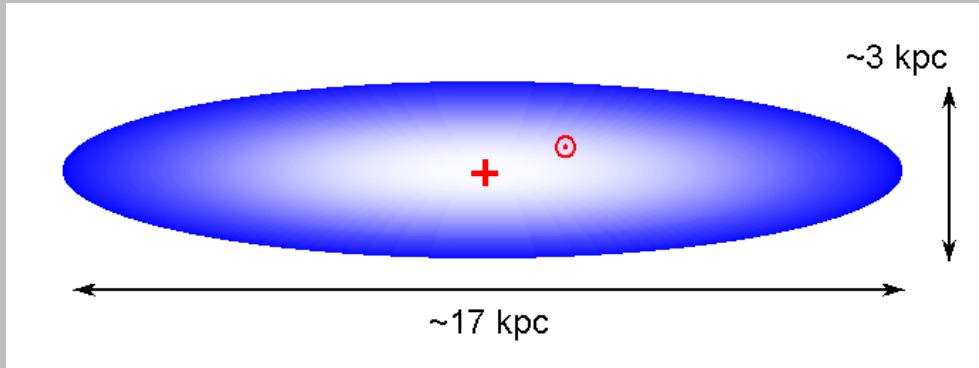


## The Size of the Milky Way (1920s perspective)

**Jacobus Kapteyn:** used star counts to measure the size of the Galaxy: ellipsoidal, 20 kpc across, Sun is a few kpc from center.

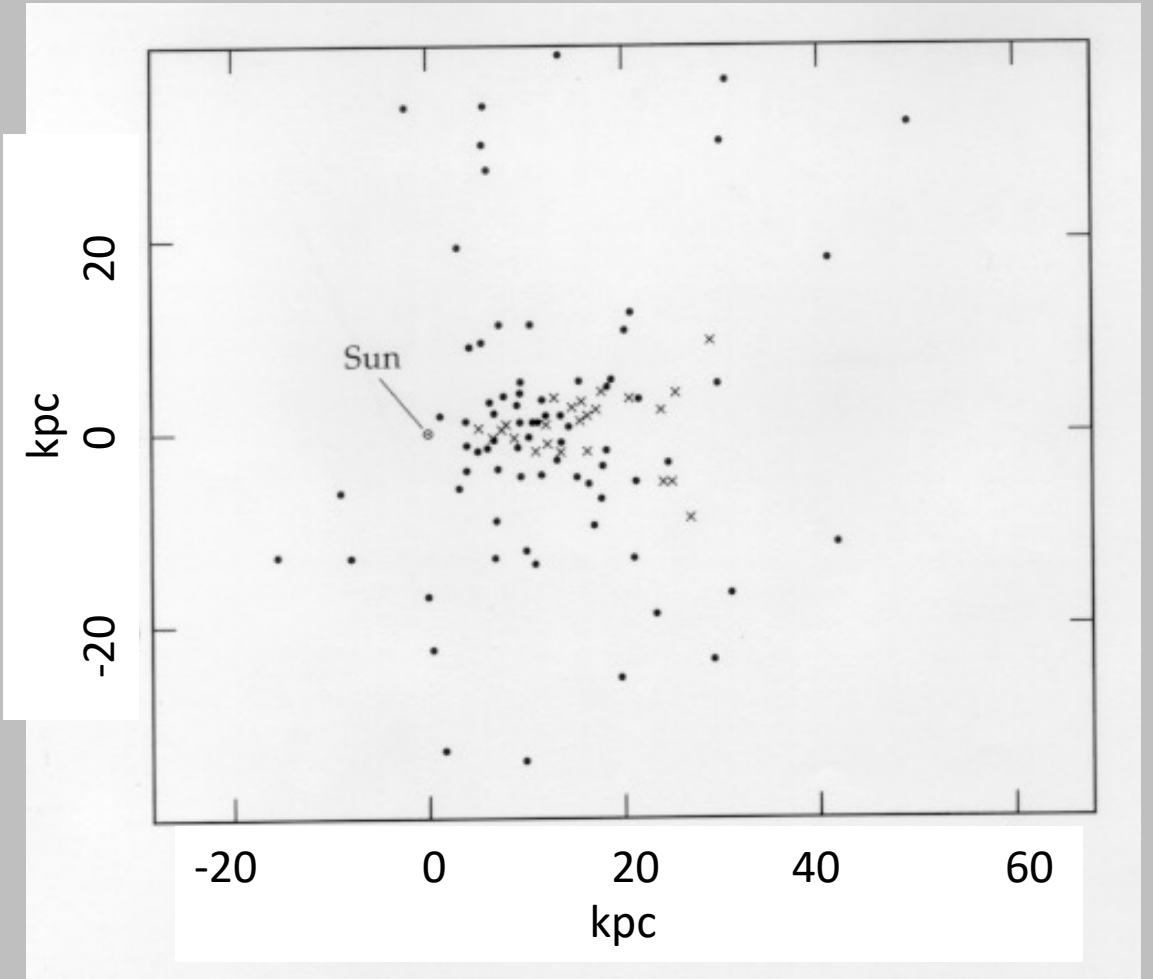


**Both were wrong, because astronomers of the time didn't know about the effects of dust.**

Dust blocks light from faint, distant stars, so Kapteyn couldn't see those distant stars and thought the Galaxy ran out of stars about 10 kpc away.

Shapley's variable stars were bright enough to see, but dust made them fainter, so Shapley thought they were further away. *(But Shapley was closer to the truth than Kapteyn!)*

**Harlow Shapley:** uses variable stars to get distances to globular clusters, determines Galaxy is ~ 100 kpc across and the Sun is ~ 15 kpc from the center.



## Metallicity and Chemical Evolution

Stars form from interstellar gas with a given metallicity (chemical abundance), and this sets the metallicity of the star.

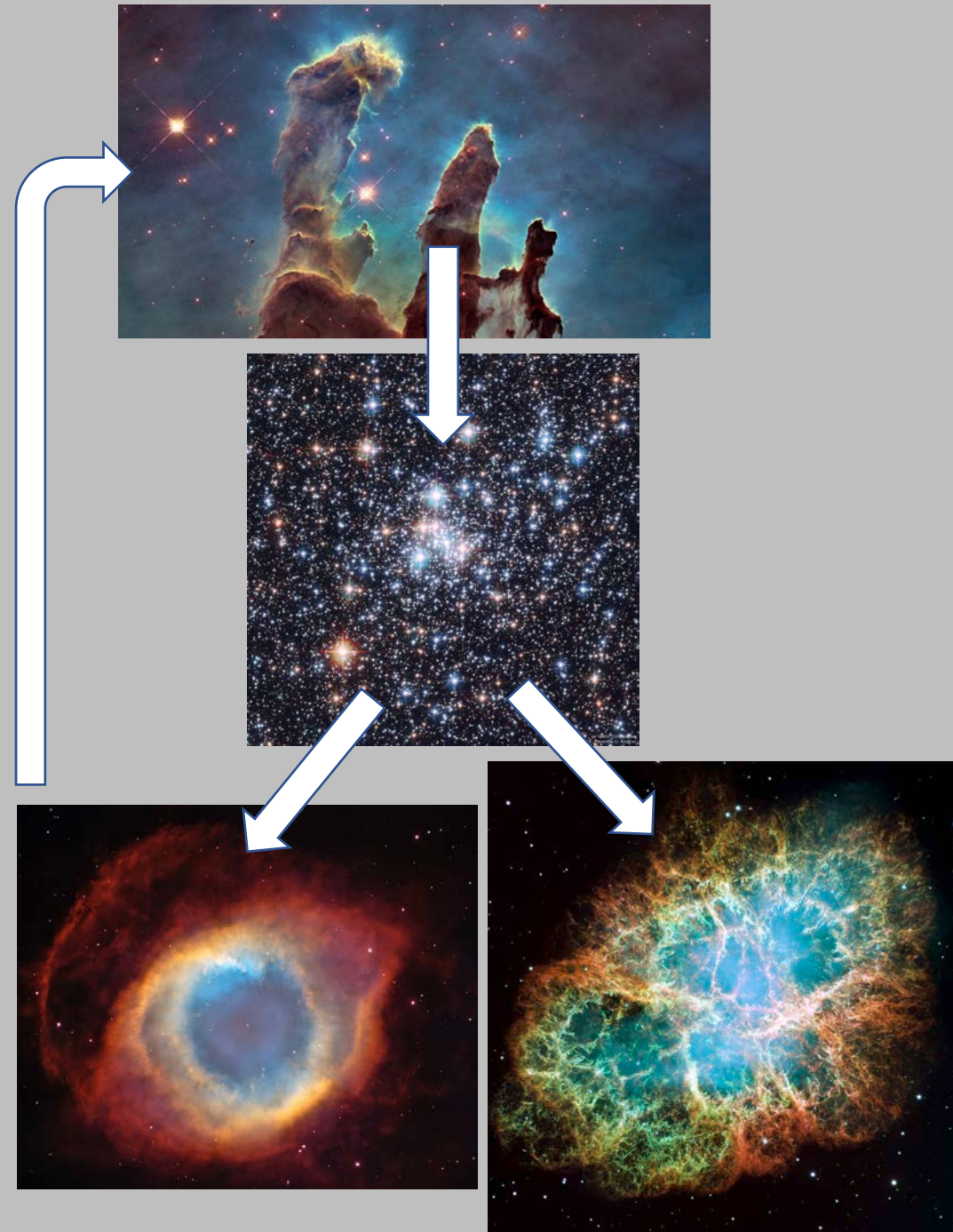
As the star undergoes nuclear fusion, it converts hydrogen into helium and heavier elements, but all this happens deep in the core of the star. The chemical abundances of the star's outer layers is largely unaffected. **A star's metallicity does not change with time.**

When the star dies it ejects its heavy elements into the surrounding gas, enriching the gas and raising the metallicity of the gas.

New stars form from this gas, and these **new stars have higher metallicity** than the previous generations.

Over time, as long as new stars are forming, **the metallicity of the overall population increases.**

Metallicity can build up rapidly if the star formation rates are high, or more gradually if star formation is limited. **But metallicity is not an absolute clock.** Old stars in our Galaxy have a wide range of metallicity.



## Metallicity of Stars

We can define chemical composition, or **metallicity**, for stars using the **Iron to Hydrogen ratio**. For the Sun, this is given by

$$\log(Fe/H)_{\odot} \approx -4.33$$

or about 20,000 hydrogen (H) atoms for every Iron (Fe) atom.

We measure this value for other stars relative to the Sun, using a quantity called **[Fe/H]**:

$$[Fe/H] = \log \left[ \frac{(Fe/H)_*}{(Fe/H)_{\odot}} \right] = \log(Fe/H)_* - \log(Fe/H)_{\odot}$$

Defined this way, the Sun has  $[Fe/H]_{\odot} \equiv 0.0$

$[Fe/H] = +0.5$  : metal-rich star, metallicity is 3x solar

$[Fe/H] = 0.0$  : solar metallicity star

$[Fe/H] = -2.0$  : metal-poor star, metallicity is 1/100 solar.

Stars can span a wide range of metallicity:

$$-4.5 < [Fe/H] < +1.0$$

From ASTR221:		Mass Fraction	Solar Value
elemental abundance of the stars.	Hydrogen	X	0.70
	Helium	Y	0.28
	Everything else ("metals")	Z	0.02

### Notes:

- "Bracket notation" can be used to define abundance of any element. Iron commonly used because it is easy to measure.
- Sometimes stellar modelers use  $[Z/H]$ , which is measuring all metals combined.

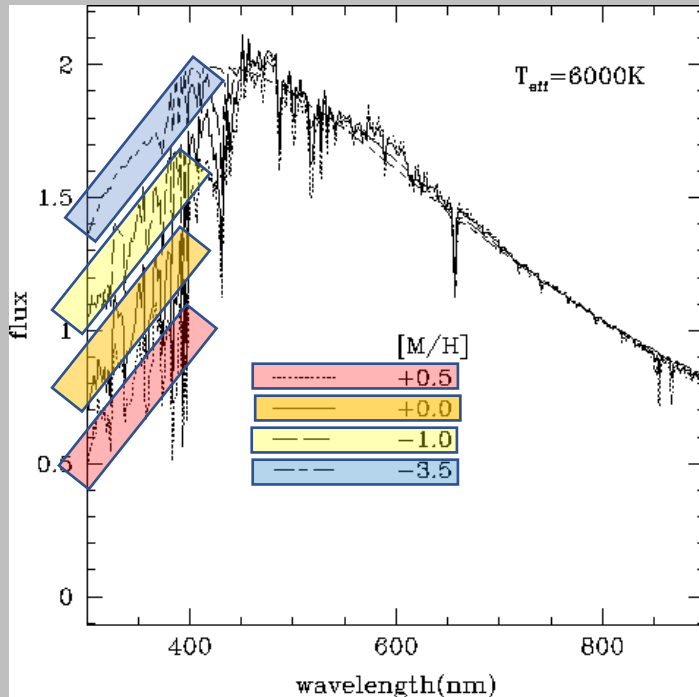
## Metallicity of Stars

How does metallicity affect the *observed* properties of stars?

**Simple rule of thumb: metal-poor makes stars bluer, metal-rich makes stars redder. Why?**

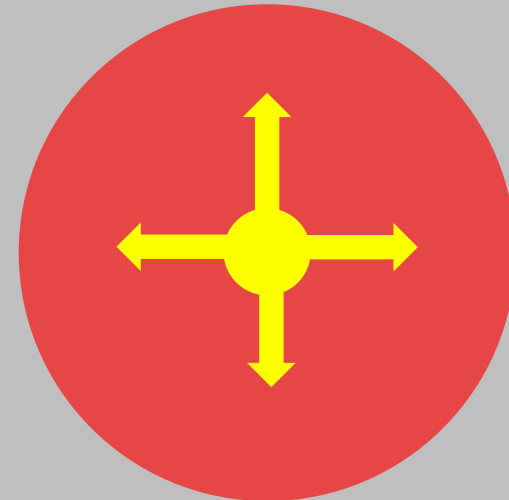
### Line blanketing

Metals (particularly Iron) preferentially absorb light at bluer wavelength. More metals means more blue absorption, which makes stars redder.



### Opacity

The metals absorb energy trying to get out from the interior of the star. This bottled up energy pushes out and makes red giants swell up even more. Larger red giants are cooler red giants (and thus redder).



# Metallicity of Stars

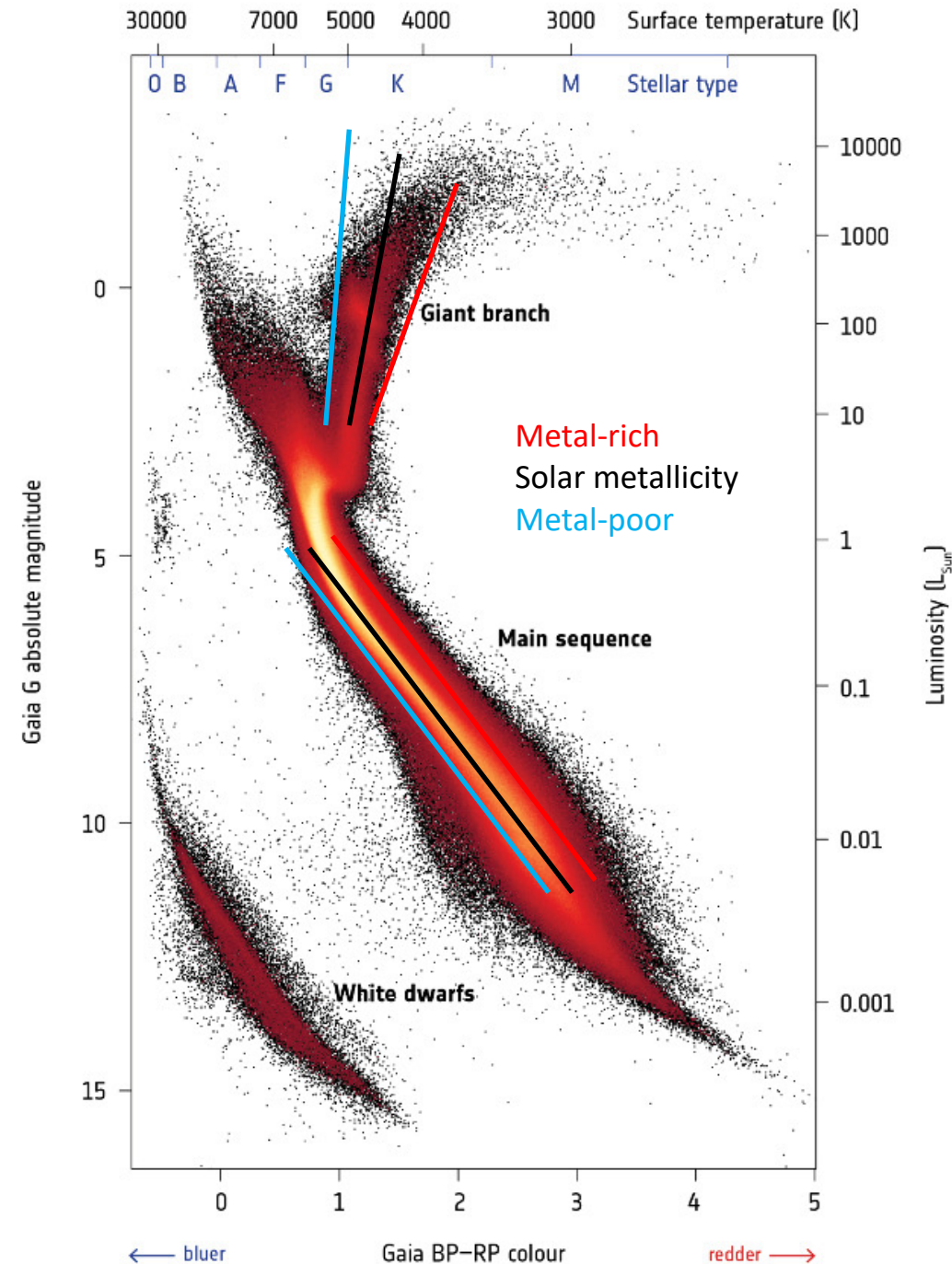
How does metallicity affect the *color magnitude diagram*?

- RGB tracks get redder at high metallicity
- MS tracks get bluer at low metallicity, historically metal-poor MS stars were called “sub-dwarfs”

This means that lots of things can affect the colors of stars and star clusters:

- Age (older populations are redder on average)
- Metallicity (metal rich populations are redder on average)
- Dust (dusty populations are redder on average)

Distangling all these effects is complicated, often requiring multiwavelength observations and spectroscopy.



## Distances to stars: Parallax

As the Earth orbits the Sun, the position of nearby stars in the sky shifts relative to background objects.

The parallax angle is one-half of this angular shift, then the distance to the star is given by simple trigonometry:

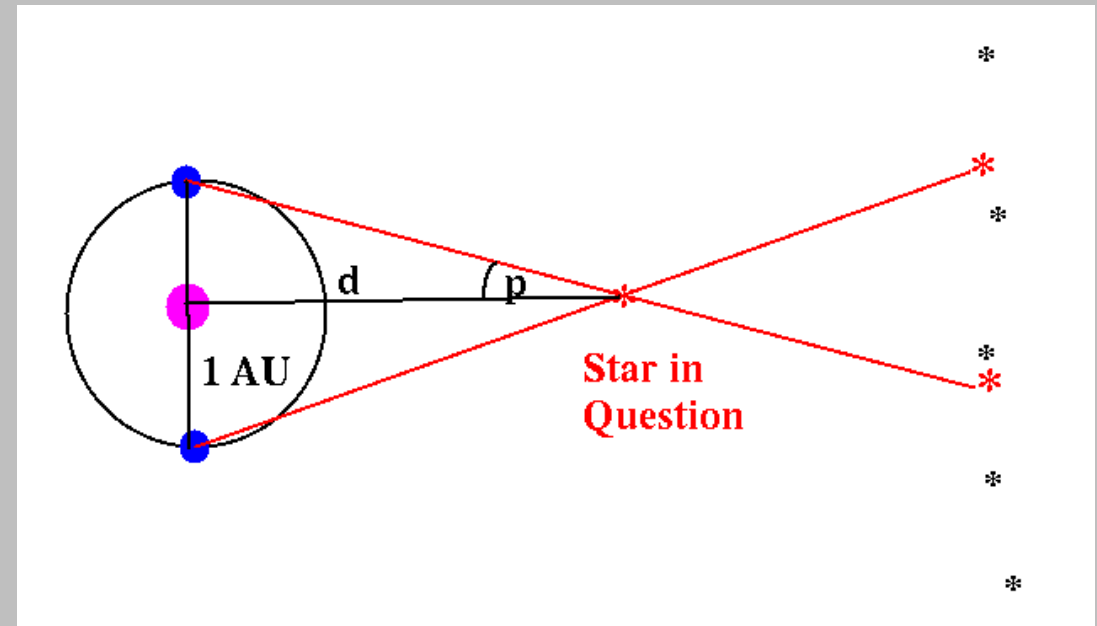
$$d = \frac{1 \text{ AU}}{\tan p}$$

In ASTR 221, we showed that if we measure  $p$  in arcsec ( $''$ ) and define a parsec to be the distance where  $p = 1''$ , we get

$$d[\text{pc}] = \frac{1}{p[']}]$$

Animations (courtesy Erik Tollerud and James Davenport)

- [Parallax only](#)
- [Parallax + proper motion](#)



Satellite Parallax Missions

	Hipparcos	Gaia
Dates	1989-1993	2014-2019
Limiting magnitude	~ 12	~ 20
Parallax precision	milliarcsec	20-200 microarcsec
Distance	1 kpc	10 kpc
N(stars)	100,000	20-200 million!

## Distances to Star Clusters: Main Sequence Fitting

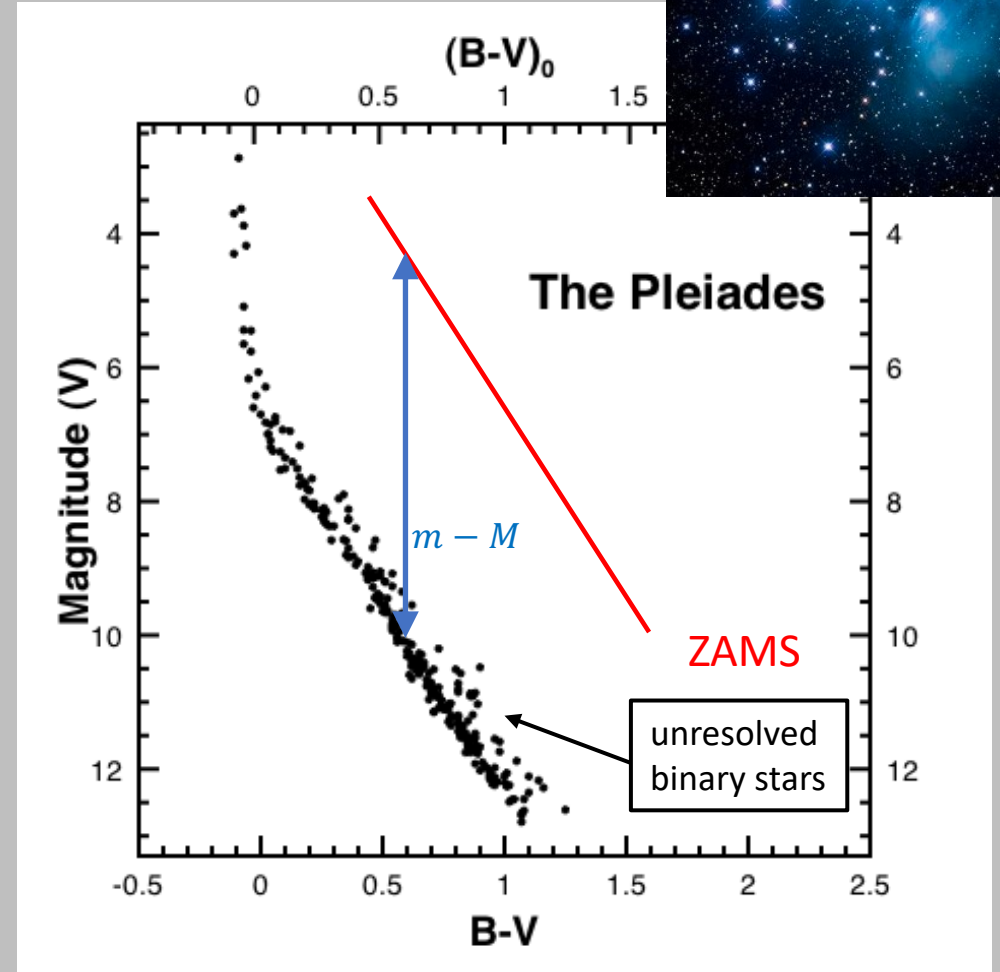
Clusters are groups of stars all at the same distance. We can plot a color-magnitude diagram using apparent magnitude ( $m$ ) and it will be shifted vertically from absolute-magnitude calibrated ( $M$ ) “zero-age” main sequence simply by the distance modulus:

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

Two ways to do this, both conceptually the same:

- 1) Measure the apparent magnitude of cluster stars at a given color on the main sequence and compare to the absolute magnitude of main sequence stars at that color. The difference is the distance modulus.
- 2) Overplot an absolute magnitude main sequence, shifting it by different amounts until it lines up with the observed cluster main sequence. The shift that lines it up is the distance modulus.

Open star cluster (young stars)



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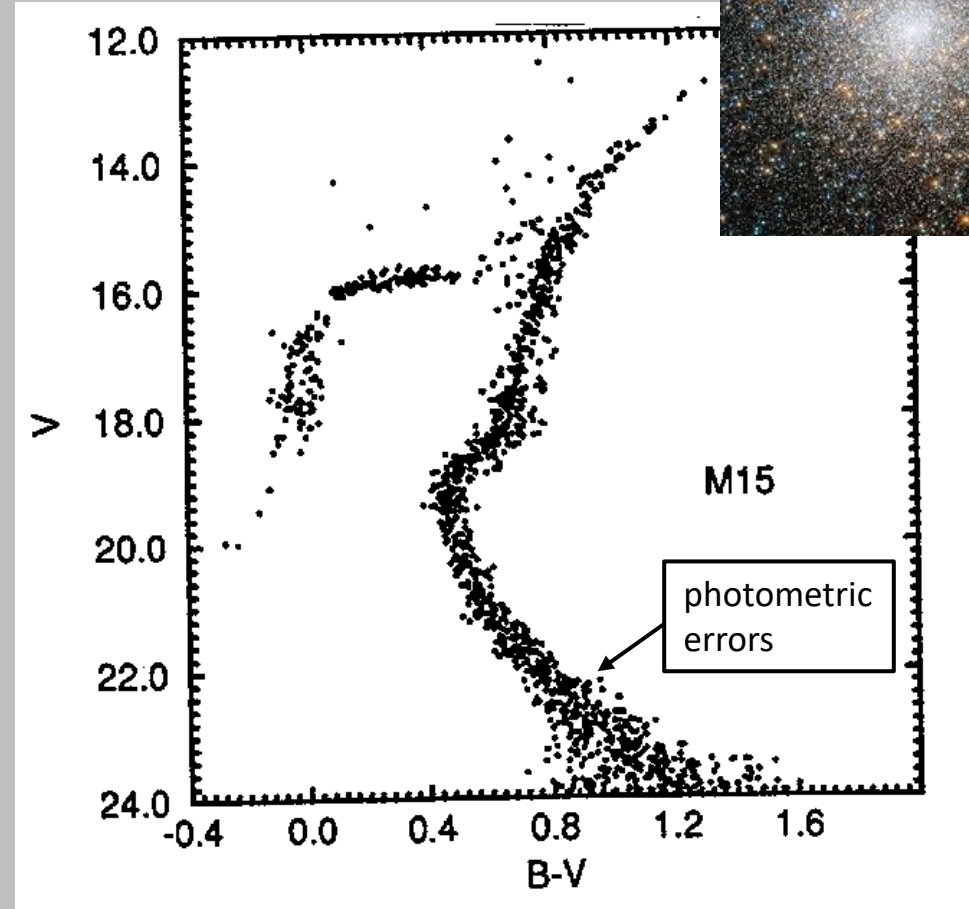
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Works for globular clusters, too, just make sure you are looking at the main sequence!

Globular star cluster (old stars)





# Color Magnitude Diagrams of Star Clusters: Deriving ages

As a star cluster ages, its high mass stars rapidly evolve off the main sequence. This “turnoff point” is a good indicator of the age of the star cluster.

