Part 3: Galaxies and the Universe

Tuesday, March 21 — Reading: Chapter 12.1 — 12.3
- Our Galaxy = The Milky Way

Thursday, March 23 — Reading: Chapter 13.1 — 13.2
- Galaxies: types, properties, clusters of galaxies, dark matter

Tuesday, March 28 — Reading: Chapters 13.3, 15
- Galaxies: formation, evolution; distance scales; expansion of the Universe

Thursday, March 30 — Reading: Chapter 12.4, 14
- Galaxies: active galaxies and quasars; supermassive black holes

Tuesday, April 4 — Reading: Chapter 15
- Cosmology: Big Bang ➡ background radiation; formation of structure

Wednesday, April 5 — Help session: 4 to 6 PM in Welch 2.246

Thursday, April 6 — Exam 5


If people were stars, cities …


… would be galaxies.
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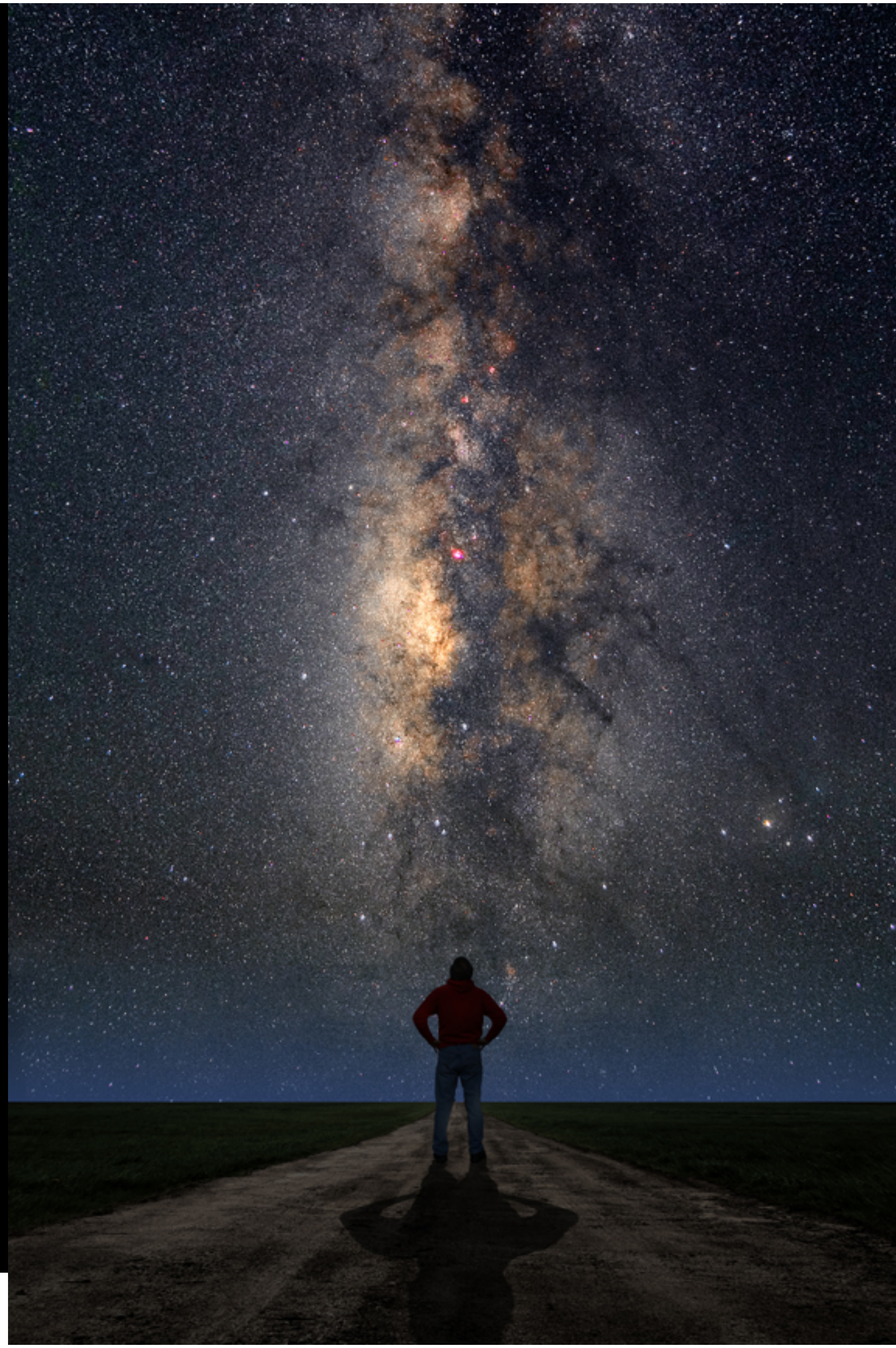
Galaxies made of stars & gas & dark matter are the fundamental building blocks of the Universe.

Cities are held together by societies and economics.

Galaxies are held together by gravity.



Our Milky Way Galaxy

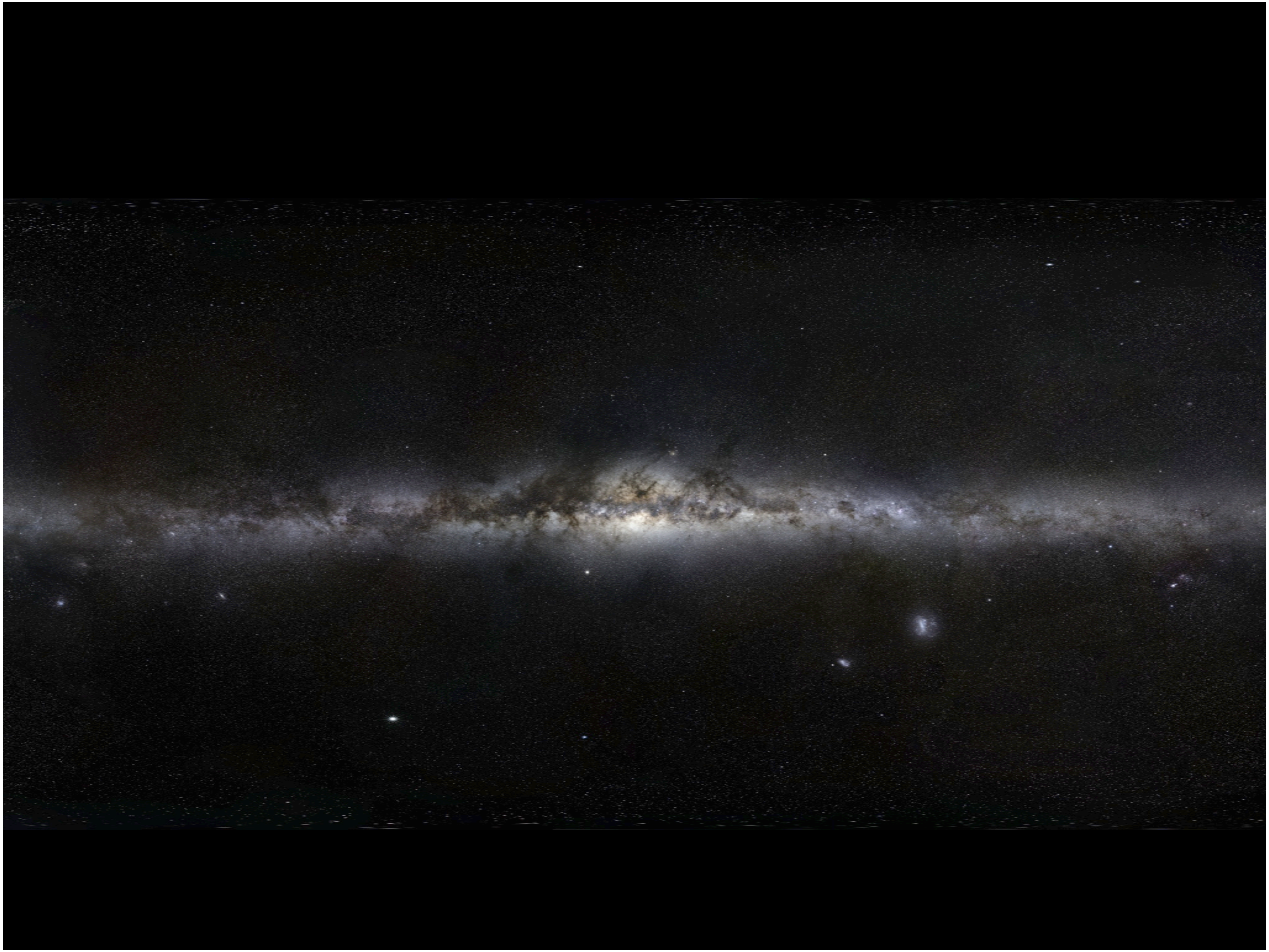
If people were stars, cities would be galaxies.

We live in a galaxy called the Milky Way. It is a flat disk of about 100 billion stars plus gas embedded in an almost spherical halo of stars, globular clusters of stars, and a dark halo of unknown material. The dark halo is several times more massive than all of the visible stars combined.

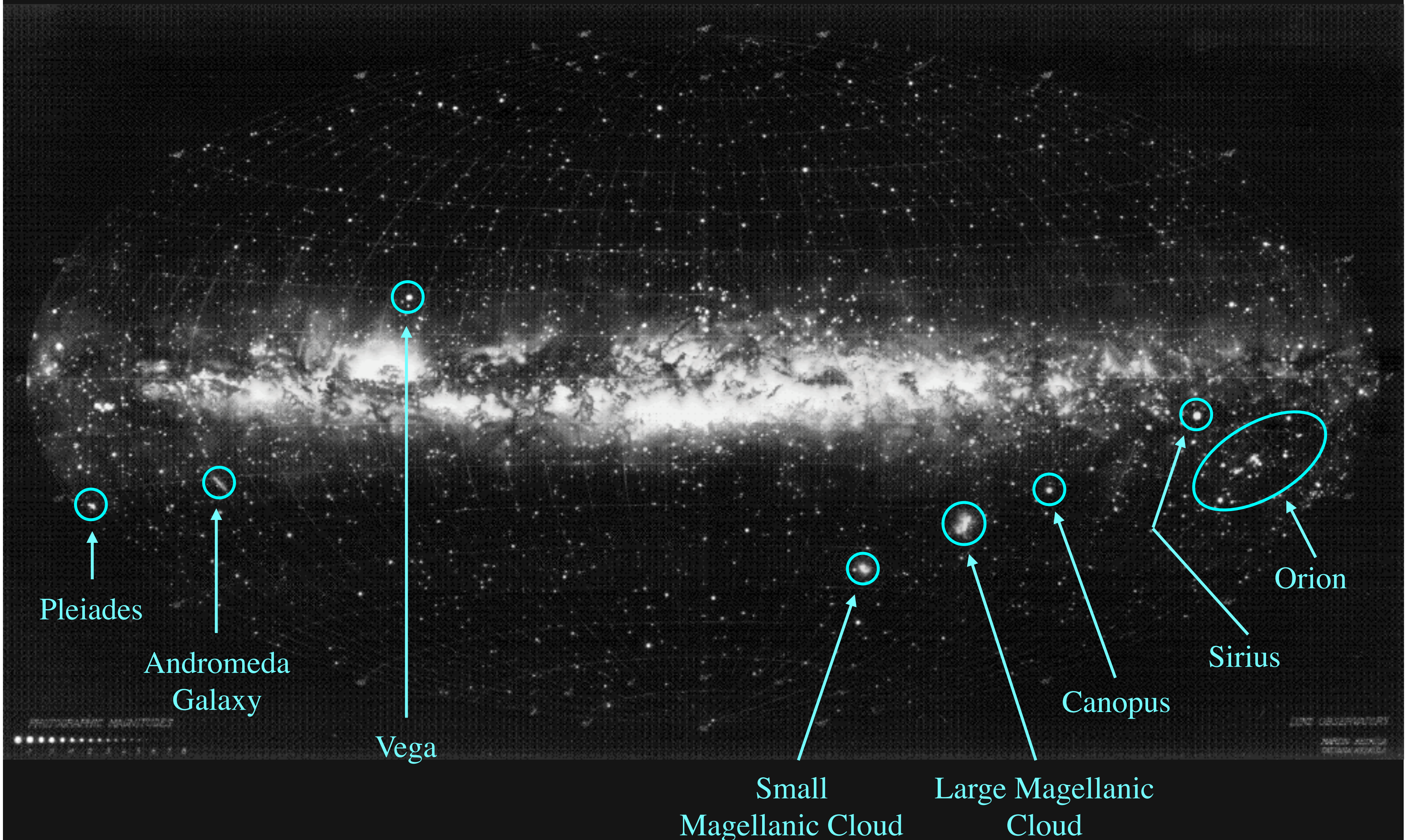
Properties of our Galaxy

Diameter of disk	~ 100,000 ly
Diameter of halo	~ 300,000 ly
Number of stars	~ 10^{11}
Total mass	~ 10^{12} $M_\odot$
Age	~ 13 $\times$ 10^9 y
Hubble type	Sbc
Sun's distance from the center	~ 30,000 ly
Sun's orbital velocity	~ 220 km / s
Sun's orbital period	~ 250 million y


Wally Pacholka / AstroPics.com



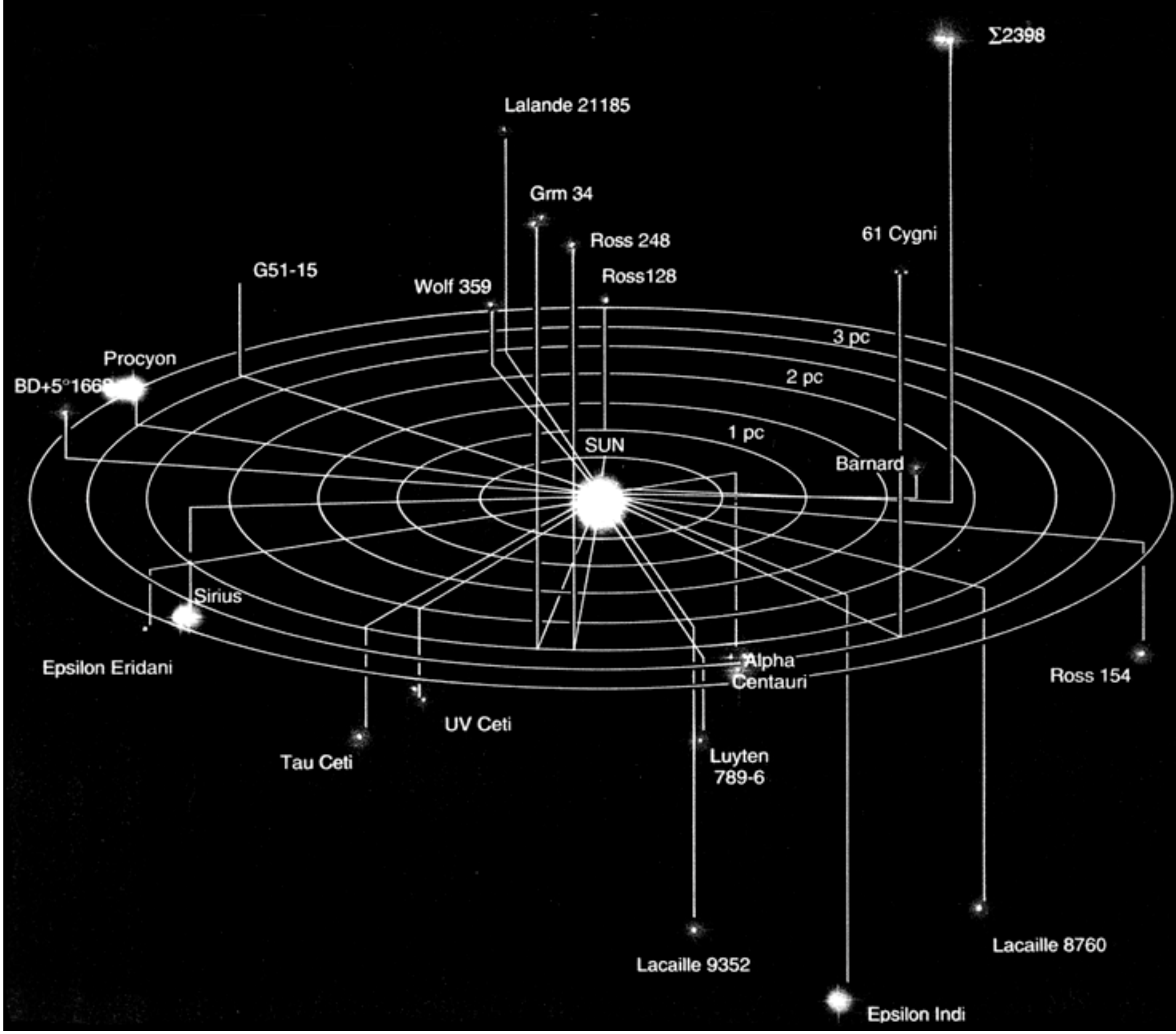
The Milky Way Galaxy



Our Galaxy: Portrait by Jon Lomberg

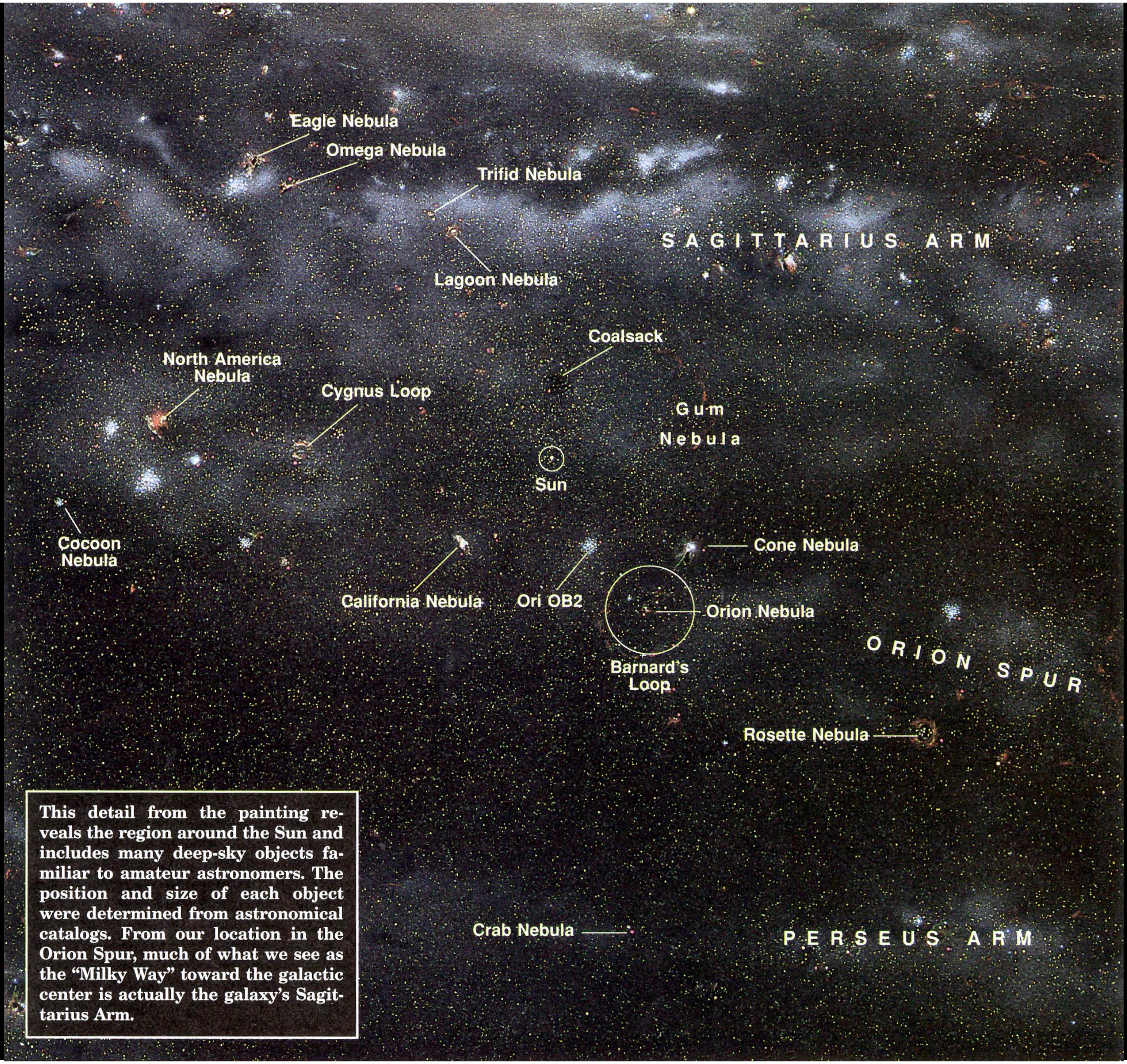
We live in the suburbs of our Galaxy.

The Solar Neighborhood



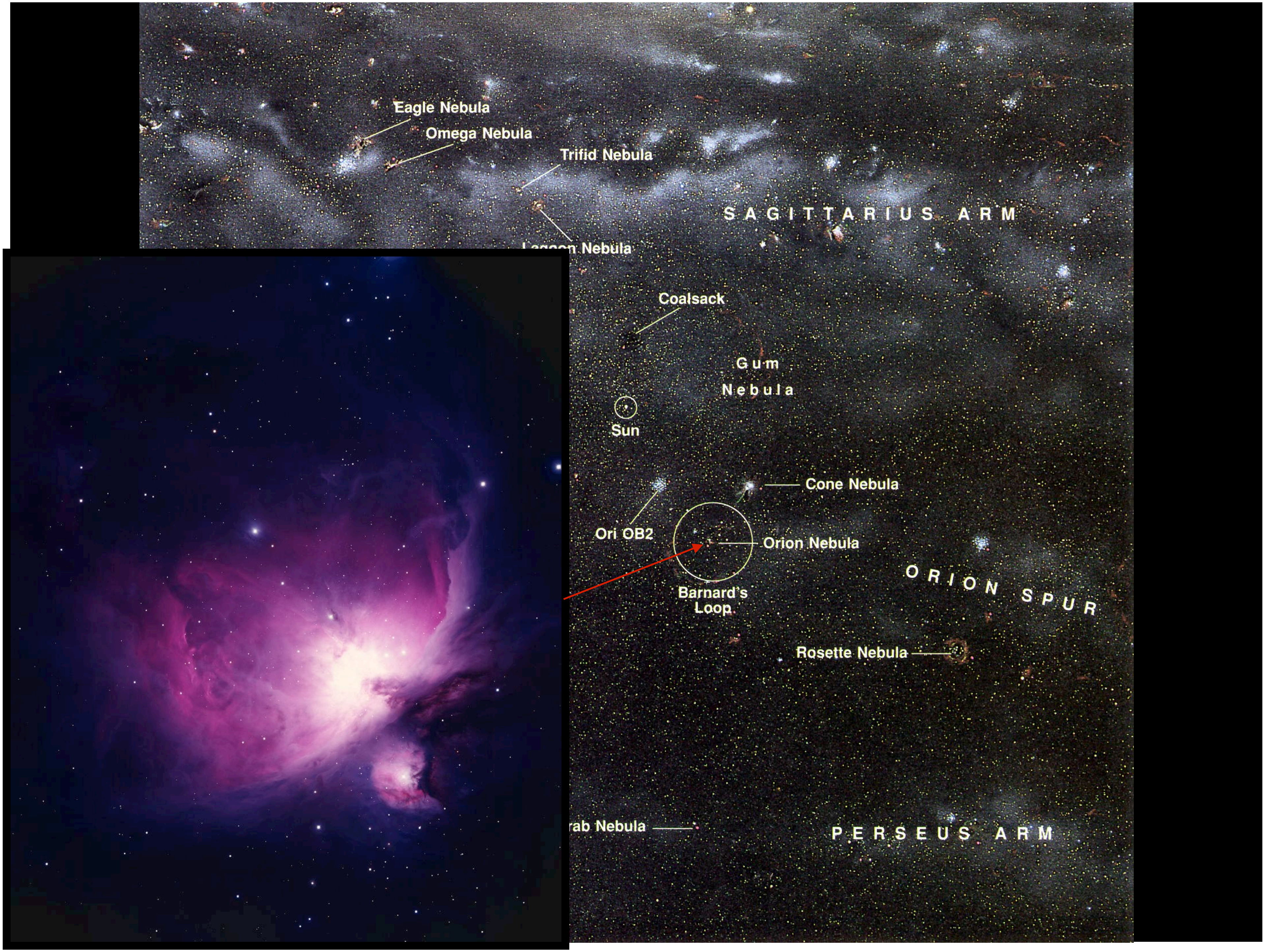
A plot of the 30 closest stars to the Sun, projected so as to reveal their three-dimensional relationships.

The typical separation of stars near the Sun is
~ 1 pc
~ 200,000 AU



This detail from the painting reveals the region around the Sun and includes many deep-sky objects familiar to amateur astronomers. The position and size of each object were determined from astronomical catalogs. From our location in the Orion Spur, much of what we see as the "Milky Way" toward the galactic center is actually the galaxy's Sagittarius Arm.

Eagle Nebula
Omega Nebula
Trifid Nebula
SAGITTARIUS ARM
Lagoon Nebula
Coalsack
North America Nebula
Cygnus Loop
Gum Nebula
Sun
Cone Nebula
Ori OB2
Orion Nebula
Barnard's Loop
ORION SPUR
Rosette Nebula
Nebula
PERSEUS ARM


Eagle Nebula
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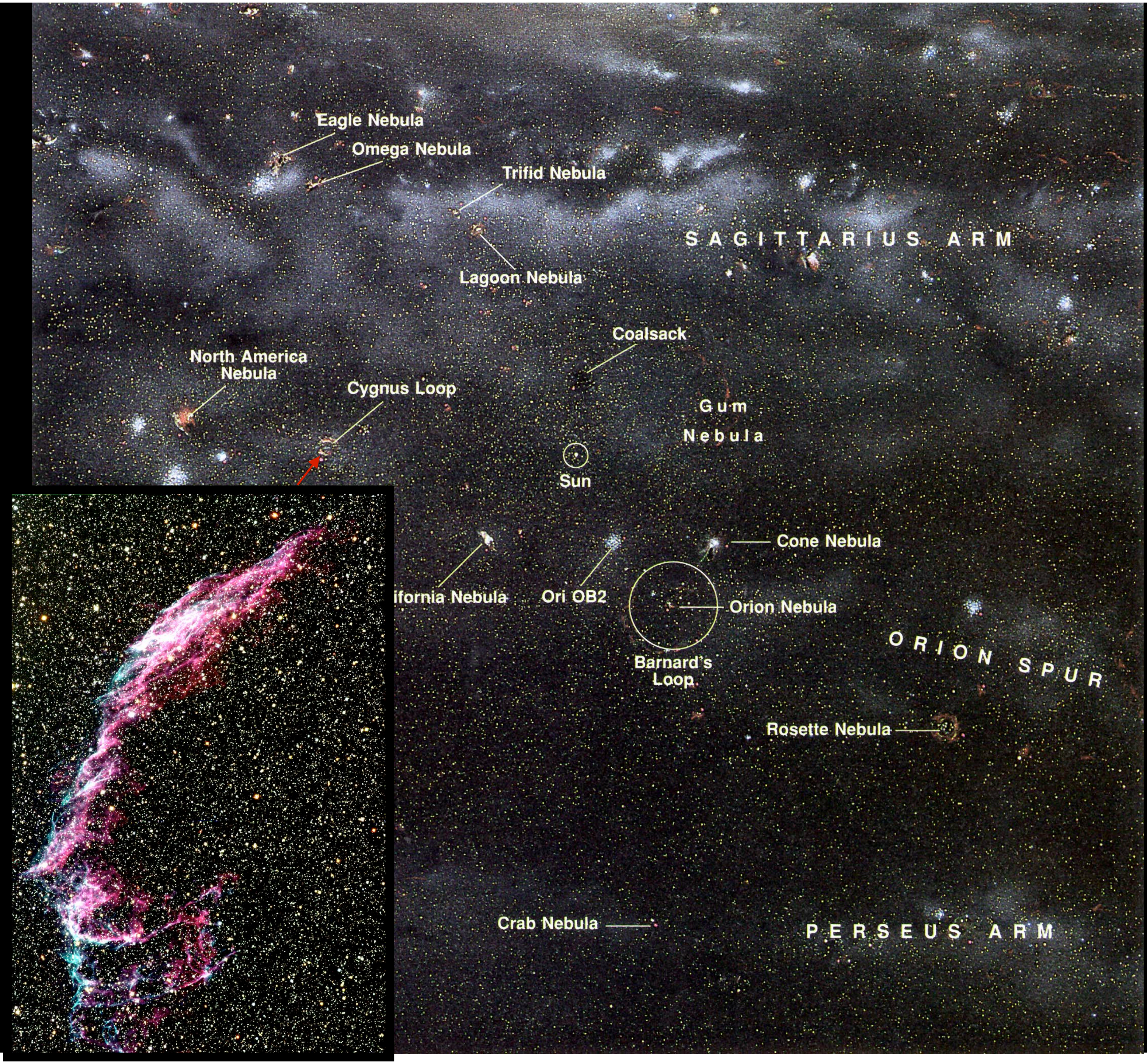

Eagle Nebula
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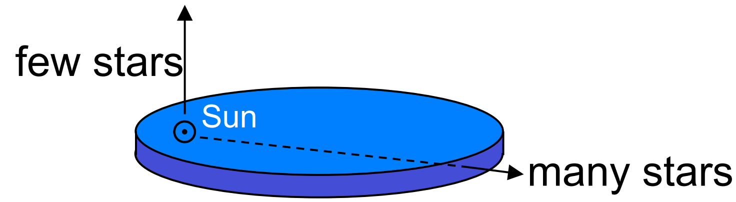
Sun
Cocoon Nebula
Cone Nebula
California Nebula
Ori OB2
Orion Nebula
Barnard's Loop
ORION SPUR
Rosette Nebula
Crab Nebula
PERSEUS ARM

Immanuel Kant's Hypothesis (1755)

The Milky Way is a rotating disk of stars. Our Sun is 2/3 of the way out from the center.

We see the Milky Way as a diffuse band of light encircling the sky. Galileo showed that this light comes from many faint stars. Immanuel Kant suggested that the Milky Way is a flat, spinning disk of stars viewed from inside. He also suggested that other nebulae are similar "island universes" strewn randomly through space; their appearance depends on their orientation.



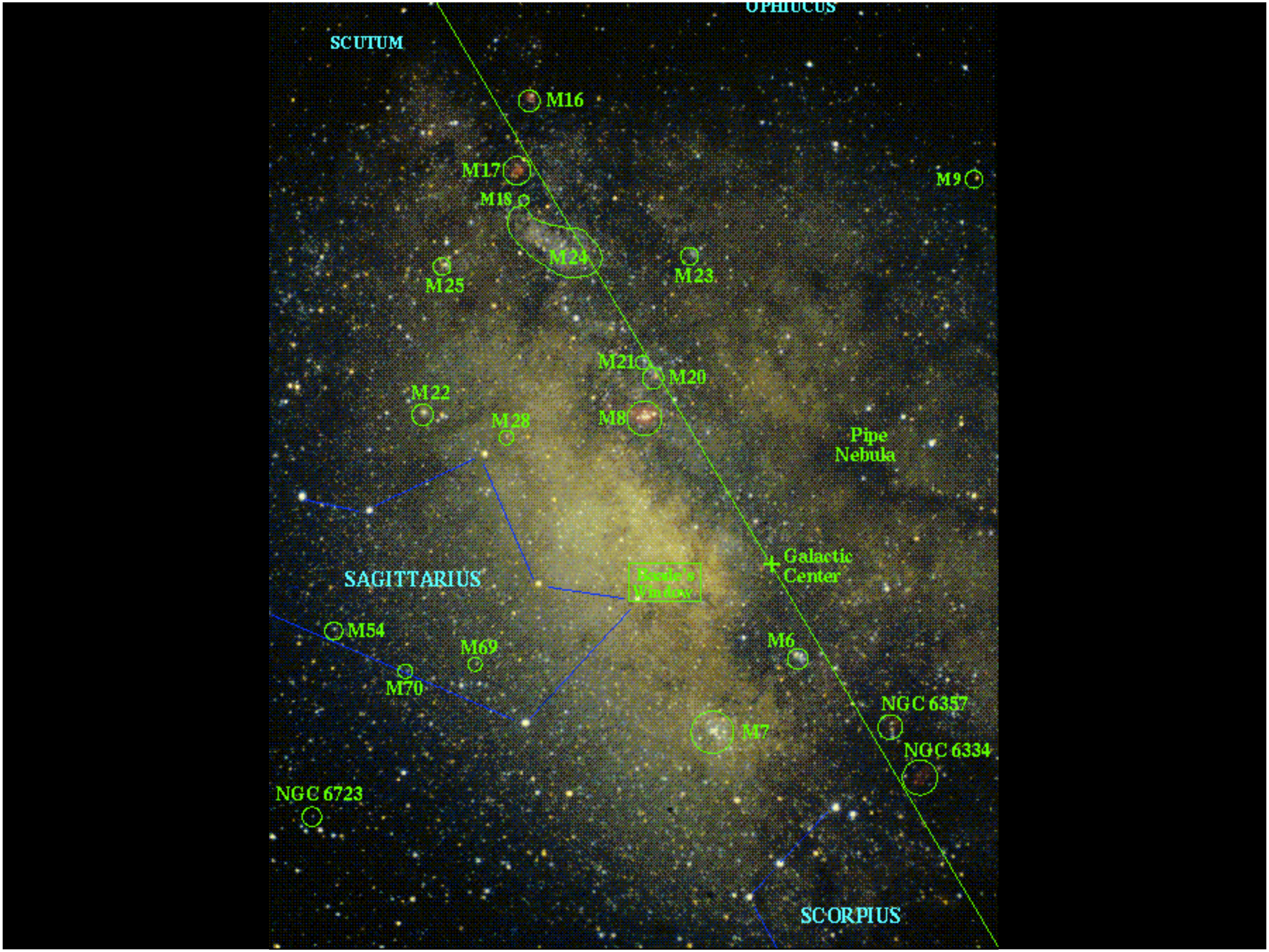
Solar System Analogy

Stars in the Milky Way orbit around a common center, traveling in the same direction and mostly in the same plane, which is the plane of the Milky Way. In this sense, stars are analogous to planets, and the plane of the Milky Way is analogous to the ecliptic.

Other Galaxies

Seen from far away, the Milky Way would appear as a faintly glowing circle or oval, depending on the viewing angle. Astronomers were already discovering such objects in the 1800s and early 1900s. The closest big example is the Andromeda Galaxy.

Galactic Center


OPHIUCUS
SCUTUM
M16
M17
M18
M9
M24
M25
M23
M21
M20
M22
M28
M8
Pipe
Nebula
Galactic
Center
SAGITTARIUS
Baade's
Window
M54
M69
M70
M6
NGC 6357
M7
NGC 6334
NGC 6723
SCORPIUS

Groping in the Dark

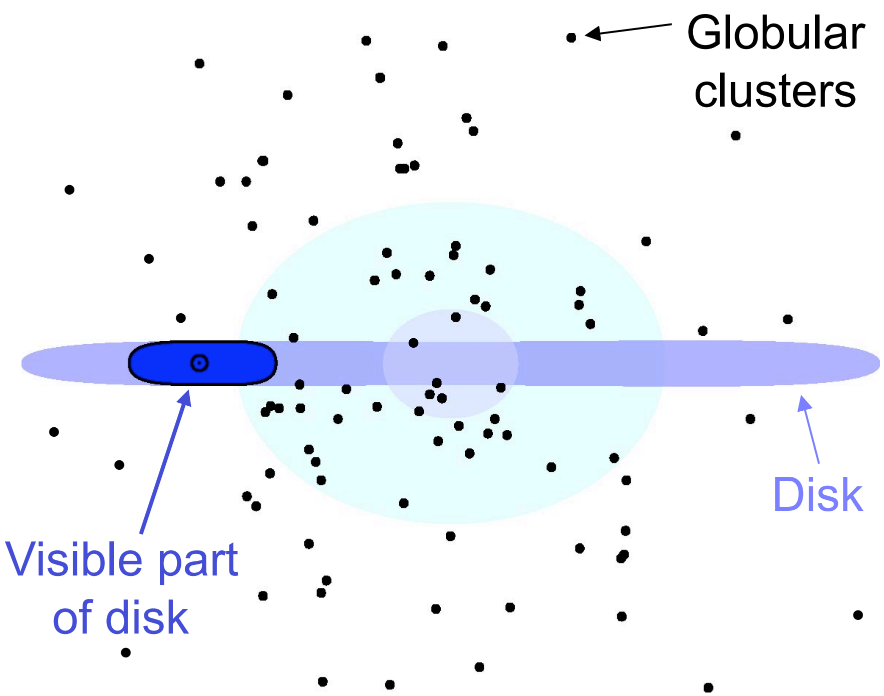
Astronomers made little further progress in understanding the Milky Way until the 1920s.

Problems with Dust

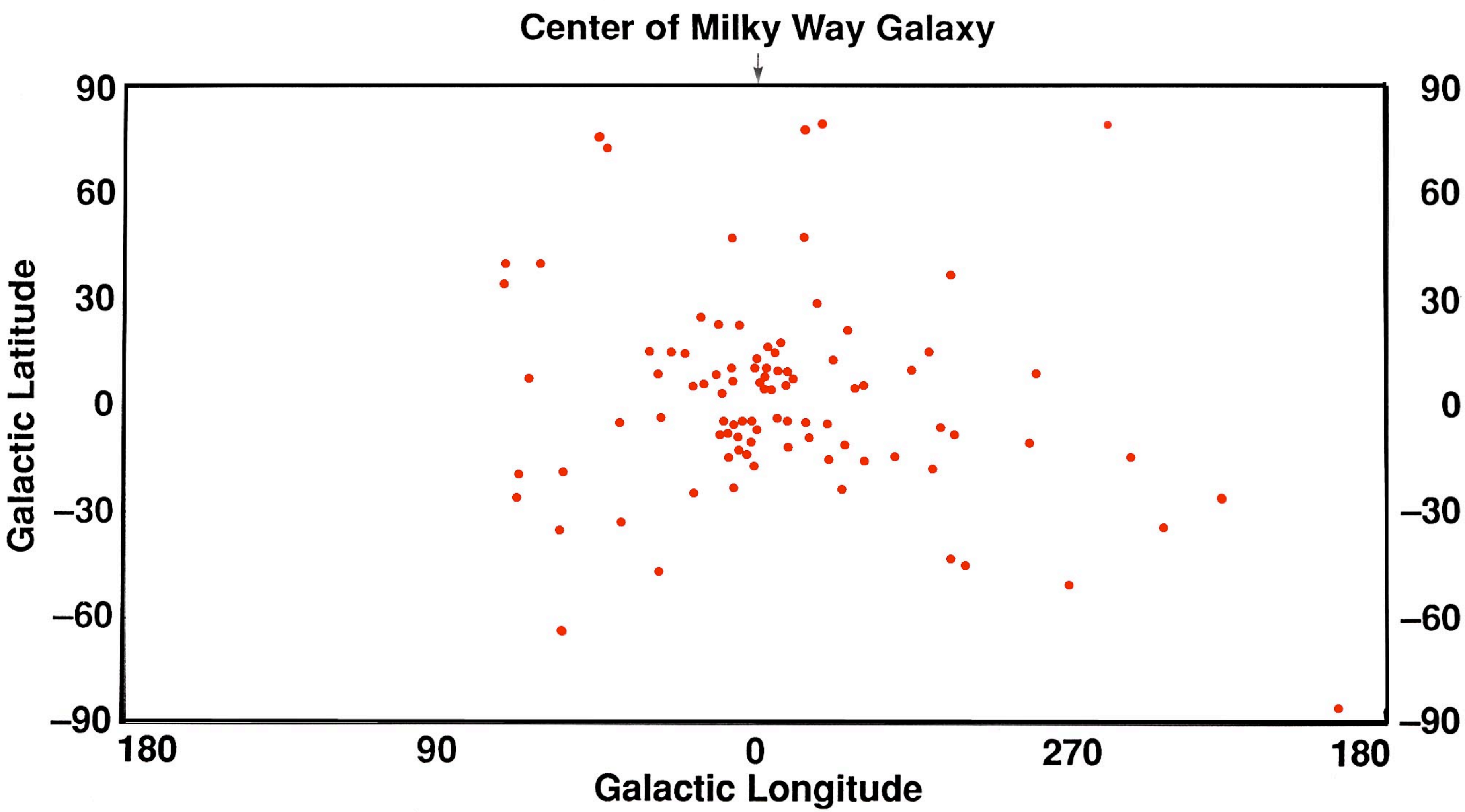
We can see only a few thousand parsecs (kpc) in the disk plane, because starlight is absorbed by interstellar dust. Not realizing this, astronomers who tried to map our Galaxy by counting stars in different directions <u>incorrectly</u> concluded that the Sun is near the center of the Milky Way.

Shapley's Discovery

Harlow Shapley measured distances to globular clusters and plotted their three-dimensional distribution. He found that globular clusters are scattered around a point about 8.5 kpc (30,000 ly) from the Sun. He guessed correctly that this is the center of the Milky Way.



Distribution of Globular Clusters in the Sky



Recall: Stability provides a powerful thermostat, but only on the Main Sequence!

A main sequence star is stable.

It adjusts to any disturbance so as to maintain a nearly constant radius, temperature and absolute luminosity.

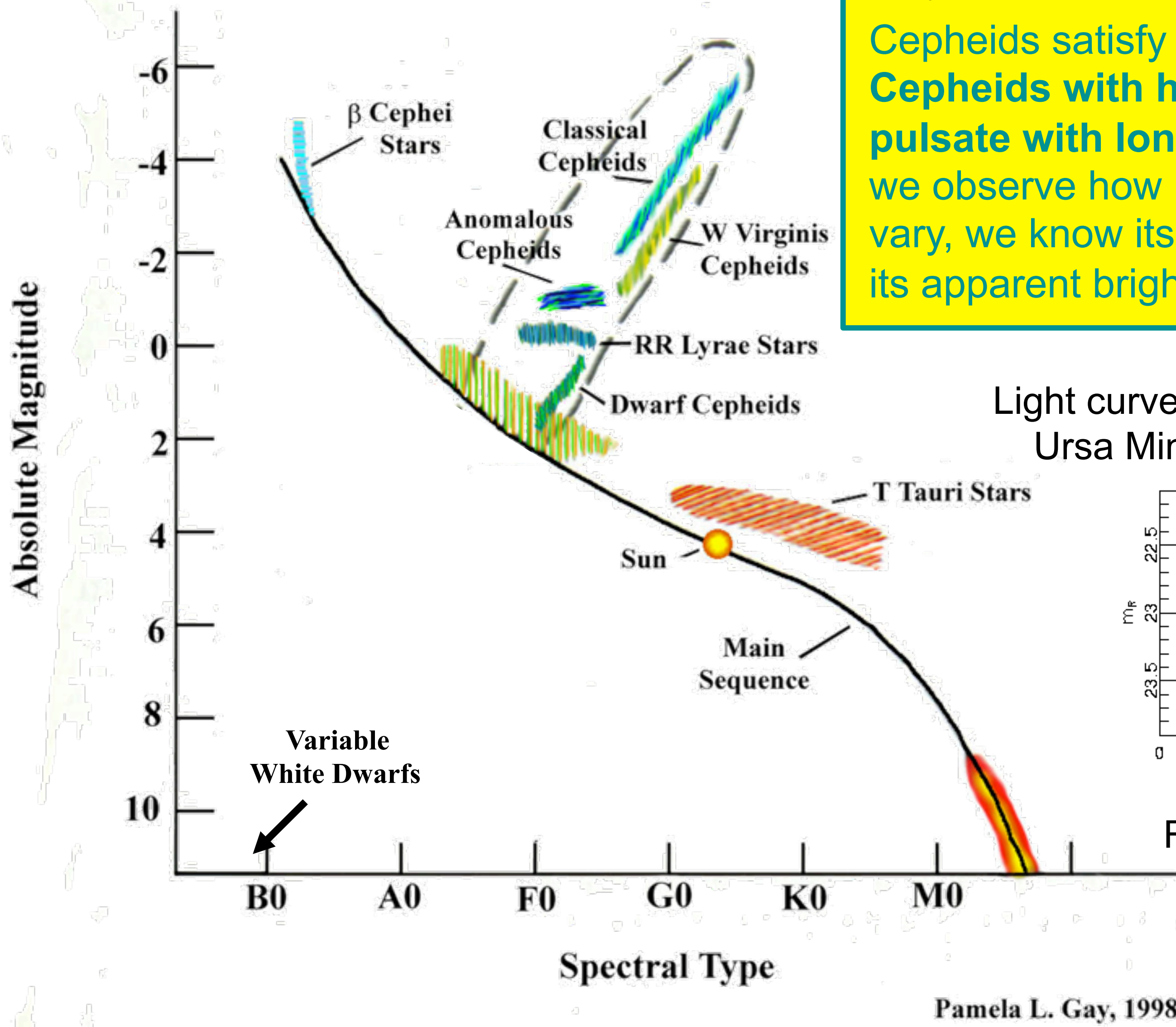
Suppose the star contracts a little. Then its center gets hotter. But the proton—proton cycle's energy output is proportional to temperature^{5}. The CNO cycle's energy output is proportional to temperature$^{(15-20)}$. Therefore much more energy is generated. So the temperature rises. But this increases the pressure. So now the pressure is too big for the weight of the gas above it. Therefore the star expands and cools off again. This reduces the nuclear reaction rate back to what is needed to keep the star in equilibrium.

If too little energy is generated, the star contracts, heats up, and increases its energy generation.

So a star is wonderfully well thermostated.
This keeps its energy output nearly constant.

This is why the Sun has been so stable for 4.5 billion years.
This is why life on Earth is possible.

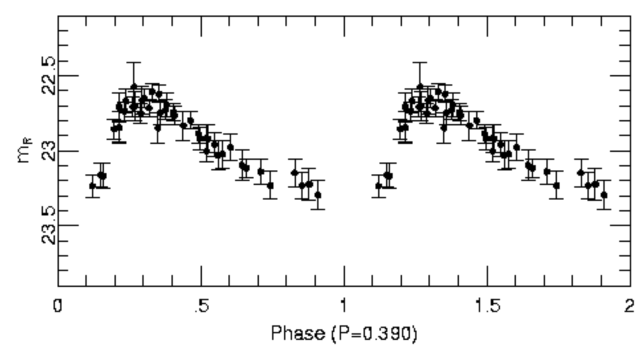
Shapley measured distances to globular clusters using Cepheid variables.



In parts of the HR diagram, stars are unstable: they pulsate in radius and in brightness.

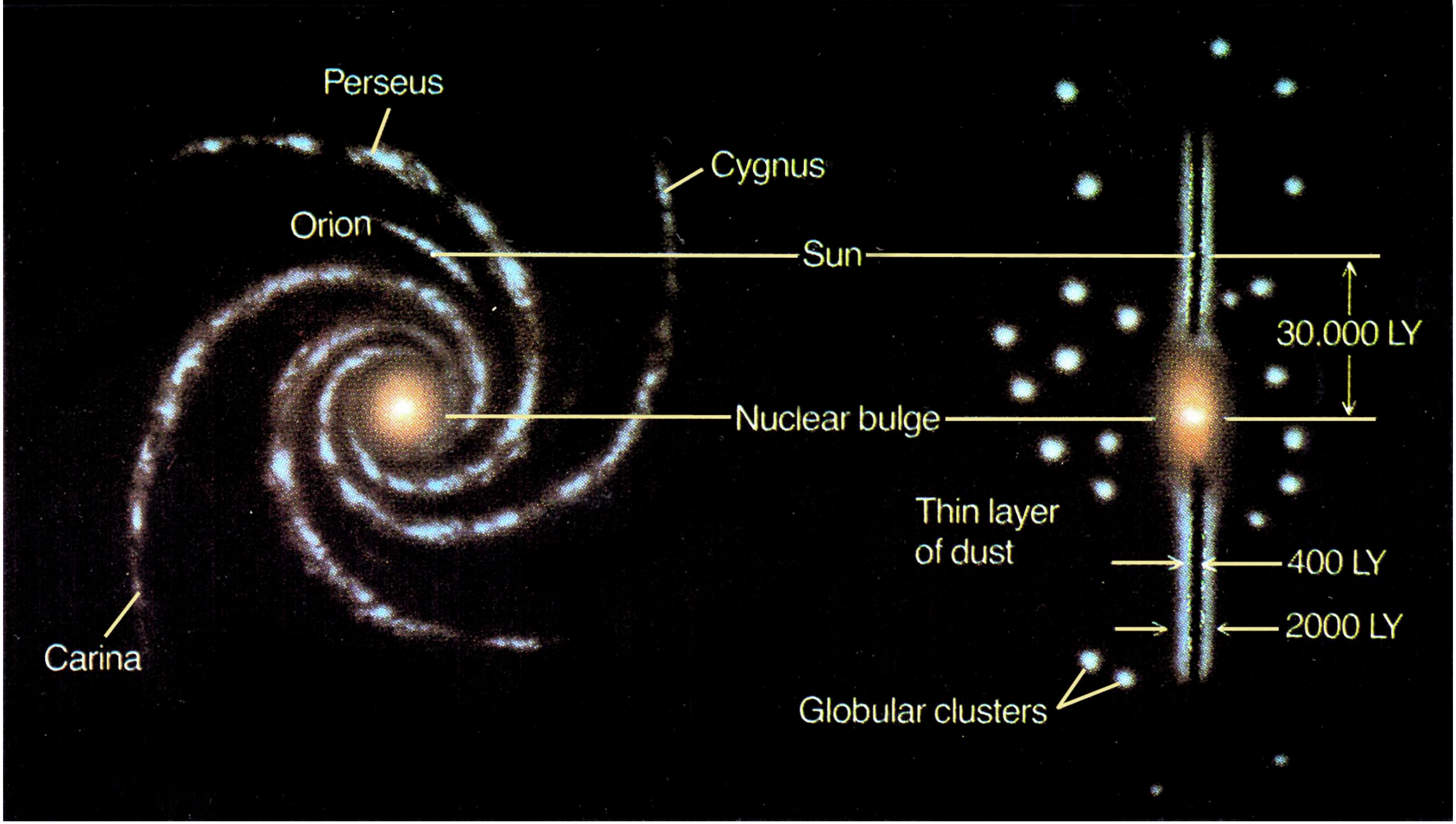
Cepheids satisfy a period-luminosity relation: **Cepheids with higher average luminosities pulsate with longer periods.** Therefore, if we observe how long it takes for a Cepheid to vary, we know its absolute luminosity. From its apparent brightness, we get its distance.

Light curve of an RR Lyrae variable in the Ursa Minor Dwarf Spheroidal Galaxy

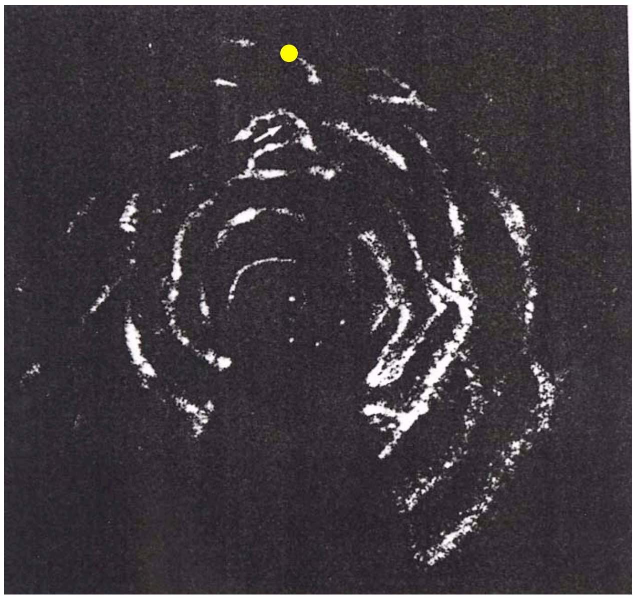


RR Lyrae variables are similar: all of them have the same absolute luminosity.

The Structure of Our Galaxy



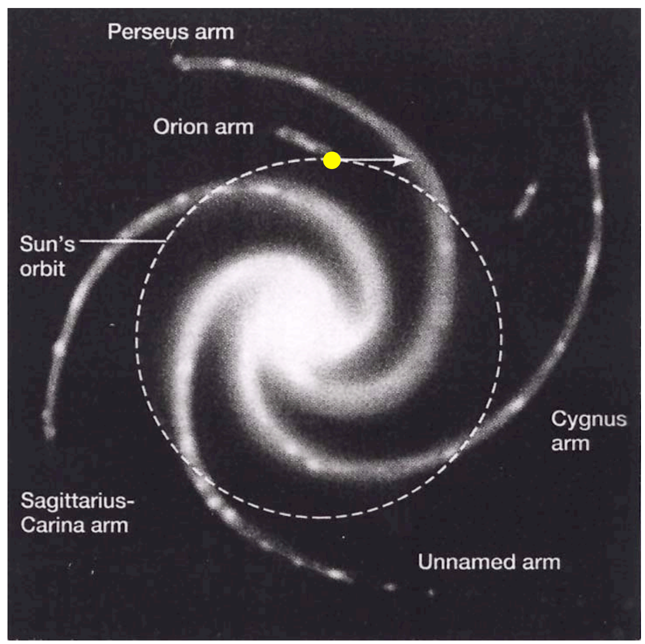
Cold Gas Traces Spiral Structure:
Our Milky Way is a not-very-regular, multi-armed spiral

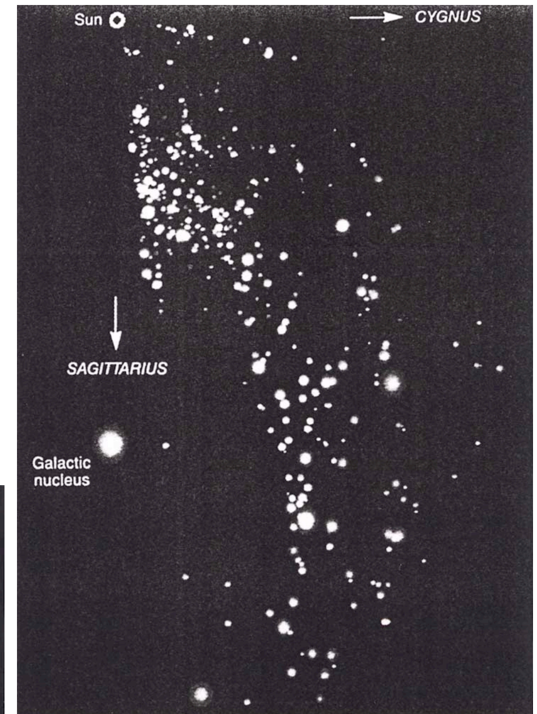


Hydrogen atoms

The Sun

Highly idealized model

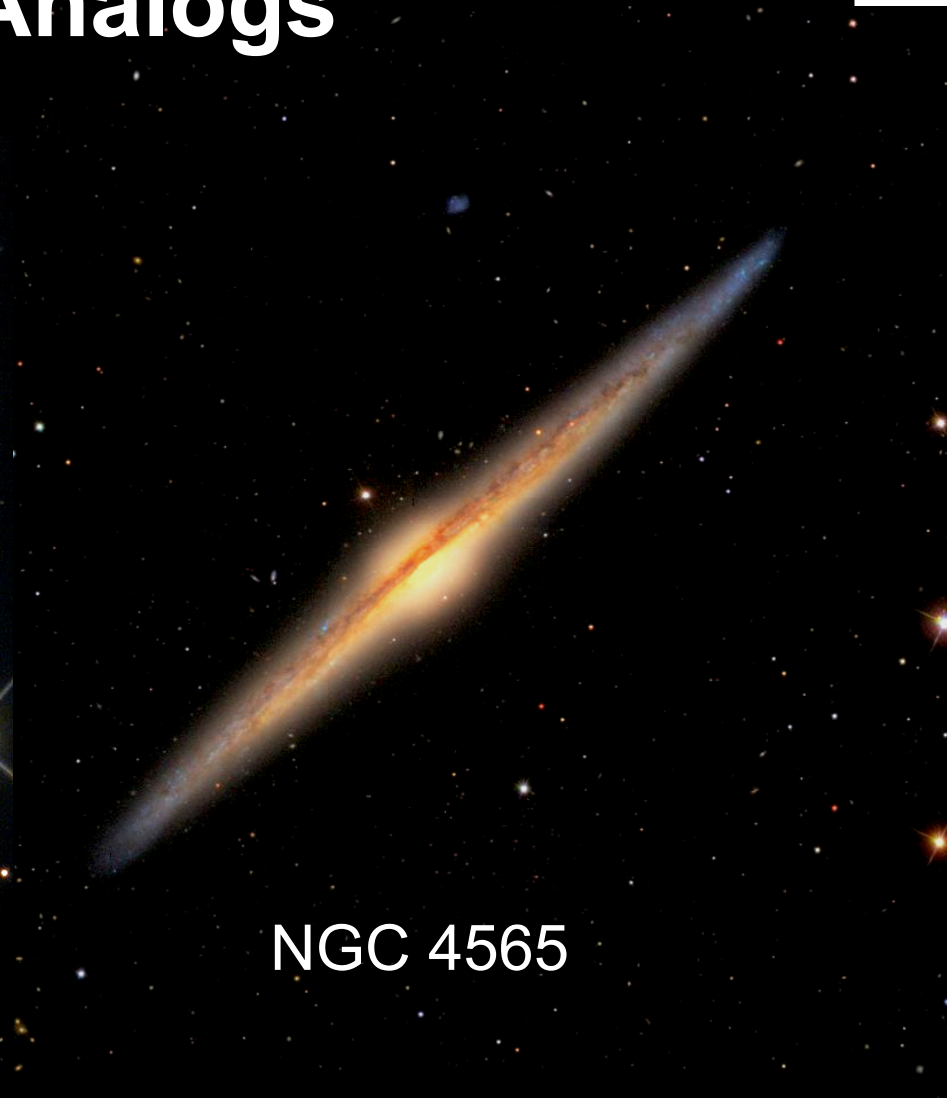




Molecular Clouds

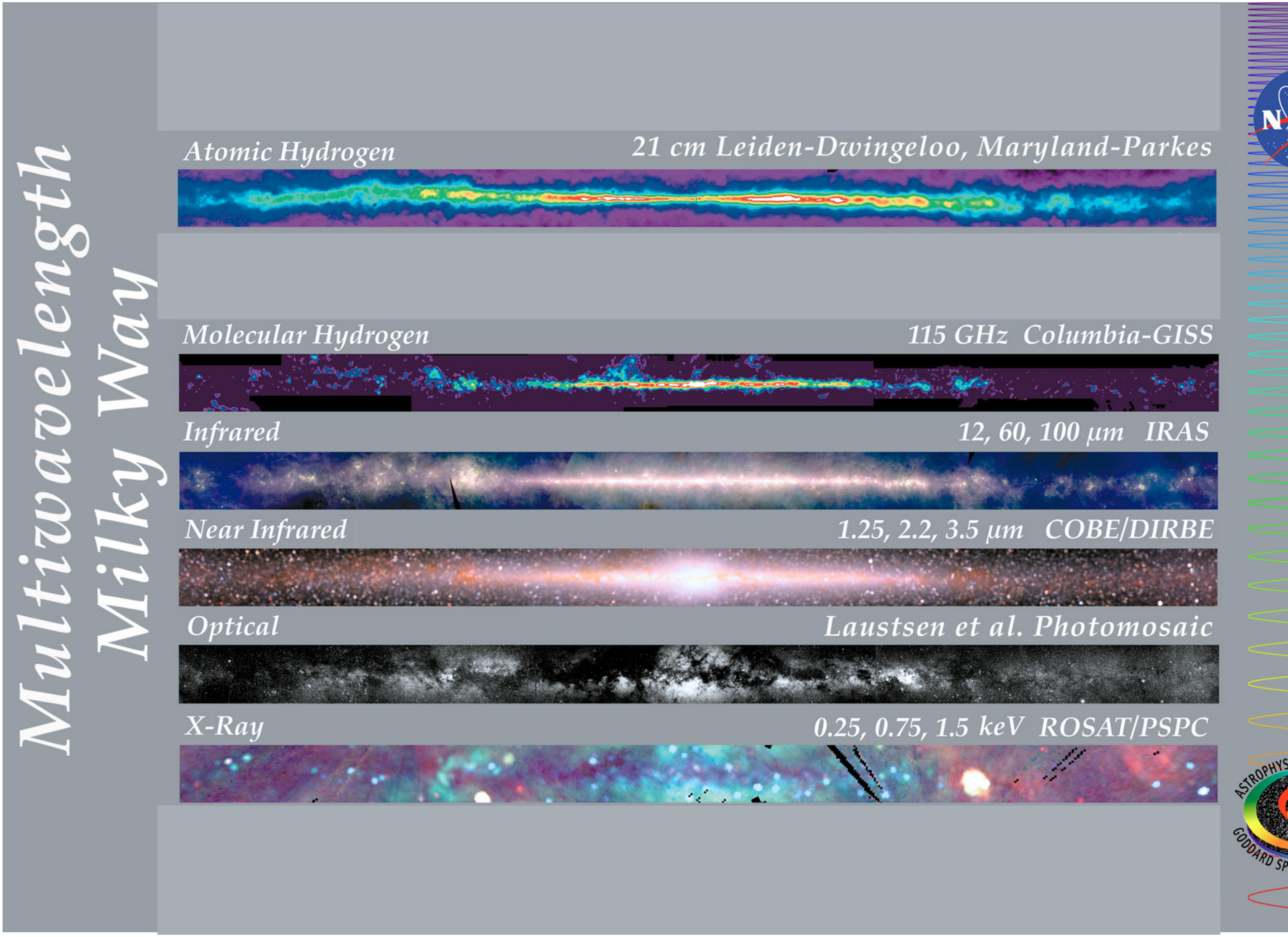
Milky Way Analogs

NGC 2336

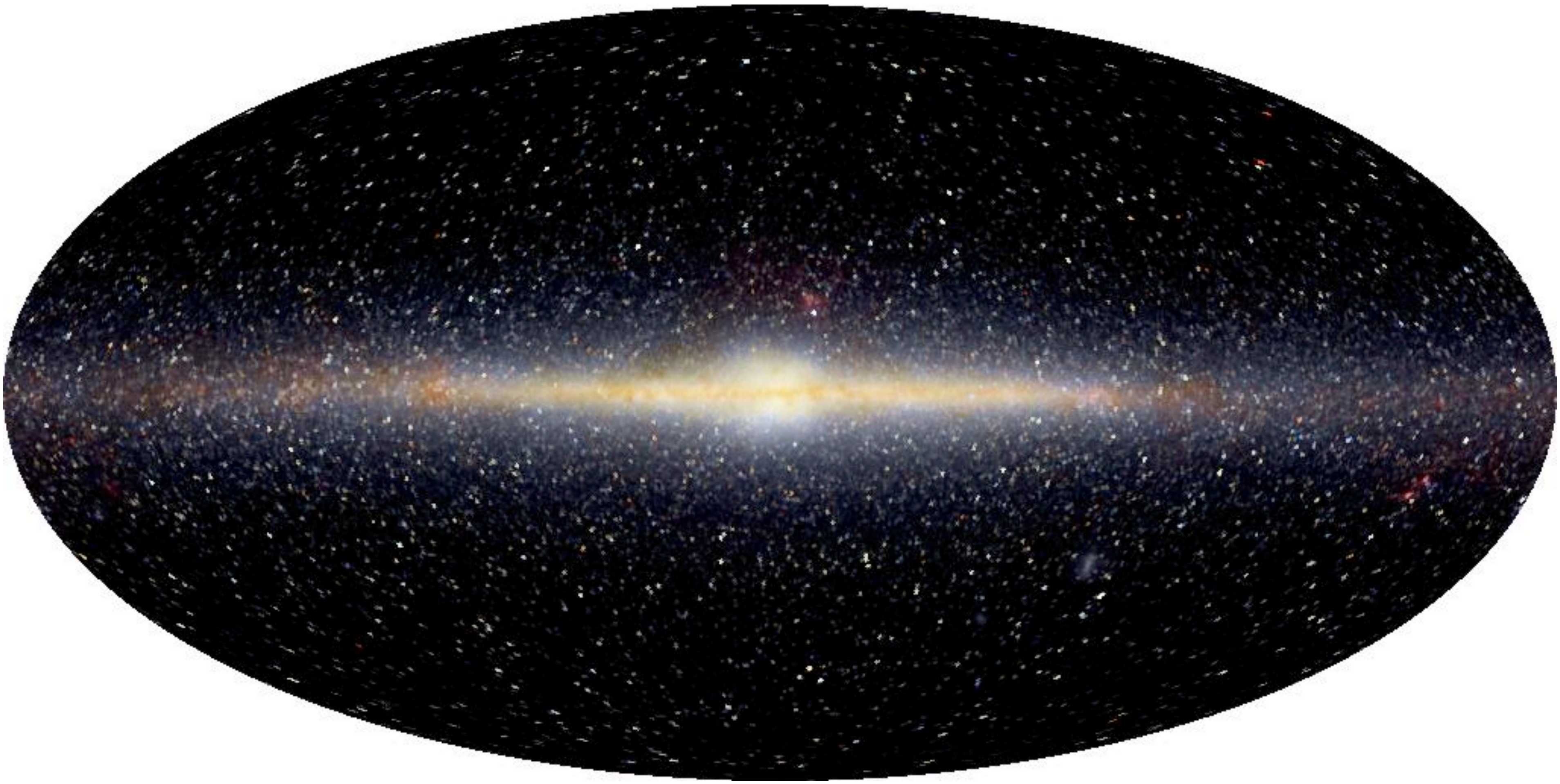


NGC 4565

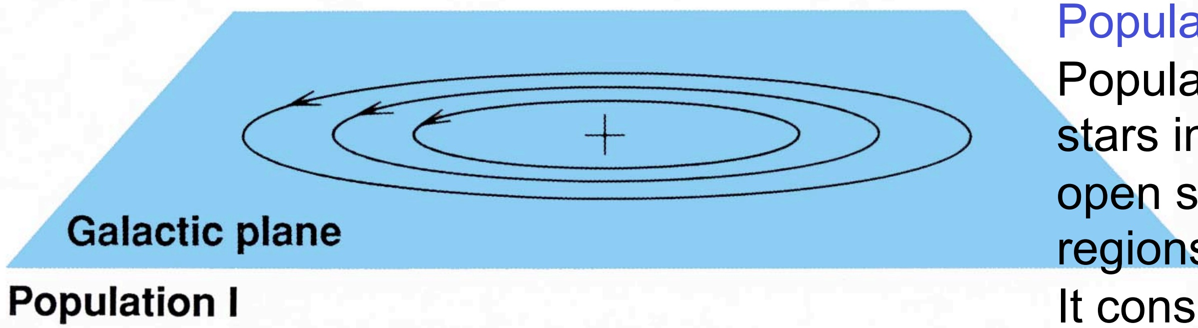
Astronomers believe that, to an outside observer, our Milky Way galaxy looks similar to these galaxies.


Multiwavelength Milky Way
Atomic Hydrogen
21 cm Leiden-Dwingeloo, Maryland-Parkes
Molecular Hydrogen
115 GHz Columbia-GISS
Infrared
12, 60, 100 μm IRAS
Near Infrared
1.25, 2.2, 3.5 μm COBE/DIRBE
Optical
Laustsen et al. Photomosaic
X-Ray
0.25, 0.75, 1.5 keV ROSAT/PSPC

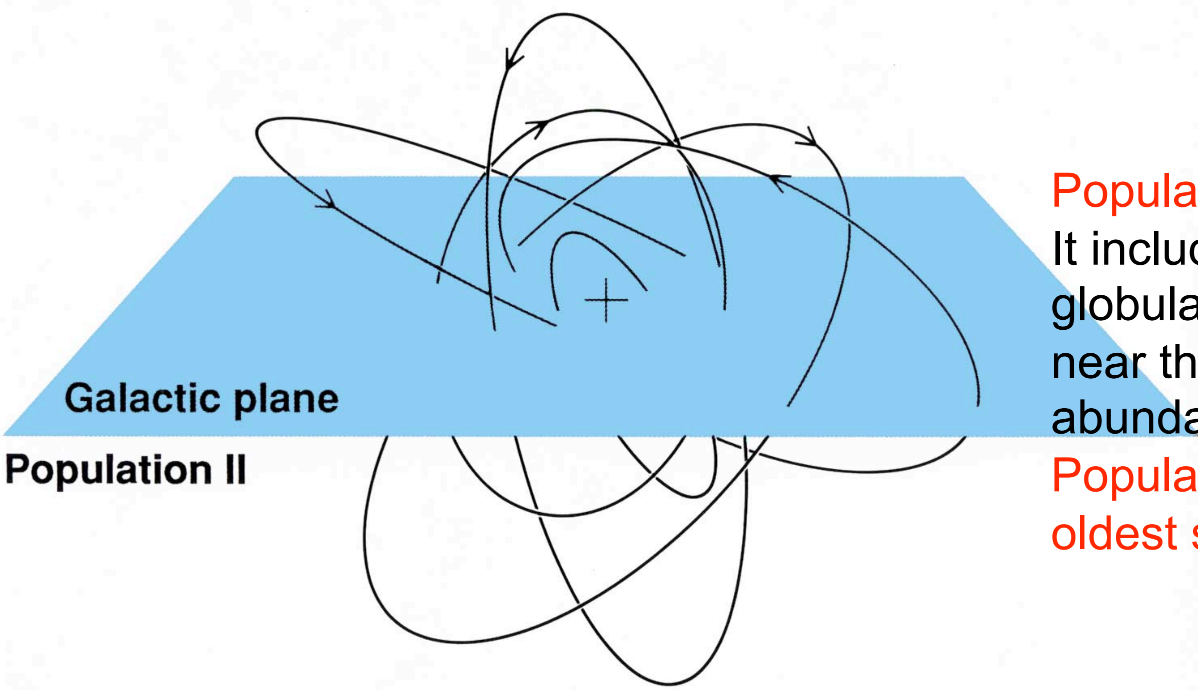
Our Galaxy in Infrared Light (COBE)



Populations of Stars

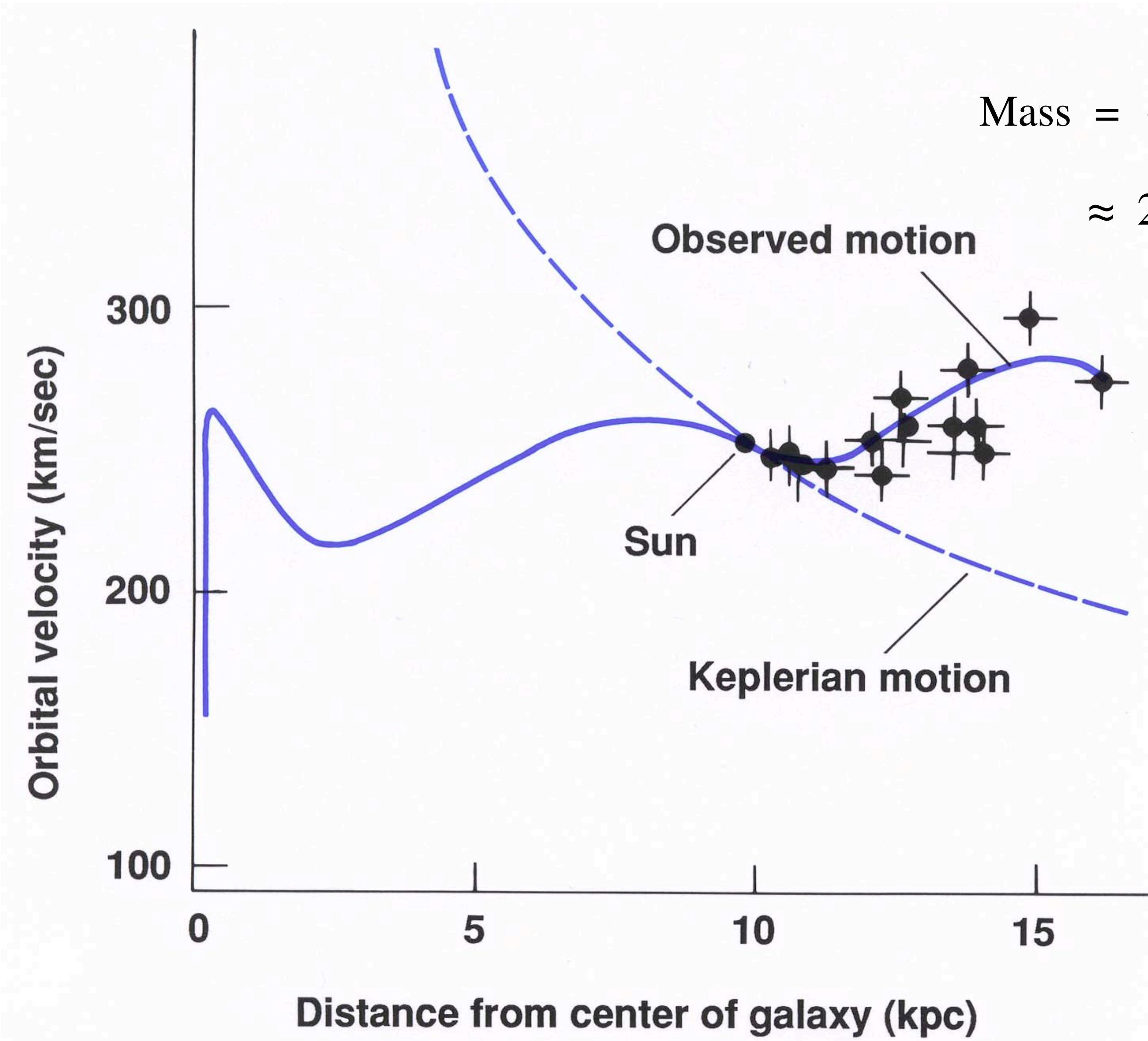


Population I is the disk of our galaxy. Population I includes our Sun, the stars in the solar neighborhood, open star clusters, star formation regions, and molecular clouds. It consists of the youngest stars.



Population II is the halo of our galaxy. It includes the “bulge” and stellar halo, globular clusters, and those few stars near the Sun that have very low metal abundances and high velocities. Population II consists (roughly) of the oldest stars.

The Mass of Our Galaxy



$$\text{Mass} = \frac{(\text{rotation velocity})^2\ (\text{radius})}{G}$$

$\approx 2 \times 10^{11}\ M_\odot$ out to a radius of 17 kpc or 55,000 ly.

Galaxies

If people were stars, cities would be galaxies.

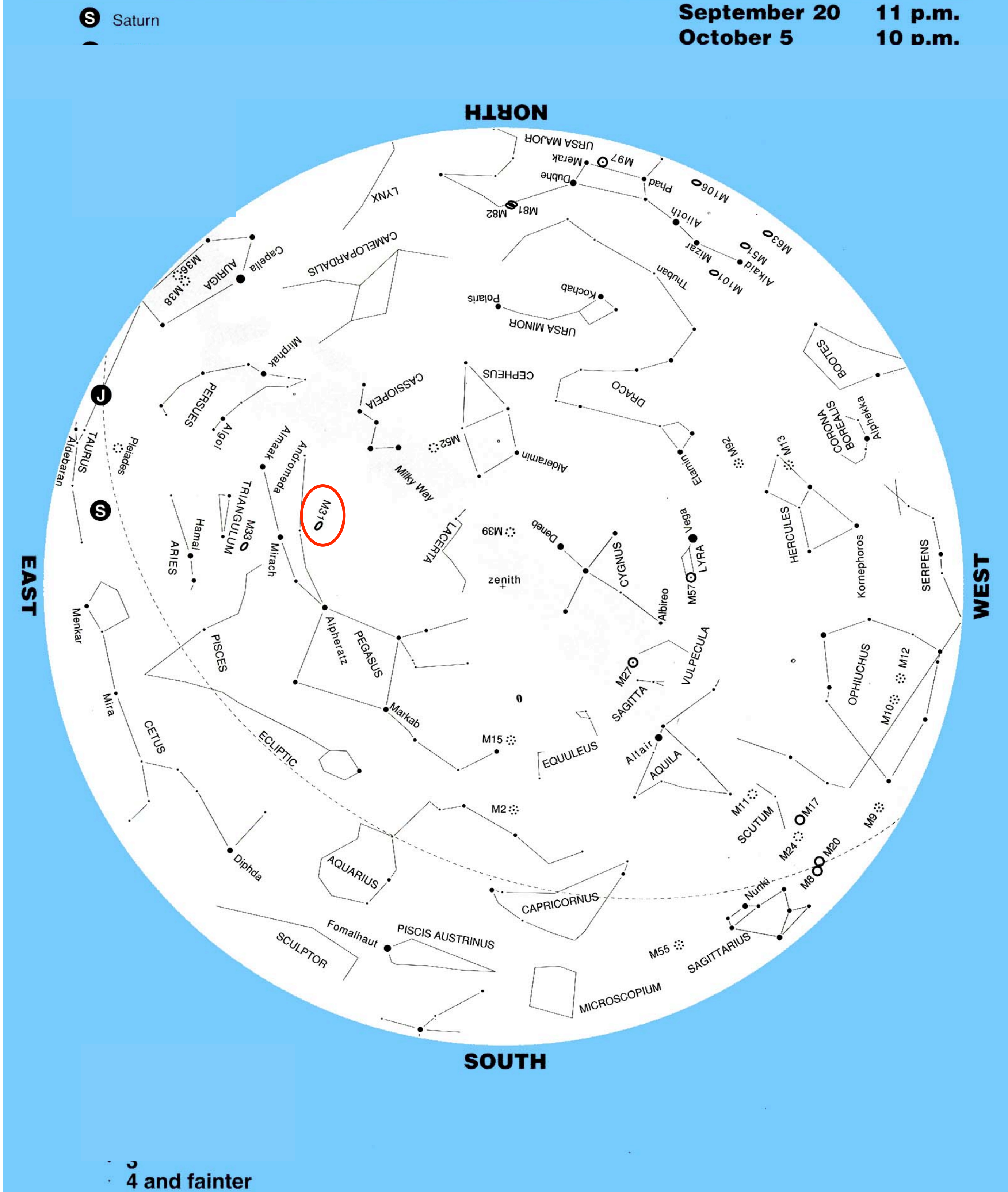
Galaxies are the basic building blocks of the Universe.

A galaxy is a large cluster of stars, gas, and dark matter that is held together by the gravitational attraction between its constituents.

Typical galaxy masses are 10^7 to 10^{13} $M_\odot$ and typical galaxy diameters are 1000 to 500,000 ly.

The smallest galaxies known have only a few hundred stars. Many star clusters in our Milky Way have more stars. So: Why do we call the above "galaxies" and not "star clusters"?

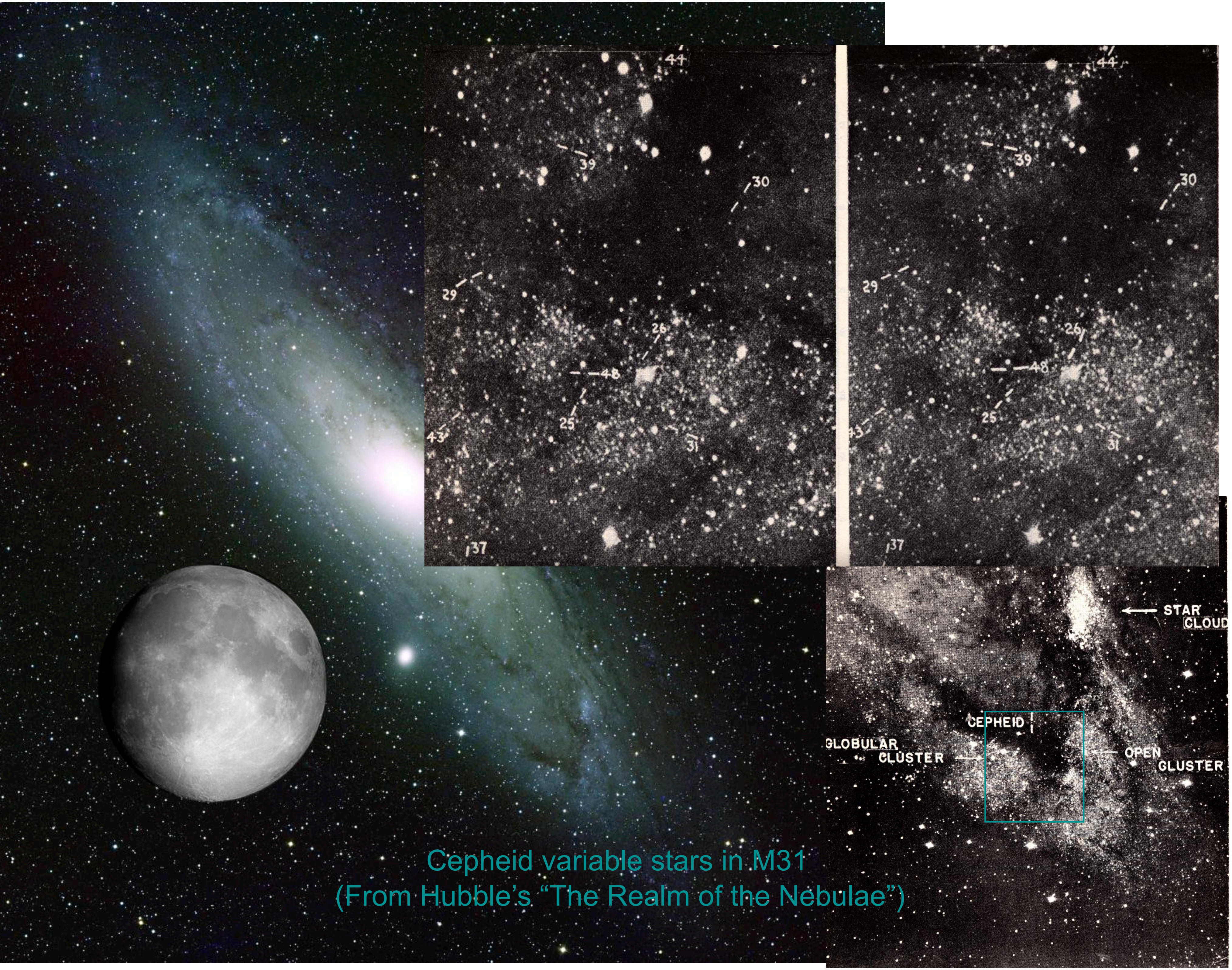
Answer: They contain lots of dark matter (next lecture).



M31

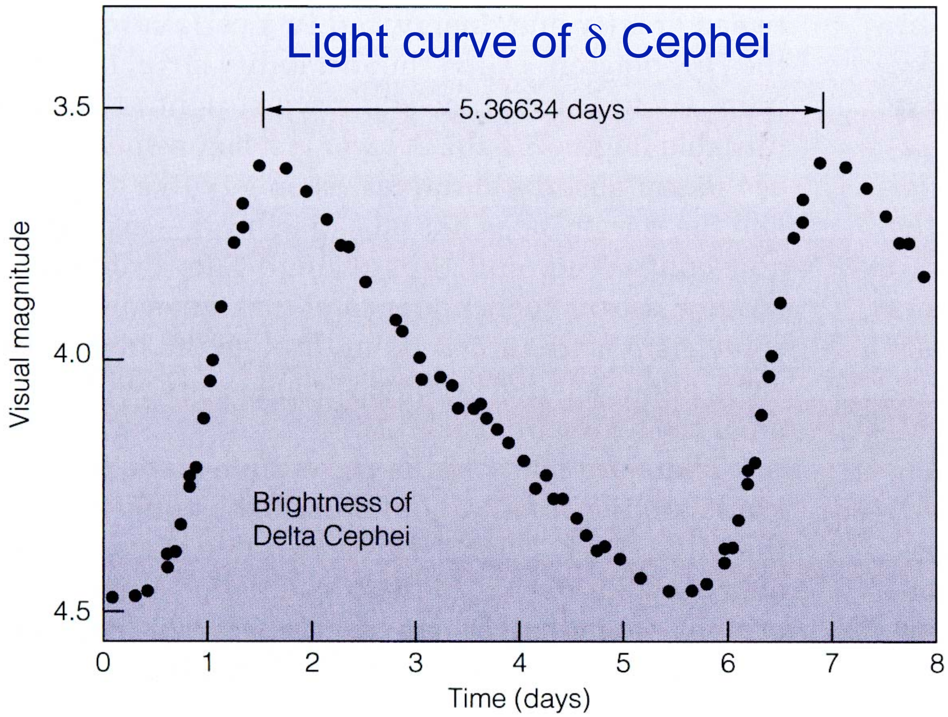
The Andromeda Galaxy is the only object in the northern sky that can be seen with the naked eye that is not part of our own Galaxy. This spiral galaxy is another member of the Local Group and is somewhat larger than the Milky Way.

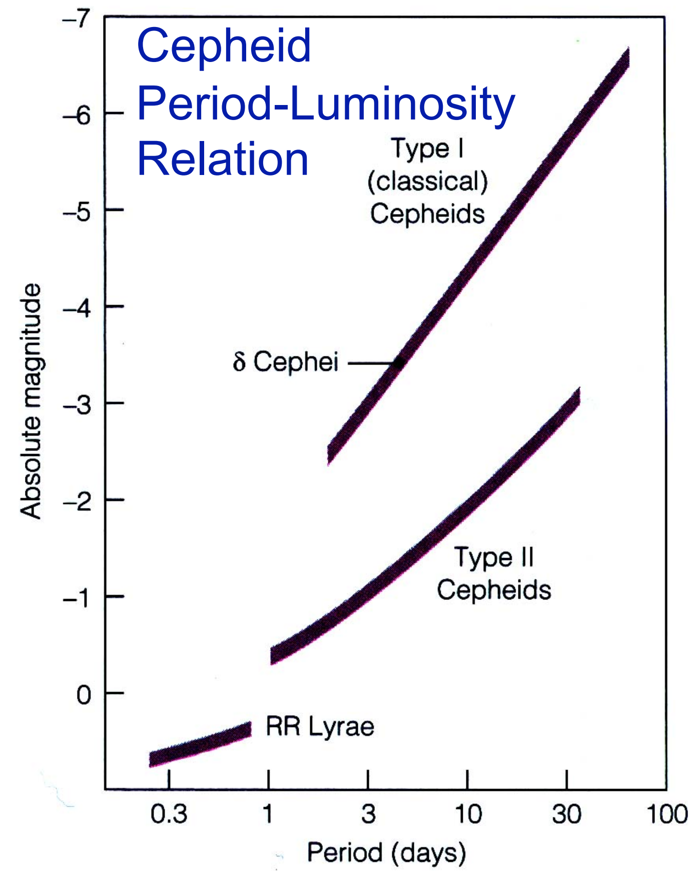
The Andromeda Galaxy is 3.3 million light years away. It is the farthest object that we can see with the naked eye.



Cepheid variable stars in M31
(From Hubble's "The Realm of the Nebulae")

The Discovery of Galaxies

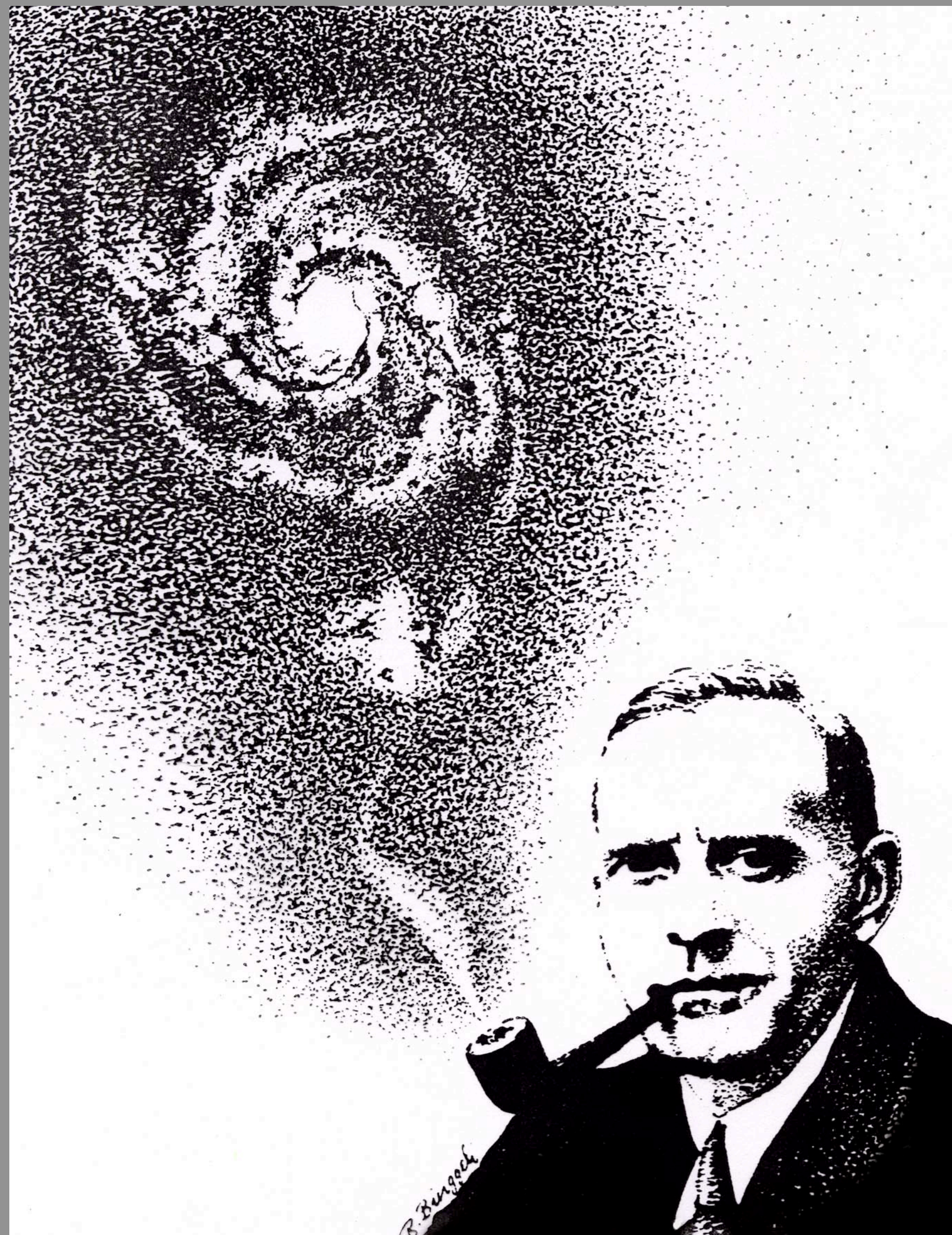




In the early 1900s, people understood that many nebulae are in our Galaxy. Some people (Harlow Shapley) thought that everything is in our Galaxy. Others (Heber Curtis; Immanuel Kant) thought that some nebulae are “island universes” outside our Galaxy.

The issue was settled by Edwin Hubble, who used Cepheid variables to measure the distance to the Andromeda “nebula”. He got 900,000 light years $\Rightarrow$ Andromeda is a separate “galaxy” unconnected with the Milky Way. Hubble’s answer was too short by a factor of 3, but the existence of galaxies was never again in doubt.

Edwin Hubble

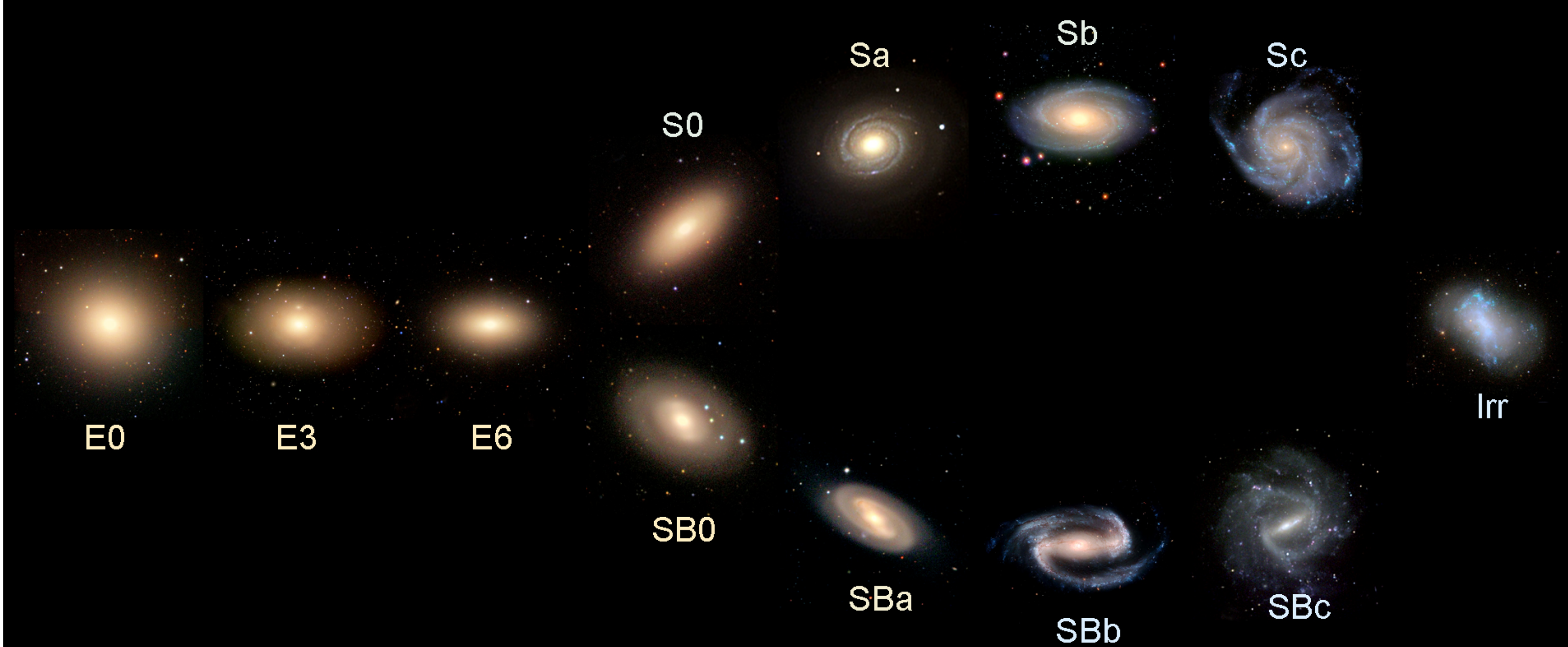


Kinds of Galaxies

The most fundamental distinction is the one between “bulges” or elliptical galaxies (shaped like flattened footballs)
and
galaxies with flat, spinning disks (like frisbees).

The disks of many galaxies show beautiful spiral structure.

Hubble's Galaxy Classification Scheme



At first, this diagram was thought to represent how galaxies evolve. Now we know that this is wrong. But people still refer to elliptical galaxies as “early-type” and to spiral galaxies as “late-type”.

Types of Galaxies: The Hubble Sequence

Elliptical galaxies are almost featureless ellipses of light. They are made of old stars (Population II). They are typically a few times more massive than the Galaxy, but they range from a few percent to more than 10 times the mass of the Galaxy. They vary in apparent elongation from round to about 2:1 flattened, but this is mostly because different ellipticals are seen at different orientations.

Basic points:

- Ellipticals are ellipsoids
- No structural details
- Orbits are very 3-dimensional
  - Little net rotation
  - Random motions are large
- Most stars are old


M 87

Types of Galaxies: The Hubble Sequence

Elliptical galaxies sometimes contain thousands of globular clusters.

Types of Galaxies: The Hubble Sequence

Spiral galaxies contain a disk of stars and gas arranged in a spiral pattern. Sa and Sb galaxies also contain a central bulge that is like a small elliptical. The bulge is old (Population II). Usually the disk is made partly of young stars (Population I). There are two sub-types: barred and ordinary spirals.

Along the sequence Sa → Sc,
- the contribution of the bulge decreases,
- the fractional amount of gas increases,
- the contribution of young stars increases
- the disk looks more patchy, and
- the spiral arms become more open.

Our Milky Way is a typical spiral, intermediate between Sb and Sc. It has a weak bar.

Some basic points:
- disks are flat
- disks have spiral structure
- orbits are almost in a single plane
  - disks rotate
  - random motions are small
  - stars have a large range of ages

Types of Galaxies: The Hubble Sequence

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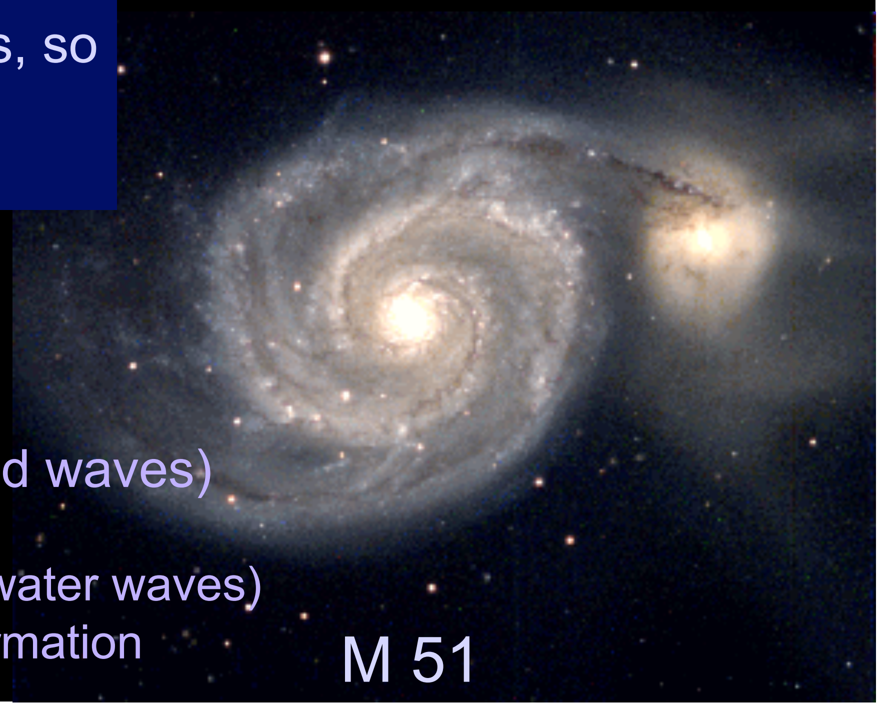
Along the sequence Sa → Sc,
- the contribution of the bulge decreases,
- the fractional amount of gas increases,
- the contribution of young stars increases, so
- the disk looks more patchy, and
- the spiral arms become more open.

Spiral Structure:
- center rotates faster than periphery ⇒
- spiral structure ought to wind up quickly
- spiral arms are density waves (like sound waves)
  - pattern rotates almost rigidly
  - stars, gas flow through the waves (as in water waves)
  - gas compression in wave triggers star formation



M 51

Density waves in water – movie