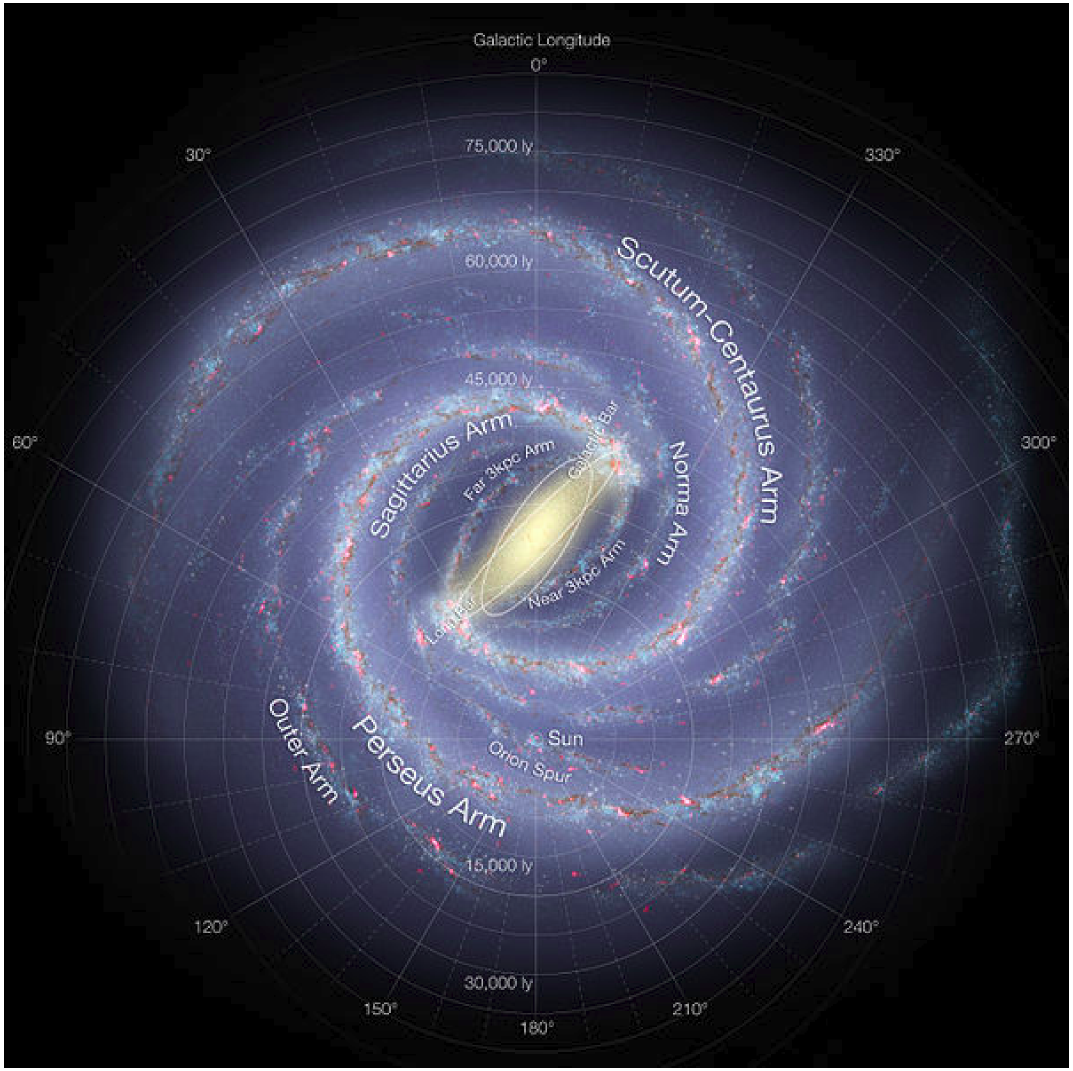
The Distance Ladder I.

The Milky Way Galaxy

(Ch. 23)



Units of Chapter 23

1. Our Milky Way Galaxy

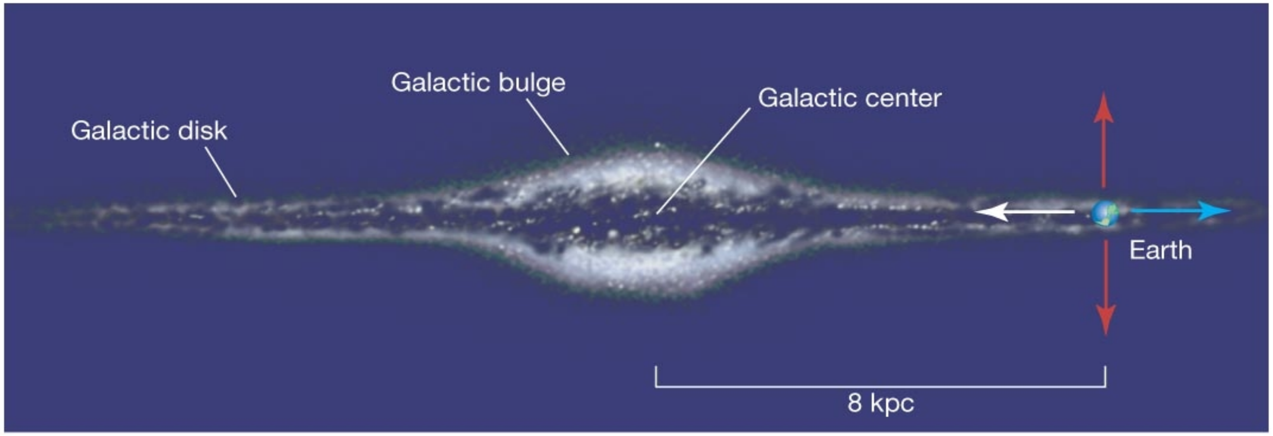
a) Dimensions and structure
b) Spiral Arms
c) Mass and Dark Matter
d) Nucleus

2. Distances within the Milky Way

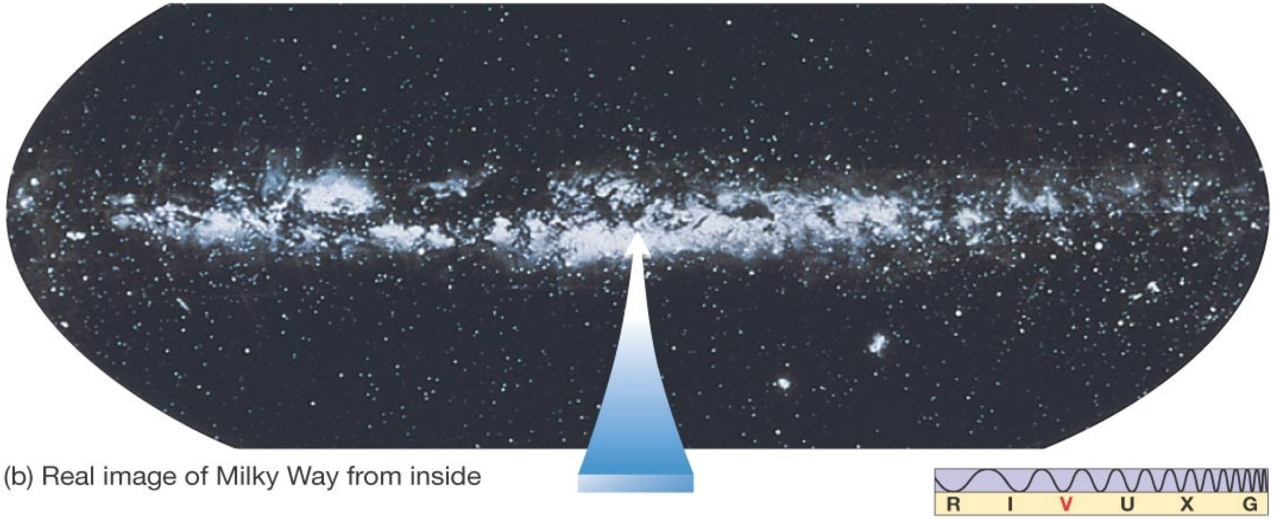
a) Stellar and spectroscopic parallax
b) “Standard Candles” or “Beasts of a kind” concept
c) Herschel's star counts
d) “Intrinsic” Variable Stars
e) Other Distance Indicators

23.1 Our Parent Galaxy

The Milky Way is what our galaxy appears as in the night sky.



(a) Artist's view of Milky Way from afar

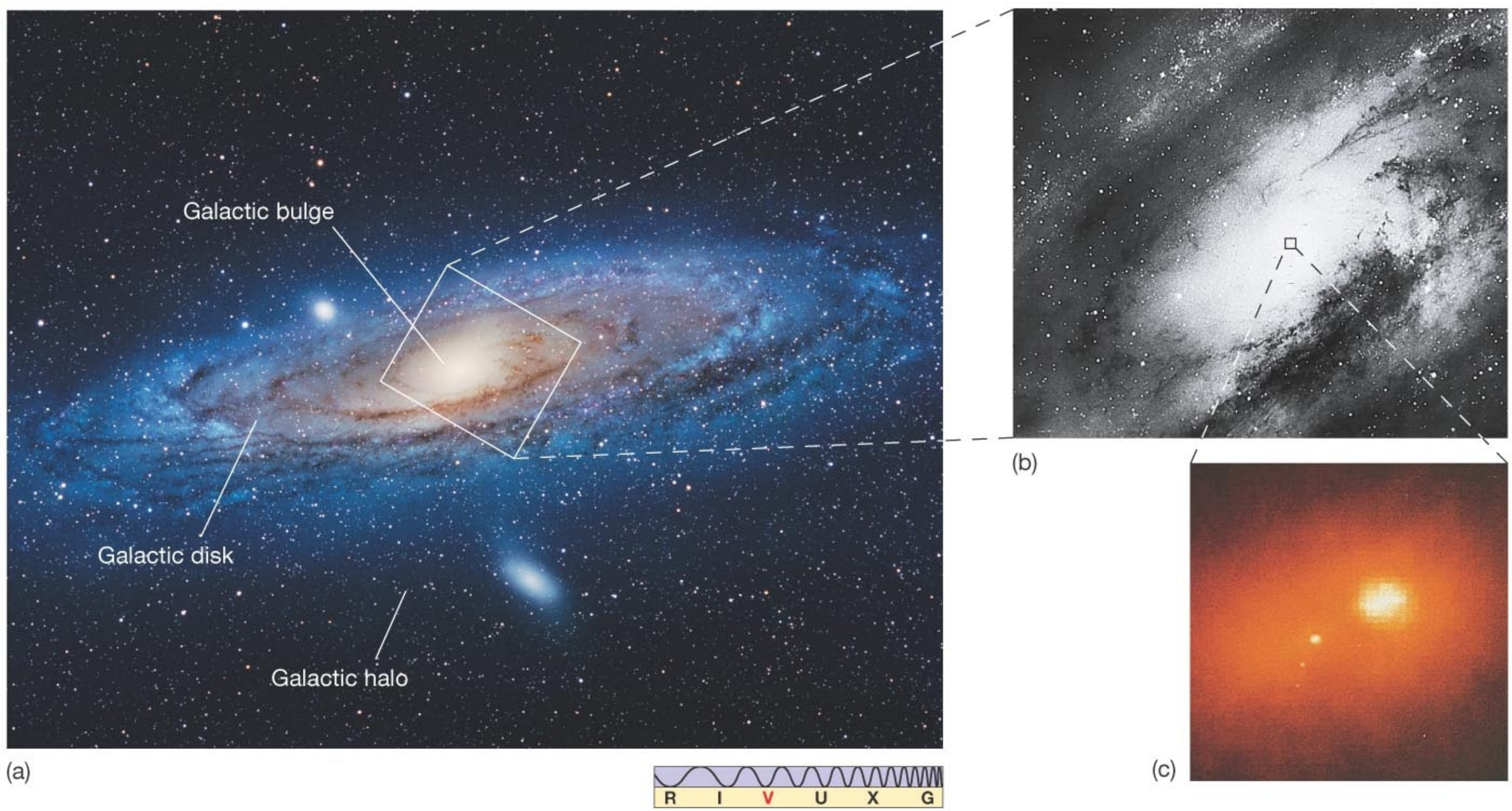


(b) Real image of Milky Way from inside

See other MW photos On A.P.O.D.!

23.1 Our Parent Galaxy

Our galaxy is a **spiral** galaxy. The Andromeda Galaxy, our closest spiral neighbor, probably resembles the Milky Way fairly closely.



23.1 Our Parent Galaxy

Here are two other spiral galaxies, one viewed from the top and the other from the side:

(a)

(b)

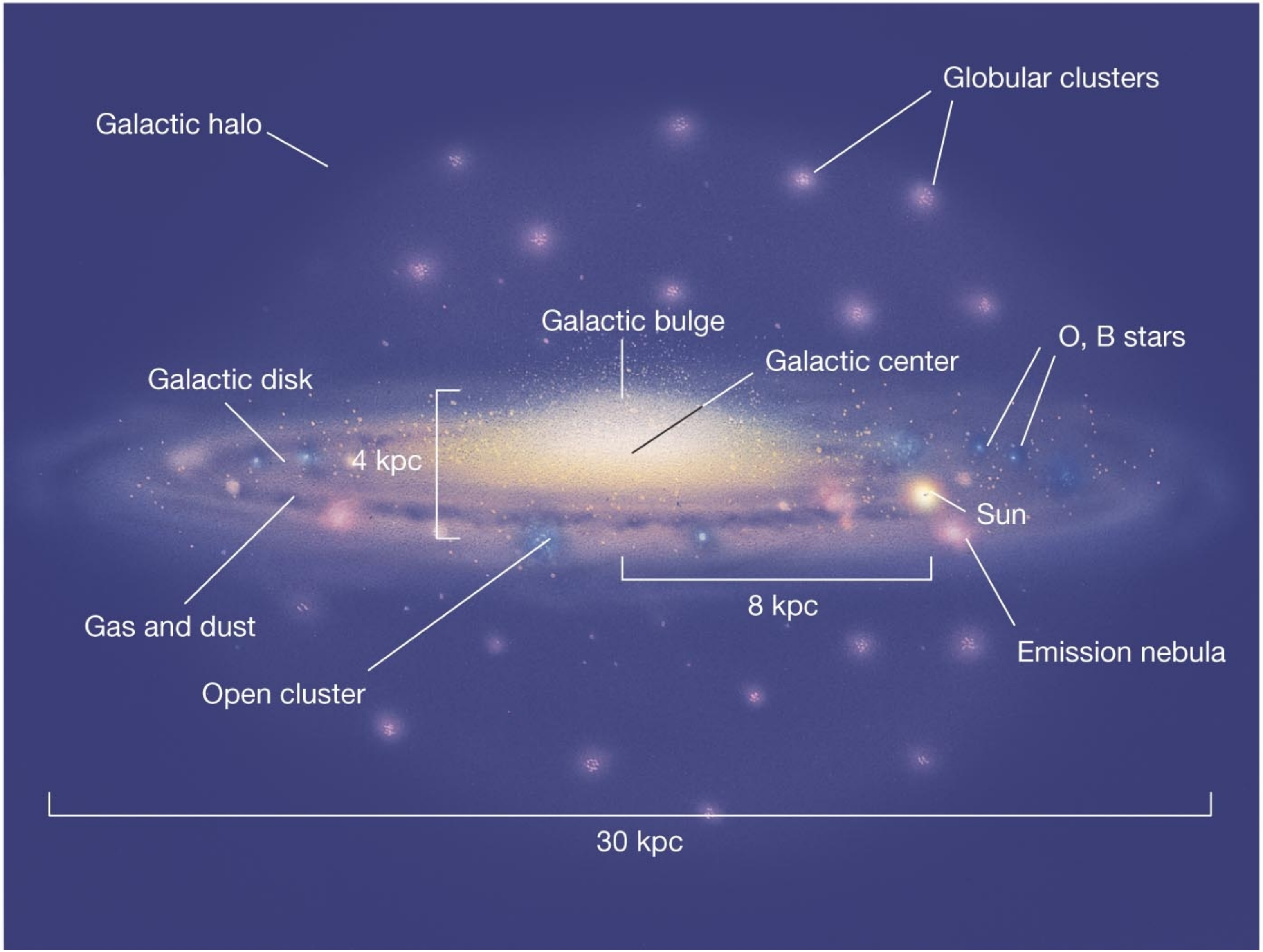
"Face on" **"Edge on"**

23.1 Our Parent Galaxy

Here is a better twin to the MW, NGC 6744. Barred, medium-sized bulge, flocculant spiral.

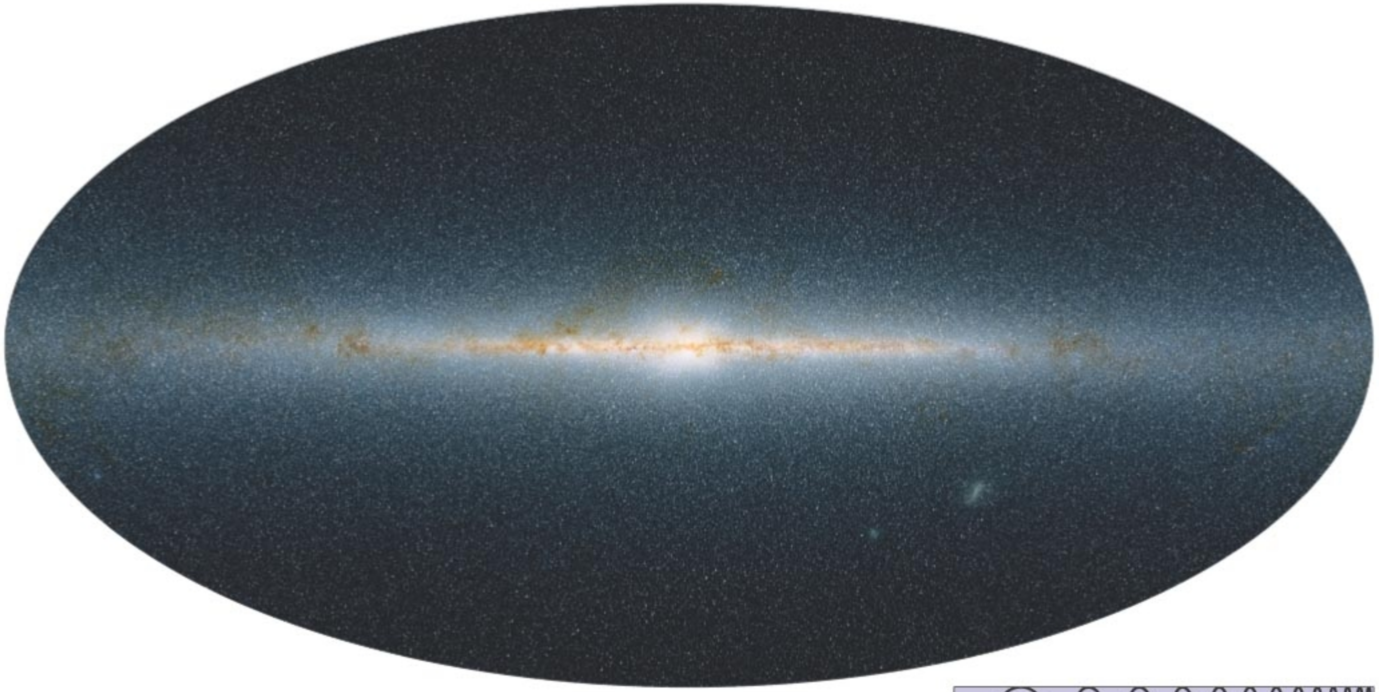
23.3 Galactic Structure

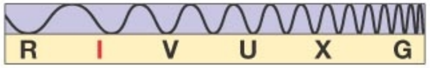
The various parts of our galaxy:



23.3 Galactic Structure

This **infrared** view of our galaxy shows a much clearer view of the galactic center than the visible-light view does, as infrared is not absorbed as much by gas and dust.

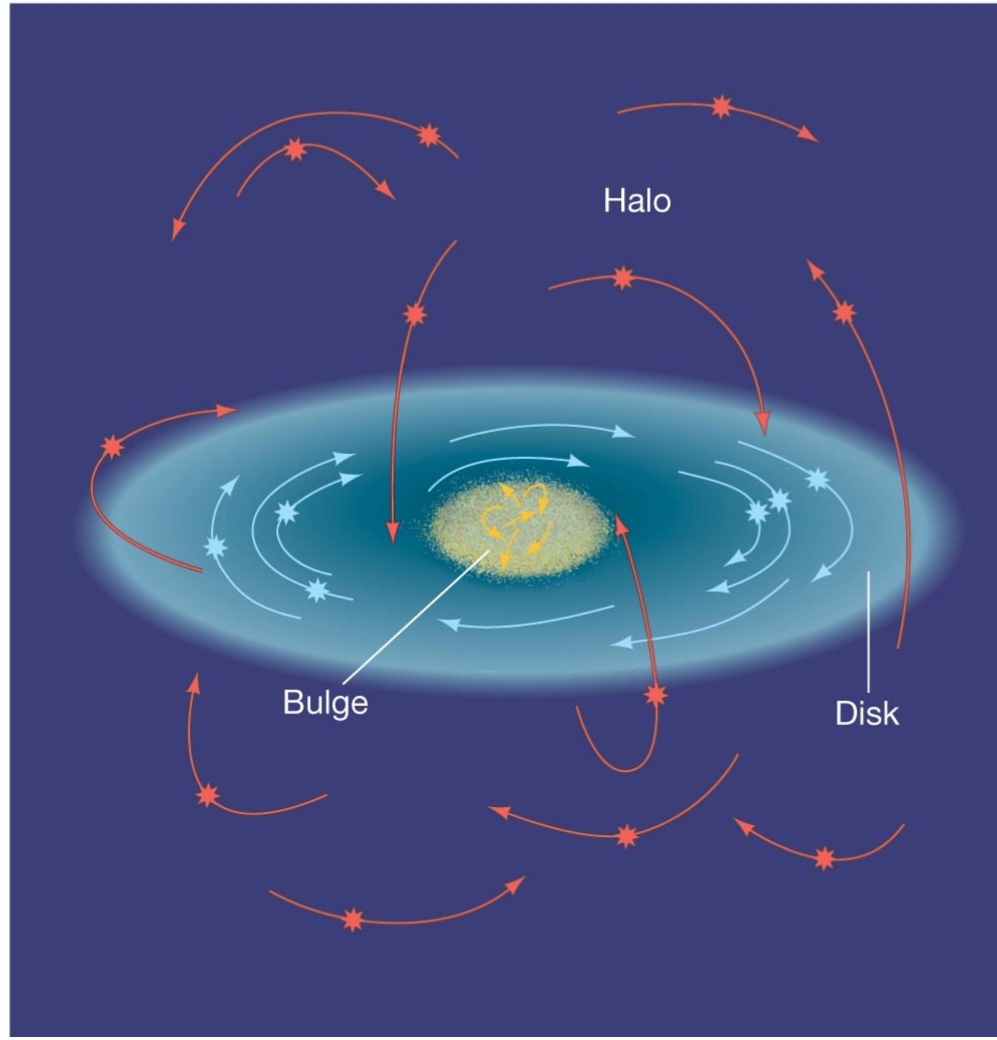




23.3 Galactic Structure - kinematics

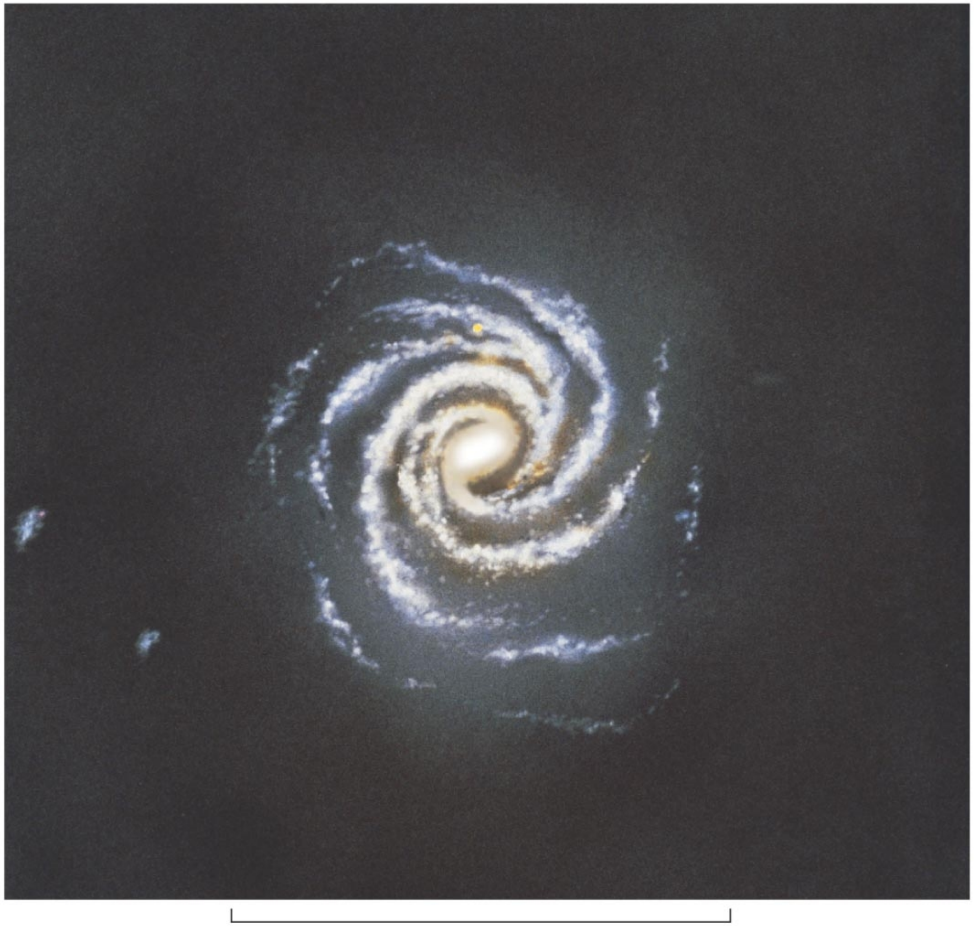
Stellar orbits in the **disk** move in a common plane (*co-planar*) and in the same direction (clockwise).

The orbits in the **halo** and **bulge** are much more random (*isotropic*).



23.5 Galactic Spiral Arms

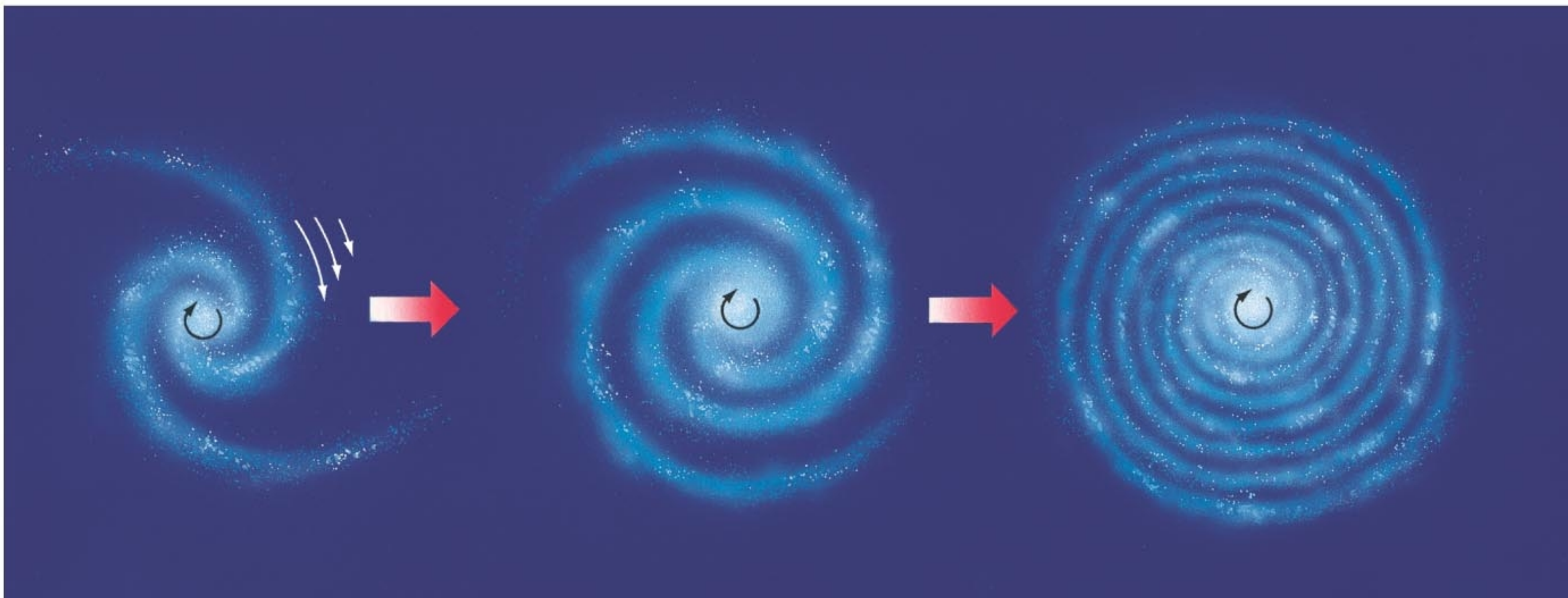
Measurement of the position and motion of gas clouds shows that the Milky Way has a spiral form:



See Wikipedia “Milky Way” for better diagrams.

23.5 Galactic Spiral Arms

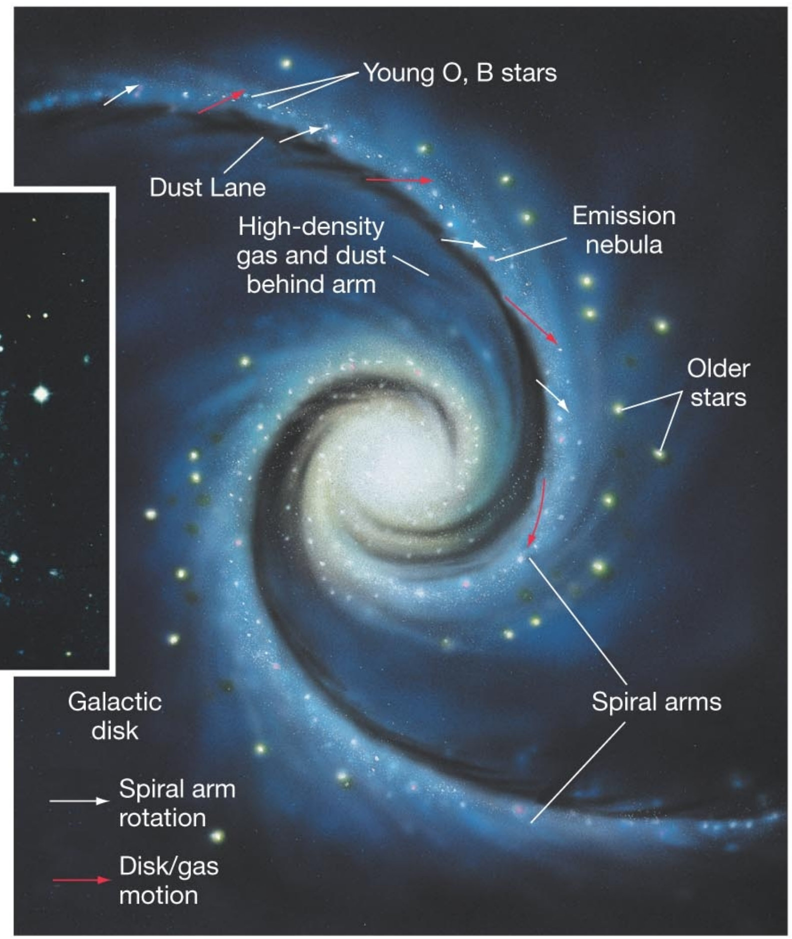
The **spiral arms** cannot rotate exactly as the stars do; they would “wind up”.
(The “winding problem”.)



The speed of the stars is almost constant with radius, so inner stars make it around in less time than outer stars. The Sun's period is ~240 Myrs. MW formed ~50 rotations ago.

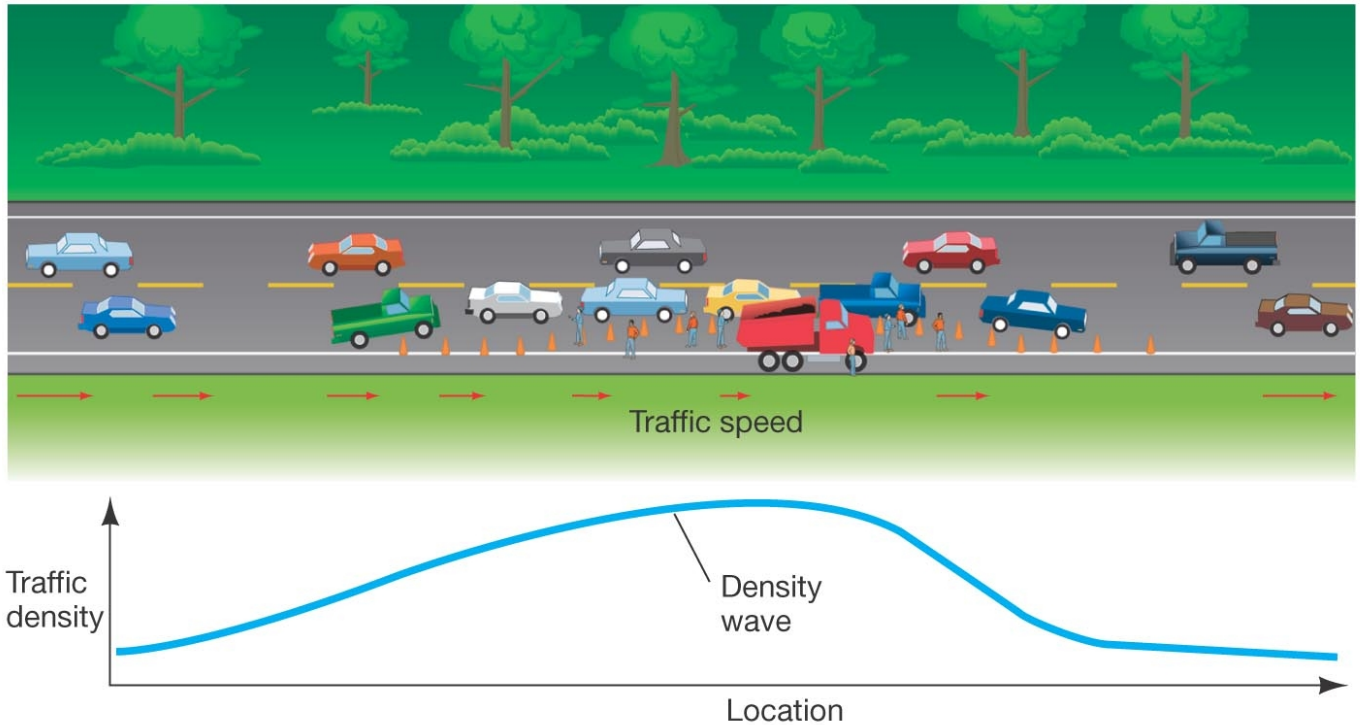
23.5 Galactic Spiral Arms

Rather, they appear to be density waves, with stars moving in and out of them such as cars move in and out of a traffic jam:



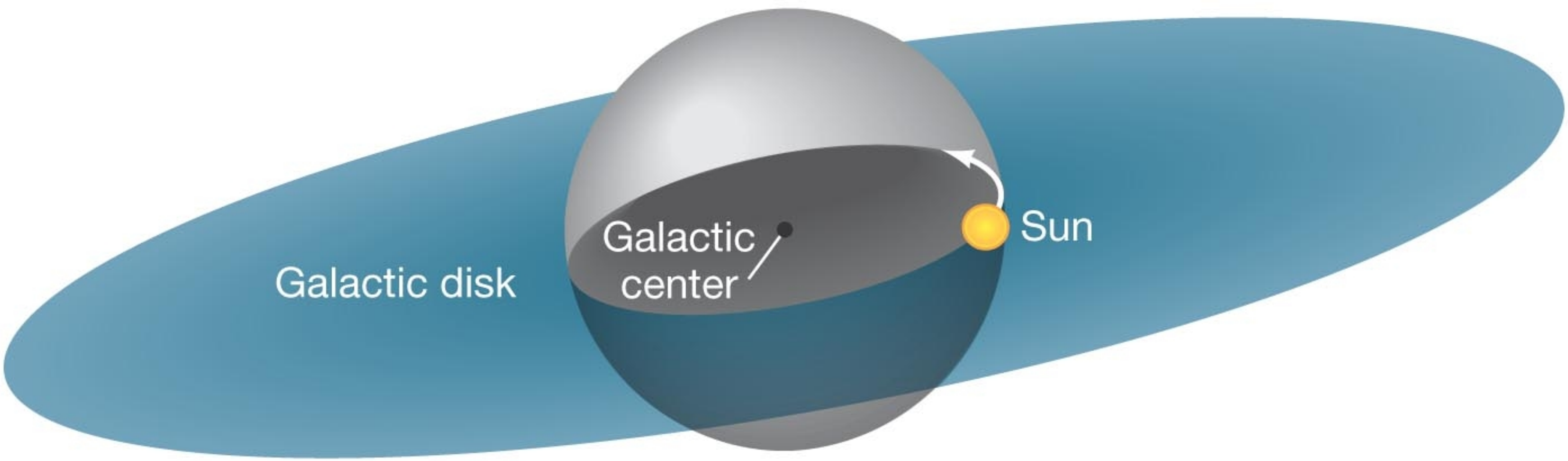
Discovery 23-2: Density Waves

Spiral arms as density waves, rather than as structures made up of particular stars, may be understood using a traffic jam analogy. The jam persists even though particular cars move in and out of it, and it can persist long after the event that triggered it is over.



23.6 The Mass of the Milky Way Galaxy

The **orbital speed** of an object depends only on the amount of **mass** within a sphere extending out to that object:



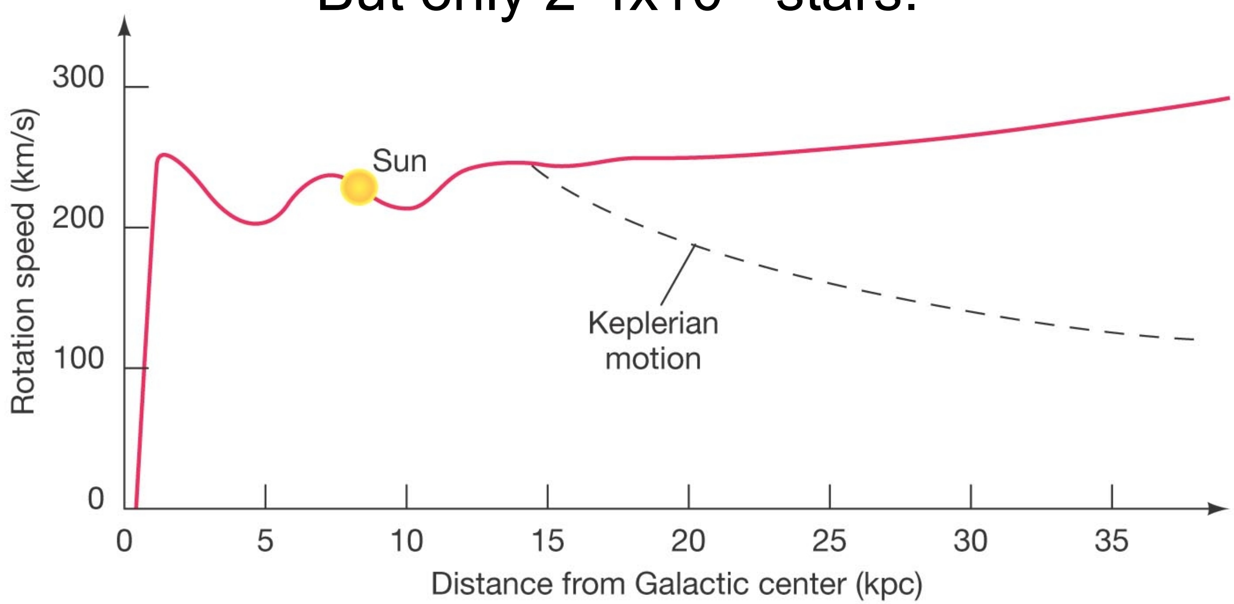
23.6 The Mass of the Milky Way Galaxy

Beyond the limits of the visible galaxy, the velocity should diminish with distance, as the dashed curve shows. Instead, it is flat or rising.

$M_{enclosed}(r=8kpc) \sim 10^{11}\ M_\odot$

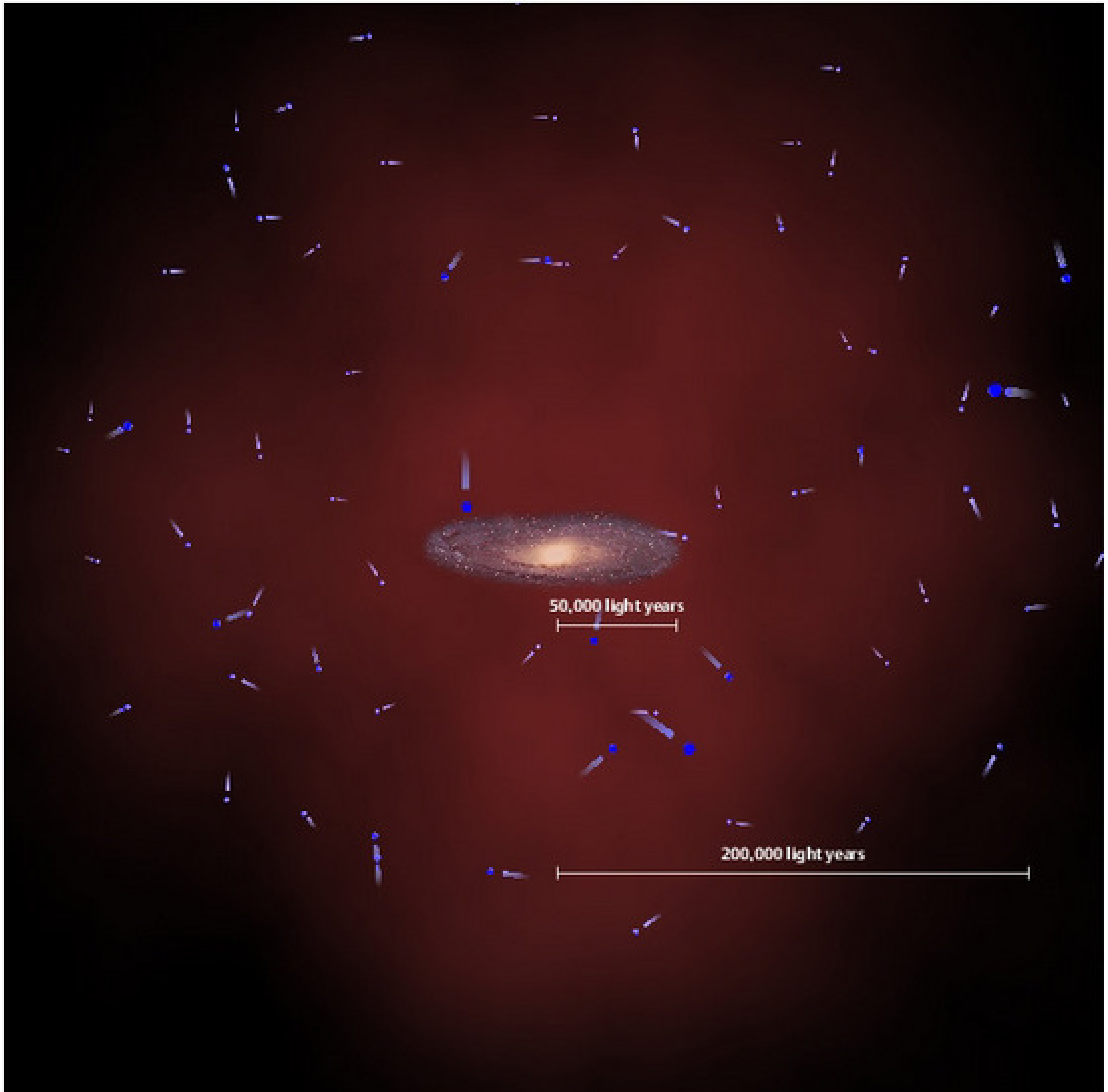
$M_{enclosed}(r=20kpc) \sim 8\text{-}15 \times 10^{11}\ M_\odot$

But only $2\text{-}4 \times 10^{11}$ stars.



23.6 The Mass of the Milky Way Galaxy

The MW has a dark matter halo!



Candidates:

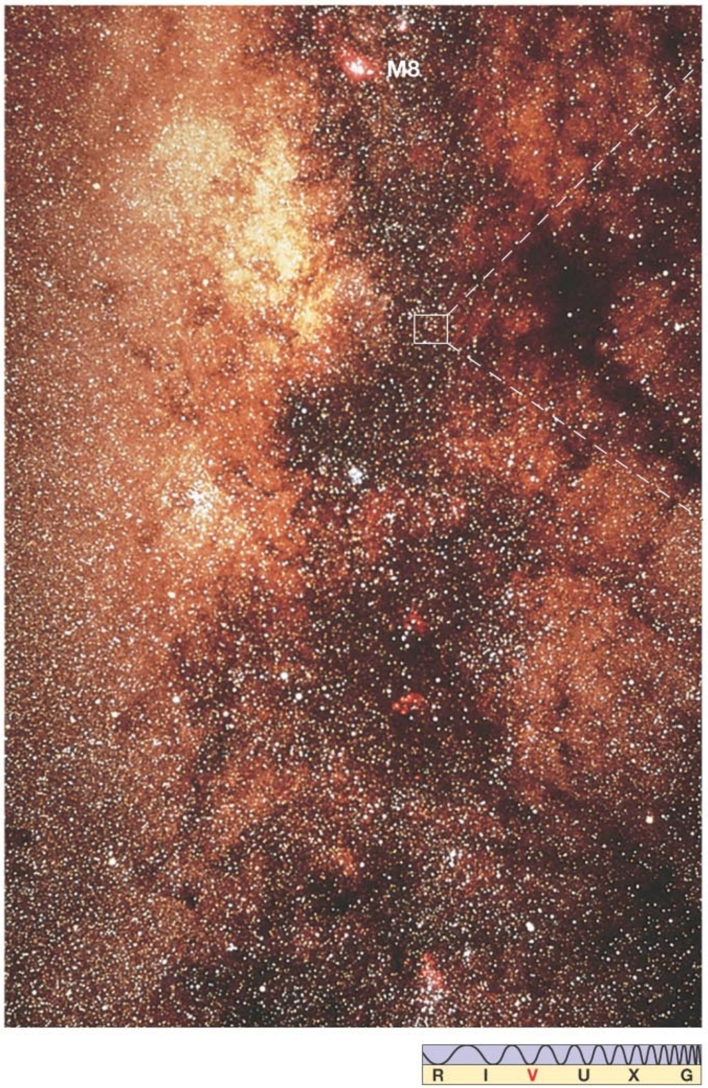
MACHOS:

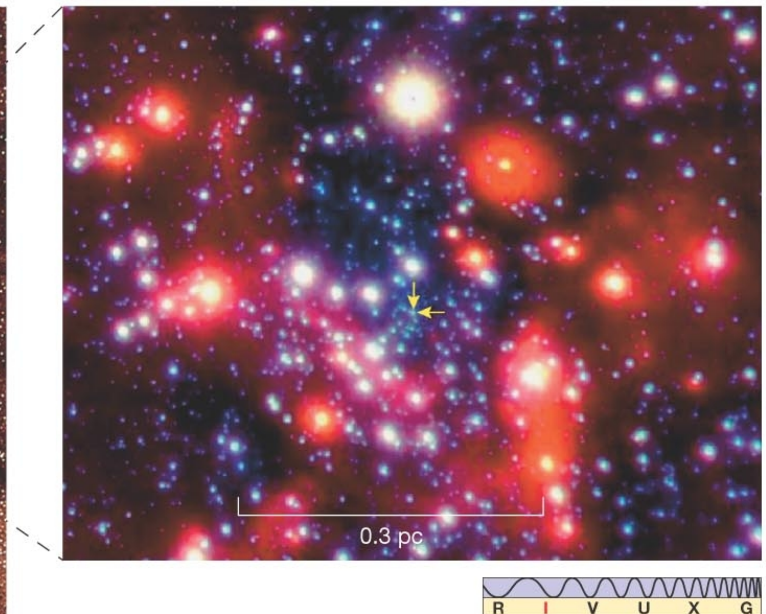
- Brown dwarfs
- Red dwarfs
- Stellar black holes
- Neutron stars

WIMPS:

- Axions, neutrinos, unknown

23.7 The Galactic Center

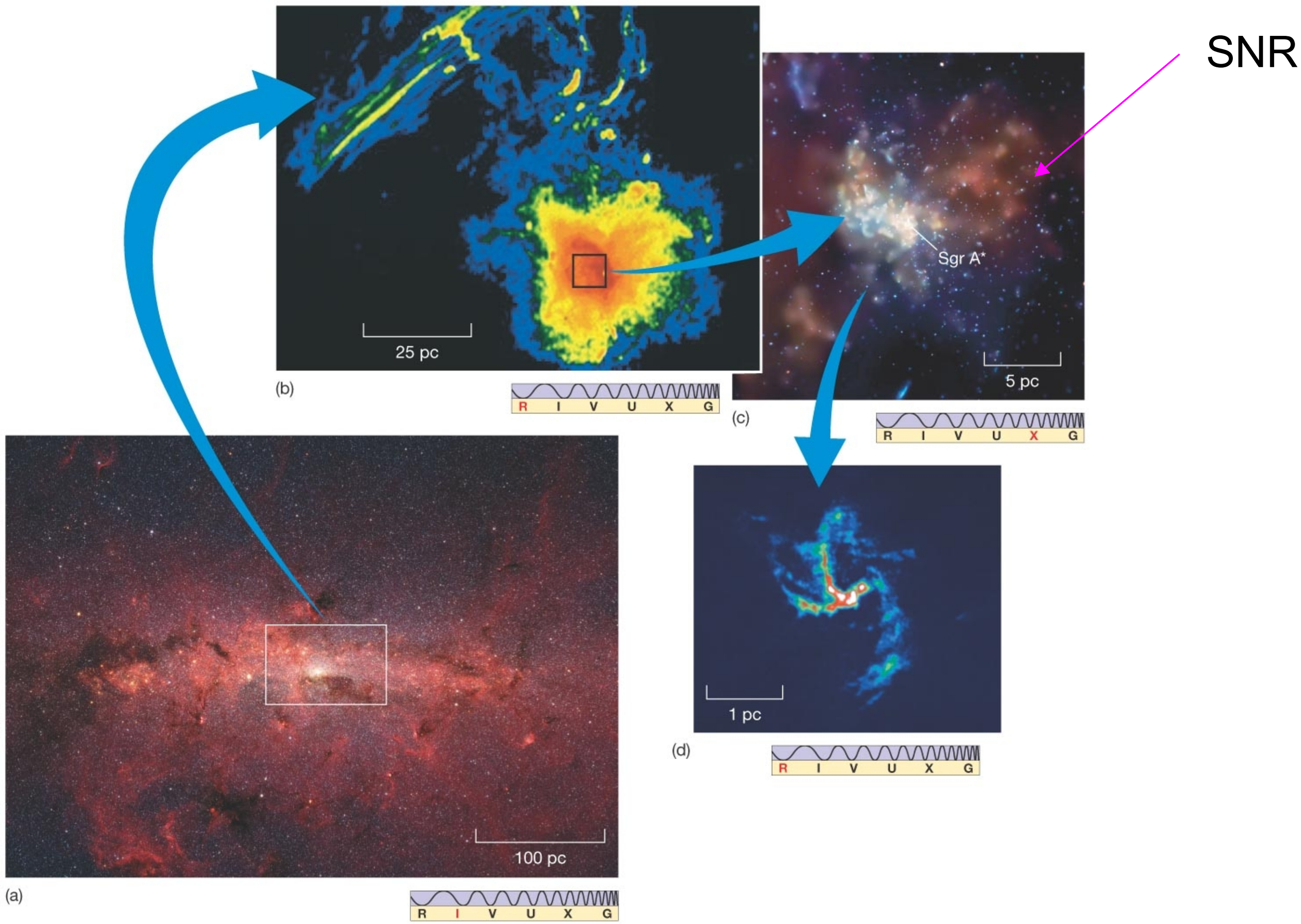




Two views toward the galactic center.

23.7 The Galactic Center

These images—in infrared, radio, and X-ray—offer a different view of the galactic center:



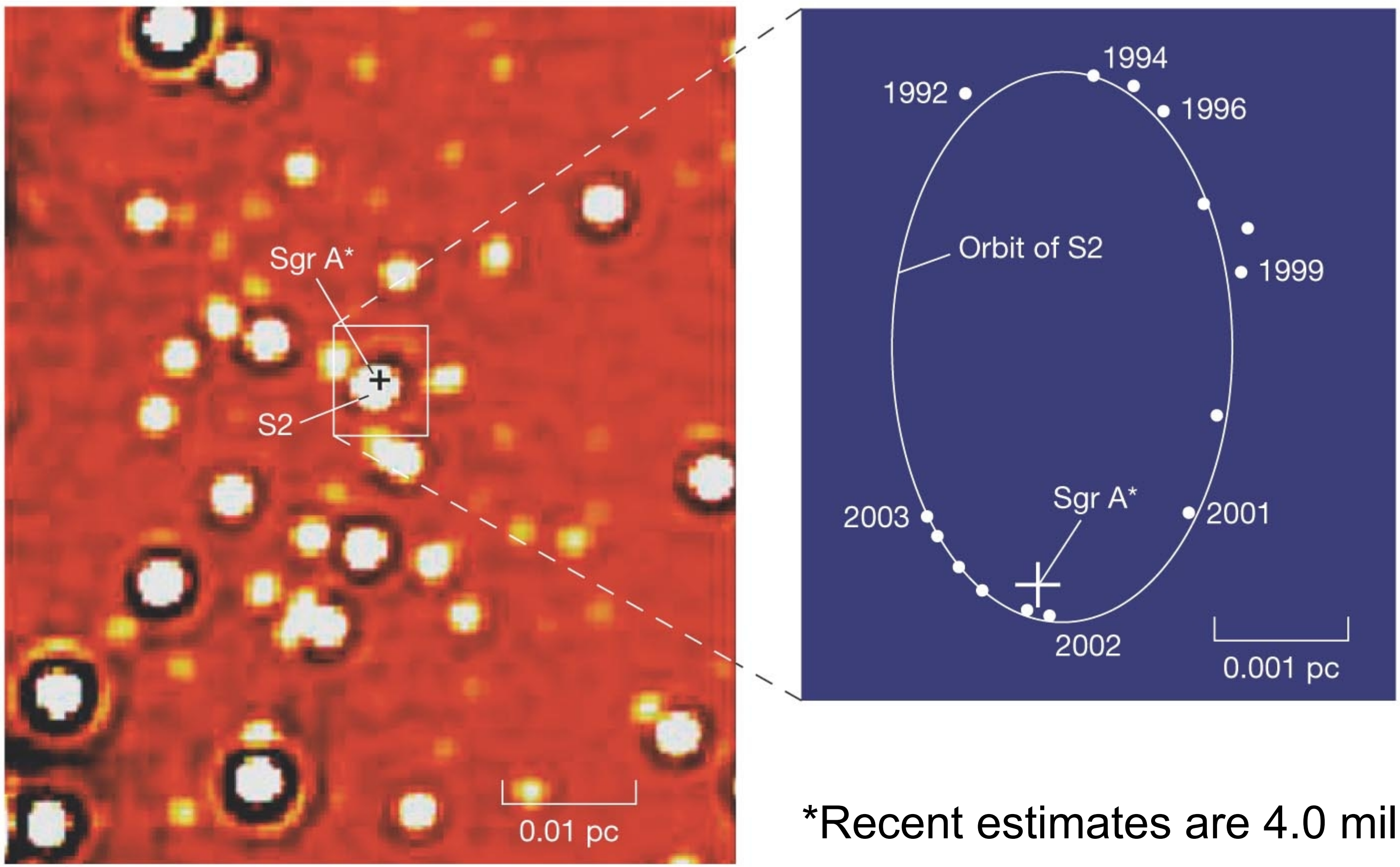
23.7 The Galactic Center

The galactic center appears to have:

- A stellar density a million times higher than near Earth – a nuclear star cluster.
- A ring of molecular gas 400 pc across
- Strong magnetic fields
- A rotating ring or disk of matter a few parsecs across
- A strong X-ray source at the center, thought to be a …
- Supermassive Black Hole (4×10^6 Msun)

23.7 The Galactic Center

These objects are very close to the galactic center. The orbit on the right is the best fit; it's consistent with a central black hole of 3.7* million solar masses.



*Recent estimates are 4.0 million

See animation: https://www.youtube.com/watch?v=495OIRMV-1c

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a) Stellar and spectroscopic parallax
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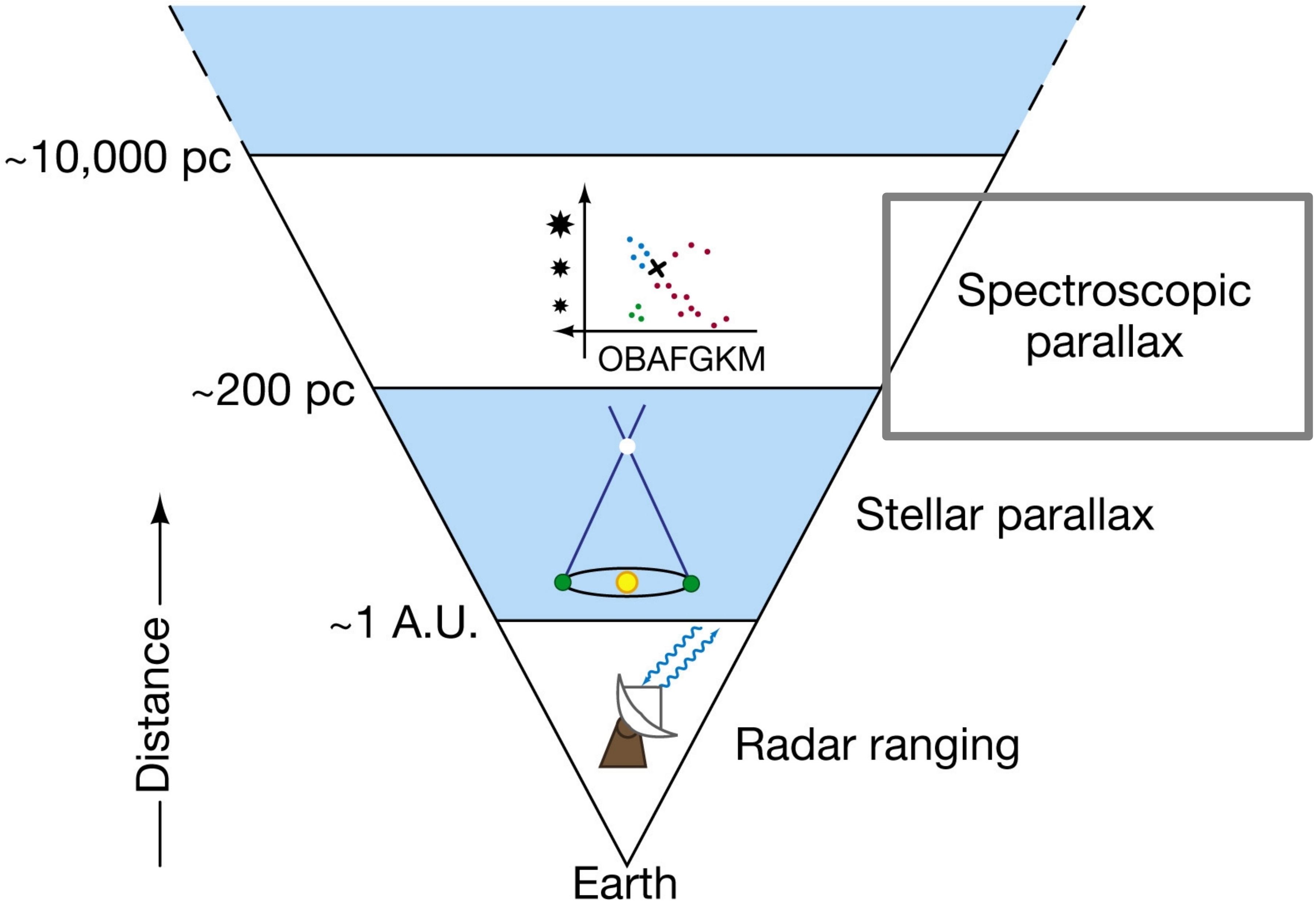
c) Herschel's (& Kaptyn's) star counts
d) “Intrinsic” Variable Stars
e) Other Distance Indicators

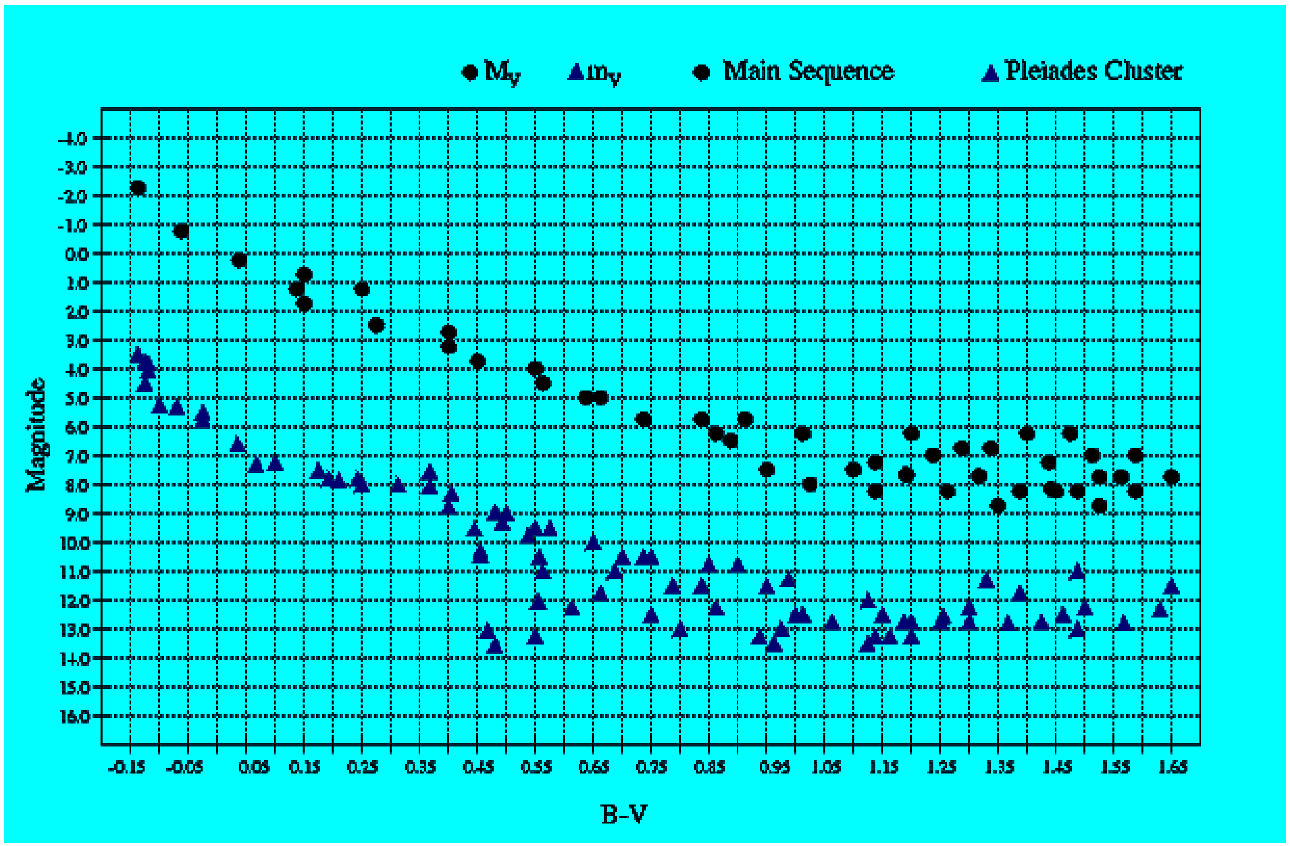
Figure 17-17
Stellar Distances



Stellar and Spectroscopic Parallax

<u>Spectroscopic Parallax</u> **works for stars for which a good spectrum can be observed (about 8 kpc), but ...**

- **Not precise for individual stars, especially giants**
- **Entire clusters of stars works better! ("main-sequence fitting")**



$m - M = 5\log(d/10)$

Spec Parallax assumes that all stars of a given type (e.g., A0V) have the same M. (That makes A0V stars "standard candles").

Recall this slide from “Stellar Properties” ...

Spectroscopic parallax

-a way to measure distances to stars based on their spectrum.

c) How it's measured (cont.)

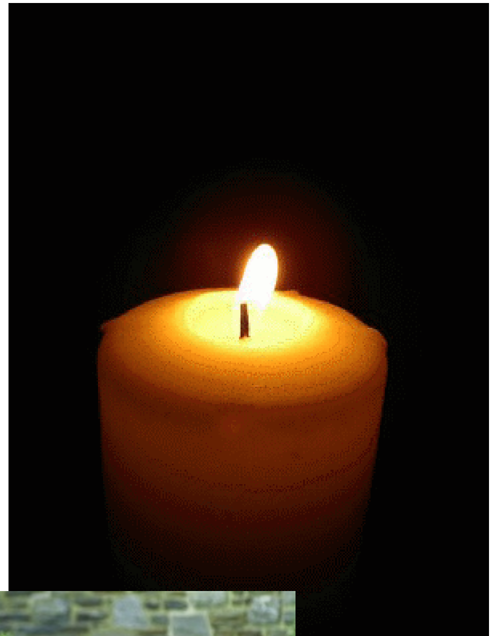
For a cluster of stars: two-color photometry can be done on a cluster of stars to obtain color index (B-V or B/V) and apparent brightness, *m*, for each star. A plot of *m* vs B-V will exhibit a Main Sequence just like a real H-R diagram (a plot of *M* vs B-V). The vertical offset of the cluster's main sequence from the main sequence on *M* vs B-V gives us (*m*-*M*) and thus a distance for the entire cluster. (This is called *main-sequence fitting*.)

d) Theory behind interpretation of measurement.

m-M = 5 log (D/10pc). Where D is the distance in pc.

“Beasts of a kind”: standard candles/yardsticks

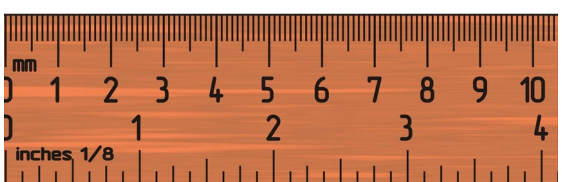
Nearby



Far away

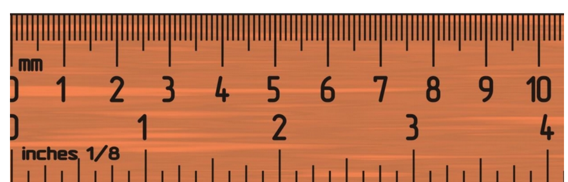
Flux, $F \sim 1/d^2$

Nearby



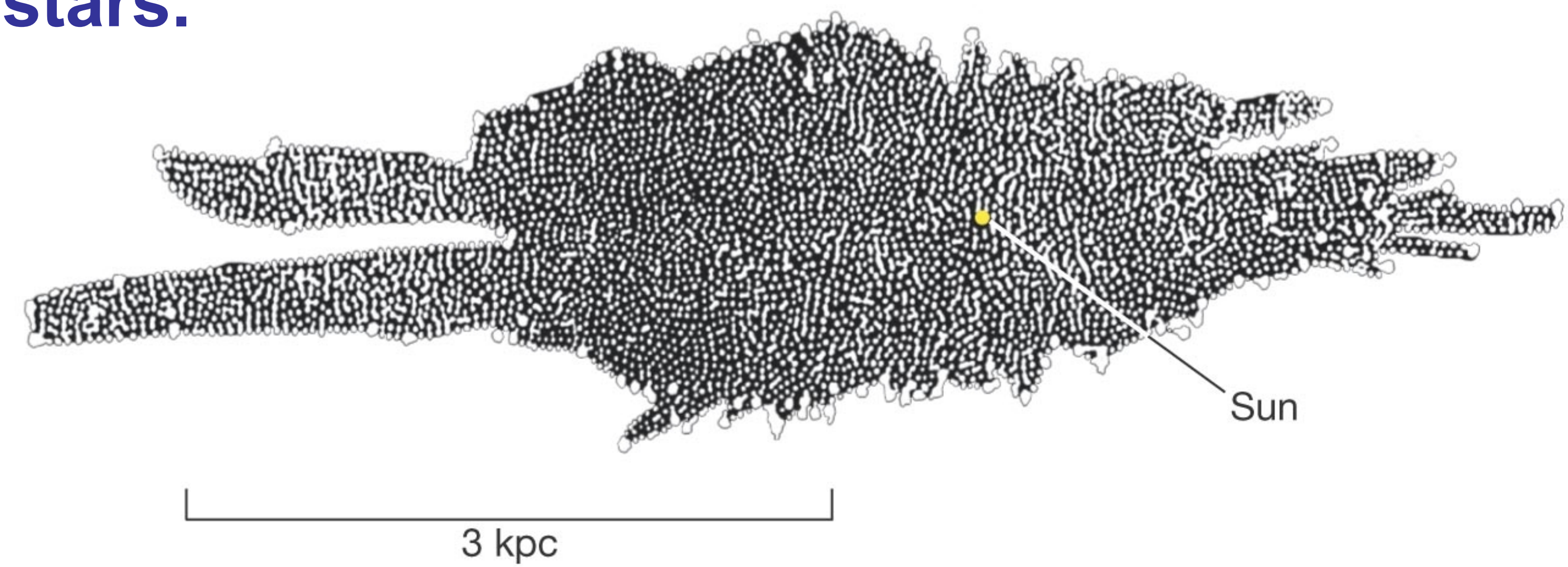
Far away

Angle, $\theta \sim 1/d$



23.2 Measuring the Milky Way

One of the first attempts to **measure** the Milky Way was done by W. Herschel using visible stars.



Problems:

1. patchy dust blocked view! (extinction)
2. all stars do not have the same luminosity!!
3. star number density not uniform

23.2 Measuring the Milky Way

A model based on star brightnesses, types, & motions was done by Jacobus Kapteyn (1850-1922).

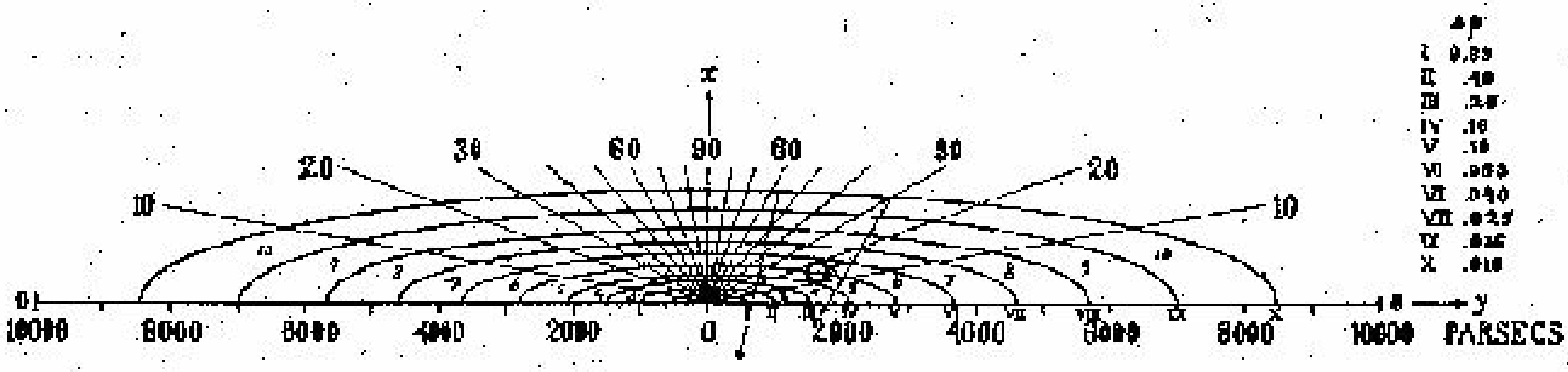
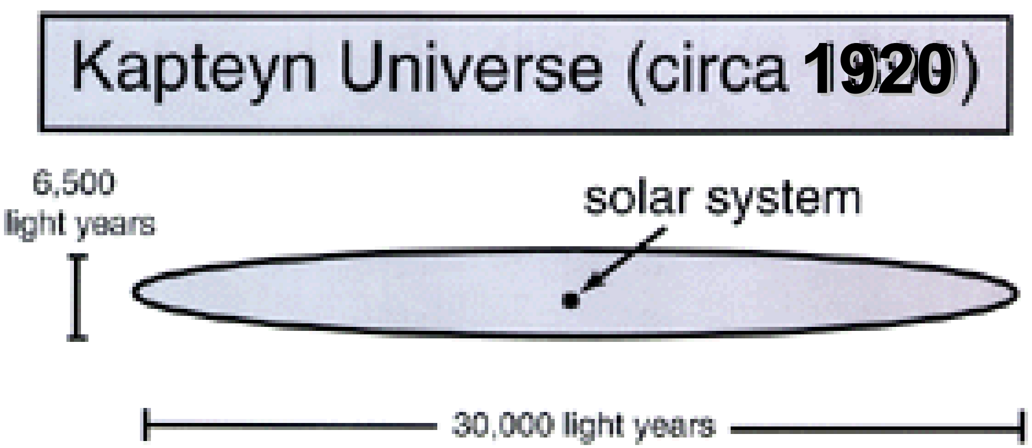


FIG. I

Still lacked corrections for extinction.
Sun 2000 LY from center.



23.2 Variable stars & distances

Extrinsic variables: eclipsing binaries

Cataclysmic variables: novae, supernovae.

``Intrinsic variables" - pulsating regularly: RR Lyrae stars and Cepheids. - very good for distances!

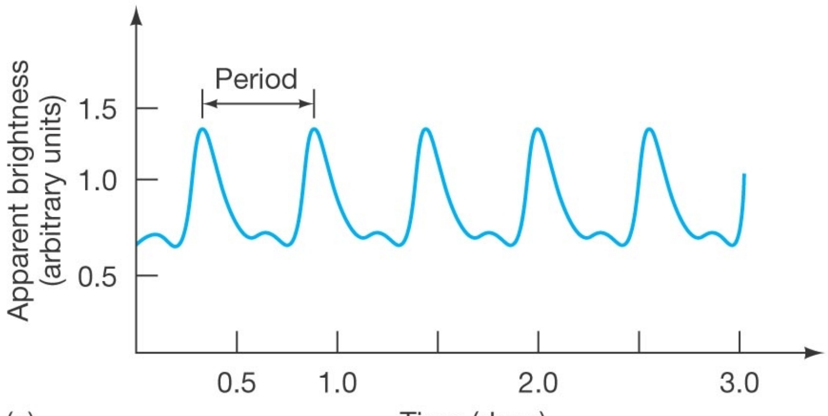
Long period, semi-regular variables (like Mira) – not good for distances

Henrietta Leavitt: measured Cepheids in the Magellanic Clouds. Finds P-L relation!

23.2 Variable stars & distances

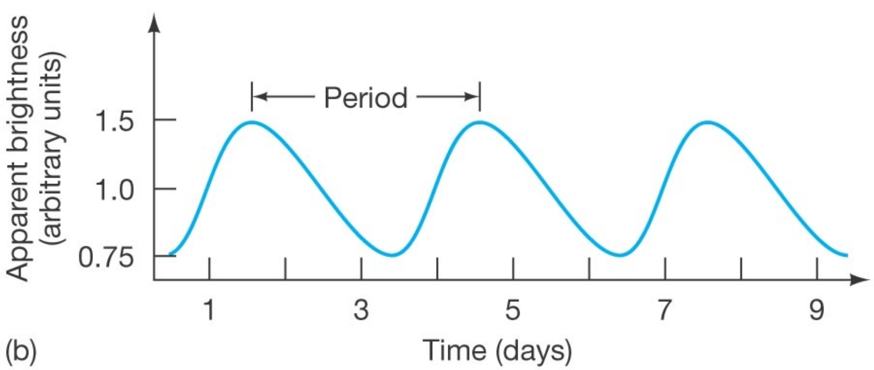
The **intrinsic variables** (like RR Lyrae and Cepheid) work best for distances!

The upper plot is an RR Lyrae star. All such stars have essentially the same luminosity curve with periods from 0.5 to 1 day.



(a)

The lower plot is a Cepheid variable; Cepheid periods range from about 1 to 100 days.

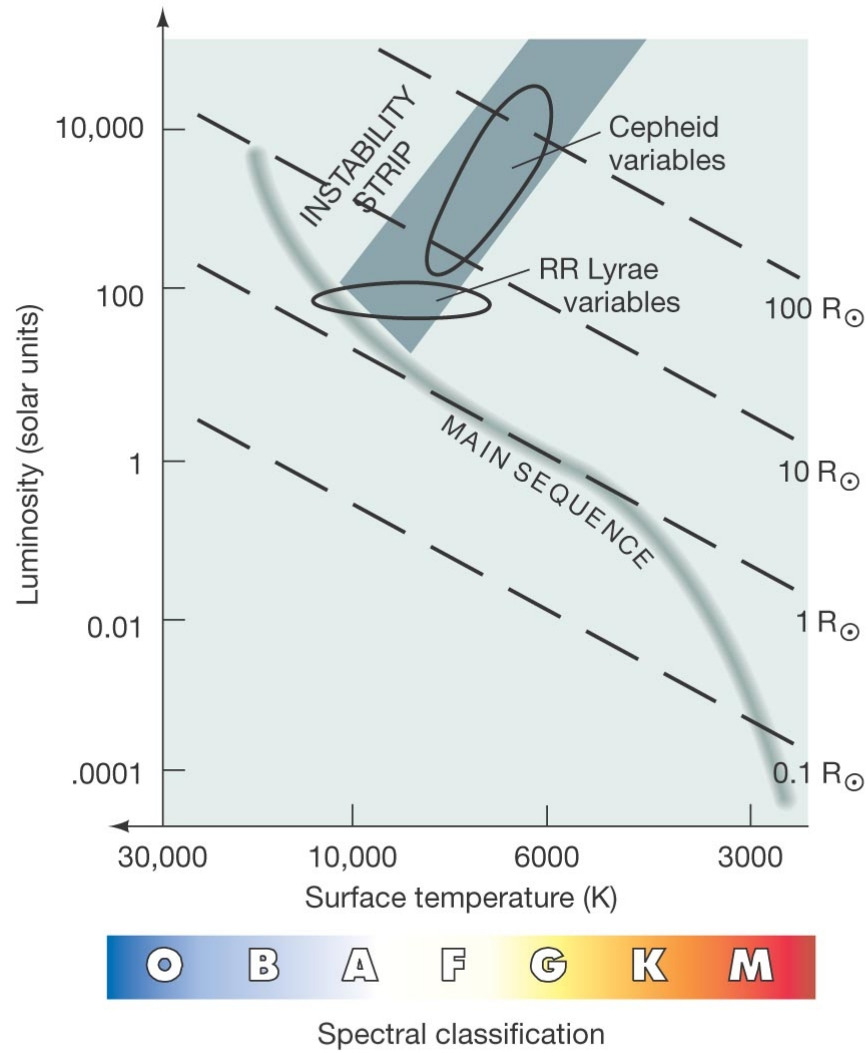


(b)

23.2 Variable stars & distances

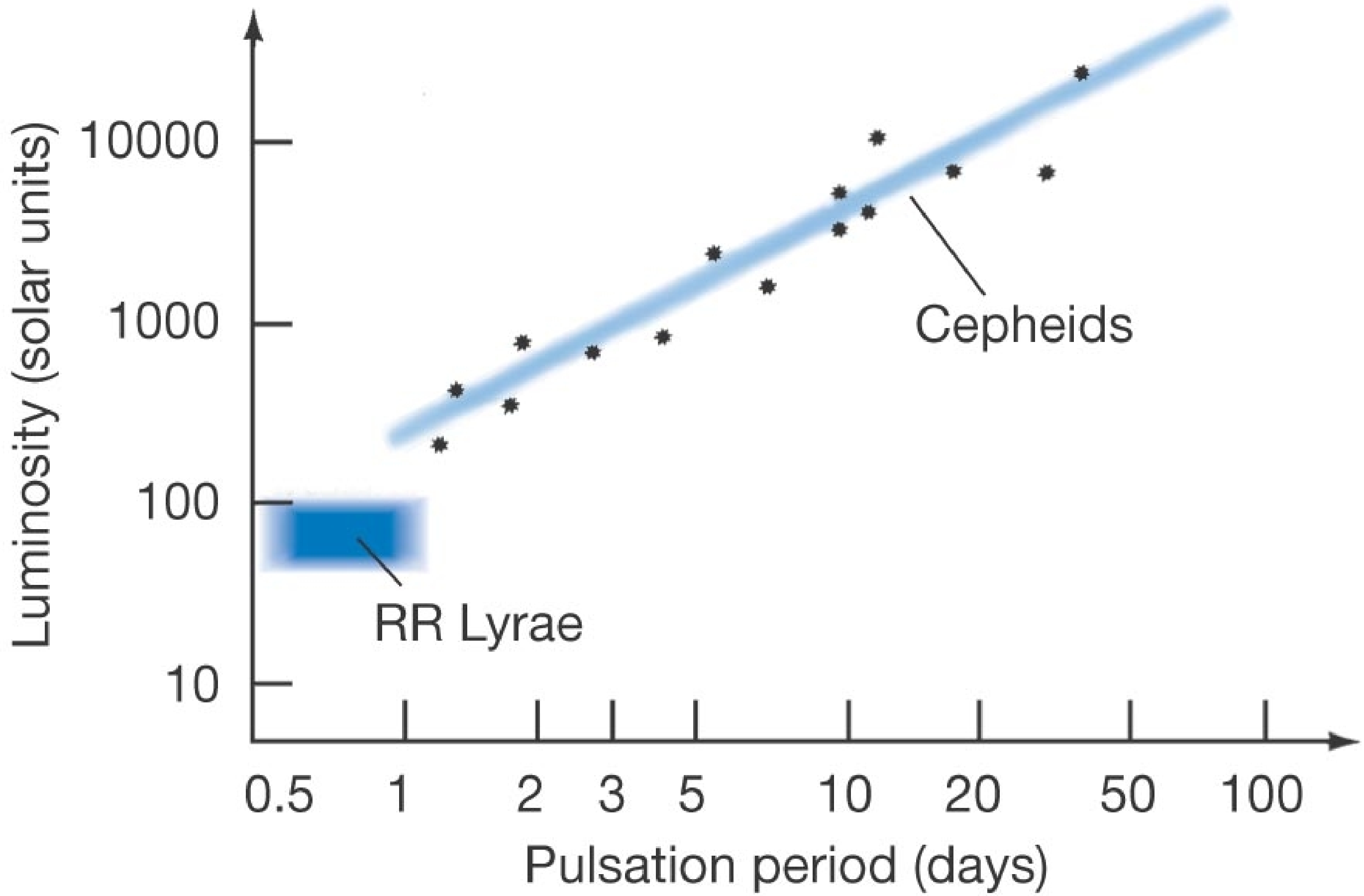
The variability of these stars comes from a dynamic balance between gravity and pressure—they have large oscillations around stability.

- HeII opacity-



23.2 Variable stars & distances

The usefulness of these stars comes from their period–luminosity relation:



These are just “Classical” Cepheids, like those observed by Leavitte in the SMC.

23.2 Variable stars & distances

This allows us to measure the **distances** to these stars:

• **RR Lyrae** stars all have about the same **luminosity**; knowing their **apparent magnitude** allows us to calculate the **distance**.

• **Cepheids** have a **luminosity** that is strongly correlated with the **period** of their oscillations; once the period is measured, the luminosity is known and we can proceed as above. (*Period-Luminosity relation*)

•Q: how were the Cepheid <u>luminosities</u> found?
(First using globular cluster Cepheids, then using 8 nearby open clusters.)

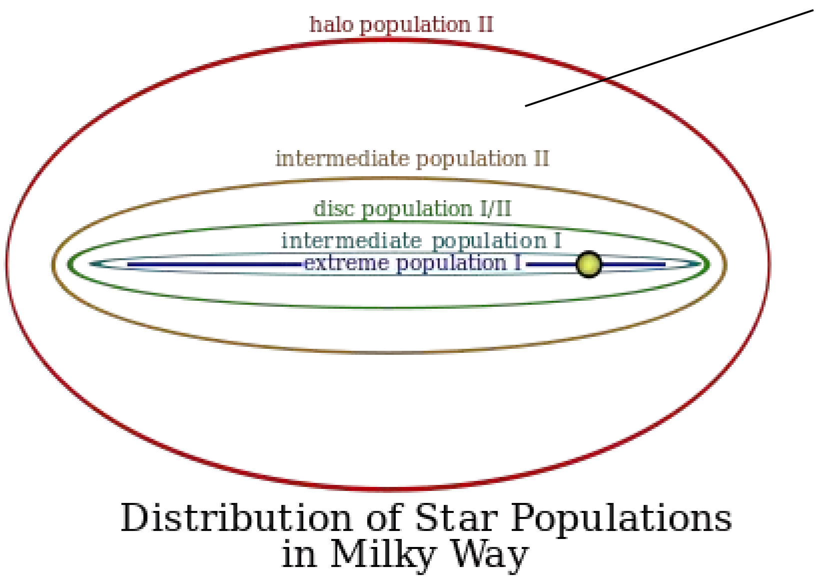
•Q: Does composition make a difference?
Yes – there are Type I and Type II Cepheids.
The story of Walter Baade (doubled universe, 1952) ...

23.2 Variable stars & distances

Walter Baade introduced stellar populations.

•First noticed different color of bulge and disk of spirals.

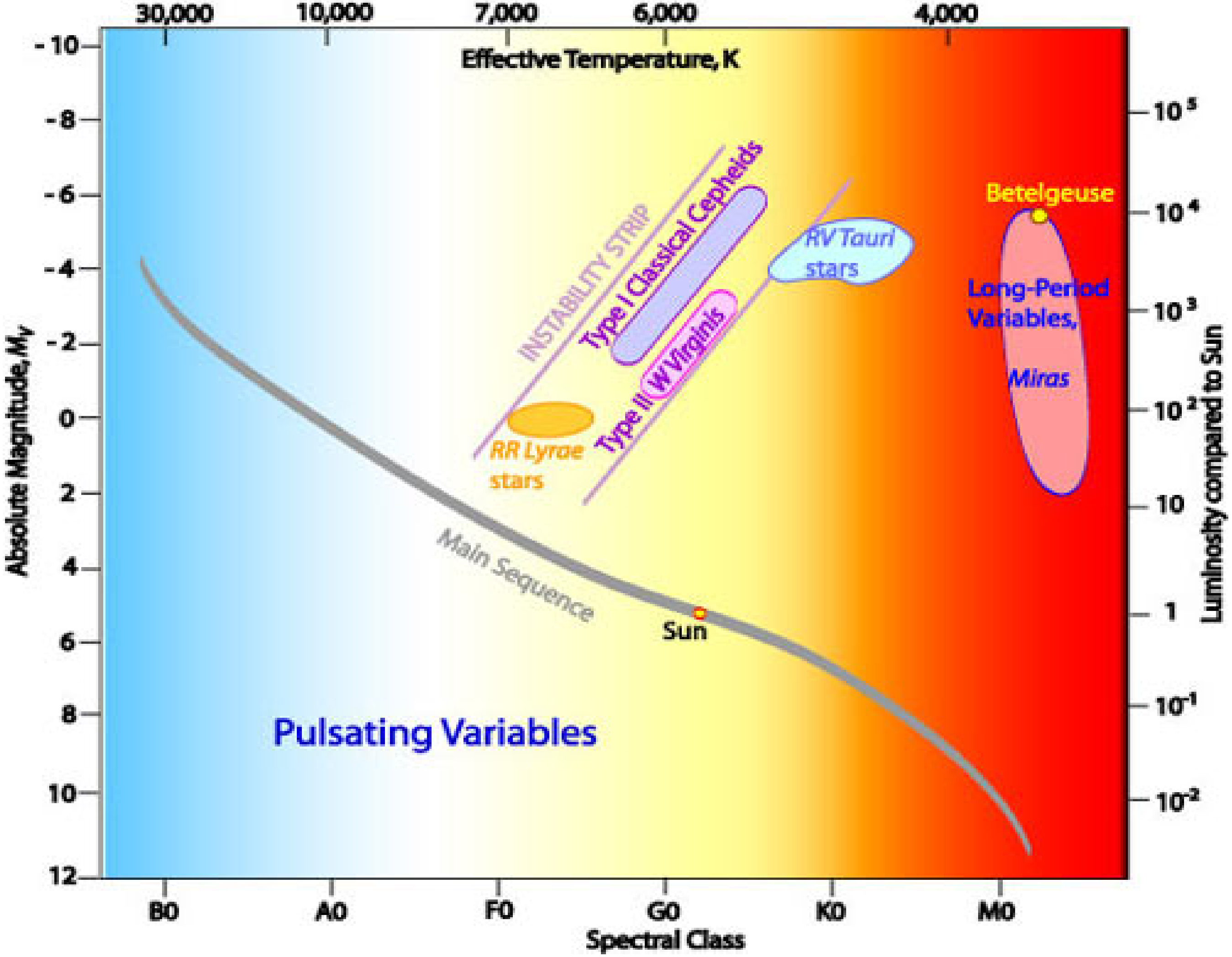
•Defined in terms of metallicity, [Fe/H]:
Pop I= high metal (formed recently, young)
Pop II = low metal (formed early on, old)
Pop III = hypothetical *first* population of stars.



Glob. Clusters are also Pop II.

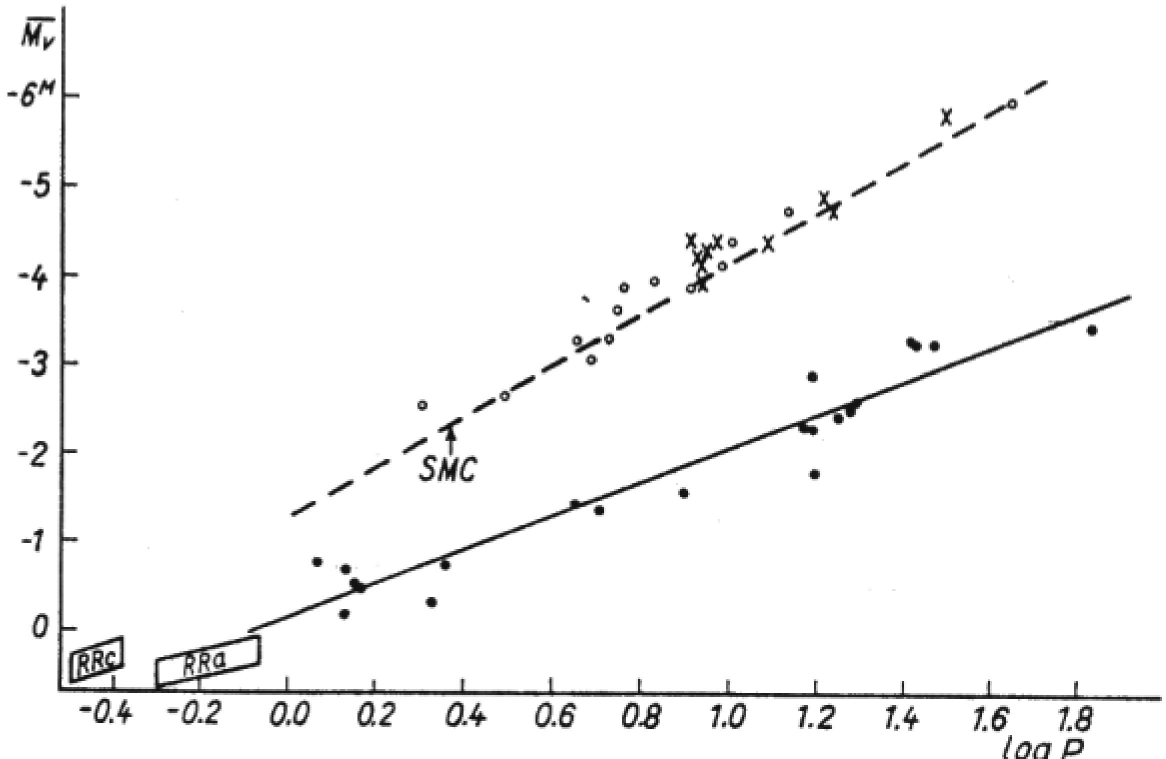
23.2 Variable stars & distances

It was realized that there was a fainter, population II version of the Cepheid.



23.2 Variable stars & distances

The PL relationship for the classical Cepheids is on top, the PL relationship for the W Vir Cepheids is on the bottom.



Pop I stars

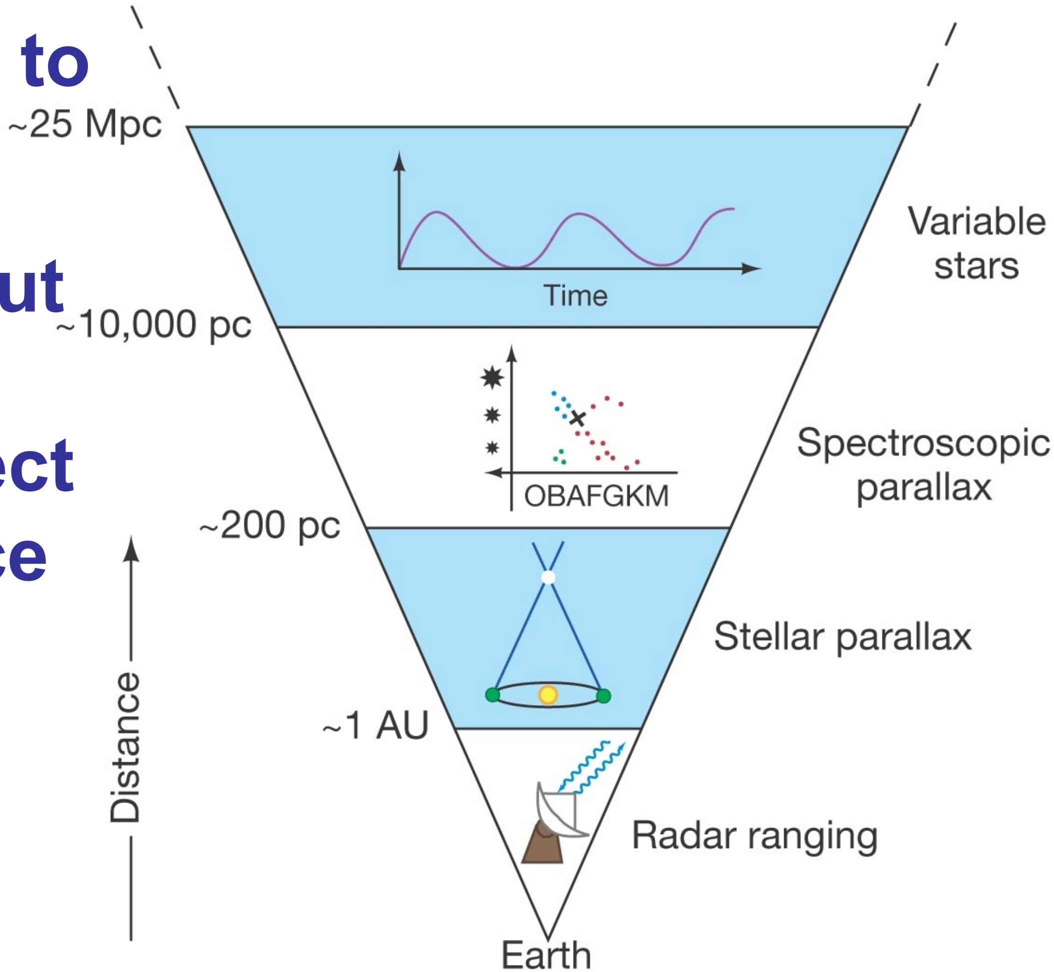
Pop II stars

They found Pop II cepheids in nearby globular clusters and in the field and used them to establish the y-axis of the PL relation. But the SMC stars were actually Pop I stars. They needed a separate, higher, PL relation.

23.2 Measuring the Milky Way

Our cosmic distance ladder now extends to 25 Mpc.

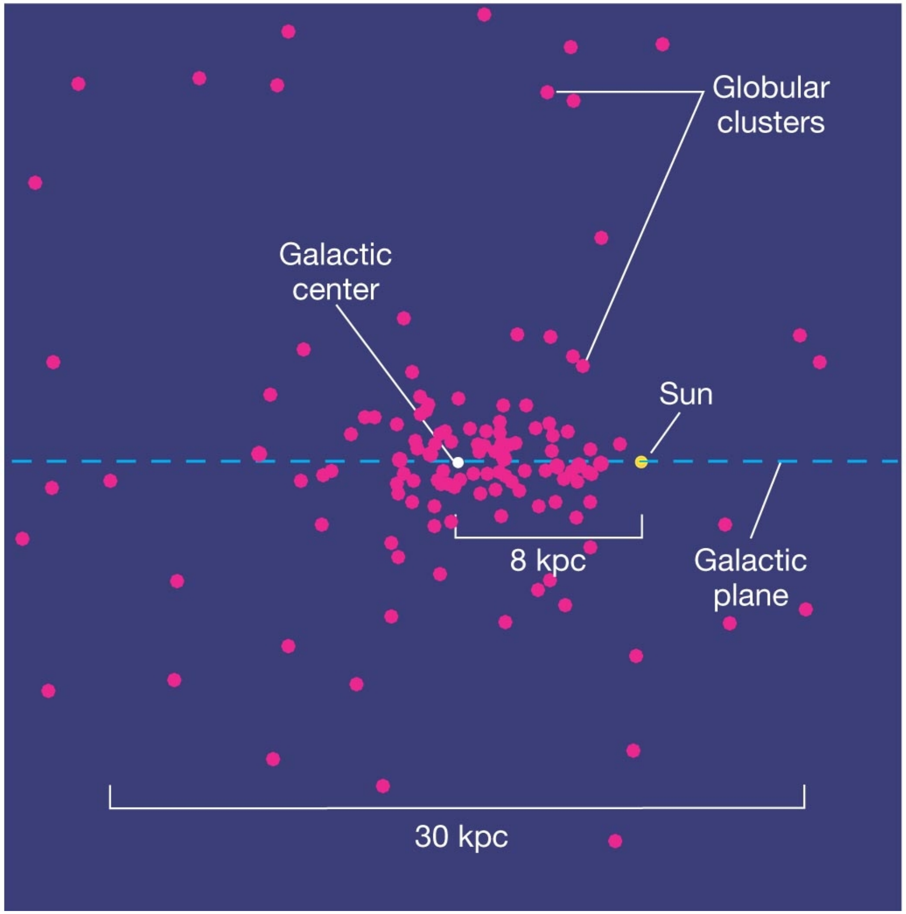
Finding Cepheids out to 25 Mpc was the original “Key” project for the Hubble Space Telescope.



23.2 Measuring the Milky Way

Many RR Lyrae stars are found in **globular clusters**. Harlow Shapley used these to estimate the size of the M.W. (c. 1920).

He correctly determined that we were far from the center. But he overestimated the sizes (diam = 300,000 LY; distance from cent=50,000 LY).



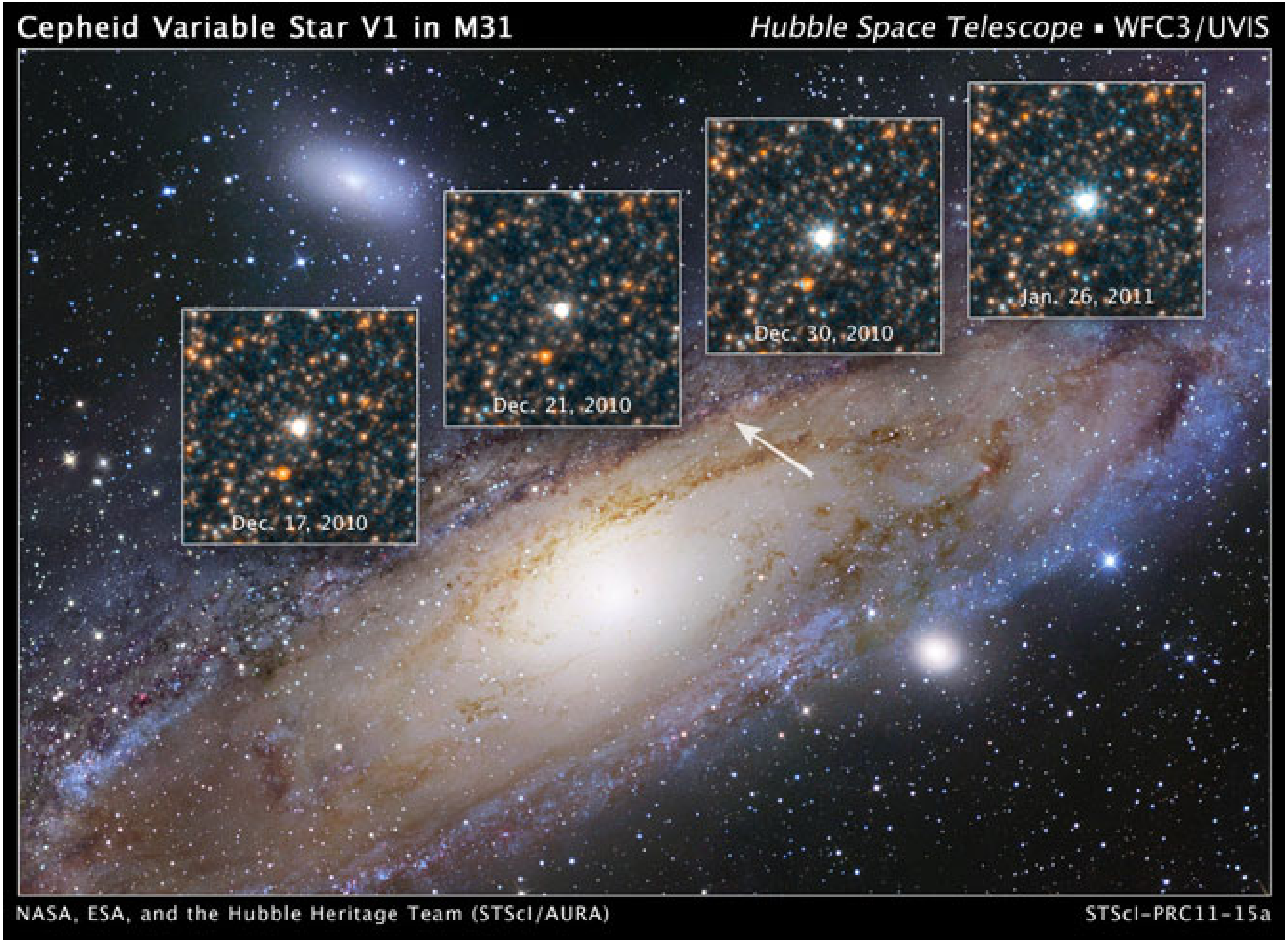
The Shapley – Curtis debate (1920)

Main issue: are spiral nebulae part of our Galaxy or are they other "island universes"? Issue #2: how big is the MW?

1) Size of the Milky way
   Shapley used globulars and RR Lyrae – got 300,000 LY
   Curtis underestimated
2) Distribution of spiral nebulae in sky
   Zone of avoidance explained by Curtis
3) Novae in spiral nebulae
   Shapley mistook supernovae for novae. This made spiral nebulae look closer than proposed by Curtis.
4) Brightness and spectra of spiral nebulae
   Colors looked redder than our galaxy (it was reddening)
   Spectra – the nebulae were made of many stars (not one)
5) Rotation of the nebulae (van Maanen's proper motions)
   Erroneous measurements of rotation made it impossible for The spiral nebulae to be far away.

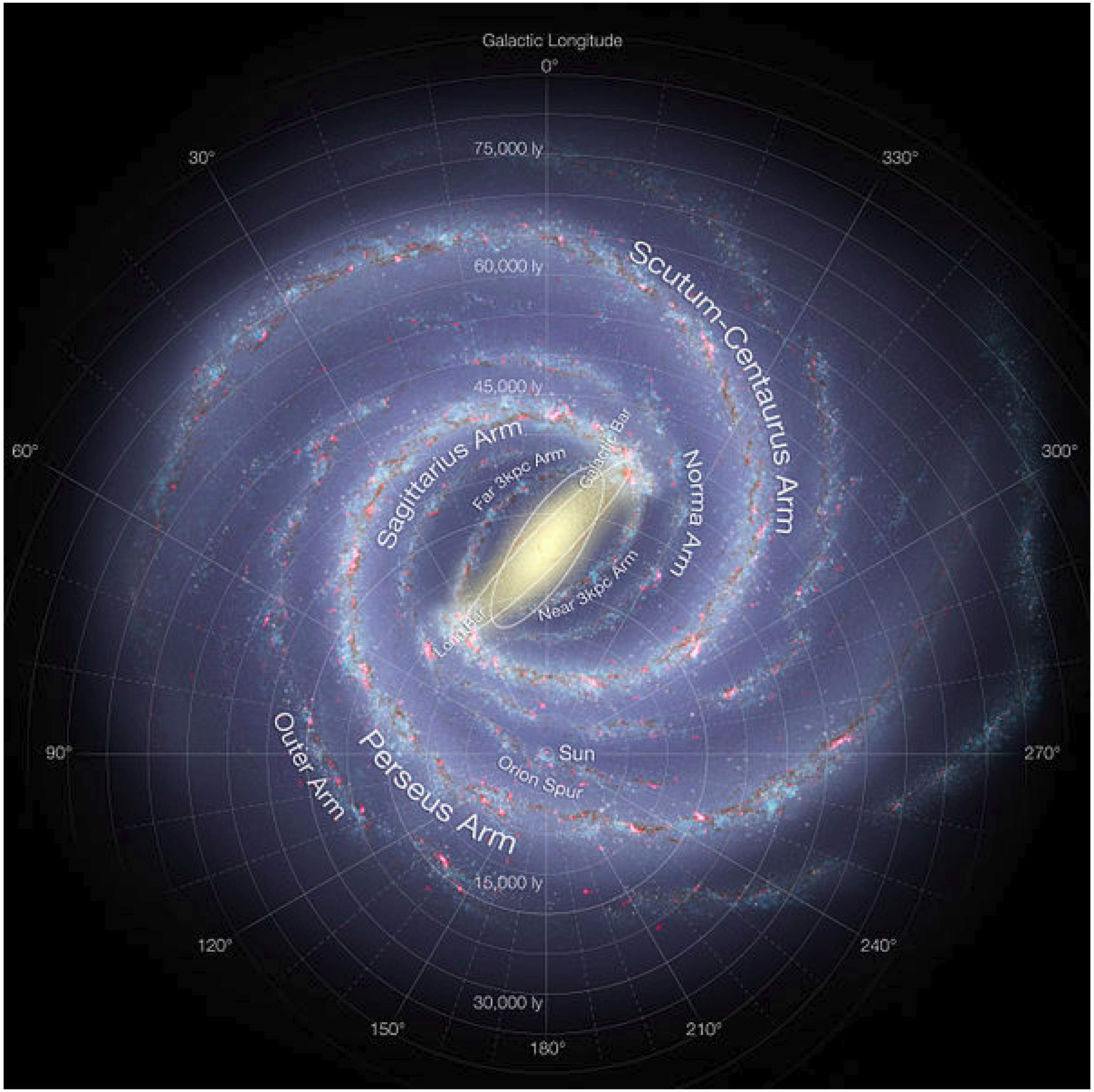
Result: Curtis was right – they are island universes. The story of Edwin Hubble ...

23.2 Measuring the Milky Way - *and beyond!*



23.2 Measuring the Milky Way

Modern mapping of the M.W. Has relied on a variety of observations, especially 20 cm radio observations of the HI gas.



Ch. 23 Summary

- A good "standard candle" is luminous
- Variable stars can be used for distance measurement through the period–luminosity relationship.
- The center and size of the Galaxy can be estimated using globular clusters.
- Modern mapping of the MW is done with radio interferometry of gas clouds.

Summary of Chapter 23 (cont.)

- Spiral arms may be density waves.
- The galactic rotation curve shows large amounts of undetectable mass at large radii called dark matter.
- Activity near galactic center suggests presence of a ~4 million solar-mass black hole