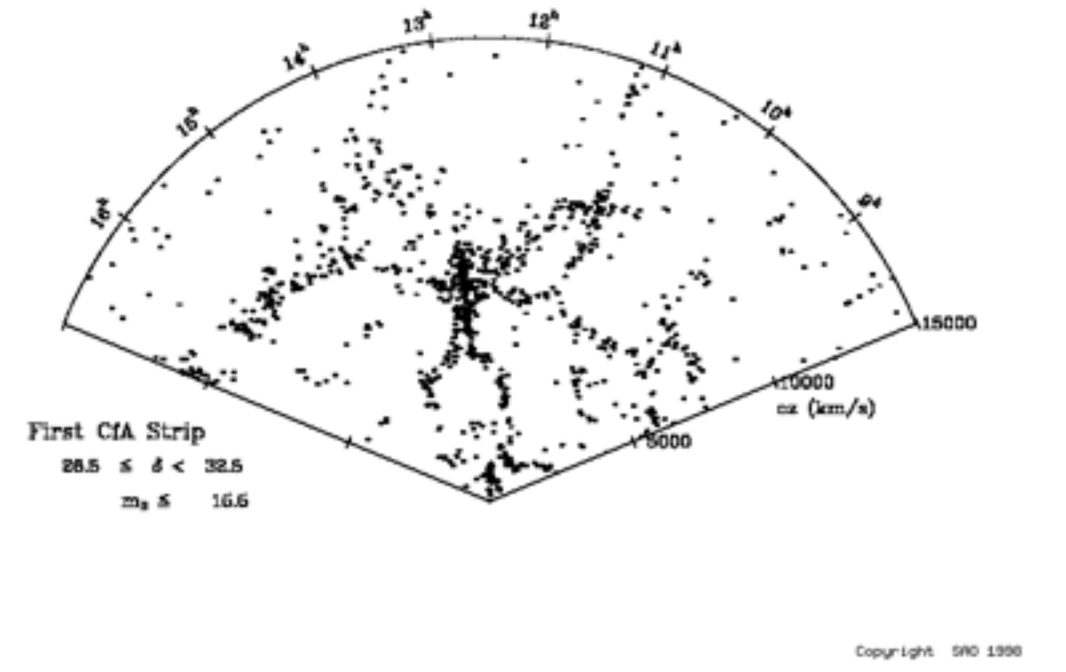
No galaxy is an island…

- **1980s**
- 1980: Alan Guth & Alexei Starobinski independently conceive of early period of rapid, accelerated expansion (“inflation”).
- Importance of environment recognized:
  - Properties of galaxies vary with environment (e.g., morphology-density relation, Dressler 1980)
  - First large galaxy redshift surveys showed there is large-scale structure in the Universe (e.g., CfA Redshift Survey, 1982)

Dressler 1980, ApJ, 236, 351



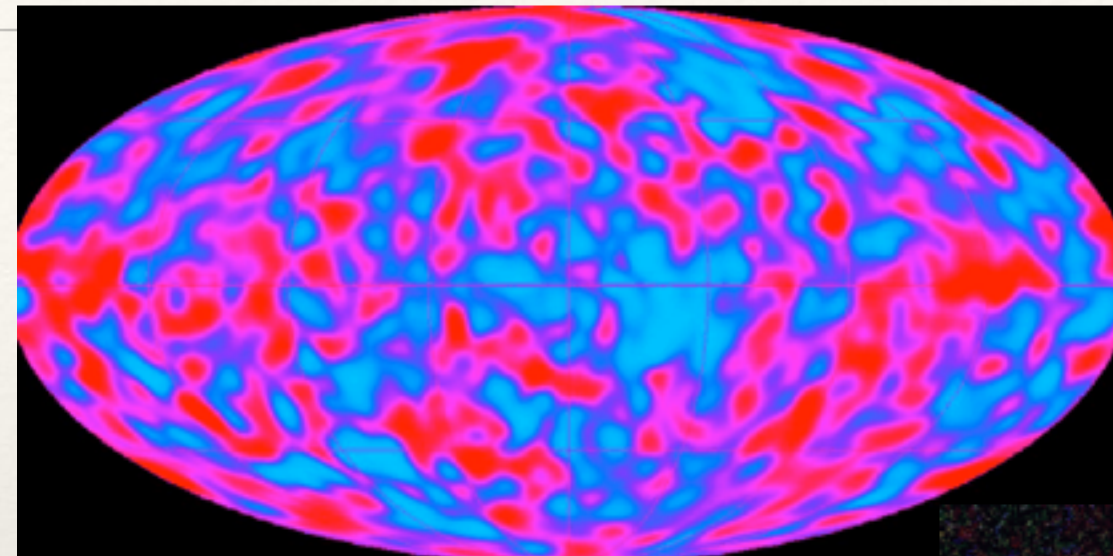
CfA Redshift Survey



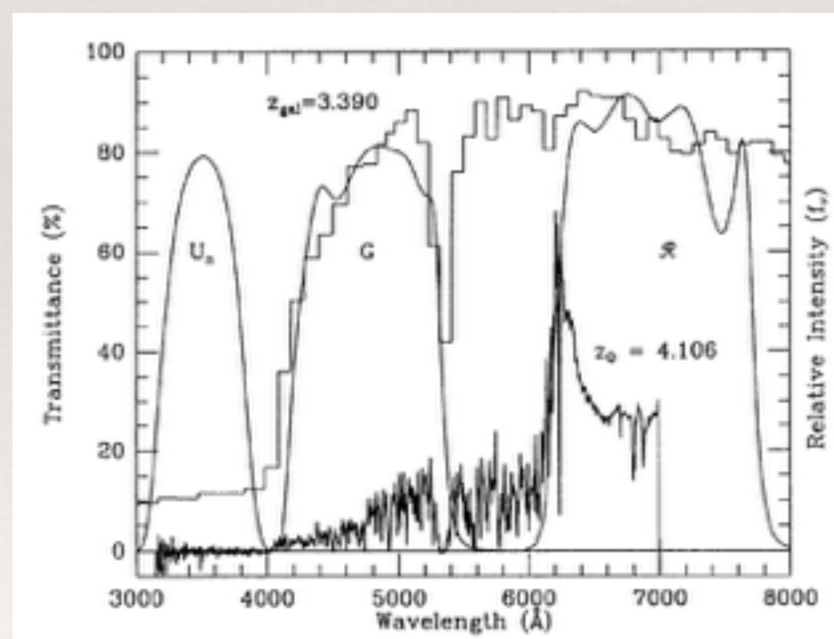
Finding more distant galaxies…

- **1990s**

- 1992: COBE satellite measures stunningly accurate blackbody spectrum with slight anisotropies
- Development of new techniques for finding and confirming high redshift galaxies (z>2)
- 1996: Hubble Deep Field (HDF) image from HST shows galaxies out to z~3
- N-body simulations of galaxy formation



COBE (NASA)

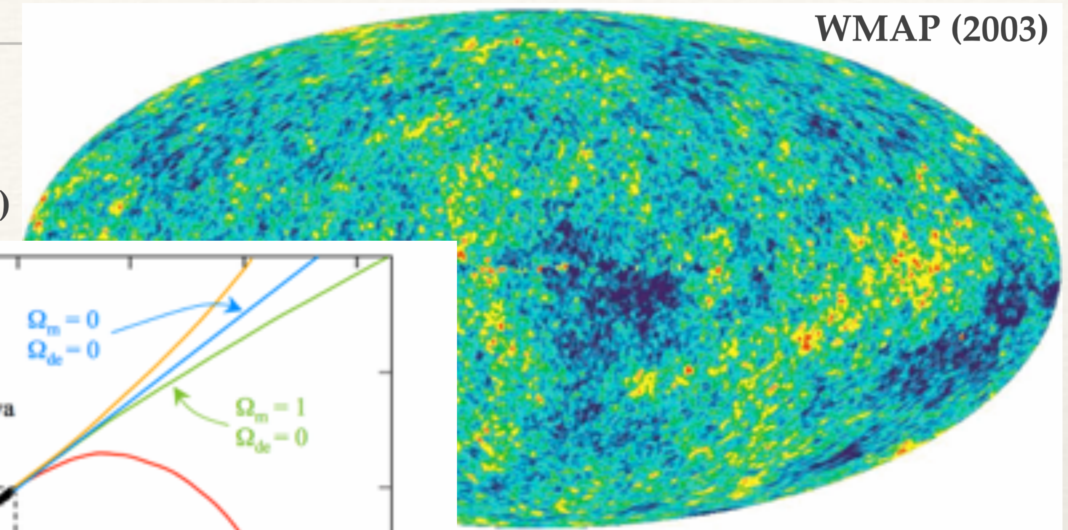


Steidel & Hamilton
1992, AJ, 104, 941

Piece of the HDF

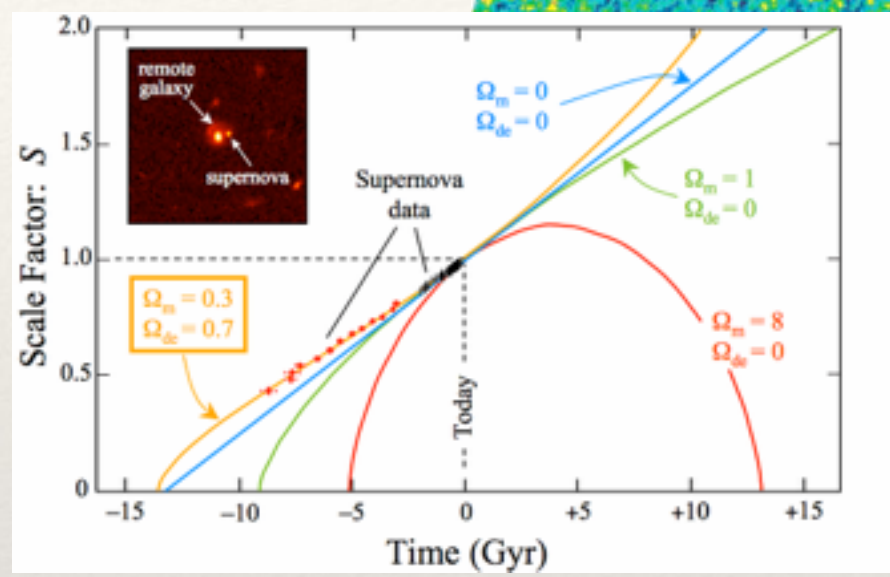
Cosmology, surveys, reionization, oh my!

- **2000s**
- Precision cosmology and LCDM (Type Ia supernovae and WMAP).
- Multiwavelength observations of galaxies — IR (Spitzer), submm (JCMT).
- Large (e.g., SDSS) spectroscopic surveys provide statistical description of galaxy distribution and population.
- Very high redshift galaxies (z>5) and epoch of reionization.
- Recognition of importance of central black holes.
- Simulations with gas physics (and star formation prescriptions) took off, e.g. Gadget-2

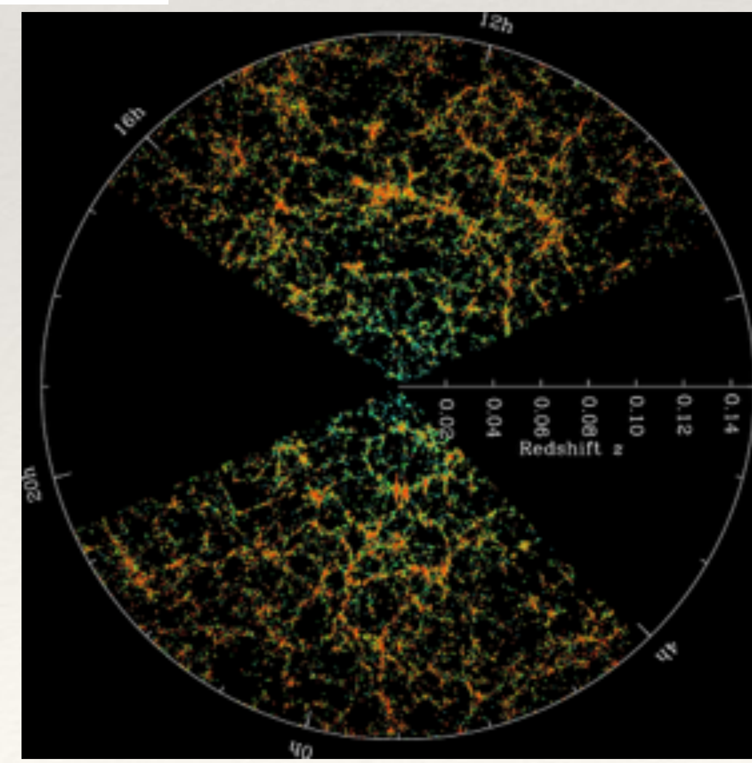


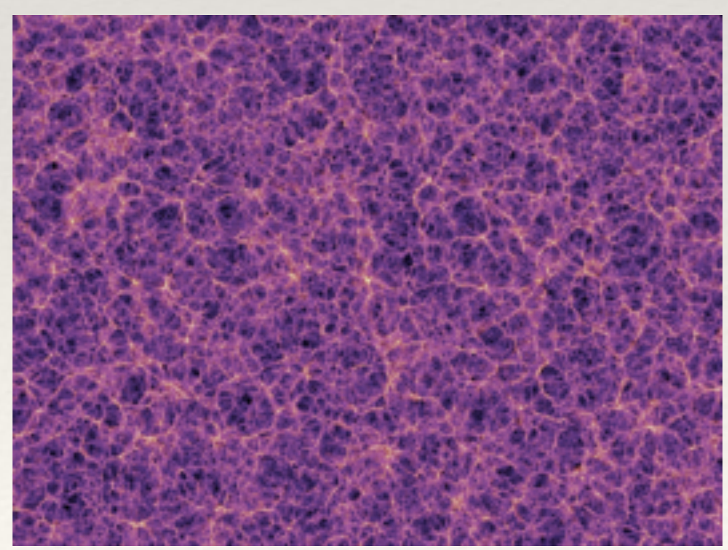
WMAP (2003)

High-z SN Projects (1998)



SDSS-I (2000-2008)

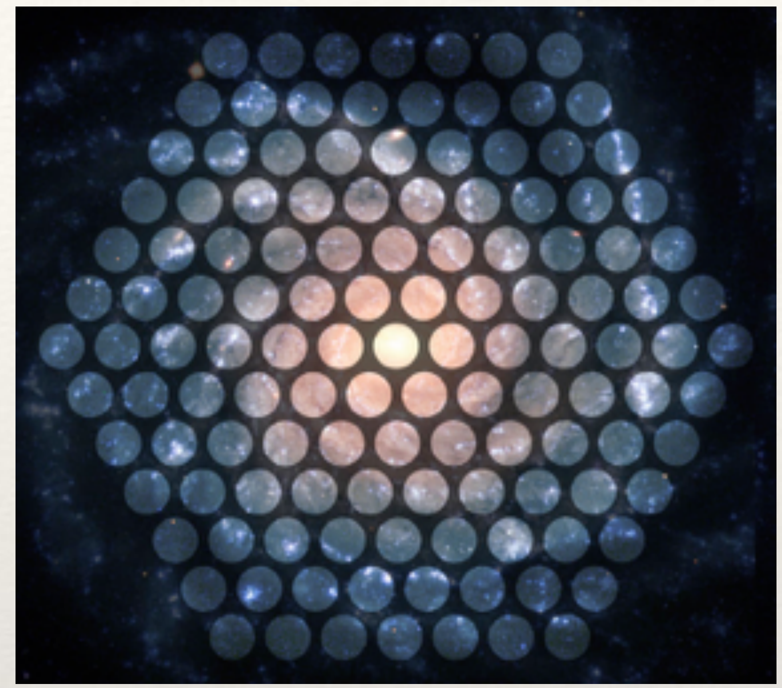


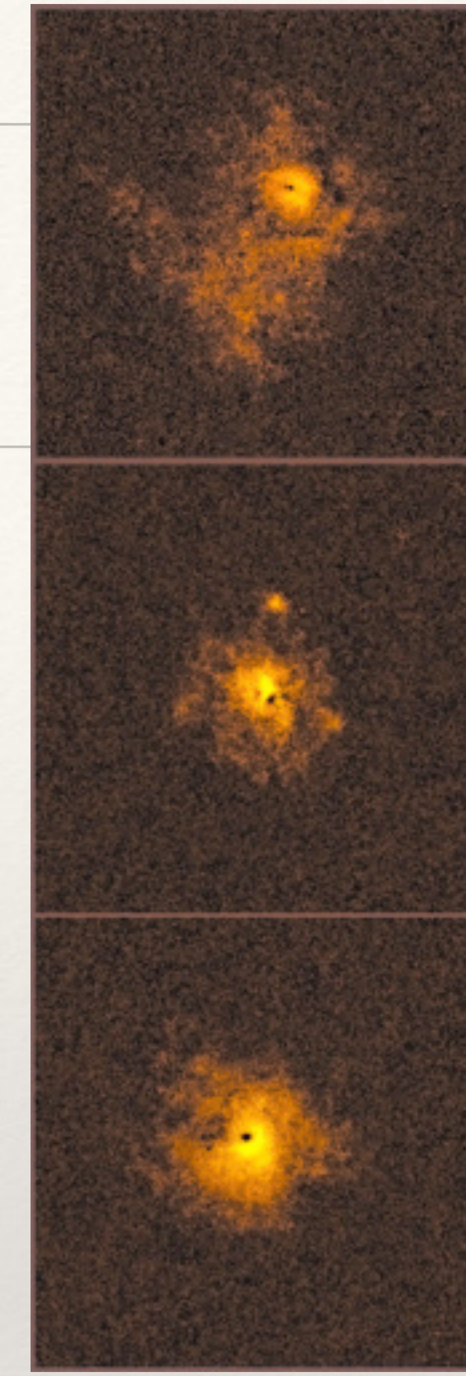


Gadget-2 Simulations (Springel et al. 2005)

State of the Art

- **2010s - now**
- Extended gas halos in galaxies; the baryon cycle and connections with the intergalactic medium (IGM)/ circumgalactic medium (CGM).
- Integral field spectroscopy of galaxies (e.g., CALIFA, SDSS/ MaNGA, MUSE, KCWI)
- Ultra diffuse galaxies (UDGs, e.g. in Coma)
- Big Milky Way spectroscopic surveys (SDSS/ APOGEE, GAIA-ESO, GALAH).


SDSS - MANGA

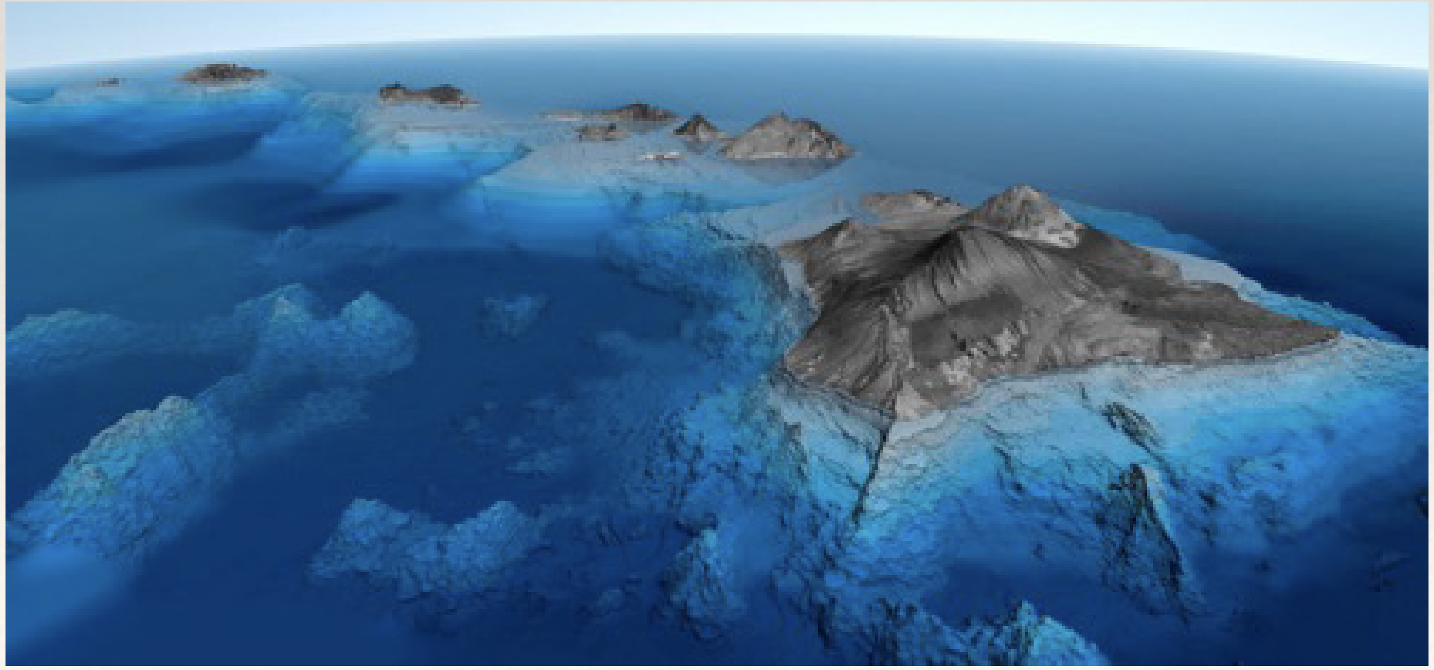

MUSE; Borisova et al. 2016

The Future?

- The first galaxies? — James Webb Space Telescope
- Era of time domain astronomy — e.g., SDSS-V, Vera Rubin Observatory (formerly LSST)
- Detection of dark matter??
- Dark energy???
- ????

Be ready to discuss

- Of all the revelations in extragalactic astronomy that we discuss, which do you think was the most shocking and revolutionary to the people of the time?
- In what respect(s) is this image appropriate and/or inappropriate to a course on galaxies?



Assignment

- reading assignment : chapter 1 of Binney & Merrifield (copyright 1998!)
- weekly summary / questions, as groups
  - main points of the week
  - most confusing point/question(s)
  - complete as groups and submit by Friday 5:00pm
  - Credit will be awarded for being thoughtful and showing engagement with the material.