Relativistic Universe

Galaxies

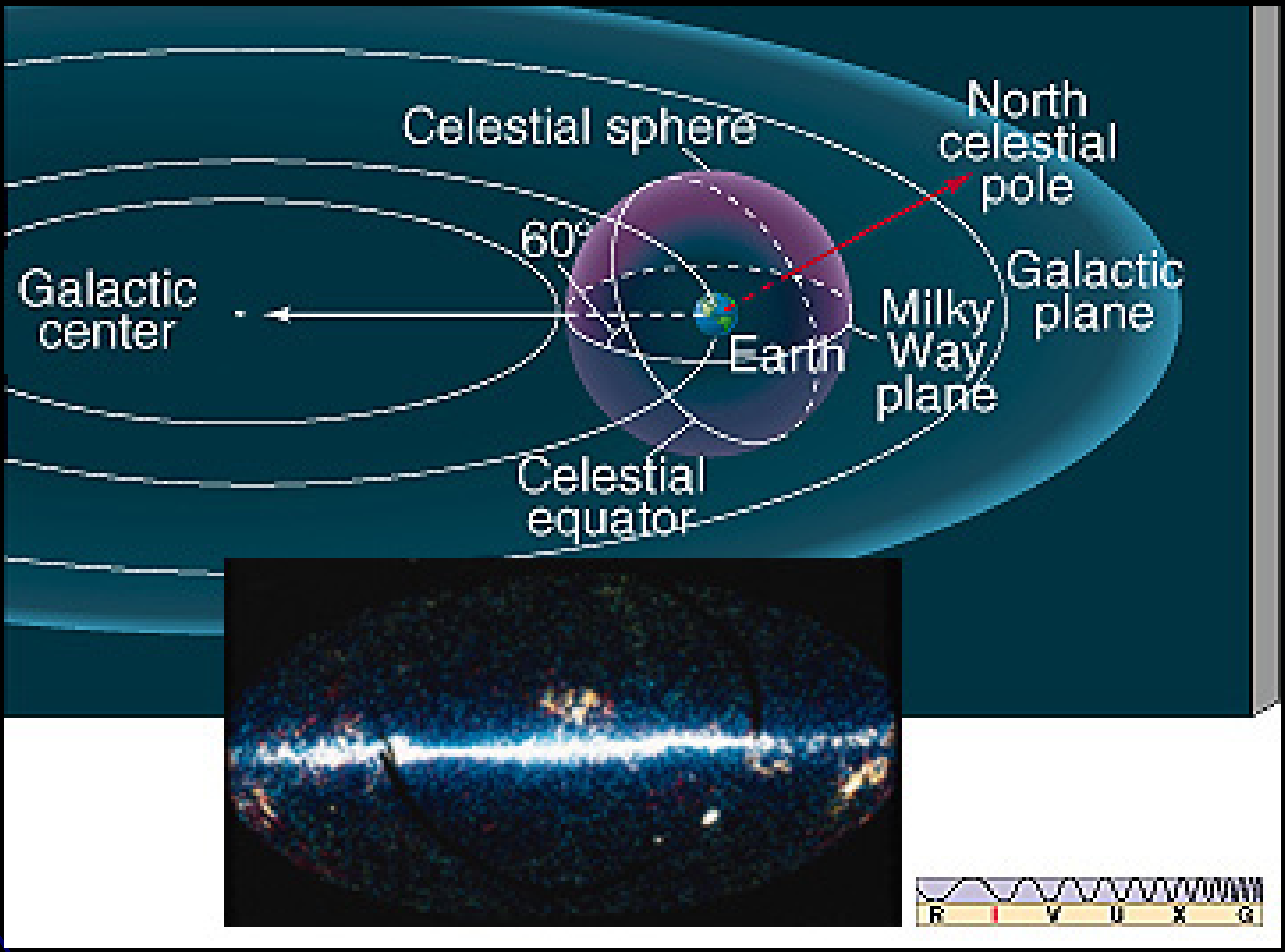
The Structure of the Galaxy

Because we are within the galaxy, it is difficult to map out its structure. This is especially true when looking in the Galactic plane, because of all the dust. We are not near the center of the galaxy, but where is the center? How far away is it?

Measuring Distances in the Galaxy

Although parallax measurements are reliable, most stars are too distant for any parallax measurement!

Reliable parallaxes only exist out to ~1000 pc.



Standard Candles

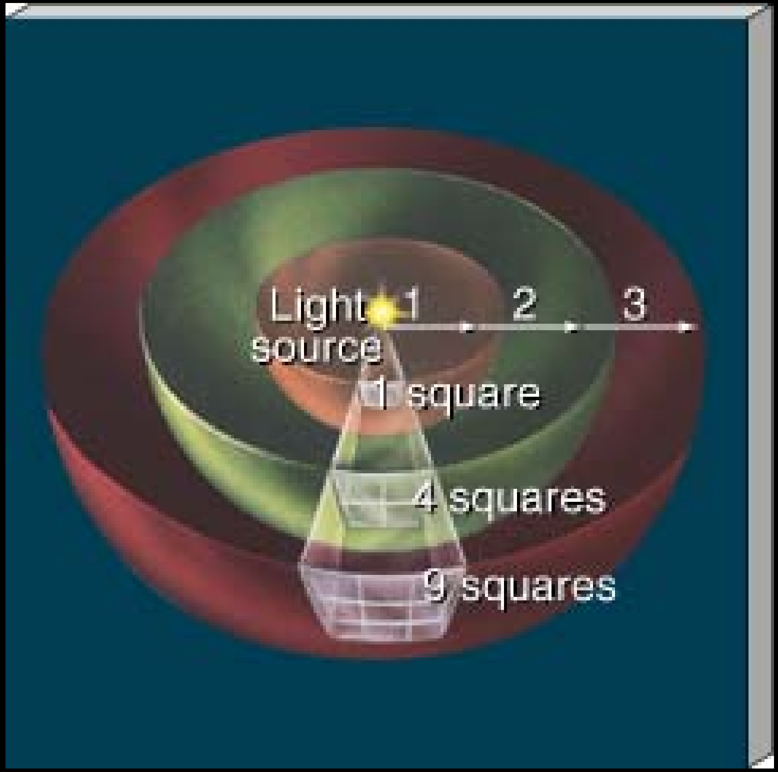
Suppose you *knew* the absolute luminosity (or magnitude) of some object. If you did, you could determine the distance to the object simply from the inverse square law of light.

$l = L / r^2$ where

l is the *apparent* luminosity,

L is the *absolute* luminosity, and

r is the distance.



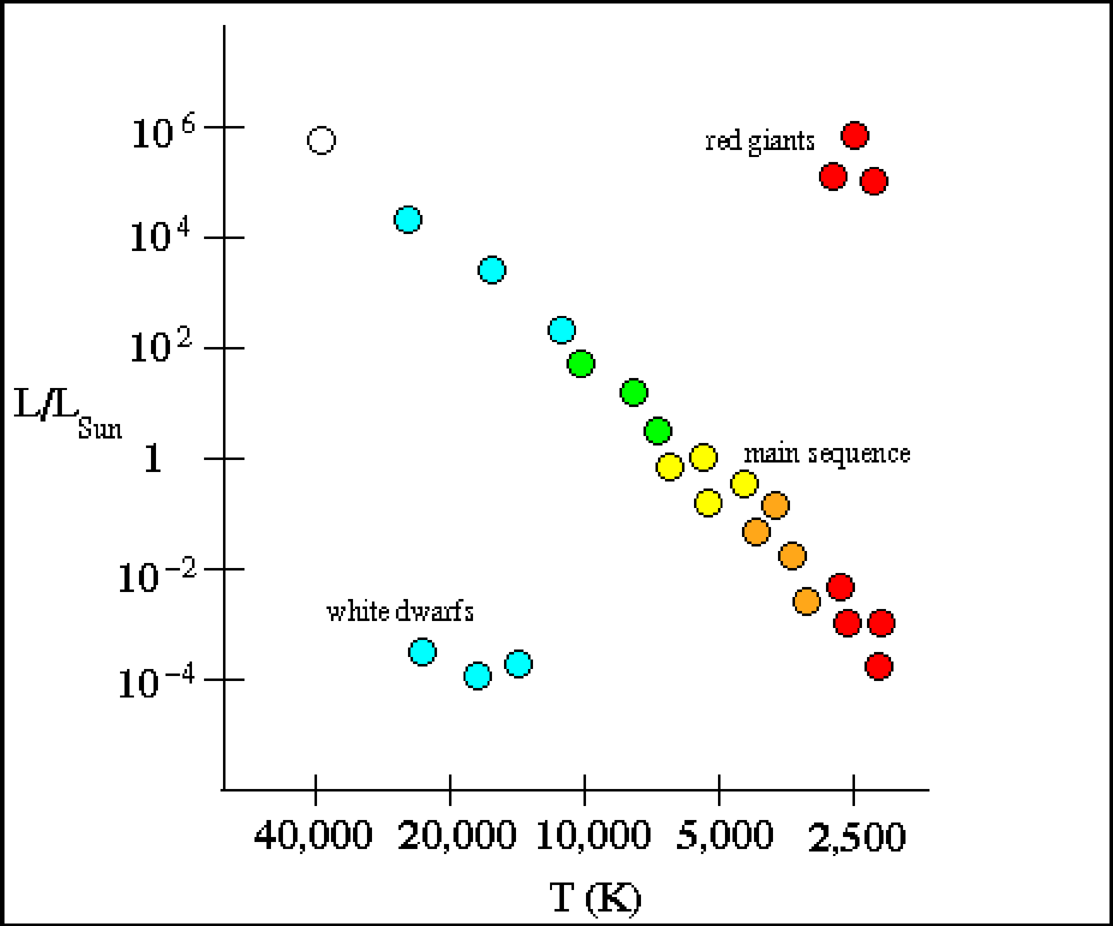
Any object whose luminosity you know is a **standard candle**.

Ideally, you would like a standard candle to be ***bright***, so that it can be seen far away.

Spectroscopic Parallax/Main Sequence Fitting

Consider: for main sequence stars, there is a relationship between the temperature (or color or spectral type) of a star and its absolute luminosity (or magnitude).

For these types of stars, you can tell their absolute luminosity just by observing their color (or spectral type). They can therefore be used as standard candles.



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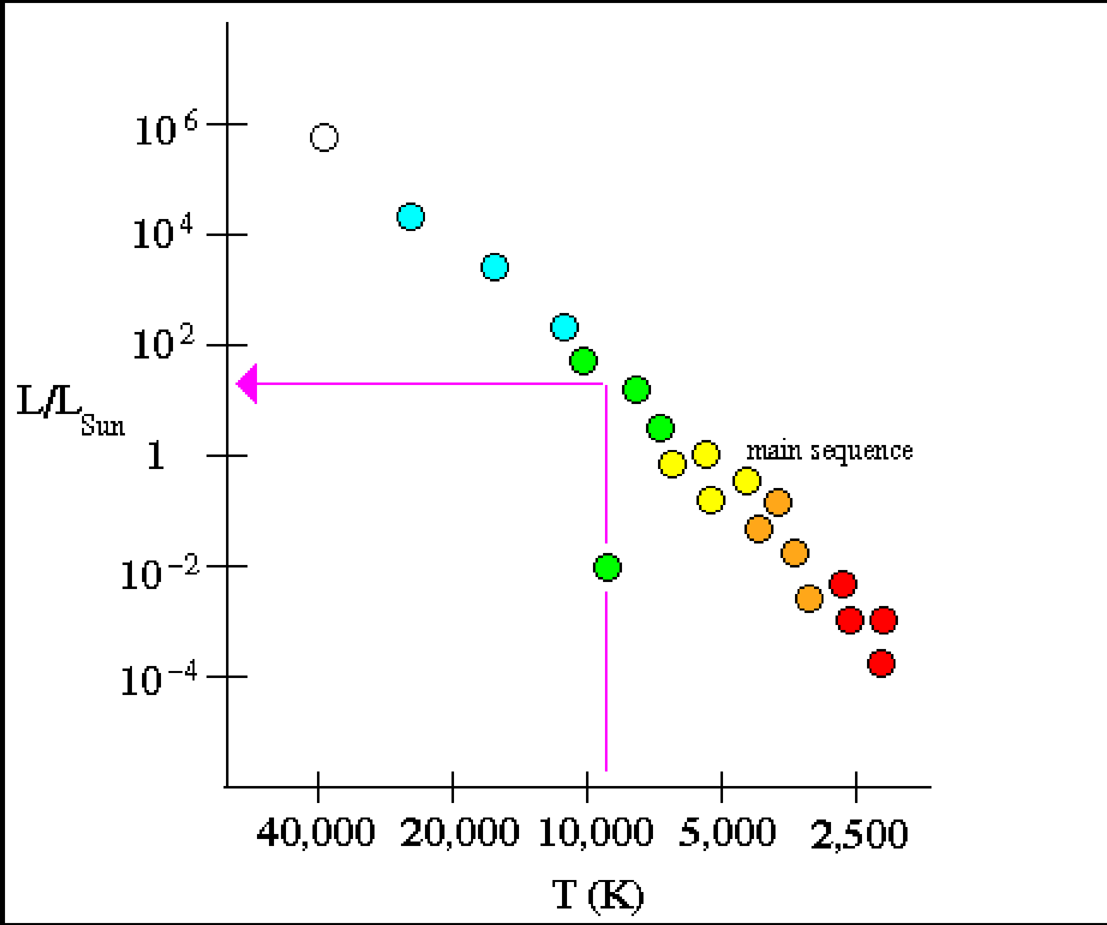
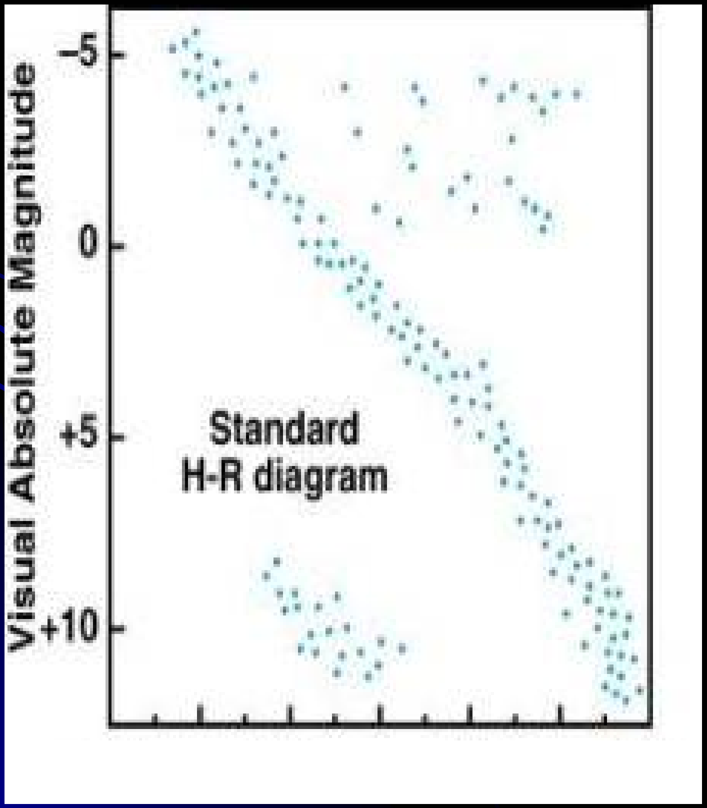
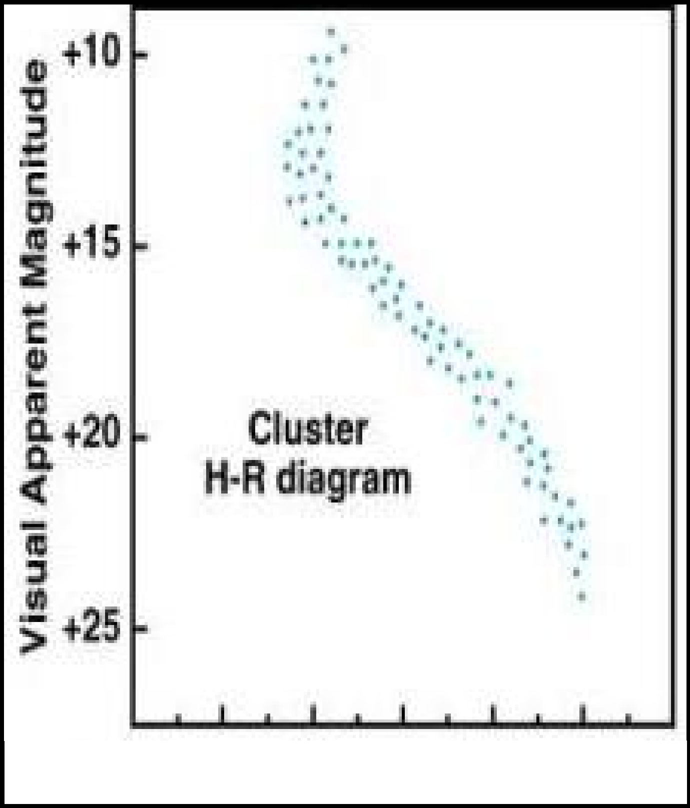


Main Sequence Fitting and Open Clusters

Main Sequence Fitting (or spectroscopic parallax) works well for open clusters, since the main sequence stars are bright.

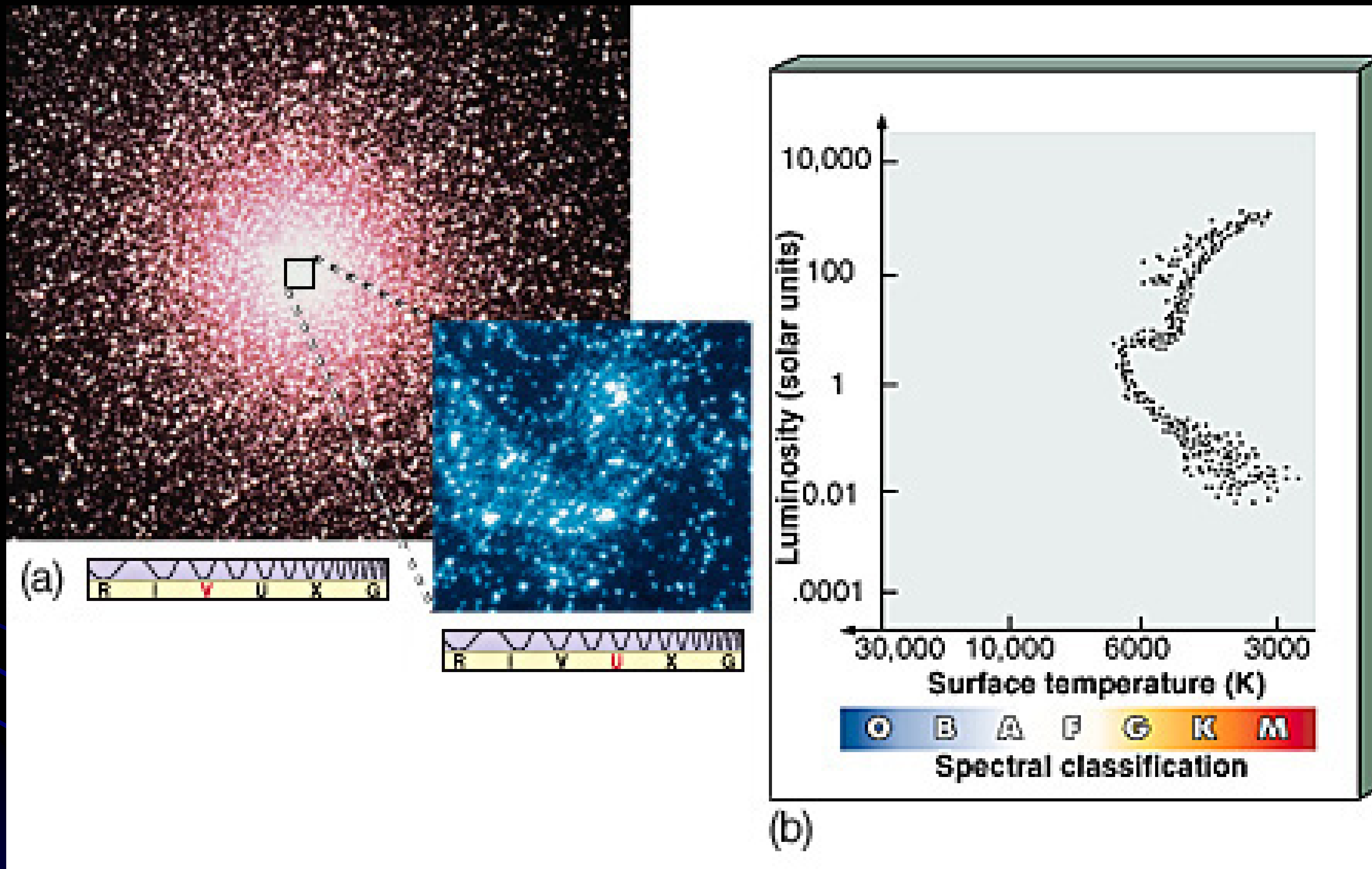




Open Clusters and Extinction

While one could (in principle) observe and measure open clusters at great distances, these systems are young, and are often located behind large patches of dust.

Main Sequence Fitting and Globular Clusters

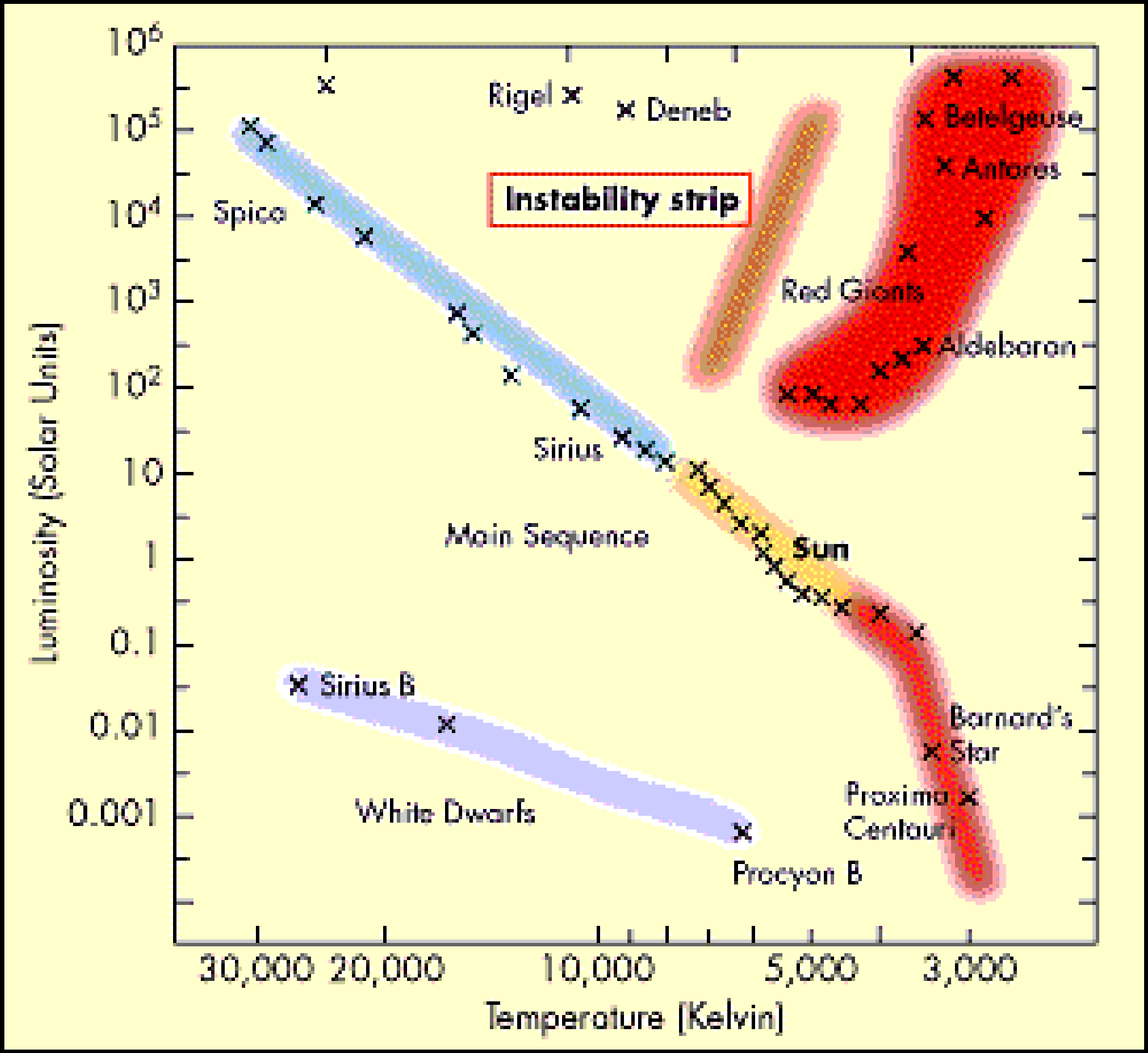


Globular clusters are Pop II objects and are not associated with dust. However, all their bright main-sequence stars have long since died. Only faint main-sequence stars are left.

Digression: The Instability Strip

Not all stars are stable. There is a narrow region in the HR diagram where stars cannot maintain a constant brightness. Instead, they pulsate, getting bigger and smaller (*i.e.*, brighter and dimmer) over time.

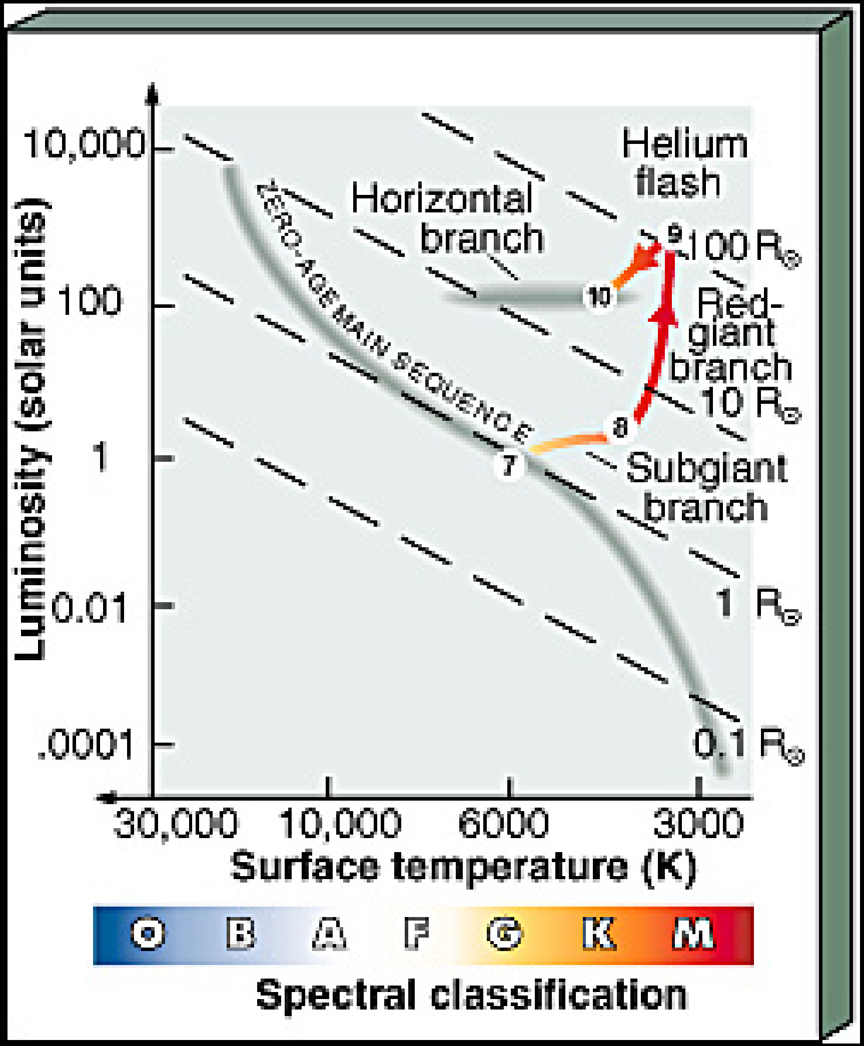
This area is called the Instability Strip.



RR Lyrae Variables

Recall that after a low-mass star goes up the giant branch for the first time, it ignites helium in its core and briefly becomes more like a main-sequence star.

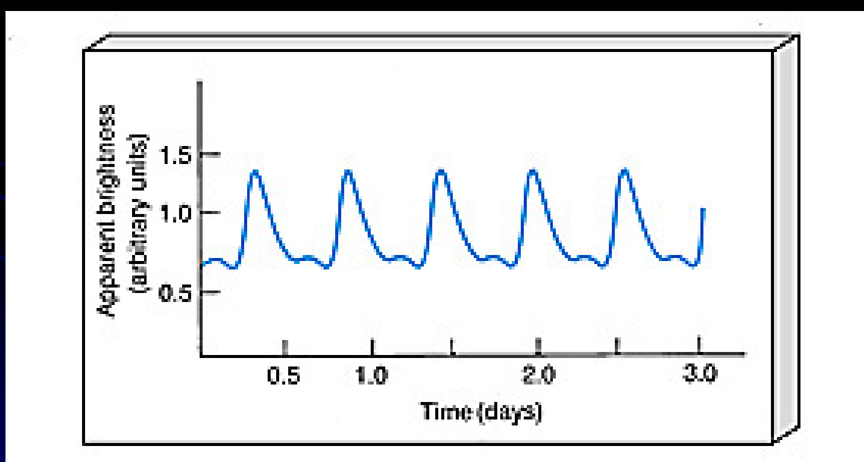
Some of these stars fall in the instability strip. These are called RR Lyrae stars.

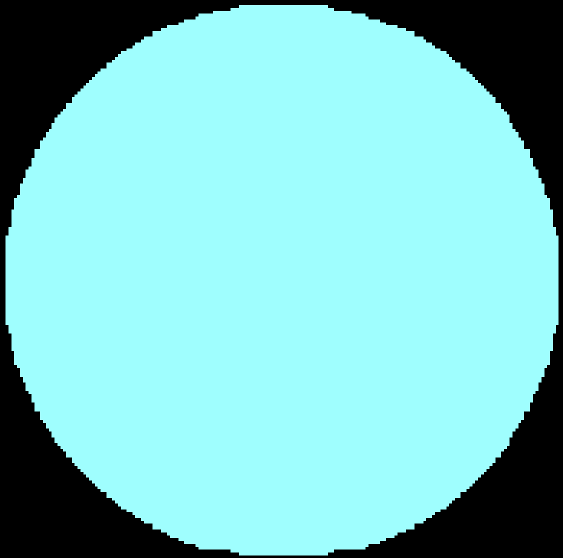


Note that RR Lyrae stars are significantly brighter than globular cluster main sequence stars.

RR Lyrae Pulsations

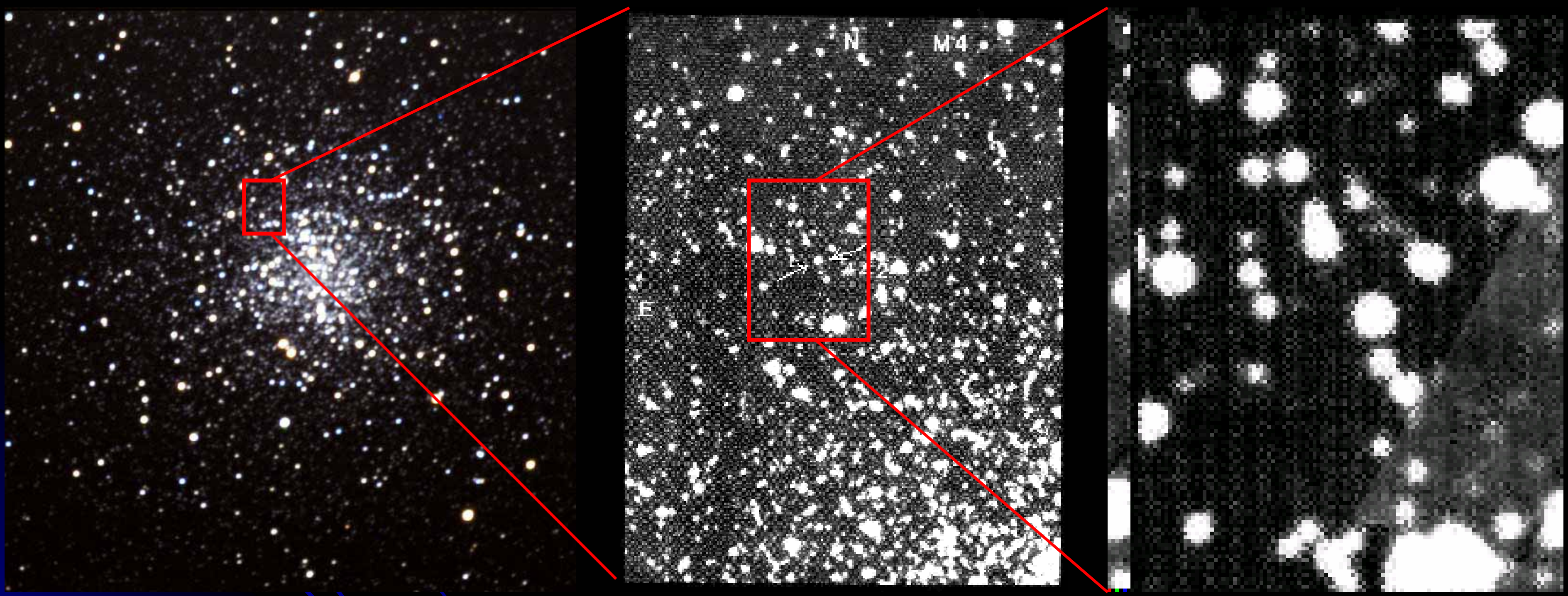
RR Lyrae stars can double their brightness within a day. They are very accurate clocks.





Finding RR Lyrae Stars

Globular clusters contain many RR Lyrae stars. They are very easy to find.



Within a cluster, all RR Lyrae stars have the same apparent (average) brightness. This suggests they are standard candles.

Building a Distance Ladder

There is no globular cluster close enough for a parallax measurement. So…

1) Identify a nearby globular cluster
2) Derive its distance via spectroscopic parallax
3) Using its distance, derive the absolute brightness of all its RR Lyrae stars. These stars are now standard candles.
4) Observe a more distant globular cluster (whose main sequence stars are too faint to see). Measure the brightness of its RR Lyrae stars.
5) Derive its distance assuming RR Lyrae stars are standard candles.

The Distance Ladder

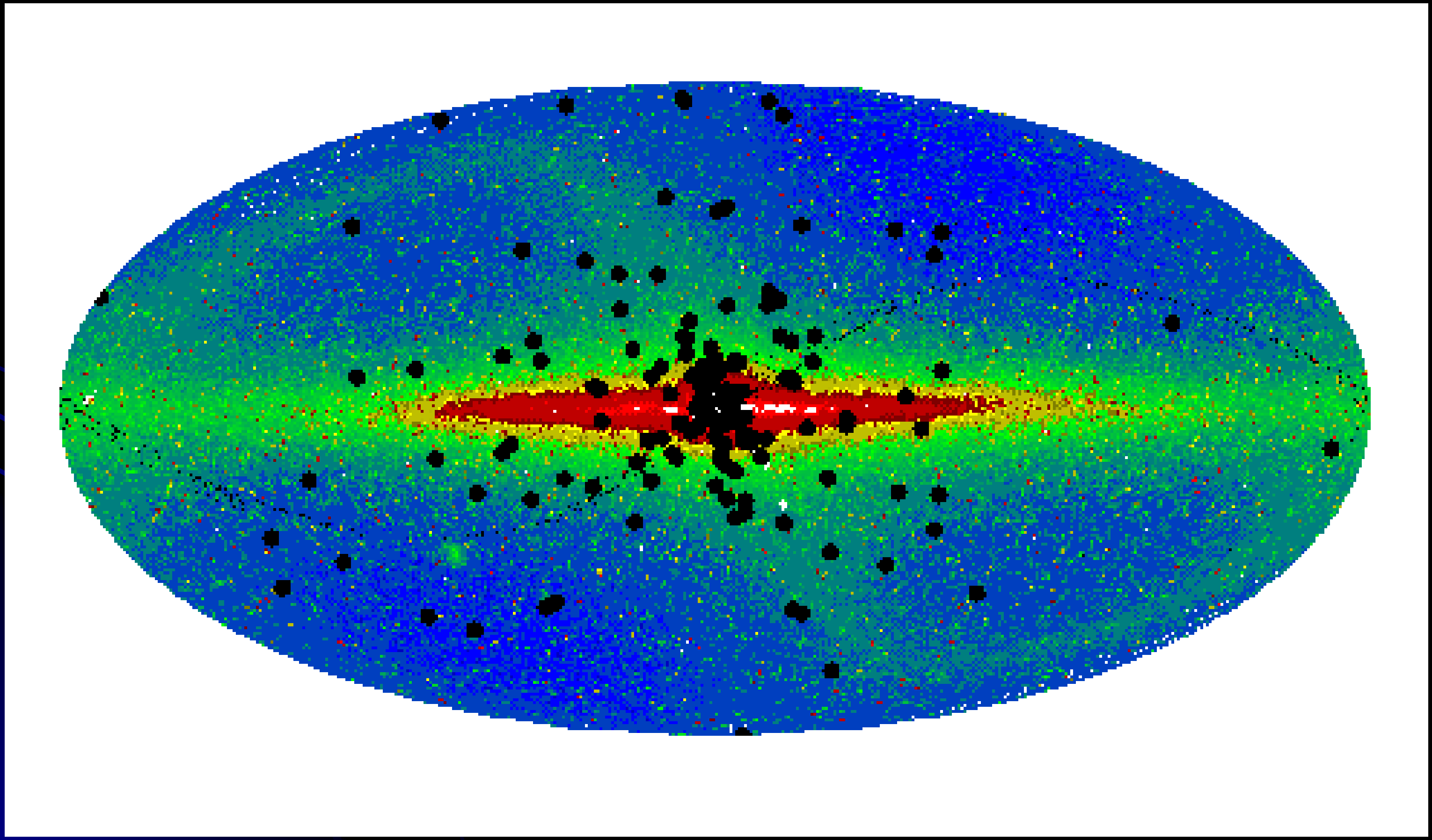
RR Lyrae Stars

Spectroscopic Parallax

Trigonometric Parallax

The Distribution of Globular Clusters

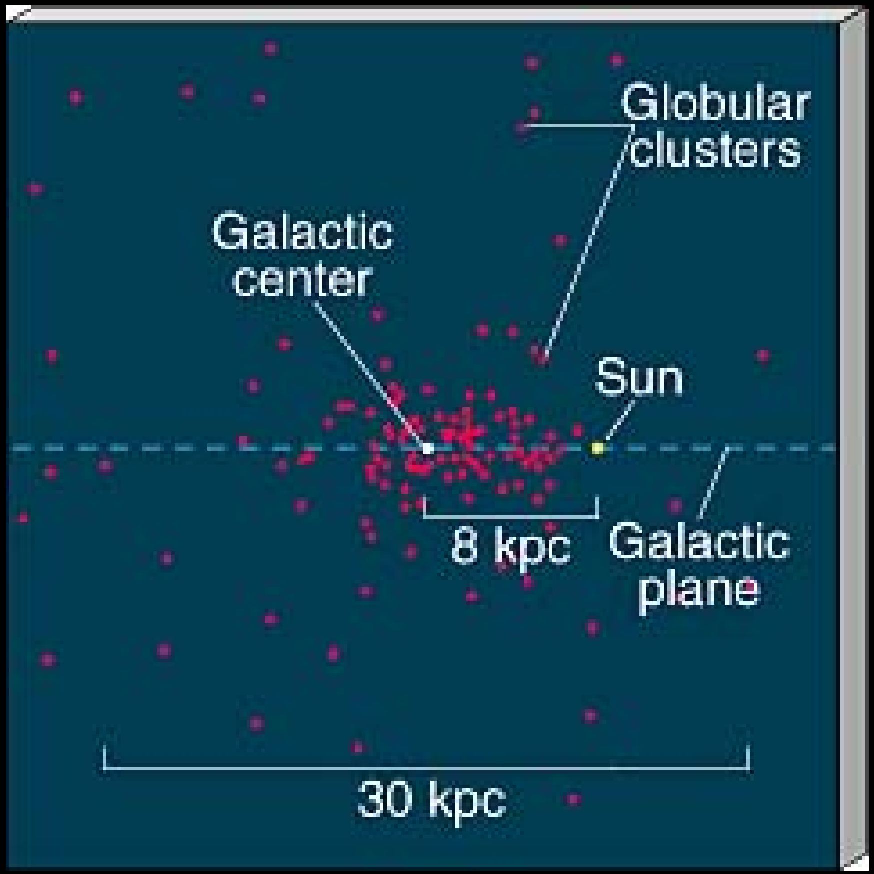
Globular Clusters are not confined to the galactic plane, but they do prefer one specific direction in the sky.



The Distribution of Globular Clusters

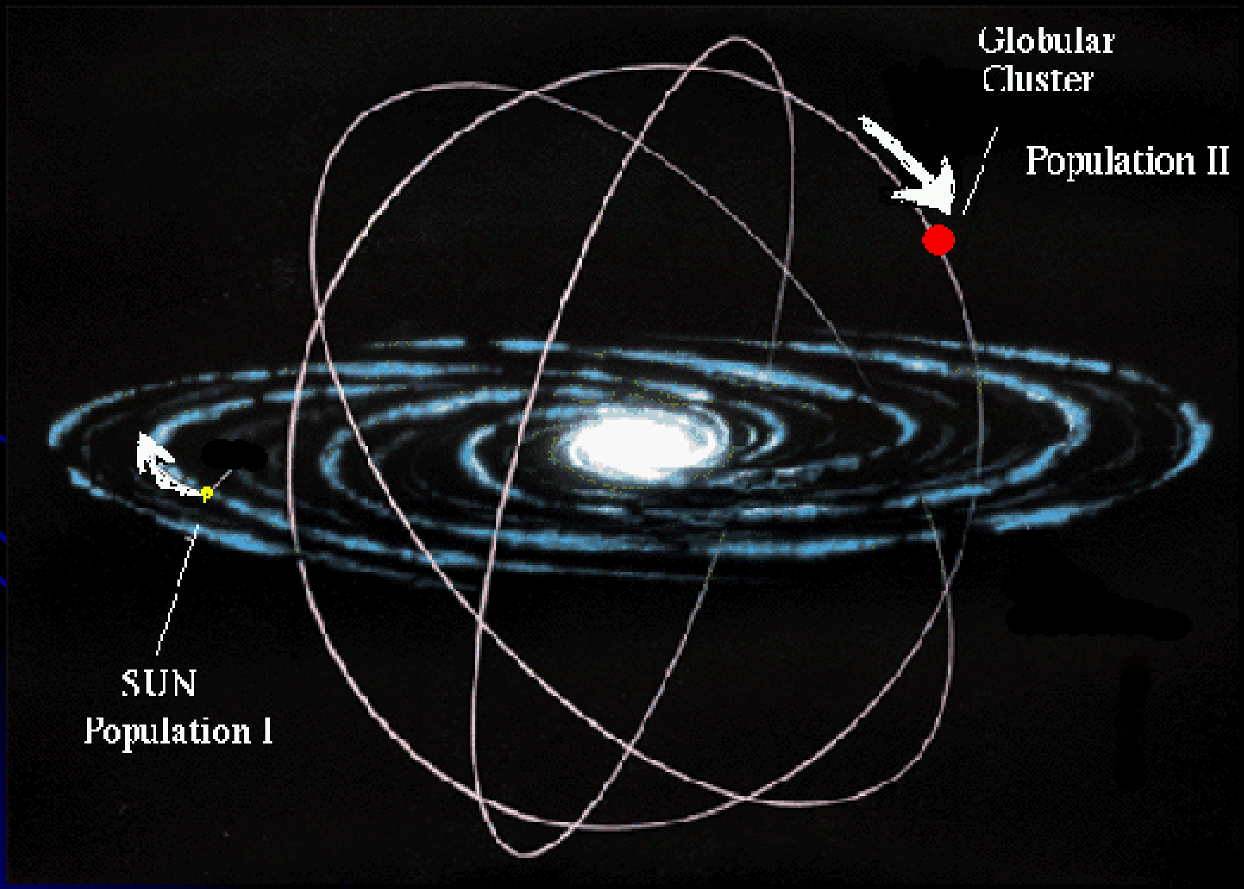
The center of the globular cluster system is not the Sun. Instead, the globulars are scattered about a point 8000 pc from us. This is the galactic center!

(Note: this was first done in 1918 by Harlow Shapley. Since then, the calibration of RR Lyrae stars have changed slightly, but the relative distances have remained the same.)



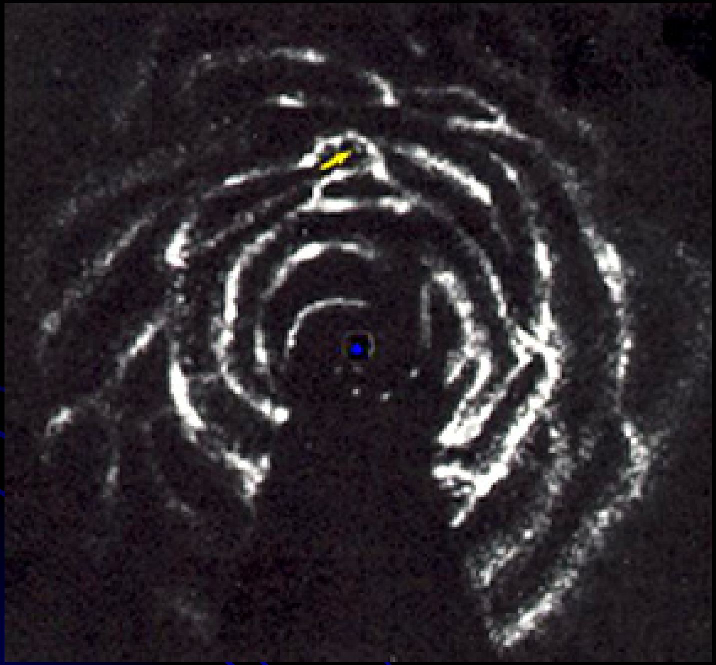
Our Galaxy: The Population II Component

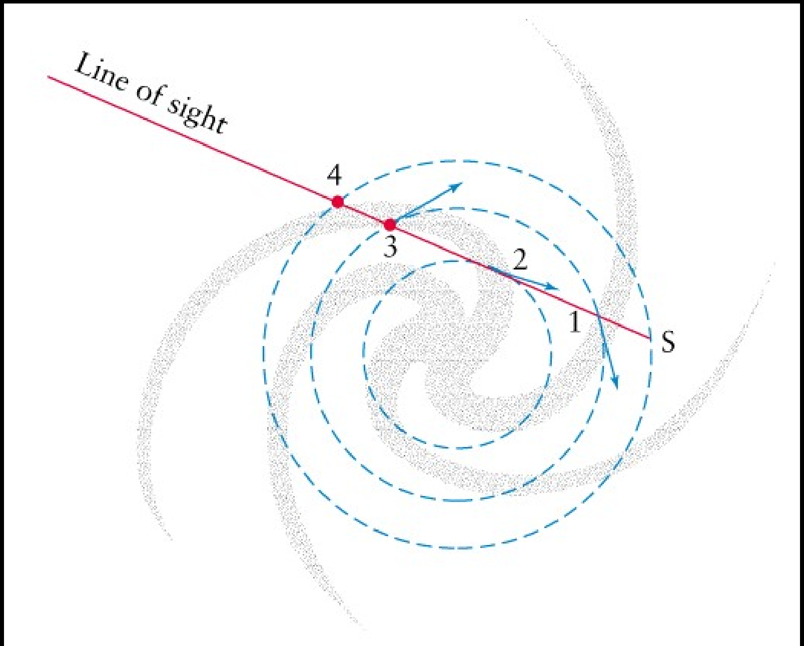
Population II objects, such as old stars and globular clusters, are distributed in a roughly spherically bulge or halo. Pop II objects orbit in random directions, and their density decreases rapidly as one goes to larger and larger radius.



Our Galaxy: The Population I Component

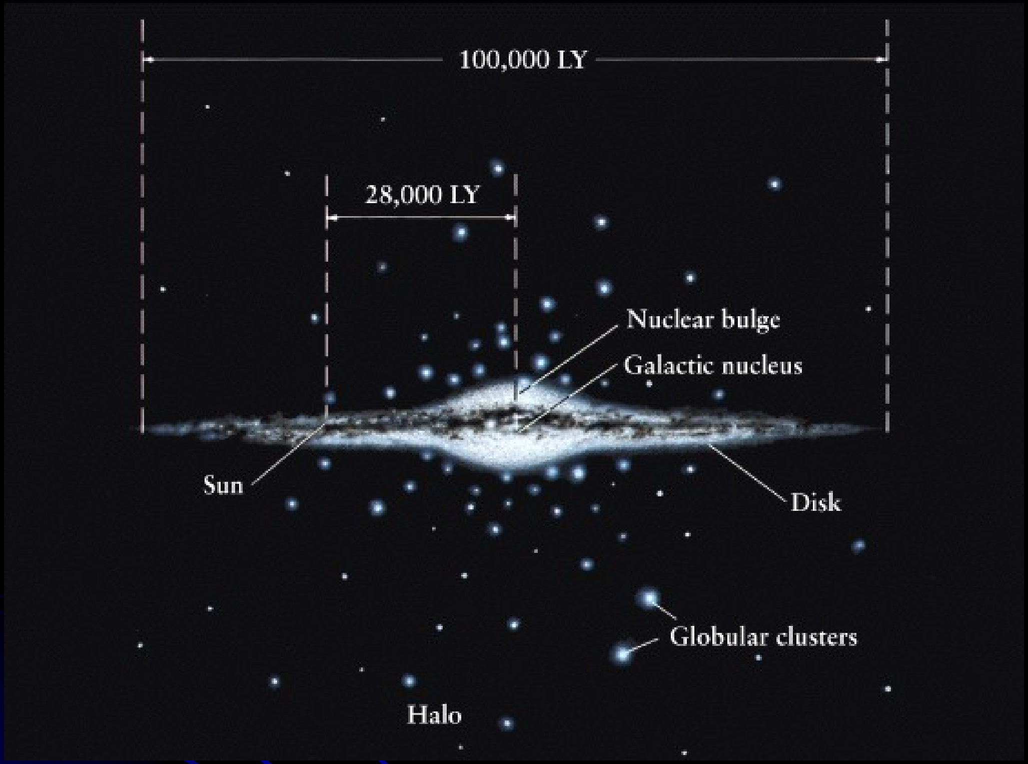
When we look through the dust of the galaxy (using the 21 cm emission of atomic hydrogen), we see a flat disk of gas rotating about the galactic center. The very youngest objects are located within several spiral arms.

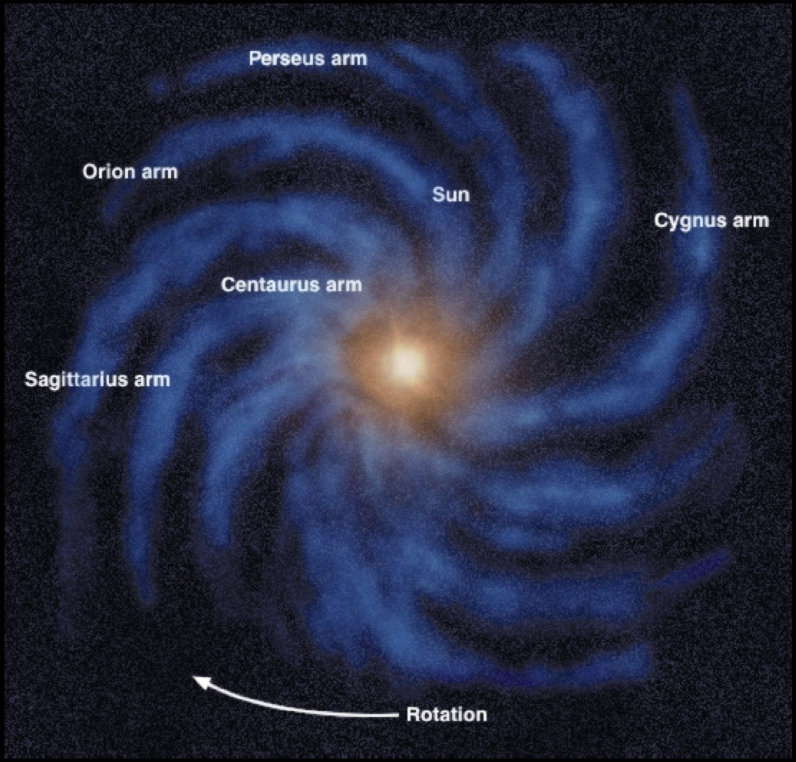




Our Sun is located in the disk, between spiral arms, about two-thirds of the way out. It takes the Sun about 200,000,000 yrs to complete one orbit.

Edge on and Face-on View

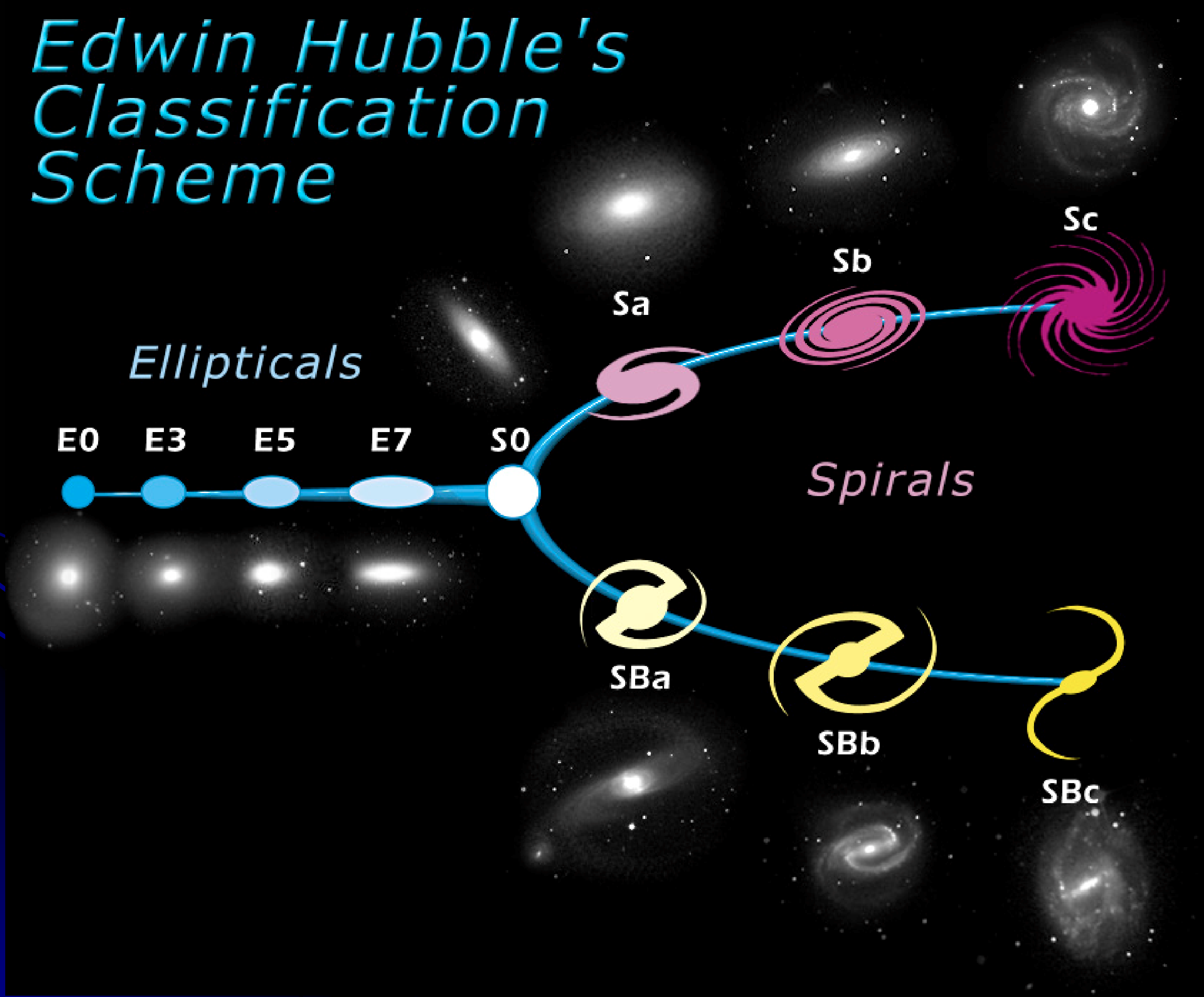




The Milky Way galaxy can be modeled as the combination a spherical Pop II bulge, and a flat Pop I disk, with most of the star formation occurring in spirals arms.

The Hubble Tuning-Fork Diagram

The traditional way of classifying galaxies is though …



Elliptical Galaxies

Elliptical galaxies are exclusively Pop II systems. They are classified E0 (round) through E7 (very elliptical).

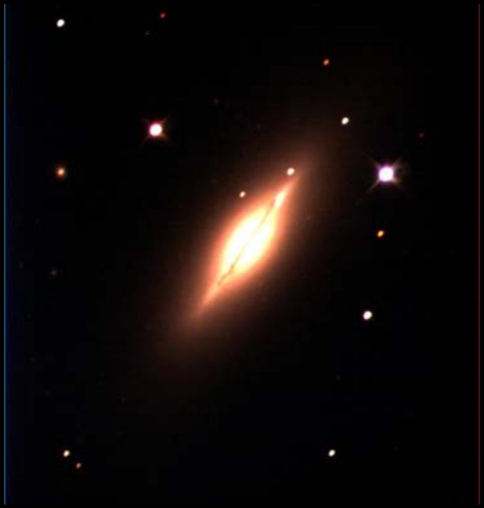





Lenticular (S0 and SB0) Galaxies

S0 and SB0 galaxies are transition objects. They are disk systems, but almost exclusively Pop II, with no star formation, no spiral arms, and very little cold gas or dust.






Sa and SBa Galaxies

Sa and SBa galaxies have a large (dominant) Pop II bulge, and a very smooth disk with only a trace of spiral arms.

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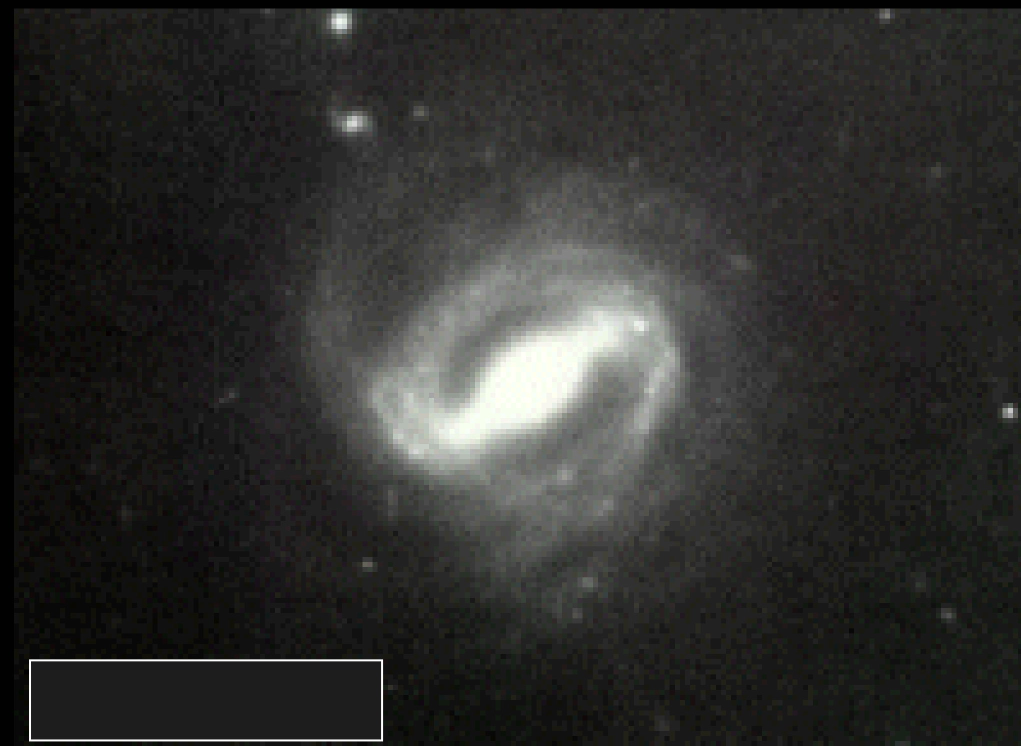
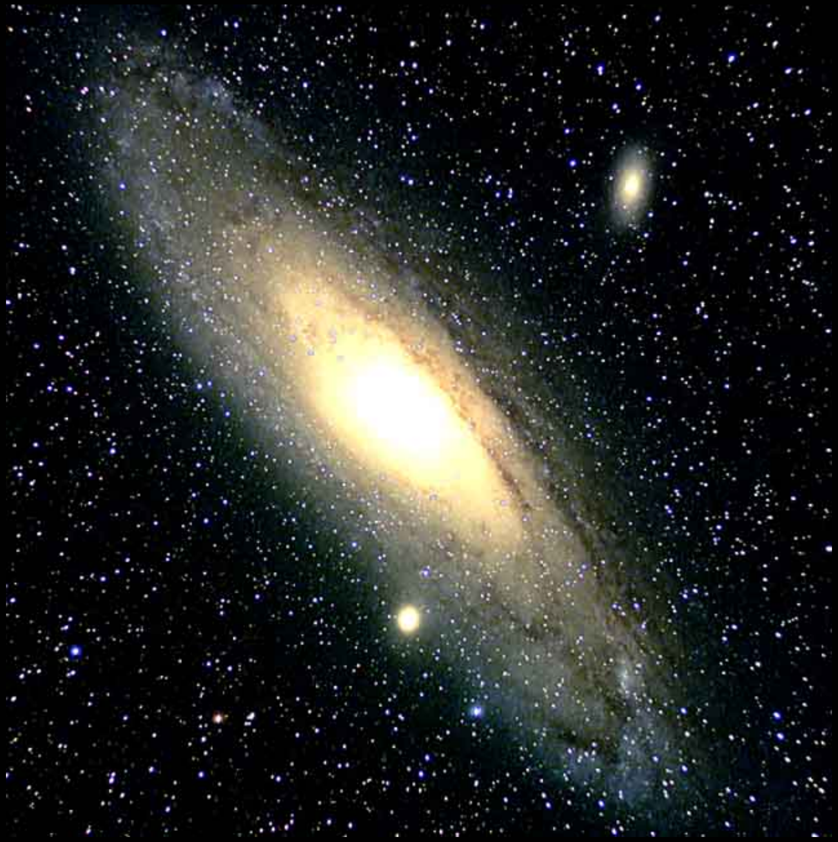


Sb and SBb Galaxies

In Sb and SBb galaxies, the bulge and disk components are comparable. Spiral structure is becoming visible in the disk, and some individual H II regions can be seen.



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Sc and SBc Galaxies

Sc and SBc galaxies have little or no bulge and a prominent disk with clearly defined spiral arms. These arms appear knotty due to their many H II regions.

Sc and SBc Galaxies

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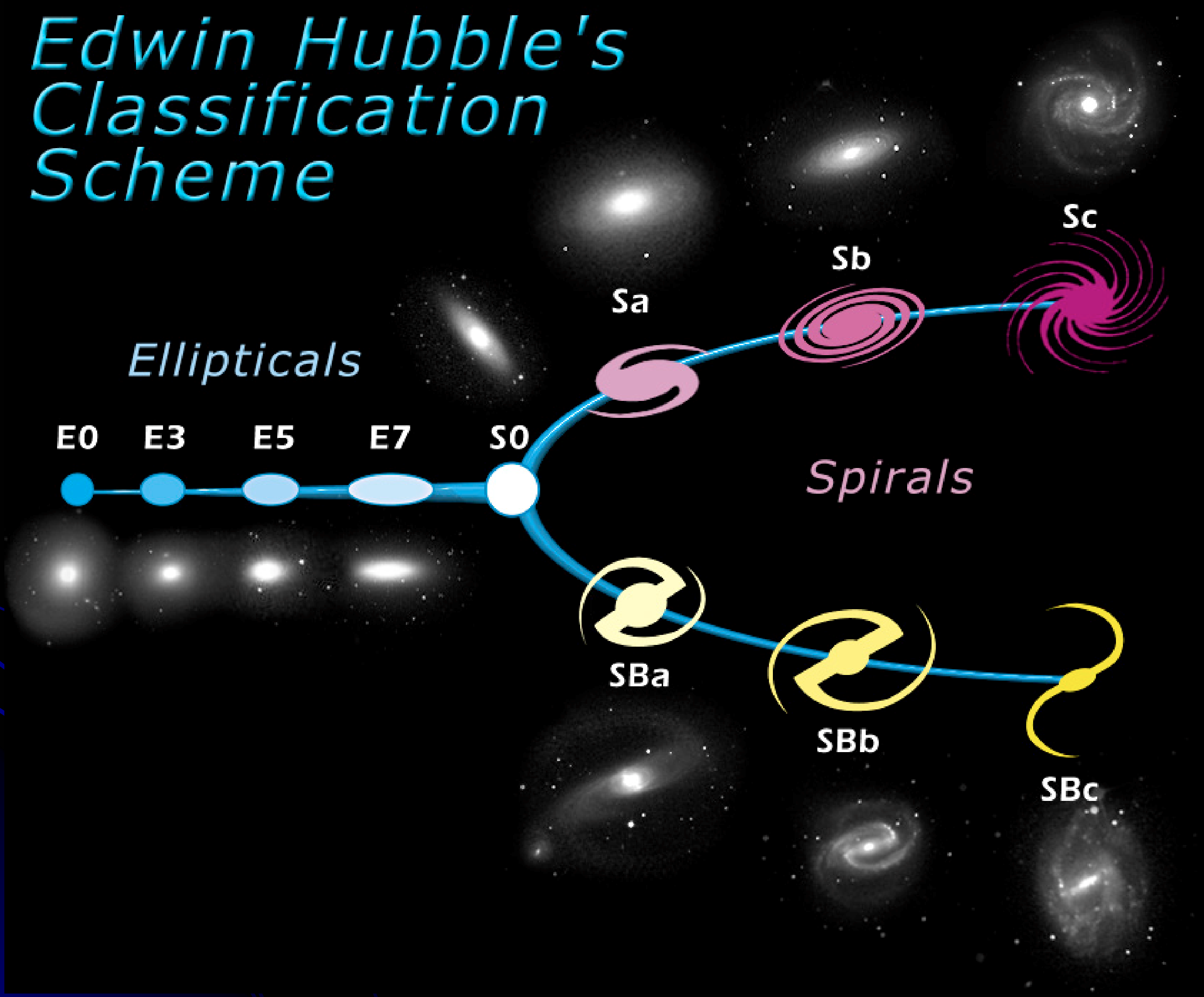
Irregular Galaxies

Irr galaxies are extreme Pop I systems. They have a large amount of dust, gas, and young stars, but no spiral structure

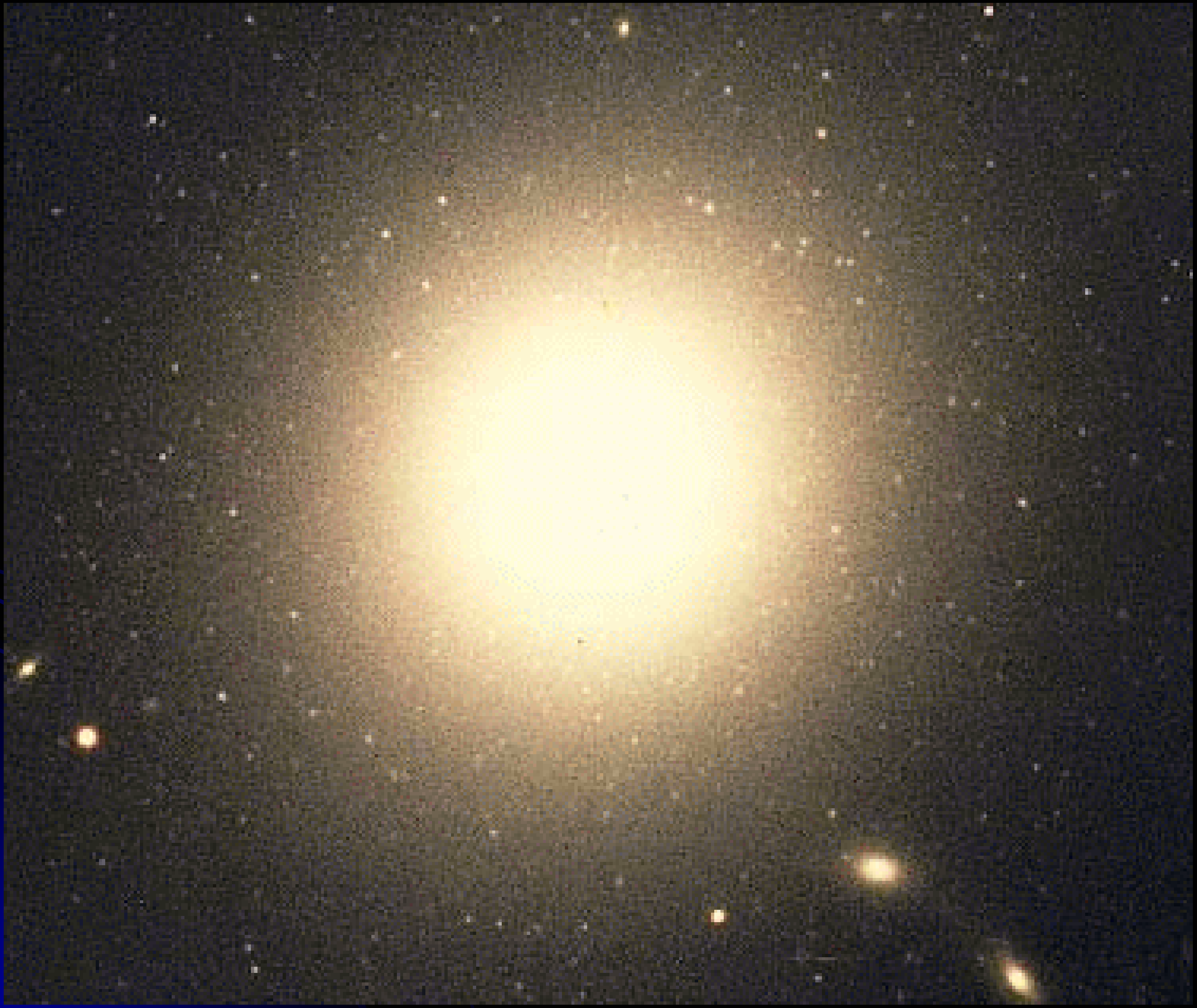
The Hubble Tuning-Fork Diagram



Classify this Galaxy

Sc

Classify this Galaxy

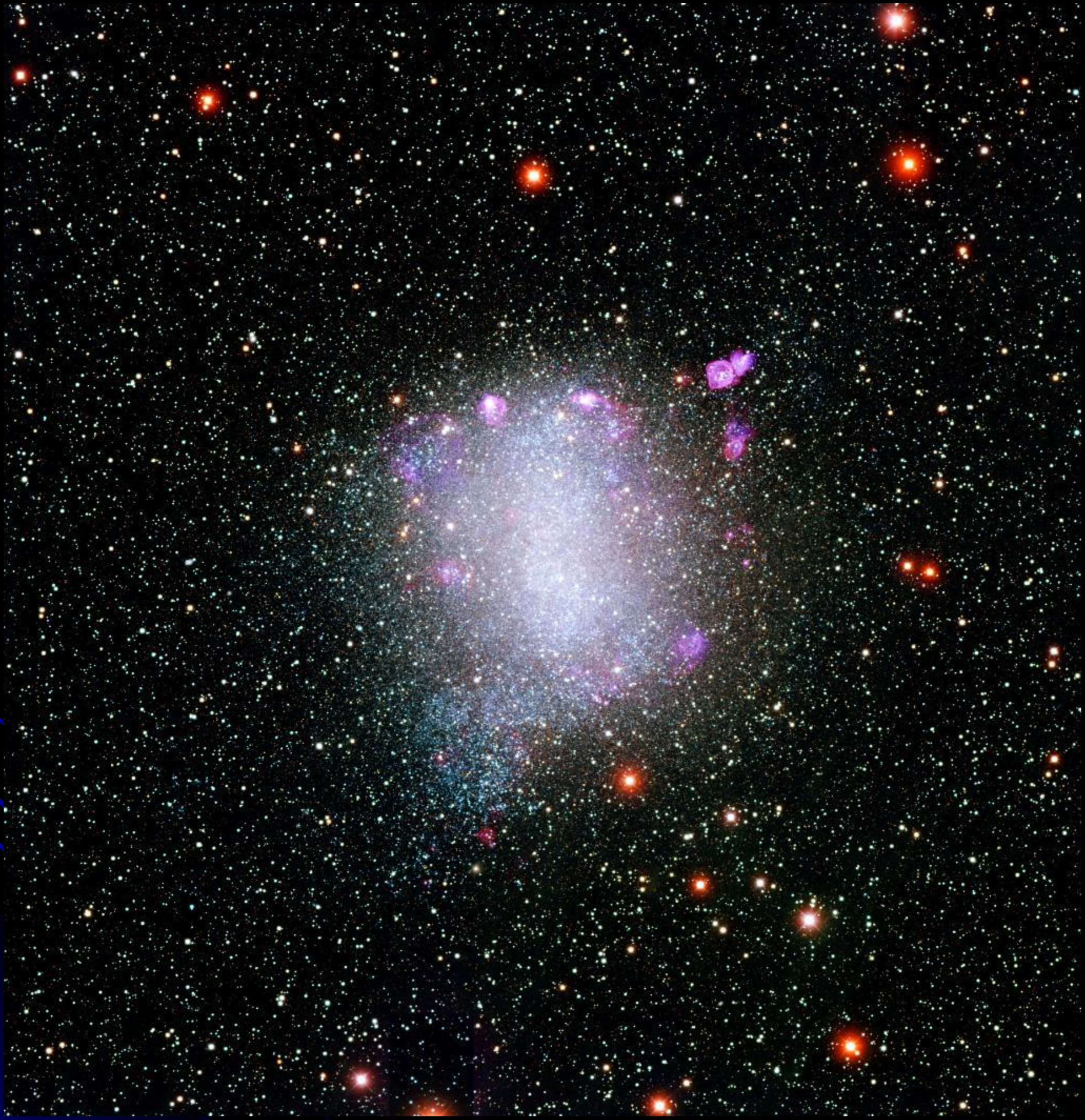


E1

Classify this Galaxy

Sa

Classify this Galaxy



Irr

Classify this Galaxy

Sab

Classify this Galaxy

SBbc

Classify this Galaxy

Sb (?)

Classify this Galaxy

Sc

Classify this Galaxy

E pec

Classify this Galaxy

Sb

Classify this Galaxy

Sc

Classify this Galaxy

Sc (?)

Classify this Galaxy

SBc pec

The Milky Way is probably …

Sc or possibly **SBc**

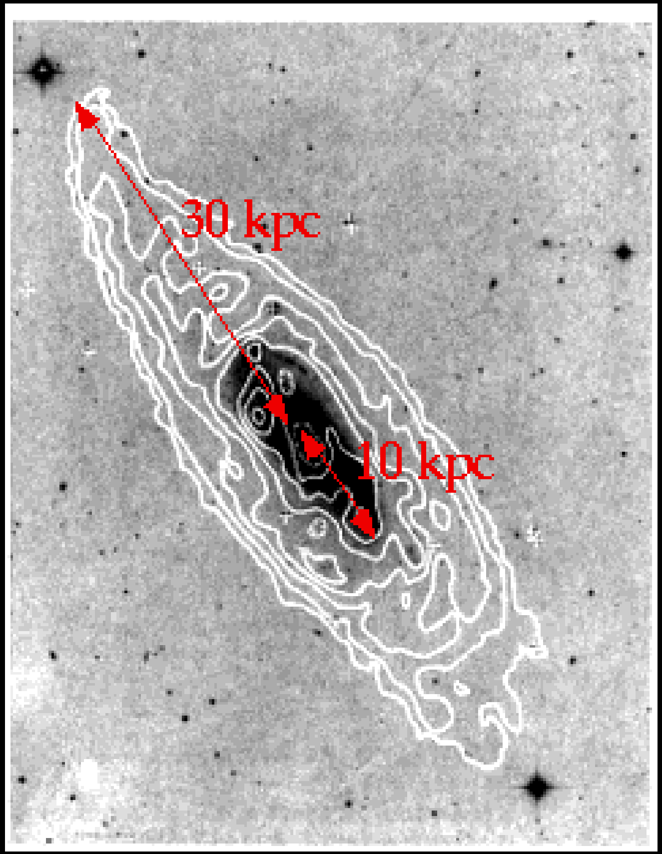
Constituents of the Galaxy

- Interstellar Medium
  - Atomic Hydrogen – H I
  - Molecular Hydrogen – H_2
    - Traced by the molecule CO
  - Ionized Hydrogen – H II
  - Dust
- Stars
  - Population I
  - Population II

Visually Estimating Galaxy Masses

Since we know the masses and luminosities of stars, and we know how interstellar gas emits, we can estimate the masses of galaxies from what we see.

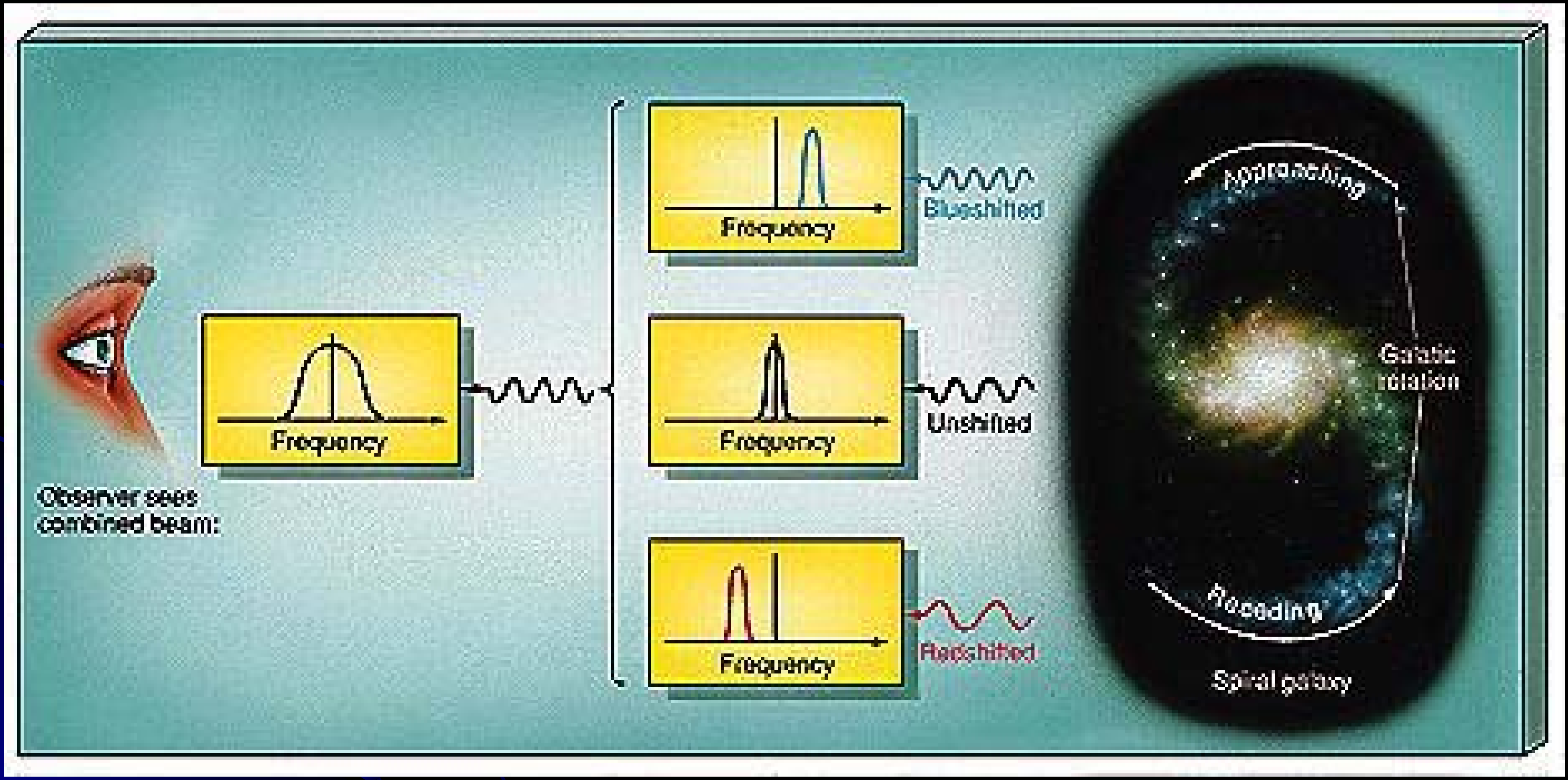
optical light



21 cm overlaid on optical

Dynamically Estimating Galaxy Masses

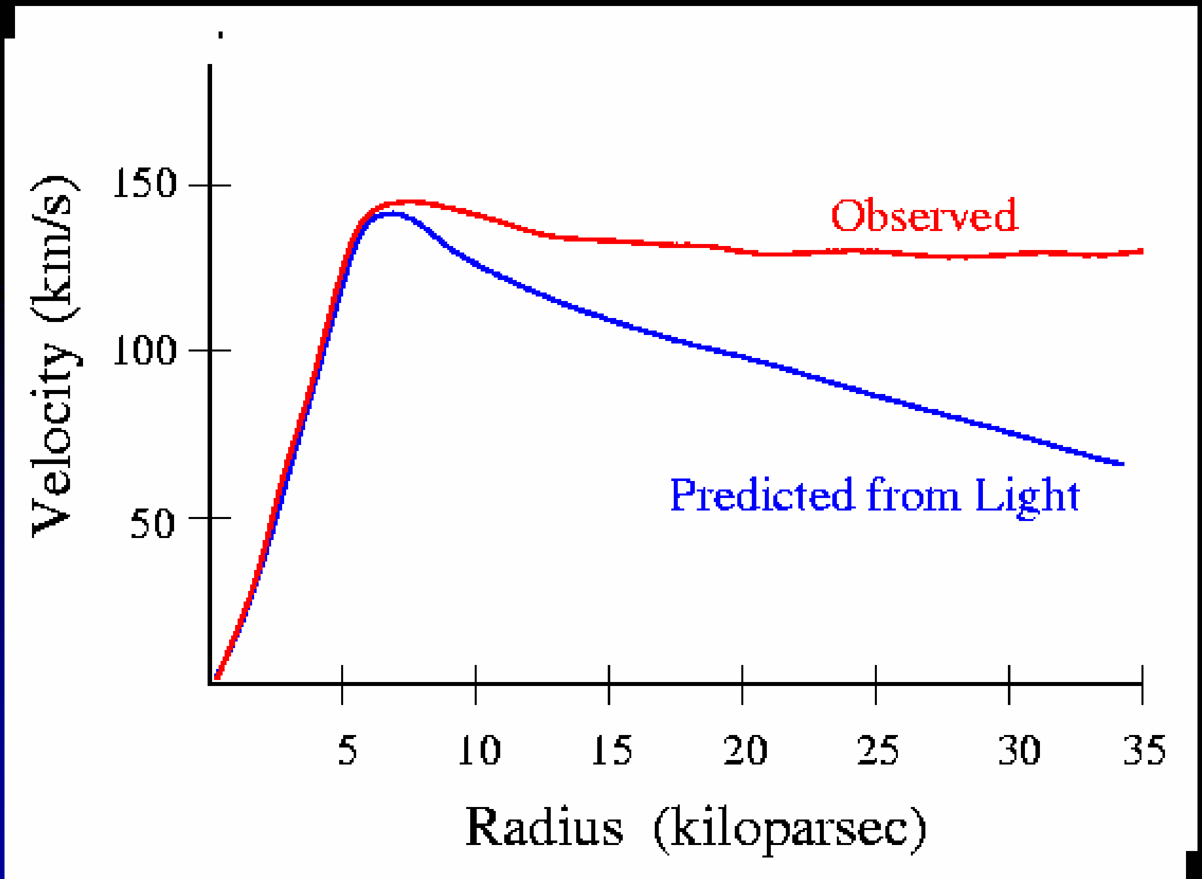
Alternatively, since H I gas emits as an emission line, it is very easy to determine its velocity. We can therefore measure how fast the gas around a galaxy is rotating.



Dynamical Estimation of Galaxy Masses

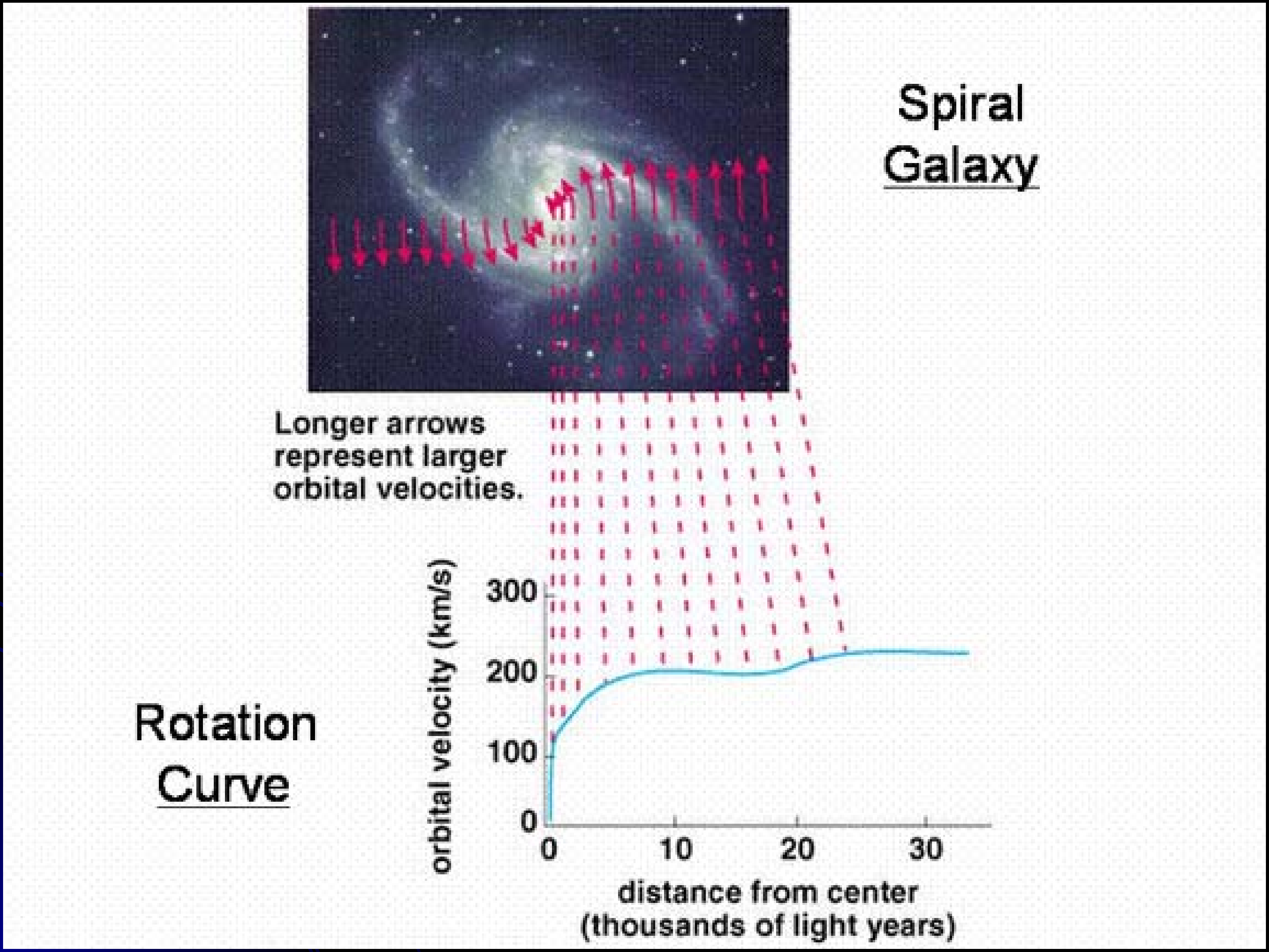
According to Newton's laws, once outside a galaxy, the rotation velocity of gas should decrease with distance. But that's not observed!

$$\mathbf{v} = 2\,\pi\,\sqrt{\mathbf{M}} \cdot \frac{1}{\sqrt{\mathbf{r}}}$$



Standard explanation: There must be *a lot* of mass in the outer regions of galaxies that we are not observing!

This is called
DARK MATTER



Spiral Galaxy
Longer arrows represent larger orbital velocities.
Rotation Curve
orbital velocity (km/s)
300
200
100
0
0
10
20
30
distance from center (thousands of light years)

A few things we know for sure…

$$\square^2\Phi = 4\pi G\rho$$

$$F = ma$$

which basically means

$$mV^2/R \underset{i.e,}{=} GMm/R^2$$

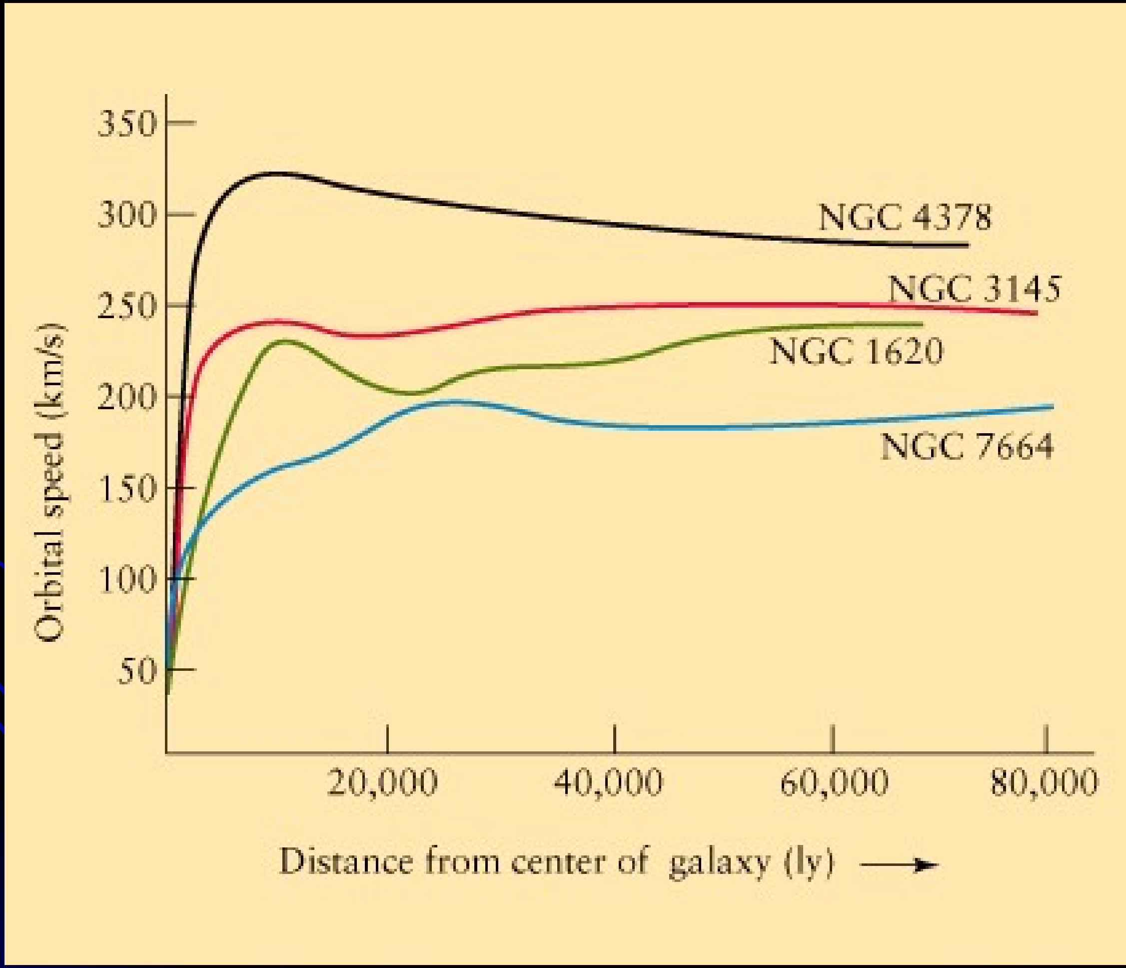
$$V^2 = GM/R$$

ergo…

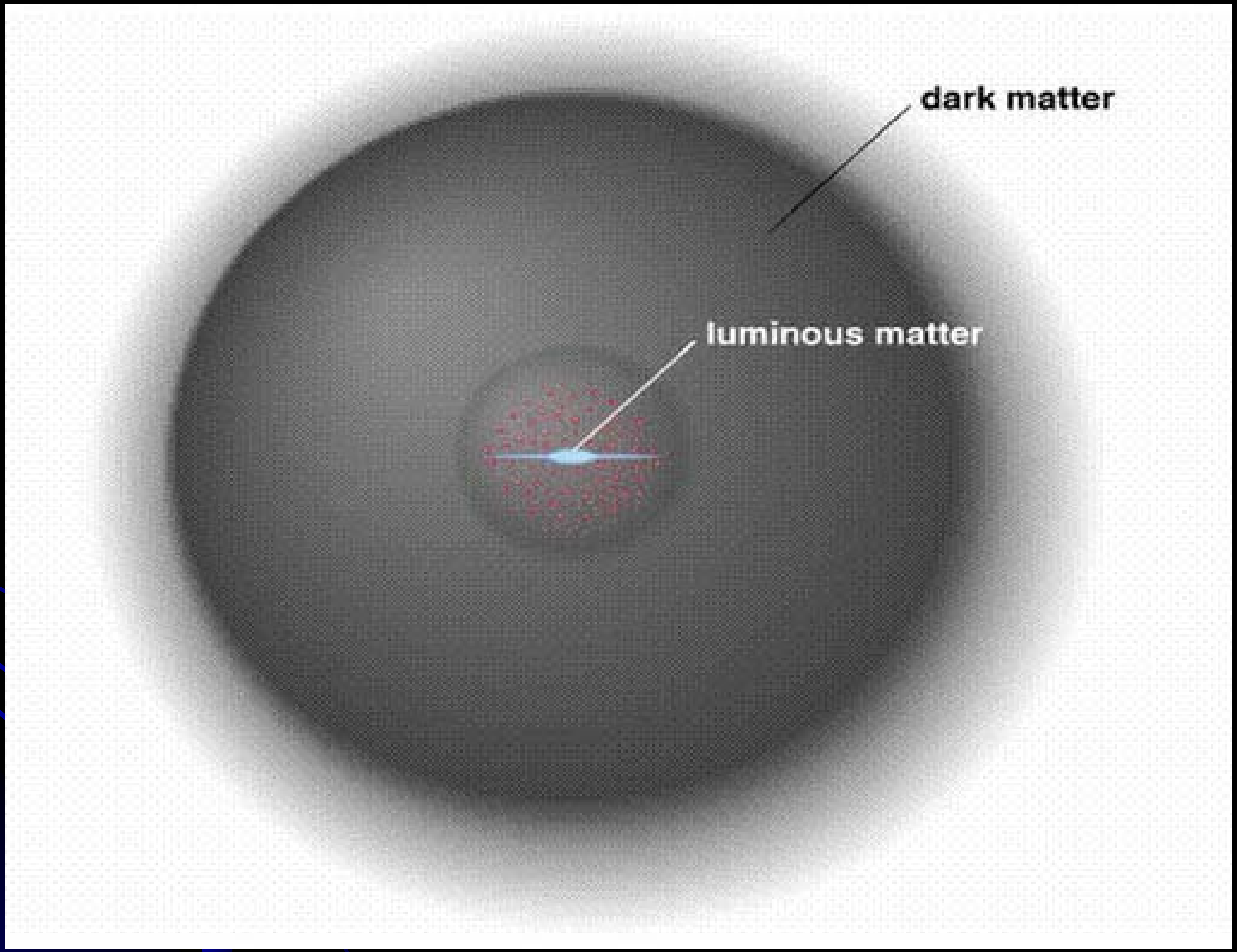
The universe is filled with nonbaryonic cold dark matter.

Dynamical Estimation of Galaxy Masses

Virtually all spiral galaxies have these "flat" rotation curves. The outer regions of spirals must be dominated by dark matter.



It seems that



Cold dark matter

Baryonic Dark Matter

Many candidates:

brown dwarfs

Jupiters

very faint stars

very cold molecular gas

warm ($\sim 10^5$ K) ionized gas

Can usually figure out a way to detect them: most have been ruled out.

Hot dark matter

Hot Dark Matter

Obvious candidate:
neutrinos

neutrinos got mass!...
...but not enough.

Also
- neutrinos suppress structure formation
- can't crowd together closely enough

MOND

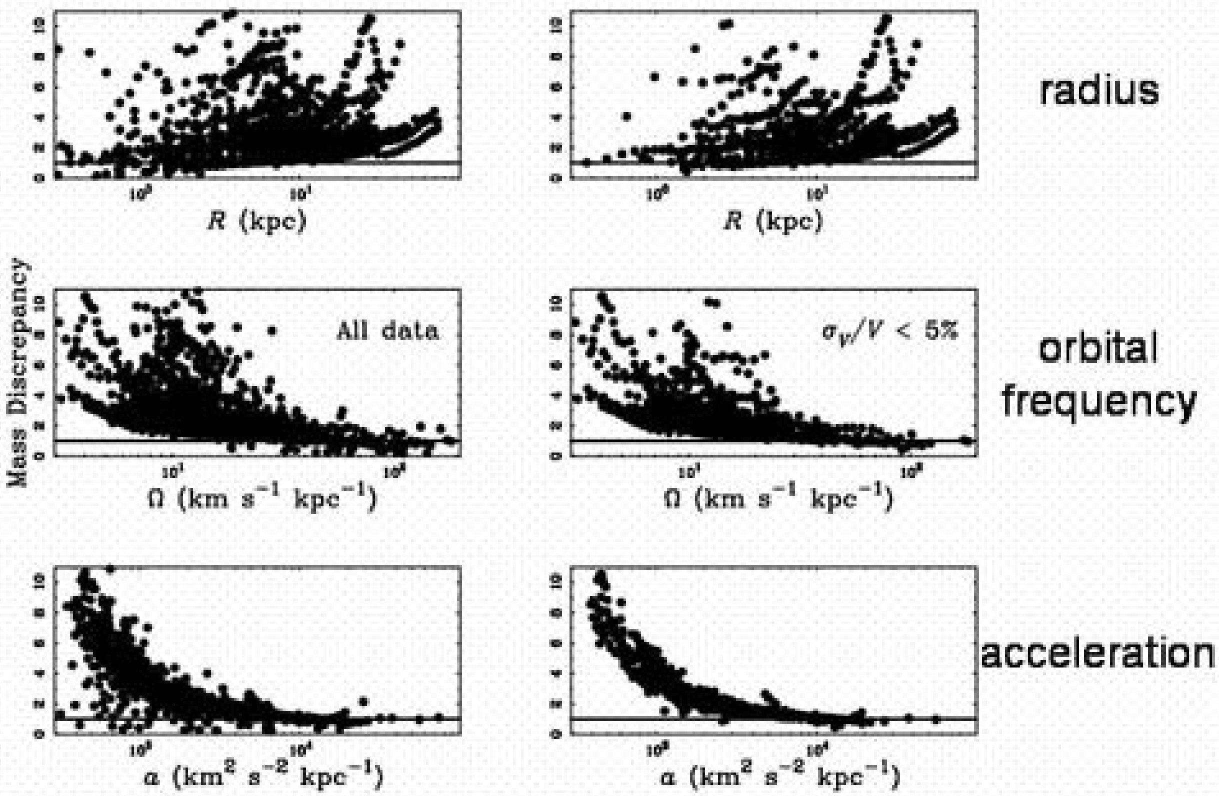
- Instead of dark matter we may try to modify laws of dynamics. This was done by Milgrom in 1983. He assumed that

$$\text{for } a \gg a_0, \quad a = g_N = \frac{GM}{R^2}$$

$$\text{for } a \ll a_0, \quad a = \sqrt{g_N a_0}$$

MOND can be interpreted as violation of either inertia (F=ma) or gravity law (Poisson eqn)

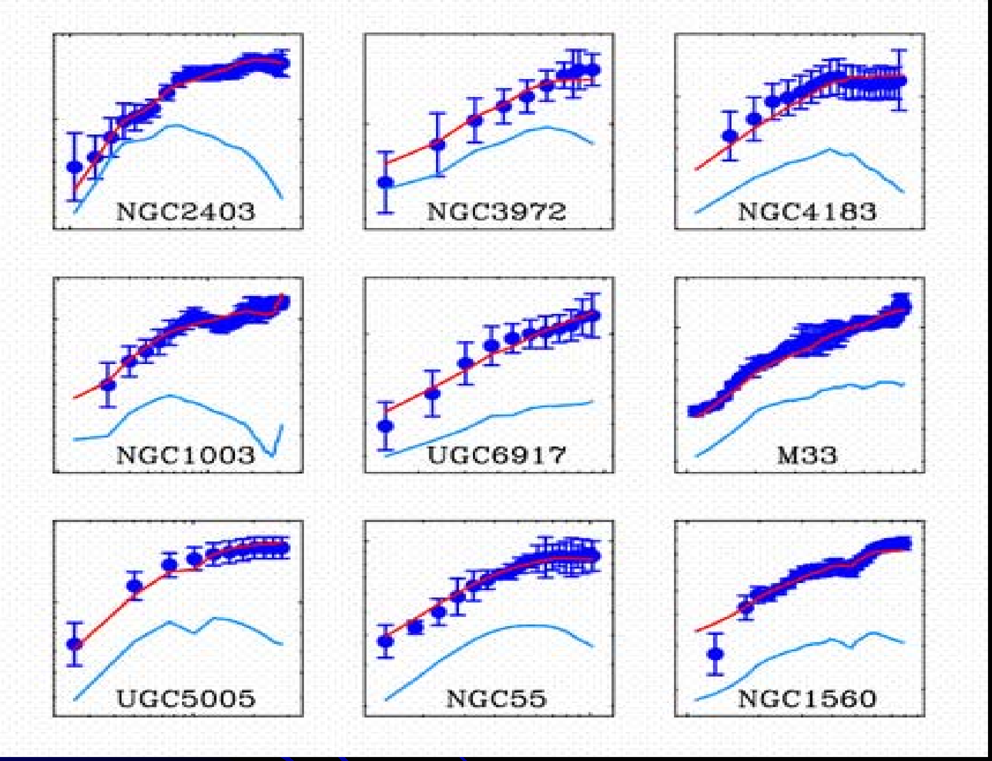
- If MOND works there should be observed correlation between acceleration and mass discrepancy. And indeed there is such a correlation.
- The acceleration scale turns out to be a_0 = 1.2 x 10-10 m s^{-2}, i.e., about one Angstrom per second per second

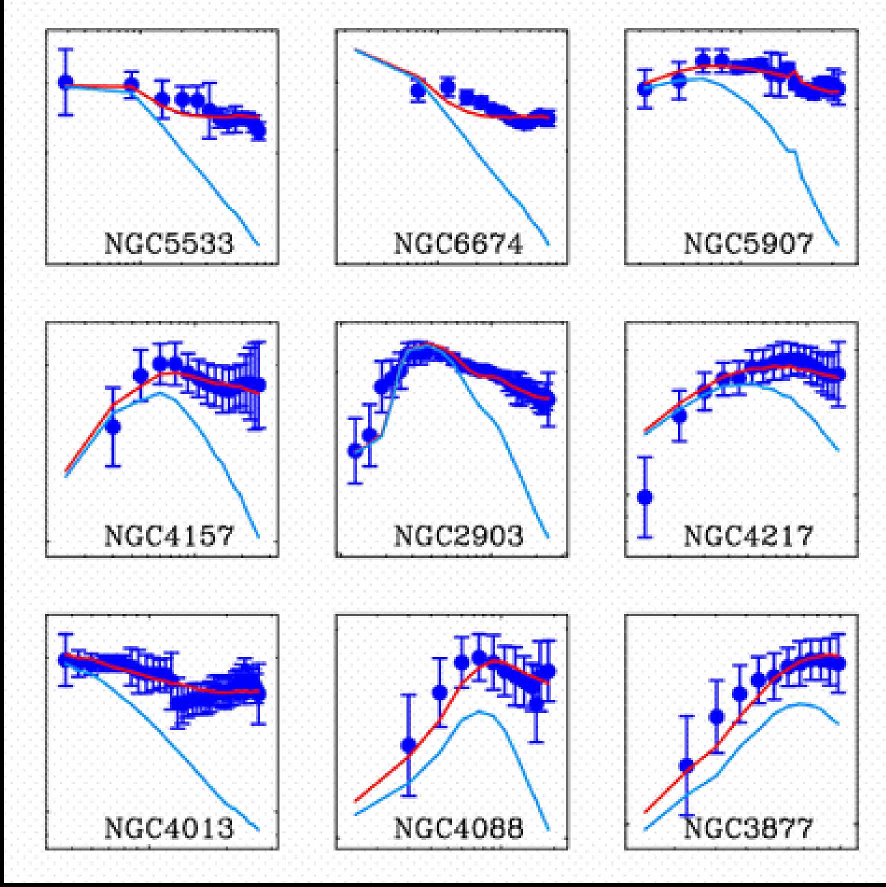


74 galaxies
> 1000 points
(all data)

60 galaxies
> 600 points
(errors < 5%)

Various galaxies rotation curves

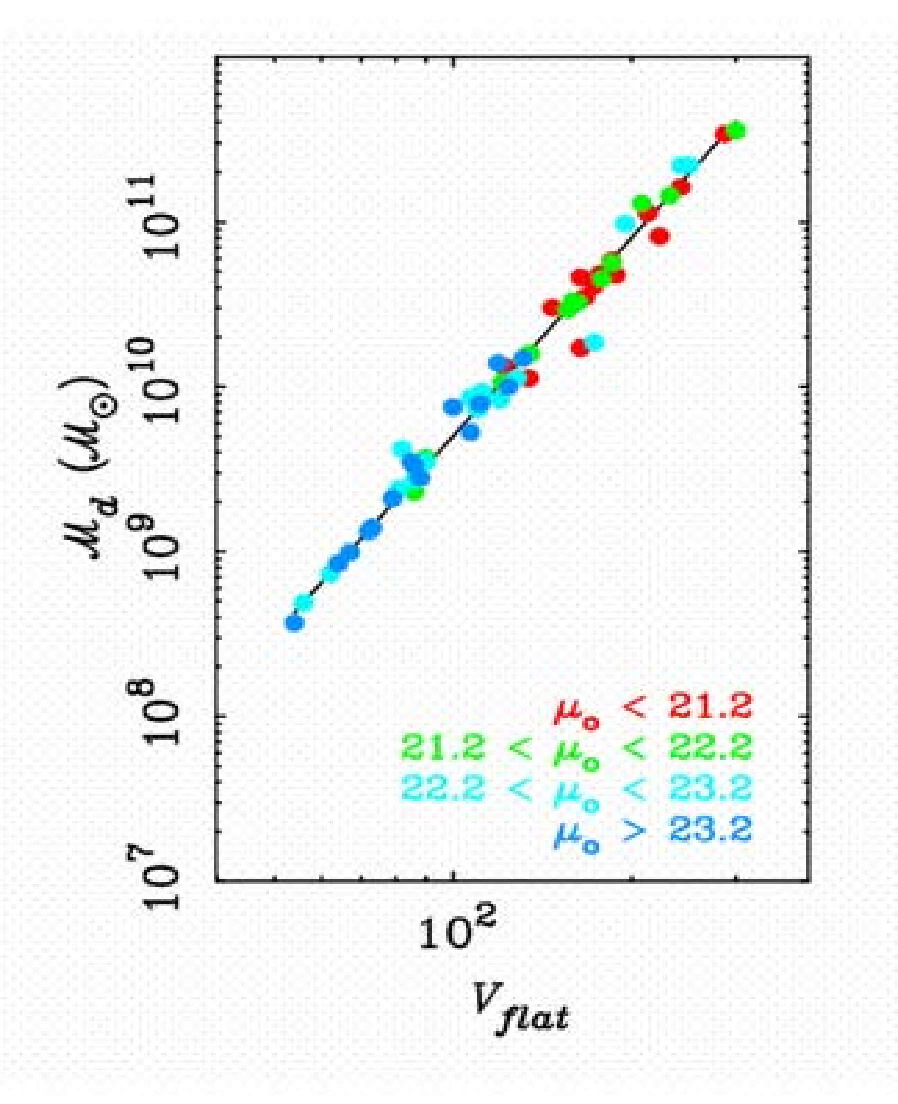




Tully-Fisher relation

- The asymptotic rotational velocity, V_∞, depends only on the total mass of the body, M, via $V^4_\infty = MGa_0$. This predicts a Tully-Fisher relation between velocity and luminosity if the M/L values are narrowly distributed (i.e., if there is proportionality between mass and luminosity.)

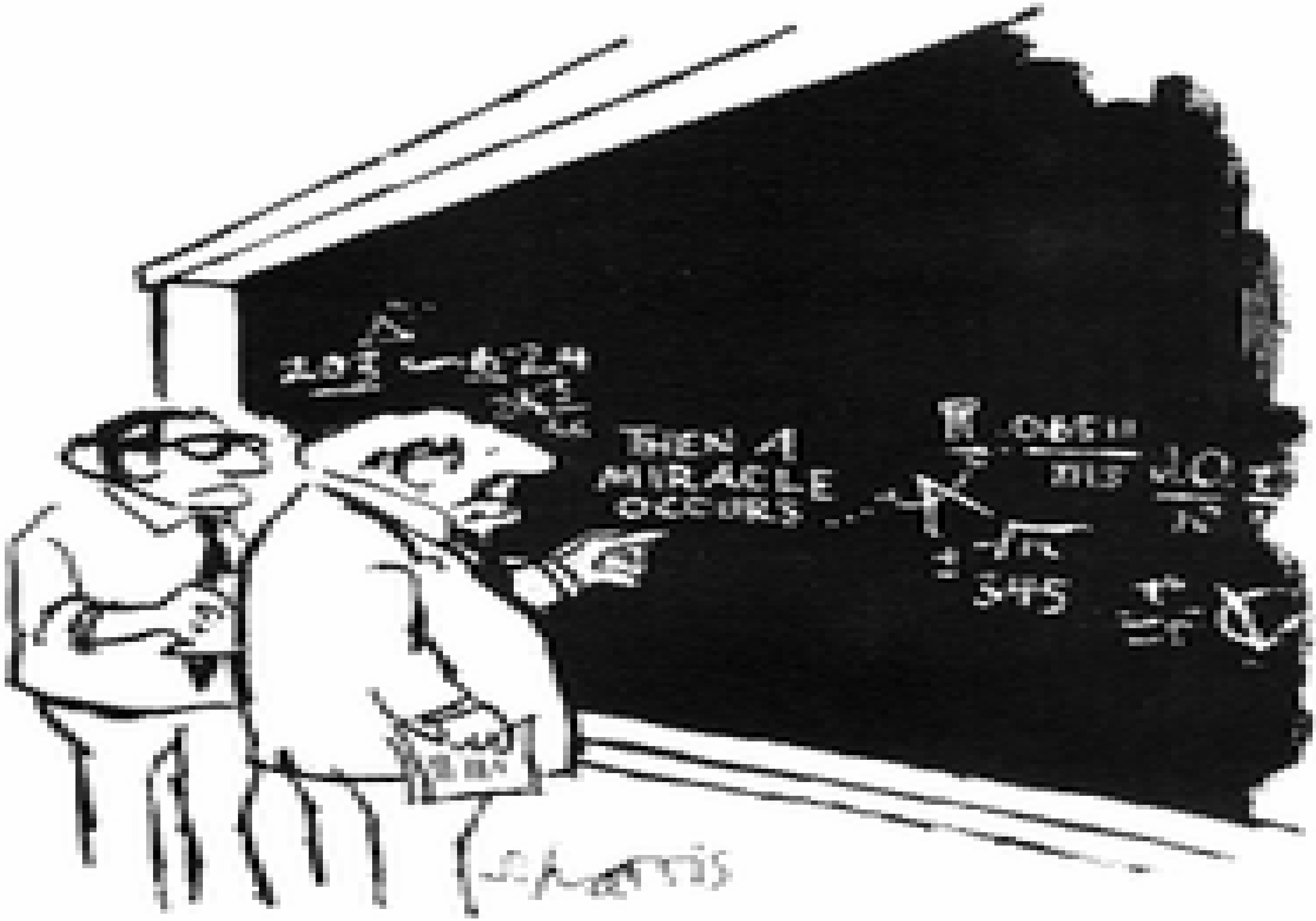
And indeed this is exactly what we see



<u>MOND works</u>. *Either*

MOND is correct, or

Dark Matter mimics MOND



"I think you should be more explicit here in step two."