Goals for this talk:

• explore a topic of research in galaxy structure, evolution, and dynamics: barred galaxies

• highlight the way that astronomy research proceeds incrementally

• emphasize how we use observational data along with complementary theoretical studies (computer simulations) to advance astrophysics knowledge
What is a galaxy?

A collection of stars, gas, dust, dark matter held together by gravity.

Astronomers estimate that there are hundreds of billions of galaxies in the Universe.

Gas : stars : dark matter = 1 : 10 : 100
How large is our galaxy and what is our place in it?
How did we come to learn about the nature of our galaxy and its place in the Universe?
In the 1700’s Herschel set out to determine the size of the Universe - counted stars in several directions; noted the existence of “spiral nebulae” and that they were likely also made up of stars.

Beginning of 20th century - Kapteyn postulates our galaxy is the whole Universe, with extent 30,000 light years - sun was near center.

In the following years many studies were published claiming that “spiral nebulae” were galaxies separate from our own.

In the 1920’s the “great debate” of Astronomy took place - is our galaxy one of many, or is our galaxy the whole Universe?
The great debate in Astronomy (1920)

Shapley - Universe consists of only our galaxy with the sun in the outer parts; “spiral nebulae” are part of our galaxy

Curtis - “spiral nebulae” are external to our galaxy and are galaxies in their own right; Universe is much much larger than just our galaxy

Edwin Hubble settled the debate in 1924

Hubble used special types of stars called Cepheid variables to determine the distance between our galaxy and M31 (one of the “spiral nebulae” that we now know as the Andromeda galaxy).
First step in any new scientific field/area is to identify objects and classify them!
Morphological classifications of galaxies: the Hubble sequence

**aims:** organize the majority of observed objects in a way that tells us something about the underlying physics using unambiguous criteria.
Elliptical galaxies:
• round to watermelon-shaped (based on how they appear to us from earth)
• made up of mostly old, red, stars
• very little gas and dust, largely featureless
• some of the most massive galaxies in the Universe are elliptical galaxies

We're not going to talk about these galaxies today
Spiral (disk) galaxies:
• flat like a pancake
• made up of old and young (blue) stars, lots of gas and dust
• ongoing formation of new stars
• Milky Way is an average spiral galaxy

These are the types of galaxies we’re going to talk about
Anatomy of a spiral (disk) galaxy

- **Face-on view**
  - Bulge
  - Disk
  - Supermassive black hole
  - Dark matter halo (not to scale)

- **Side view**
  - Bulge
  - Disk
  - Bar
Anatomy of a spiral (disk) galaxy

- disk galaxies with lots of gas and dust = active star formation
- majority of new stars formed in the spiral arms, where gas piles up
- planets form around these stars from leftover debris (gas/dust)
Galactic dark matter halos

• we cannot “see” dark matter because it emits no visible radiation
• dark matter is detected through gravitational effects

• in galaxies: the dynamical (total gravitating) mass is much greater (x10) than what we can see in the stars and gas
How are galaxies classified into the Hubble sequence?

- **Ellipticals**: no visible disk, no visible gas/dust/spiral arms, mostly featureless spheroidal shape.
- **Spirals**: disk, flattened, gas, dust content increases, spiral arms become more open, bulge less prominent.
- **Dwarfs & Irregulars**: irregular shape, mostly young blue stars, lots of gas, small, faint.

Studying galaxies based on their appearance: galaxy morphology.

Why are there two branches here? Galaxies look of the same type but some have bars and some do not?
Using morphology to learn about the evolution of disk galaxies
Interesting that disk galaxies are split into parallel sequences of barred and unbarred.

Why should one galaxy be unbarred while a seemingly identical galaxy has a bar structure?

Is the bar structure even significant? What physical processes in the galaxy are related to it?
Early studies (1930s-1990s) tabulated the fraction of disk galaxies that are barred. Associations were noted between bar structures and rings, the appearance of spiral arms, and dust lanes. All of these studies used expert and sophisticated visual classification techniques. At the same time, computer simulations of galaxies and theoretical studies provided complementary information that put the observations into context.
Results from observational and theoretical studies: not only do bars have a dramatic impact on galaxy appearance, but they play an important role in the internal evolution of galaxies.

- Bar structures **exert a torque on the gas** in the galaxy and drive large gas inflows to central parts of galaxies where the gas piles up.
- Leads to dramatic central bursts of star formation, which builds up bulge component; nuclear rings.
- Smaller amount of gas may be pushed out to make inner rings; outer rings.
- May help fuel active galactic nuclei (central supermassive black hole), but other small-scale mechanisms are necessary.

Evidence from: streaming motions of gas along bar, velocity jumps across bar, central gas concentrations in barred and unbarred galaxies, theoretical models.
simulated galaxy disk

- low gas density in most of bar region
- most of gas concentrated in center and in two narrow lanes at 20° to the bar
- density enhancements at ends of bar
simulated galaxy disk

before the shock, gas flows outward

location of shock

after the shock, gas flows inward

large velocity gradient and shear present at location of shock
From comparison of simulations with observed data, determined that the appearance and properties of the bar depend on the size (concentration) of the bulge, and also on the size and properties of the dark matter halo. Are these theoretical predictions borne out by observational data?
Observational studies: progress in the past decade

Surveys with space-based telescopes have greatly pushed the envelope on morphological studies.
Observational studies: progress in the past decade

- Observational studies have recently been able to establish that the likelihood of a galaxy having a bar indeed depends on many factors: bulge size, amount of gas, dark matter halo, galaxy mass/luminosity.
- The dependence of the bar fraction on galaxy properties is more complex than previously thought.

Knowing (most of) the physical processes about how bars work in galaxies, can we learn something about how disk galaxies form and evolve in a cosmological context?
How and when galaxies assembled during the history of the universe is one of the biggest questions in extragalactic astrophysics and cosmology.

When we observe the most distant galaxies (that we can see) we are seeing the universe when it was very young.

Hubble Ultra Deep Field - deepest image of the universe ever taken
“lookback time” ~ 13 billion years
image contains ~ 10,000 galaxies
exposure time ~ 1 million seconds (11.5 days)
size of image ~ 1/13 millionth of the whole sky
Analyzing images of galaxies at varying distances helps us piece together a picture of how galaxies formed and came to look the way they do today.

Very distant galaxies see them as they were ~ 10 billion years ago.

“Nearby” galaxies see them as they are present day.
Galaxy formation is dictated by gravity

- Dark matter and gas “condense” into clumps, which pull in more material
- These clumps form the first stars, which were much more massive than stars we see today
- Some very large clouds of gas form the first proto-galaxies: small disks of rotating gas
  - Small proto-galaxies (disks of gas) merge

- Disks are destroyed and small spherical structures form
  - More gas accretes to make a new disk (bulge + disk)
  - More mergers, followed by more accretion, etc. ...

The first galaxies would not fit in the Hubble sequence. When did galaxies mature and assume their “present-day” shapes?
Supercomputer simulation of the formation of a spiral galaxy similar to our own Milky Way

http://www.astro.washington.edu/users/fabio/movies/MW1hr.mpg
How does studying bar structures fit into all this?

Simulations tell us that certain things are necessary in order for a bar to be able to form in a galaxy disk:
• Disk must be massive enough (compared to DM halo), and “cold” enough (not too many random motions of stars and gas)
• Direct mergers with galaxies of similar size must not be happening frequently (would destroy the galaxy disk and therefore the bar)

Still happen in the present day, but much less frequently than 8-10 billion years ago during the epoch of galaxy assembly.
High-resolution studies with HST tell us that by redshift = 1 (8 billion years ago), the highest mass disk galaxies (stellar masses > $10^{11} M_{\text{sun}}$) have a similar fraction of bar structures as present day galaxies of the same mass.

At lookback times of 8 billion years, the highest-mass galaxies are already mature enough to form bar instabilities, and look like the galaxies we see in the Hubble sequence today.
On the other hand, the same HST studies tell us that for lower-mass galaxies, the bar fraction increases by a factor of two over the last 8 billion years. This tells us that these lower-mass galaxies take longer to “mature” and assemble into galaxies that look like those in the Hubble sequence that we see today.
Takeaway points

• There are many different types of galaxies - to classify them we use the Hubble sequence

• Studying the different properties of galaxies along the Hubble sequence can give us insights into the physics and evolution of galaxies over cosmic times

• Observational data and theoretical studies work in a complementary manner to advance knowledge in astronomy
Astronomers use different wavelengths of light to trace different components (cool stars, hot stars, gas at different temperatures)

- X-ray image traces very hot $10^7$ K gas (+ NS)
- UV image traces hot (30000 K) massive (>10 Mo) stars
- Visible light: intermediate temp and mass (5 to 0.8 Mo) stars
- Near infrared/image traces cool lowest mass (0.3 Mo) stars
- Mid infrared image traces hot (few tens of K) dust
- Radio emission line at 21 cm traces cold atomic hydrogen