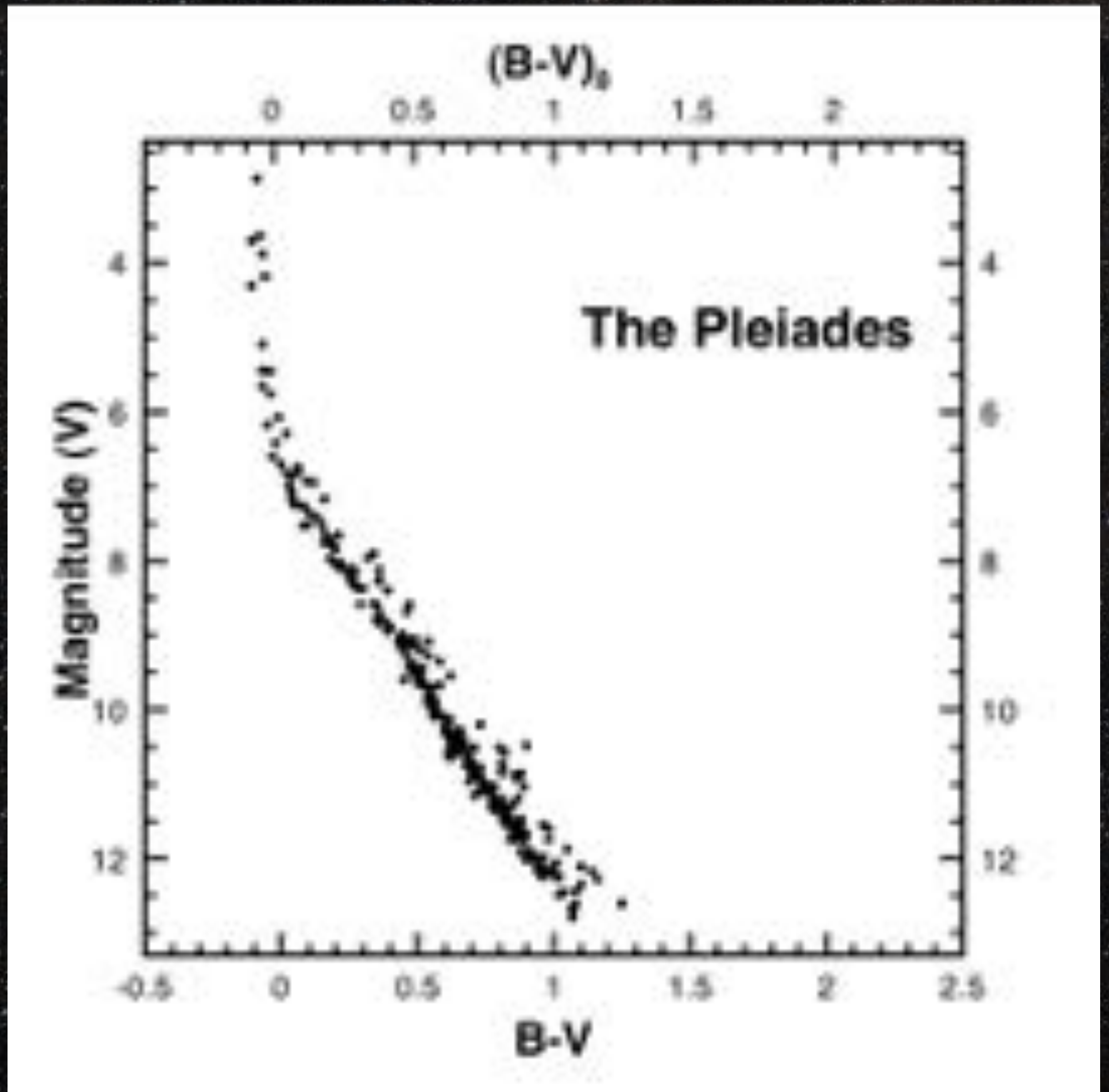
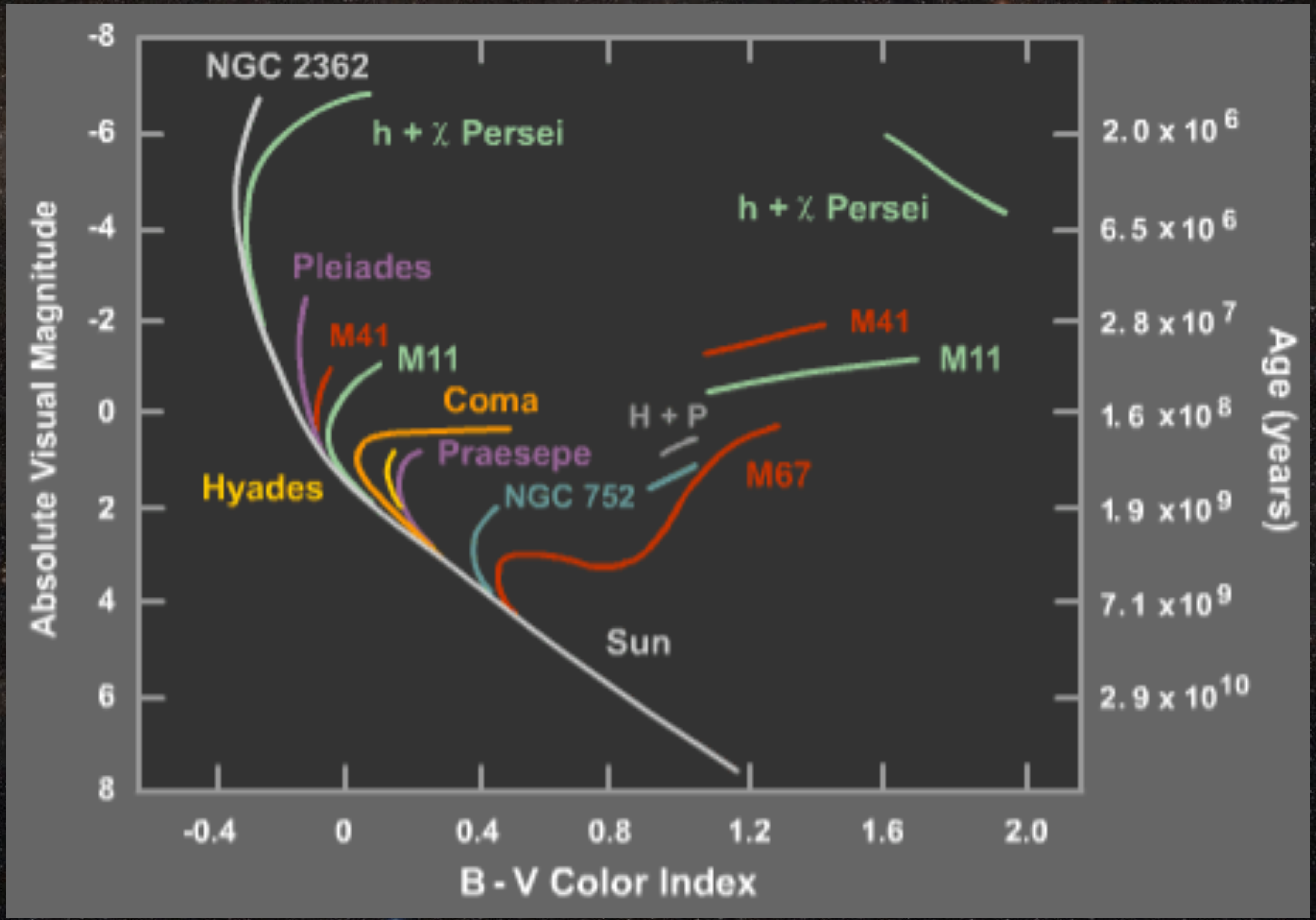
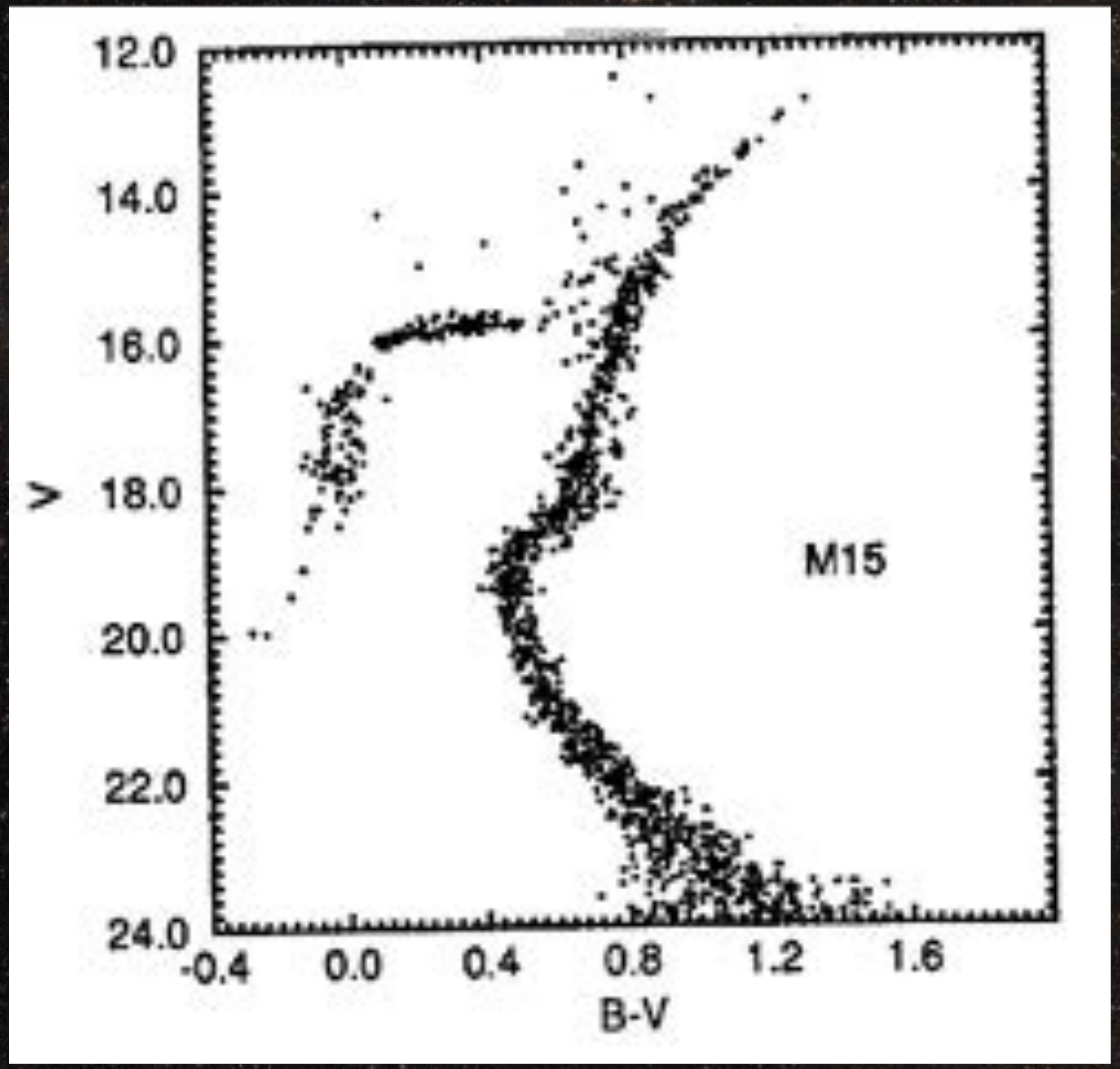
Color Magnitude Diagrams of Star Clusters: Deriving Ages

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 a star cluster.







Measuring Distances in the Milky Way

Dust & Variable Stars

Interstellar Dust

(α, β, x, y, z) = (96.0° 180.0° 0 pc 0 pc 0 pc)
Mon OB1
California
Mon R2
λ Ori
Ori B
Taurus
Perseus
Ori A
+15°
+0°
−15°
−30°
−15°
+0°
+15°
+30°

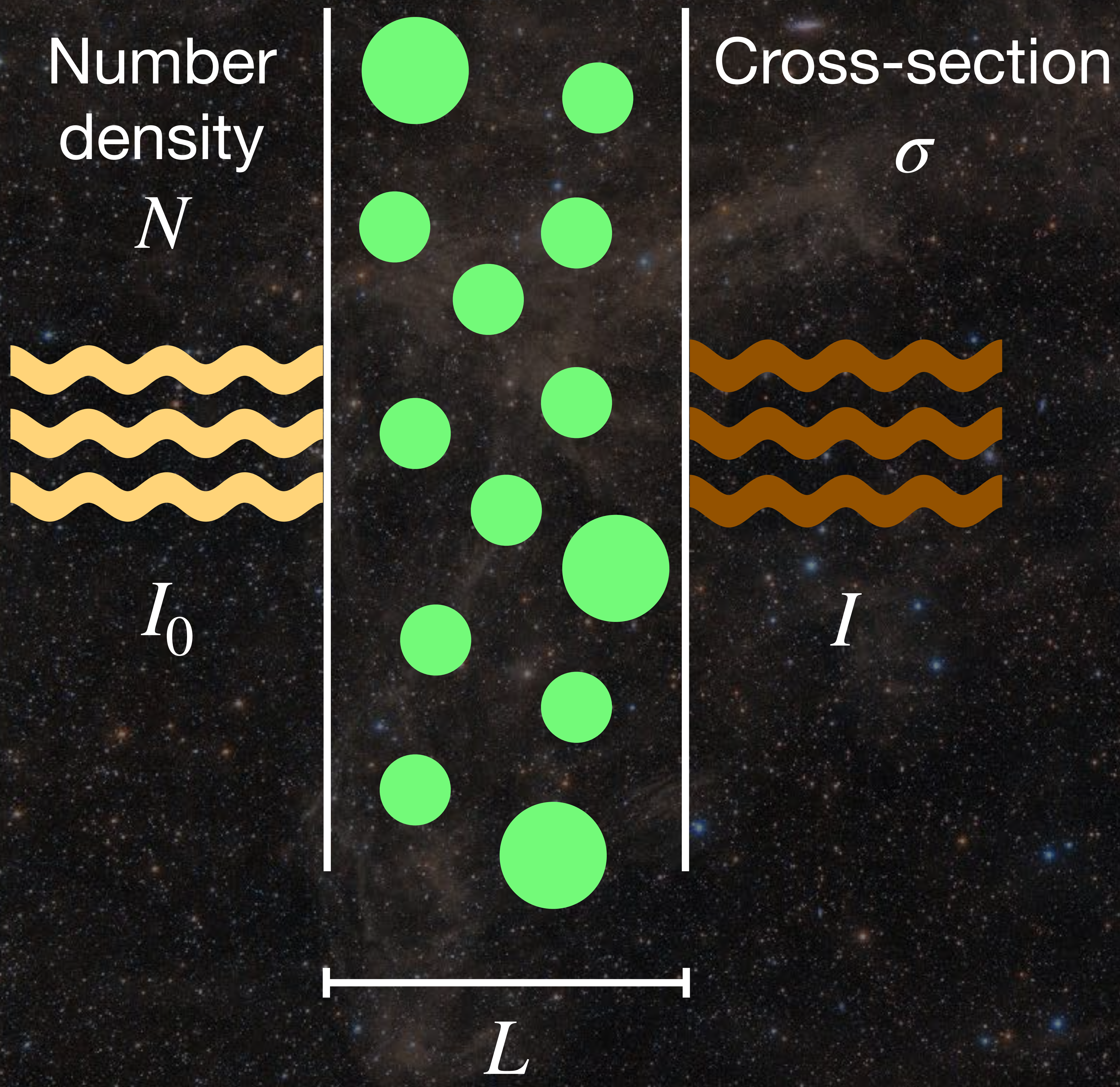
Interstellar Dust

What does dust do to starlight?

- It absorbs light
- It reddens light
- It scatters light
- It emits light

Interstellar Absorption

Remember the equation of radiative transfer?



We have $I = I_0 e^{-\tau}$, where $\tau = N\sigma L$

Rewrite this as $I/I_0 = e^{-\tau}$

Convert to magnitudes!

$$
\begin{aligned}
m - m_0 &= -2.5 \log e^{-\tau} \\
&= -2.5(-\tau) \log e \\
&= 1.086\tau
\end{aligned}
$$

Interstellar Absorption

Define extinction as $A = 1.086\tau$, how would we correct our magnitudes?

$$m = m_{\text{obs}} - A$$

How does this affect our distance measurements?

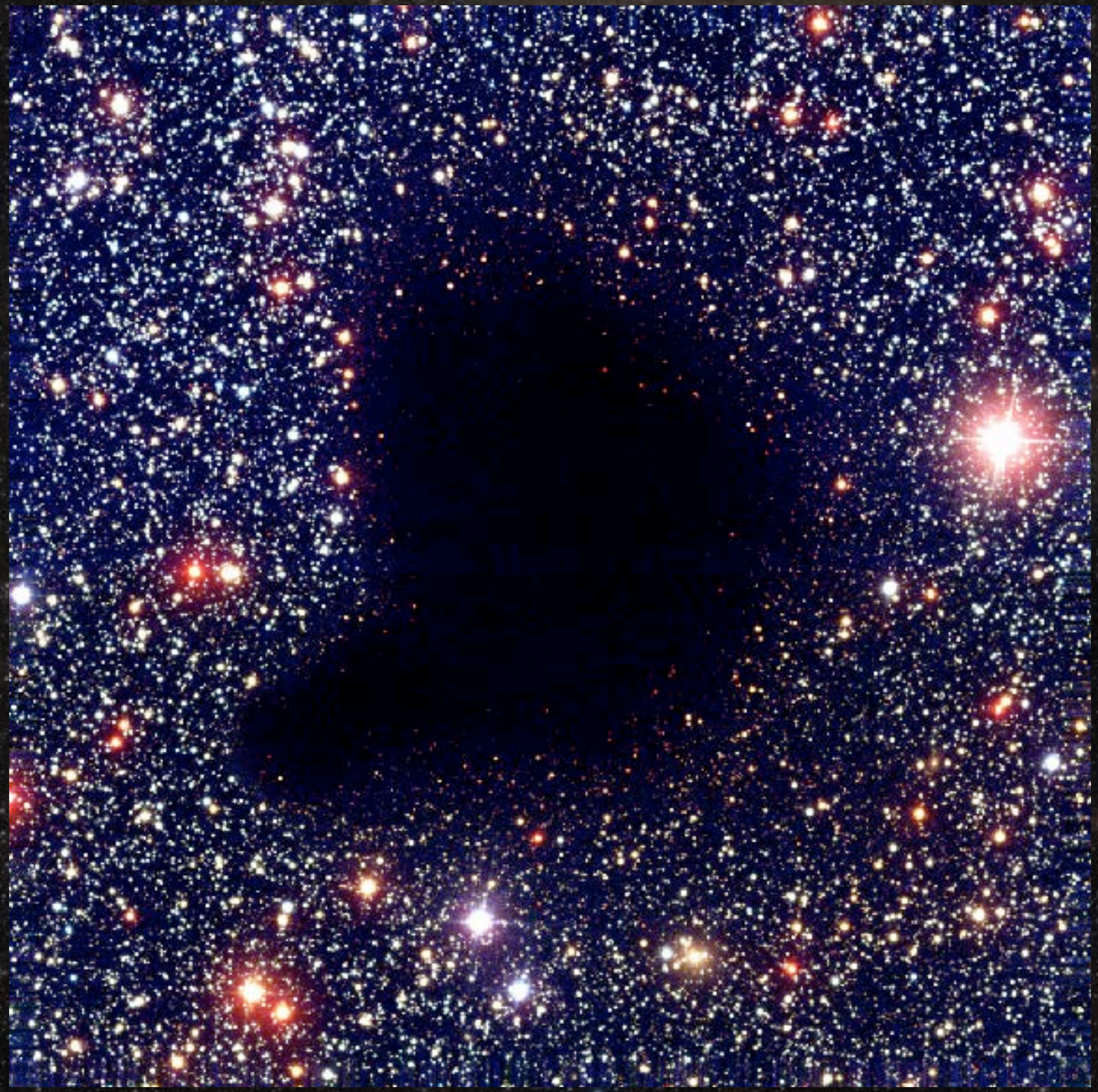
We need to correct our distance modulus as well!

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

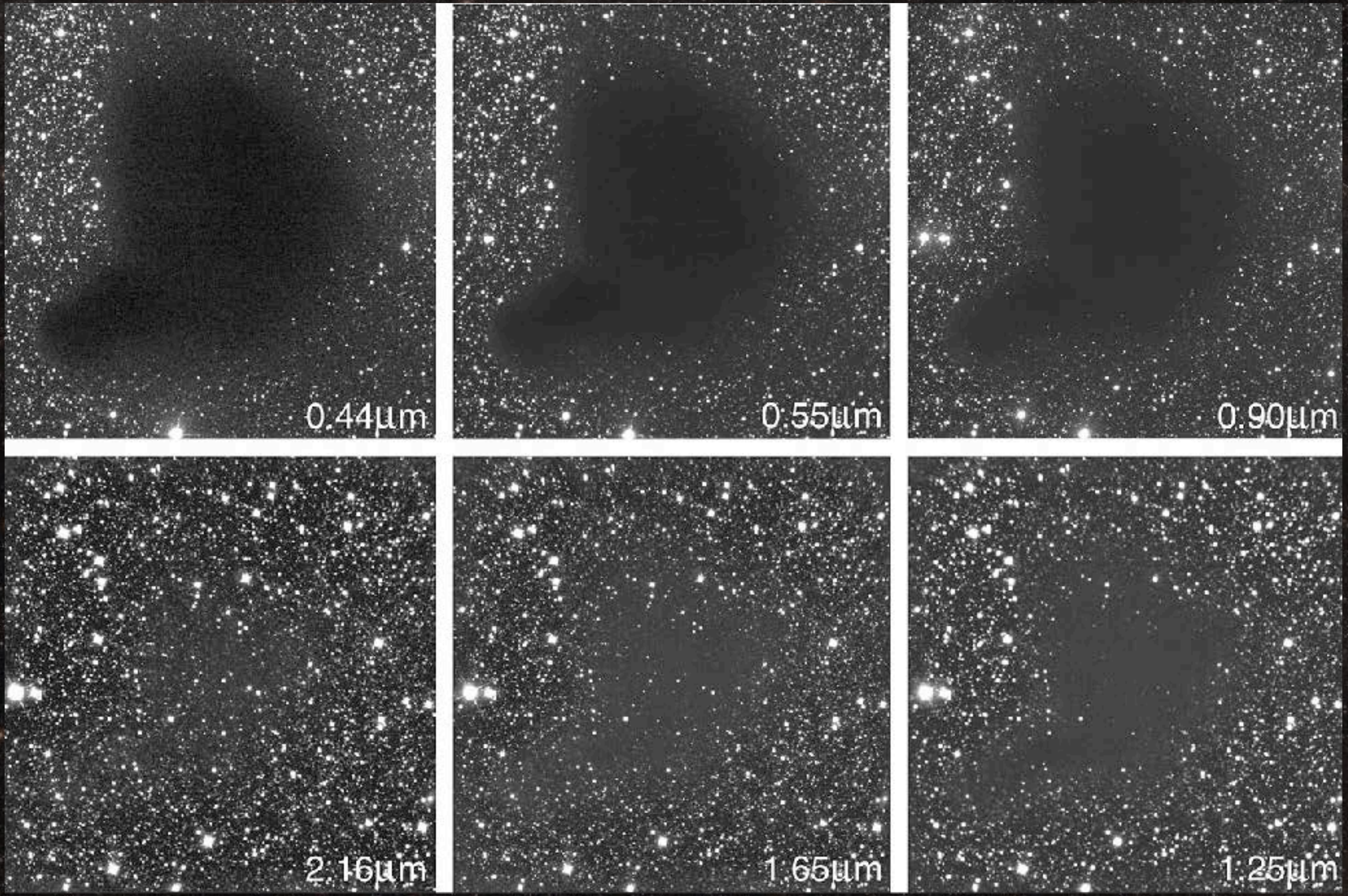
Interstellar Reddening

However, interstellar extinction is not equally effective at all wavelengths: the shorter the wavelength, the higher the extinction—blue light is more extinguished than red light

Stars behind a lot of dust look redder than they actually are, called interstellar reddening



Barnard 68



Interstellar Reddening

If we measure the $B-V$ color of a star, we'll be measuring a redder color than the true color, $(B-V)_0$

We define the reddening as

$$E(B-V) = (B-V) - (B-V)_0$$

The more extinction there is, the more reddening there is!

$$A_B = 4.1E(B-V) \quad \text{(Blue)}$$

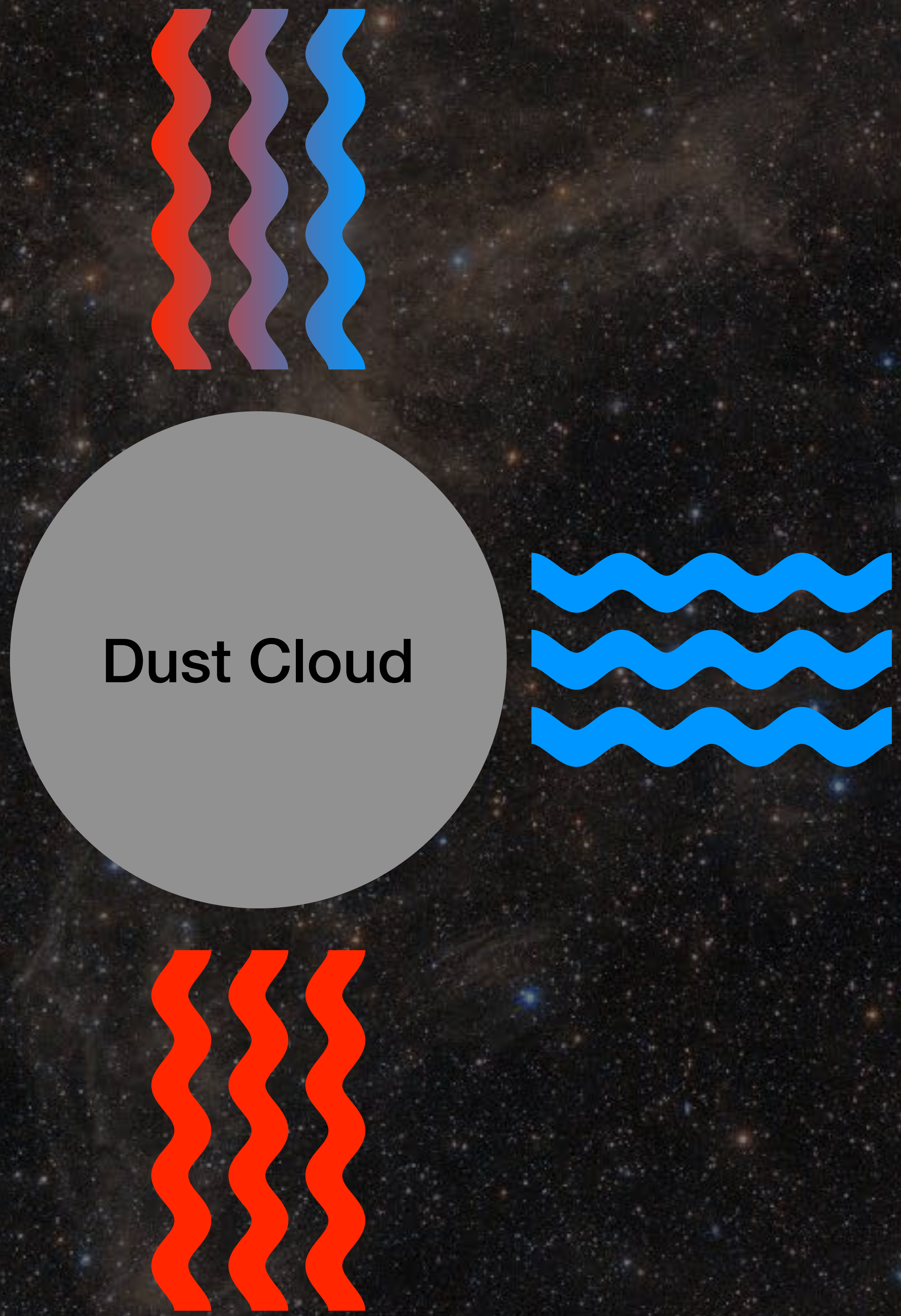
$$A_V = 3.1E(B-V) \quad \text{(Visual)}$$

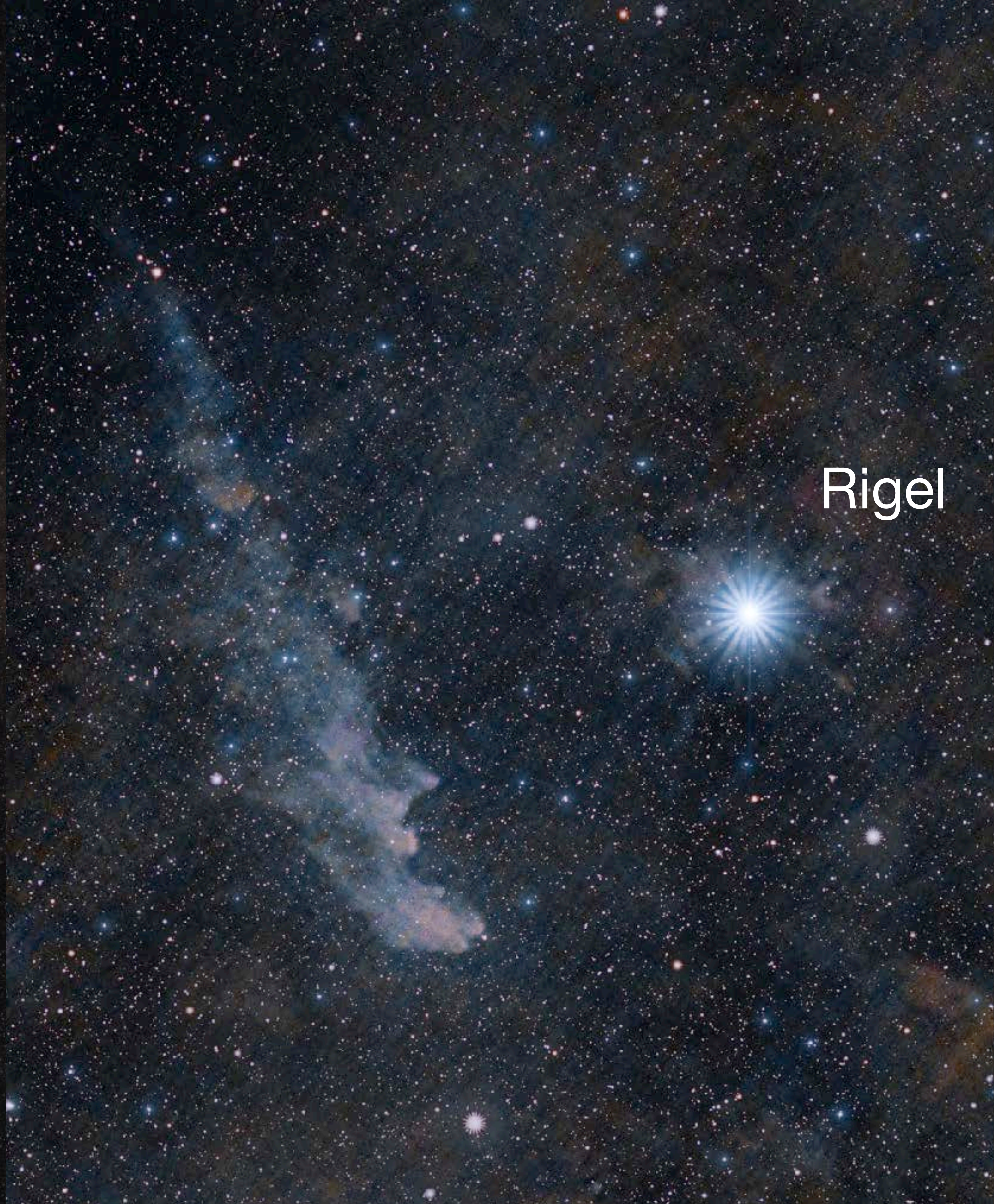
$$A_R = 2.7E(B-V) \quad \text{(Red)}$$

$$A_K = 0.5E(B-V) \quad \text{(Near Infrared)}$$

Interstellar Scattering

Extinction is not due to absorption alone since dust absorbs and scatters light

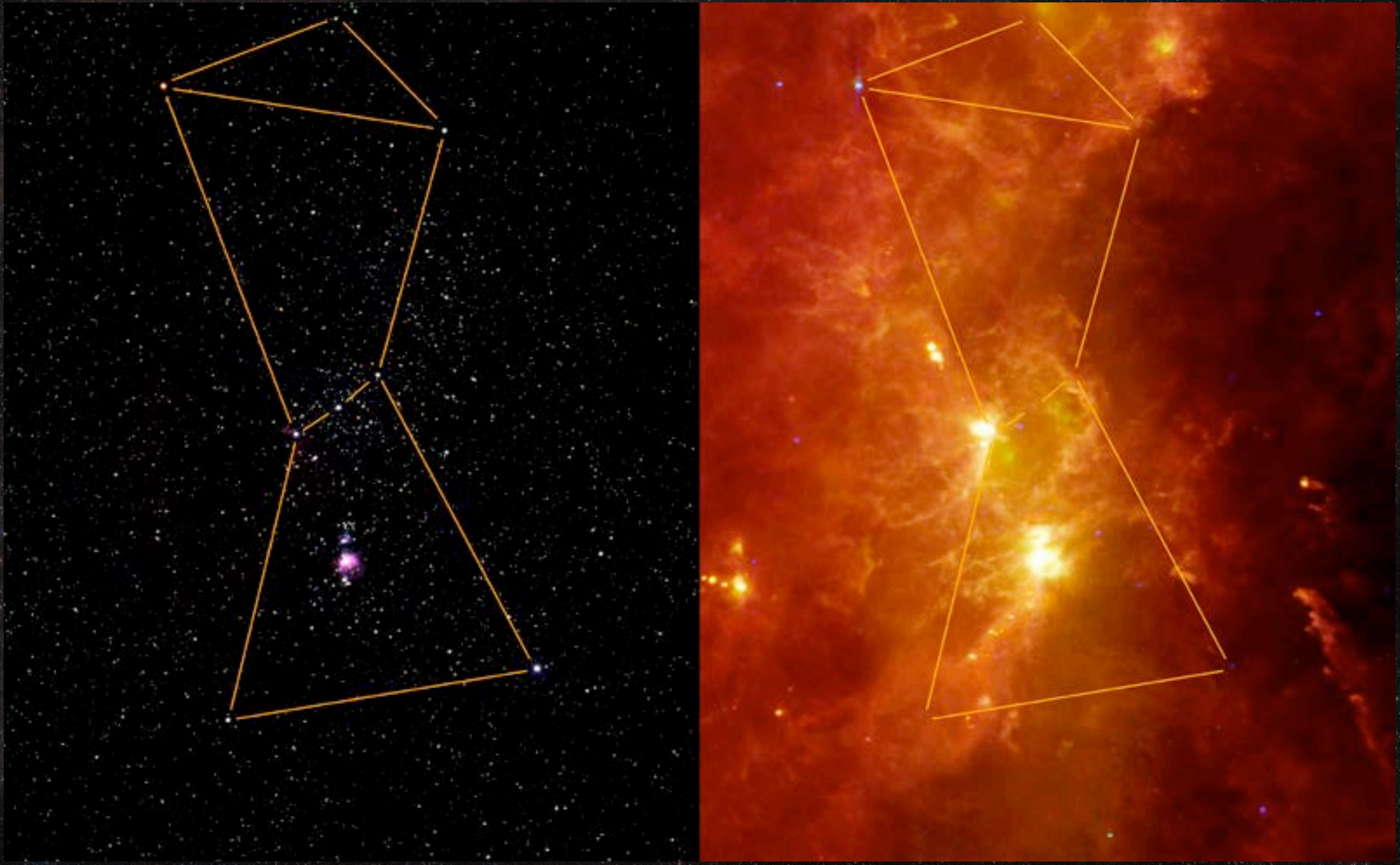




The Witch Head Nebula (IC 2118)

Interstellar Emission

At mid- and far-infrared wavelengths, the dust glows: a combination of thermal blackbody and emission lines



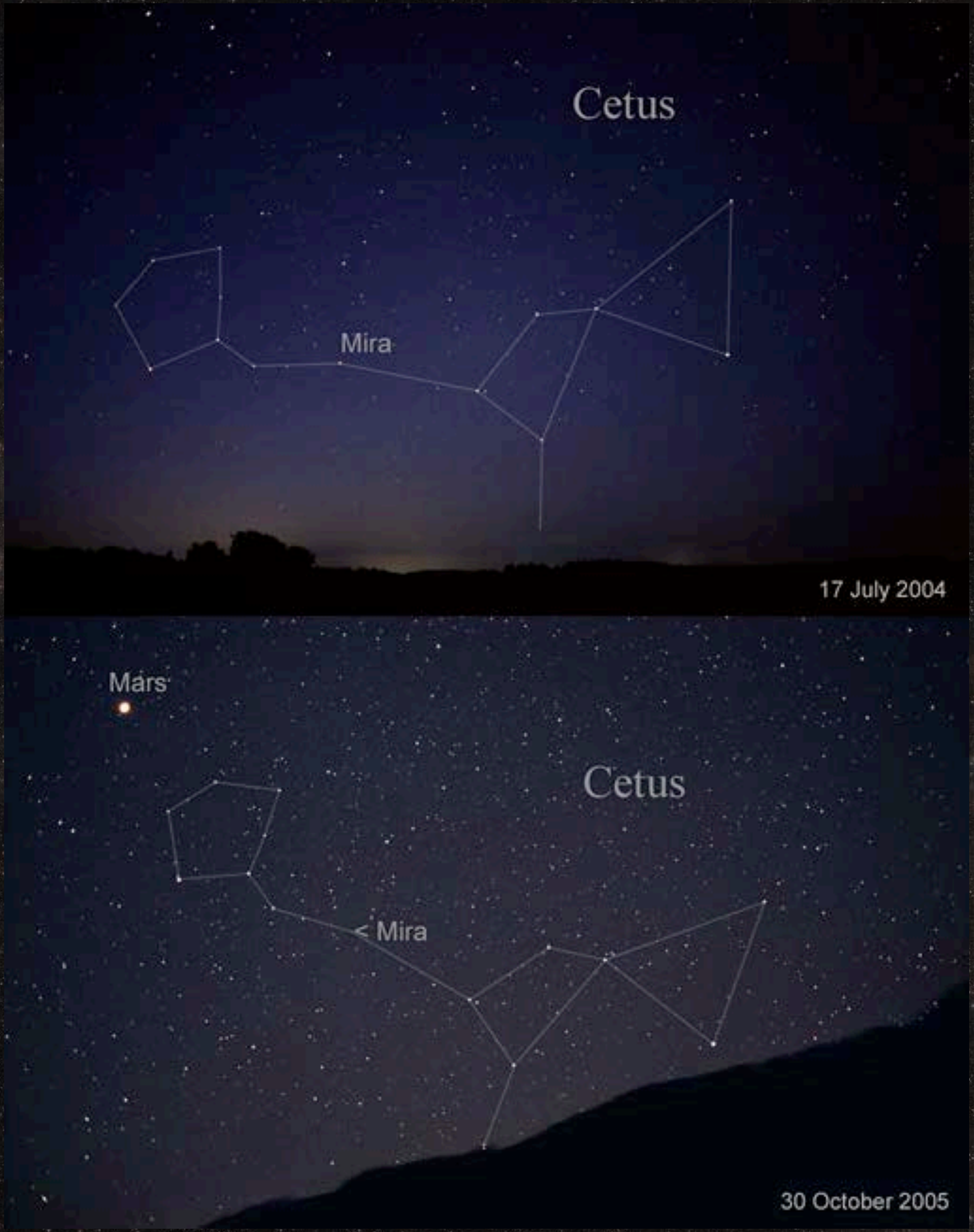

Visible Light
HST

Near-infrared Light
NIRCam, JWST

Variable Stars

In 1662, the Polish astronomer Johannes Hevelius observed a star brighten and dim over an 11-month period, and named it *Mira*, Latin for “wonderful”

Johannes Hevelius
1611-1687

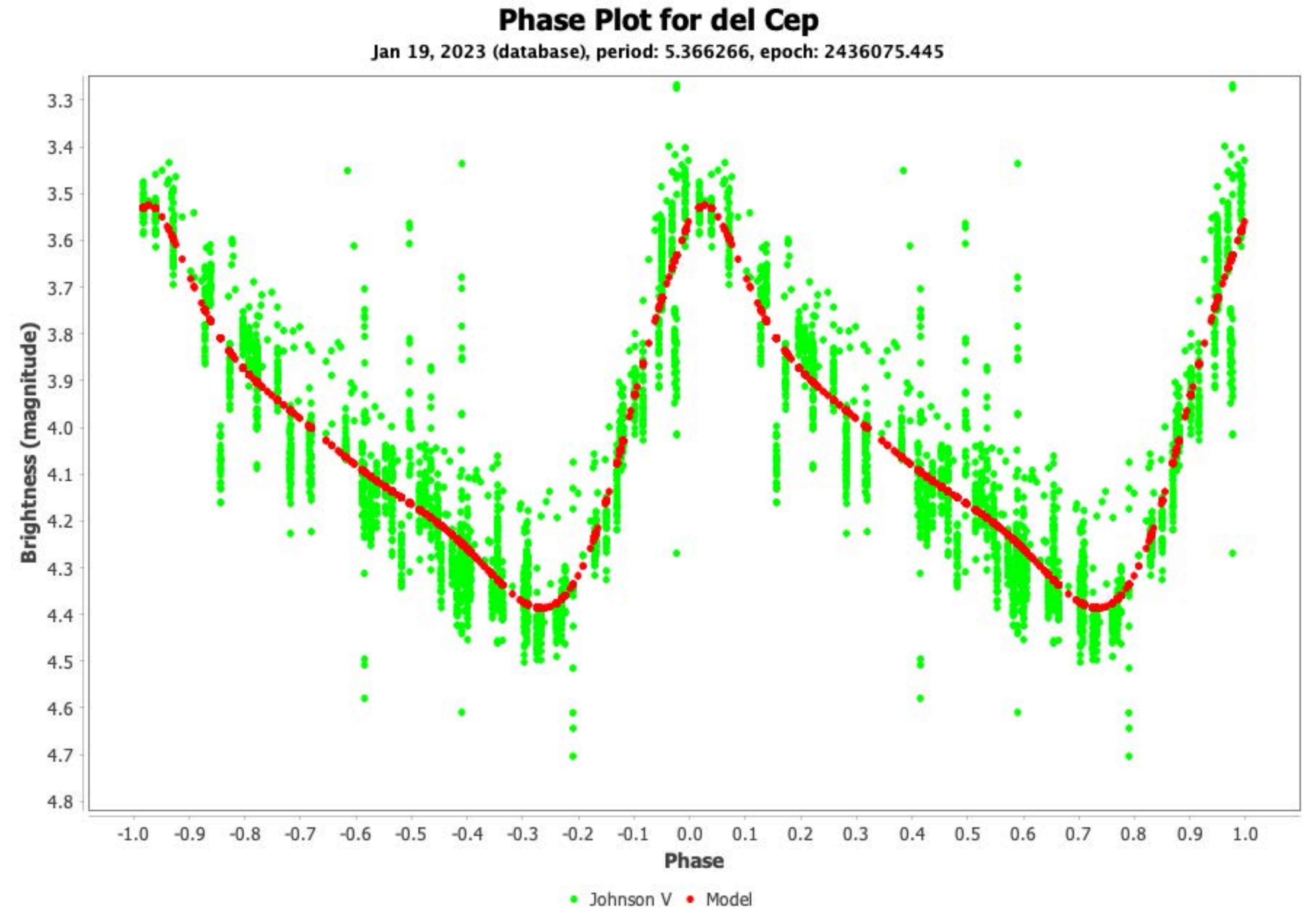


Variable Stars

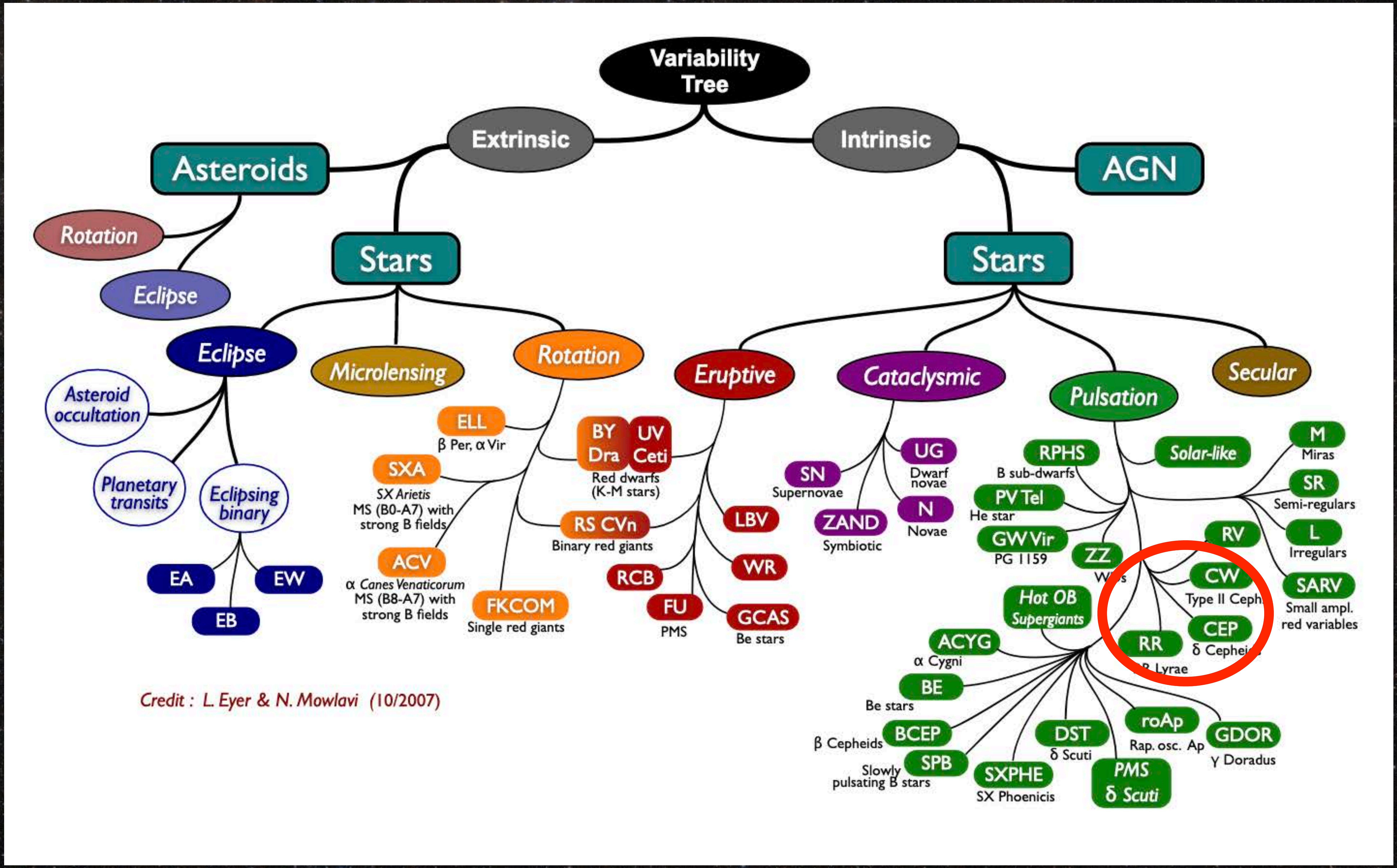
Nearly two centuries passed before another variable star was discovered, this time by English astronomer John Goodricke

He discovered that the star δ Cephei varies regularly with a period of 5 days, 8 hours, 48 minutes

John Goodricke
1764-1786



Variable Stars



Today, over 1,000,000 variable stars are known and cataloged!

Broadly fall into two categories: extrinsic and intrinsic

For our class, we'll care about three subtypes

Cepheids & Distances

Henrietta Swan Leavitt compared photographs taken at different times to look for variable stars in the Small Magellanic Cloud, discovering 2,400 Cepheids in the process

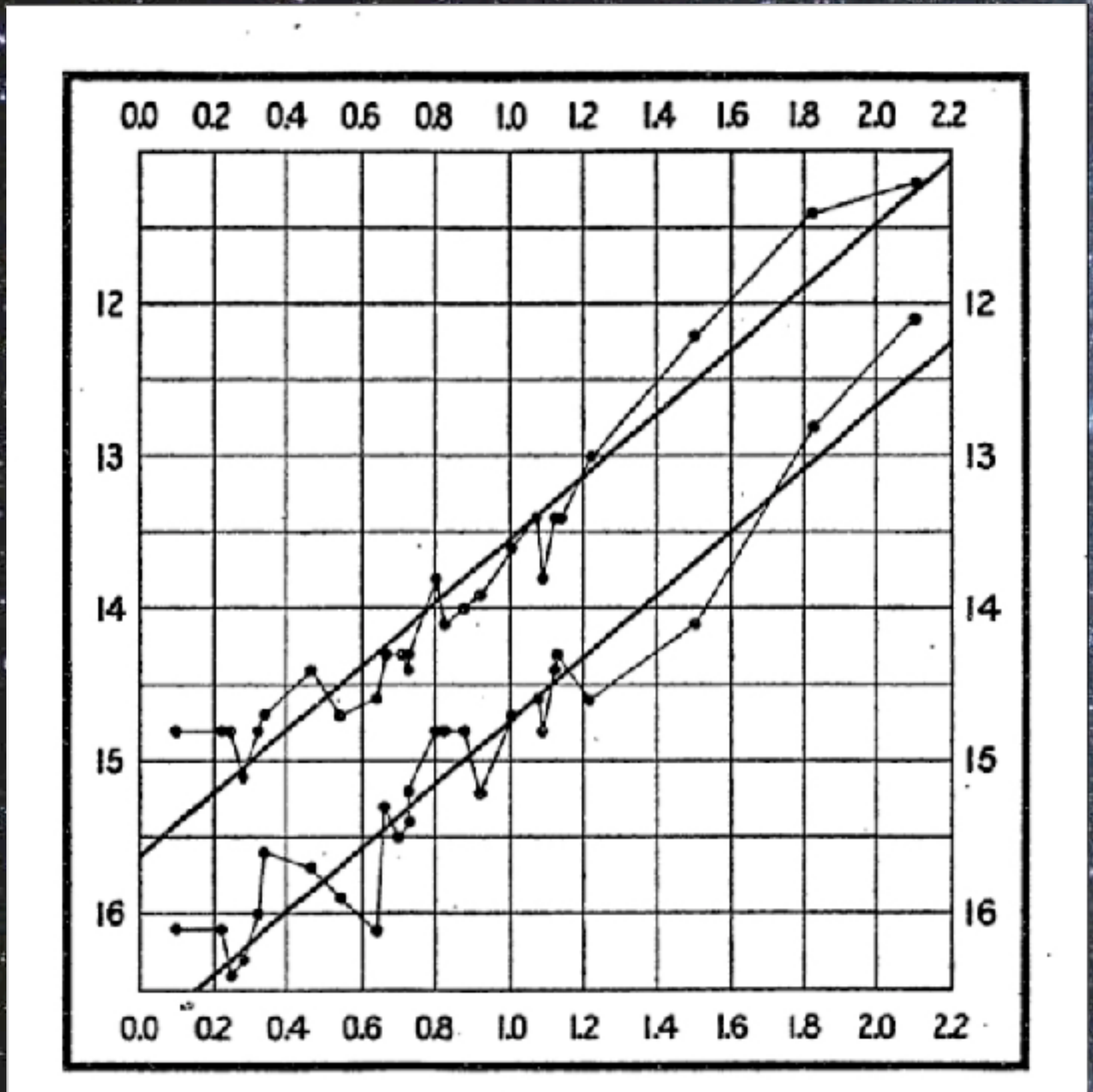


FIG. 2.

She noticed that the brighter ones took longer to change brightness!

Leavitt+1912

Henrietta Swan Leavitt
1868-1921

Small Magellanic Cloud (SMC)

Period-Luminosity Relationship

Since all the Cepheids in the SMC are at the same distance, the brighter ones must be intrinsically brighter and related to their periods

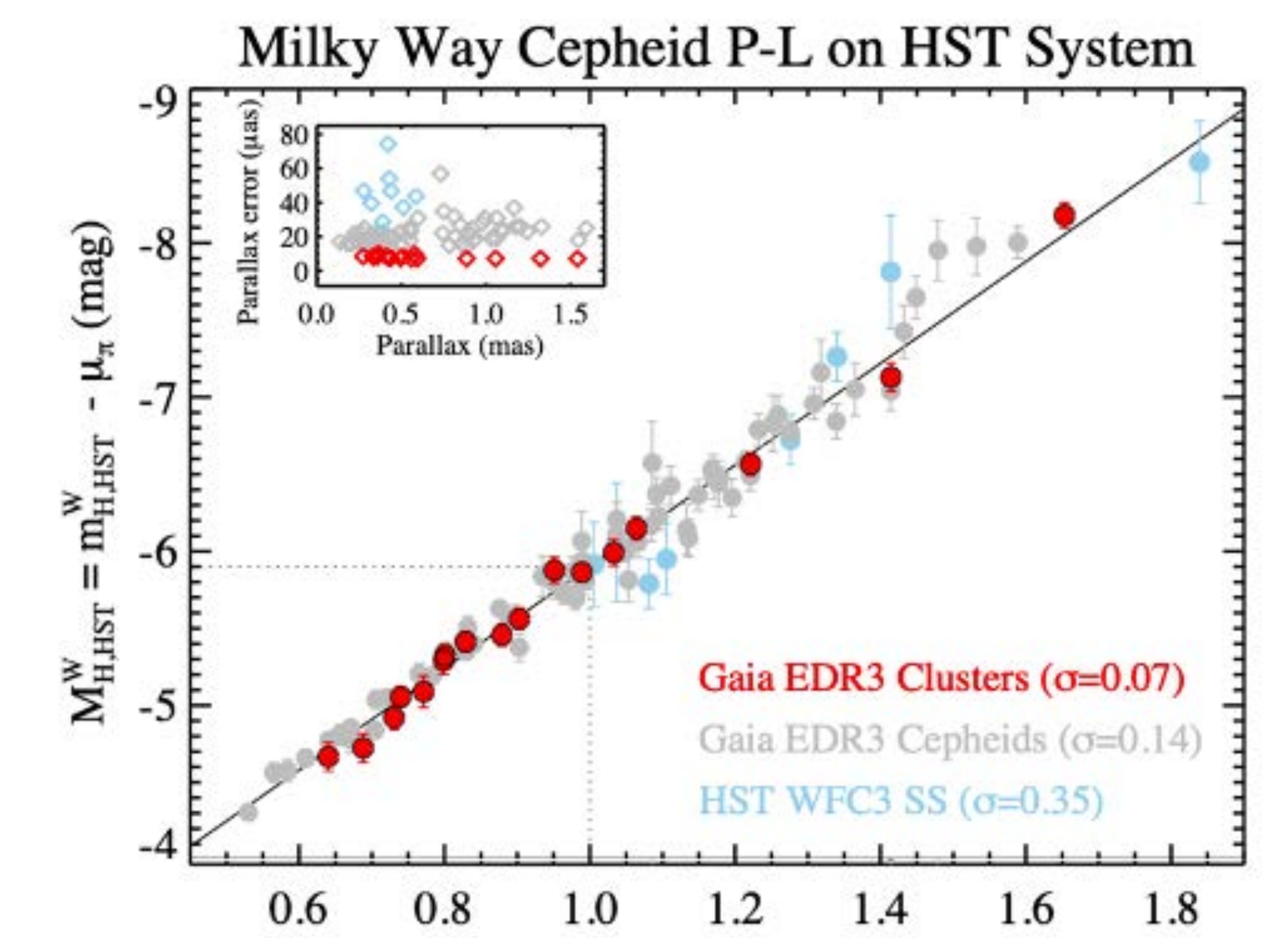
If we had an independent distance measurement to the SMC (or to any Cepheid), we can calibrate this relationship and use it as a distance indicator!

Advantages:

- Cepheids are bright; we can see them in nearby galaxies
- Cepheids are driven by stellar pulsation, which is well understood

Disadvantages:

- Cepheids are relatively rare
- Cepheids' period depends on their chemical composition



Riess+22

$$M_V = -2.43[\log P - 1] - 4.05$$

or

$$M_V = -2.43 \log P - 1.62$$

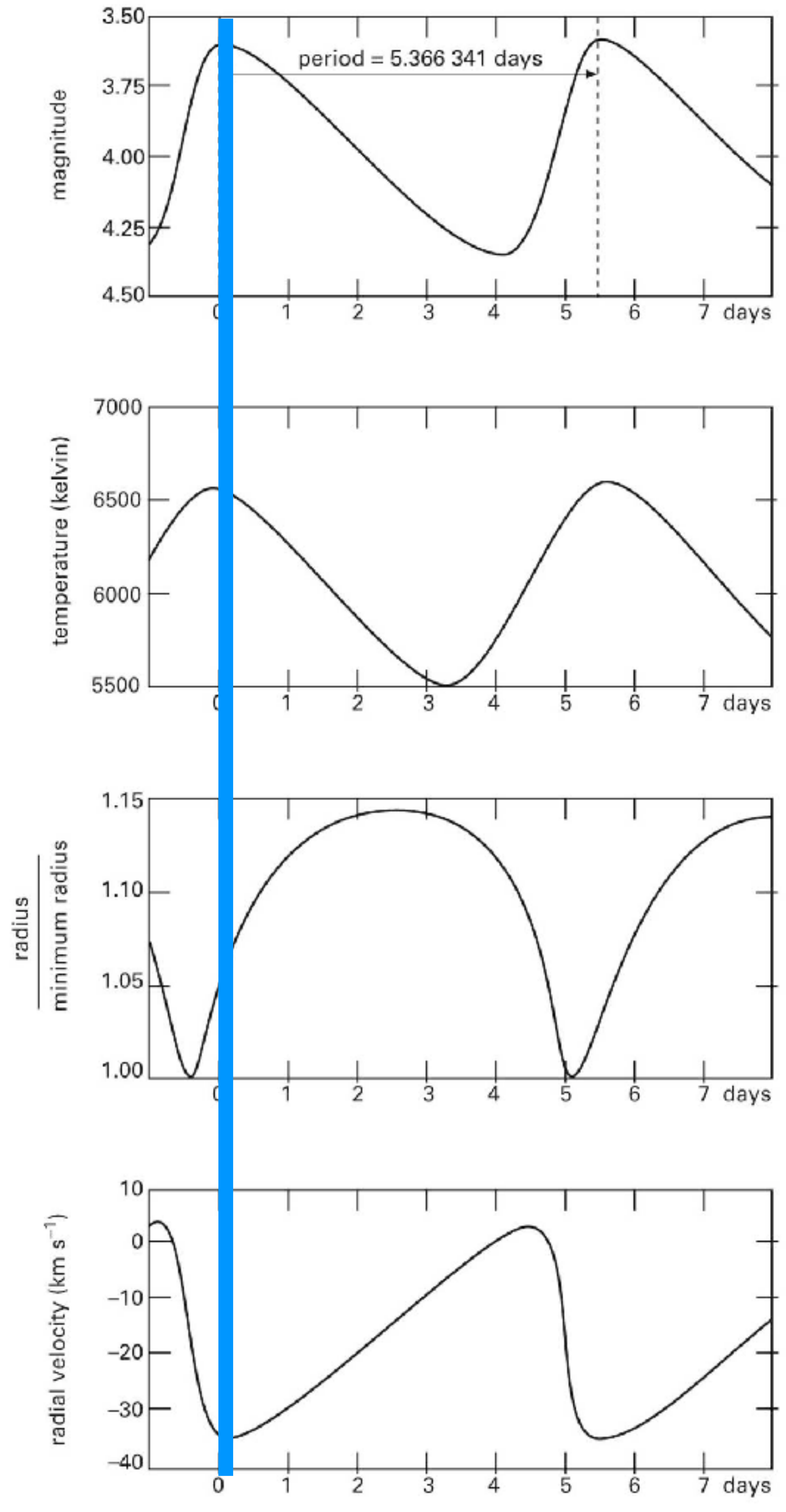
Cepheid Variations

Remember the Stefan-Boltzmann Law: $L = 4\pi\sigma R^2 T^4$

As the temperature gets hotter, the luminosity rapidly increases!

(The change in radius plays a minor role)

The star is brightest when its surface is expanding outward rapidly, *after* it has passed through its minimum radius



Cepheid variables: variation in brightness, temperature, radius, and radial velocity of expanding and contracting layers of Delta Cephei

The Instability Strip

What kinds of stars are these?

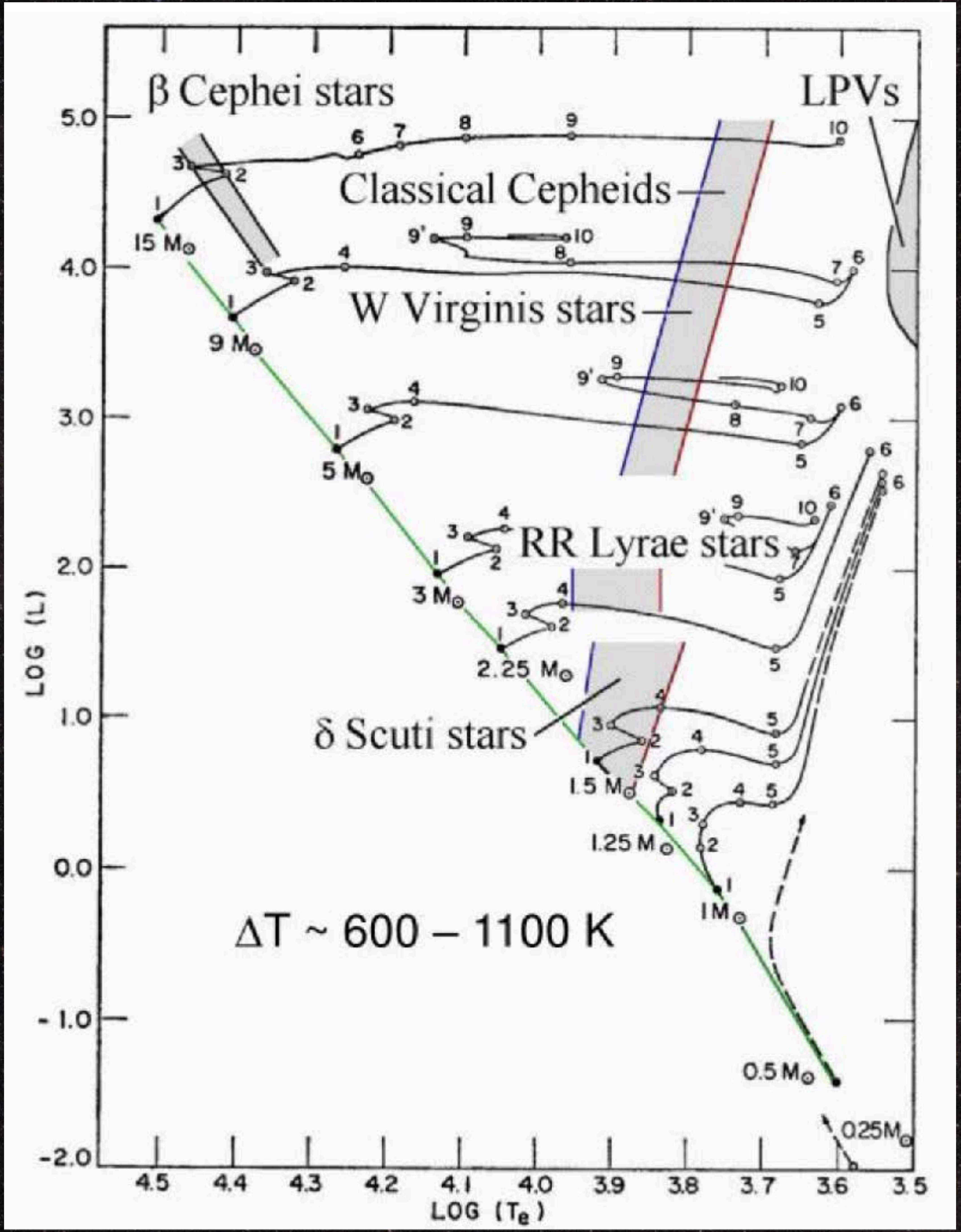
Pulsation is a short phase of a star's life as it evolves away from the main sequence

As stars evolve, they pulsate as they enter the instability strip and cease pulsation as they leave

Therefore, Cepheids are evolved high-mass stars!

Other types exist in the instability strip:

- W Virginis stars (metal-poor, low-luminosity Cepheids)
- RR Lyrae stars (evolved low-mass stars on HB)
- δ Scuti stars (evolved F stars more massive than Sun)
- ZZ Ceti stars (pulsating white dwarfs)



Pulsation Physics

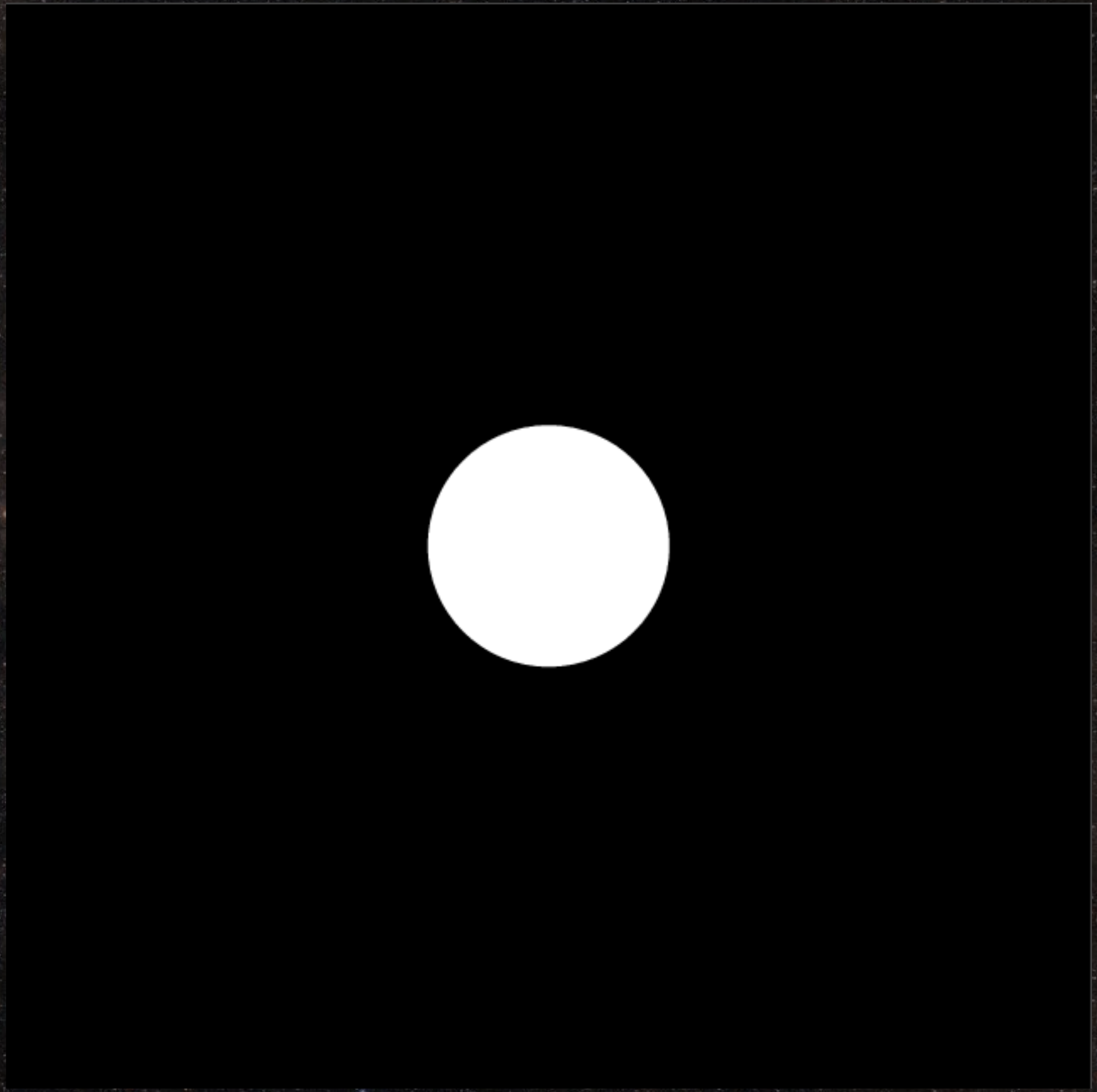
Take a normal star and squeeze it. What happens?

- Density, temperature, and pressure increase
- Star “rebounds” and expands, but overshoots
- Density, temperature, and pressure drop
- Star falls back
- Repeat

What did we forget? *Opacity!*

In a normal star, when the temperature increases, opacity decreases and vice versa

Opacity stabilizes against radial oscillations!



Pulsation Physics

However, under special conditions, opacity can work in the opposite direction!

Take a portion of a star where helium is singly ionized; if the temperature rises, helium will become doubly ionized and that will absorb energy

That means that in a helium ionization zone, opacity rises as temperature rises!

Now squeeze the star:

- Density, temperature, and pressure increase
- Helium absorbs the energy and becomes ionized
- Pressure can only be released via expansion
- Density, temperature, pressure decrease
- Helium recombines, opacity decreases
- Lack of pressure, star falls back
- Repeat