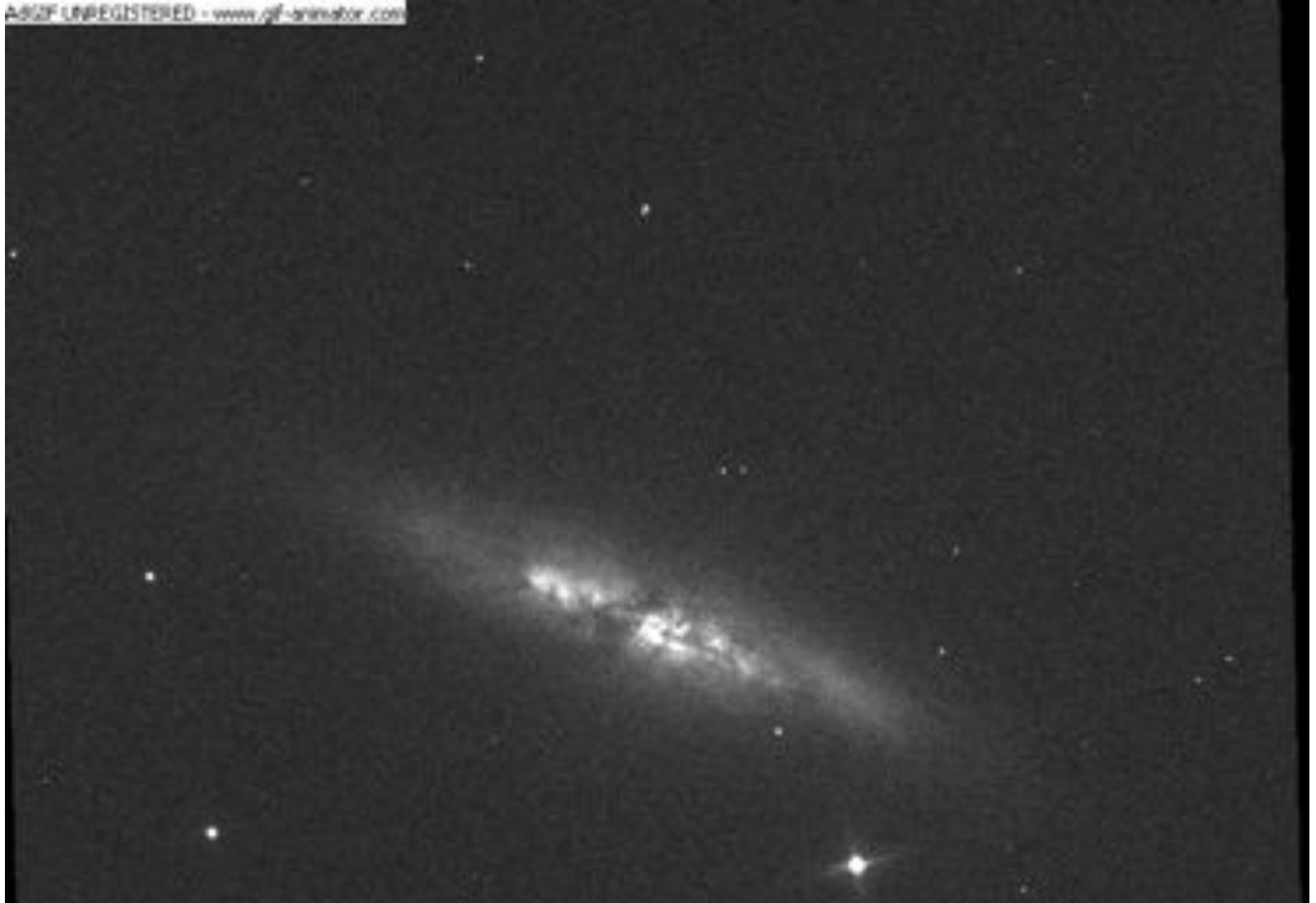


## *6. Star Colors and the Hertzsprung-Russell Diagram*

<http://apod.nasa.gov/apod/>



Supernovae Type Ia in M82  
January 22, 2014  
Still rising – may go to  $m = 8$  (or 10?)

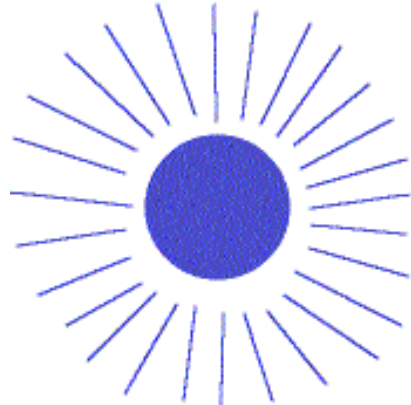
## ***What we can learn about stars from their light: II Color***

In addition to its brightness, light in general is characterized by its *color*.

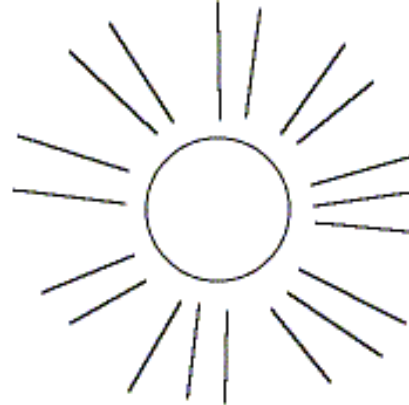
Depending on the *temperature* of the matter at the star's surface where the light last interacted (its "photosphere") starlight will also have a characteristic color. The hotter the star, the bluer its color. In fact, starlight is comprised of a variety of colors or "wavelengths". Its perceived color is the band of wavelengths where most of the emission is concentrated.

E.g., the sun's yellow light can be broken up into red, orange, yellow, green and blue light by a prism or in a rainbow

From Nick Strobel's  
Astronomy Notes



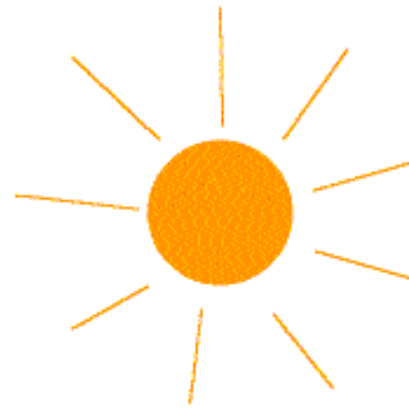
40,000 K



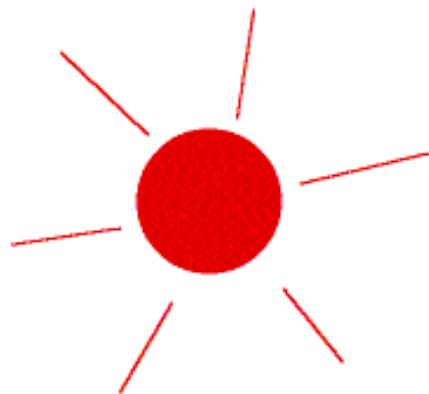
9,500 K



5,600 K



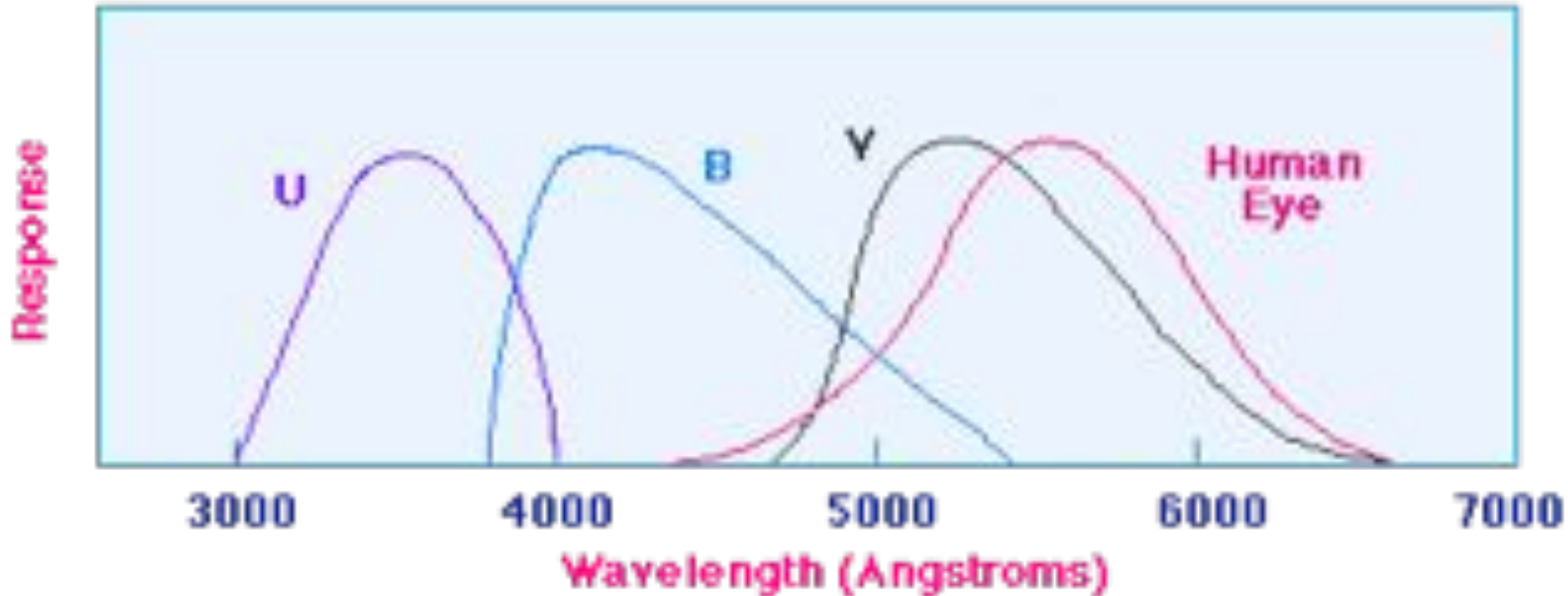
4,300 K



3,500 K

Hotter objects are  
brighter and "bluer"  
than cooler objects.

# FREQUENTLY USED FILTERS ON THE TELESCOPE (there are many more)



$$1 \text{ \AA} = 1 \text{ Angstrom} = 10^{-8} \text{ cm}$$

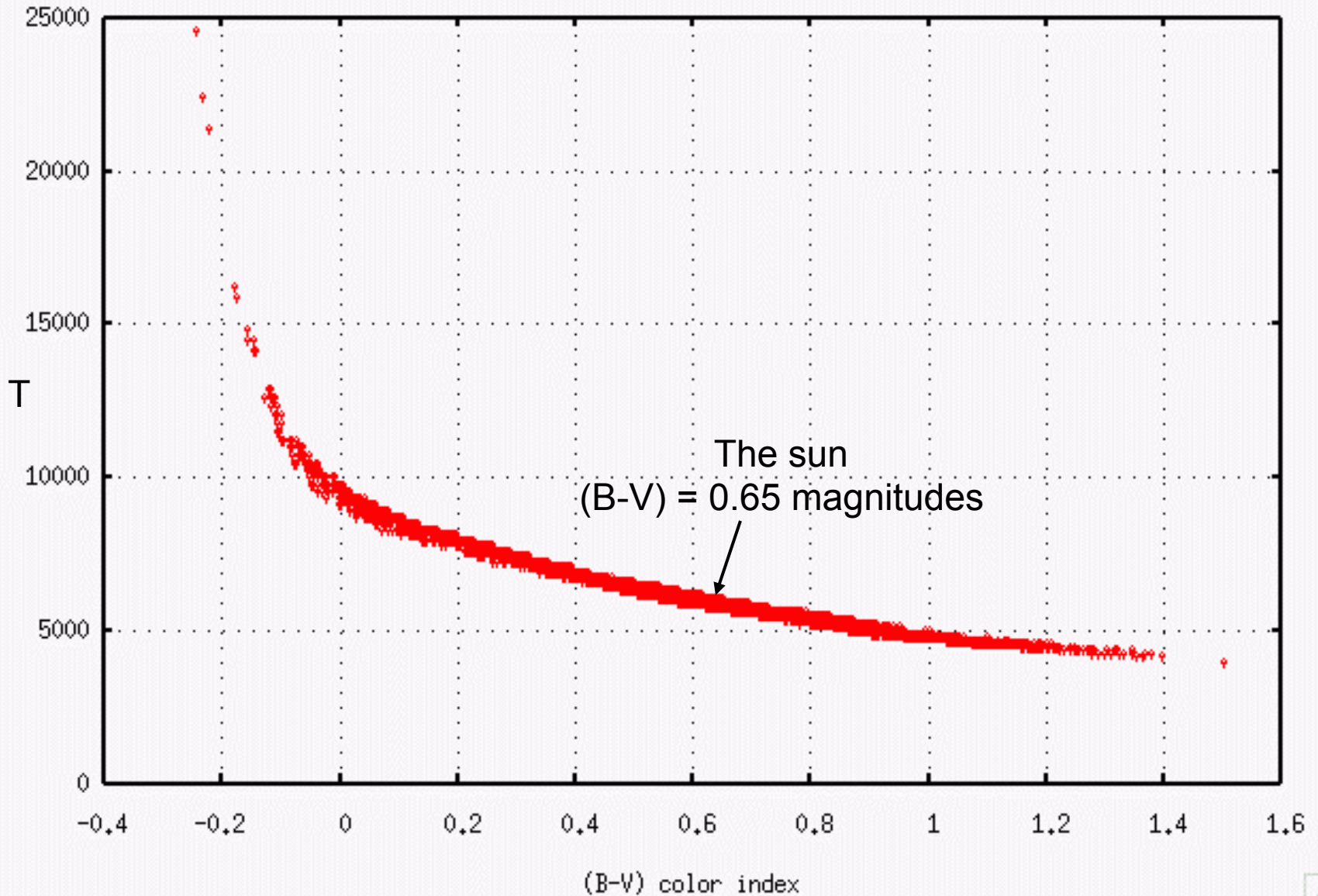
*Astronomers historically have measured the color of a star by the difference in its brightness (magnitude) in two images, one with a blue filter (B) and another with a visual filter (V). (i.e.,  $B = m_B$ ;  $V = m_V$ )*

*This difference, denoted (B-V), is a crude measure of the temperature.*

*Note that the “bluer” the object, the smaller B will be (small magnitudes mean greater fluxes), so small or more negative (B-V) means bluer and hence hotter temperature.*

# A SMALLER COLOR INDEX MEANS A HOTTER STAR

Temperature of stars in Hipparcos input catalogue



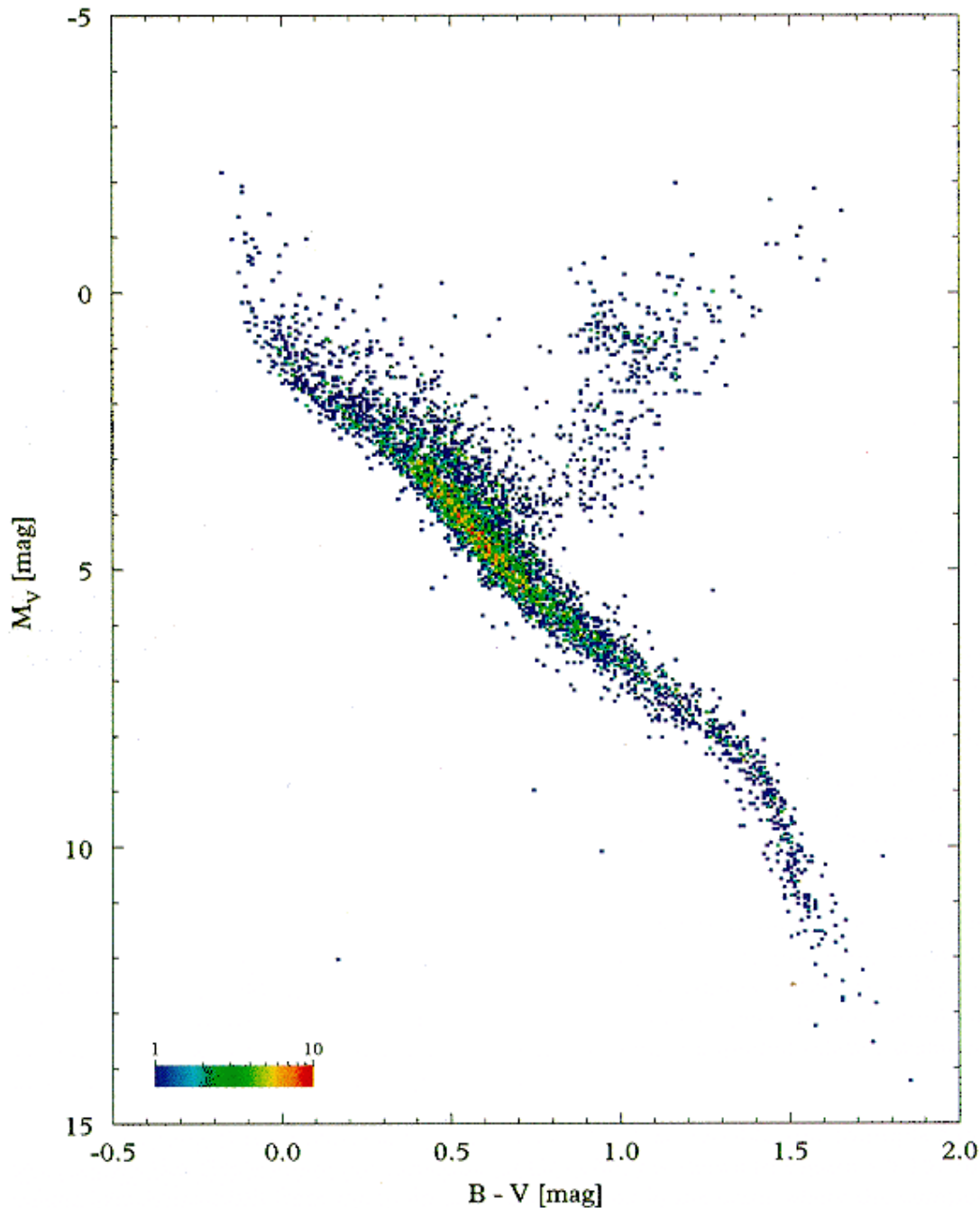
*The **Hertzsprung-Russell Diagram** - or HR-diagram - of a group of stars is a plot of their colors (or temperatures) vs. their bolometric absolute magnitudes (or luminosities)*

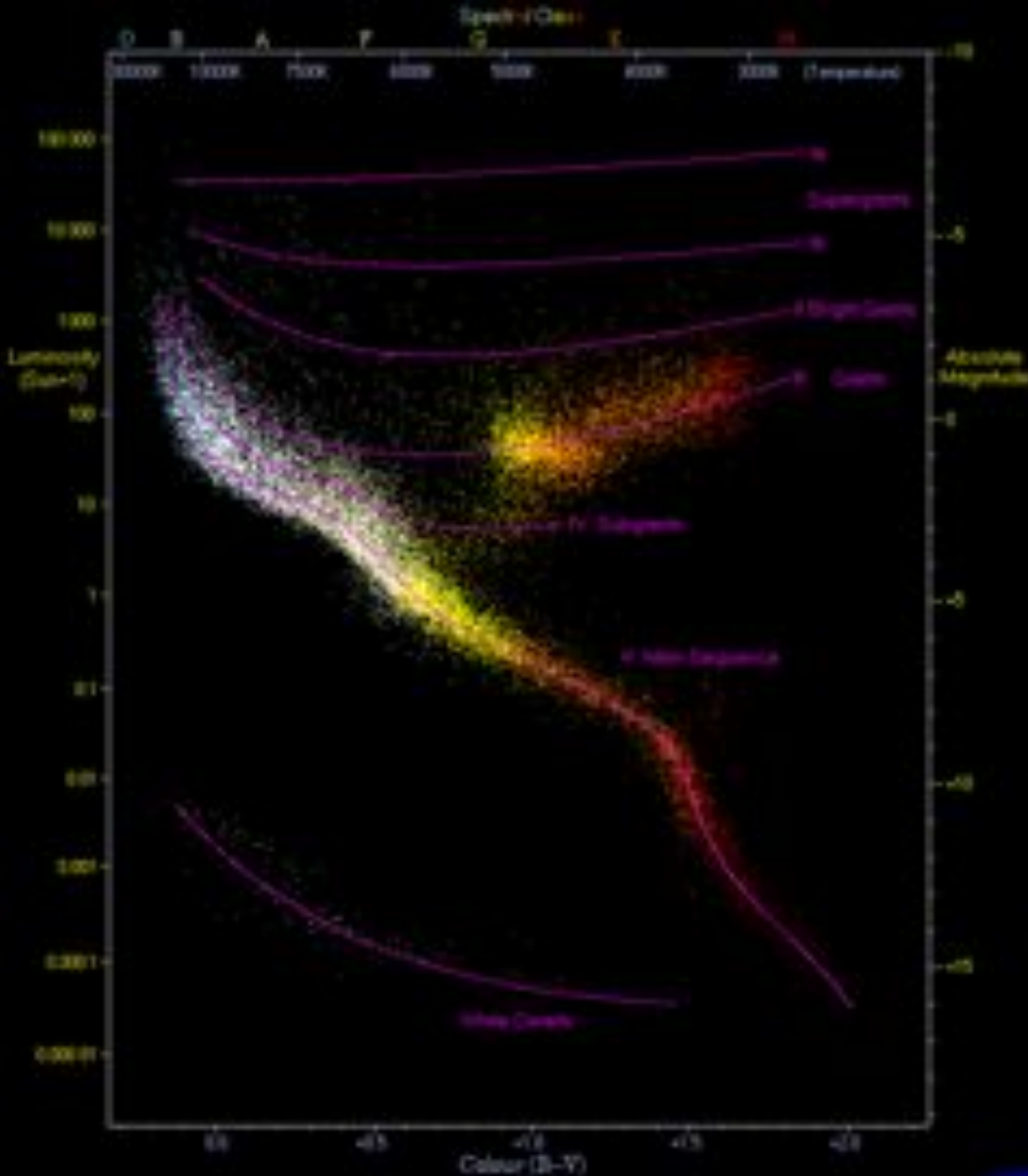


HR diagram for nearby stars from Hipparcos - 4477 stars, distance good to 5%. **Absolute visual magnitude vs. (B-V)**

(color indicates star density on the plot.  
1 red point = 10 stars)

Sun = 0.65, 4.83



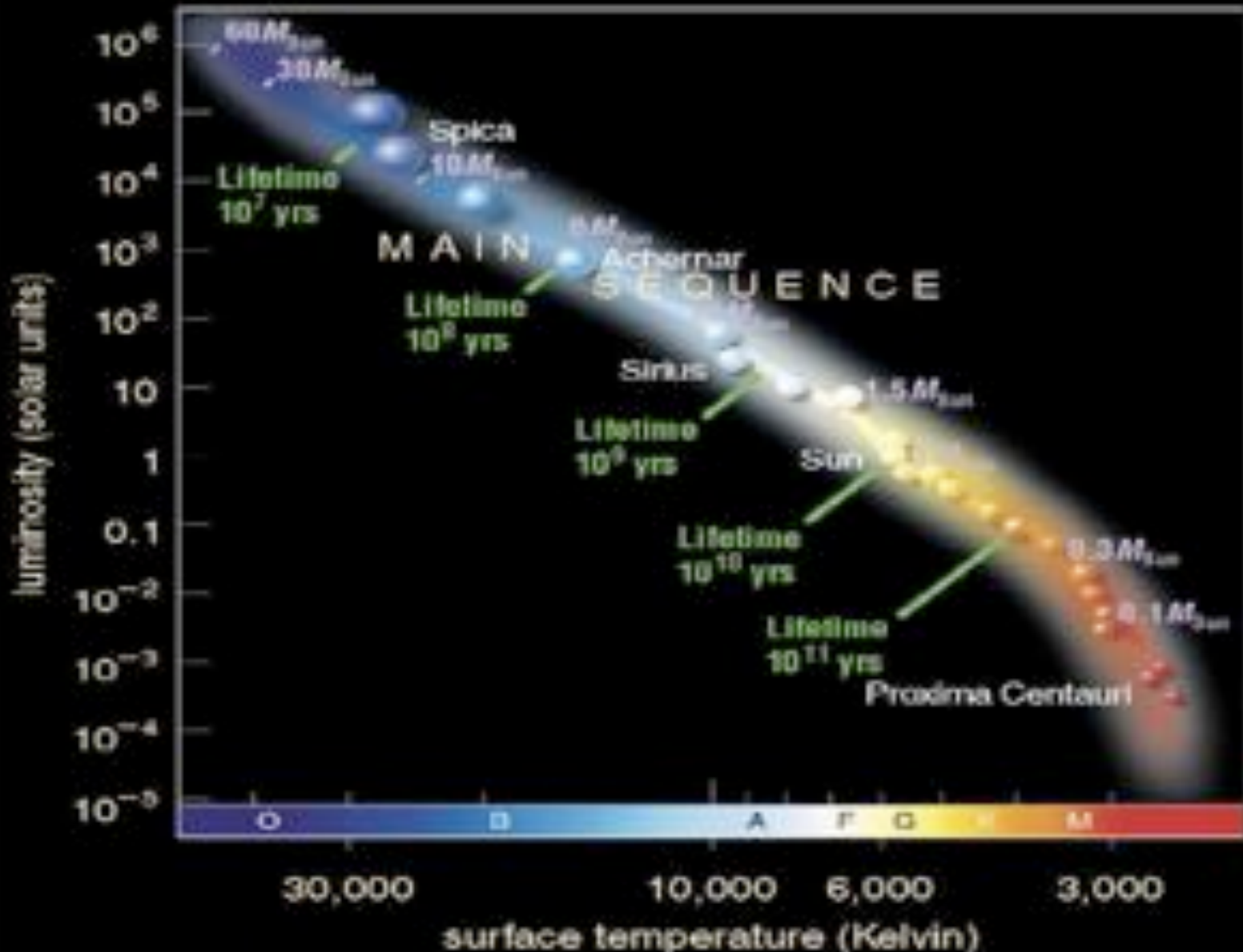


*Hertzsprung–Russell diagram with 22,000 nearby stars from the Hipparcos catalog supplemented with 1000 stars from other catalogs.*

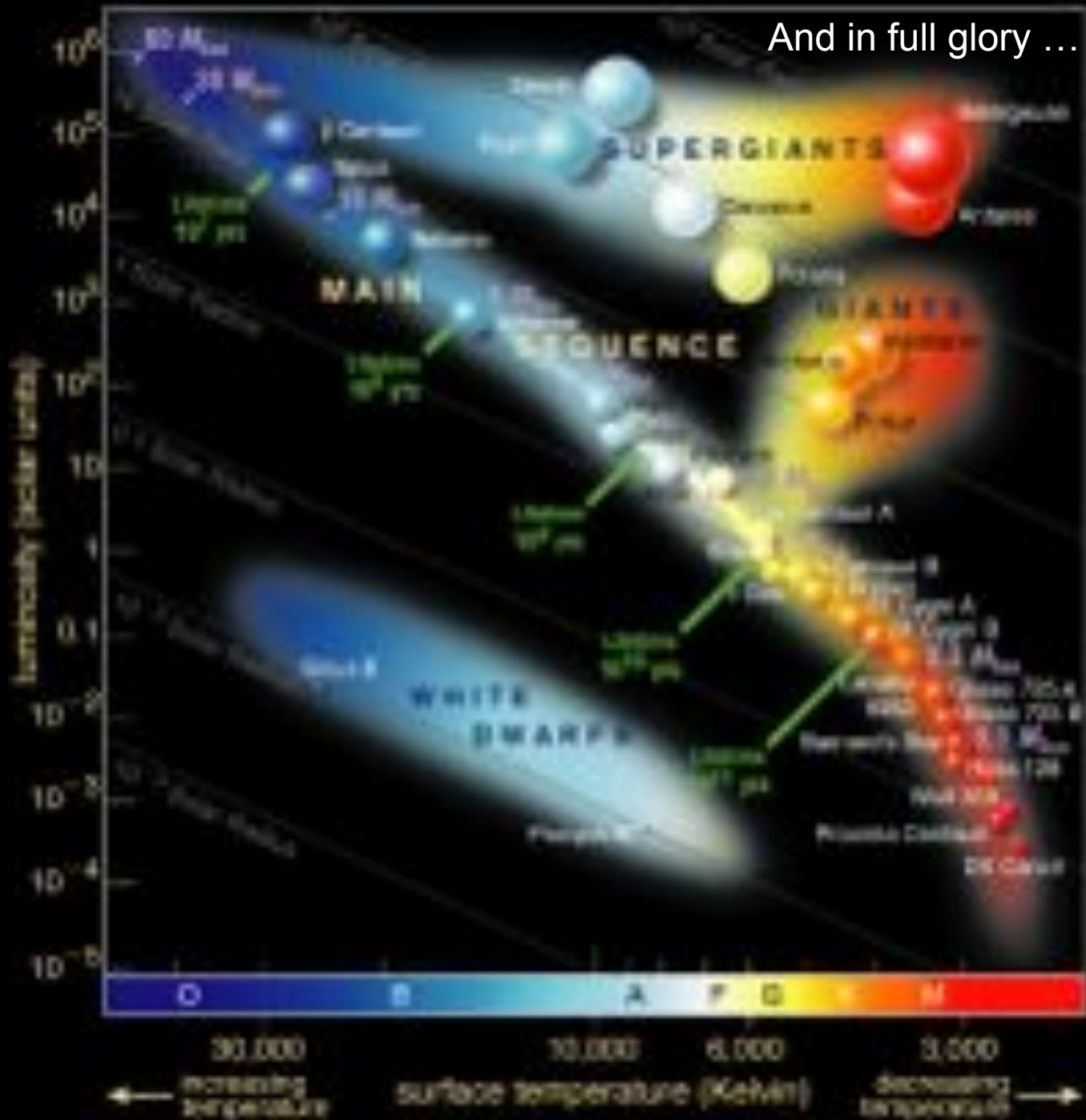
*Absolute **bolometric** magnitude has been converted into luminosity,*

*Note that the stars prefer to congregate in well defined strips*

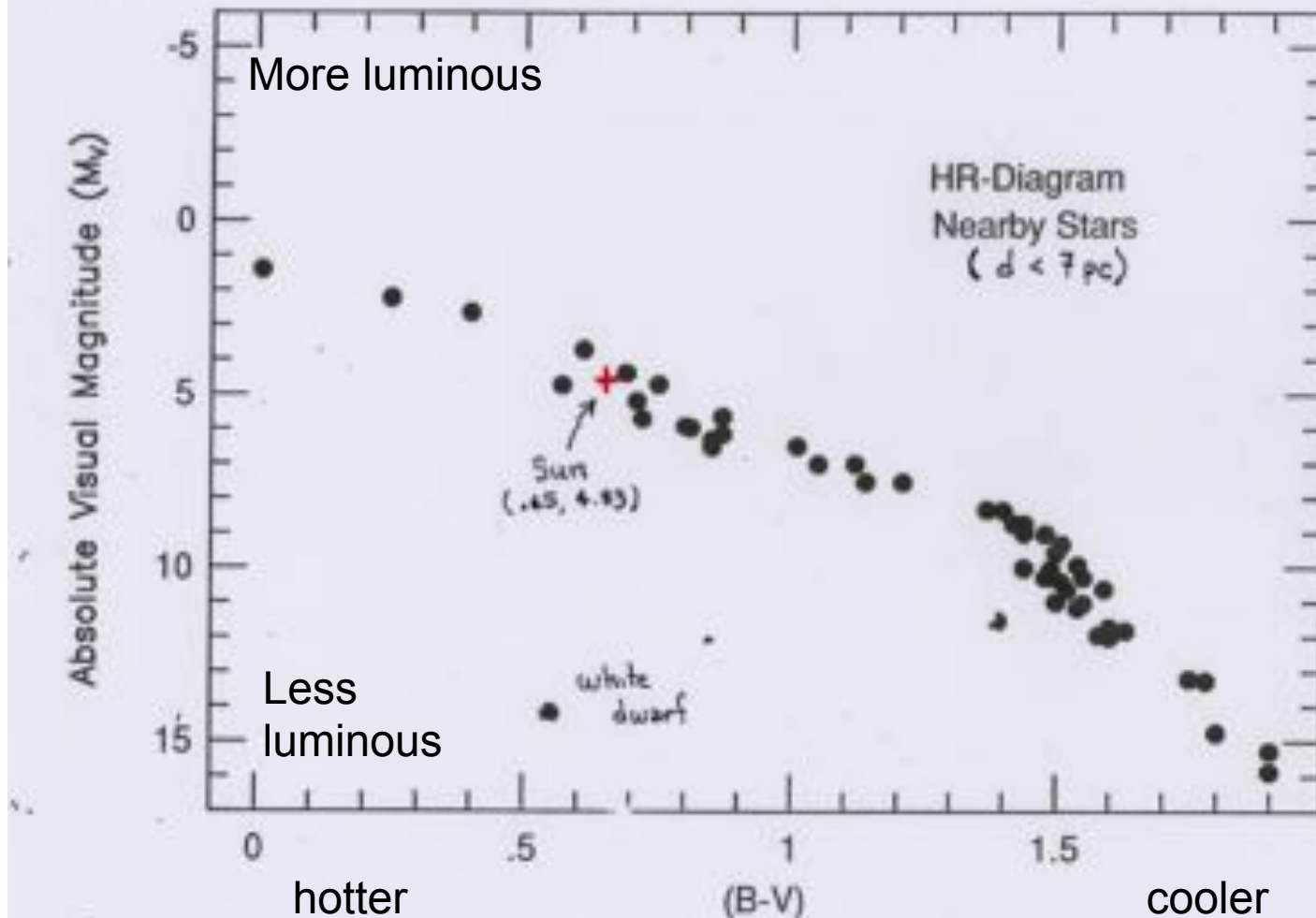
Looking ahead, color can be converted to temperature and absolute magnitude to luminosity to give the Hertzsprung-Russel diagram in more physical units



And in full glory ...



## Hertzsprung-Russell Diagram for Local Stars (a volume-limited sample)



In many cases, the stars themselves can be used as standard candles, once the HR-diagram is calibrated. But need to know it is a *main sequence* star.



### Hyades

Open cluster

Constellation Taurus

Magnitude 0.5

Angular size 330'

### Pleiades:

Open cluster

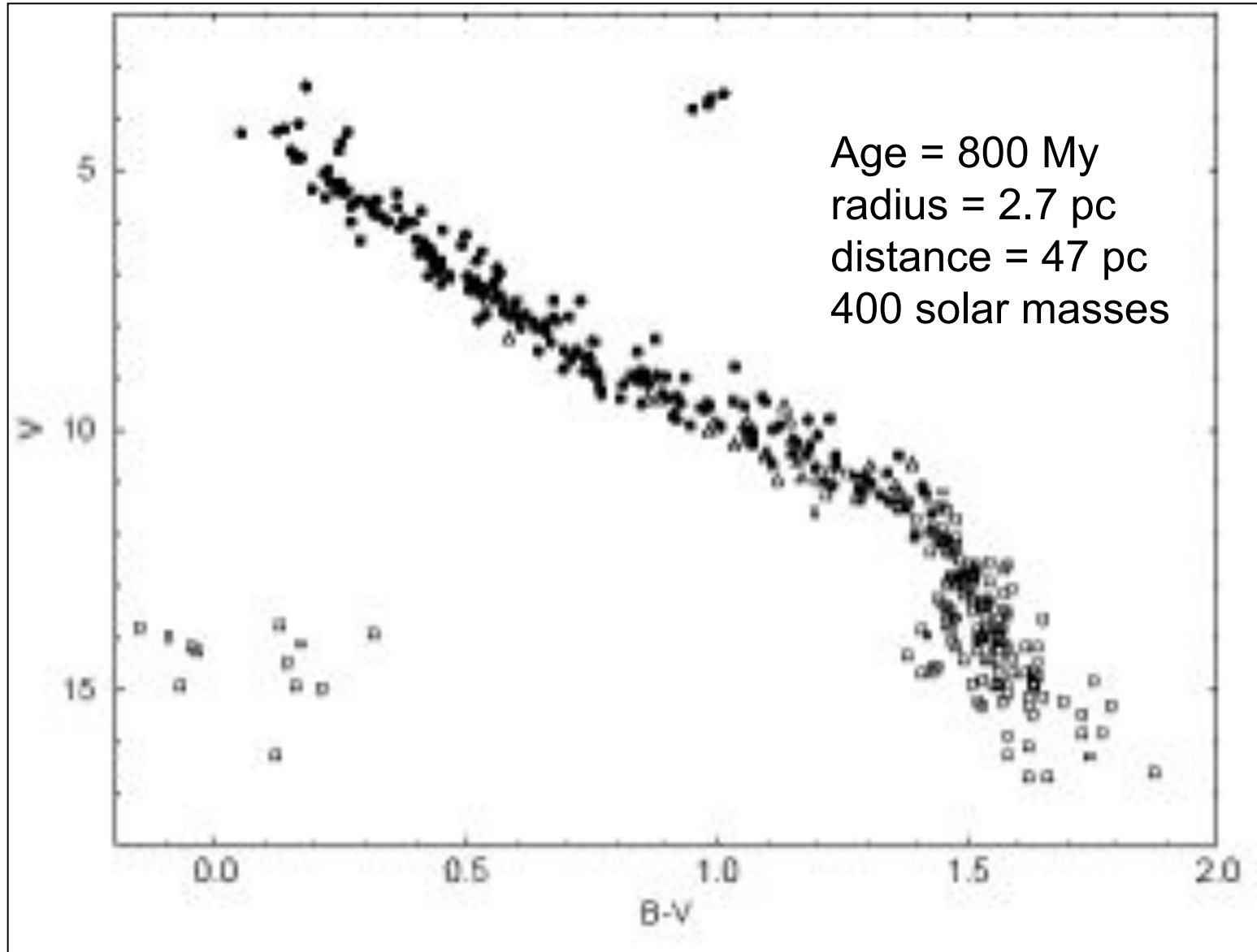
Constellation Taurus

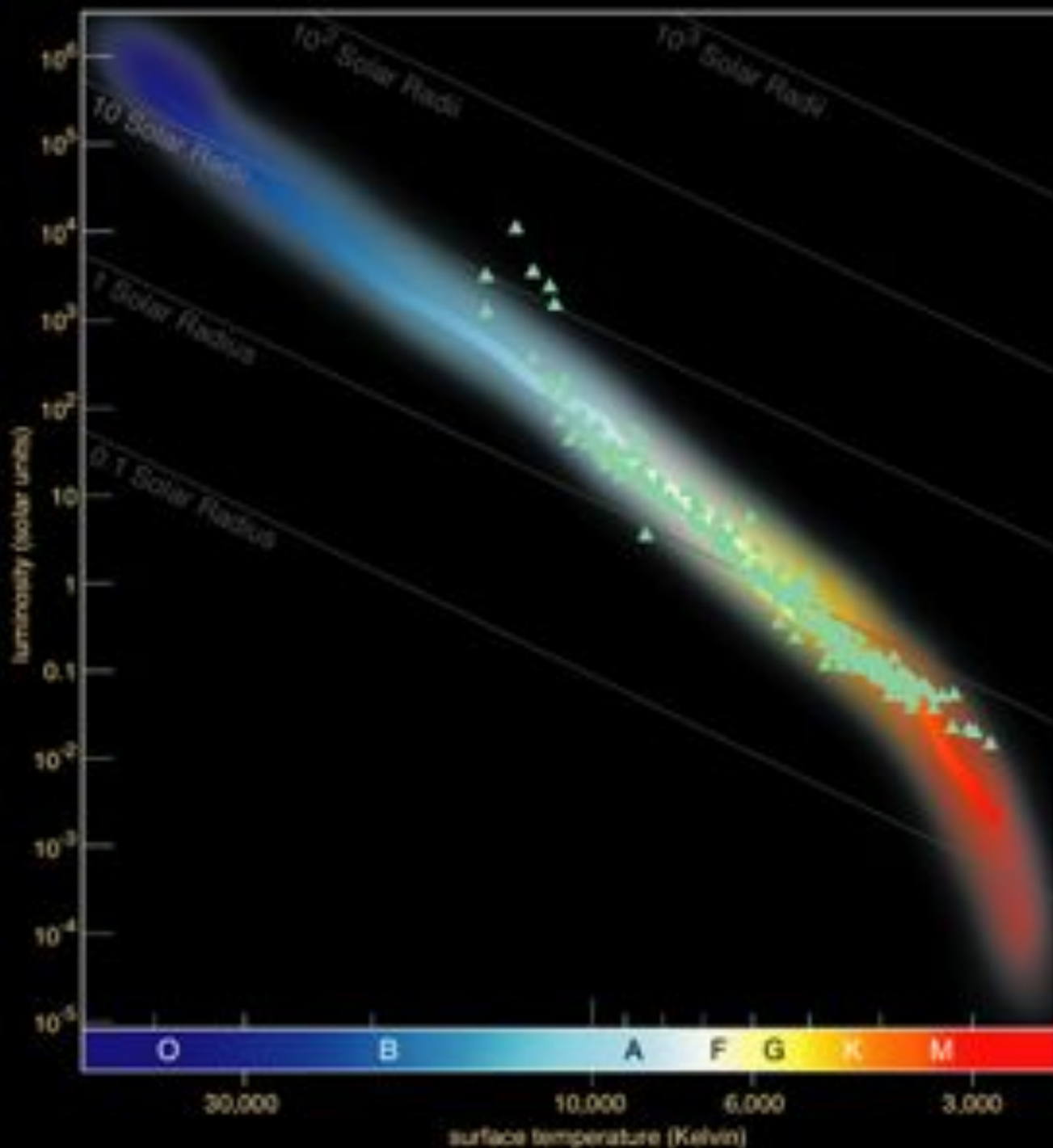
Magnitude 1.6

Angular size 110'

*Stars in each cluster were born together and are approximately equidistant*

# Hyades Cluster



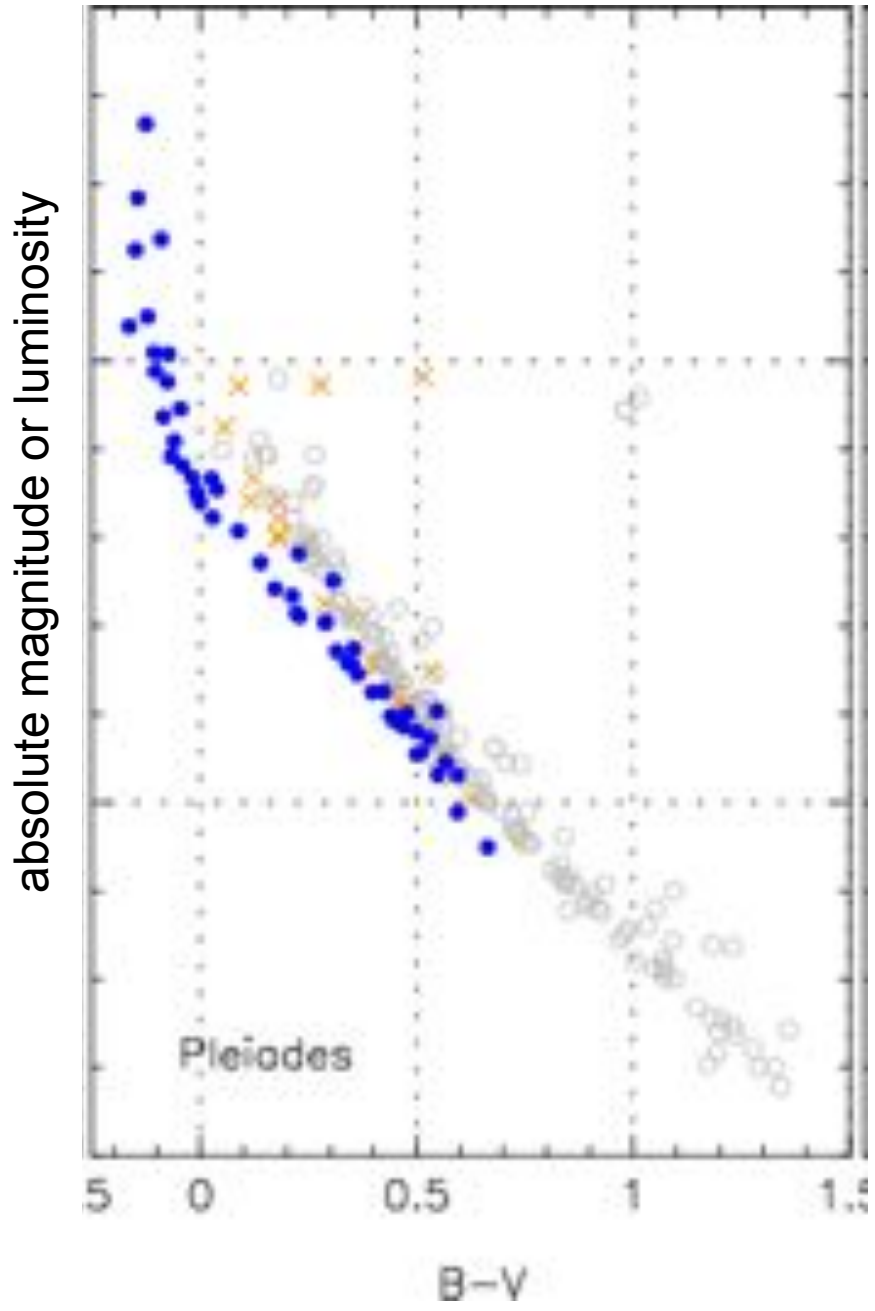


*HR Diagram for the Pleiades – an open cluster of about 1000 stars.*

*No red giants or white dwarfs. Some of the more massive stars are starting to evolve away from the main sequence*

*Age = 65 My*





Open circles are Hyades; blue points are Pleiades

One can also use the HR-diagram of a cluster (or even individual main sequence stars) to get distances.

Because of the spread in the main sequence width, the distances are not very precise (compared, e.g., with Cepheids) but there are a lot more ordinary stars than Cepheids and some of them are very luminous.

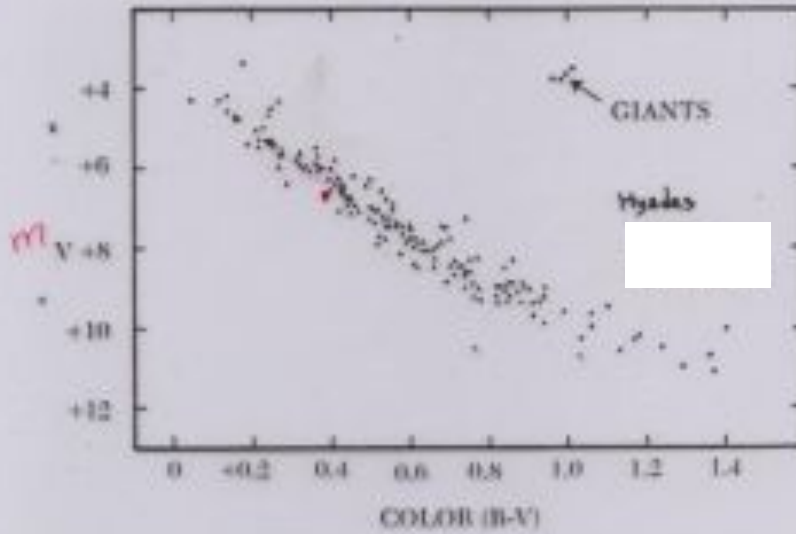
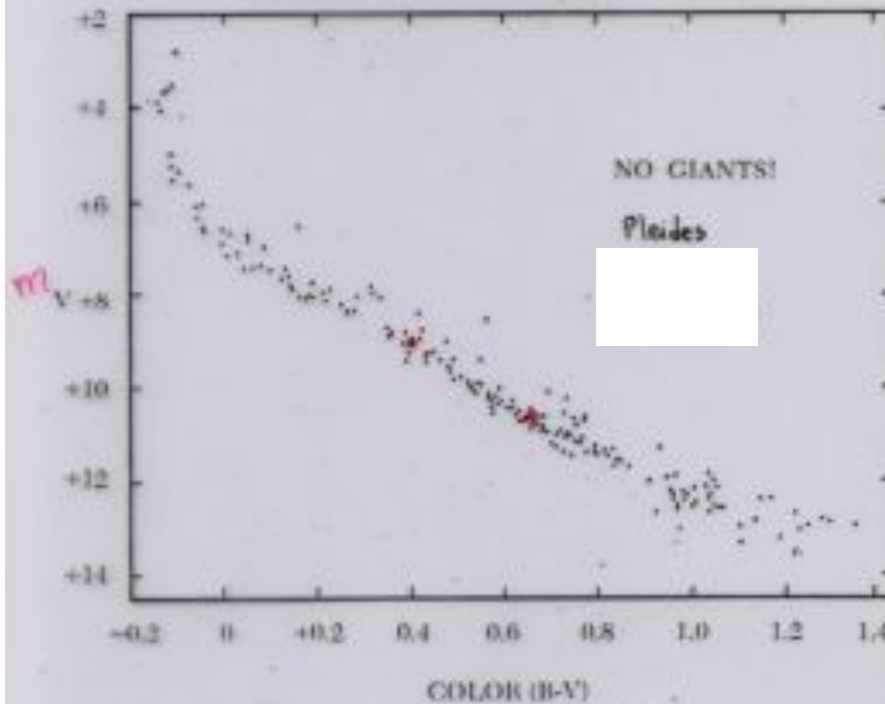


Figure 12-13. Color-Magnitude Diagram for the Hyades. Note the later main-sequence turnoff and the giants. (After H. L. Johnson)



Which is older?

Which is closer?  
By how much?

compare at  
 $B-V = 0.4$

$m = 6.5$   
and 9

E.g., at B-V = 0.4 (assume MS stars with same B-V have same absolute M)

Hyades  $m = 6.5$

Pleiades  $m = 9$

$$\Delta m = m_H - m_P = -2.5$$

$$m_2 - m_1 = 2.5 \log(\phi_1/\phi_2) \quad \text{let 2 = Hyades}$$

$$m_H - m_P = -2.5 = 2.5 \log(\phi_P/\phi_H)$$

$$\log(\phi_P/\phi_H) = -1.0$$

$$\text{So } \phi_P/\phi_H = 0.1$$

But for main sequence stars of a given B -V, L is constant,  
and since

$$\phi \equiv \frac{L}{4\pi d^2}$$

the distance to the Pleiades must be farther by a factor

of  $\sim\sqrt{10}$ , or about 3 times farther away. (Hyades 47 pc; Pleiades 140 pc)

We could also just use the sun and Pleiades cluster to get a distance. For its color, the sun would have an apparent magnitude in the Pleiades of 10.3 (see graph)

$$(B-V)_{\odot} = 0.65 \quad M_V = 4.83$$

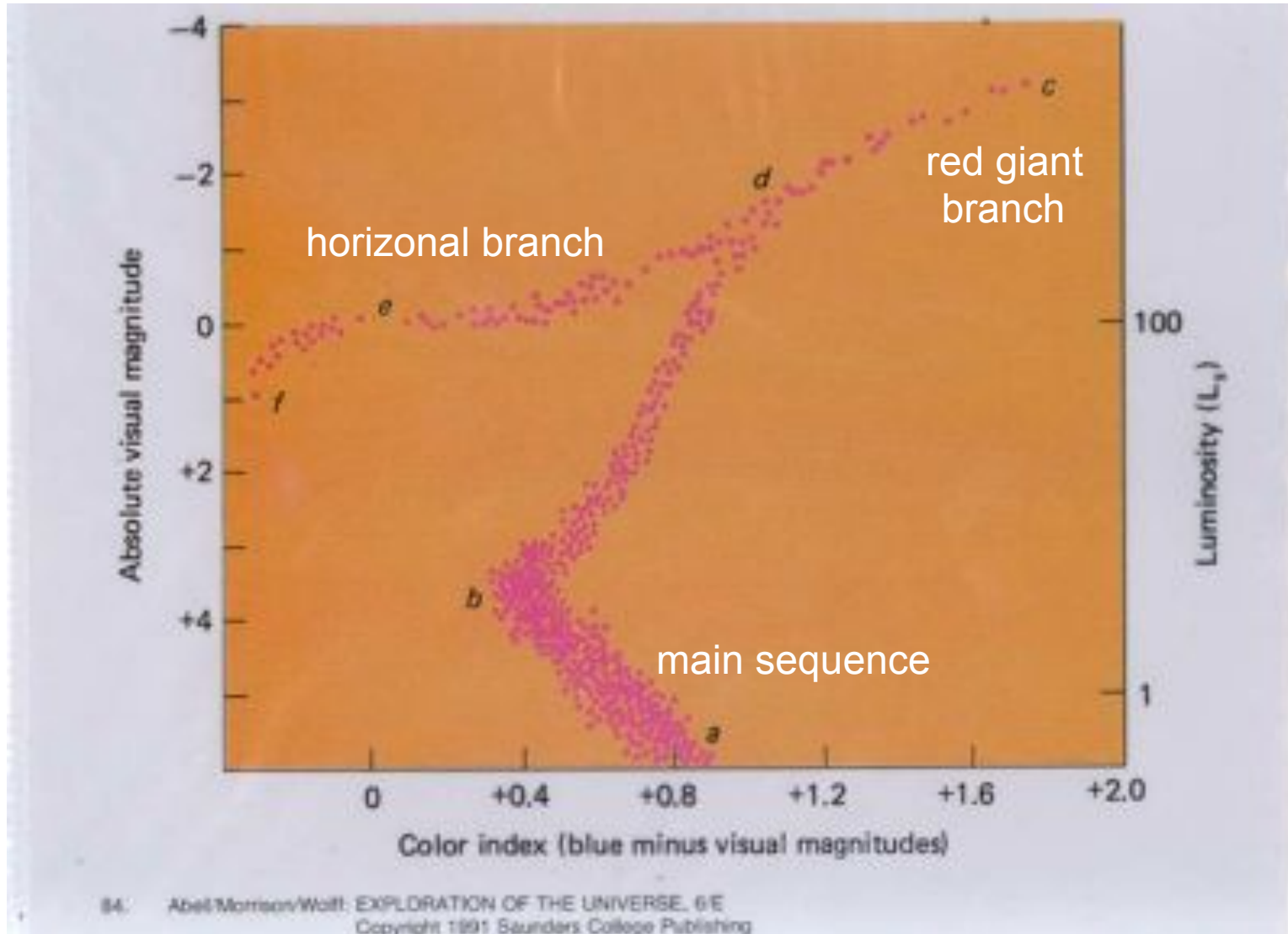
$$M - m = 5 - 5 \log (d)$$

$$\frac{4.8 - 10.3 - 5}{-5} = 2.1 = \log (d)$$

$$d = 126 \text{ pc}$$

or use any other star whose absolute magnitude is known

## An old cluster



If the cluster is highly evolved and most of the massive stars are gone, one can still use that portion of the main sequence that remains unburned.

Age of cluster = main sequence life time of the heaviest star still on the main sequence

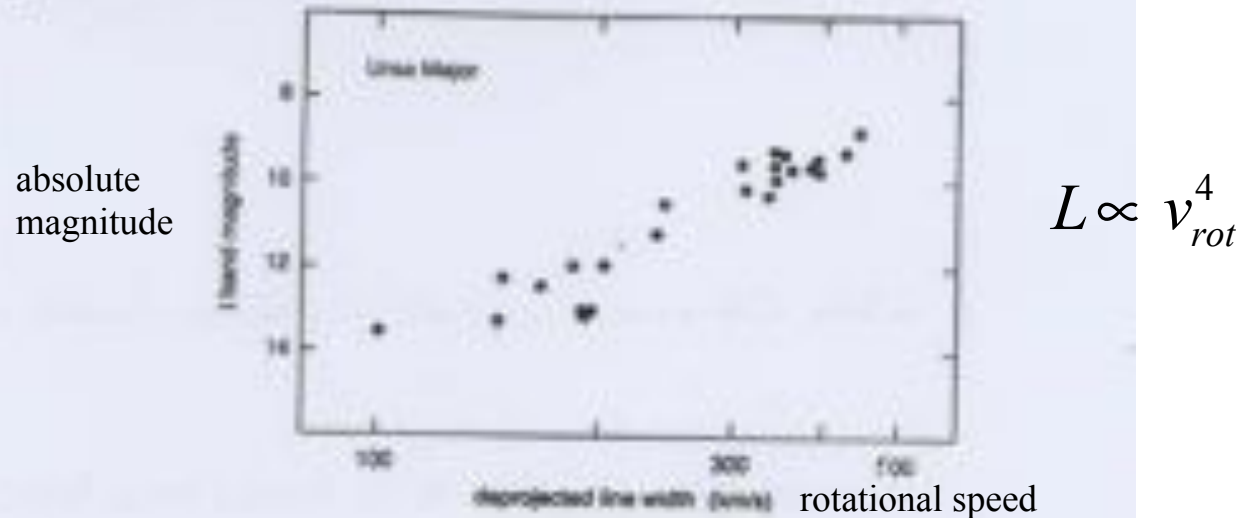
E.g., if that mass is 1.0 solar masses the cluster's age is the main sequence lifetime of a 1.0 solar mass star which is very nearly 10 billion years  
if the turn off mass is instead 0.8 solar masses

$$\tau \approx 10^{10} \text{ yr} \left( \frac{1M_{\odot}}{0.85M_{\odot}} \right)^2 = 13.8 \text{ billion years}$$

Turn off masses are our main tool for dating the ages of star clusters

## Other distance indicators

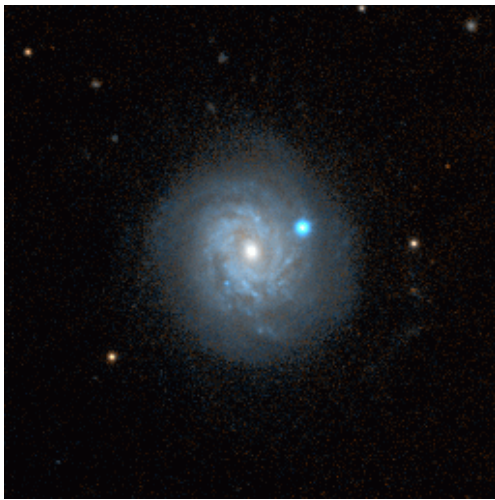
- Brightest half dozen or so galaxies in a cluster of galaxies (very uncertain)
- Tulley-Fisher relation - relates  $L$  of a galaxy to its rotation rate



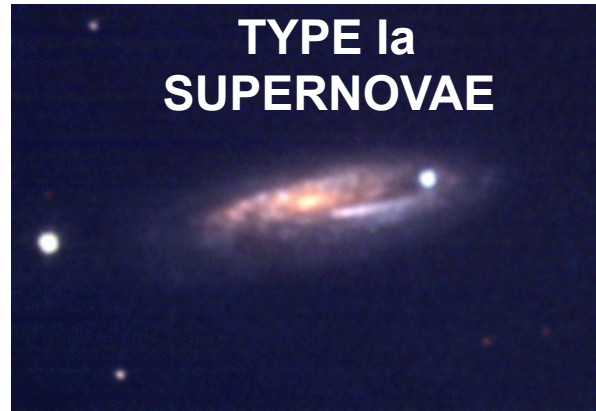
The rotational velocity of spiral galaxies, as measured by spectral line broadening, is a measure of the mass of the galaxy, and the mass in turn correlates with the luminosity.

A similar relation called the Faber-Jackson relation holds for the stellar velocity distribution in elliptical galaxies





*SN 1998aq*



*SN 1998dh*



*SN 1998bu*



*SN 1994D*

For several weeks the luminosity of a Type Ia supernova rivals that of a large galaxy -  $10^{43}$  erg s<sup>-1</sup>, or several billion solar luminosities.

It is currently quite feasible to measure supernova light curves down to a magnitude  $m = 22$ . If the absolute magnitude of a typical Type Ia supernova is  $M = -19.5$ , how far away can we use them as standard candles for getting distance?

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

$$-19.5 - 22 = 5 - 5 \log(d)$$

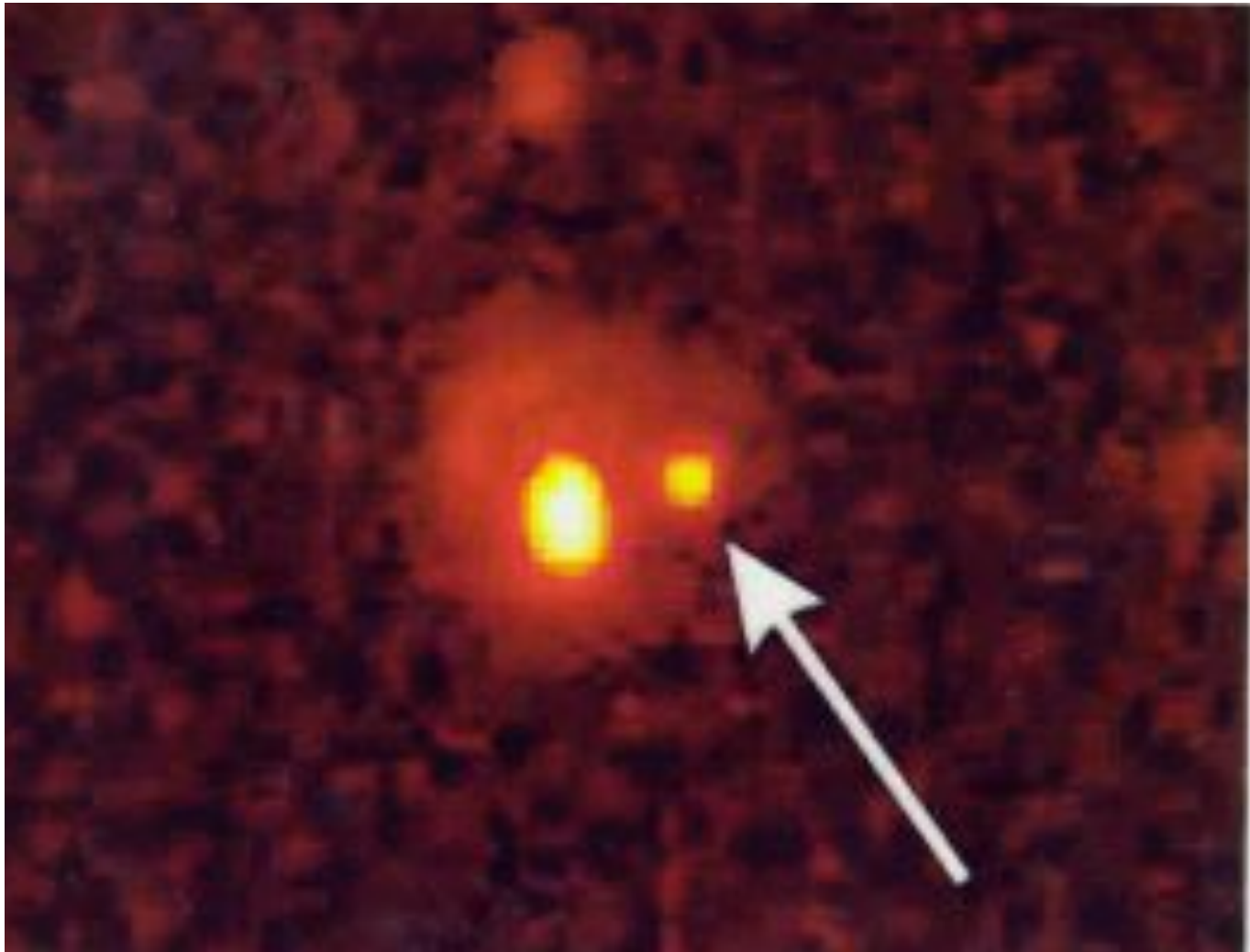
$$-41.5 - 5 = -5 \log(d)$$

$$\log(d) = \frac{-46.5}{-5} = 9.3$$

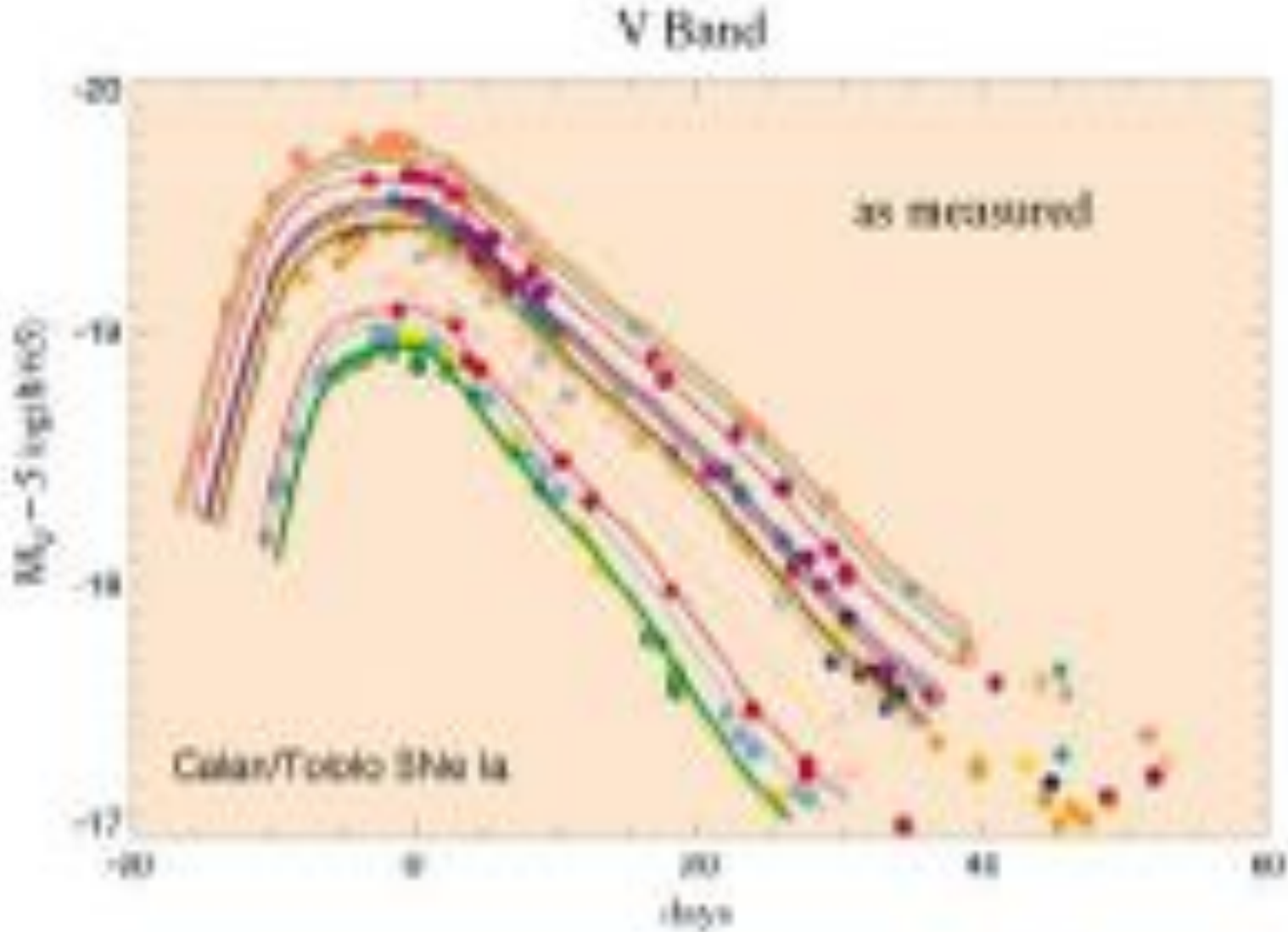
$$10^{9.3} = 2 \times 10^9 \text{ pc}$$

So, two billion parsecs or about 6 billion light years

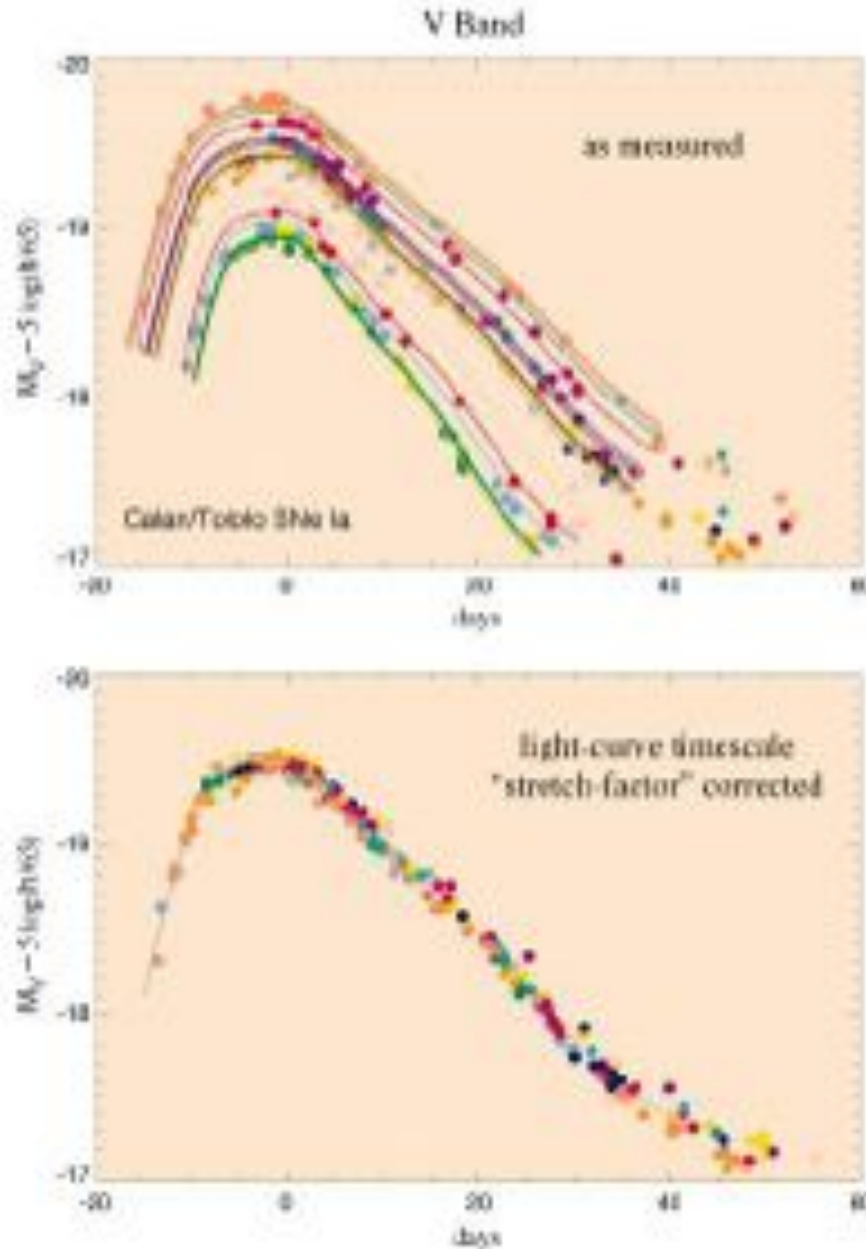
Type Ia supernova in a galaxy 7 billion light years away ( $z = 0.5$ ) - Garnavitch et al (1998)



# TYPE Ia SUPERNOVAE ARE ALMOST STANDARD CANDLES



## AND IT CAN BE MADE EVEN BETTER ...



The width of the light curve is correlated with its peak luminosity.  
“Brighter = Broader”

This relation, known as the “Phillip’s relation” exists because both the brightness and width are correlated with the amount of radioactivity ( $^{56}\text{Ni}$ ) each supernova makes (to be discussed).

Using this correlation, much of the spread in the observations can be narrowed.

## Distance Determination Summary

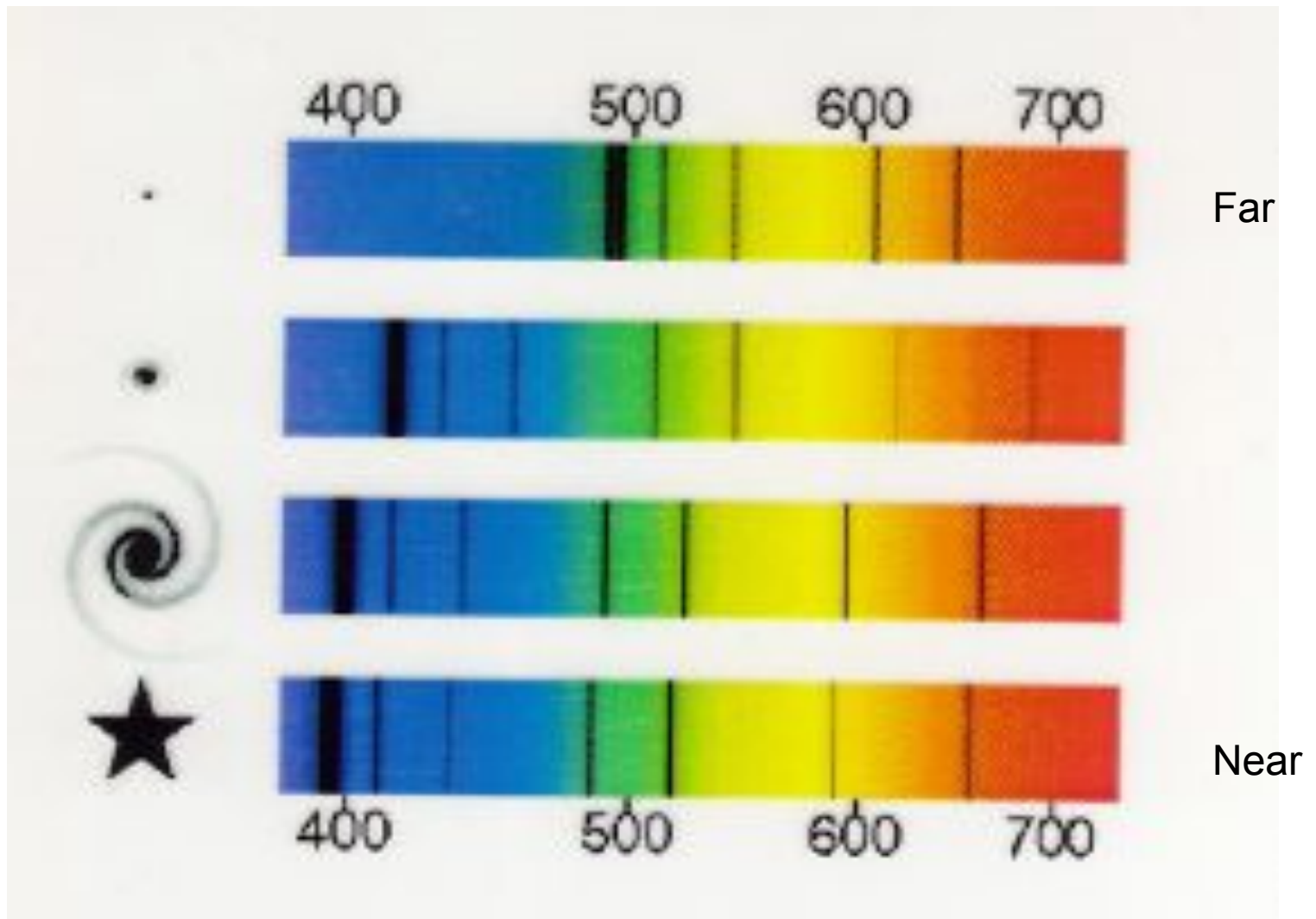
- **The AU by radar and Kepler's Third Law**
- **Ordinary trigonometric parallax.** After Hipparchos, this is good to 1000 pc. Angles of 1 mas can be accurately measured. Distances determined for about 10,000 stars.
- **Color magnitude diagram (HR-diagram)** - reliable to 10% for distances up to 50 kpc
- **Cepheid variables.** Good to about 50 Mpc using Hubble Space Telescope. Gets us to the Virgo Cluster of galaxies (about 1000 galaxies). Historical problem with calibration because of 2 populations and lack of nearby Cepheids. Hipparchos improved the situation.

- **Tully-Fisher Relation**. Relates absolute magnitude to rotational velocity for spiral galaxies.  $L \propto v_{\text{rot}}^4$ . Used with decreasing accuracy out to 1000 Mpc. Caution - galaxy based standard candles are subject to evolution. Measure  $v_{\text{rot}}$  in the radio or optical

**Faber-Jackson Relation** is a similar technique for elliptical galaxies.

- **Type Ia supernovae**. Assume a calibrated standard candle. Average  $M_{\text{bol}}$  is -19.6, but can correct for dispersion about this using “templates”. Bright SNaE of Type Ia have broader light curve peaks. Good to 10% to several 1000 Mpc. Evolution?

- Eventually the expansion of the universe becomes apparent. One measures a **cosmological red shift** that is correlated with the distance

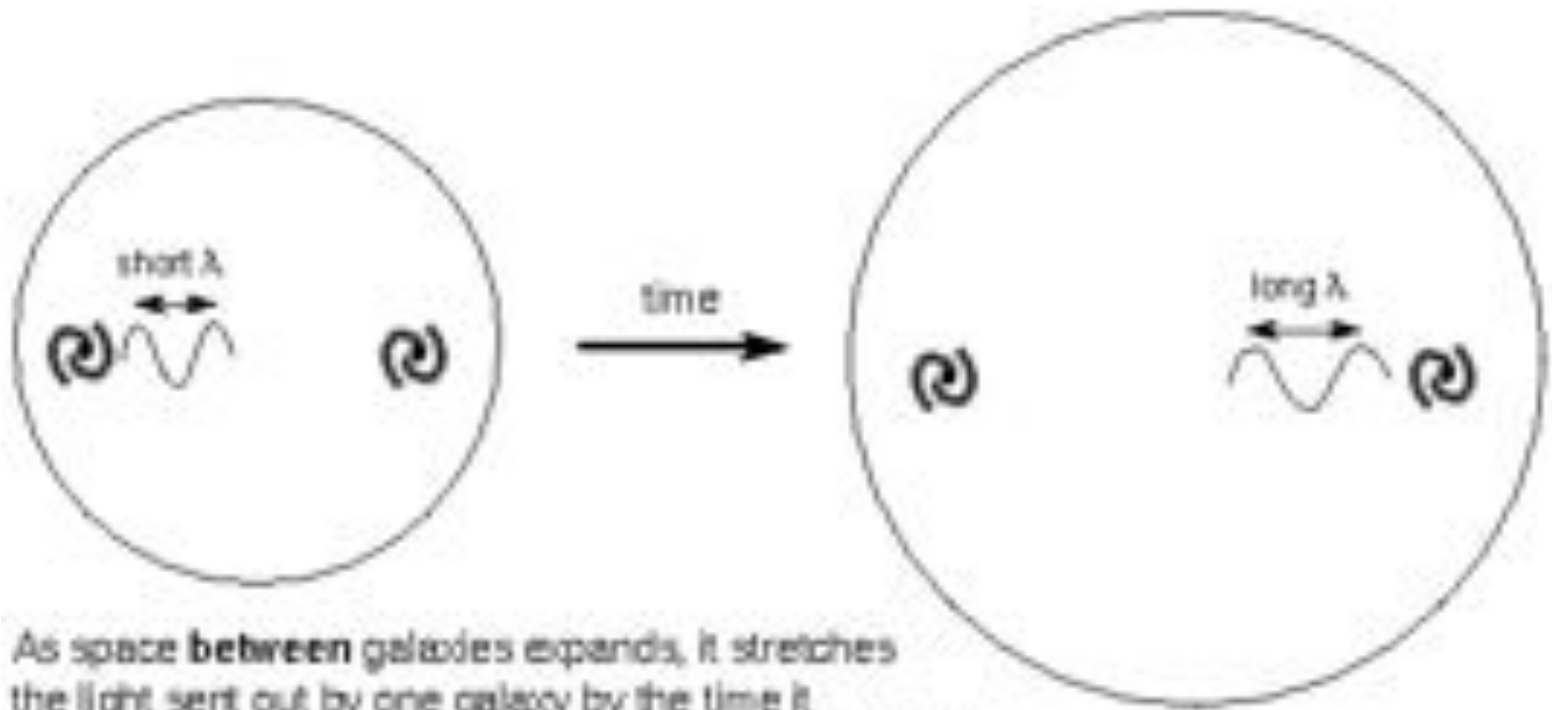


wavelength is in units of  $10^{-7}$  cm (nanometers)



From Nick Strobel's  
*Astronomy Notes*

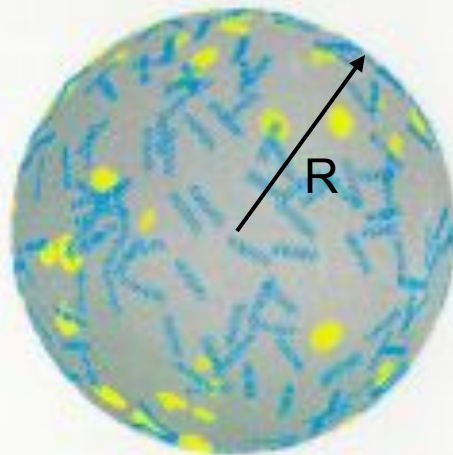
## The cosmological expansion of the universe.



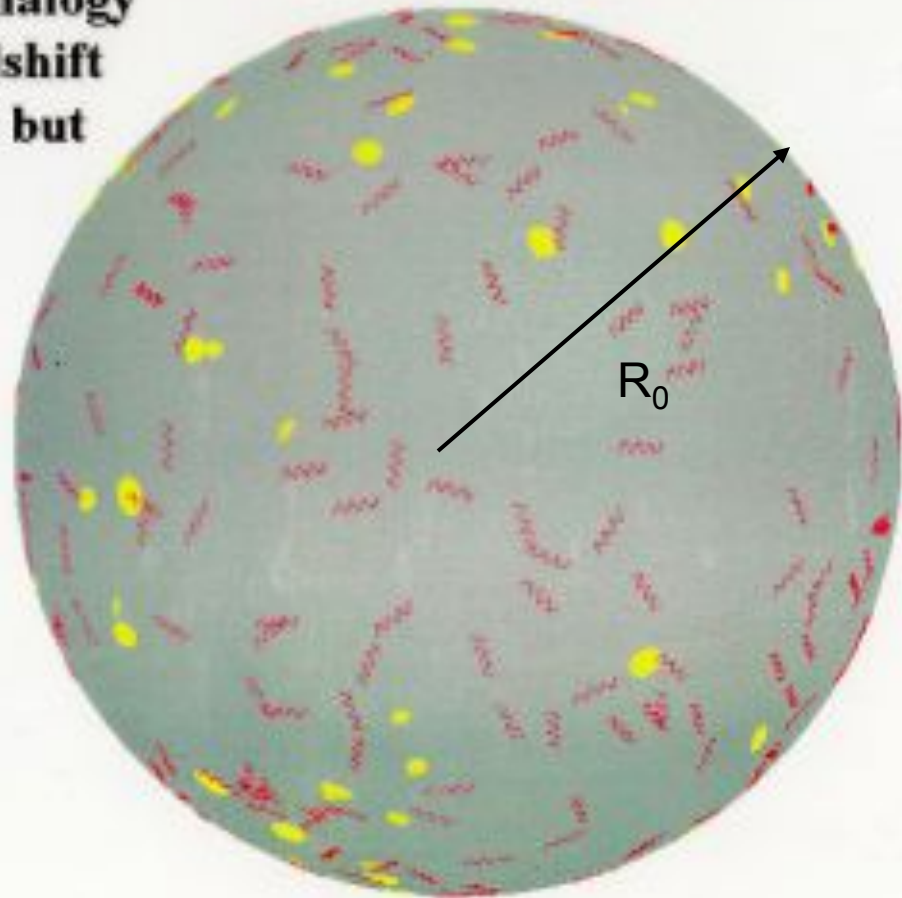
As space **between** galaxies expands, it stretches the light sent out by one galaxy by the time it reaches another far away galaxy. Looks like **redshift**.

nb. The distance to the sun is not increasing nor are you getting any larger.

**Expanding Balloon Analogy**  
**Photons move and redshift**  
**Galaxies spread apart but**  
**stay the same size**



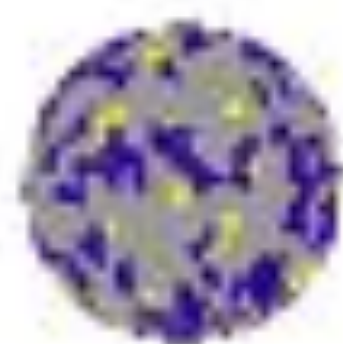
Then



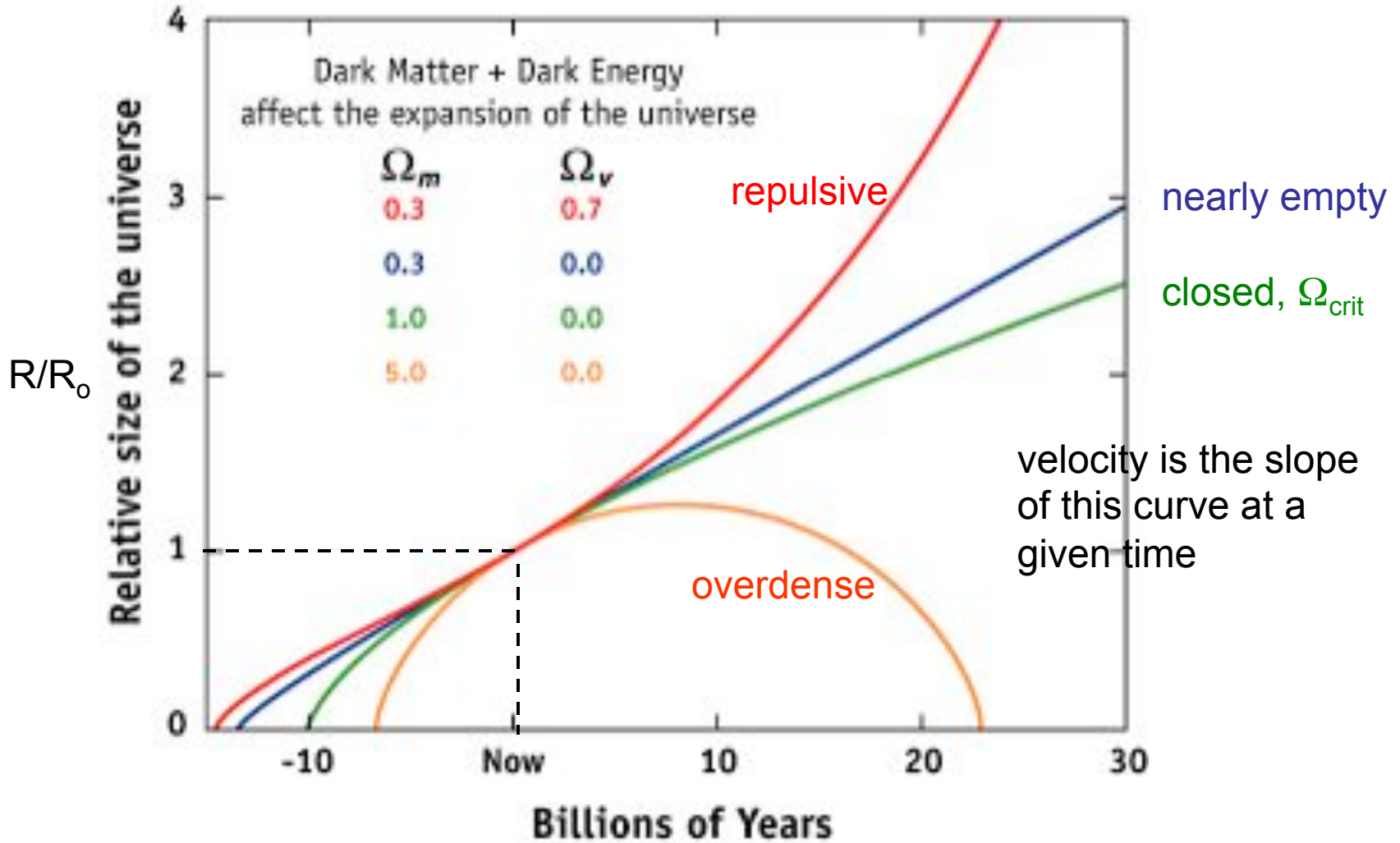
Now

$$1 + z = \frac{R_0}{R} \quad R \leq R_0$$

<http://www.astro.ucla.edu/%7Ewright/balloon0.html>



# EXPANSION OF THE UNIVERSE



The “expansion velocity” is the slope of these curves at a given time

If one could measure the distance to and recessional rate of very distant objects, expansion “speed” at different epochs in the evolution of the universe, then one might discriminate not only the age of the universe but what kind of universe we live in.

What is actually measured is the *redshift*. The redshift is related to the age of the universe when the light was emitted, but it is actually a measure of the relative *size* of the universe.

Define 
$$H = \frac{1}{R} \left( \frac{dR}{dt} \right) \quad \left[ "v" \sim \frac{dR}{dt} = H R \right]$$

“Nearby”  $R$  is about  $R_0$  and  $dR/dt$  is nearly constant so  $H$  is a constant  $H_0$  called the Hubble constant.

One gets a linear relation between expansion “speed” (as measured by redshift) and distance

$$v = H_0 d \quad \text{if } v \ll c, \quad z \sim v/c$$

If  $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$  (from Cepheid Variables + Type Ia SN+WMAP)

$$1 \text{ Mpc} = 3.08 \times 10^{24} \text{ cm} = 3.08 \times 10^{19} \text{ km}$$

$$H_0 = (71 / 3.08 \times 10^{19}) \text{ s}^{-1}$$

$$1 / H_0 = (3.08 \times 10^{19} / 71) \text{ s}$$

$$= 4.33 \times 10^{17} \text{ s} = \mathbf{13.7 \text{ billion years}}$$

but this is for a universe that expanded with constant speed (i.e., contains no matter). For one that contains just enough matter to coast to infinity and stop -

$$\left(\frac{2}{3}\right)(1 / H_0) = \mathbf{9.1 \text{ by}}$$

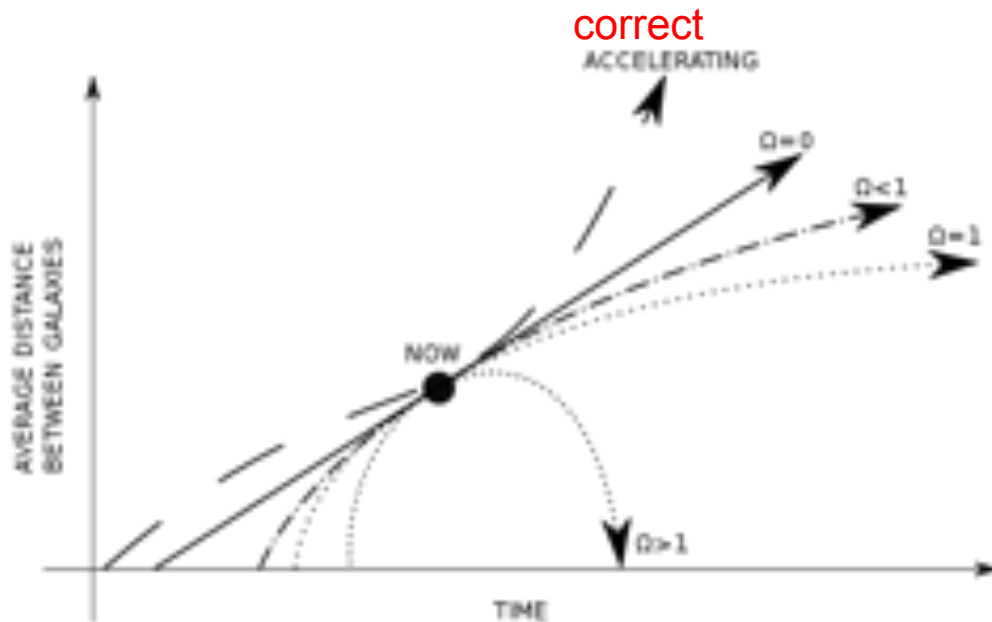
But other measures are consistent with 12 – 14 billion years.

- Globular cluster ages
- Radioactive dating of the elements

# WMAP (2011)

$$H_0 = 71 \pm 2 \text{ km}/(\text{s Mpc})$$

$$\text{Age} = 13.75 \pm 0.11 \text{ billion years}$$

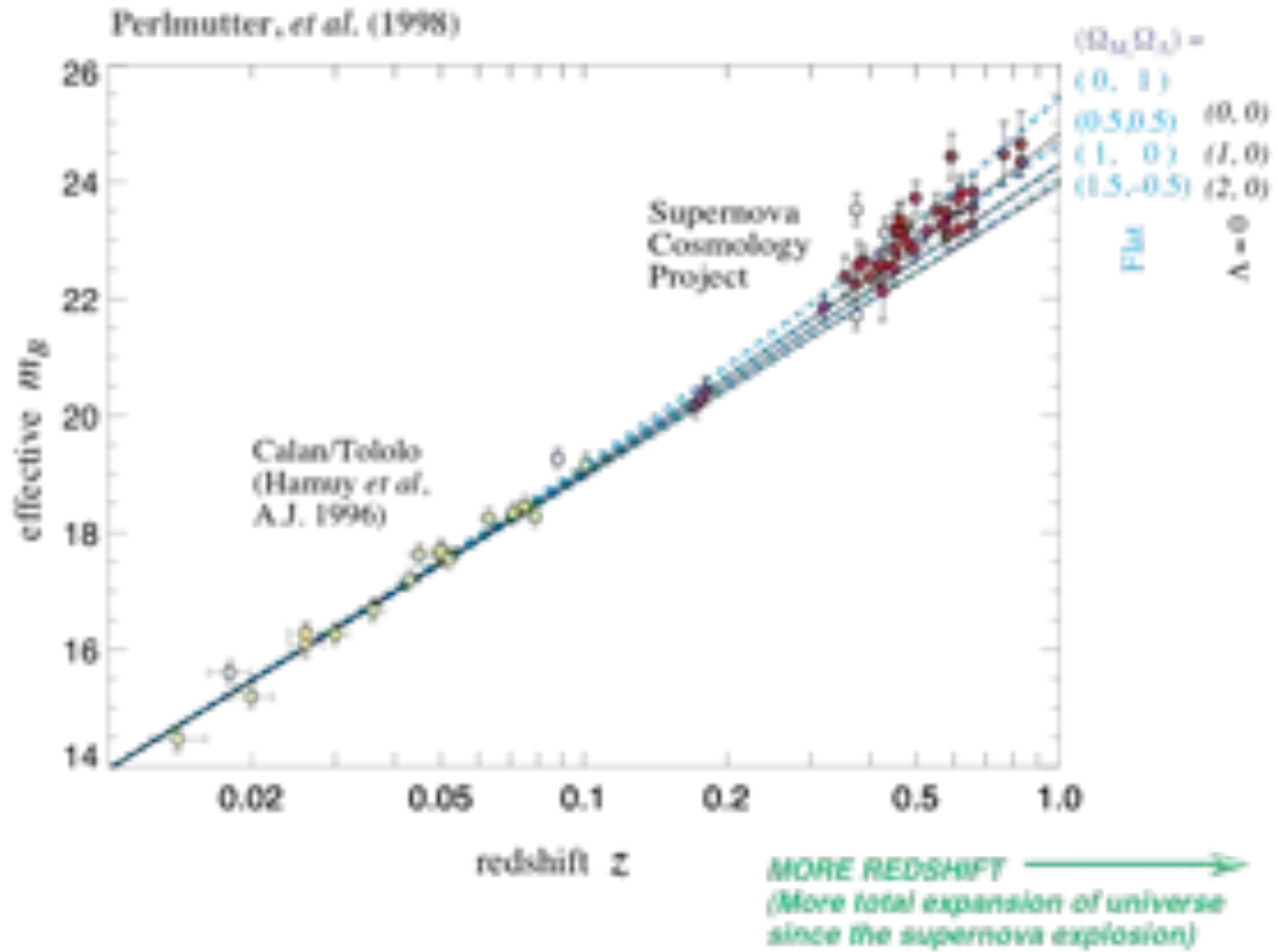


[http://map.gsfc.nasa.gov/universe/uni\\_age.html](http://map.gsfc.nasa.gov/universe/uni_age.html)

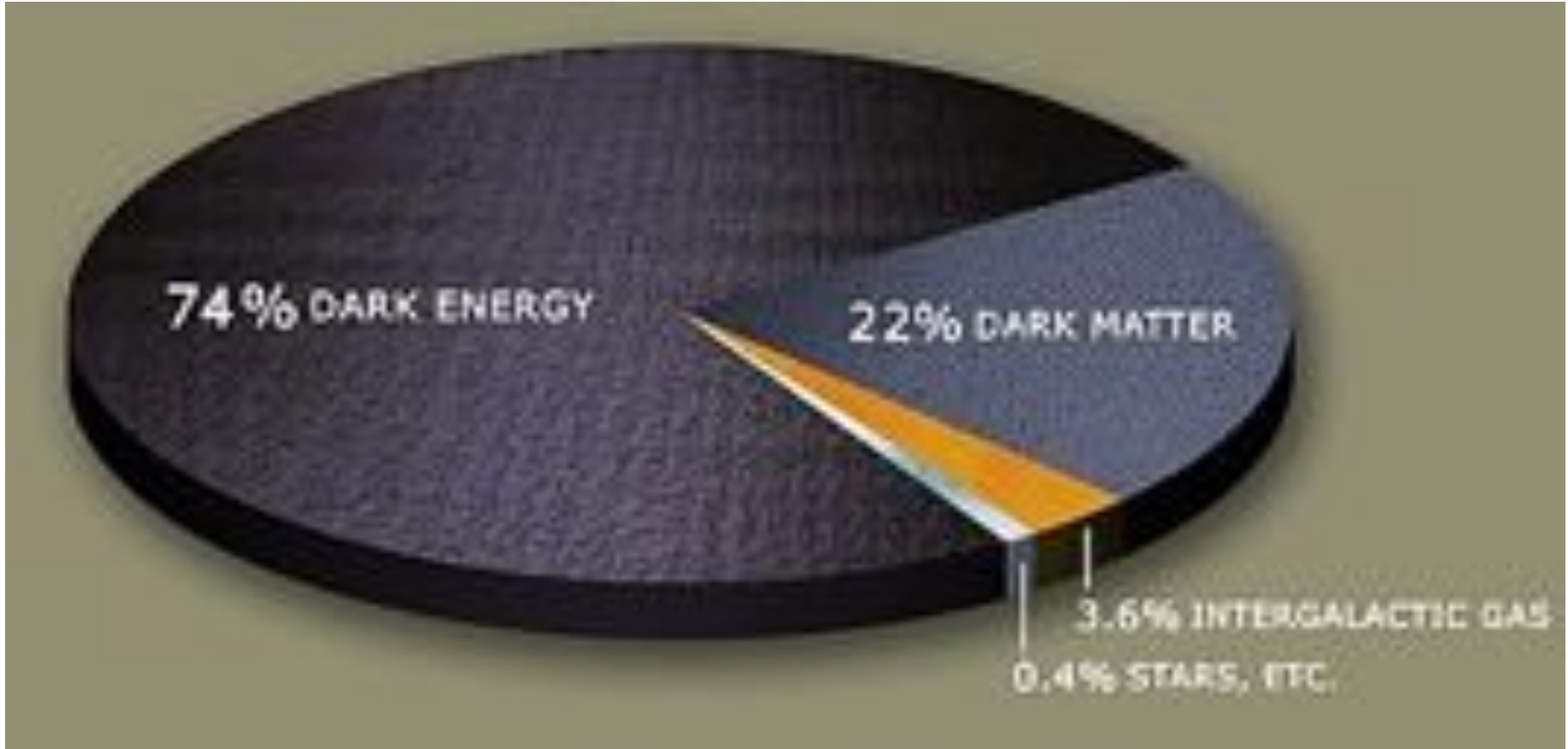
[http://en.wikipedia.org/wiki/Age\\_of\\_the\\_universe](http://en.wikipedia.org/wiki/Age_of_the_universe)

If the expansion of the universe is now accelerating, it moved slower in the past and took longer to get to its present size than just  $1/H_0$  would suggest.

\*







[http://en.wikipedia.org/wiki/Dark\\_energy](http://en.wikipedia.org/wiki/Dark_energy)

More recent Planck mission results suggest 26.8% dark matter, 68.3% dark energy and 4.9% ordinary matter

A major question: Is dark energy constant in space and time – a certain amount of energy per unit volume for the vacuum or does it change with time and place.

Is it a cosmological constant or some sort of scalar field (quintessence)?

Or do we misunderstand gravity on very large scales?

Dark energy has no effect on scale of the solar system which is completely dominated by ordinary matter.

Dark energy and dark matter are, for now, totally different things.

The most profound mystery in modern physical science.

