What is a galaxy?

• Large assembly of stars, gas and dust, held together by gravity

• Sizes:
  – Largest: ~1 Trillion stars (or more)
  – Smallest: ~10 Million stars
  – Milky Way & Andromeda: ~200 Billion stars

• [For comparison, Nabisco has baked ~350 Billion Oreos™ since 1913, or ~1 for each star…]
Spiral galaxies

- The Milky Way & Andromeda are examples of *spiral galaxies*.
- All spirals share a common structure:
  - Thin *disk* of stars, gas, and dust.
  - Thick *spheroid* of stars with little gas or dust.
- All spirals have disks
- Spheroids vary greatly in size.
Spheroid structure

- **Bulge**: where inner spheroid & disk merge
  - Many RR Lyrae stars
  - A little gas & dust

- **Halo**: sparse outer spheroid
  - Old metal-poor stars
  - Globular clusters
  - RR Lyrae Stars
Sombrero galaxy (M104)
Disk structure

- **Thick disk of stars (~1000 pc thick)**
  - Open clusters & loose associations of stars
  - Mix of young & old stars
  - Cepheid stars in young clusters

- **Thin disk of gas & dust (~100 pc thick)**
  - Mostly cold atomic hydrogen gas
  - Dusty giant molecular hydrogen (H$_2$) clouds
Top View of a Spiral Galaxy
Stellar Disk

Dust & Gas Disk

© IAC/RGO/D. Malin
Rotation of the disk

- Measure using the **Doppler Effect**
- **Stars**: Doppler shifts of stellar absorption lines
- **Ionized gas**: emission lines from HII regions
- **Atomic hydrogen (HI) gas**:
  - Cold H clouds emit a **radio emission line** at a wavelength of 21-cm
  - Can trace nearly the entire disk beyond where the stars have begun to thin out.
Rotating disk

Approaching Side
BLUESHIFT

Rotation Axis

Receding Side
REDSHIFT
Typical spiral galaxy rotation curve

Differential Rotation

Solid-Body Rotation

Radius from the Center (kpc)
Measuring masses of galaxies

- Star or gas cloud is held in its orbit by the gravity of the mass *interior* to its orbit.

**Newton’s gravity:**

\[
M(R) = \frac{V_{rot}^2 R}{G}
\]

- \(M(R)\) = mass interior to radius \(R\)
- \(V_{rot}\) = rotation speed
Example: Milky Way

- **Sun:**
  - $R=8$ kpc, $V_{\text{rot}}=220$ km/sec
  - Gives: $M = 9 \times 10^{10} \, M_{\odot}$ inside $R=8$ kpc

- **Gas Cloud in outer disk:**
  - $R=16$ kpc, $V_{\text{rot}}=275$ km/sec
  - Gives: $M=2.8 \times 10^{11} \, M_{\odot}$ inside $R=16$ kpc

- **A way to measure the masses of galaxies.**
Hubble classification of galaxies

• All *bright* galaxies fall into one of three broad classes according to their *shape*:
  – Spiral Galaxies (~75%)
  – Elliptical Galaxies (20%)
  – Irregular Galaxies (5%)

• Basic classification system developed by Hubble (1936).
Hubble “tuning fork” diagram
Type E: ellipticals

- Show little internal structure:
  - Elliptical in shape
  - No disks, spiral arms, or dust lanes
  - Brightest stars are red

- Classified by the degree of apparent flatness:
  - E0 is circular
  - E7 is flattest (3:1 aspect ratio)
Elliptical galaxies

E1

E5
Type S: ordinary spirals

- Classified by relative strength of the central bulge & tightness of the spiral arms
- **Types**: Sa, Sb, and Sc
  - Sa: strong bulge & tight, indistinct arms
  - Sb: intermediate type
  - Sc: small bulge & loose, well-defined arms
- The Milky Way is probably type Sb.
Ordinary spirals

Sa

Sb

Sc
Type SB: barred spirals

- Parallel group to the ordinary spirals:
  - About as many barred as ordinary spirals.
- Feature a strong central **stellar bar**:
  - Bar rotates as a unit (solid body rotation)
  - Spiral arms emerge from the ends of the bar
- Same subclasses:
  - SBa, SBb, and SBc
Barred Spirals

SBa

SBb

SBc
Type I: irregulars

- Show an irregular, often chaotic structure.
- Little evidence of systematic rotation.
- Catch-all class:
  - Proposed systematic subclasses, but many irregulars defy classification.
- Significant dwarf irregular population, classified as “dI”
Irregular galaxies

Large Magellanic Cloud  Small Magellanic Cloud
Spiral galaxies

• **Properties:**
  – Mass: $10^9 - 10^{12} \ M_{\text{sun}}$
  – Diameter: 5 – 50 kpc
  – Luminosity: $10^8 - 10^{11} \ L_{\text{sun}}$

• **Structure & dynamics:**
  – Disk + spheroid
  – Supported by relatively rapid rotation, but spheroid is puffed up by random motions.
Elliptical galaxies

- **Properties**:
  - Mass: $10^5 - 10^{13} \, M_\text{sun}$
  - Diameter: 1 – 200 kpc
  - Luminosity: $10^6 - 10^{12} \, L_\text{sun}$

- **Structure & dynamics**:
  - Spheroid of old stars with little gas or dust
  - Supported by random motions of stars with some very slow rotation
Irregular galaxies

- **Properties:**
  - Mass: $10^6 - 10^{11} \, M_{\odot}$
  - Diameter: 1 – 10 kpc
  - Luminosity: $10^6 - \text{few} \times 10^9 \, L_{\odot}$

- **Structure & dynamics:**
  - Chaotic structure, lots of young blue stars
  - Moderate rotation in Irregulars, but very chaotic motions as well.
Relative stellar & gas content

• **Spirals:**
  – Range is ~10-20% gas
  – On-going star formation in the disks
  – Mix of Pop I and Pop II stars

• **Ellipticals:**
  – Very little or no gas or dust
  – Star formation ended billions of years ago
  – See only old Pop II stars
Relative stellar & gas content

• **Irregulars:**
  – Can range up to 90% gas content
  – Often a great deal of on-going star formation
  – Dominated by young Pop I stars

• **Dwarf Irregulars:**
  – Very metal poor (<1% solar)
  – Forming stars for the *first* time only now.
Dwarf galaxies

- Low-luminosity Ellipticals & Irregulars.
  - Significant number of dwarfs
- There are no (convincing) Dwarf Spirals.
- Possibilities:
  - Small versions of their larger cousins
  - Different population of objects with superficial similarities to larger E’s and Irr’s
Groups & clusters of galaxies

• Most galaxies are found in groups and clusters

• **Basic properties:**
  – Membership: Pairs to 1000’s of galaxies.
  – Sizes: 1 – 10 Mpc across
  – Mix of bright galaxies and dwarfs

• About 3000 clusters have been cataloged to date.
The *Local Group*

- Group of 30-odd galaxies centered on the Milky Way and Andromeda:
  - Size: \(\sim 1\) Mpc
  - 4 Spirals
  - 15 Ellipticals (3 small Es & 12 dEs)
  - 13 Irregulars of various sizes
  - Total Mass \(\sim 5 \times 10^{12} M_{\text{sun}}\)
The Local Group
Virgo Cluster

- Nearest sizable cluster to the Local Group
- Relatively loose cluster, centered on two bright Ellipticals: M87 and M84

**Properties:**
- Distances: ~18 Mpc
- Size: ~ 2 Mpc
- 2500 galaxies (including many dwarfs)
- Mass: $\sim 10^{14} \text{ M}_{\odot}$
Rich clusters

- Contain 1000’s of galaxies:
  - Extend for 5–10 Mpc
  - Masses up to \( \sim 10^{15} \, M_{\text{sun}} \)
  - One or more giant Elliptical Galaxies at center.
  - Ellipticals found near the center.
  - Spirals found at the outskirts.
  - 10–20% of the mass is hot \((10^{7–8} K)\) intracluster gas seen in X-ray emission.
NGC 4881
Coma Cluster
HST · WFPC2
Distant rich cluster
(HST Image)
Superclusters

- Clusters of Clusters
- Properties:
  - Sizes up to 50 Mpc
  - Masses of $10^{15}$ to $10^{16}$ M$_{\text{sun}}$
  - 90–95% empty space (voids)
  - Long and filamentary in shape
Local supercluster

- Roughly centered on the Virgo Cluster
- Local Group is on the outskirts
- Properties:
  - Size: ~20 Mpc
  - Mass: ~$10^{15} \, M_{\text{sun}}$
  - only ~5% of the volume occupied by galaxies
Galaxies are large compared to the distances between them:

- Most galaxies are separated by only $\sim 20$ times their diameters.
- By comparison, most stars are separated by $\sim 10^7$ times their diameters.

Galaxies are likely to encounter other galaxies a few times over their histories.
Tidal interactions

- Galaxies interact via *Gravitation*.
- Because of their large sizes, two galaxies passing near each other raise *mutual tides*.
- These tides distort the shapes of the galaxies.
- Dramatic effects *without* direct collision.
- Most “peculiar galaxies” are interacting pairs.
Raising tides

- **Tidal stretching** along the encounter line.
  - Near side feels stronger gravitational pull from the companion
  - Far side feels weaker gravitational pull and lags behind the near side.
Mergers

• If two colliding galaxies can dissipate enough orbital energy:
  – Wreckage merges into a single galaxy.
  – Gas clouds collide and form new stars.
  – Some portion of the old stars are ejected from the system (carry off orbital energy).

• Mergers may play a pivotal role in the formation of galaxies
Galactic nuclei

• Galaxy Nucleus:
  – Exact center of a galaxy and its immediate surroundings.
  – If a spiral galaxy, it is the center of rotation.

• Normal Galaxies:
  – Dense central star cluster
  – A composite stellar absorption-line spectrum
  – May also show weak nebular emission lines.
Active Galactic Nuclei

- About 1% of all galaxies have **active nuclei**.
- **Bright, compact nucleus:**
  - Sometimes brighter than the entire galaxy.
  - Strong, broad *emission lines* from hot, dense, highly excited gas.
- **Rapidly Variable:**
  - Small: only a few light days across.
Bright Active Galaxy (HST Image)
Discovery of Active Galaxies

- **1943: Seyfert Galaxies**
  Carl Seyfert identified 6 galaxies with strong, broad emission lines coming from a compact, bright galaxy nucleus.

- **1950s: Radio Galaxies**
  First radio telescopes found faint galaxies at the location of intense radio emission. Also show broad emission-lines in their spectra.
The riddle of the quasars

- **1960s:**
  - Radio astronomers found intense, *point-like* sources of radio emission.
  - Photographs revealed slightly fuzzy or “*quasi-stellar*” objects at these locations.
  - The spectra were bizarre and full of broad, unrecognized emission lines.

- **Quasars:** “Quasi-Stellar Radio Sources”
The riddle of quasars solved

• **1963**: Maarten Schmidt (Caltech)
  – Recognized that the lines in Quasars were normal Hydrogen lines with extreme redshifts
  – Luminous objects located very far away.
  – The “fuzz” is the host galaxy lost in the glare of an intense active nucleus.
Cosmic beacons

- Quasars are the most luminous objects in the Universe:
  - Brightest are \( \sim 10^{14} \, L_{\text{sun}} \)
- **Brightest Quasars**:
  - Among the most distant objects in the Universe
  - Most distant is \( \sim 4 \, \text{Gpc} \)
  - Probes of the Universe on very large scales.
Distant Quasar
(HST Image)
What powers AGNs?

- Properties that need to be explained:
- **Powerful:**
  - Luminosities of Billions or Trillions of suns.
  - Emit everything from Radio to Gamma rays
- **Compact:**
  - Visible light varies on day timescales
  - X-rays can vary on a few hour timescales
The Black Hole paradigm

- A plausible energy source: accretion of matter onto a supermassive Black Hole.
  - Supermassive = $10^6 - 10^9 \, M_{\text{sun}}$
  - Schwarzschild Radii: $\sim 0.01 - 10 \, \text{AU}$

- Matter releases gravitational energy as it falls in.
  - Infalling gas settles into an accretion disk.
  - The hot inner parts of the disk shine brightly.
The central engine

• Black Hole accretion can be very efficient:
  – up to \( \sim 10\% \) maximum efficiency
  – \( \sim 1 \, M_{\text{sun}} \) /year of matter needed for bright AGNs.
  – Get “fuel” from surrounding gas and stars.

• Rapidly Spinning Black Hole:
  – Acts like a particle accelerator
  – Leads to the jets seen in radio-loud AGNs.
Do most galaxies harbor a central black hole?

- Nearly all spirals show some level of “activity” if perhaps only very faintly.
- Dynamical evidence for massive black holes in many nearby “inactive” galaxies.
- Milky Way has a $3 \times 10^6 \, M_{\text{sun}}$ Black hole, but lacks strong activity.
- Recent evidence that almost all galaxies have large black holes in the center.
Summary:

• Three basic types of galaxies:
  – Spirals
    • Disk and spheroid component
    • Rotation of disk allows measurement of galaxy mass
  – Ellipticals
  – Irregulars
• Differ in terms of
  – Relative gas content
  – Star formation History
  – Internal motions
• Galaxies tend to group into Clusters
  – Groups, clusters, and superclusters
  – Galaxies can collide and merge
• Some galaxies have “active” nuclei
  – Powered by large black holes in the center