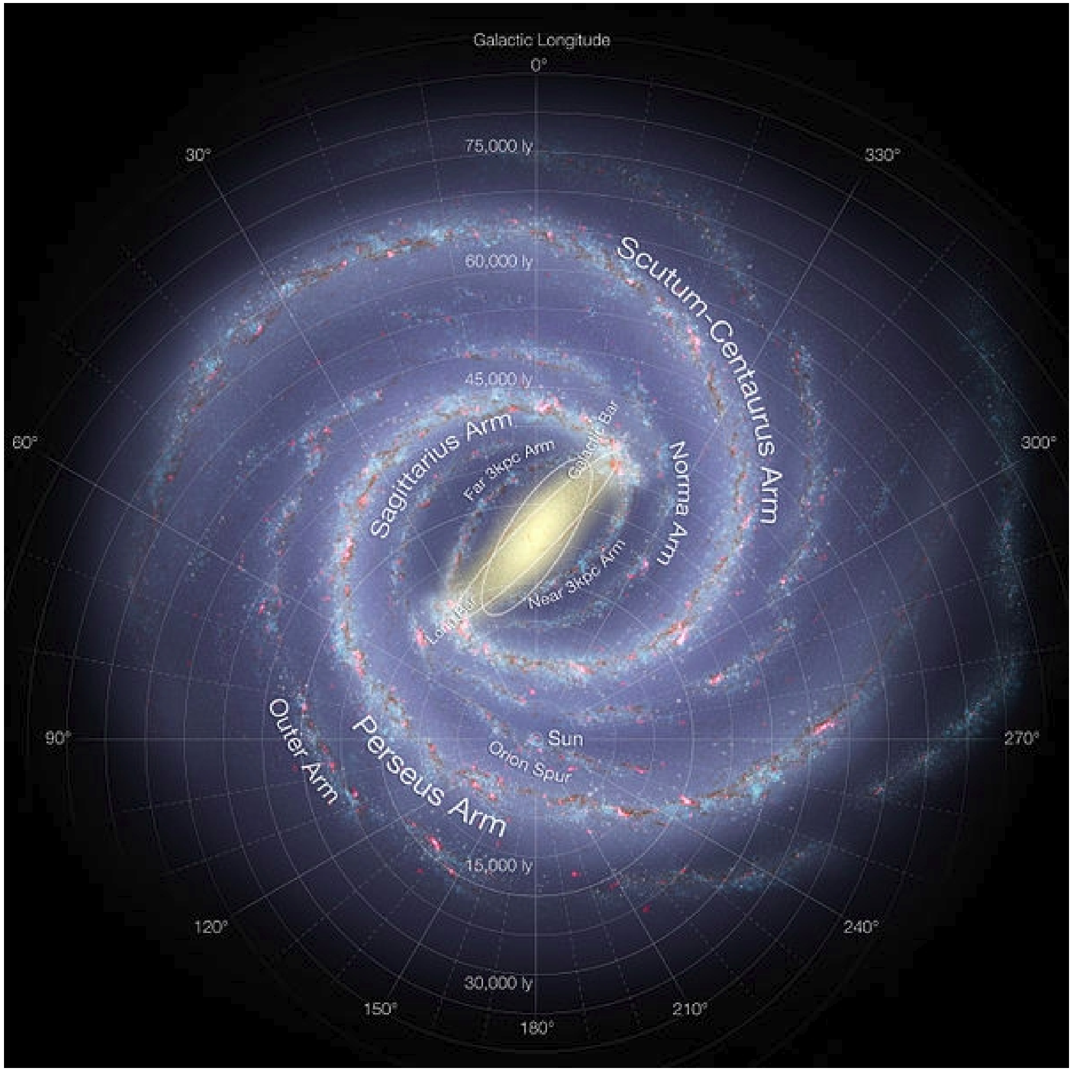
The Distance Ladder I.

The Milky Way Galaxy



(Ch. 23)

Outline

1. Our Milky Way Galaxy

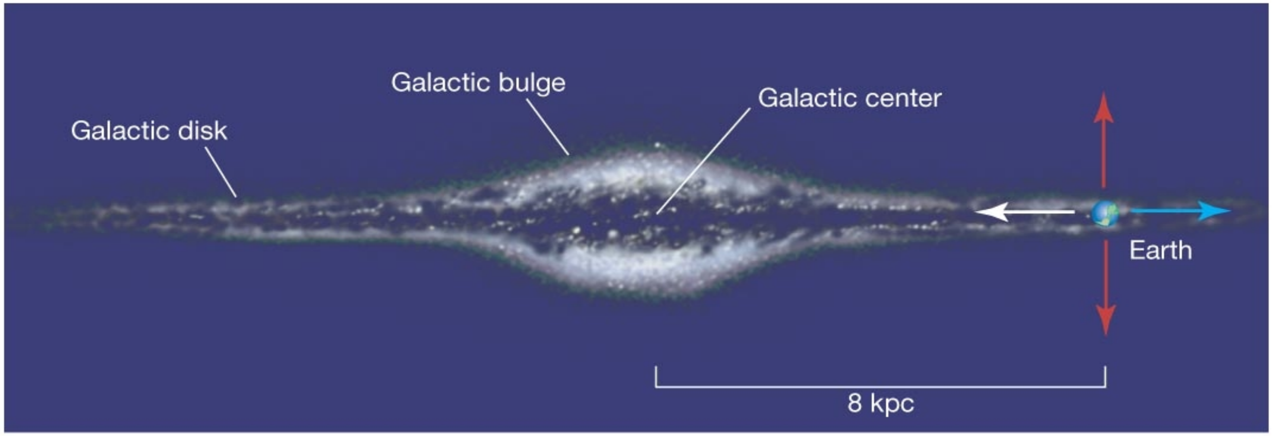
a) Dimensions and structure
b) Spiral Arms
c) Mass and Dark Matter
d) Nucleus

2. Distances within the Milky Way

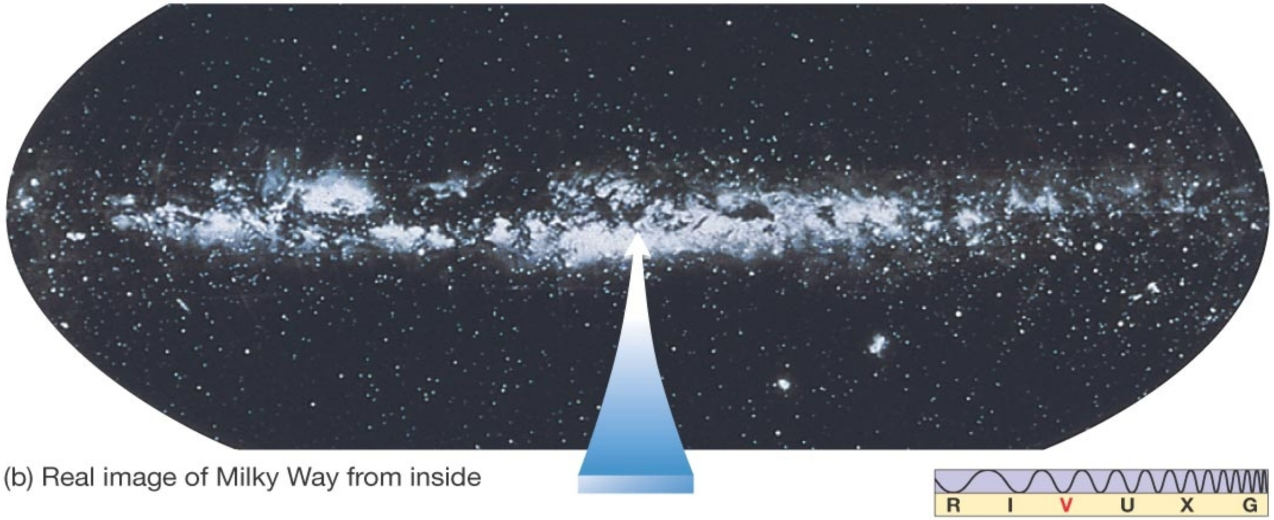
a) Stellar and spectroscopic parallax
b) “Standard Candles” or “Beasts of a kind” concept
c) Herschel's star counts
d) “Intrinsic” Variable Stars
e) Other Distance Indicators

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

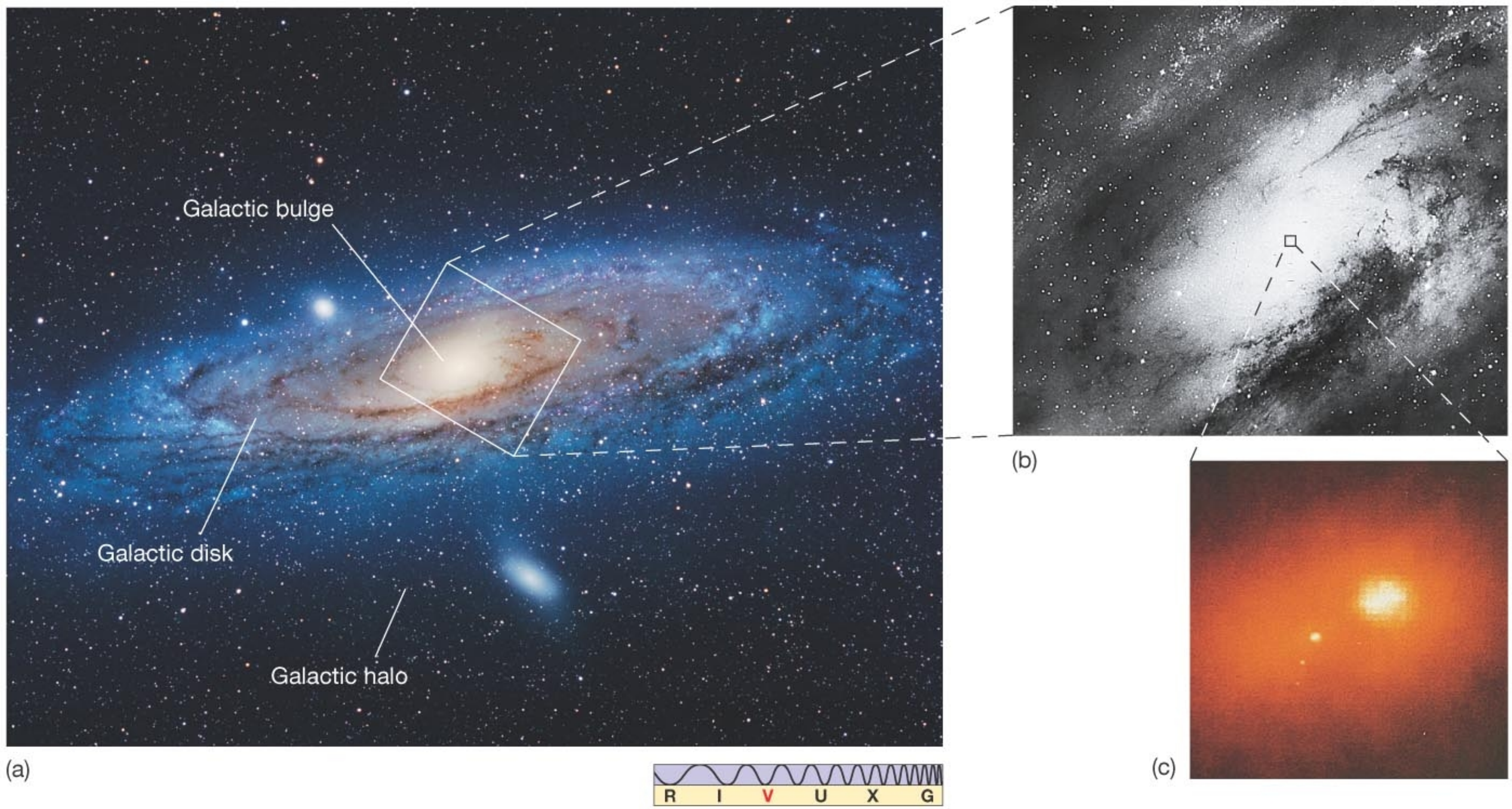


(b) Real image of Milky Way from inside

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

23.1 Our Parent Galaxy

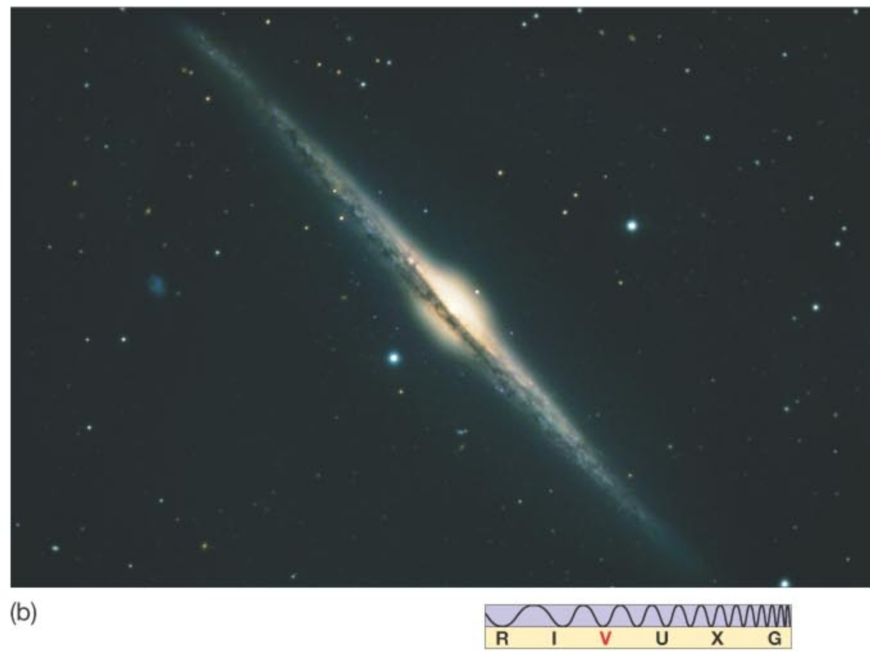
Our galaxy is a **spiral** galaxy. The Andromeda Galaxy, our closest spiral neighbor, probably resembles the Milky Way fairly closely.



23.1 Our Parent Galaxy

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

(a)



(b)

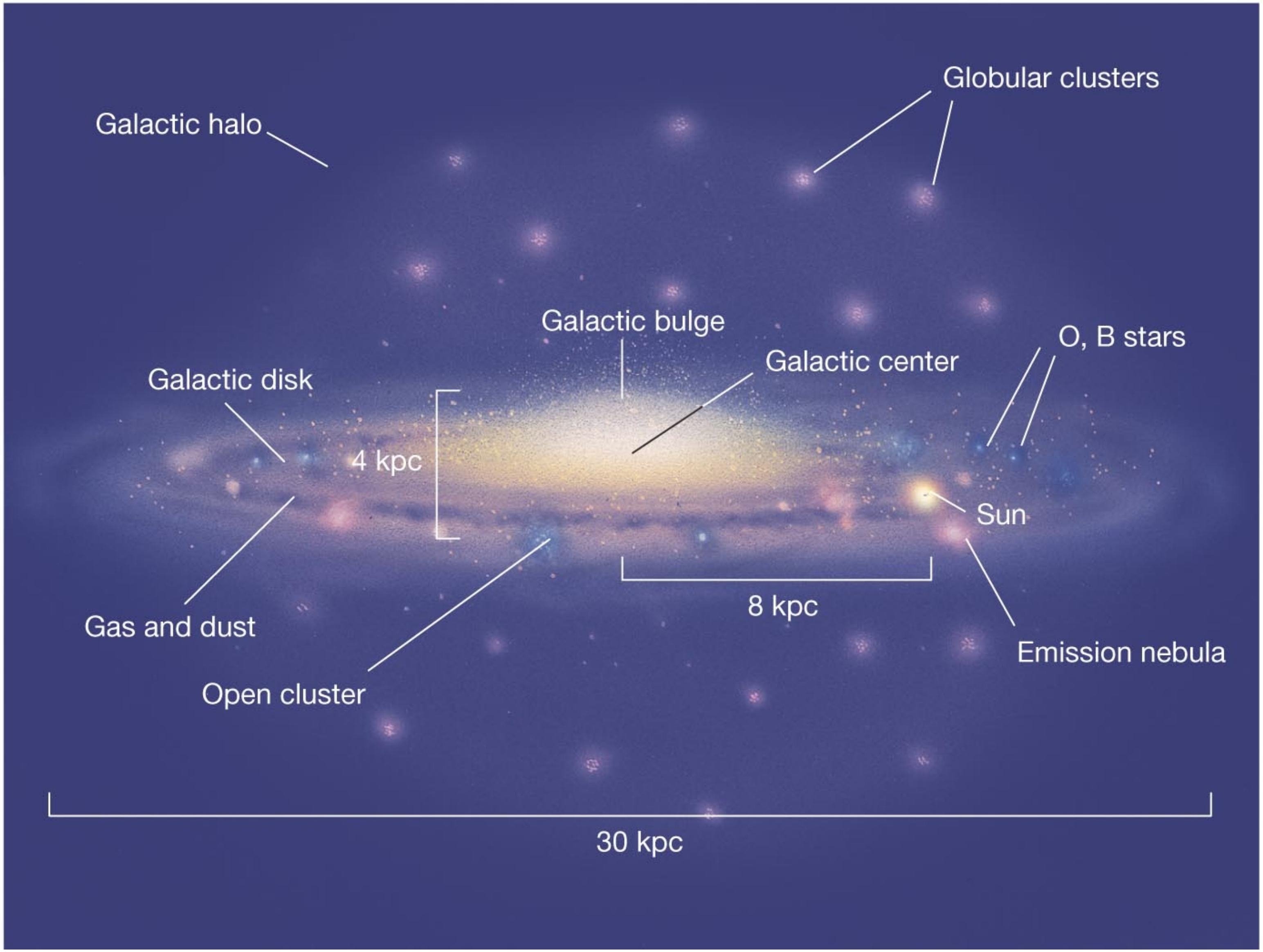
"Face on" **"Edge on"**

23.1 Our Parent Galaxy

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

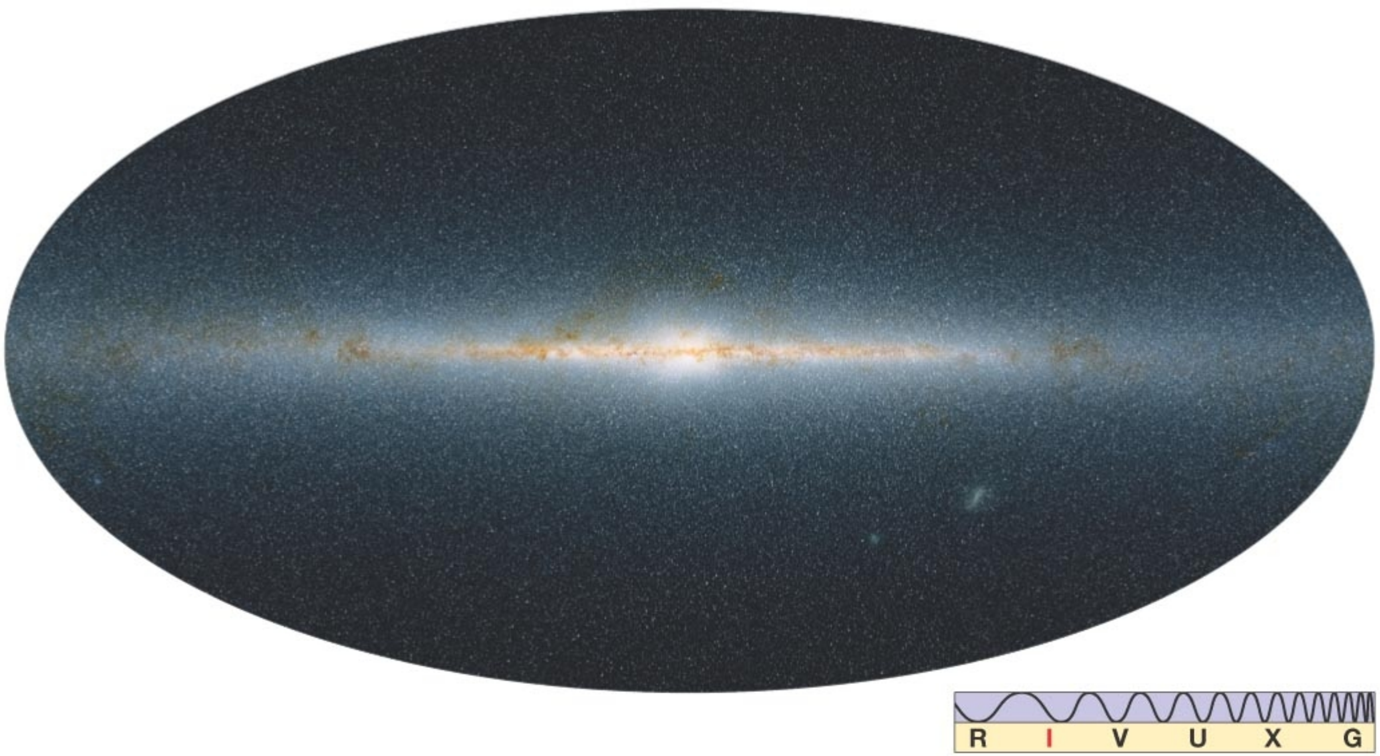
23.3 Galactic Structure

The various parts of our **galaxy**:



23.3 Galactic Structure

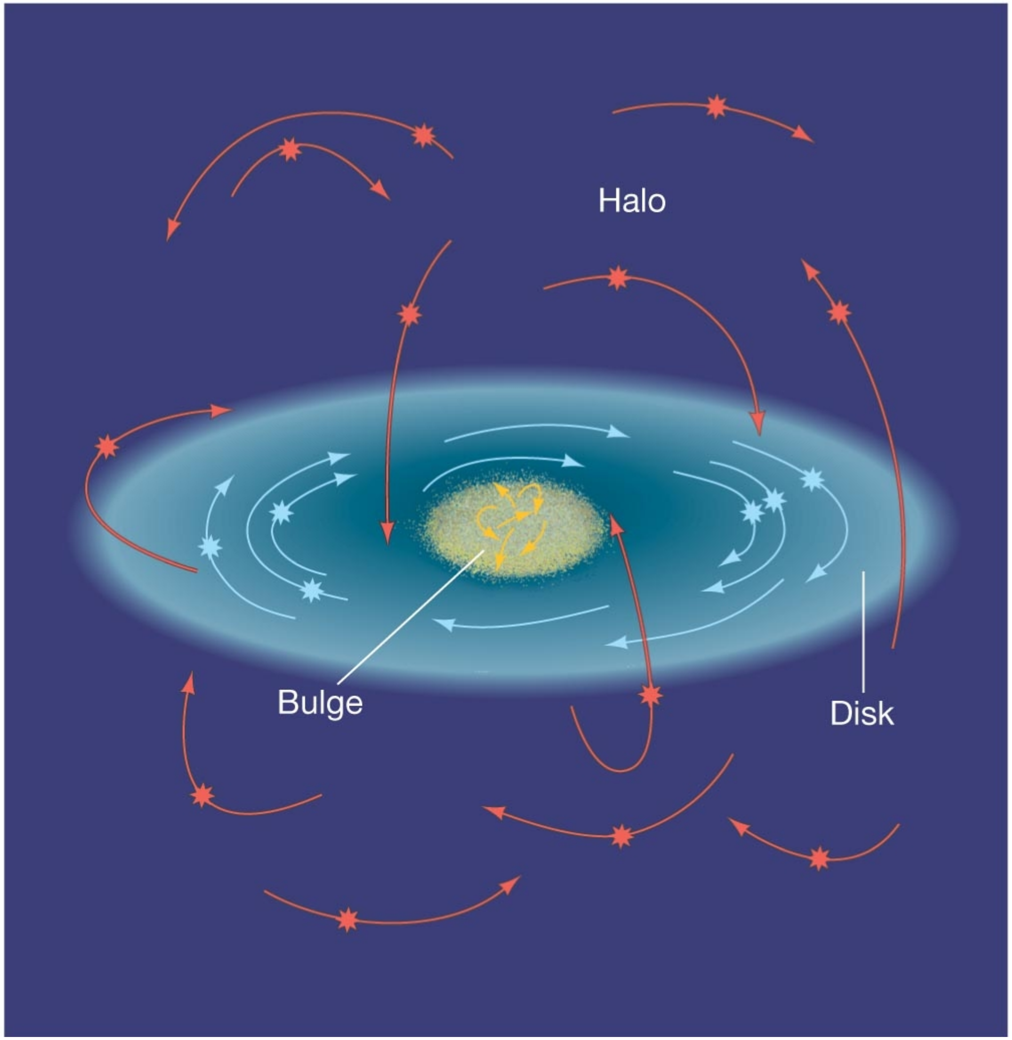
This **infrared** view of our galaxy shows a much clearer view of the galactic center than the visible-light view does, as infrared is not absorbed as much by gas and dust.



23.3 Galactic Structure - kinematics

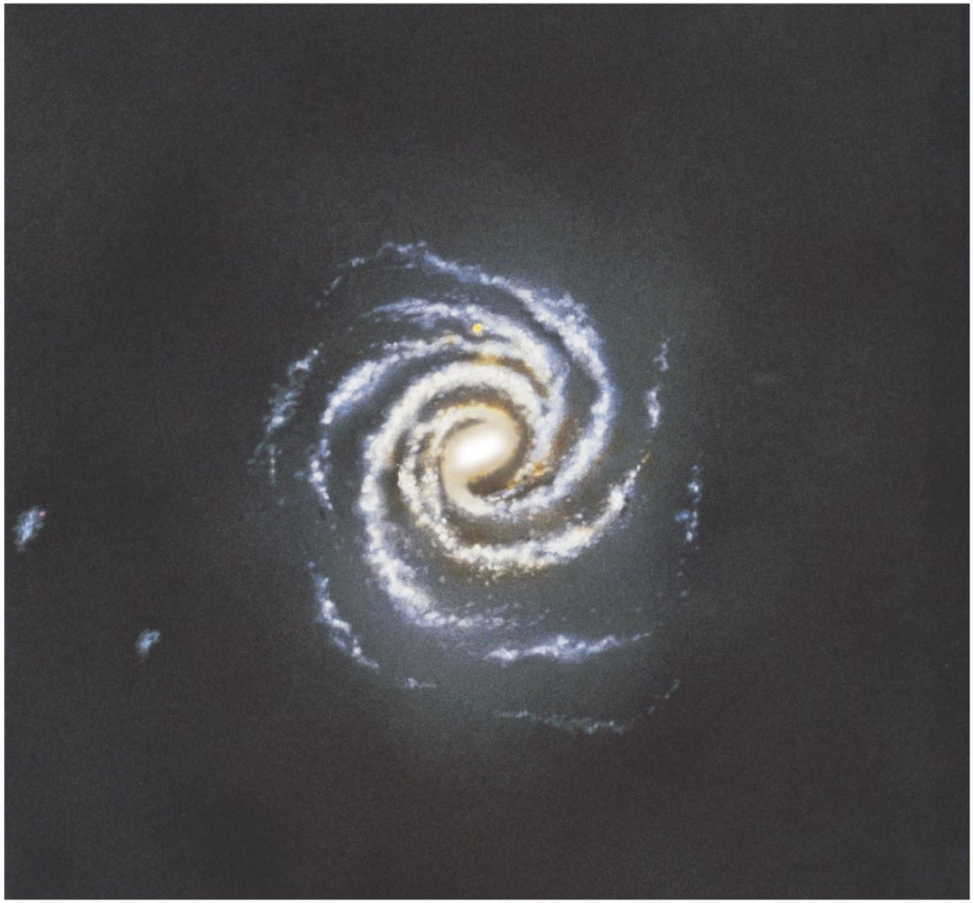
Stellar orbits in the **disk** move in a common plane (*co-planar*) and in the same direction (clockwise).

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



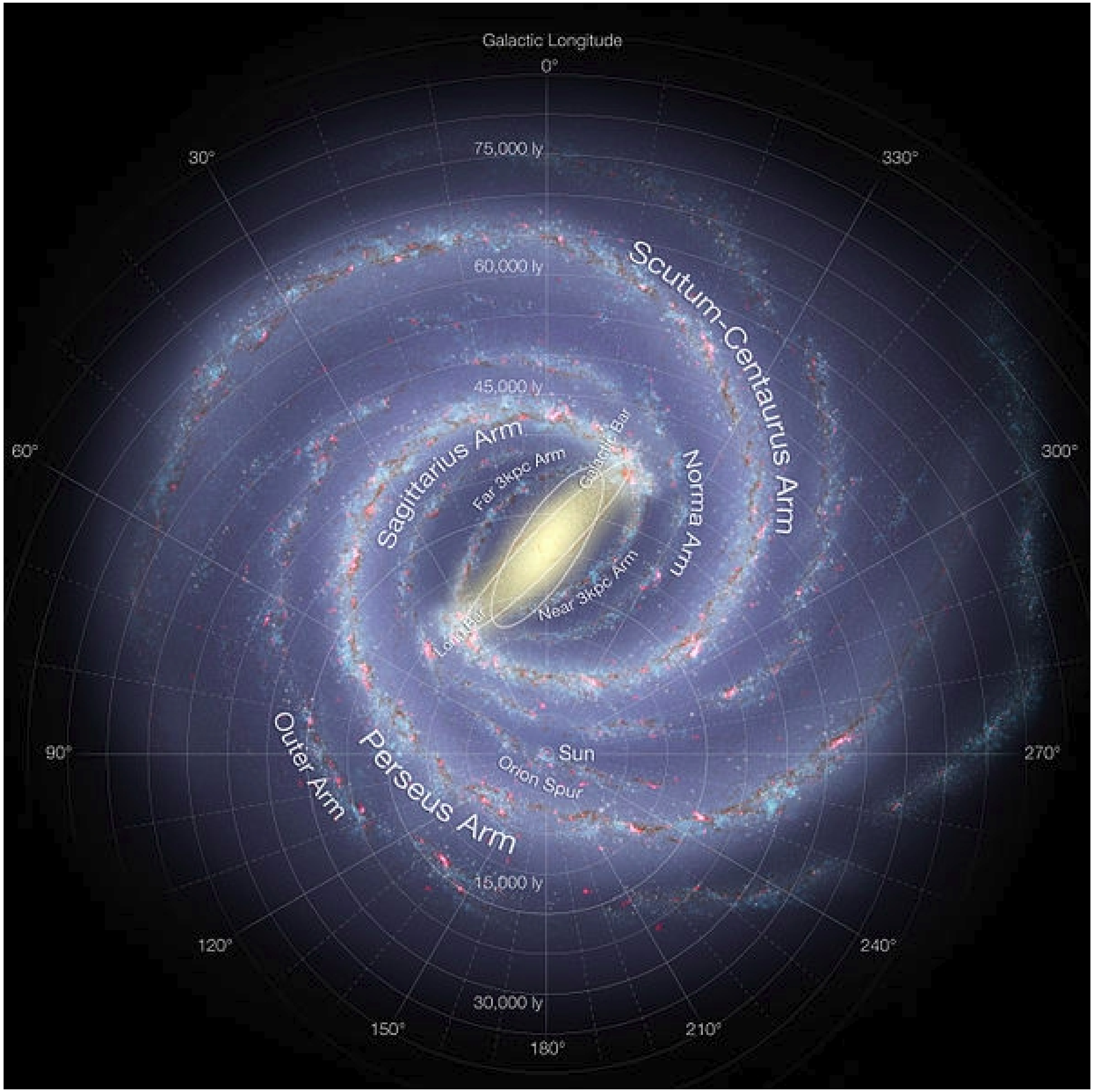
23.5 Galactic Spiral Arms

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



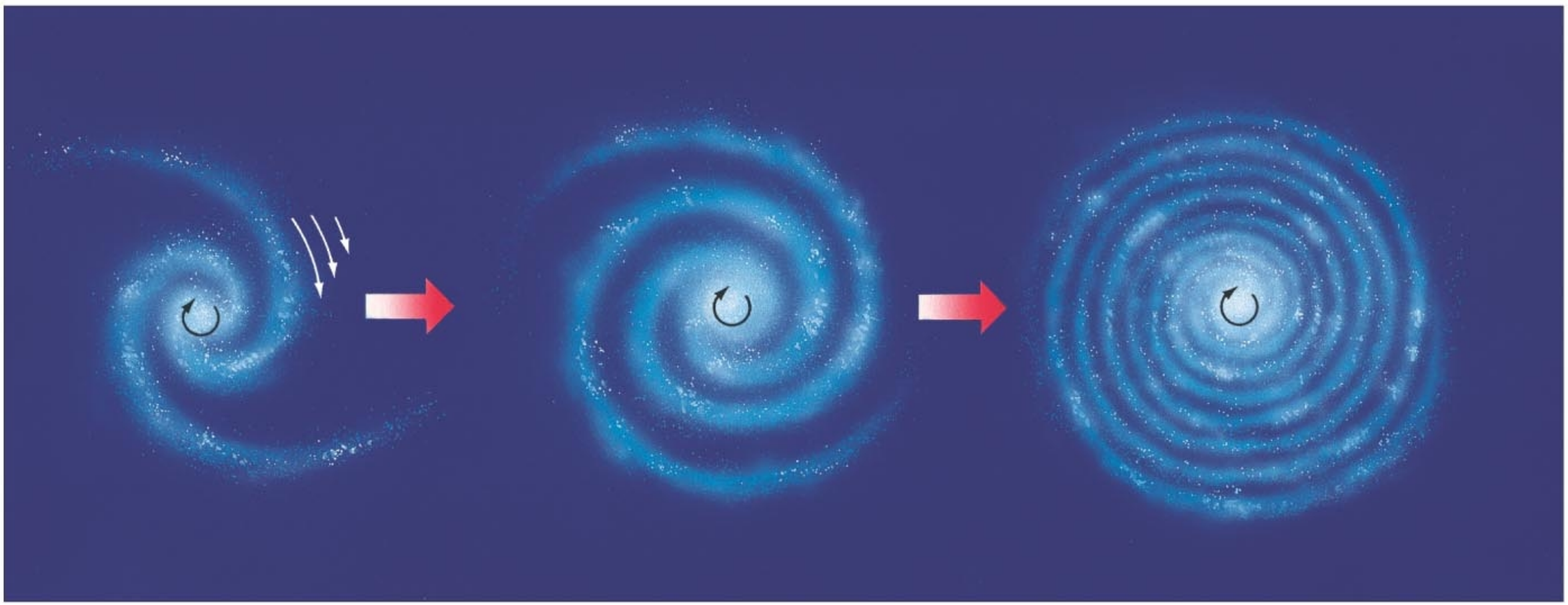
30 kpc

23.5 Galactic Spiral Arms



23.5 Galactic Spiral Arms

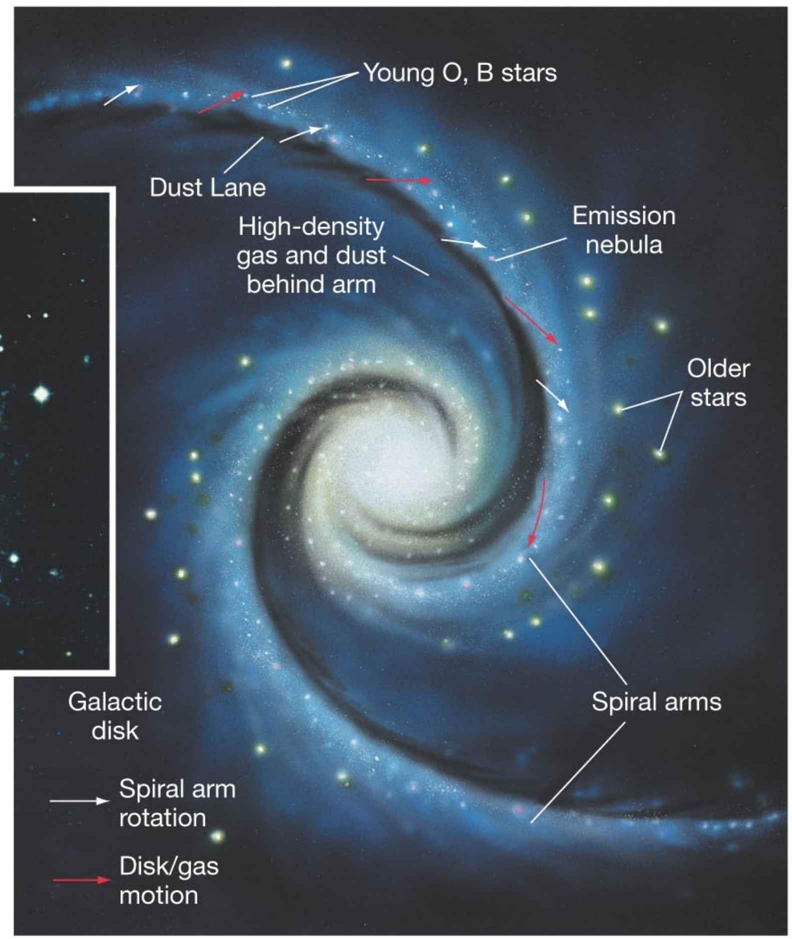
The spiral arms cannot rotate exactly as the stars do; they would "wind up". (The "winding problem".)



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.

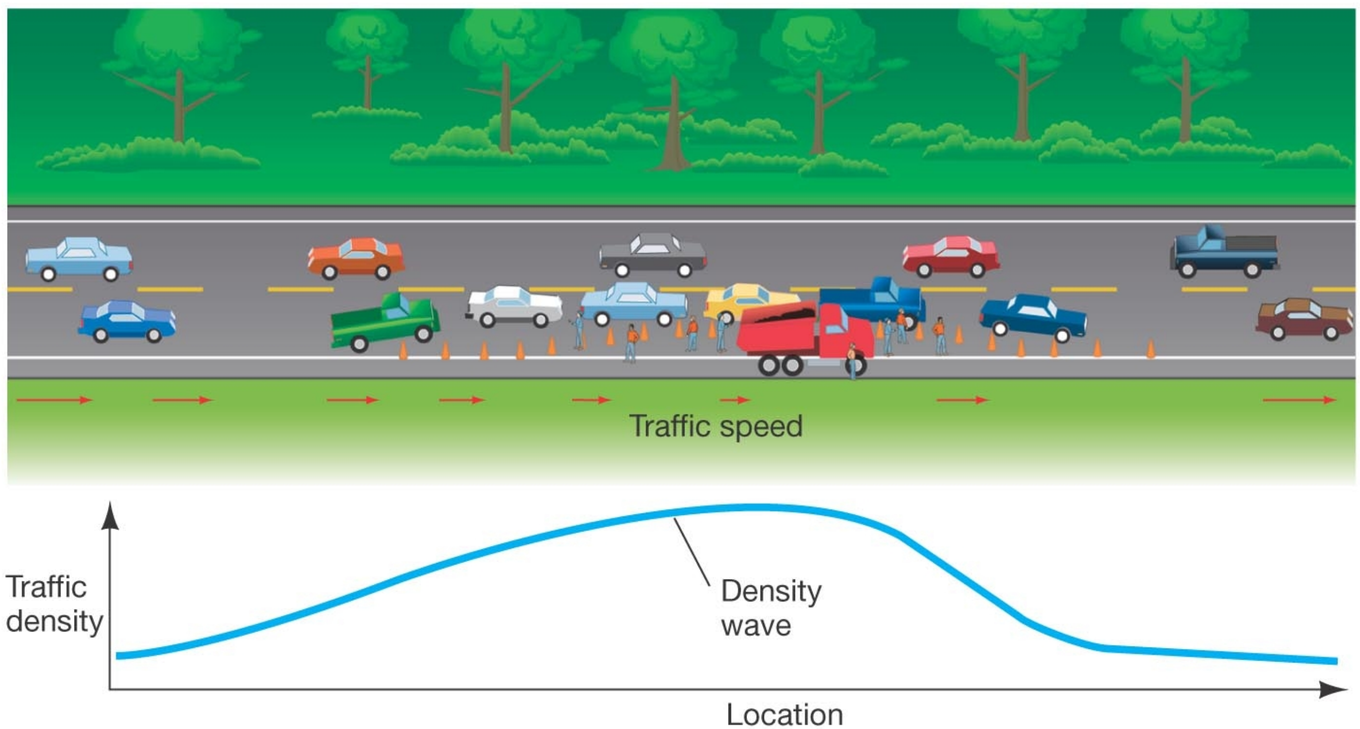
23.5 Galactic Spiral Arms

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:



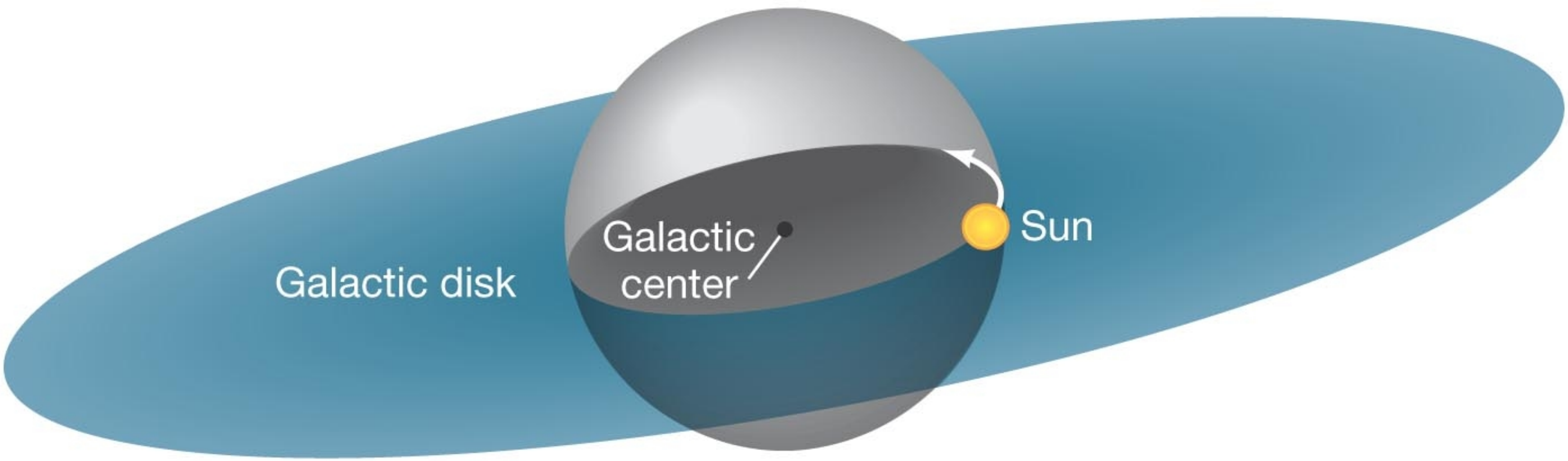
Discovery 23-2: Density Waves

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:



†Strictly speaking, this is true when the mass distribution is spherical.

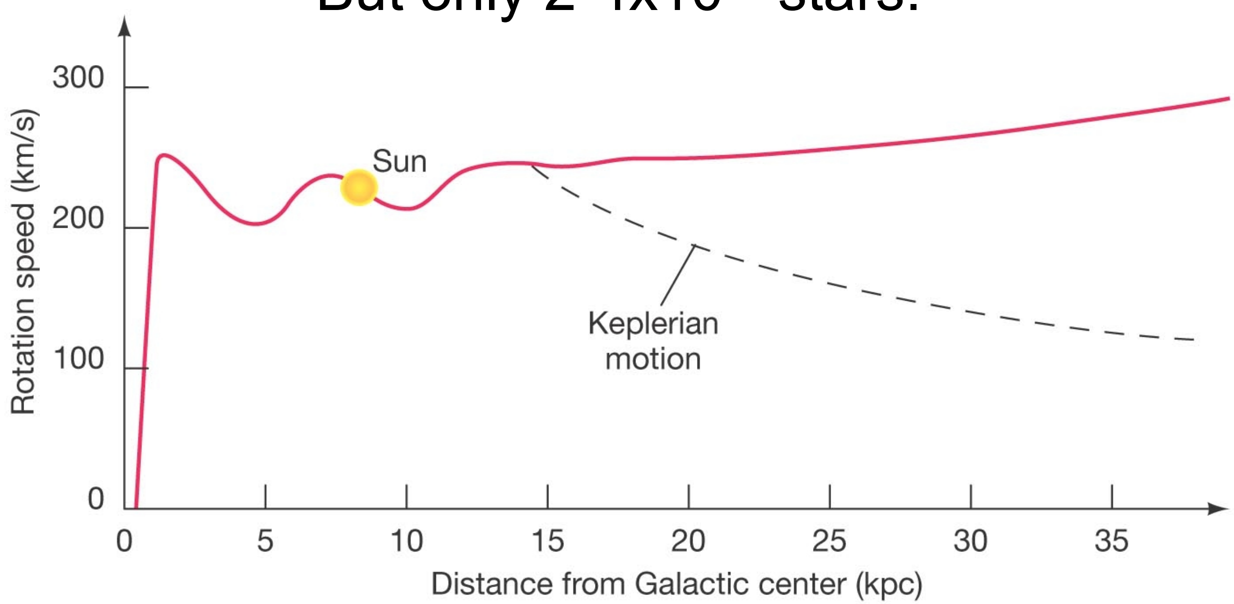
23.6 The Mass of the Milky Way Galaxy

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

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

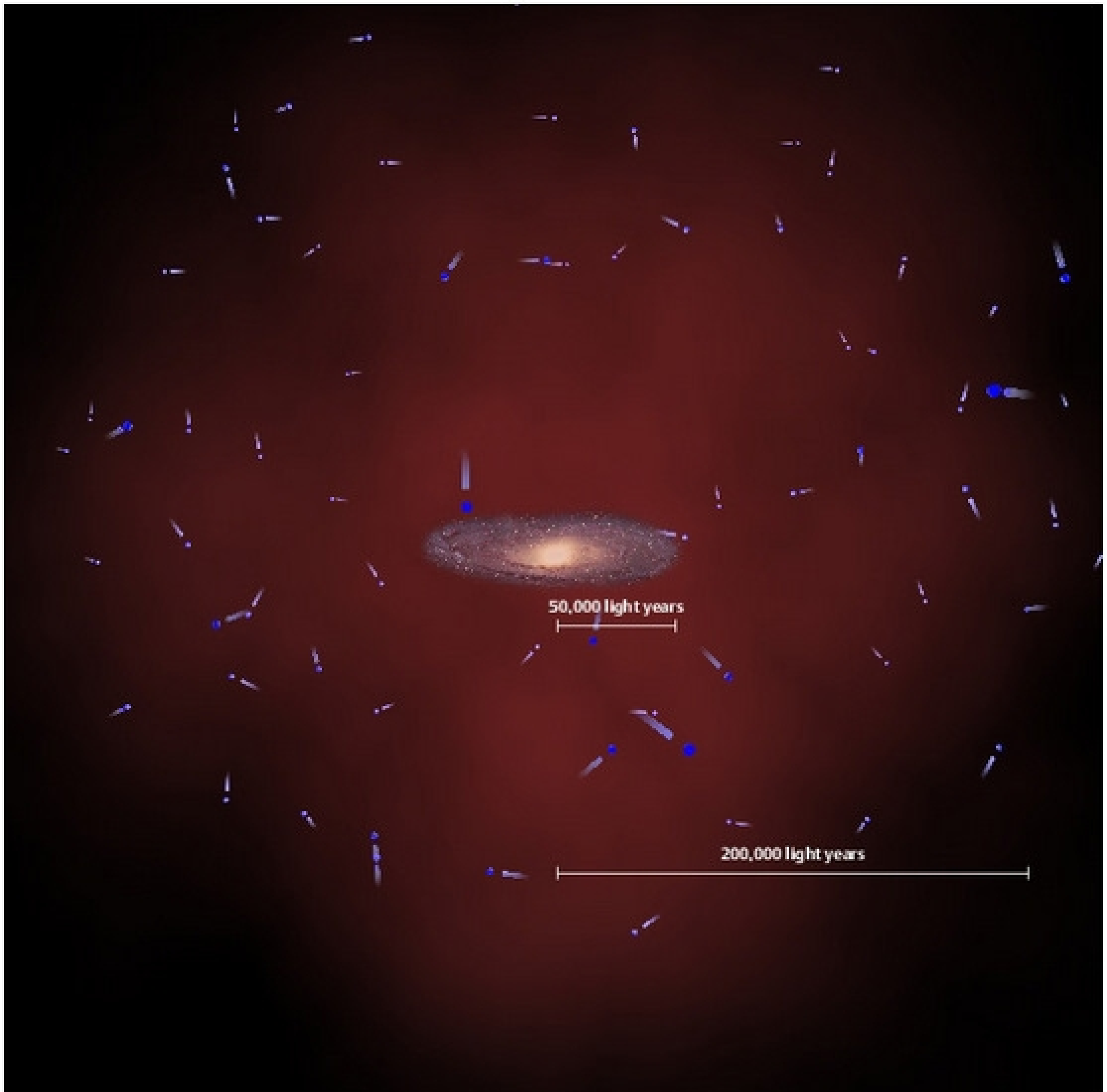
$M_{enclosed}(r=20kpc) \sim 8\text{-}15\times10^{11}\ M_\odot$

But only $2\text{-}4\times10^{11}$ stars.



23.6 The Mass of the Milky Way Galaxy

The MW has a dark matter halo!

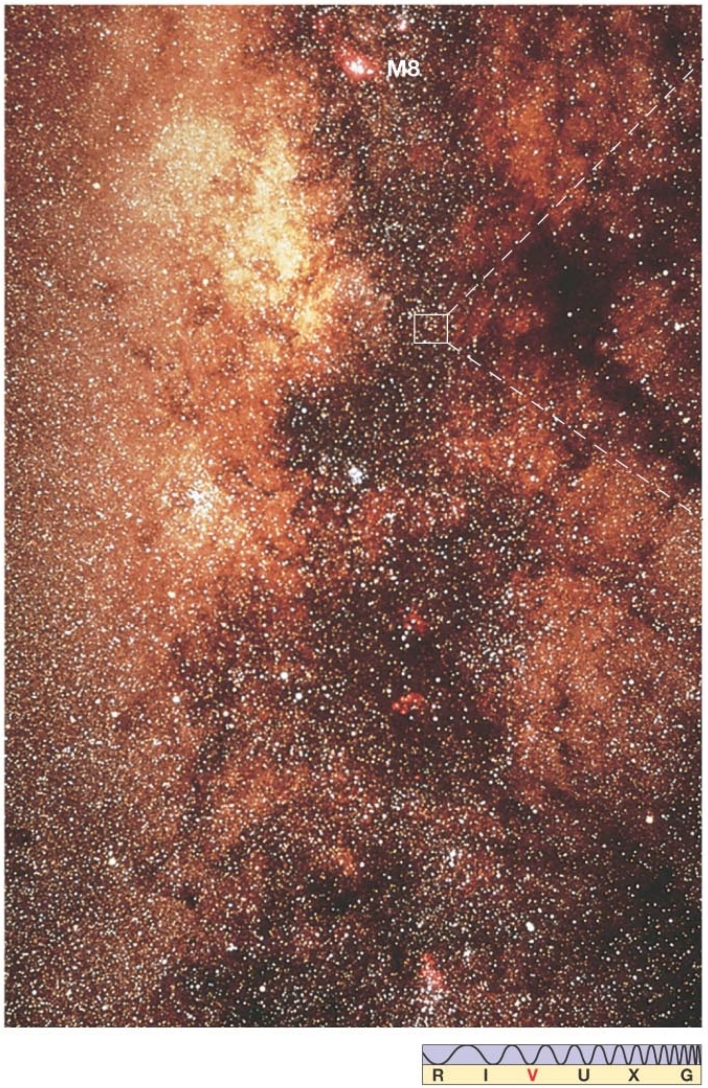


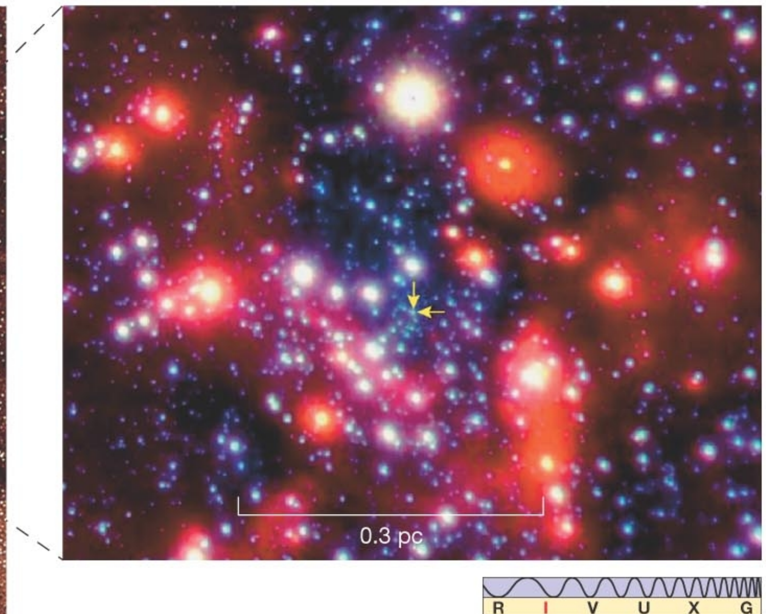
Candidates:

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

WIMPS:
- Axions, neutrinos, unknown

23.7 The Galactic Center

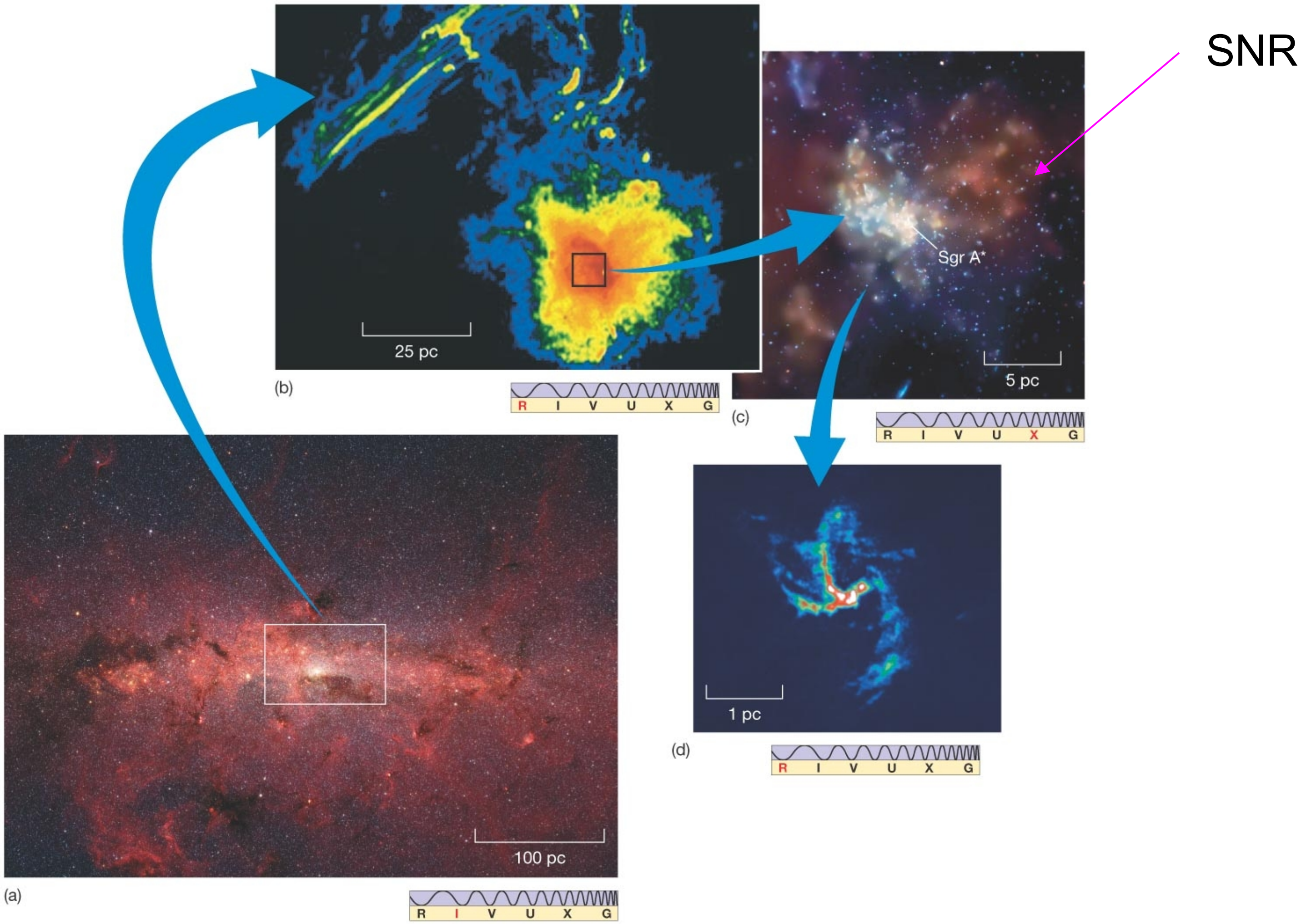




Two views toward the galactic center.

23.7 The Galactic Center

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



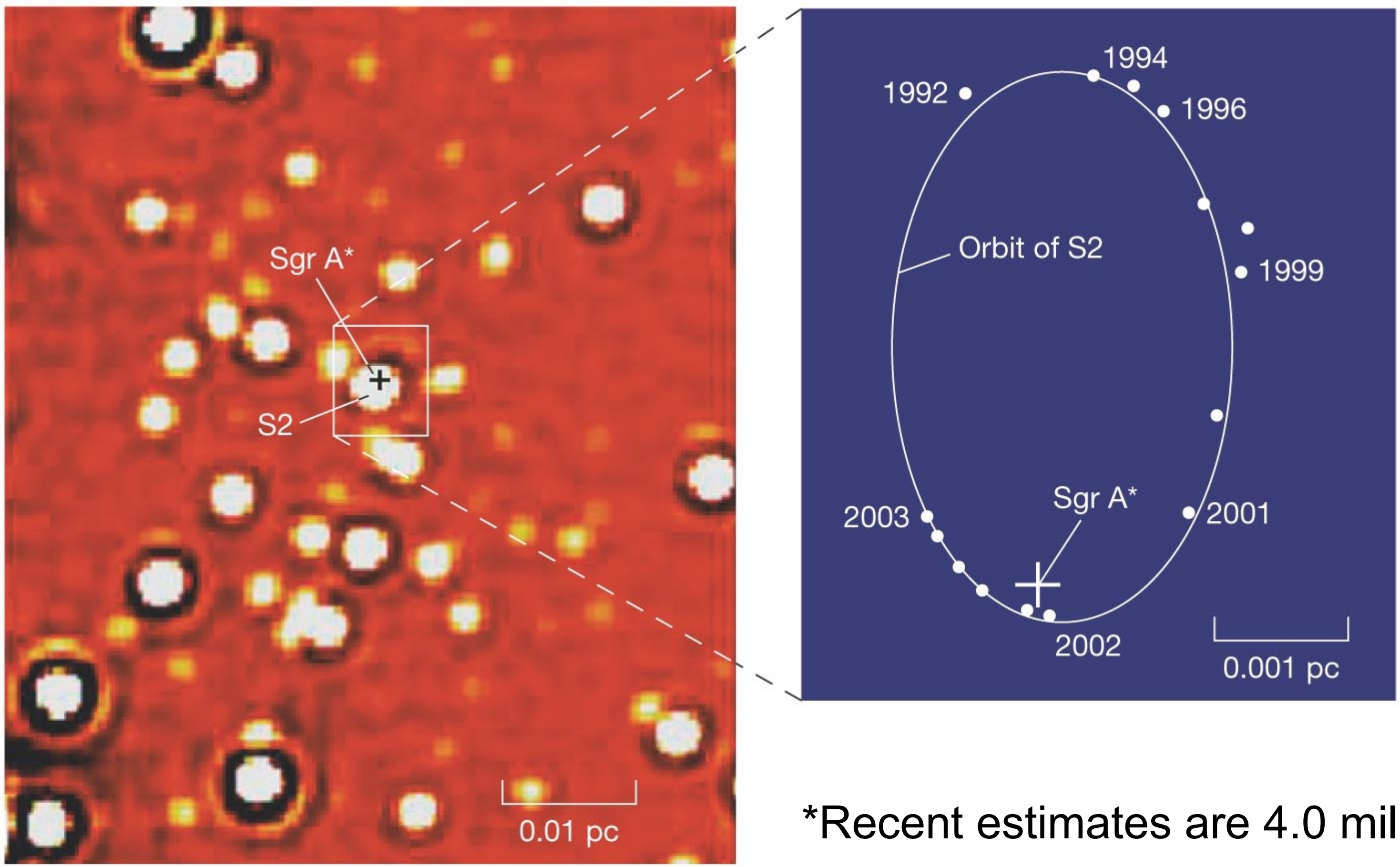
23.7 The Galactic Center

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 $M_\odot$)

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.

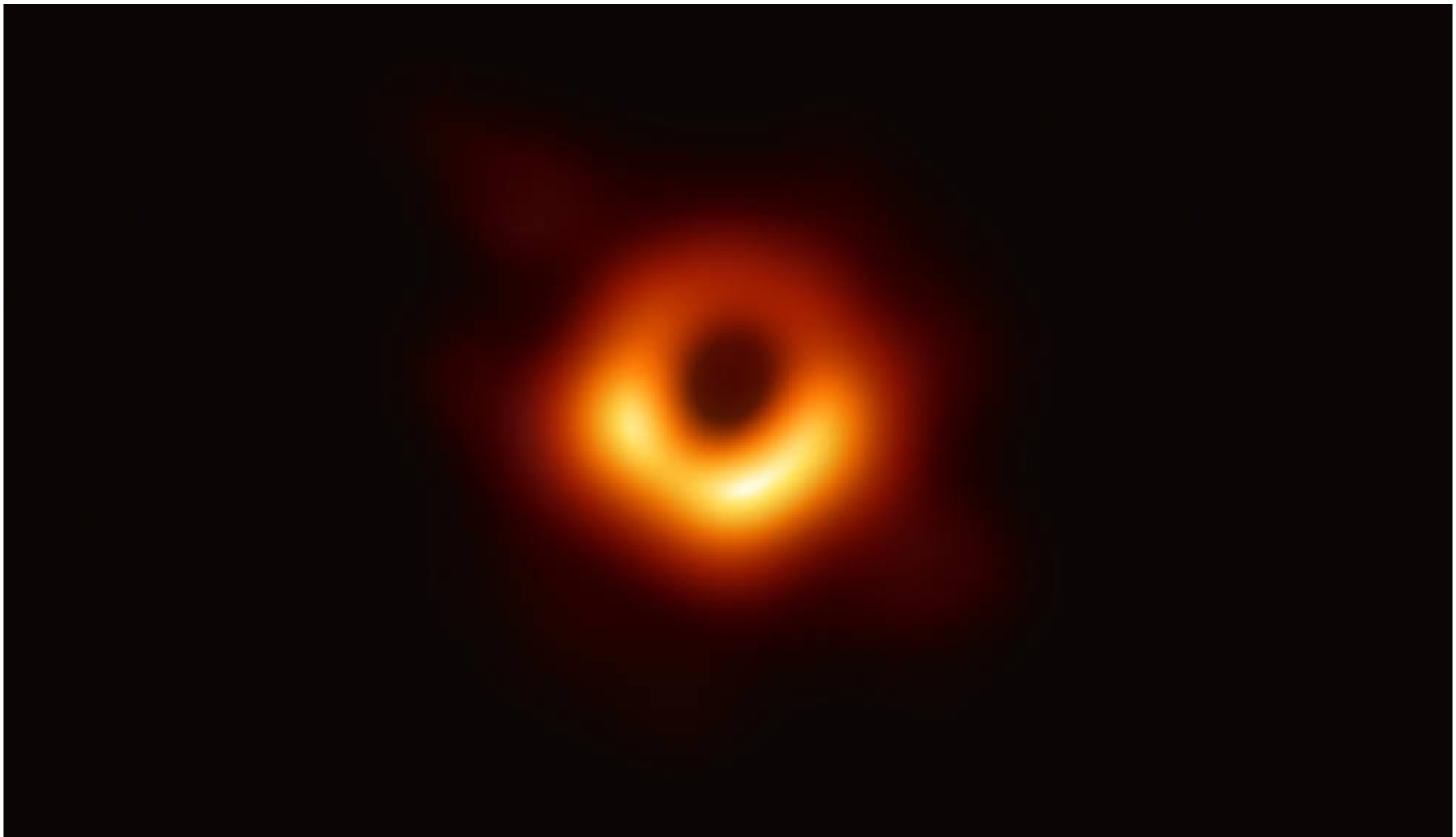


*Recent estimates are 4.0 million

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

23.7 The Galactic Center

Using a radio interferometer the size of the Earth, the *Event Horizon Telescope*, we obtained this image of the SMBH in the MW on May 2022. R_{schwz}~1.2×10^{7} km, ~10^{10} m/2.7×10^{20}m→ 7μas



Units of Chapter 23

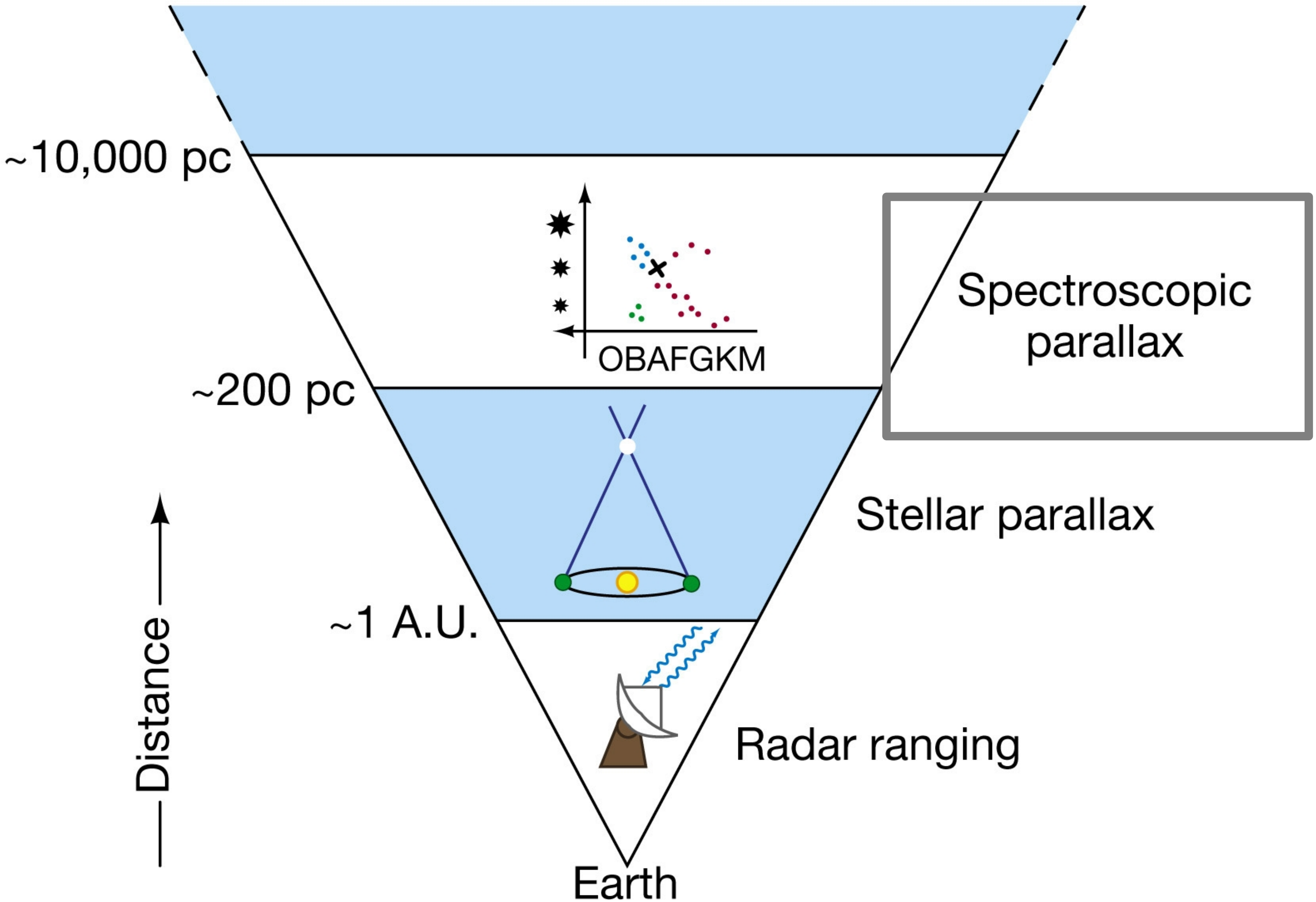
1. Our Milky Way Galaxy

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 Candle” or “Beasts of a kind” concept
c) Herschel's (& Kaptyn's) star counts
d) “Intrinsic” Variable Stars
e) Other Distance Indicators

Figure 17-17
Stellar Distances



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*.)

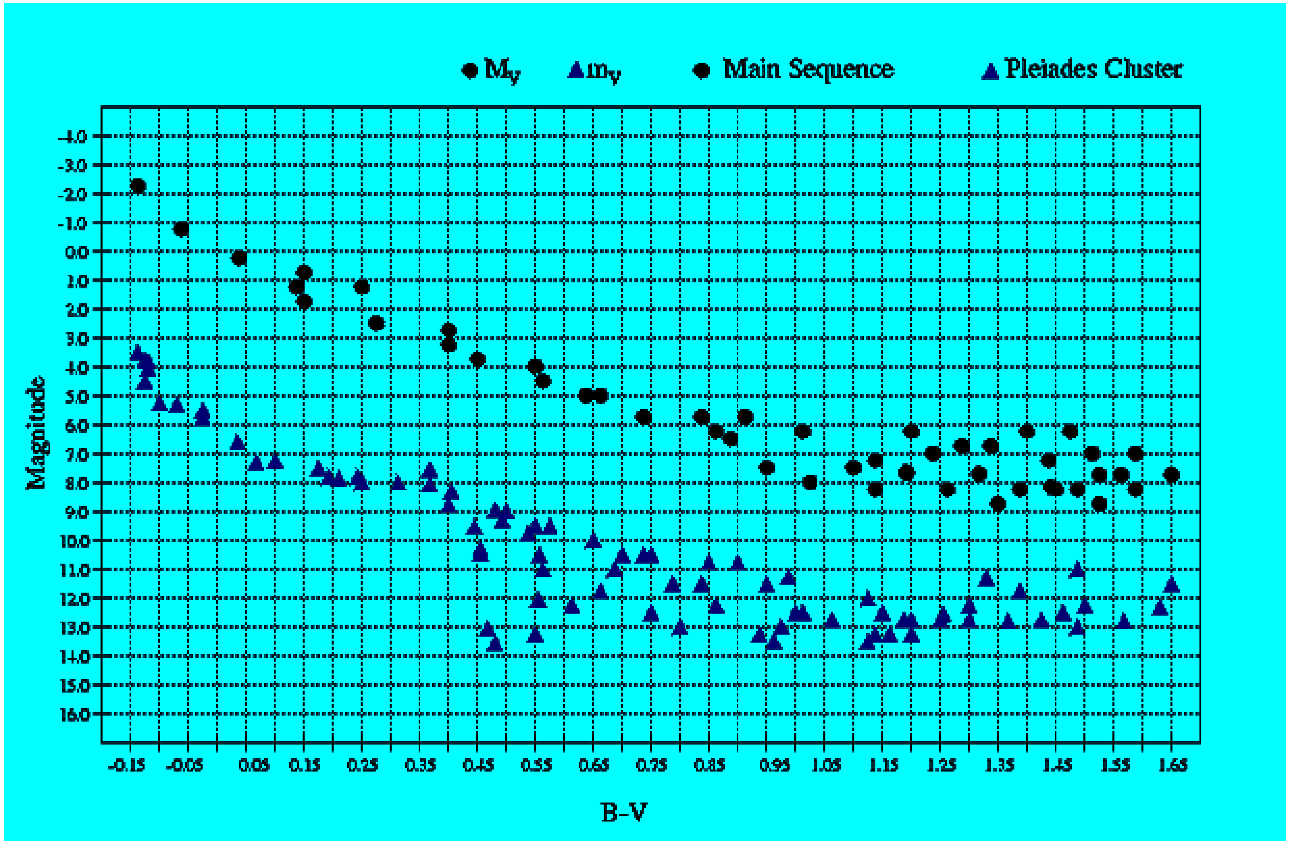
d) Theory behind interpretation of measurement.

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

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")**

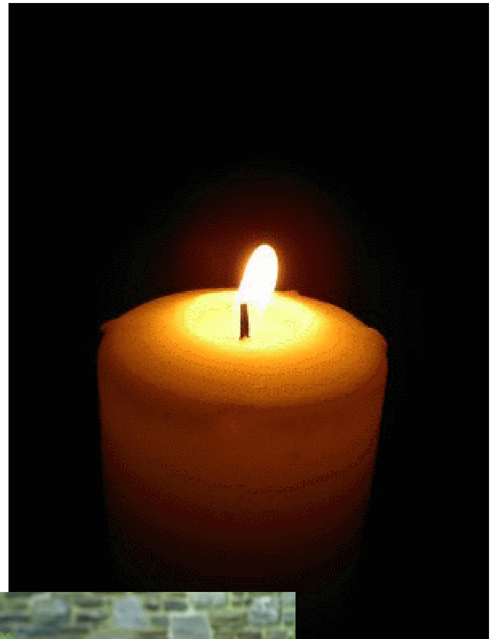


m-M=5log(d/10)

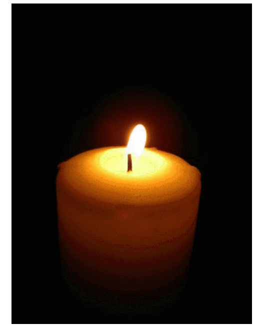
Spec Parallax assumes that all stars of a given type (e.g., A0V) have the same M. (That makes A0V stars "standard candles").

“Beasts of a kind”: standard candles/yardsticks

Nearby

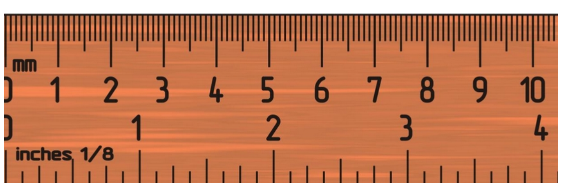


Far away



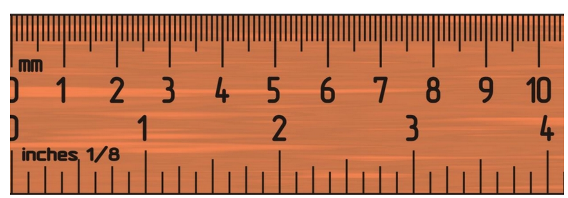
Flux, $F \sim 1/d^2$

Nearby



Far away

Angle, $\theta \sim 1/d$



Distance indicators

Variable stars:

Novae, supernovae, cepheids, RR Lyrae

Other Standard Candles:

- ***Brightest blue stars, Brightest red stars***
- ***Tip of the red giant branch (TRGB)***
- ***Planetary nebula luminosity function (PNLF)***
- ***globular cluster luminosity function (GCLF)***

Standard Yardsticks:

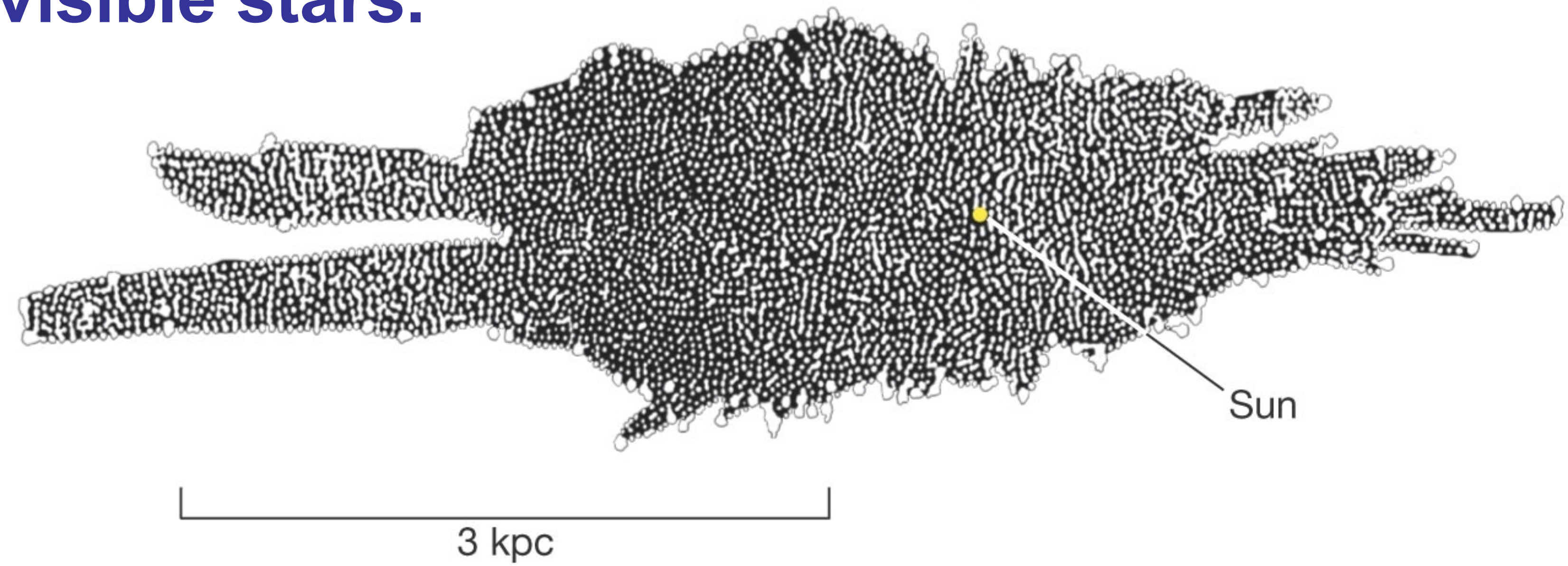
- ***Open Clusters, Globular Clusters, HII regions,***
- ***Size of galaxies of specific types***

Other techniques:

- ***Eclipsing Binaries, spectro. parallax, stel. Parallax,***
- ***Globular cluster spatial distribution***
- ***Trig parallax using radio interferometry! (2009)***

23.2 Measuring the Milky Way

One of the first attempts to **measure** the Milky Way was done by W. Herschel (c. 1790) using visible stars.



Assumptions:

1. star number density uniform out to edge
2. his telescope would reveal all stars

He was wrong on both counts!

23.2 Variable stars & distances

Basic types of variables:

1) Extrinsic variables: eclipsing binaries

2) Cataclysmic variables: novae, supernovae.

3) Intrinsic variables - pulsating regularly: RR Lyrae stars and Cepheids - very good for distances!

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

Henrietta Leavitt: measured Cepheids in the Large and Small Magellanic Clouds. Discovers a Period-Luminosity relationship!

23.2 Variable stars & distances

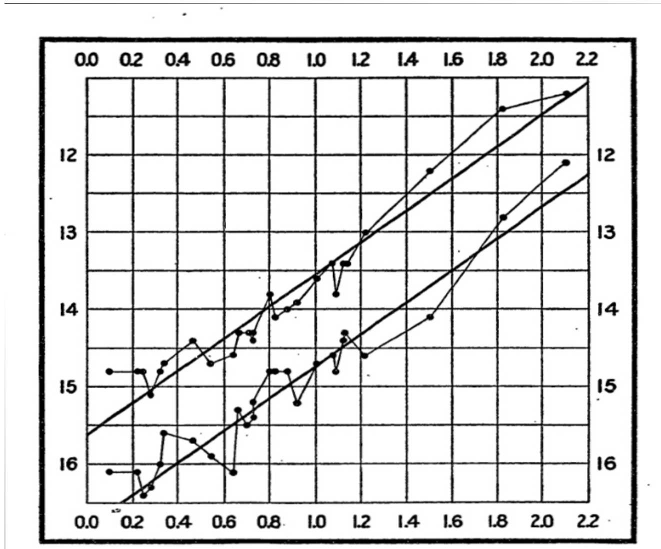
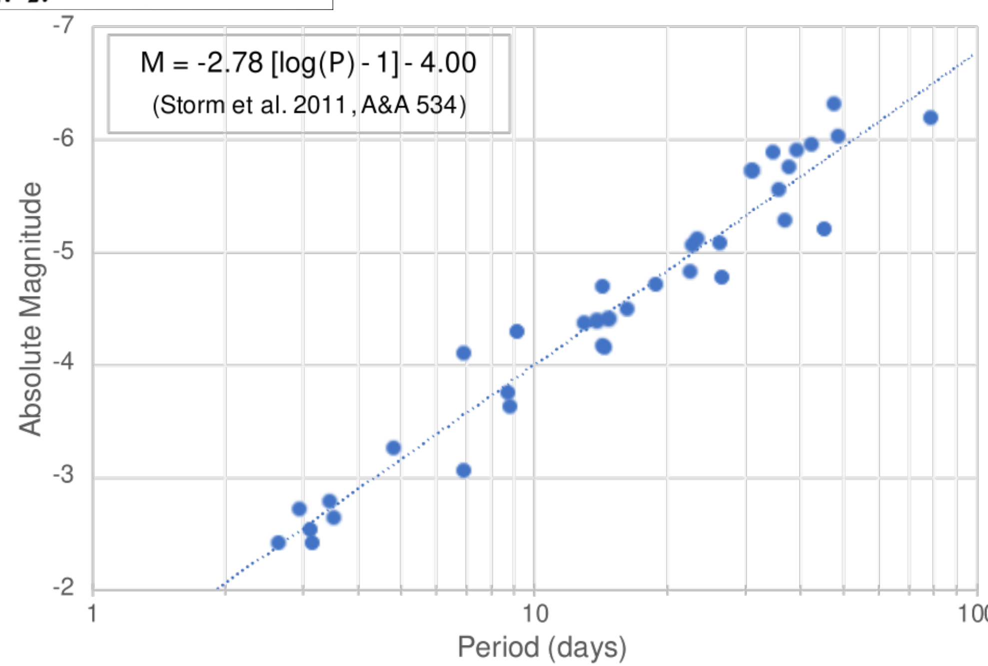


FIG. 2.

Relative magnitude vs log of period for LMC (top) and SMC.

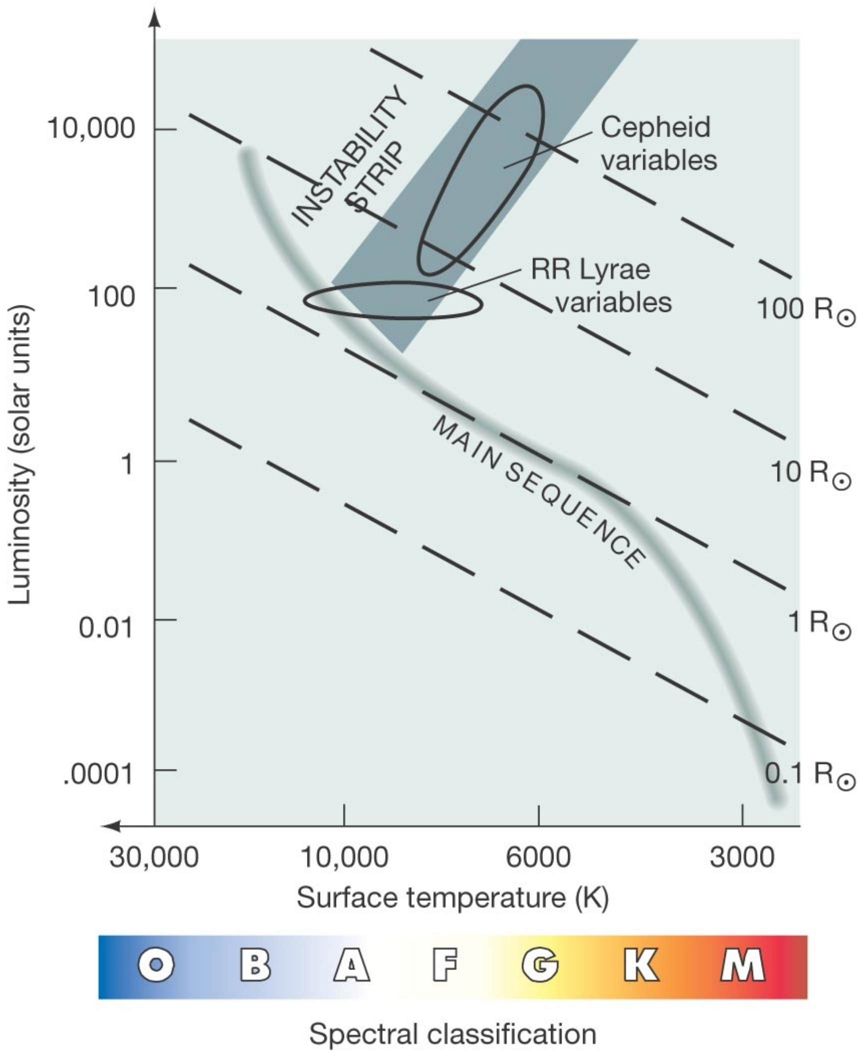
The period-luminosity relation for classical Cepheids.



23.2 Variable stars & distances

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

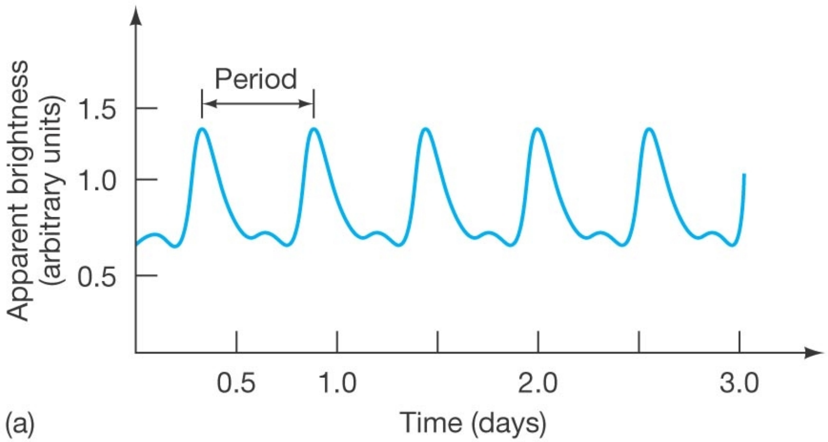
- HeII opacity-



23.2 Variable stars & distances

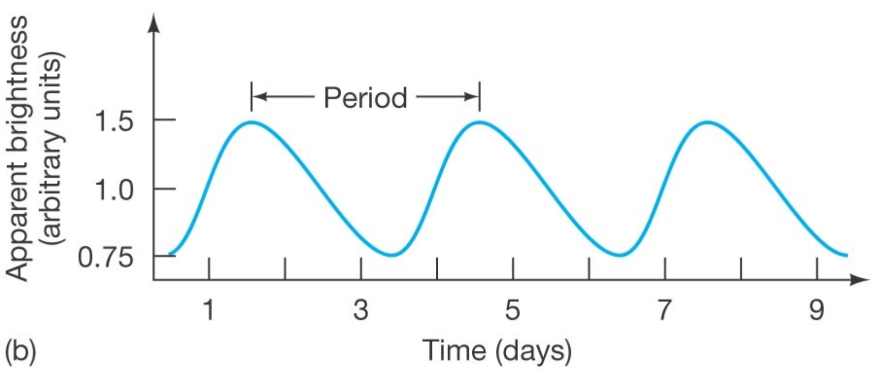
The **intrinsic variables** (like RR Lyrae and Cepheid) work best for distances!

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.



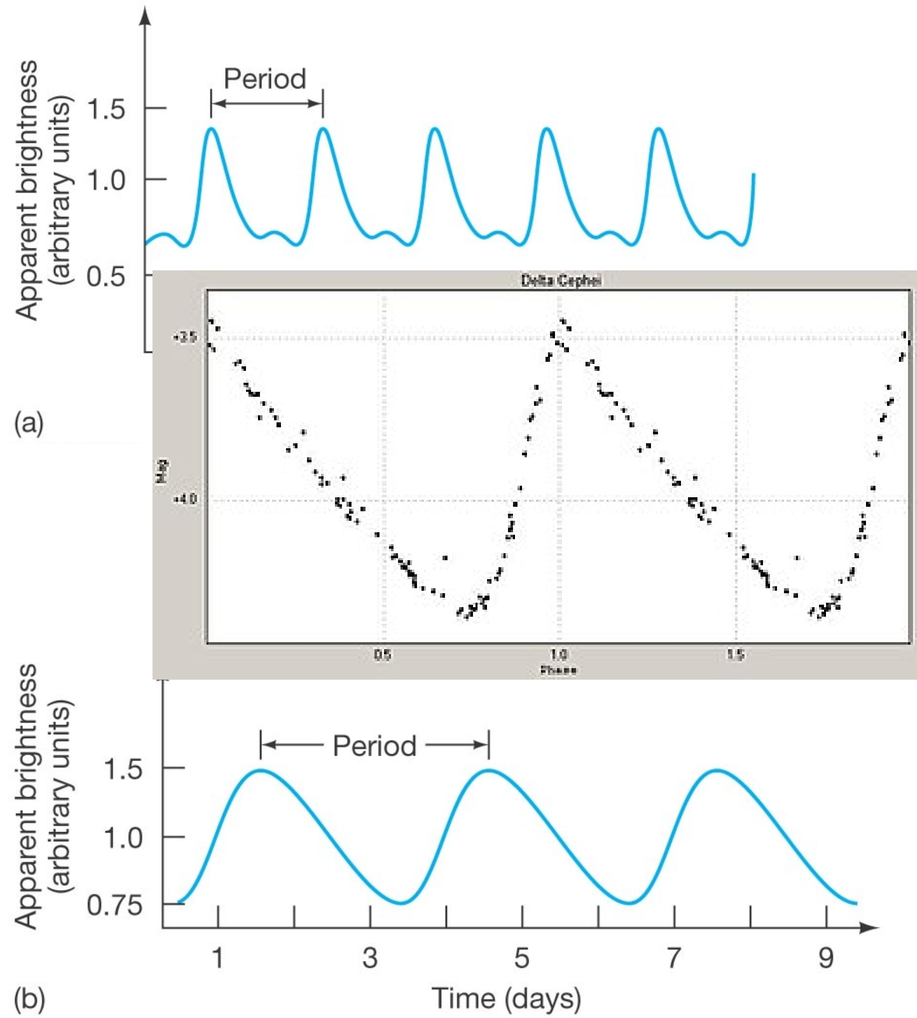
(b)

23.2 Variable stars & distances

The **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.

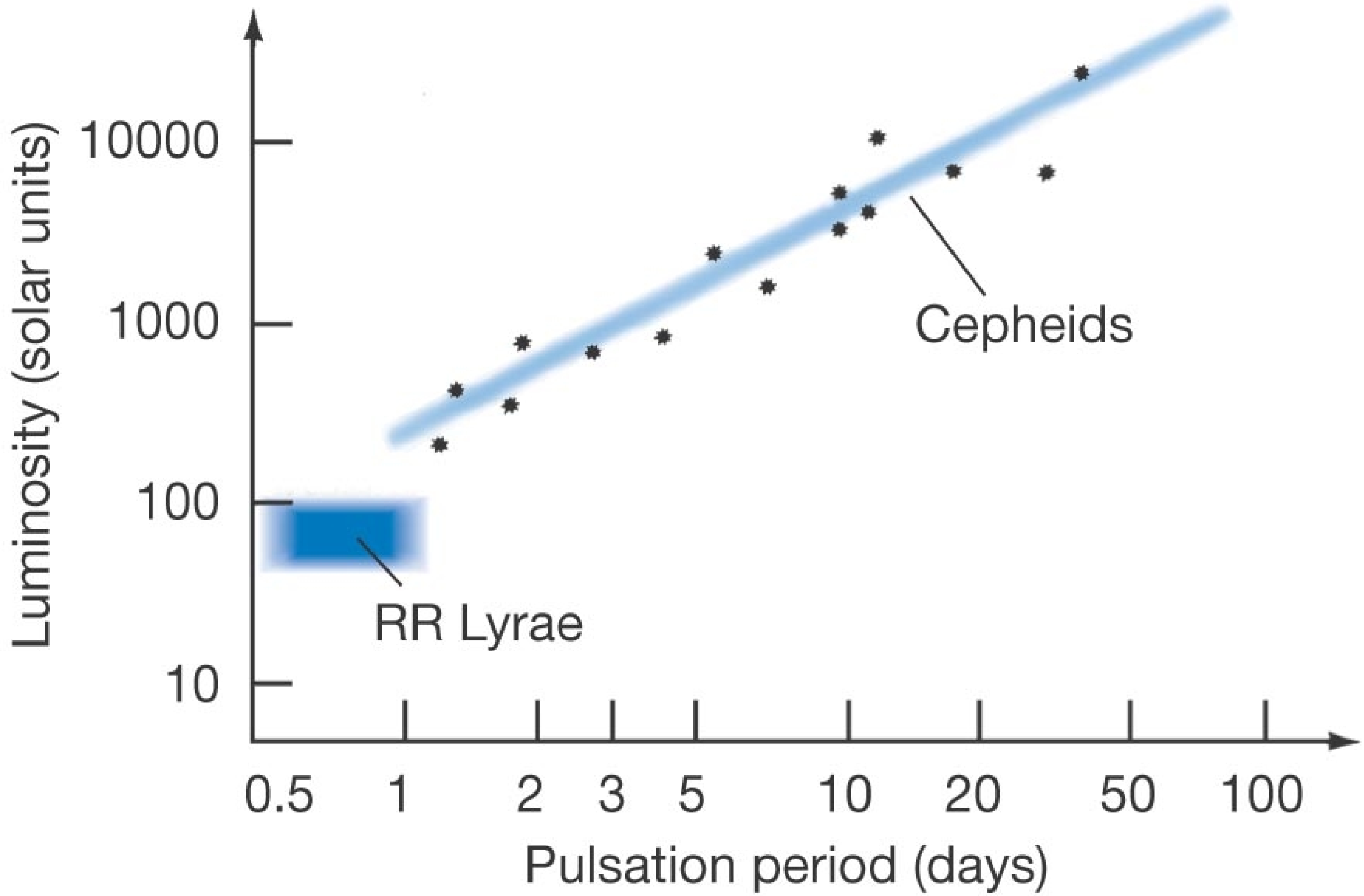
Light curve for Delta Cephei itself.
(5.36 day period):



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

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

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

Baade was a german-born astronomer who worked at Mount Wilson (Los Angeles) from 1931-1958.

*Recognized stellar populations in external galaxies

Pop. I ("like the Sun") have high metallicity, are located in disks of spirals (bluish regions), are young.

Pop. II have low metallicity, are located in the halo, bulge and globular clusters (reddish regions), are old.

Type I Cepheids are Pop. I. "Classical Cepheids"

- Found in galaxy disks and open clusters. P=1-100 days
- 4-10 $M_\odot$. 4 x (1.5 mag) more luminous than Type II.

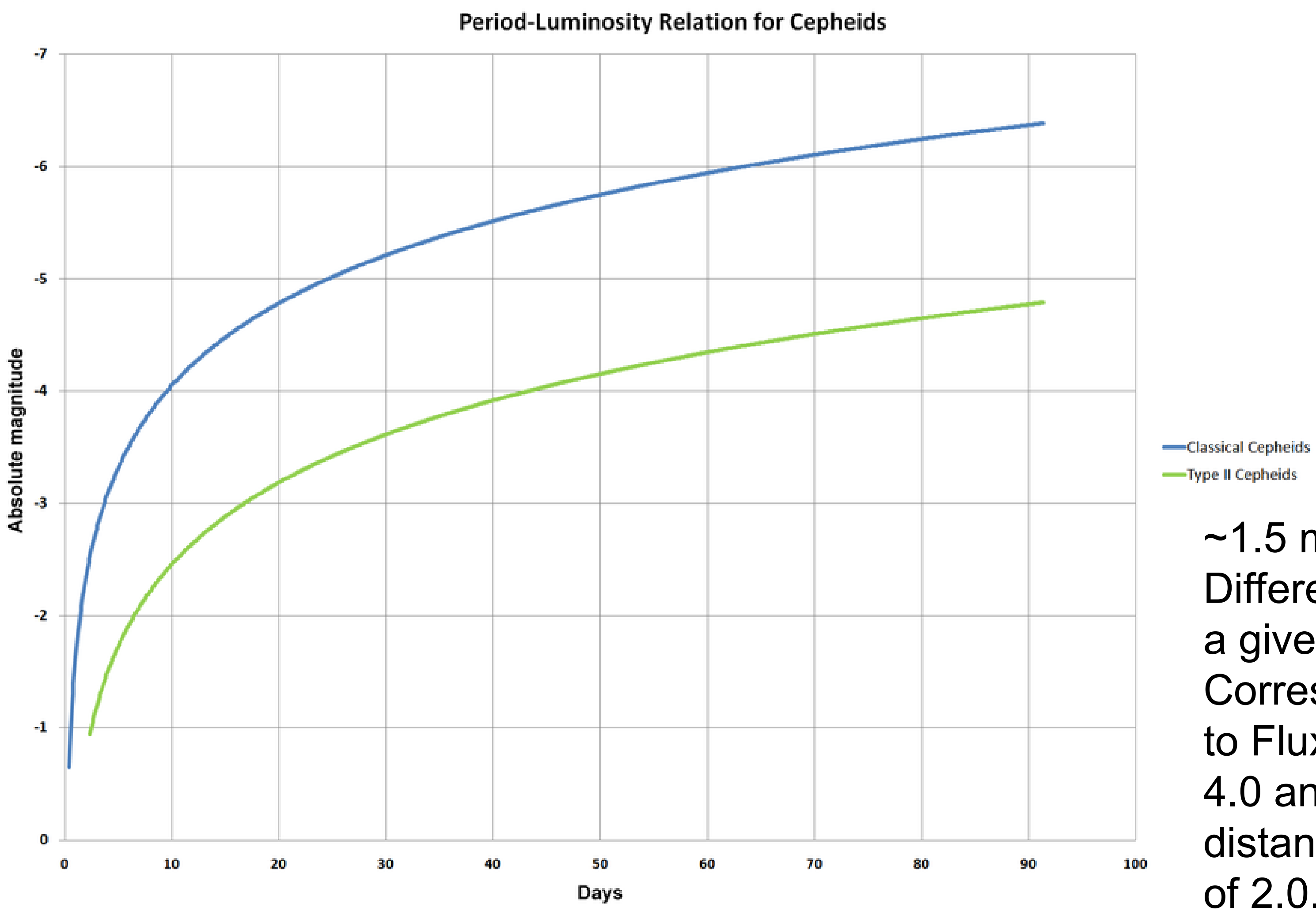
Type II Cepheids are Pop. II. "W Virginis stars"

- Found in globular clusters. P=1-100 days
- 0.4-0.6 $M_\odot$.

1952: he reports that two types of Cepheid exist. The Type I's in external galaxies were wrongly assumed to follow the Type II P-L relationship.

23.2 Variable stars & distances

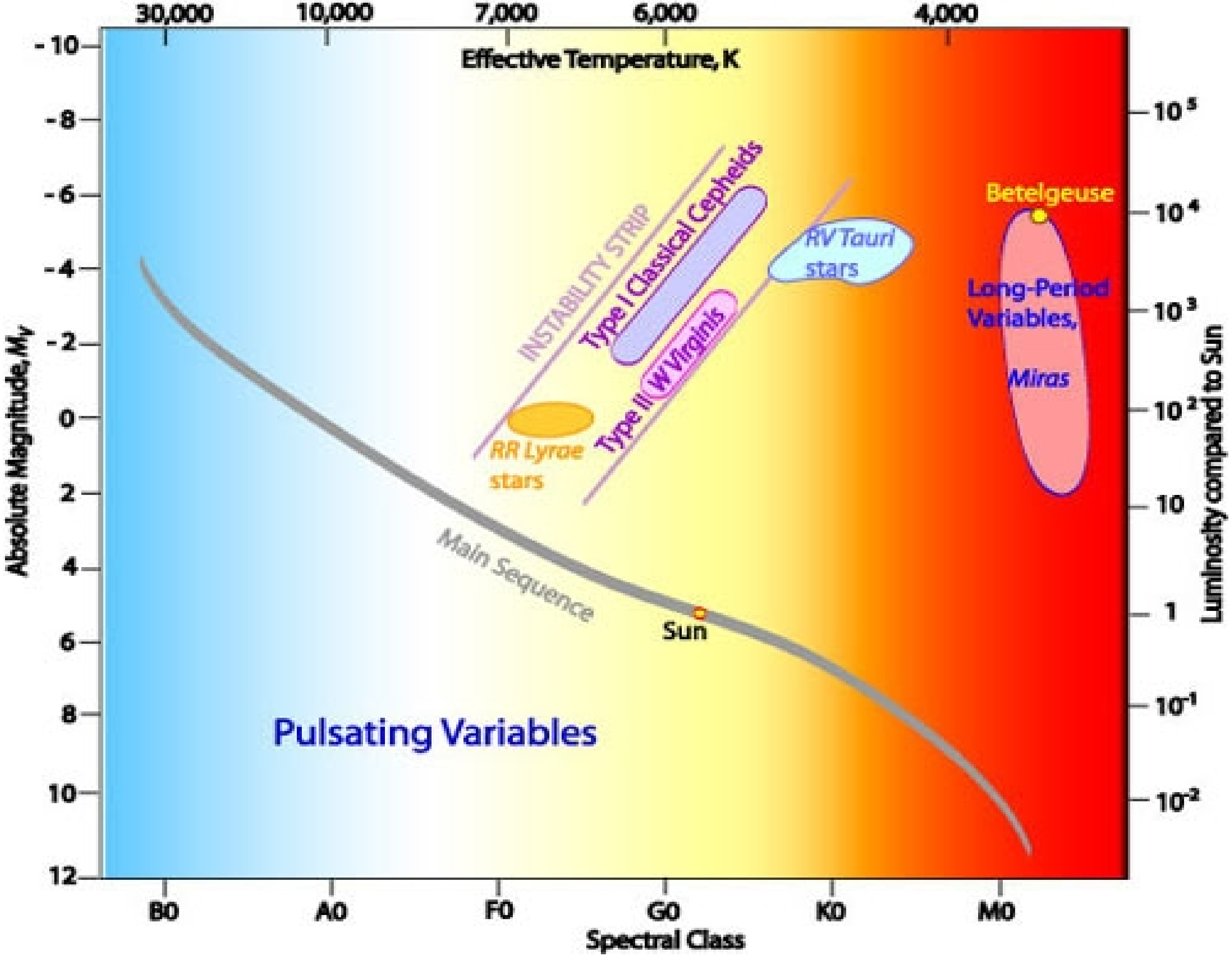
Here are the separate PL relations for Type I and Type II Cepheids.



~1.5 mag Difference at a given period. Corresponds to Flux ratio of 4.0 and a distance ratio of 2.0.

23.2 Variable stars & distances

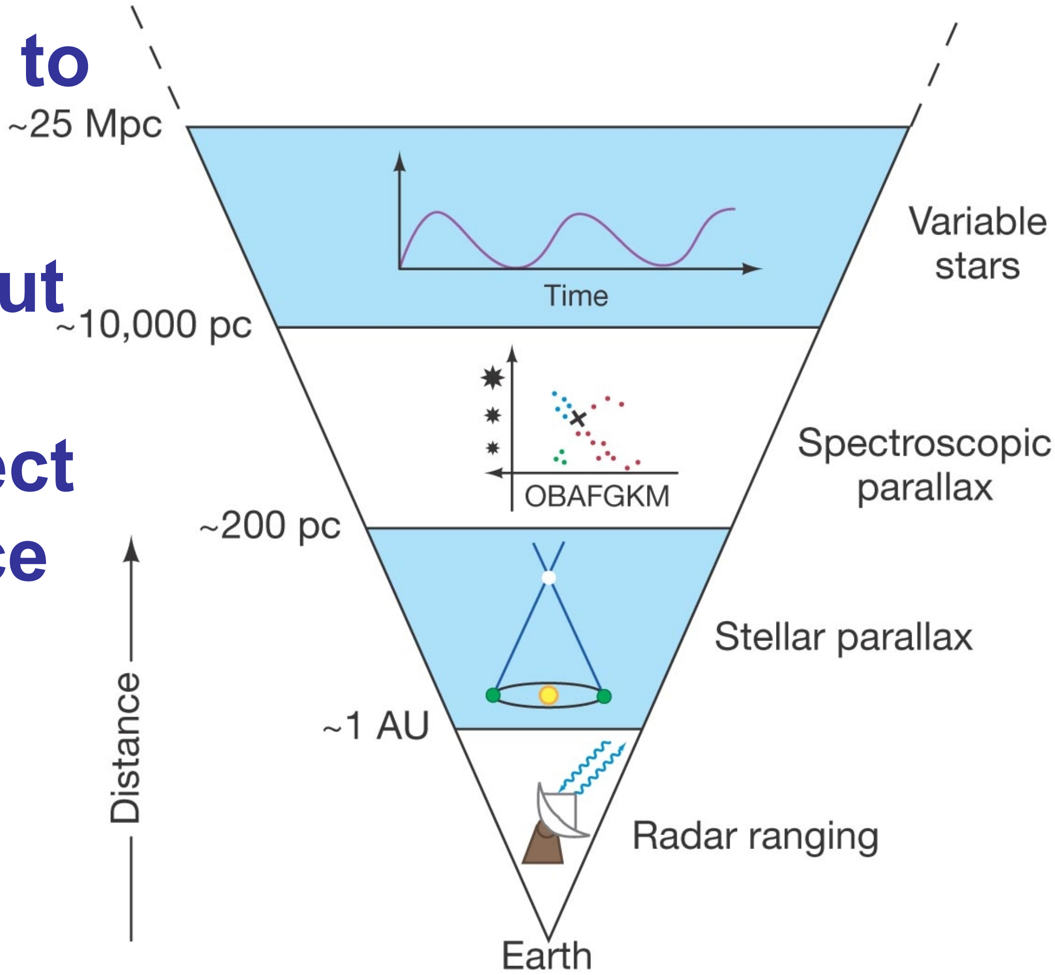
When it was realized that there was a fainter, population II version of the Cepheid, our model of the universe doubled in size.



23.2 Measuring the Milky Way

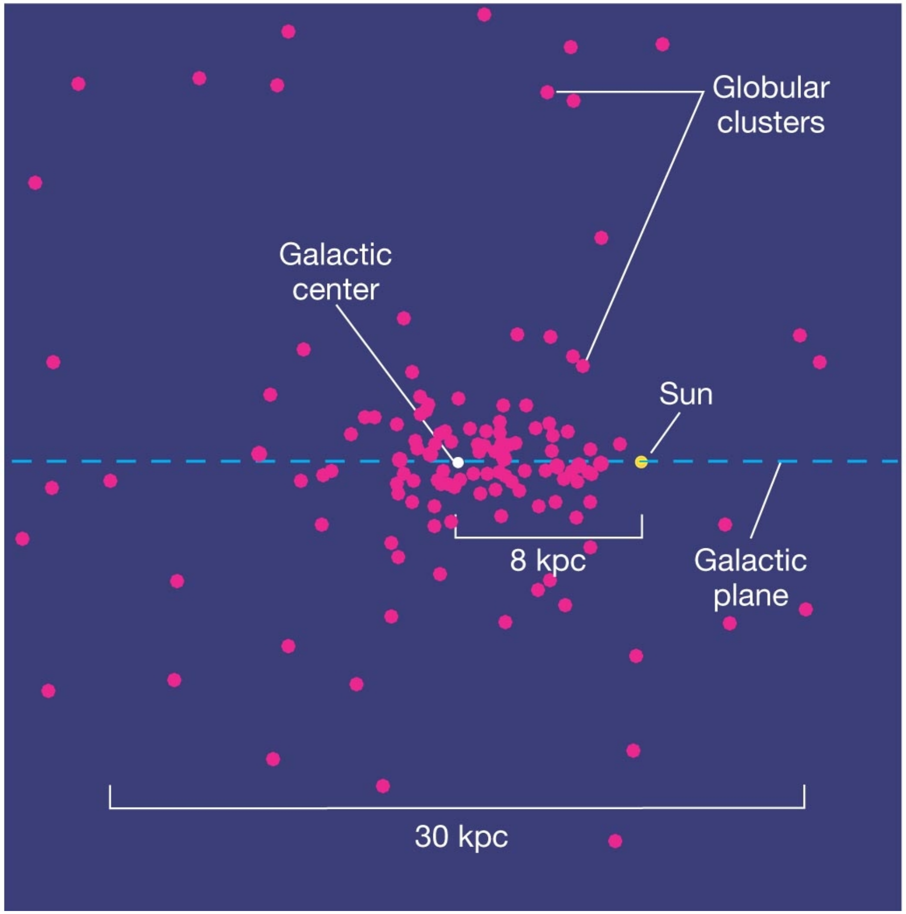
Our cosmic distance ladder now extends to 25 Mpc.

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 Nebulae in sky
   Zone of avoidance explained by Curtis
3) Novae in spiral nebulae
   Shapley mistook supernovae for novae. This made spiral neb-ulae 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
   Erroneous measurements of rotation made it seem impossible for the spiral nebulae to be far away.

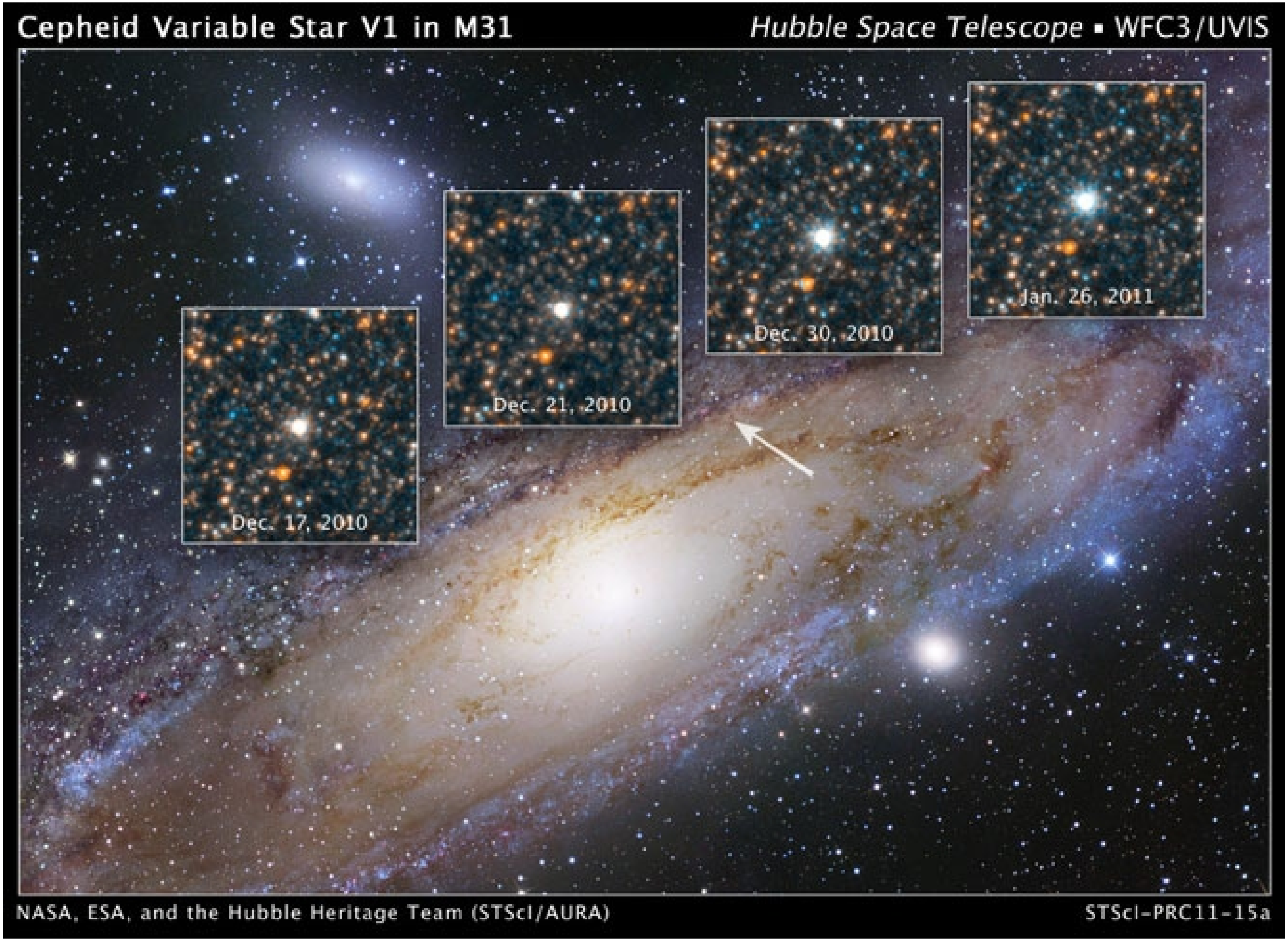
Result: Curtis was right – they are island universes. The story of Edwin Hubble ...

Edwin Hubble

- 1925 – discovers Cepheids in the Andromeda Galaxy and estimates its distance as ~900,000 LY.*
  - This proved that spiral nebulae are external galaxies.
- 1920's – adds to Vesto Slipher's observations of galaxy redshifts and distances
- 1929 – discovers Hubble's Law (*the recessional velocity of a galaxy is proportional to its distance*).
- First H_0~500 km/s/Mpc using 46 galaxies. Way too high!

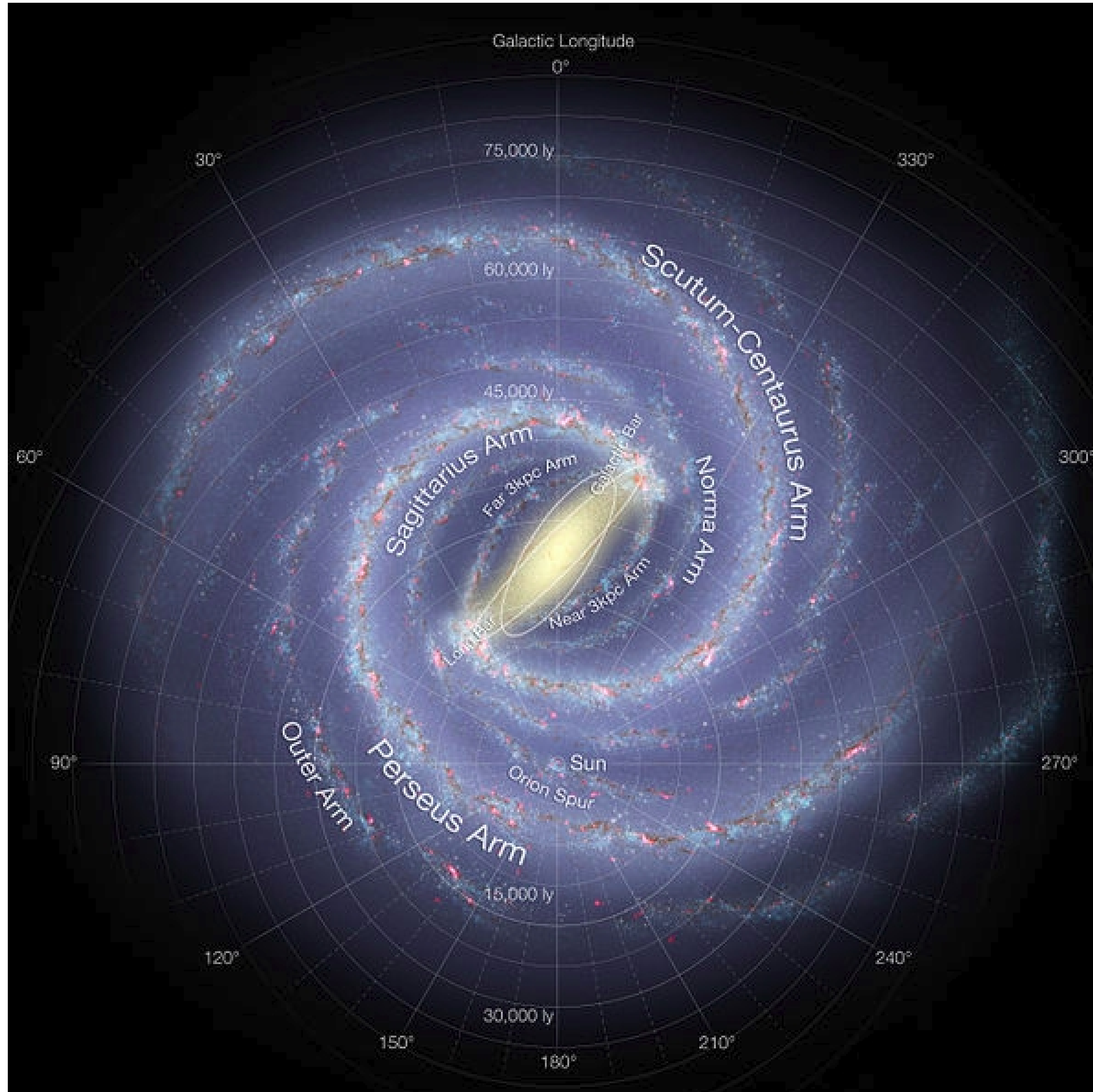
*Currently accepted distance is 2.5 MLY.

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