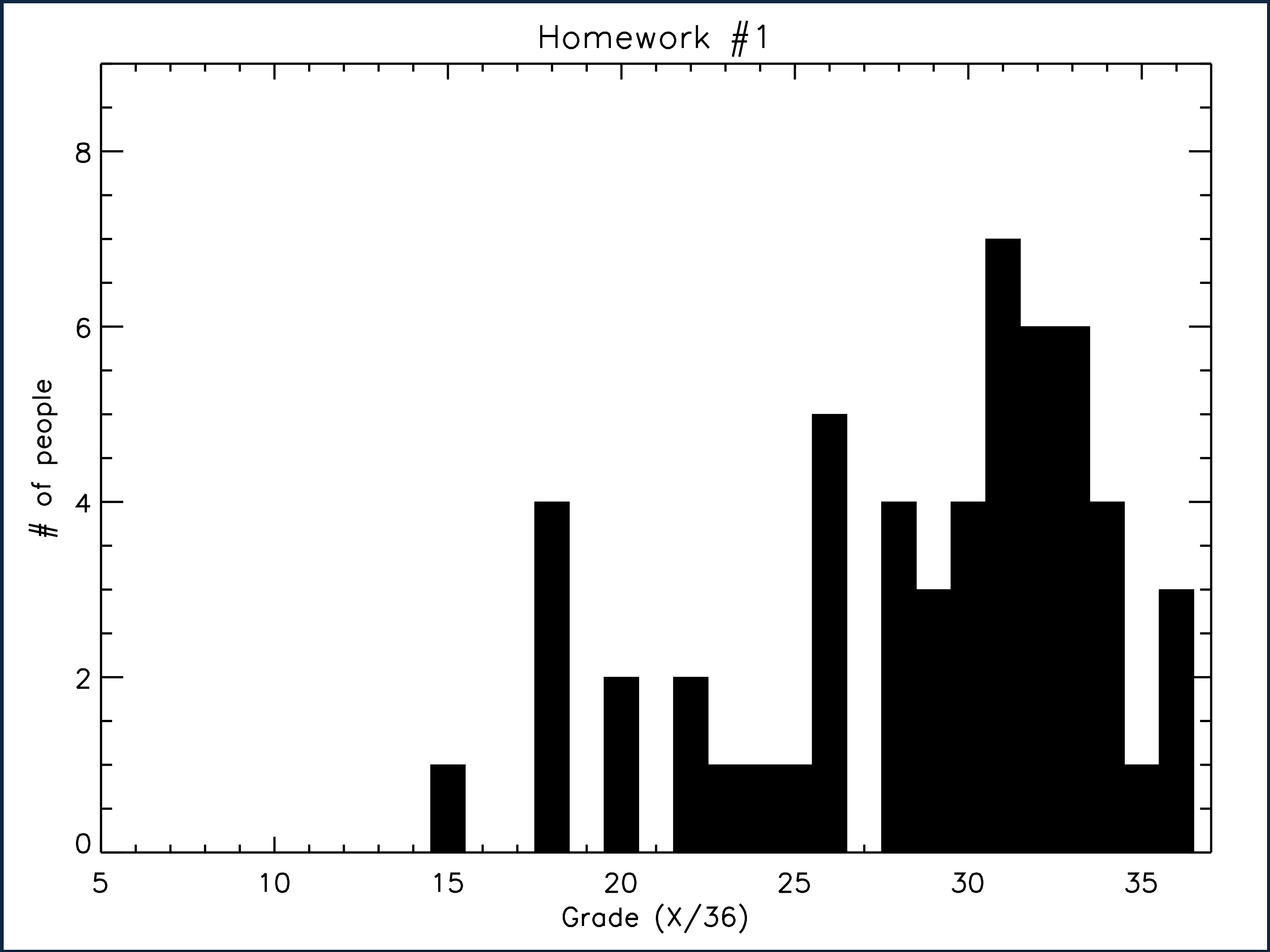
# Astronomy News

Gravitational waves *and electromagnetic radiation* have been detected from the merger of two neutron stars!

# Homework #1



# Important Exam News

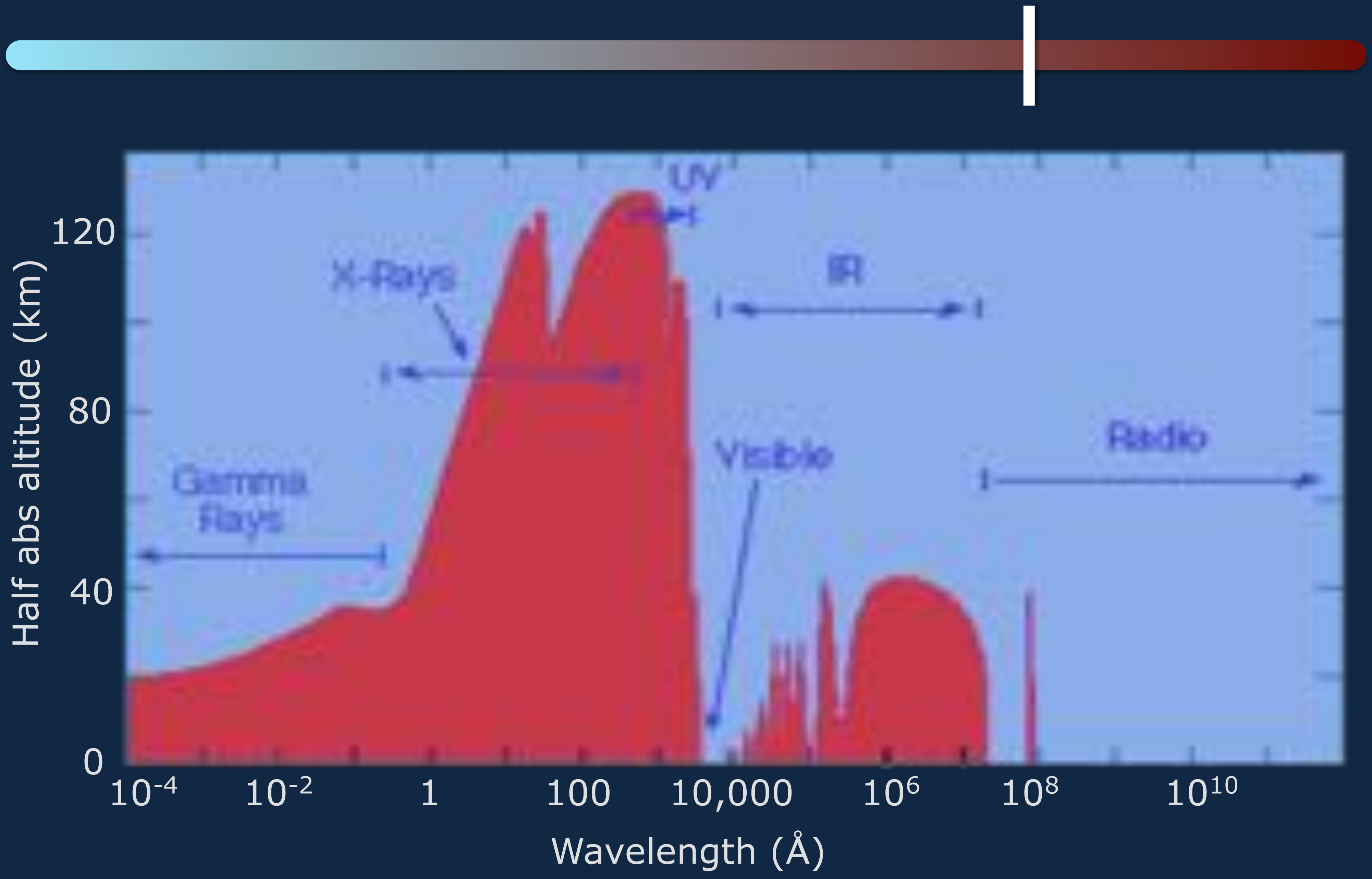
**The exams on Oct 31 and Dec 7 will be held in**

# A102

(it’s just down the hall)

(I’ll hang signs)

# Telescopes - Radio



# Telescopes - Radio

Telescopes designed as large antennae:

# Telescopes - Radio

Telescopes designed as large antennae:

# Telescopes - Radio

Radio interferometry arrays:

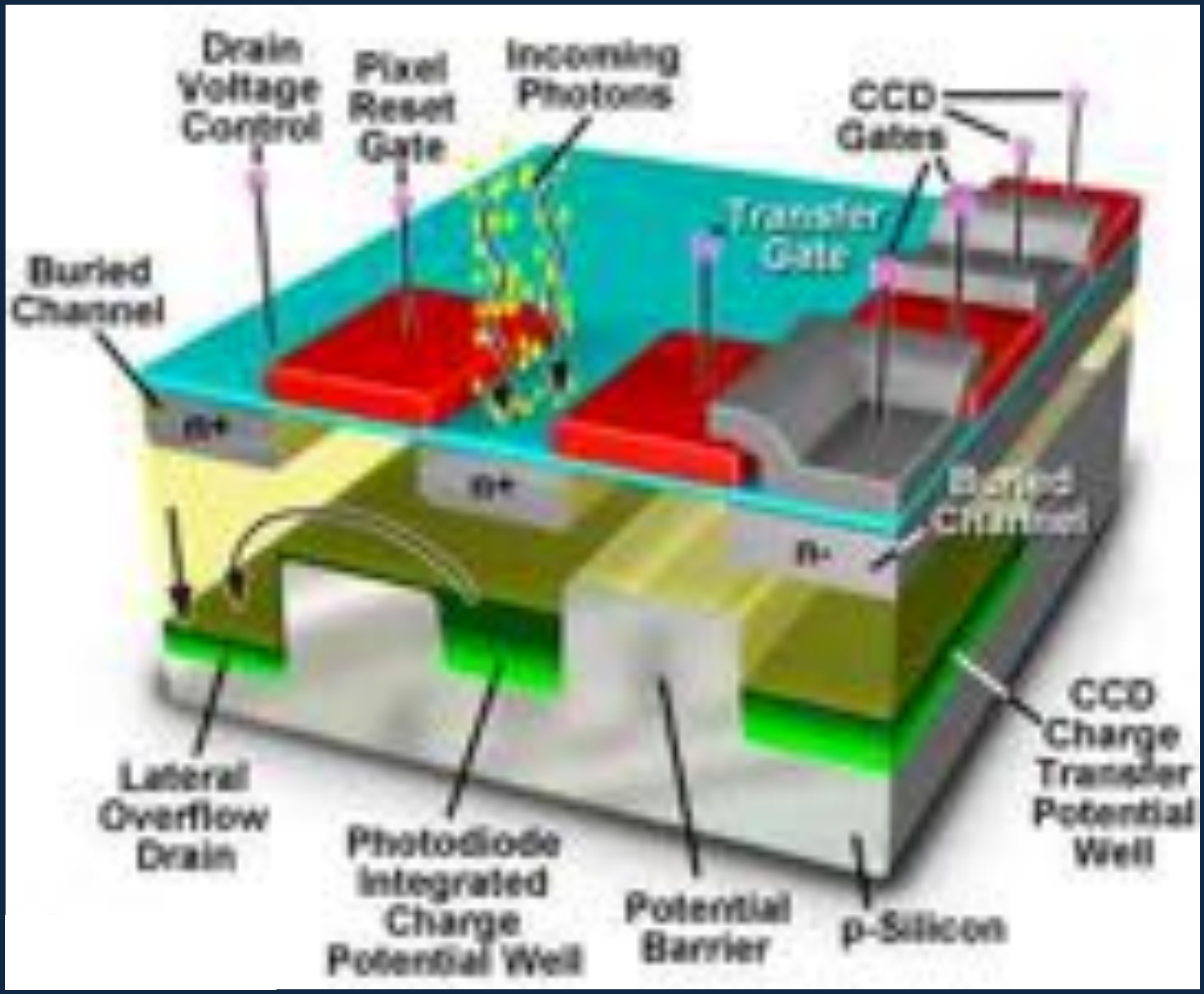
# Telescopes


Astrophysics Missions timeline
JWST
WFIRST
ASTRO-H
ST-7/LPF
NuSTAR
SOFIA
WISE
Herschel
Planck
Kepler
Fermi
Suzaku
Swift
Spitzer
GALEX
Integral
WMAP
XMM-Newton
Chandra
RXTE
Hubble
ST-7
SM-4
Formulation
Development
Operating
TIMELINE
1990
1993
1996
1999
2002
2005
2008
2011
2014
2017
2020

# Imaging

## Instruments

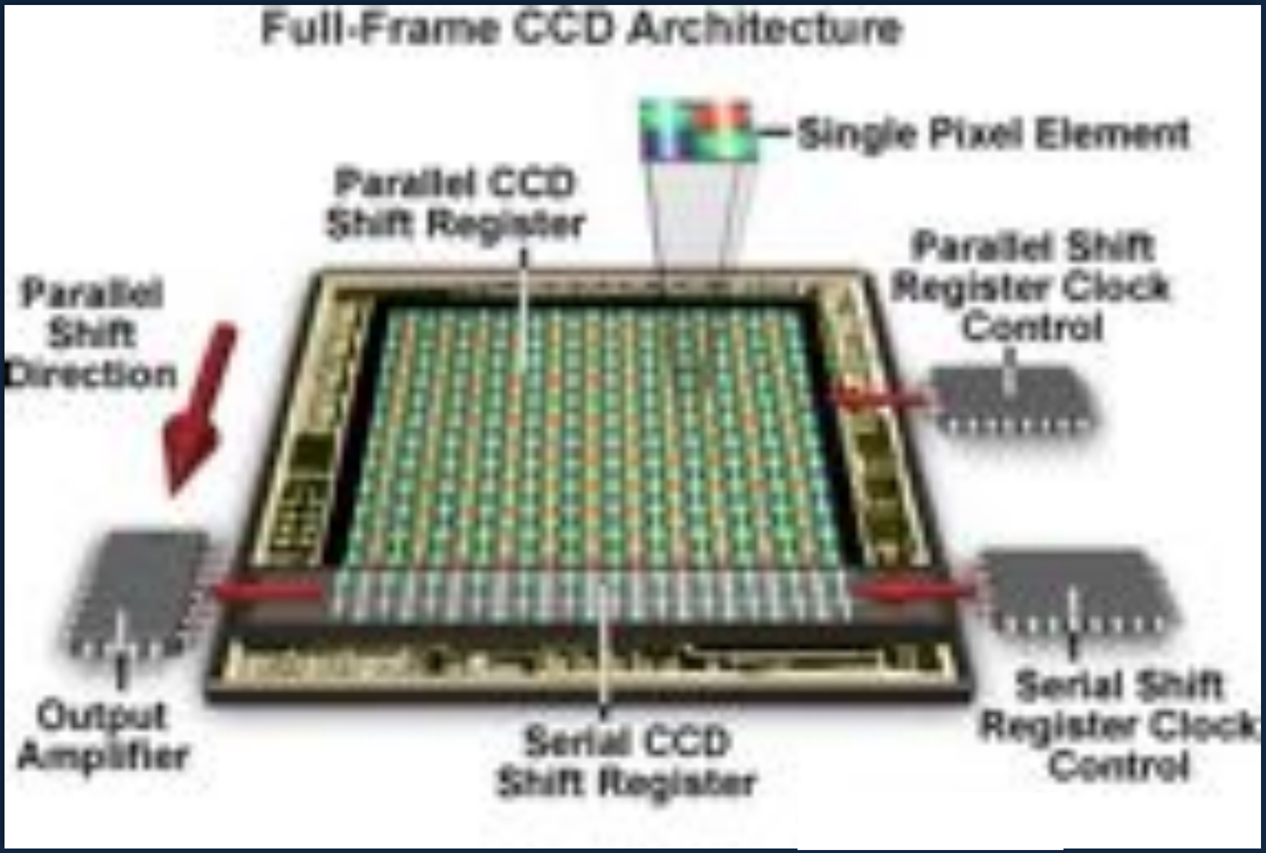
Charge Coupled Device (CCD)



# Imaging

## Instruments

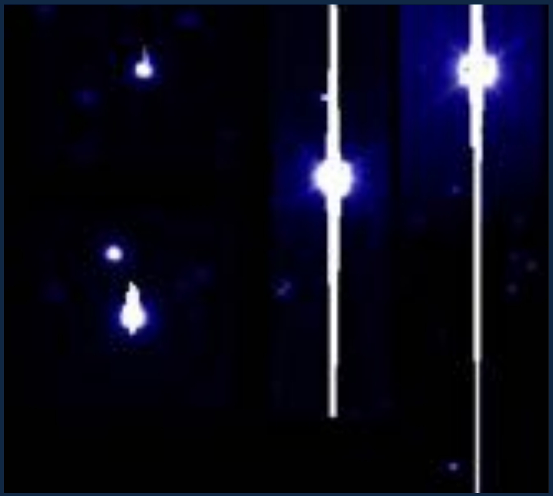
### Charge Coupled Device (CCD)




- 2D grid of 7-30μ pixels

- well capacity of 10,000 to 60,000 $e^-$

- overexposing leads to pixel saturation; spills into adjacent pixels



# Imaging

Instruments

## DISCUSSION QUESTION

The total signal received from an exposure of time t read to a CCD is: **S = FQt + Dt + B**

F = photon flux
~~Q = quantum efficiency~~
D = signal w/ no photons
B = “bias”; fixed pattern noise from electronics

**flat**: exposure of a uniform-intensity field

# Imaging

Instruments

## Discussion Question

The total signal received from an exposure of time t read to a CCD is: **S = FQt + Dt + B**

F = photon flux

~~Q = quantum efficiency~~ → **flat**

~~D = signal w/ no photons~~ → **dark**: exposure of time t with the shutter closed

B = “bias”; fixed pattern noise from electronics

# Imaging

## Discussion Question

The total signal received from an exposure of time t read to a CCD is: $\mathbf{S = FQt + Dt + B}$

- F = photon flux
- ~~Q = quantum efficiency~~ → **flat**
- ~~D = signal w/ no photons~~ → **dark**
- ~~B = "bias"; fixed pattern noise from electronics~~ → **bias**: "zero-second" exposure capturing CCD noise

# Imaging

Instruments

## DISCUSSION QUESTION

The total signal received from an exposure of time t read to a CCD is: $\mathbf{S = FQt + Dt + B}$

F = photon flux

~~Q = quantum efficiency~~ → **flat**

~~D = signal w/ no photons~~ → **dark**

~~B = "bias"; fixed pattern~~ → **bias**

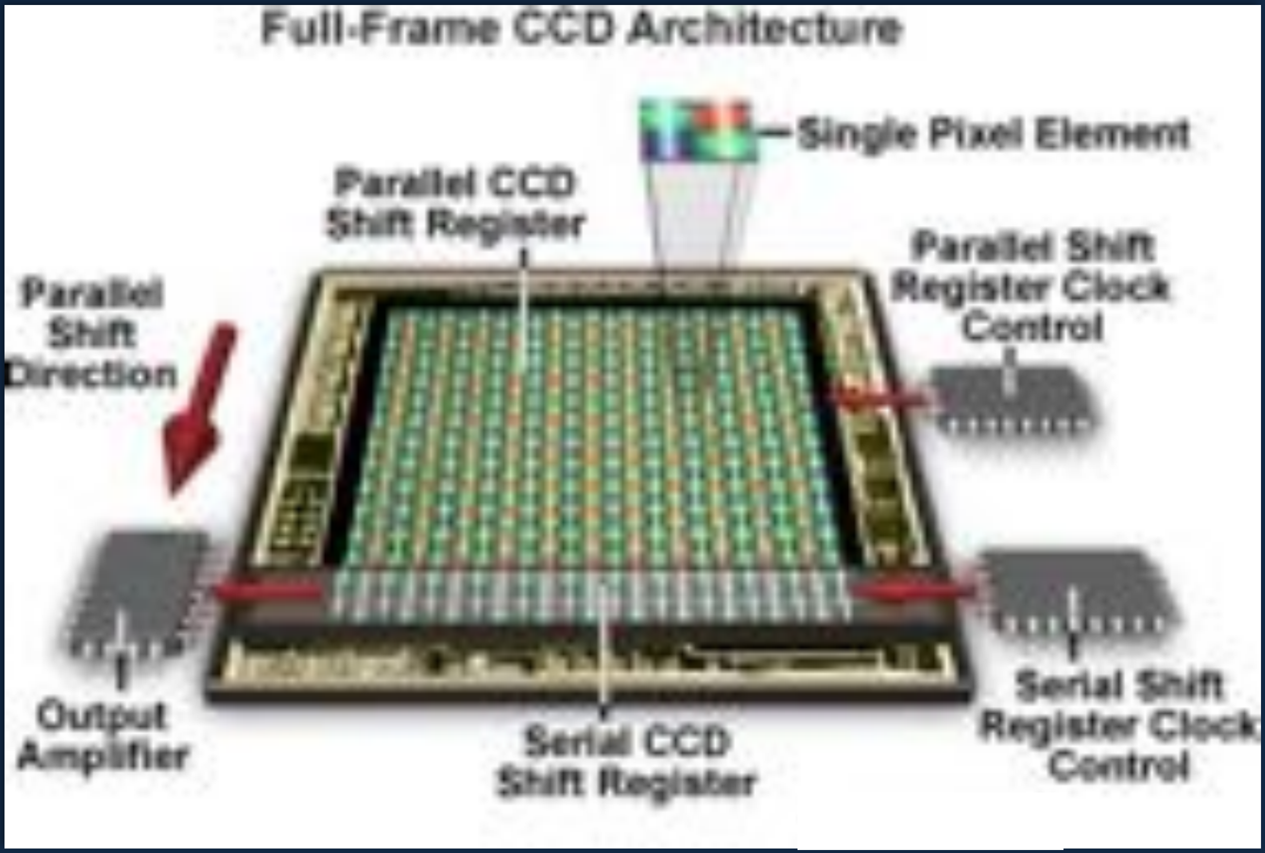
noise from electronics

Can also reduce the dark signal to a very low amount by cooling the detector…

# Imaging

## Instruments

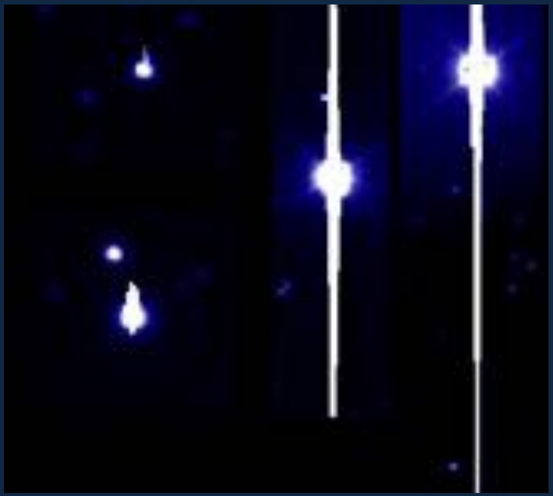
### Charge Coupled Device (CCD)




- 2D grid of 7-30μ pixels

- well capacity of 10,000 60,000 $e^-$

- overexposing leads to pixel saturation; spills into adjacent pixels

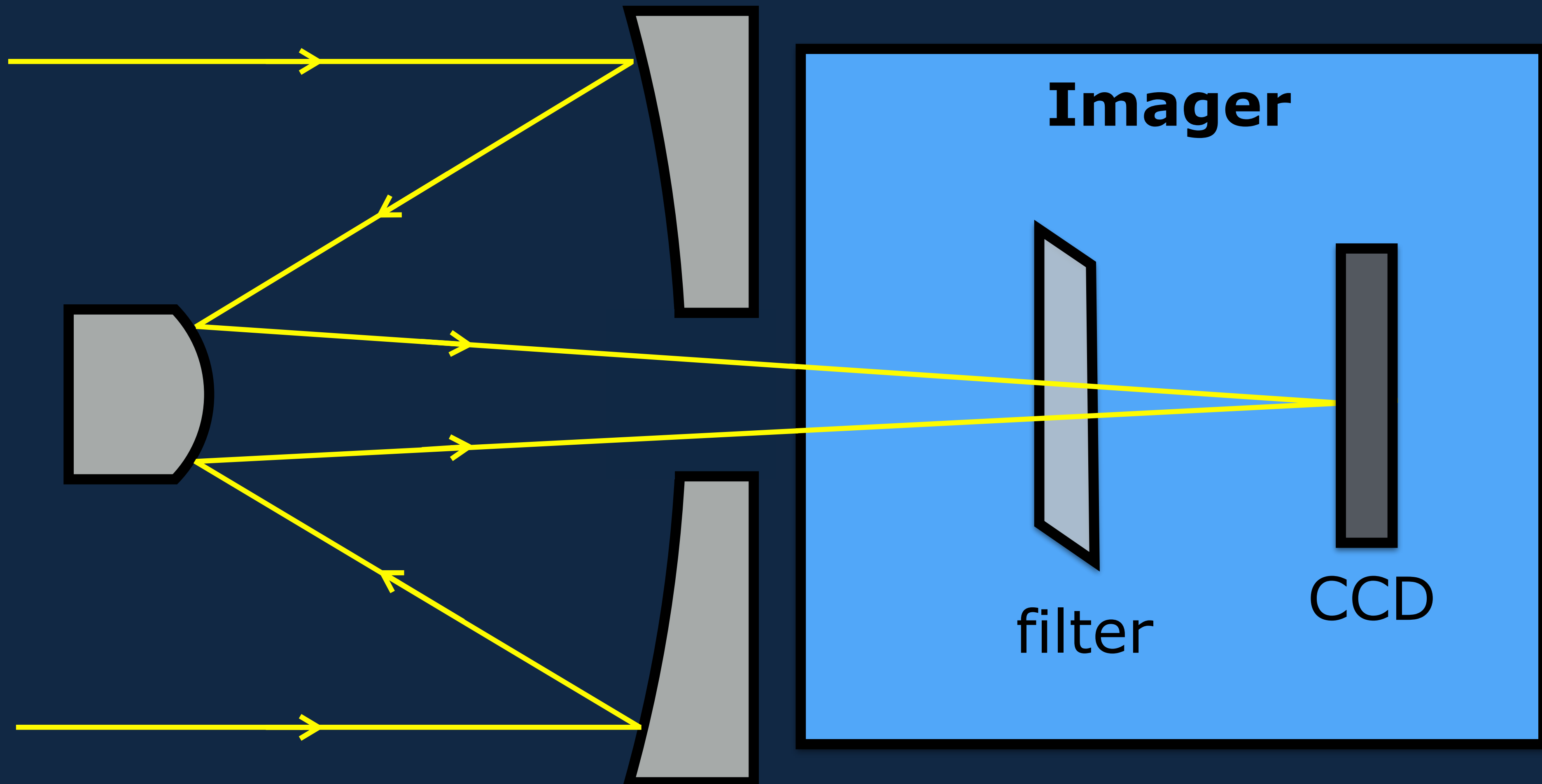


- must be kept cold to minimize thermal energy within the silicon lattice

# Imaging

## Instruments

Imager: light passes through filter to CCD



# Imaging

Instruments

Imager: light passes through filter to CCD

Johnson filters

UBVRI: visual

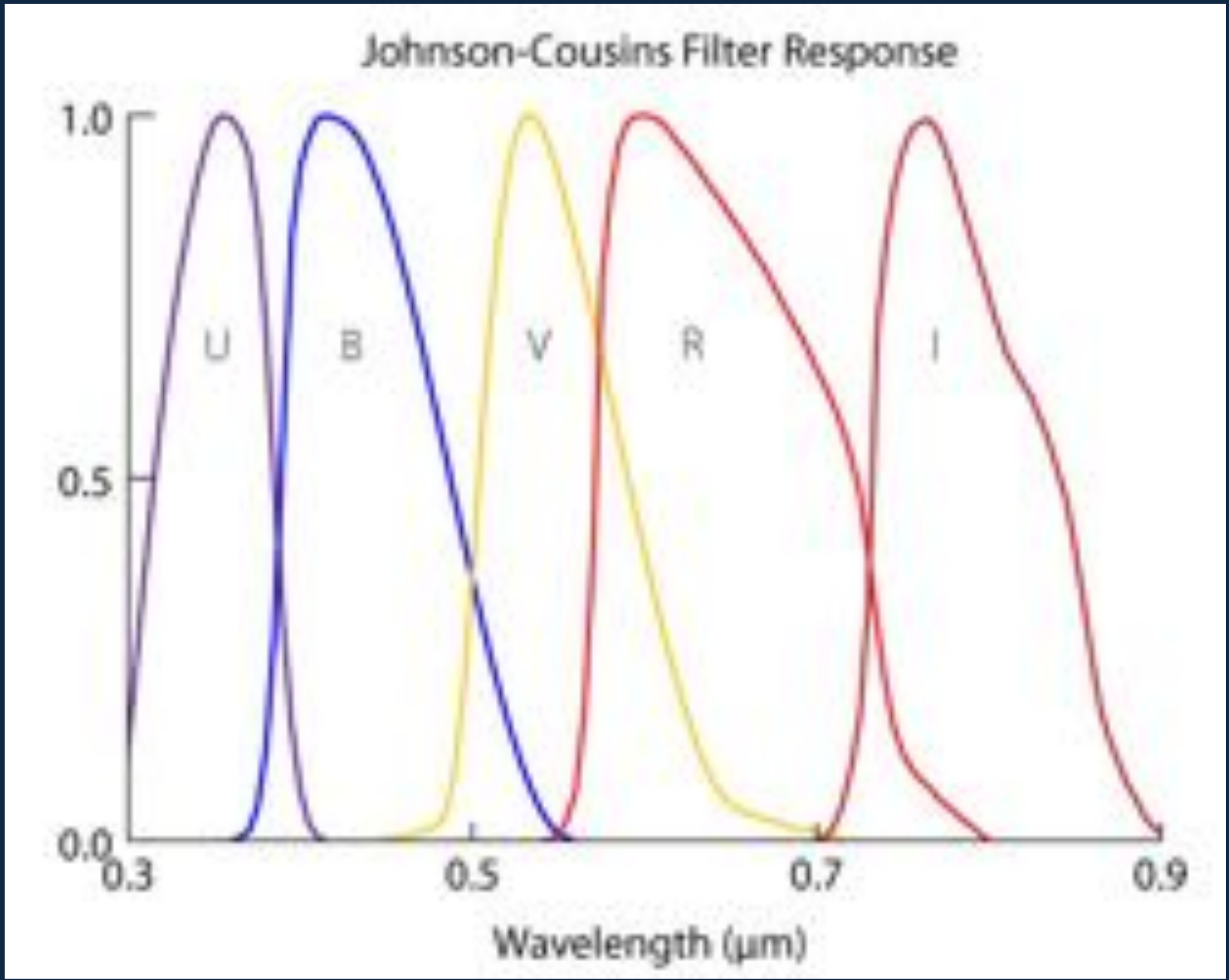
JHK: infrared

Sloan filters

ugriz: visual

Narrow-band

Optimized for spectral lines



# Imaging

## Observations

Imaging lets us measure the brightness of objects, measured in **magnitudes**.

$$\boxed{m = -2.5\log(\text{flux}) + \text{const}}$$

— system is BACKWARDS

(m=5 is brighter than m=10)

— system is logarithmic

(m=5 is 100x brighter than m=10)

# Imaging

Observations

$$\boxed{m = -2.5\log(\text{flux}) + \text{const}}$$

$(V = -2.5\log(\text{flux}_V) + \text{const}_V)$

— always filter-dependent, based on Vega (provides the zero-point for Johnson mags)

$$m_2 - m_1 = -2.5\log(f_2/f_1)$$

apparent mag, m: star as viewed from Earth

absolute mag, M: star as viewed from 10 pc

$$\boxed{m-M = 5(\log(d) -1)}$$ (d in parsecs)

**distance modulus**

# Imaging

## QUICK QUESTION

Observed from Earth, Star X has a flux 10x higher than Star Y. Star X also has an apparent magnitude of V = 17. Star Y's V magnitude is therefore:

$$m_2 - m_1 = -2.5\log(f_2/f_1)$$

A) 14.5

B) 19.5

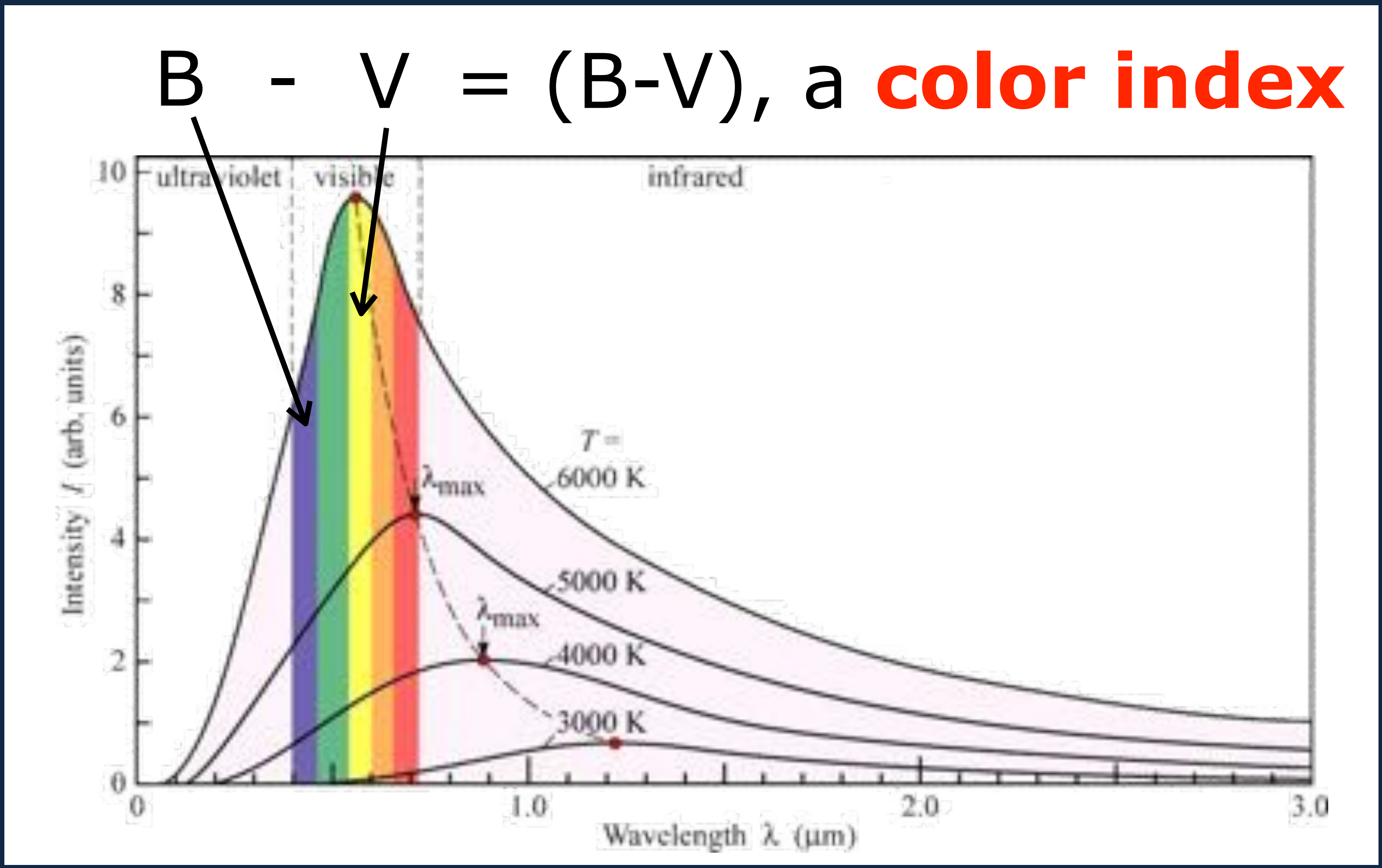
C) 170

D) 17.25

# Imaging

## Observations

With mags in two different filters, we can measure a star's color:



# Imaging

Observations

W

m

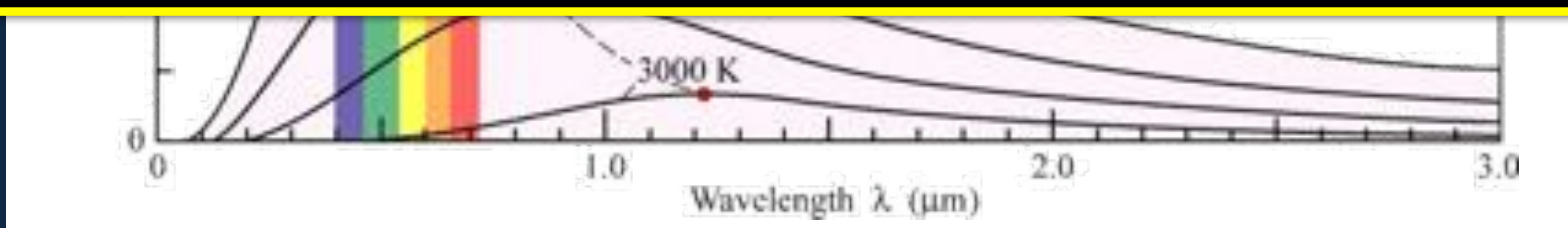
## Quick Question

Star X has (B-V) = 1.3.
Star Y has (B-V) = 3.

Which star is redder?

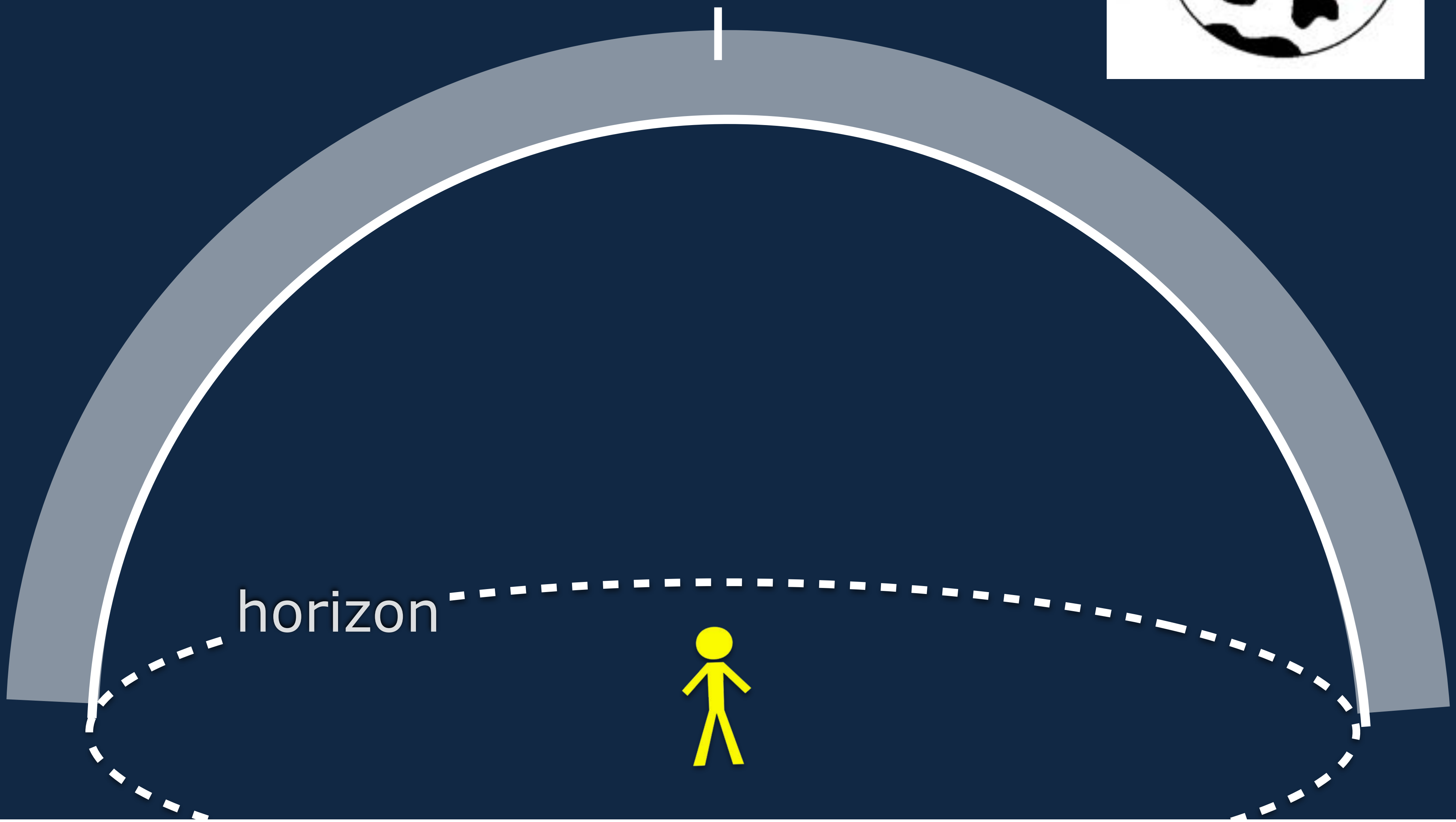
A) Star X

B) Star Y



# Imaging

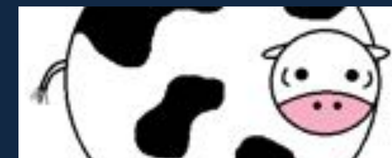
Observations



# Imaging

## Observations

zenith

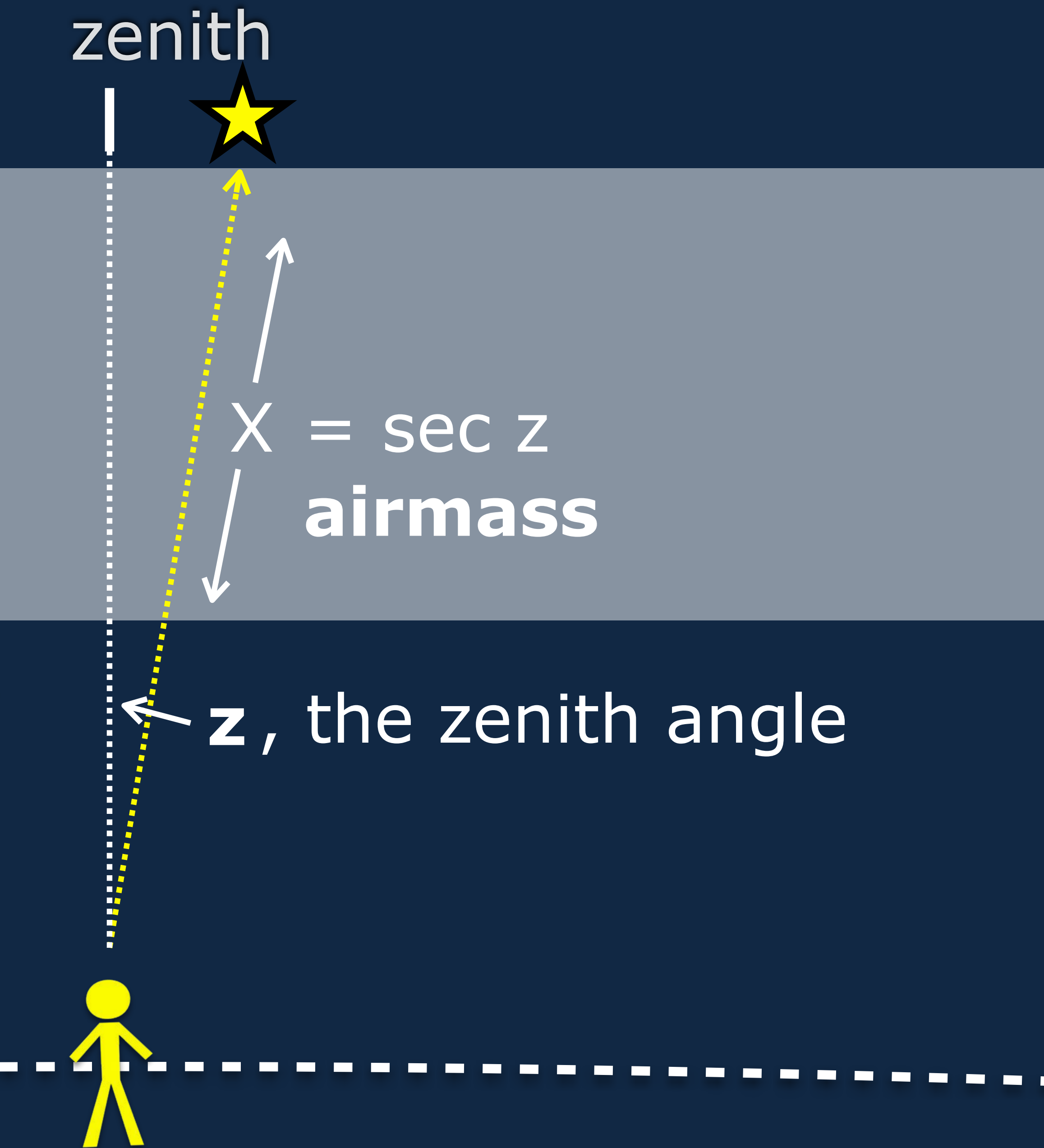


We can approximate our atmosphere as plane-parallel.

horizon

# Imaging

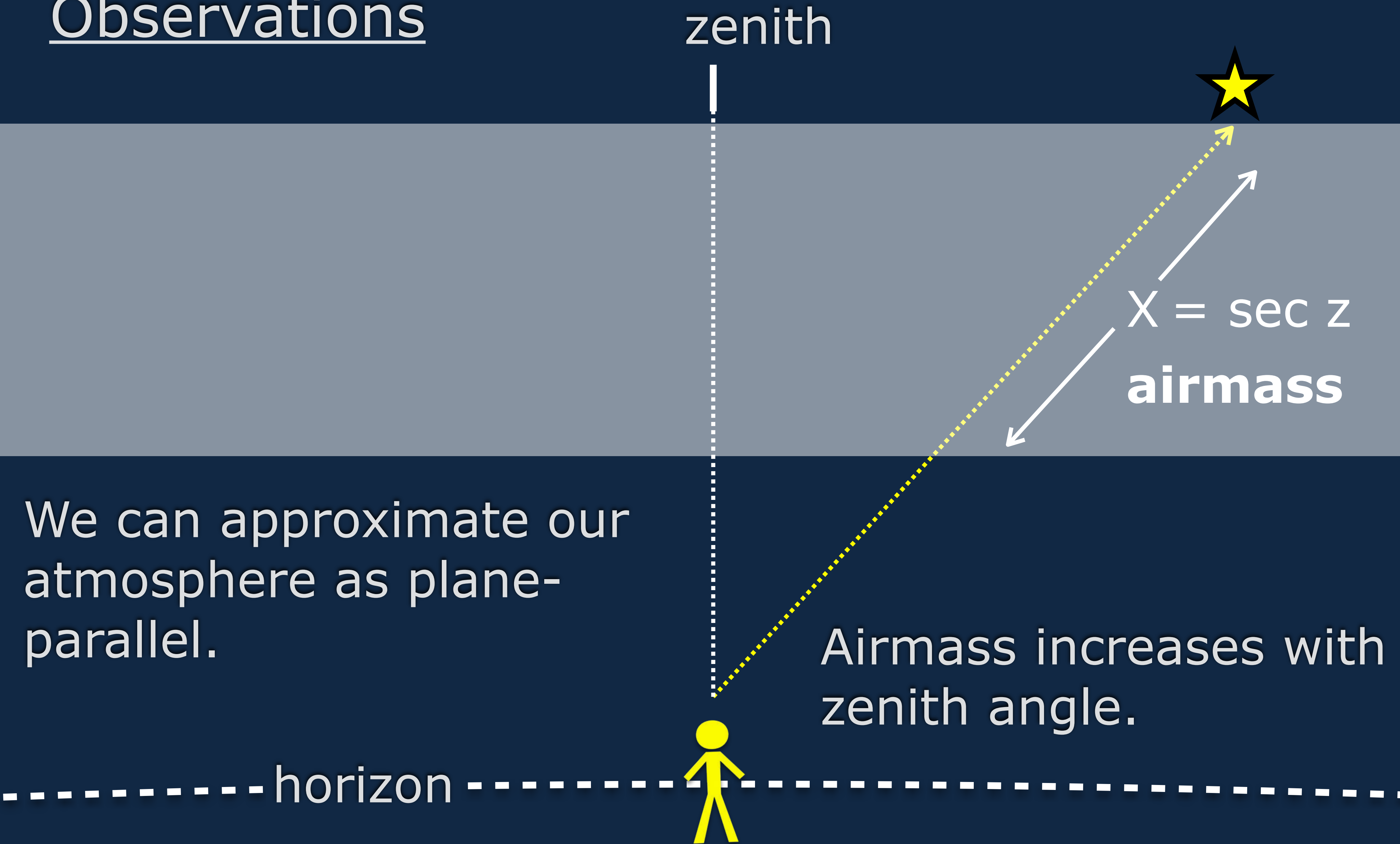
Observations




We can approximate our atmosphere as plane-parallel.

# Imaging

## Observations



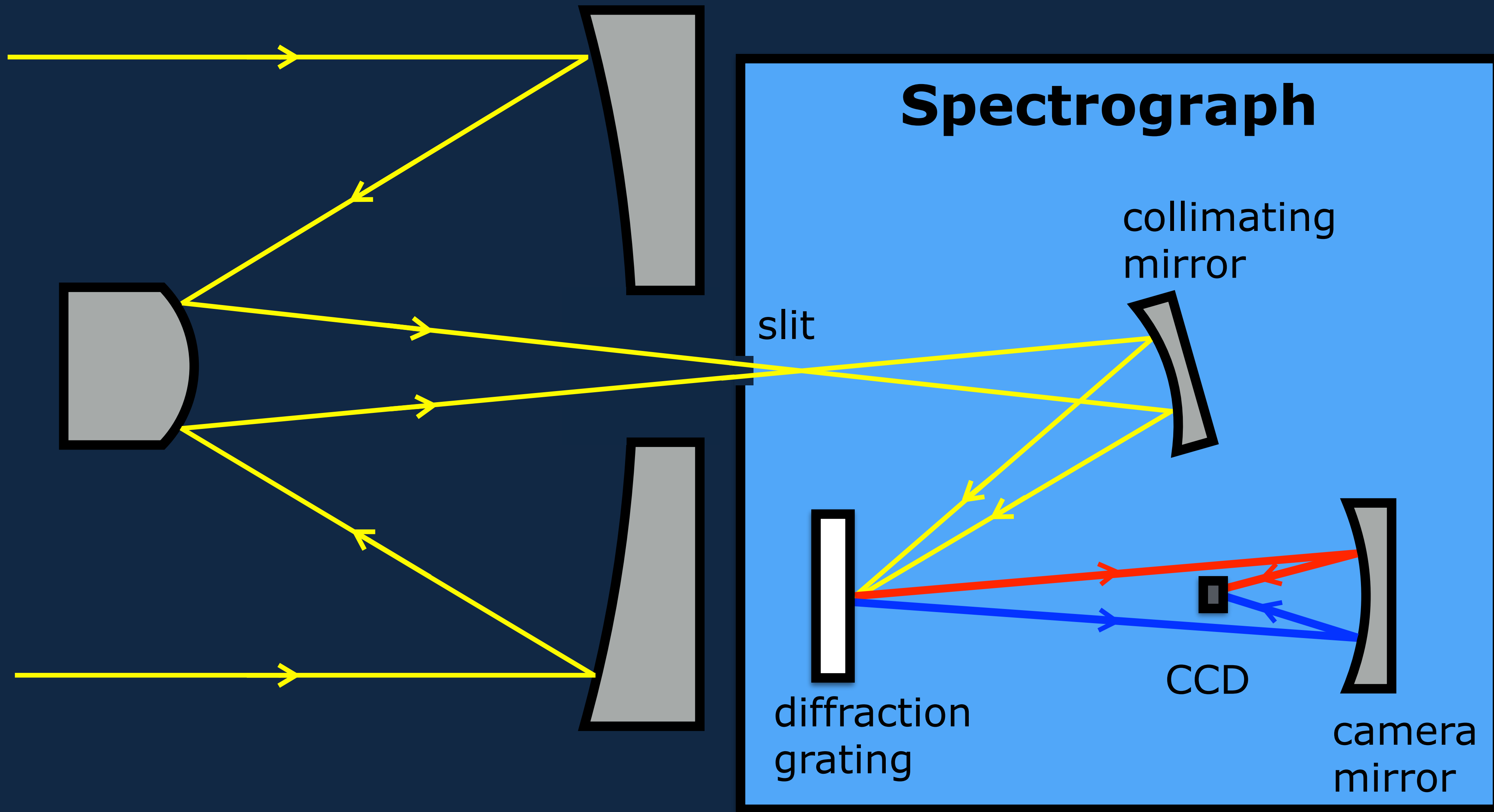

We can approximate our atmosphere as plane-parallel.

Airmass increases with zenith angle.

# Spectroscopy

## Instruments

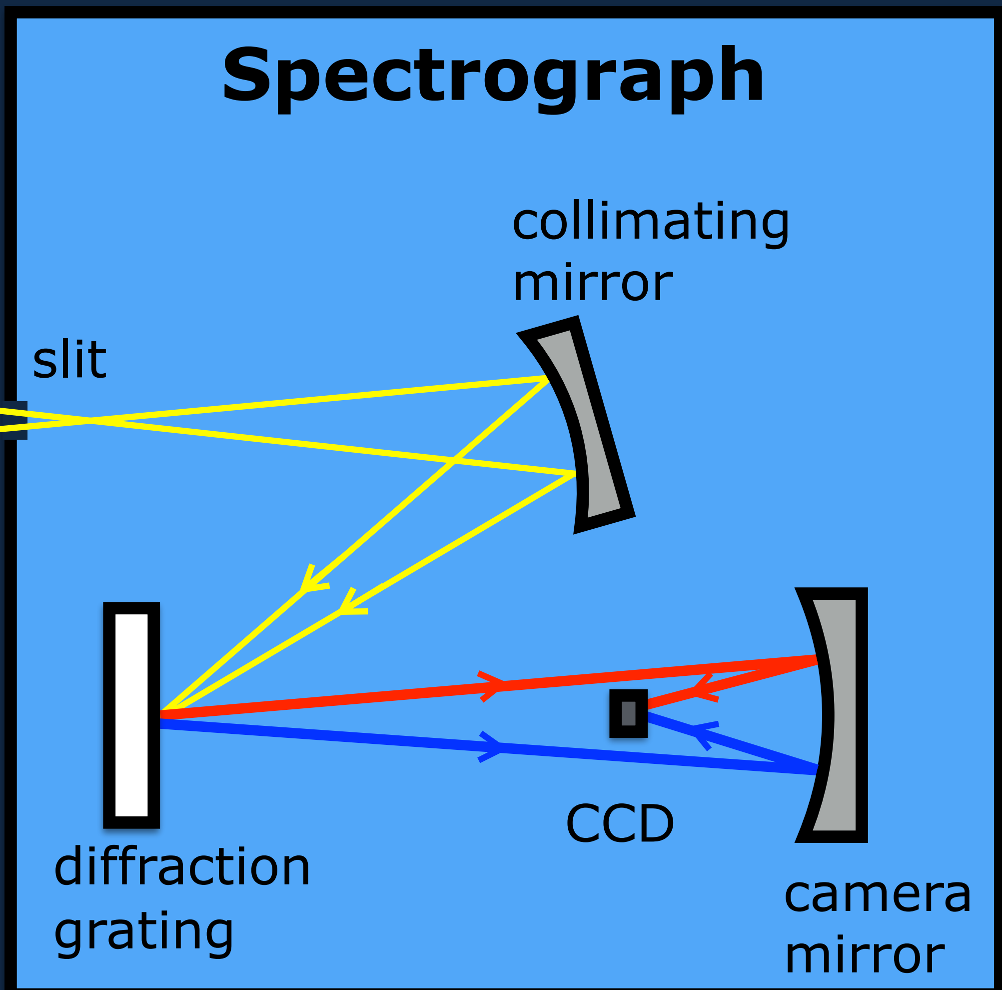
Spectrograph: breaks light into spectrum



# Spectroscopy

## Instruments

Spectrograph: breaks light into spectrum




—pixels correspond to wavelengths

—grating determines spectral resolution

—designs with multiple slits (or fiber feeds) allow simultaneous spectra of multiple objects

# Spectroscopy and Stars

## Observations

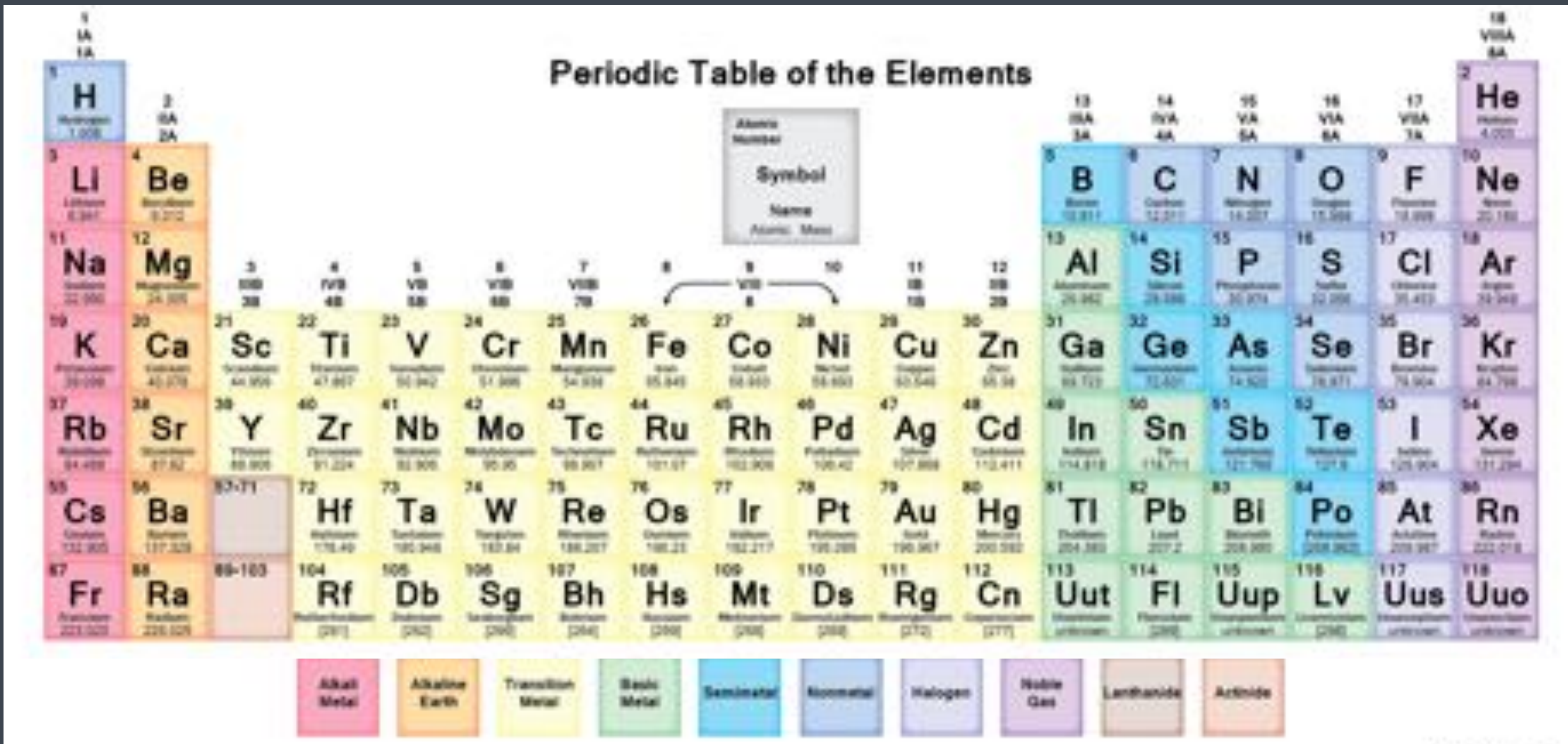
We typically classify stars by their **spectral types**.

Spectral types defined by peak wavelength and the identifications of key spectral features:

X I - neutral atom
X II - singly-ionized atom
X III - double-ionized atom

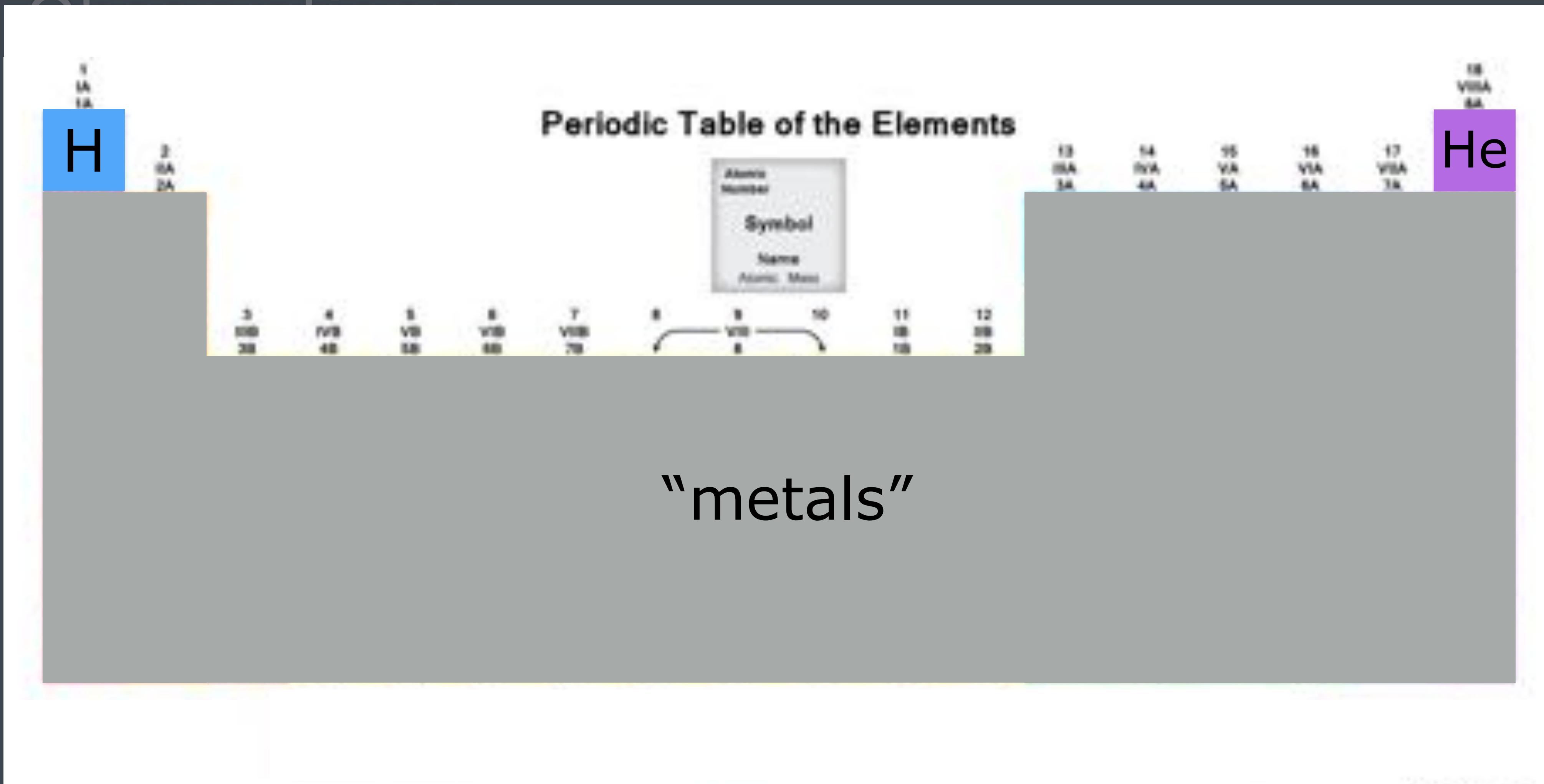
# Spectroscopy and Stars

## Observations




A note on the astronomers' periodic table…

# Spectroscopy and Stars

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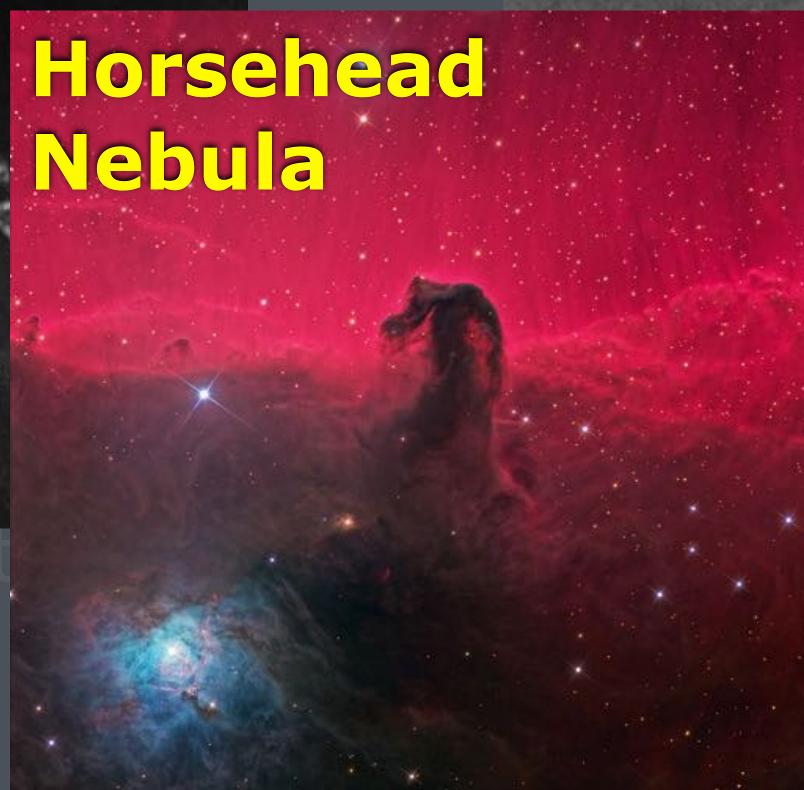
X III - double-ionized atom

Origins of spectral types goes back to late 1800's…

# Edward Pickering and the "Harvard Computers"


Spectroscopy and Stars

# Edward Pickering and the “Harvard Computers”


heir **spectral types.**

wavelength and


Origins of spect

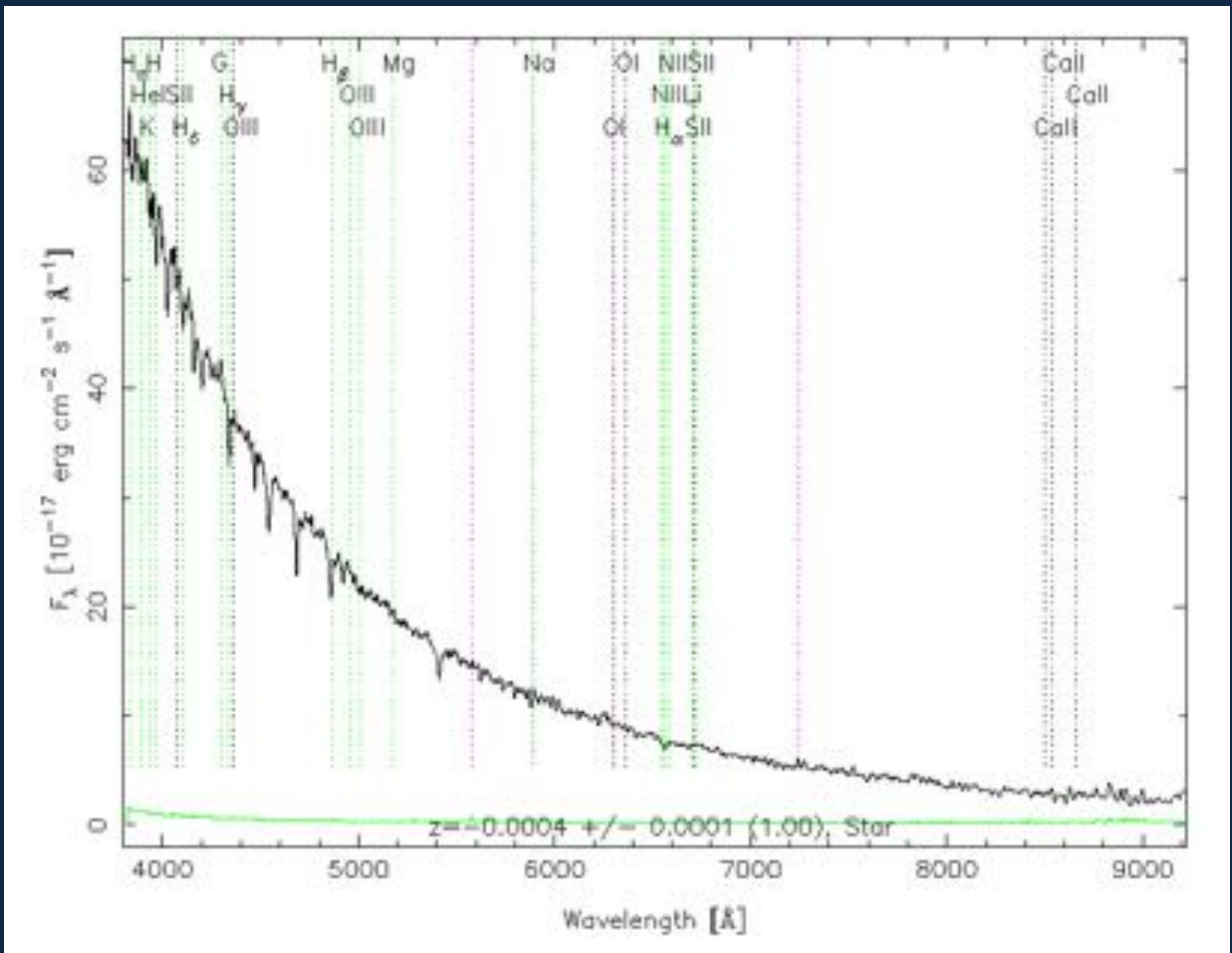
**O B A F G K M**

# Spectroscopy and Stars

## Observations

We typically classify stars by their **spectral types**.

**O B A F G K M**



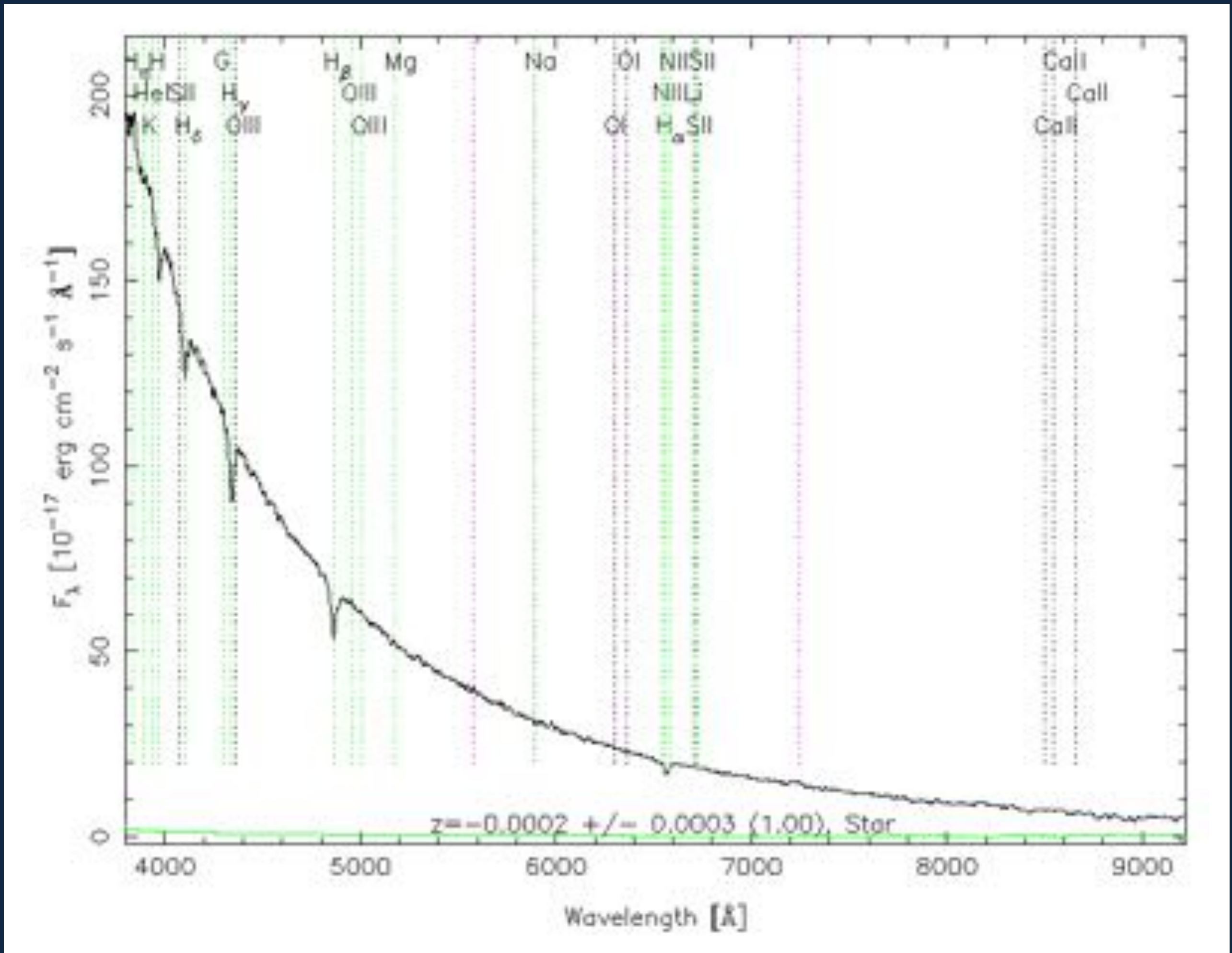

- 25000+ K
- bright in UV
- highly ionized species
- strong He II and He I lines
- weak H lines

# Spectroscopy and Stars

## Observations

We typically classify stars by their **spectral types**.

**O B A F G K M**



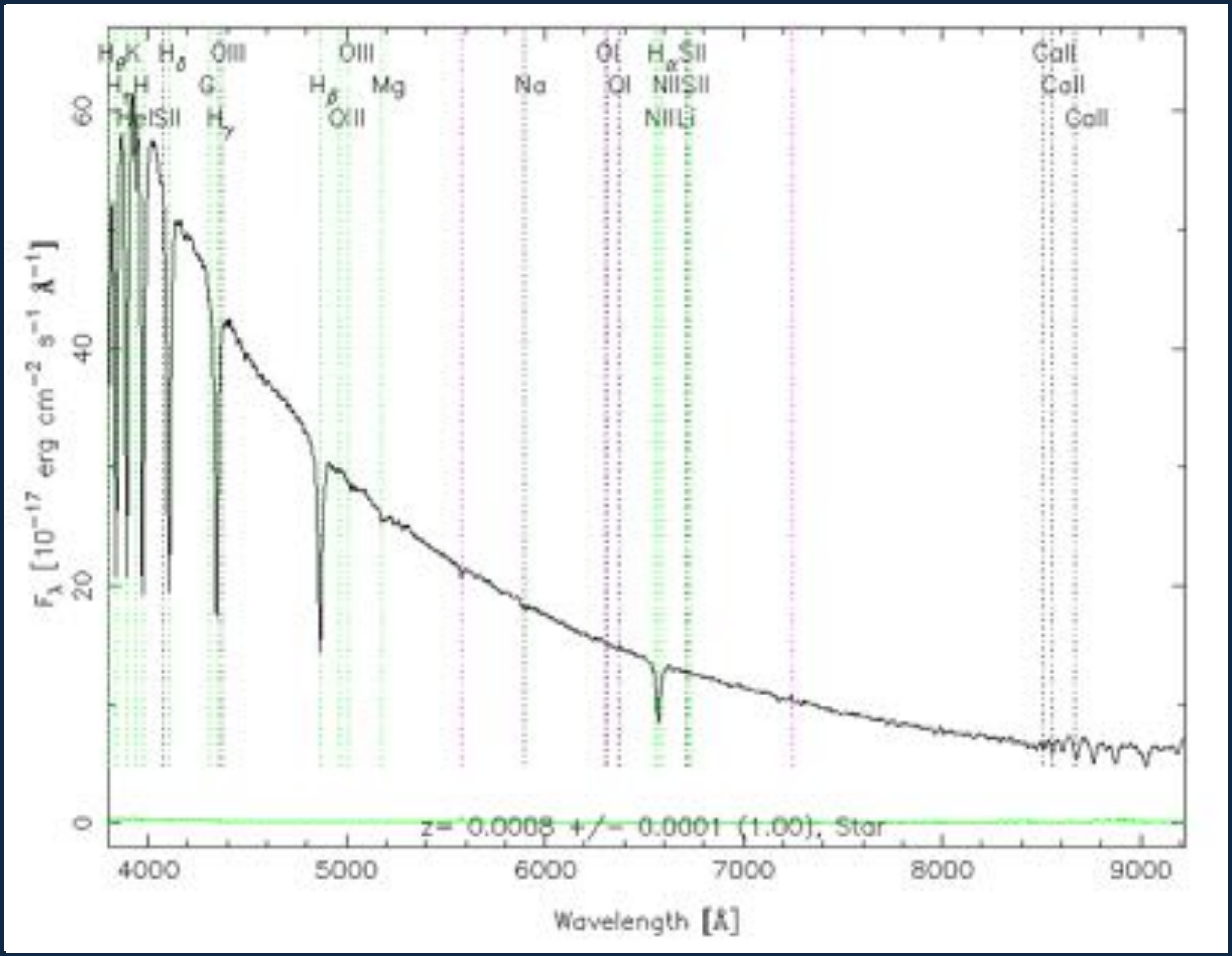

- 11000-25000 K
- less ionized species
- strong He I lines
- H lines getting stronger

# Spectroscopy and Stars

## Observations

We typically classify stars by their **spectral types**.

**O B A F G K M**



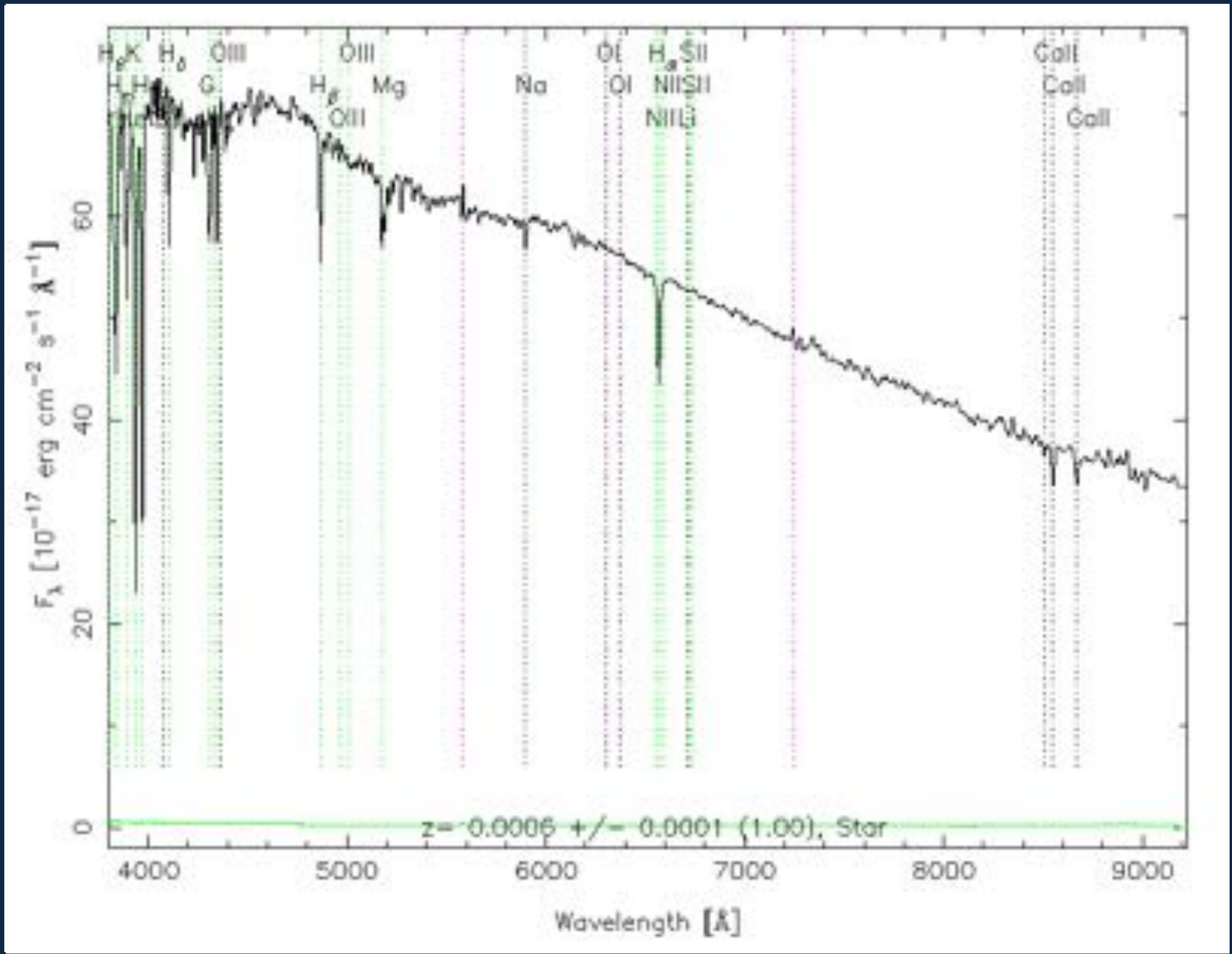

- 7500 - 11000 K
- appearance of Ca II lines
- singly-ionized metals (Mg II, Si II)
- **strongest H**

# Spectroscopy and Stars

## Observations

We typically classify stars by their **spectral types**.

**O B A F G K M**



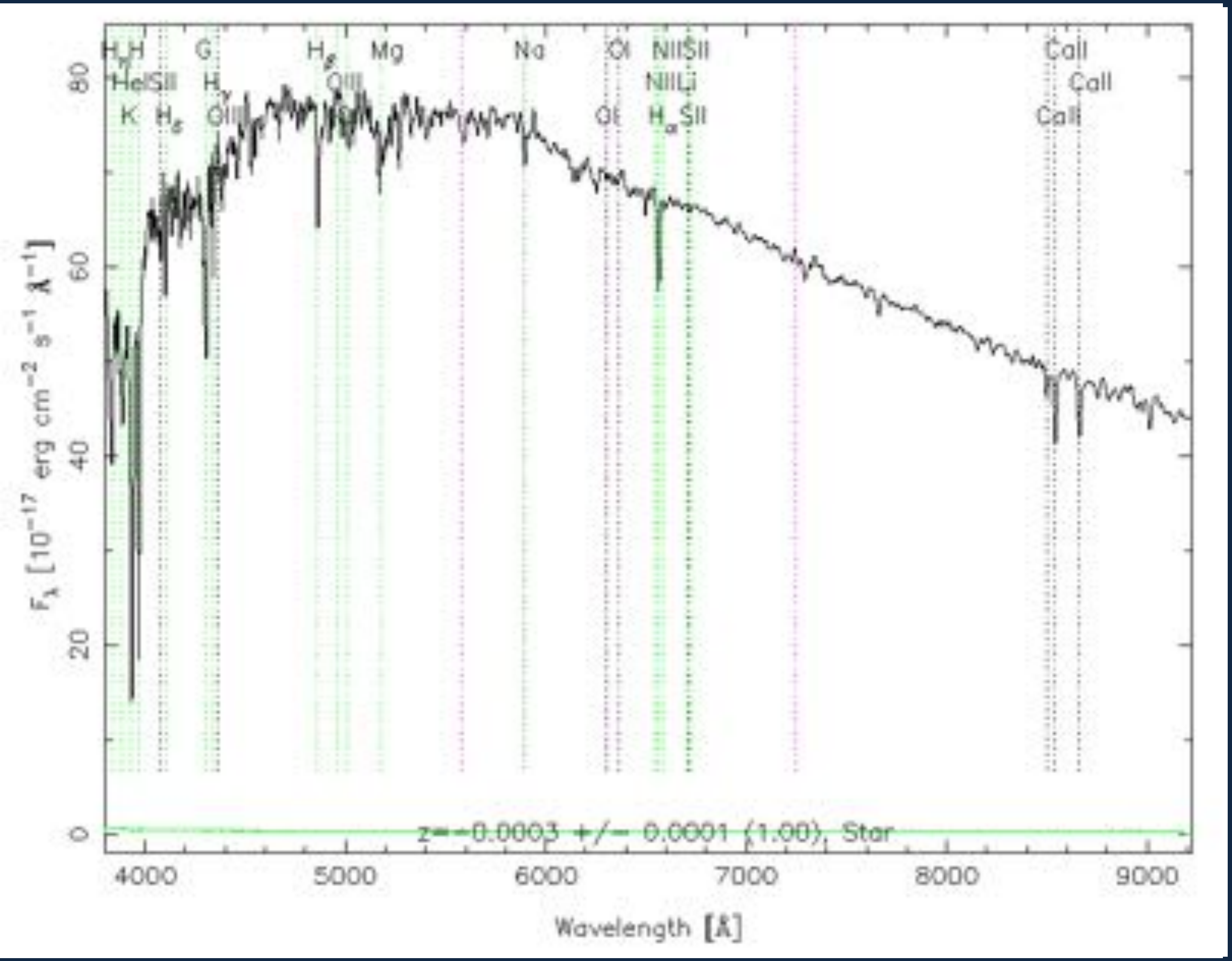

- 6000 - 7500 K
- stronger Ca II
- neutral metal absorption lines
- weaker H
- spectrum peaks in visible regime

# Spectroscopy and Stars

## Observations

We typically classify stars by their **spectral types.**

**O B A F G K M**



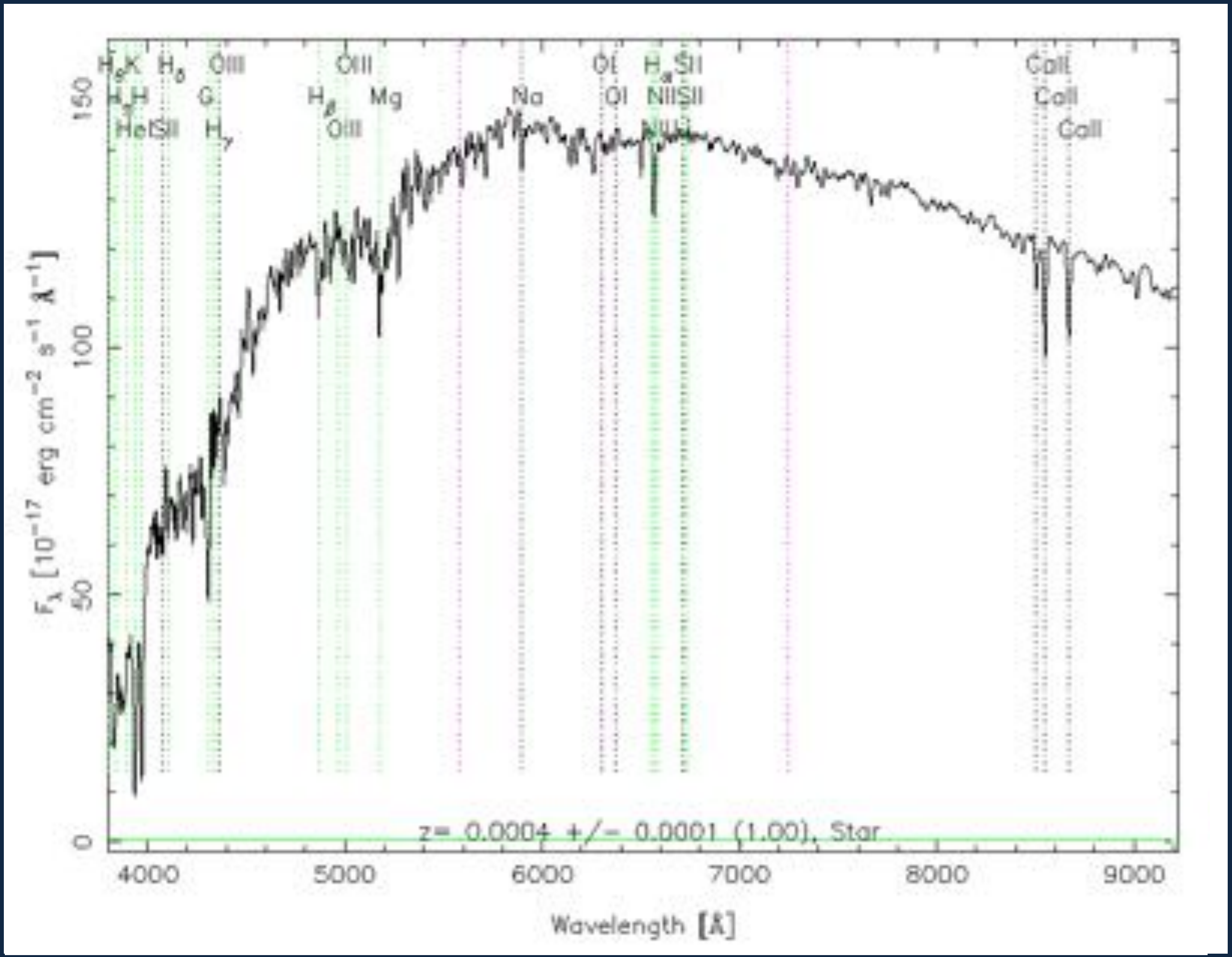

- 5000-6000 K
- strong Ca II
- more neutrals with stronger lines
- fewer singly-ionized species
- H starts to disappear

# Spectroscopy and Stars

## Observations

We typically classify stars by their **spectral types**.

**O B A F G K M**



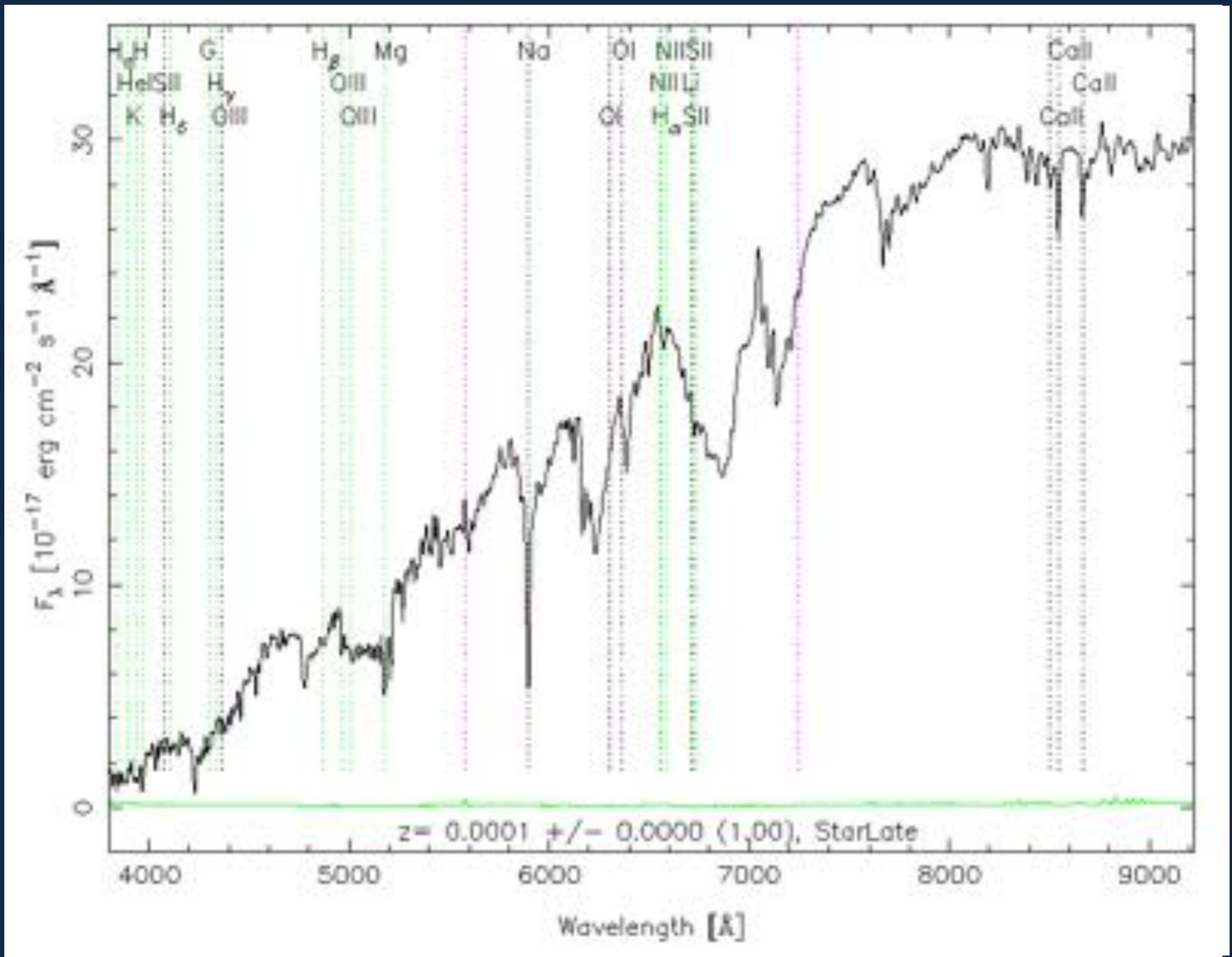

- 3800-5000 K
- dominant neutral metals
- spectrum getting redder
- molecules begin to appear

# Spectroscopy and Stars

## Observations

We typically classify stars by their **spectral types**.

**O B A F G K M**




- 3000-3800 K
- red spectrum
- strong neutral lines
- appearance of strong molecular lines (TiO)

# Spectroscopy and Stars

## Observations

We typically classify stars by their **spectral types**.

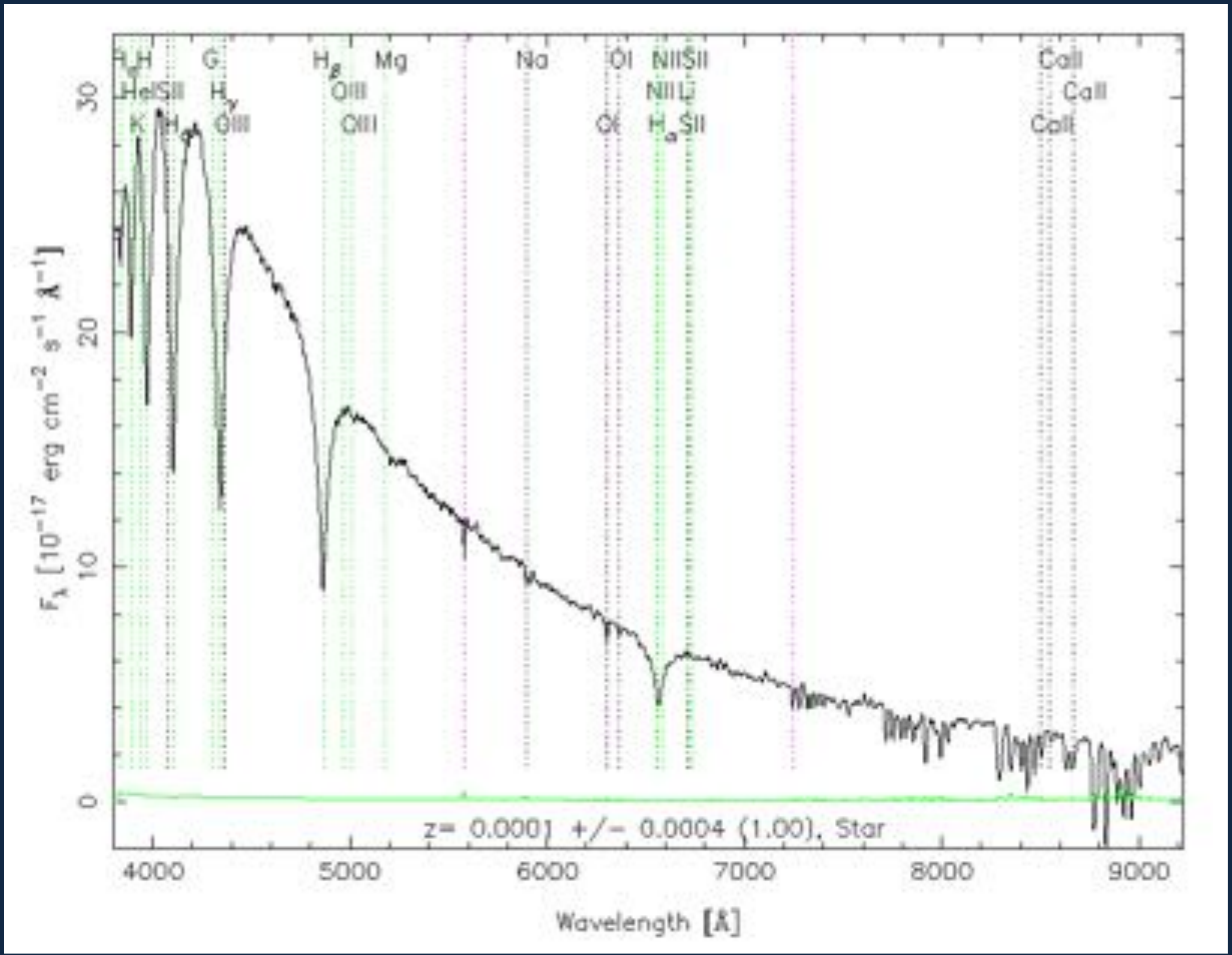
| **O** | **B** | **A** | **F** | **G** | | **K** | **M** |
|---|---|---|---|---|---|---|---|
| h | e | | i | u | / i | i | e |
| | | | n | y | r | s | |
| | | | e | | l | s | |

# Spectroscopy and Stars

## Observations

We typically classify stars by their **spectral types.**

**O B A F G K M**




**WD**

- spectrum peak in the far blue
- much broader H lines

# Homework #2

"f-ratio of f/8"

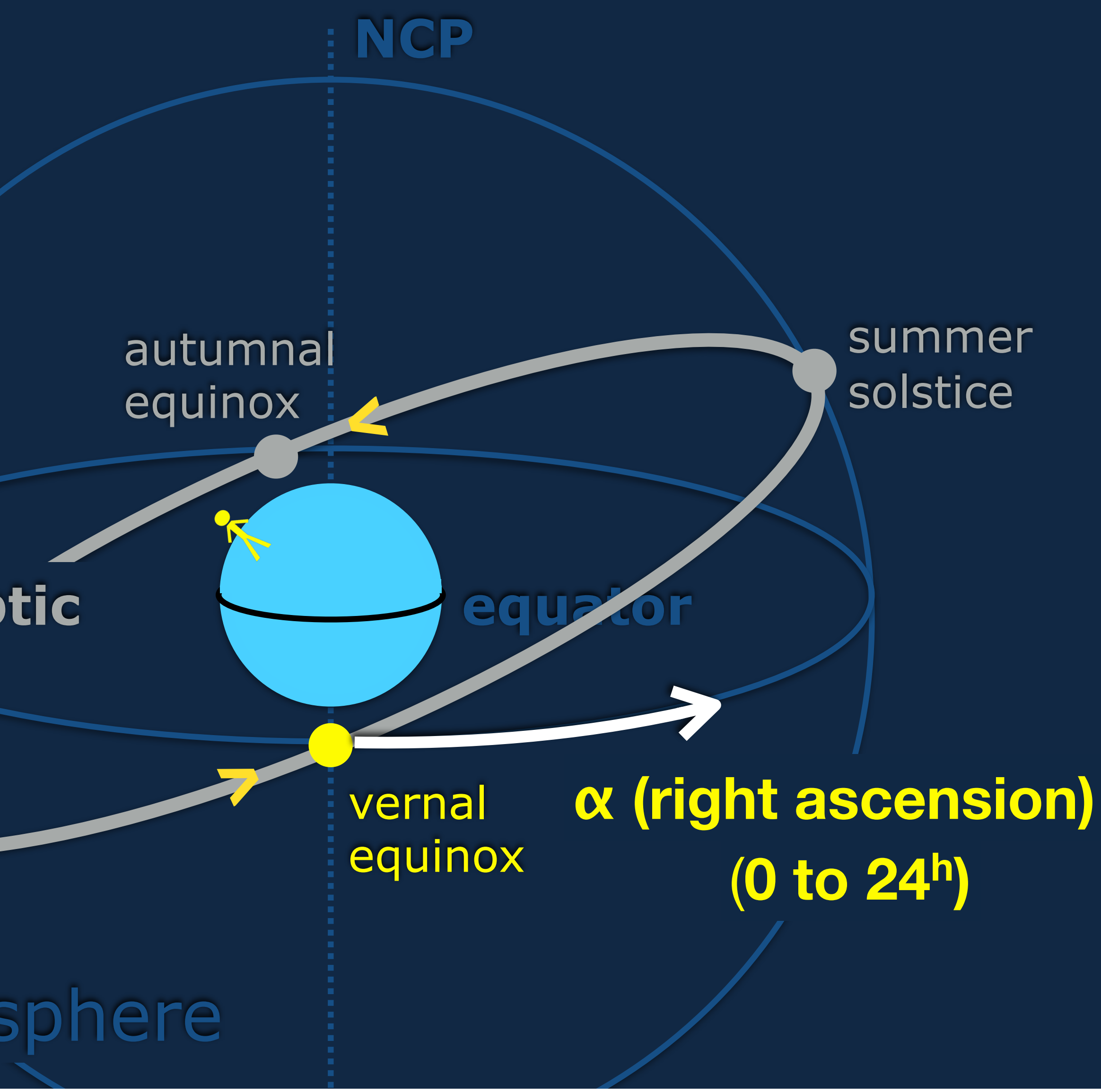
This means the f-ratio IS 8.

So $f/D = 8$

(where f=focal length, D=diameter)

# Homework #1

What is the "best month" to observe an object?
(when is it highest in the Seattle sky at midnight?)




The Sun's RA is...

0 in March

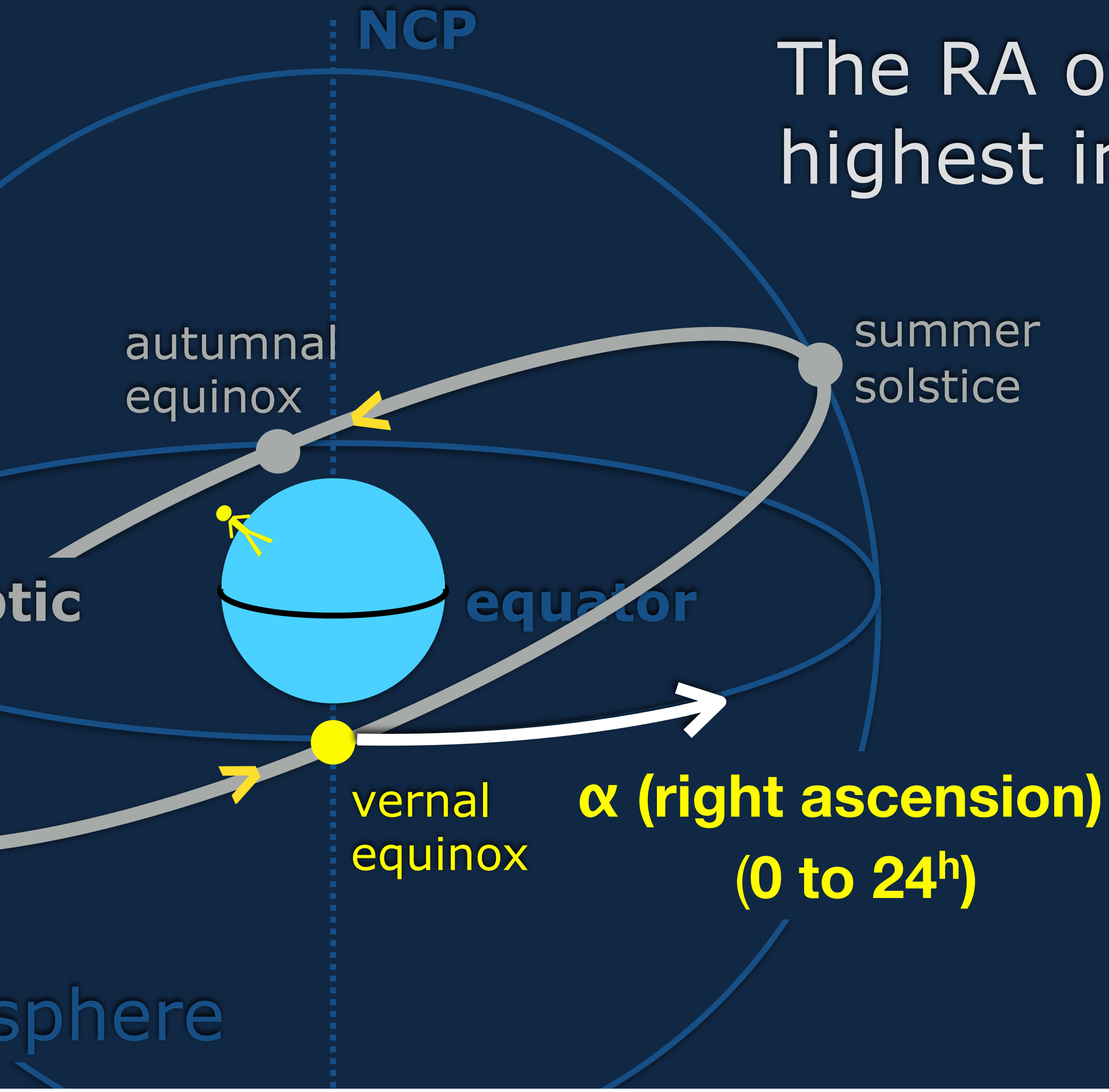
6 in June

12 in September

18 in December

# Homework #1

What is the "best month" to observe an object?
(when is it highest in the Seattle sky at midnight?)




The RA of stars that are highest in the sky at midnight!

12 in March

18 in June

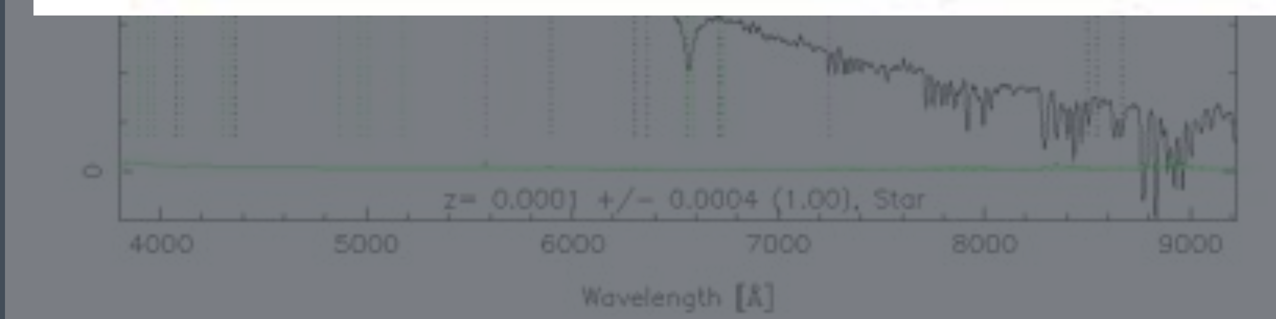
0 in September

6 in December

# Last time...

Observations

We typically classify stars by their **spectral class**.

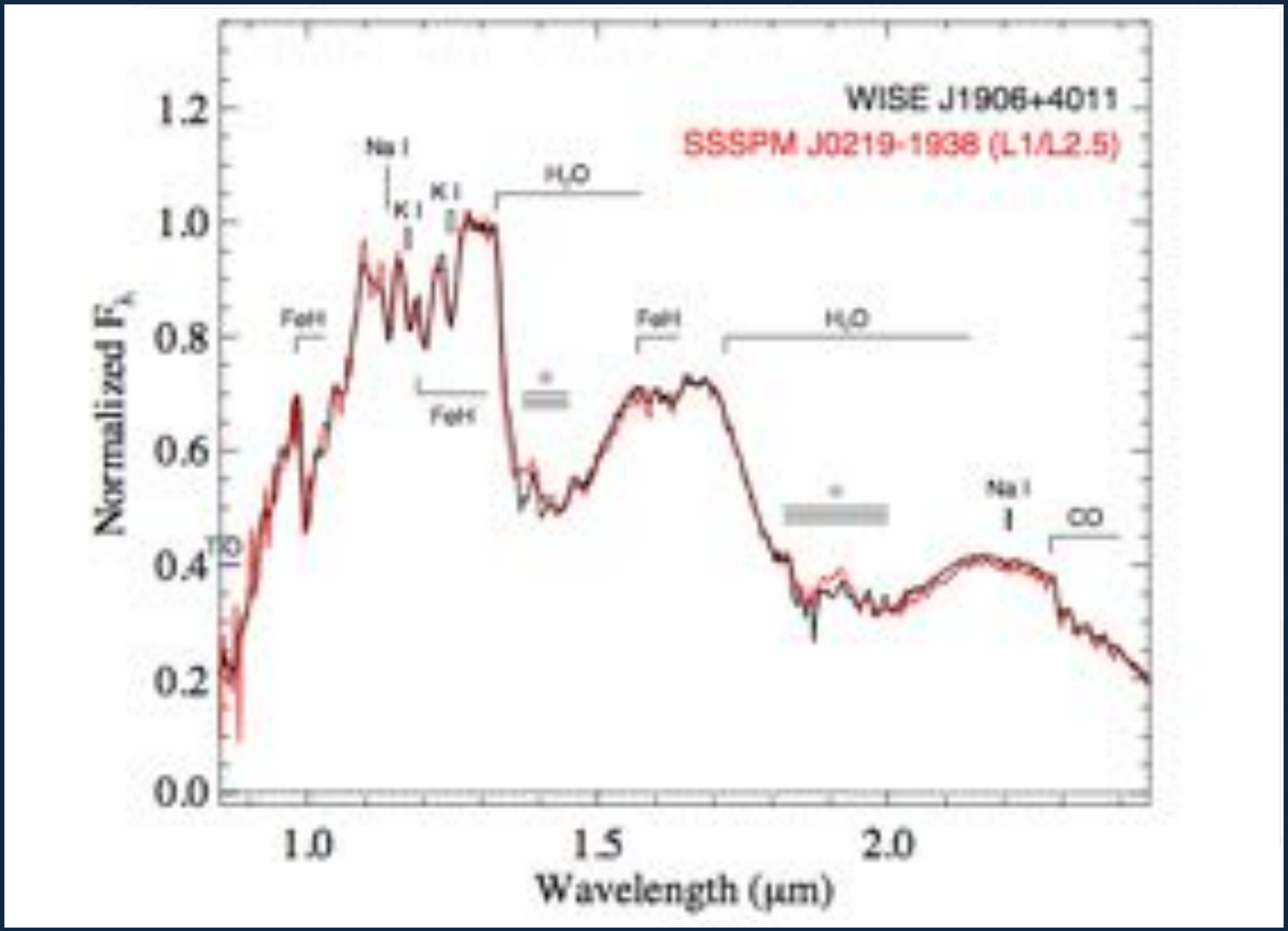



# Spectroscopy and Stars

## Observations

We typically classify stars by their **spectral class**.

**O B A F G K M**




**WD**

**L, T, and Y dwarfs**

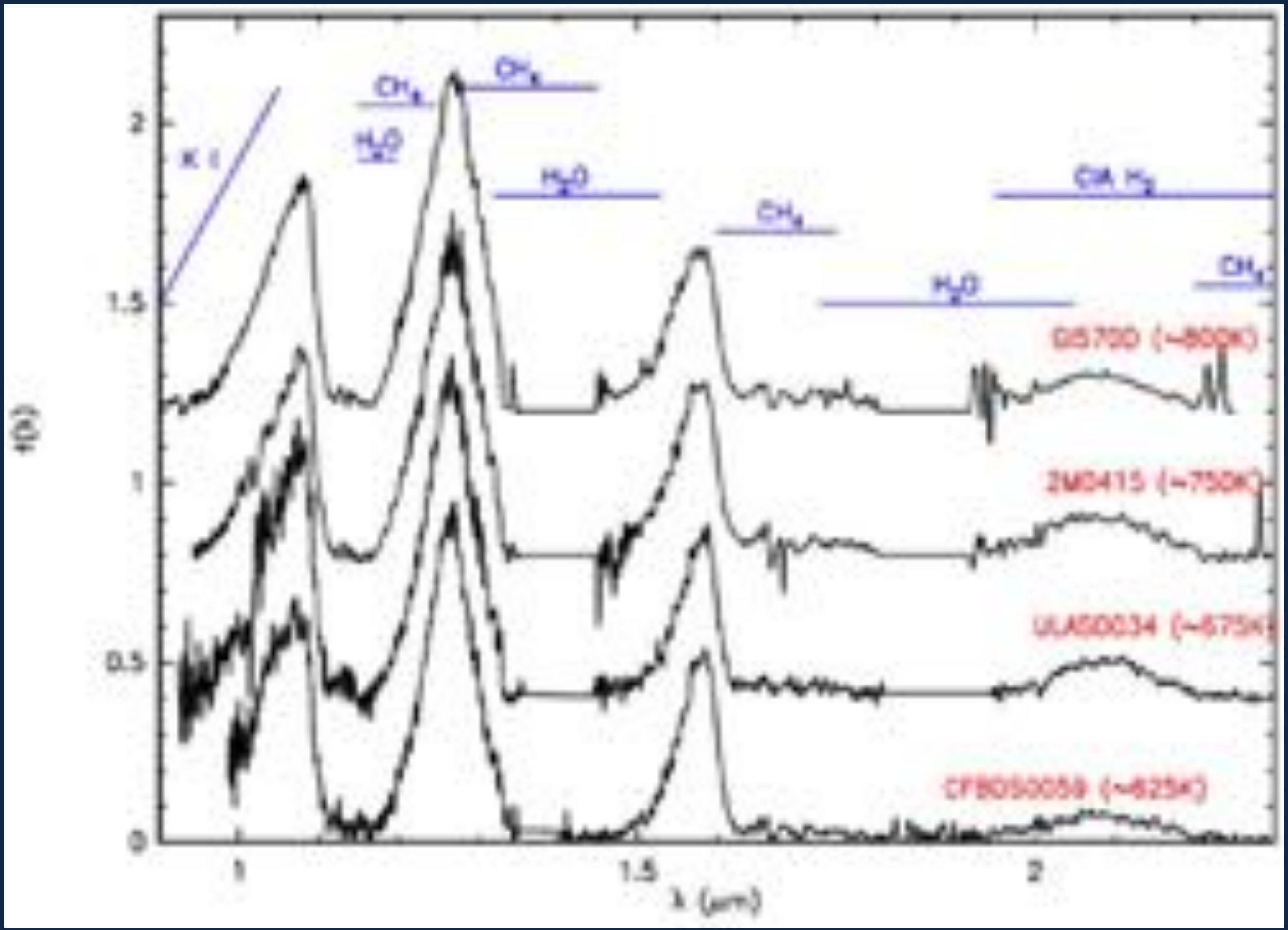
**(1400-2100 K)**

# Spectroscopy and Stars

## Observations

We typically classify stars by their **spectral class**.

**O B A F G K M**




**WD**

**L, T, and Y dwarfs**

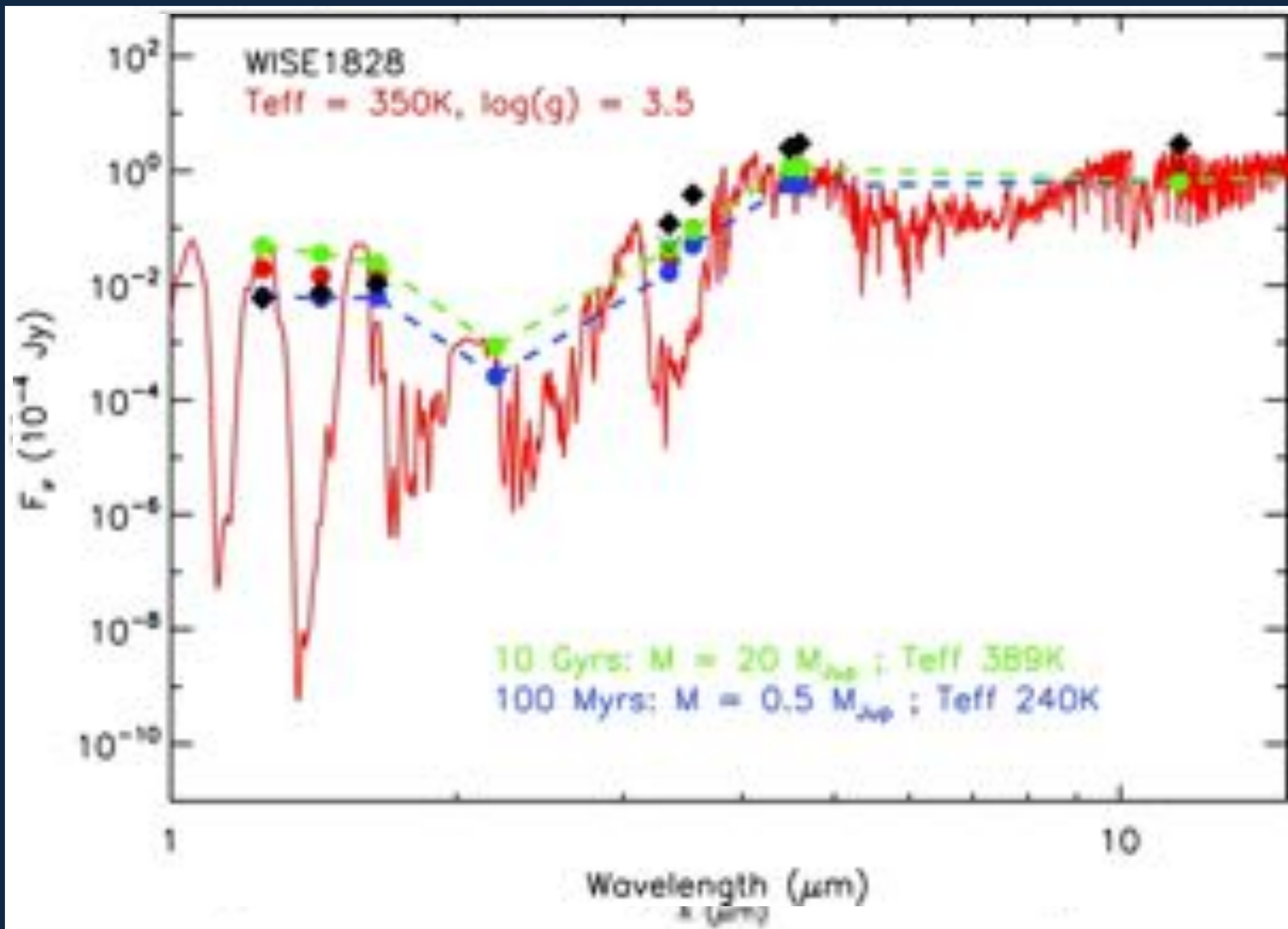
**(600 - 1400 K)**

# Spectroscopy and Stars

## Observations

We typically classify stars by their **spectral class**.

**O B A F G K M**




**WD**

**L, T, and Y dwarfs**

**(<600K?)**

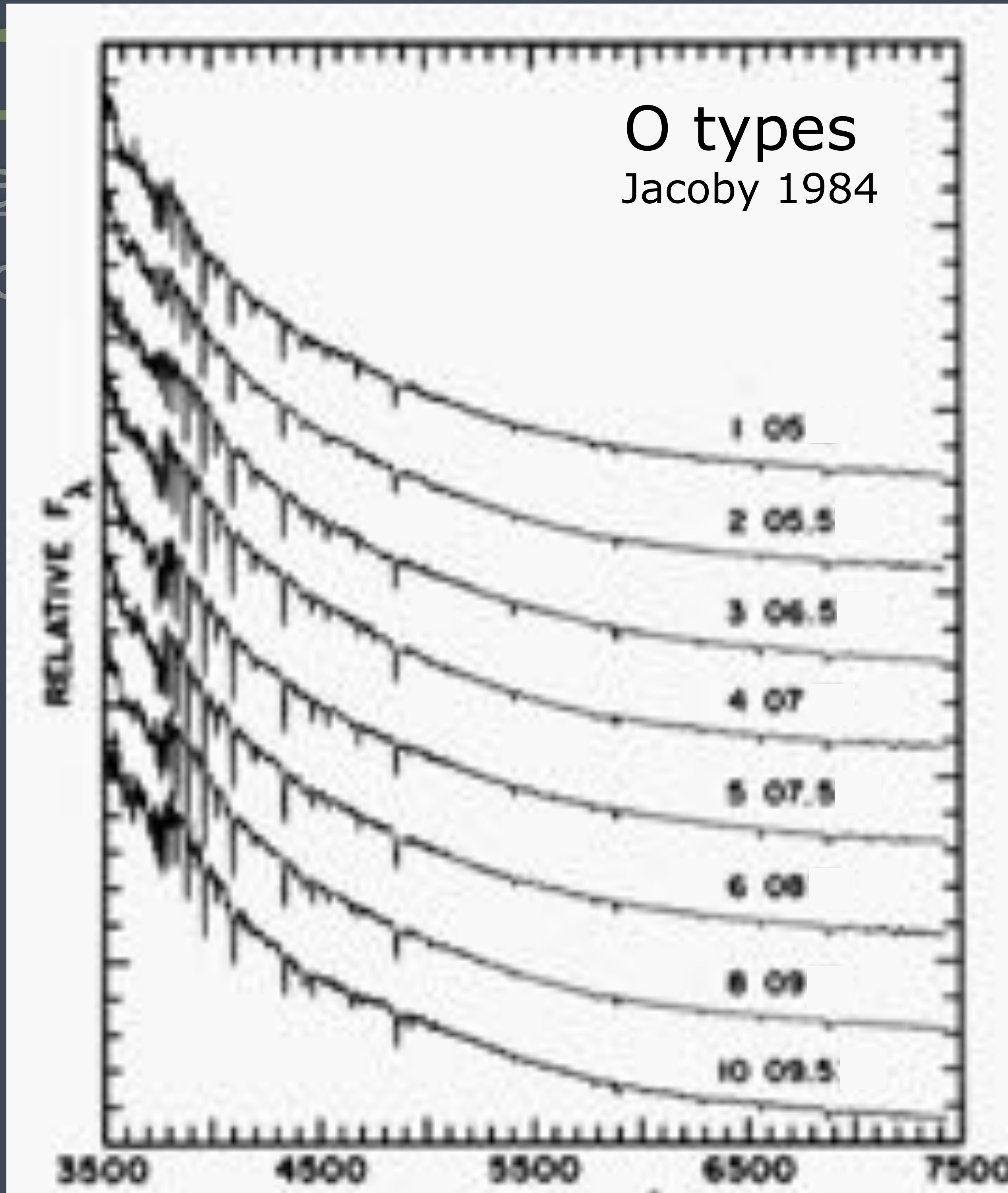
# Spectr

Observa

We typic ... ral class.

**O** ... **M**

h ... e



## Spectro

Observat

We typica ral class.

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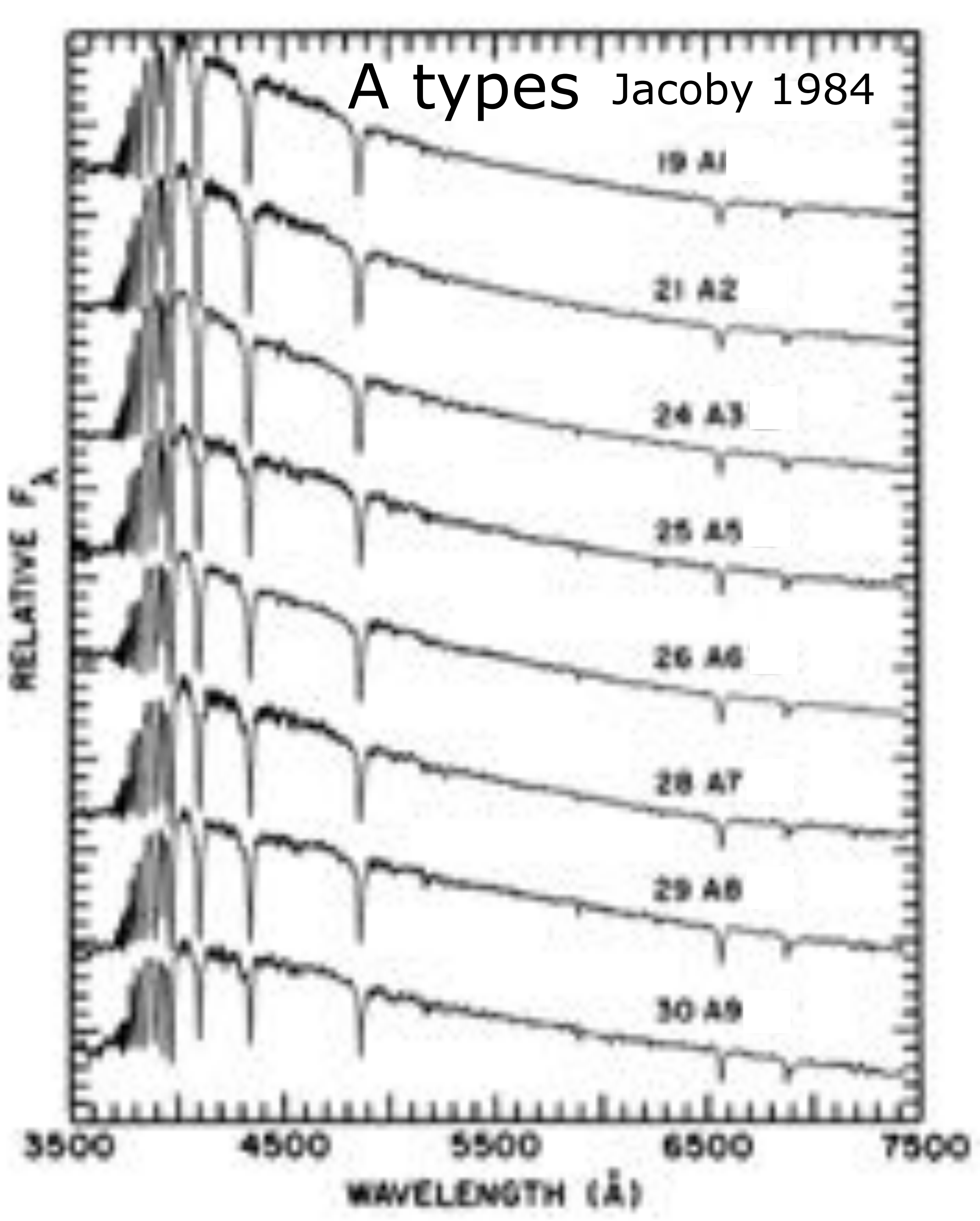

# Spectroscopy and Stars

Obs

We s.

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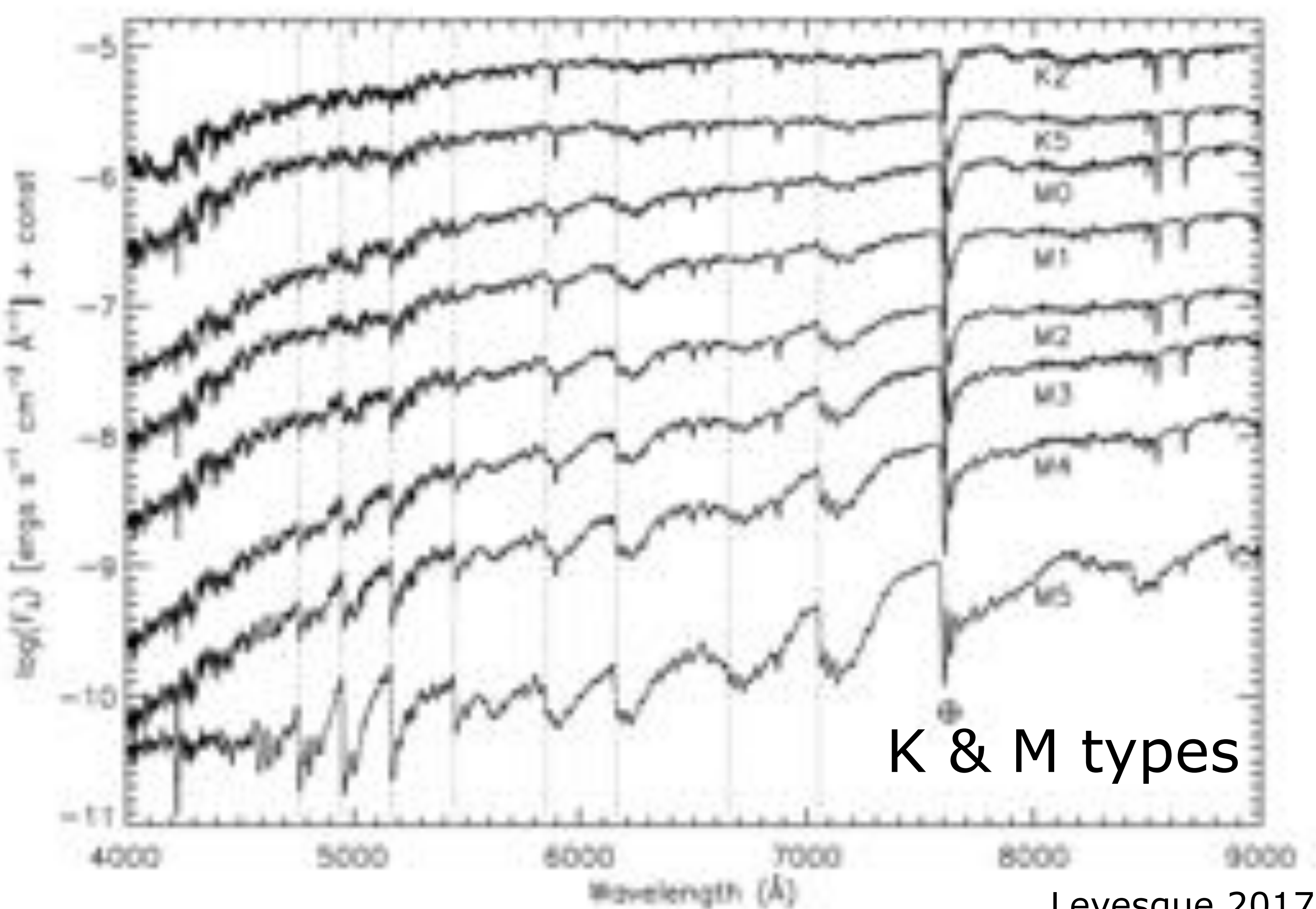



Levesque 2017

# Spectroscopy and Stars

## QUICK QUESTION(S)

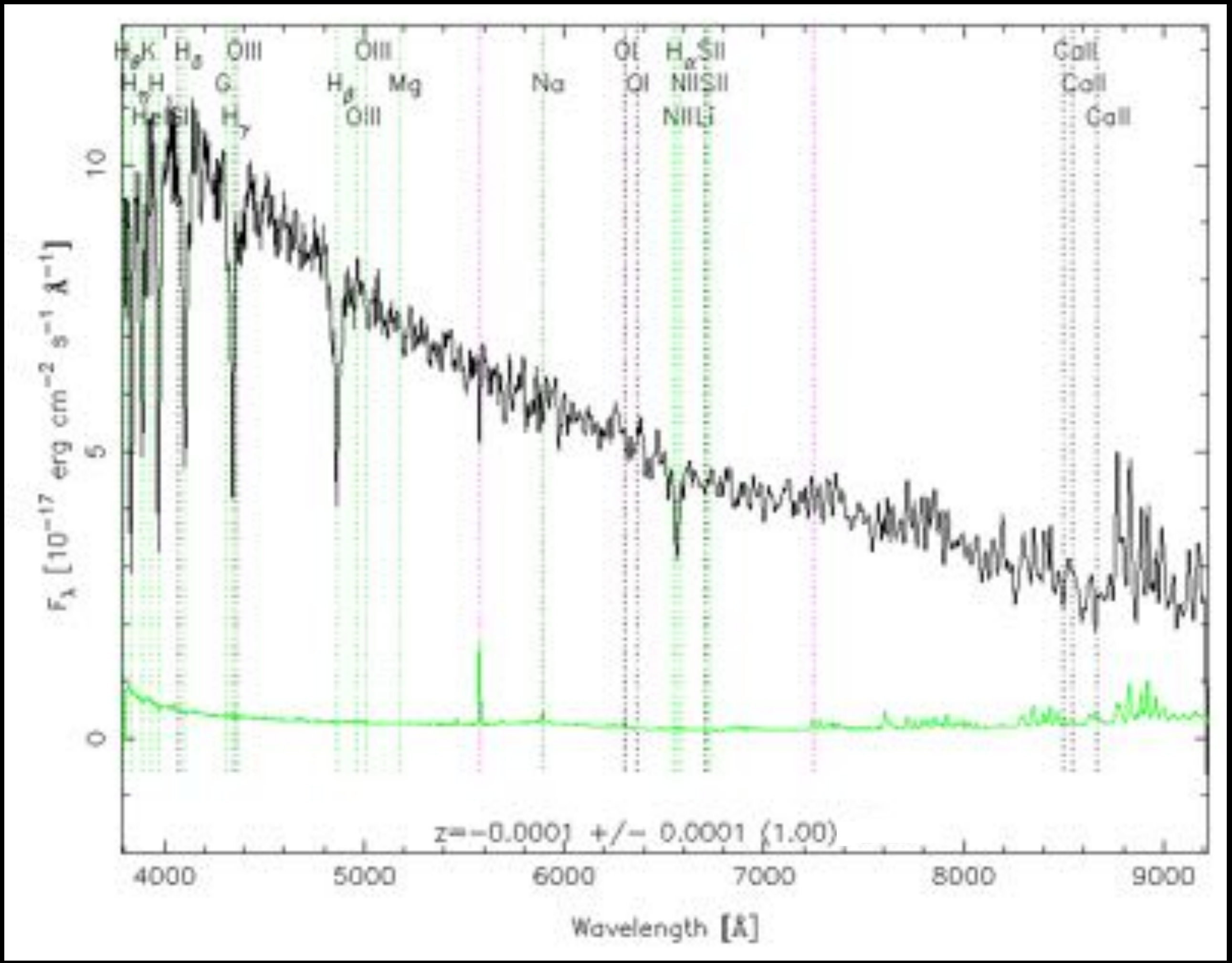
Identify the spectral type:

A) A

B) B

C) G

D) WD



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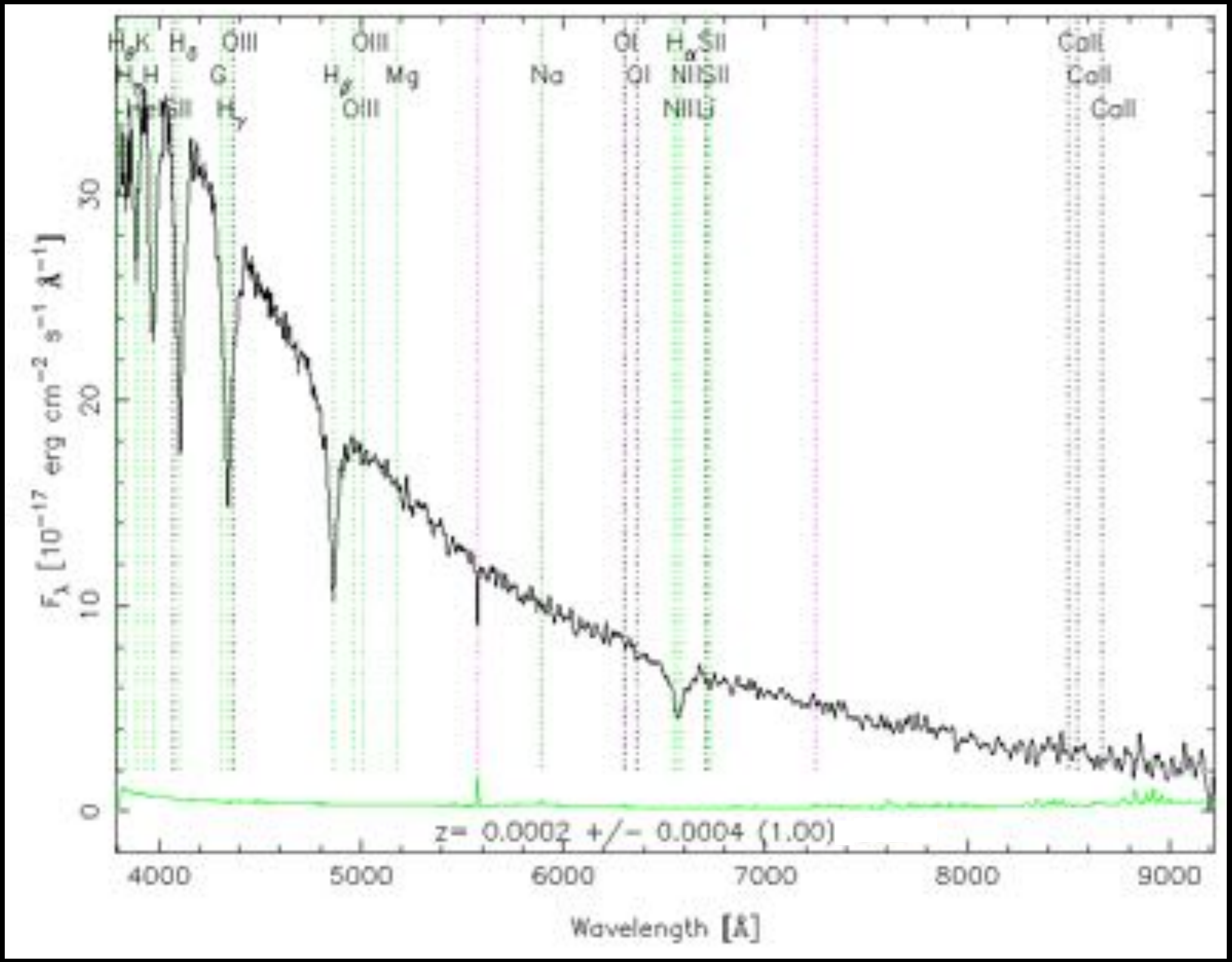

# Spectroscopy and Stars

## QUICK QUESTION(S)

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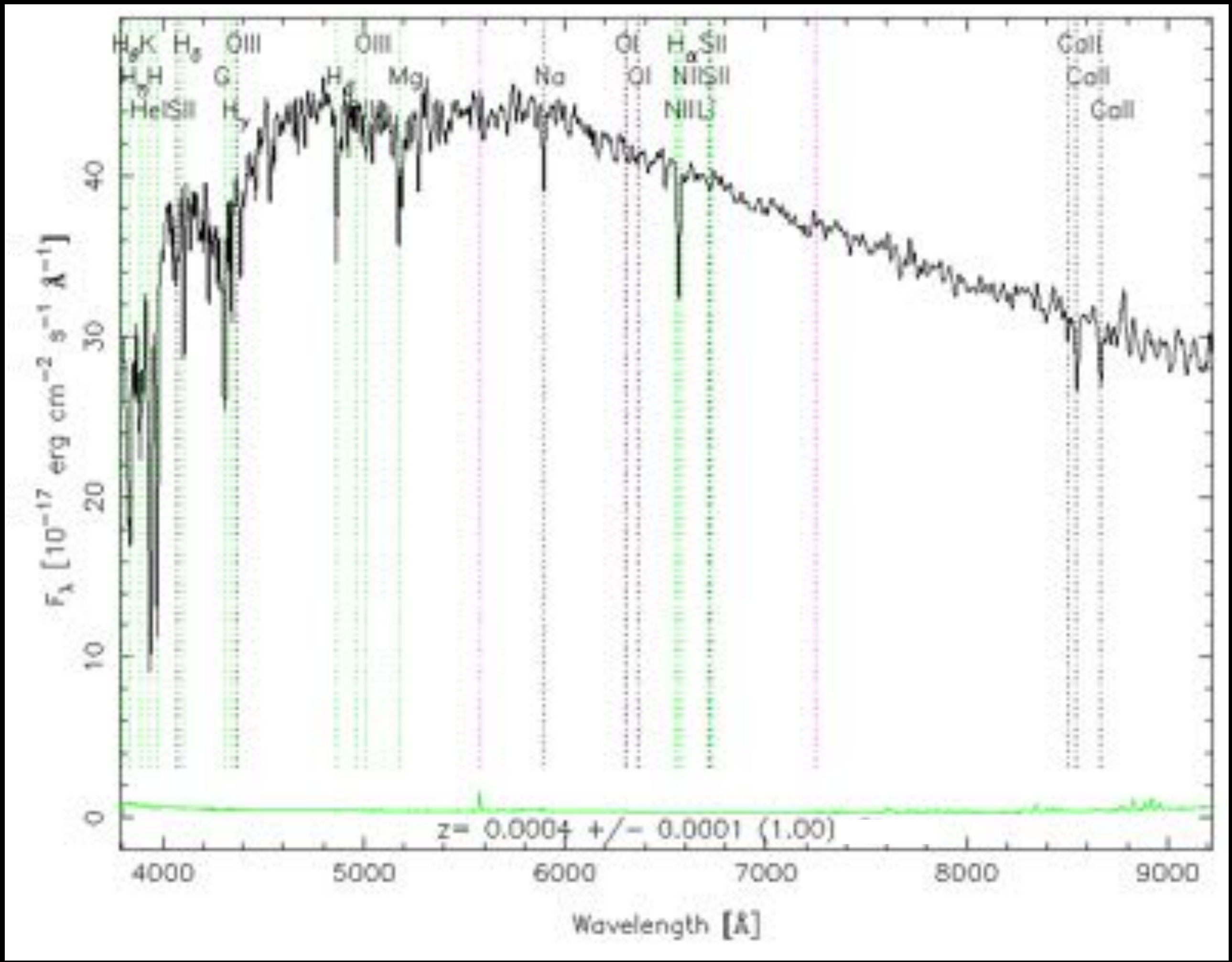


# Spectroscopy and Stars

## QUICK QUESTION(S)

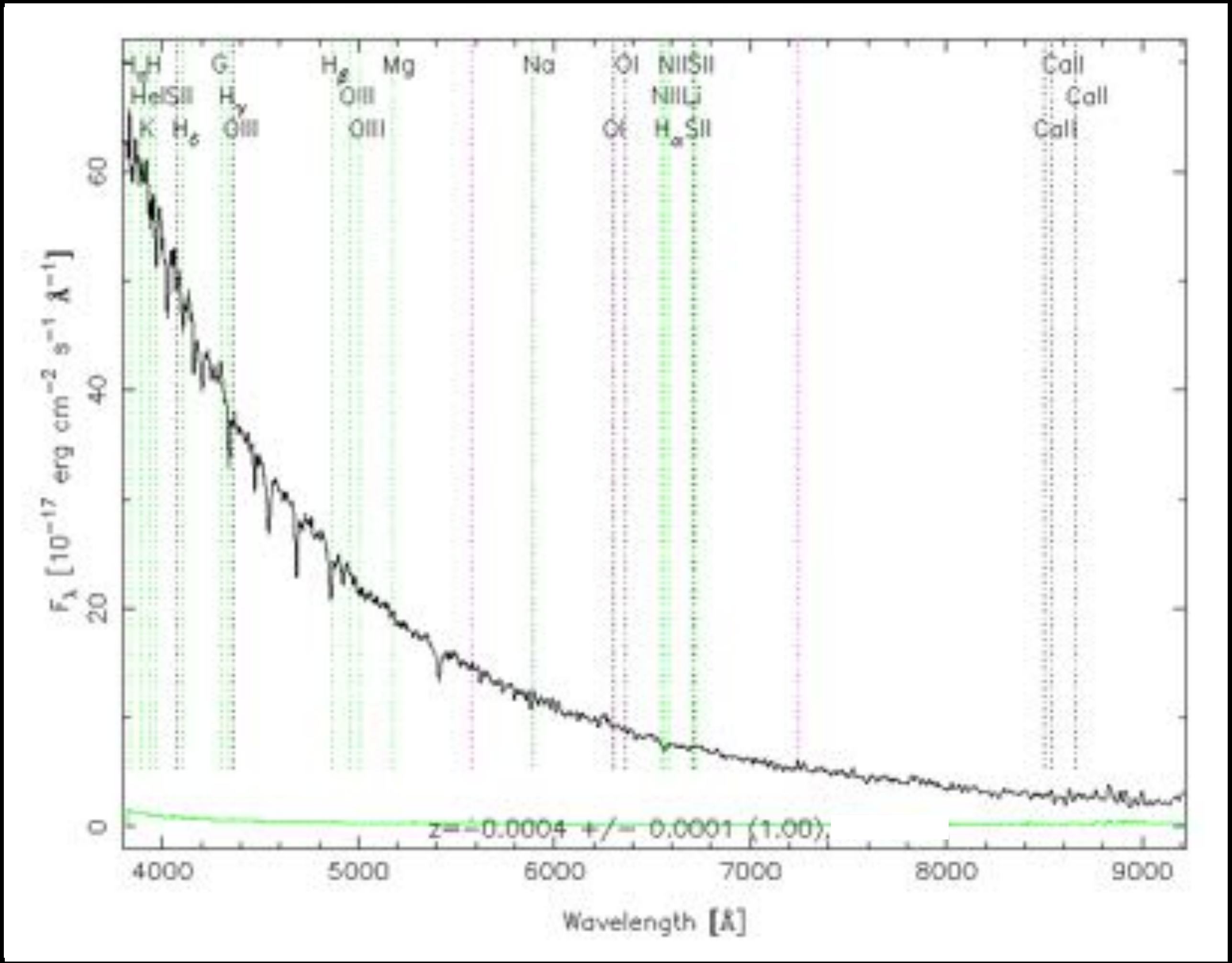
Identify the spectral type:

A) binary

B) M

C) other

D) O



# Spectroscopy and Stars

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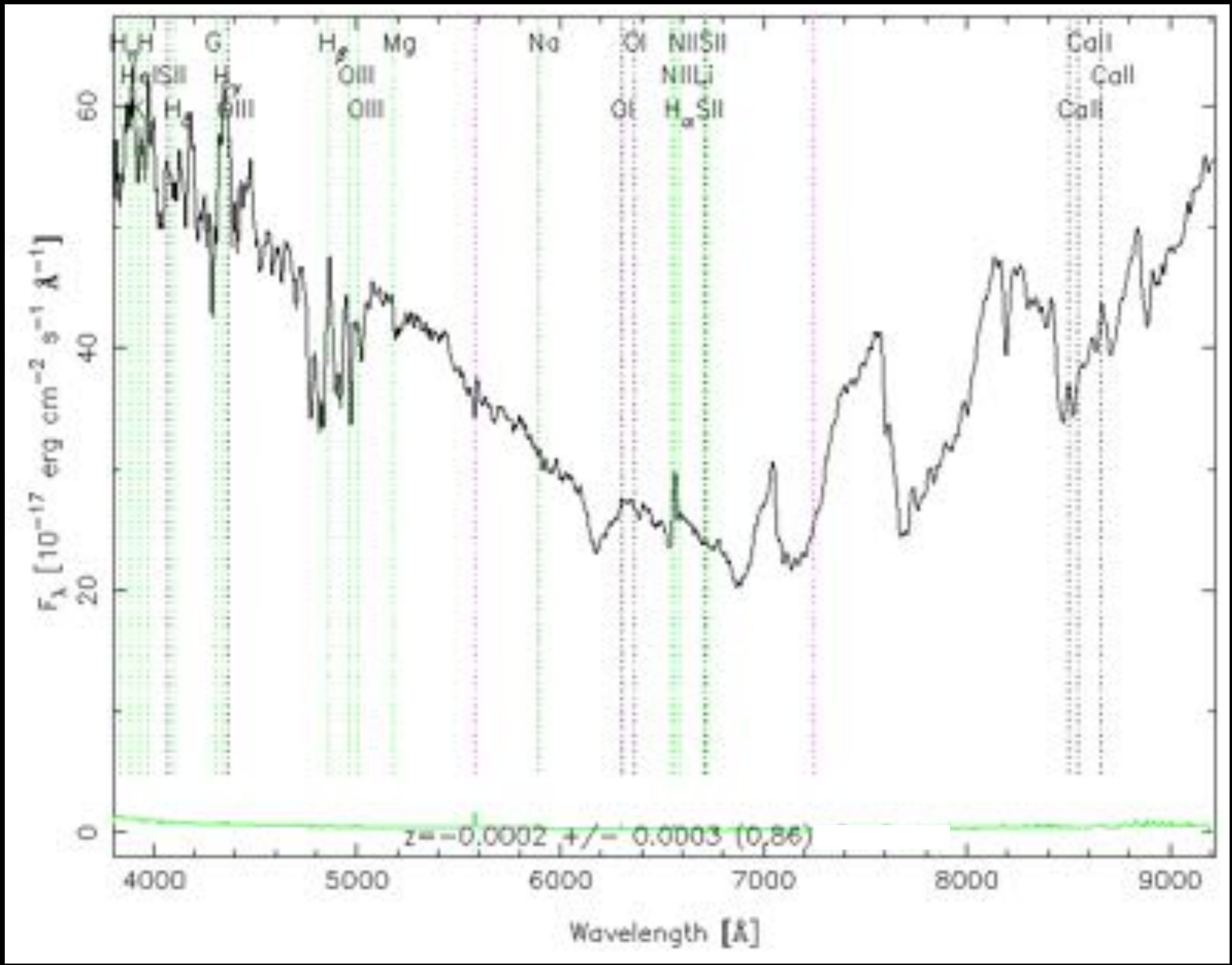


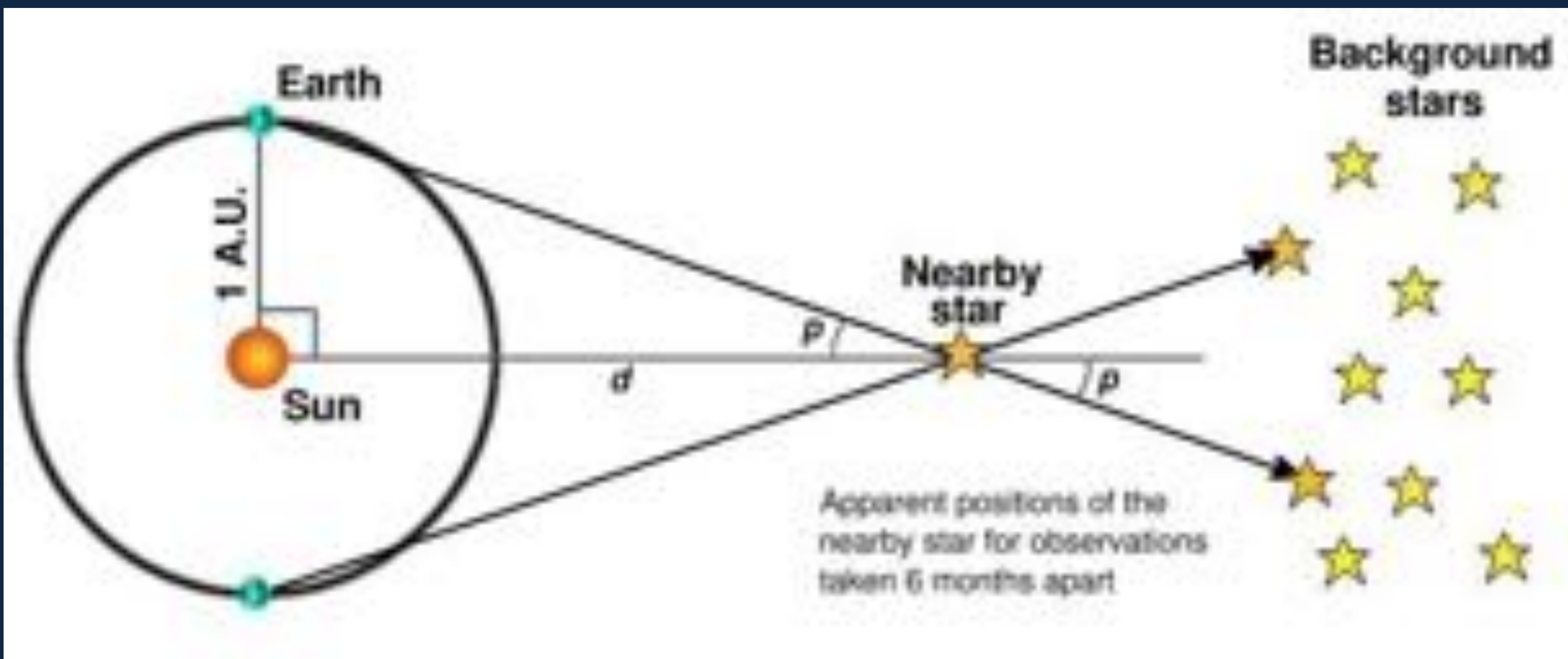
# Properties of Stars - Distance

1) Distance
2) Velocity
3) Brightness
4) Temperature
5) Mass
6) Radius

# Properties of Stars - Distance

For nearby stars we can measure their distance using **parallax**.

$$d = \frac{1\ \text{AU}}{\tan(p)} \simeq \frac{1}{p}\ \text{AU} \rightarrow \frac{206265}{p''}\ \text{AU} \quad \textbf{parsec} \quad \rightarrow \boxed{d = \frac{1}{p''}\ \text{pc}}$$



# Properties of Stars - Distance

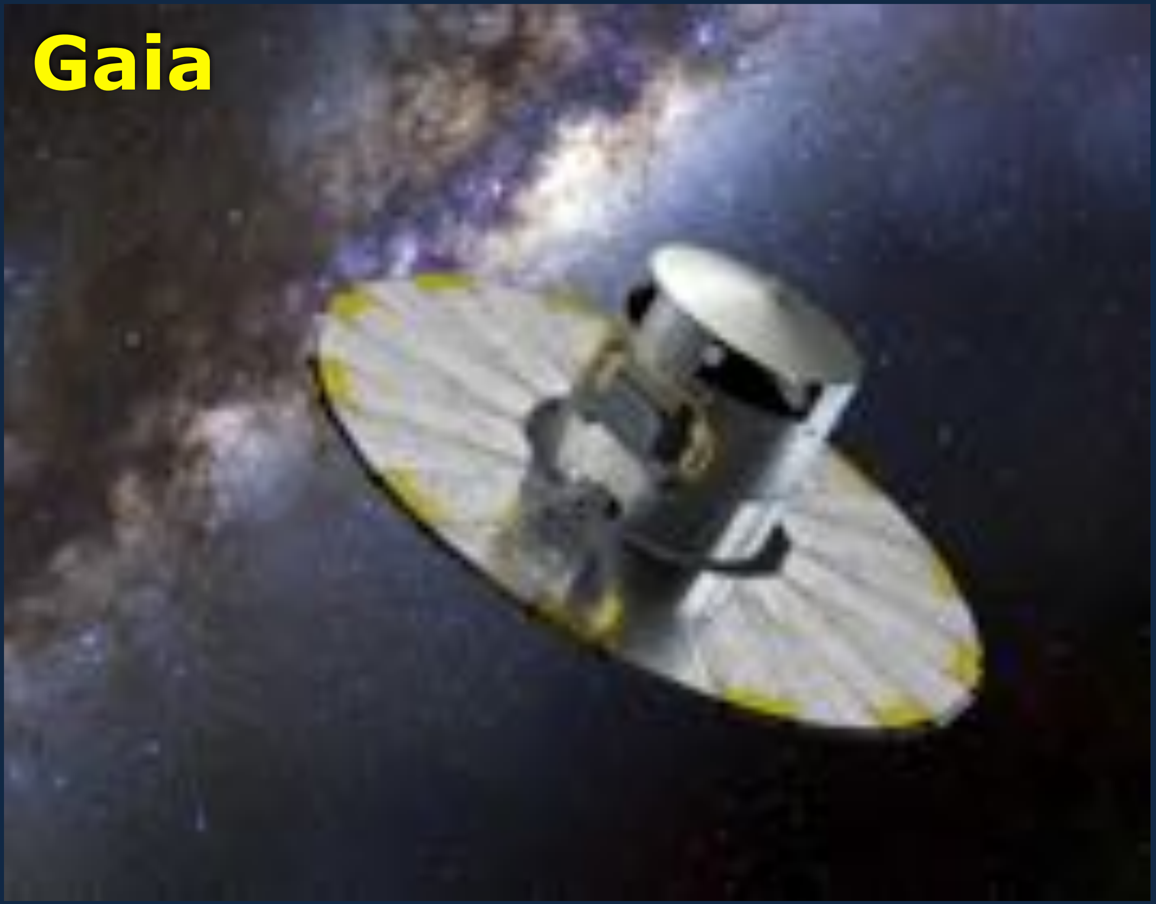
For nearby stars we can measure their distance using **parallax**.

Current limits of parallax:

ground limit ~ 0.01″
(d ~ 100pc)

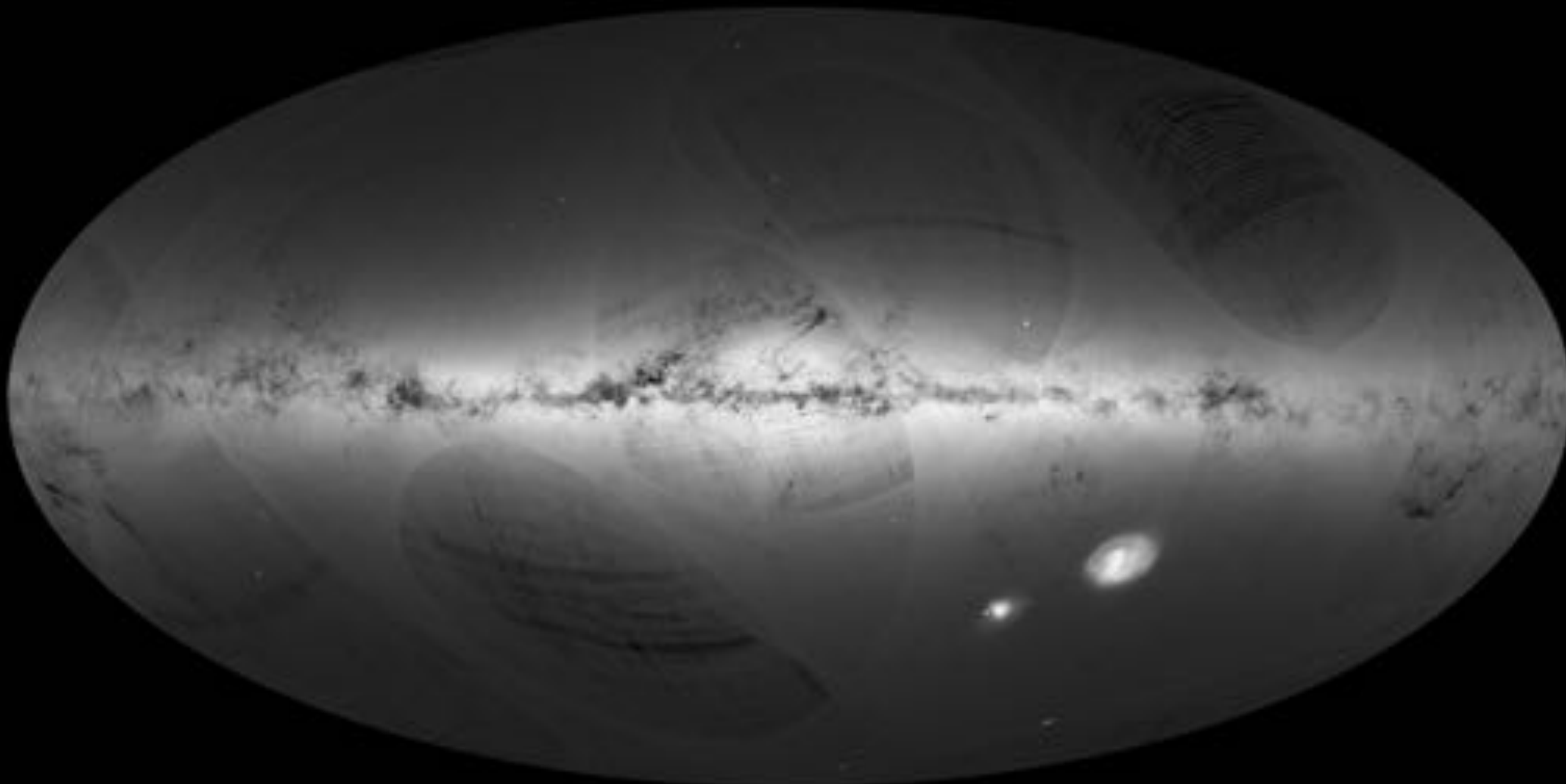
HST limit ~ 0.001″
(d ~ 1000pc)

Gaia ~ 0.00020″
(d ~ 5000pc!)



# Properties of Stars - Distance

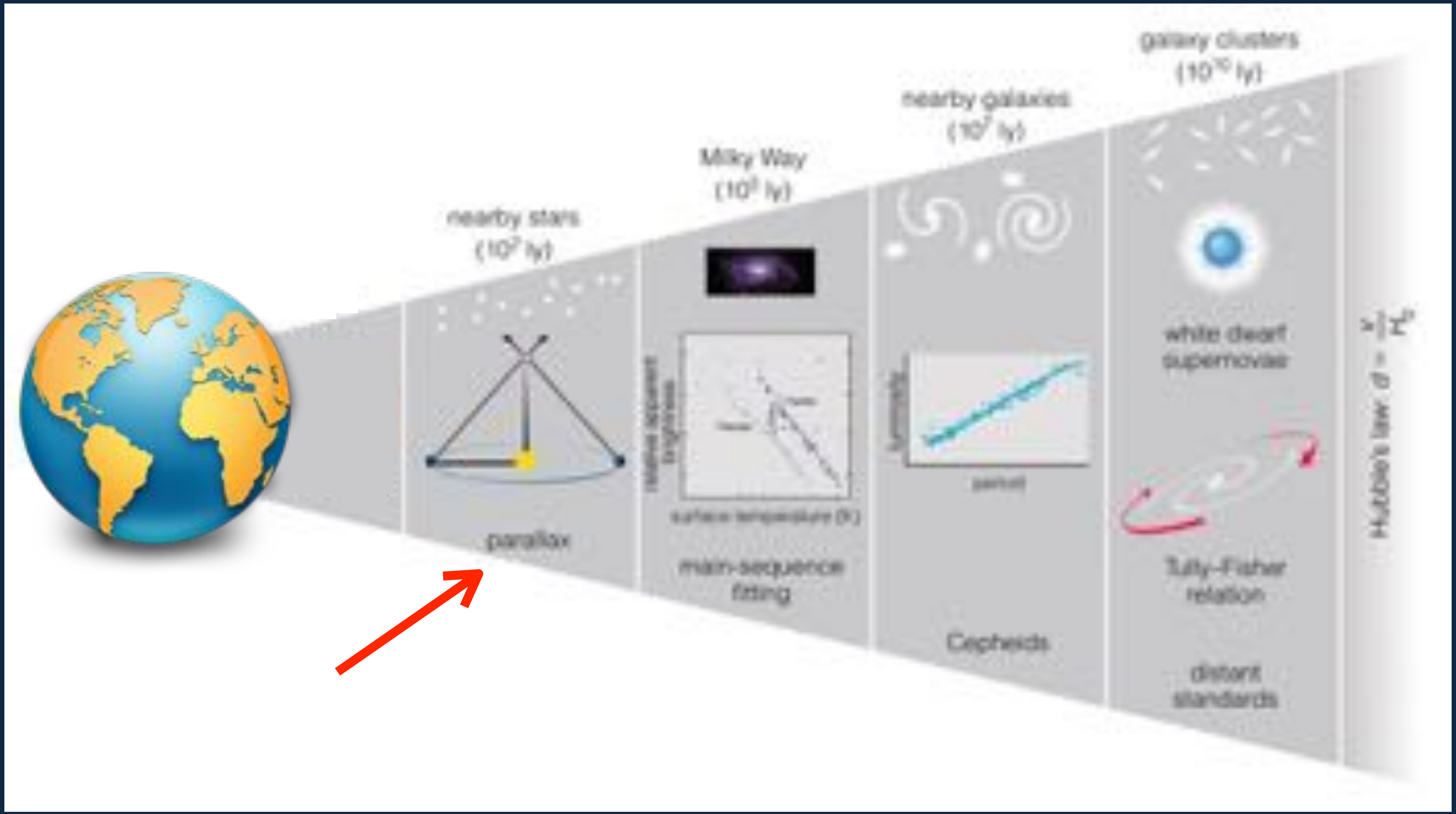
**Gaia's first sky map**



# Properties of Stars - Distance

For nearby stars we can measure their distance using parallax.

First "rung" of the **cosmic distance ladder**.



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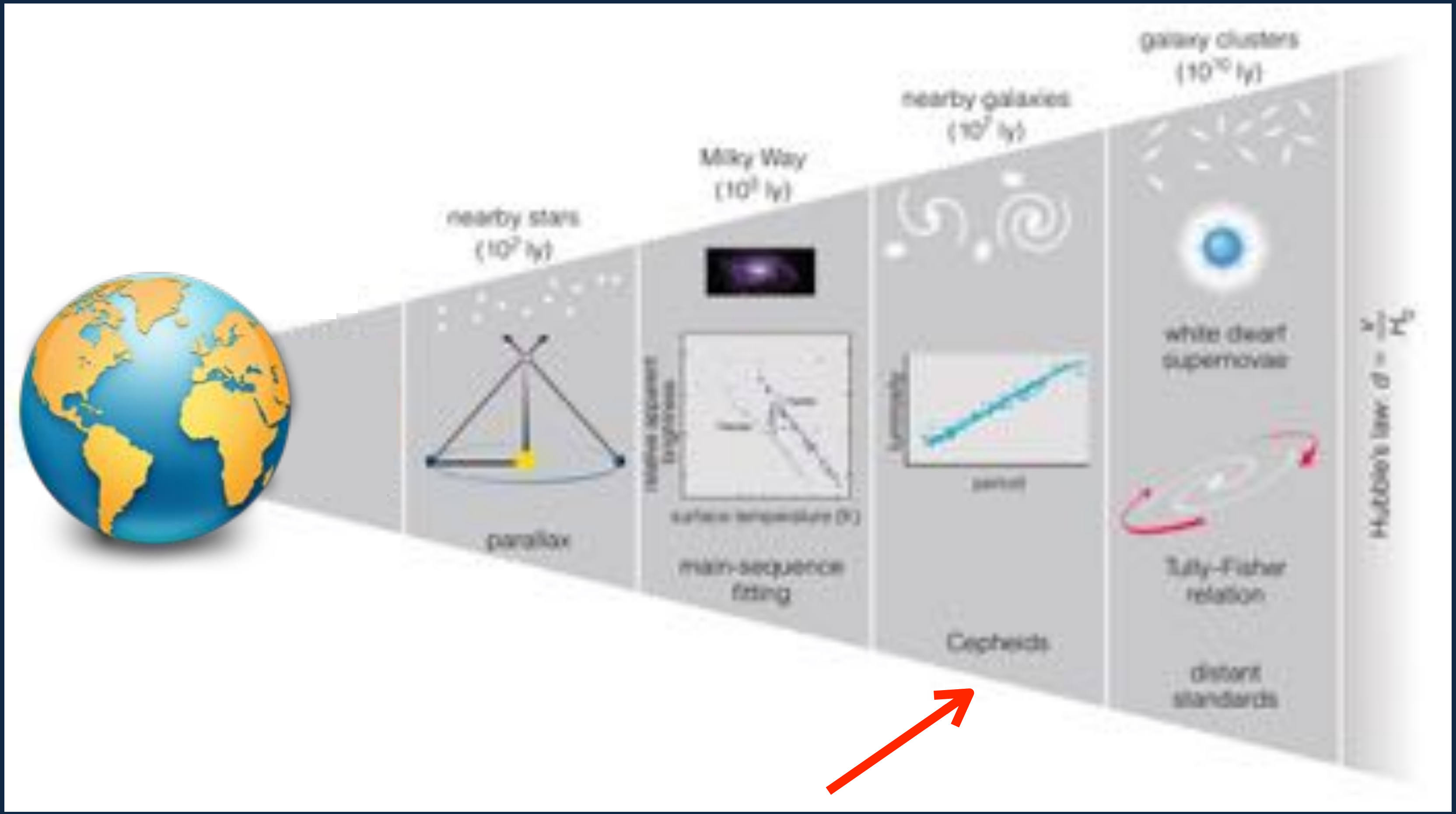


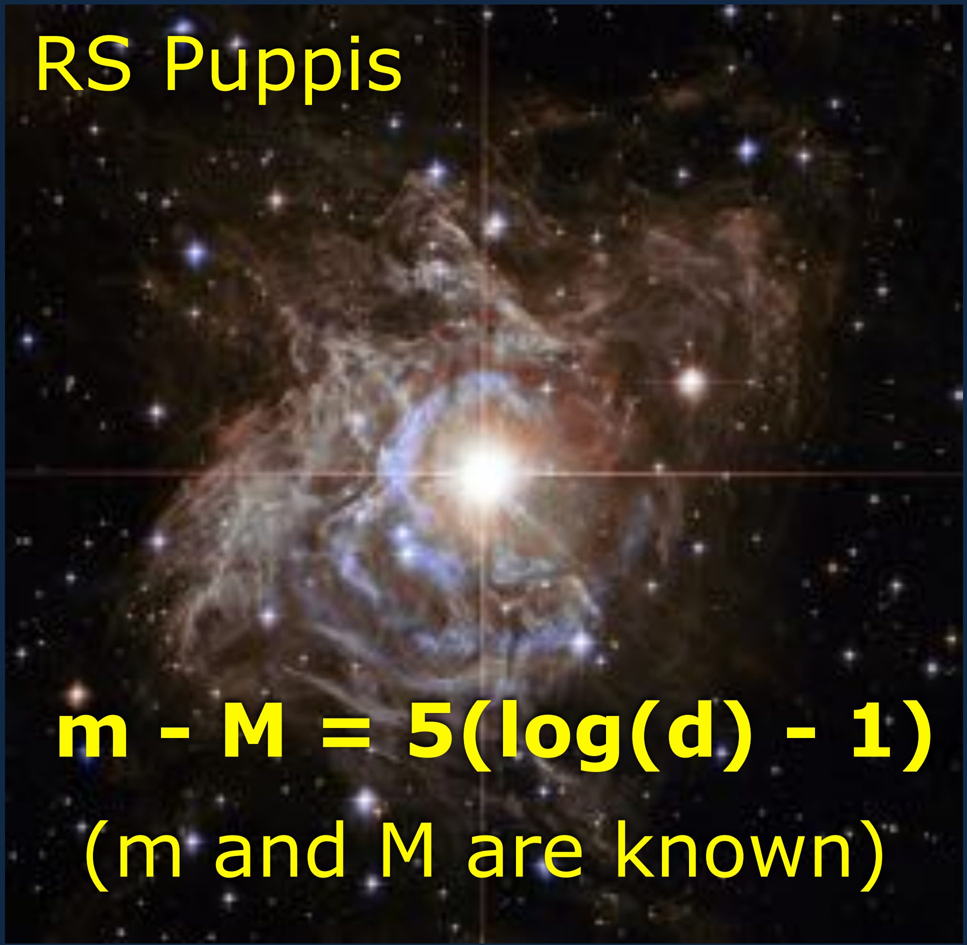
# Properties of Stars - Distance

Standard candles

The most famous standard candles are the **Cepheid variables**.

In 1908 Henrietta Swan Leavitt discovered a relation between their luminosity and variability.

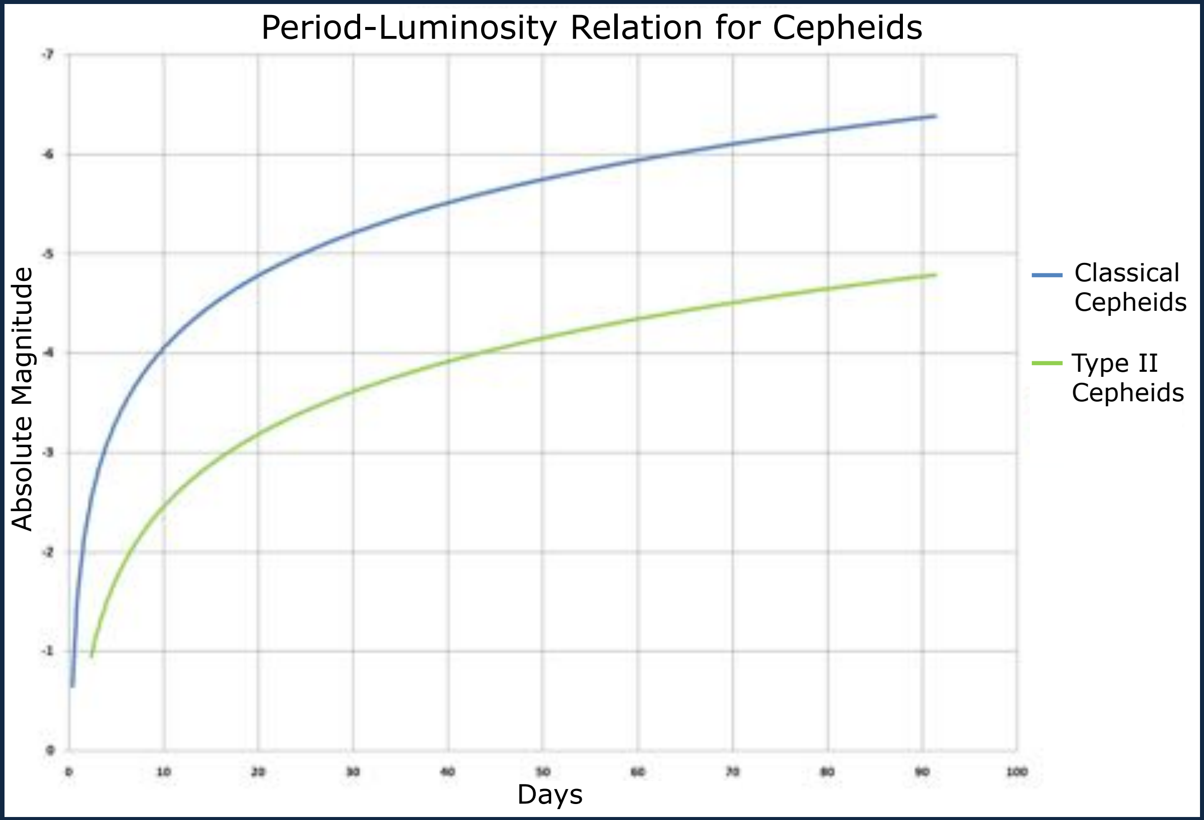
In the 1920's Edwin Hubble used Cepheids to determine the distance to M31 and develop Hubble's Law.



# Properties of Stars - Distance

## Standard candles

The most famous standard candles are the **Cepheid variables**.




In the 1950's Walter Baade realized Cepheids actually split into 2 different types; this quadrupled the assumed distance to M31.

# Properties of Stars - Velocity

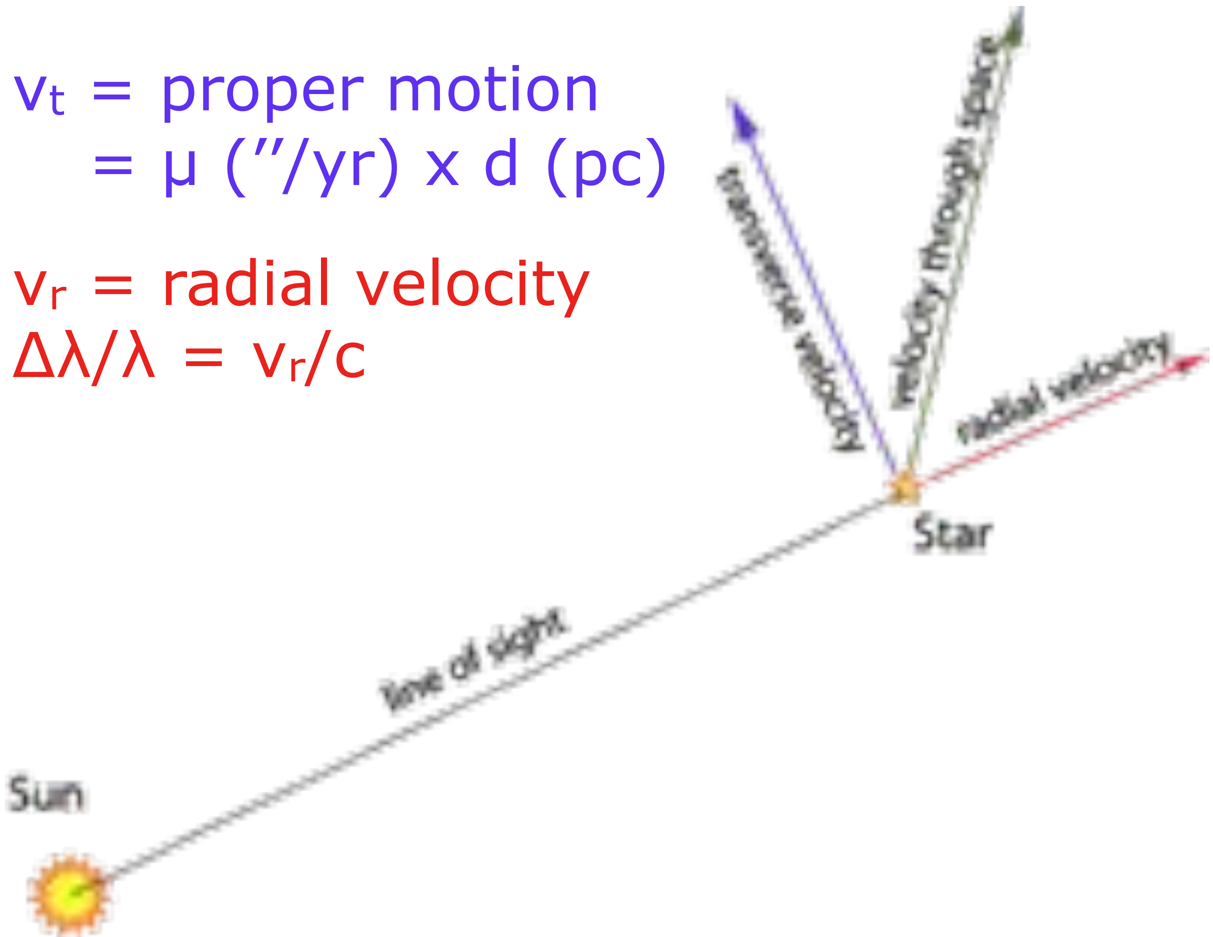
1) Distance - parallax, Cepheids
2) Velocity
3) Brightness
4) Temperature
5) Mass
6) Radius

# Properties of Stars - Velocity

Determining a star's velocity through space can be done by combining observable components…

$v_t$ = proper motion
= $\mu$ (″/yr) x d (pc)

$v_r$ = radial velocity
$\Delta\lambda/\lambda = v_r/c$



# Properties of Stars - Velocity

## Quick Question

You're observing Star Foo, which has a proper motion of 4 km/s and a radial velocity of 3 km/s. Its total motion through space is therefore:

A) 3.5 km/s

B) 5 km/s

C) 10 km/s

D) 25 km/s

# Properties of Stars - Velocity

Determining a star's velocity through space can be done by combining observable components…

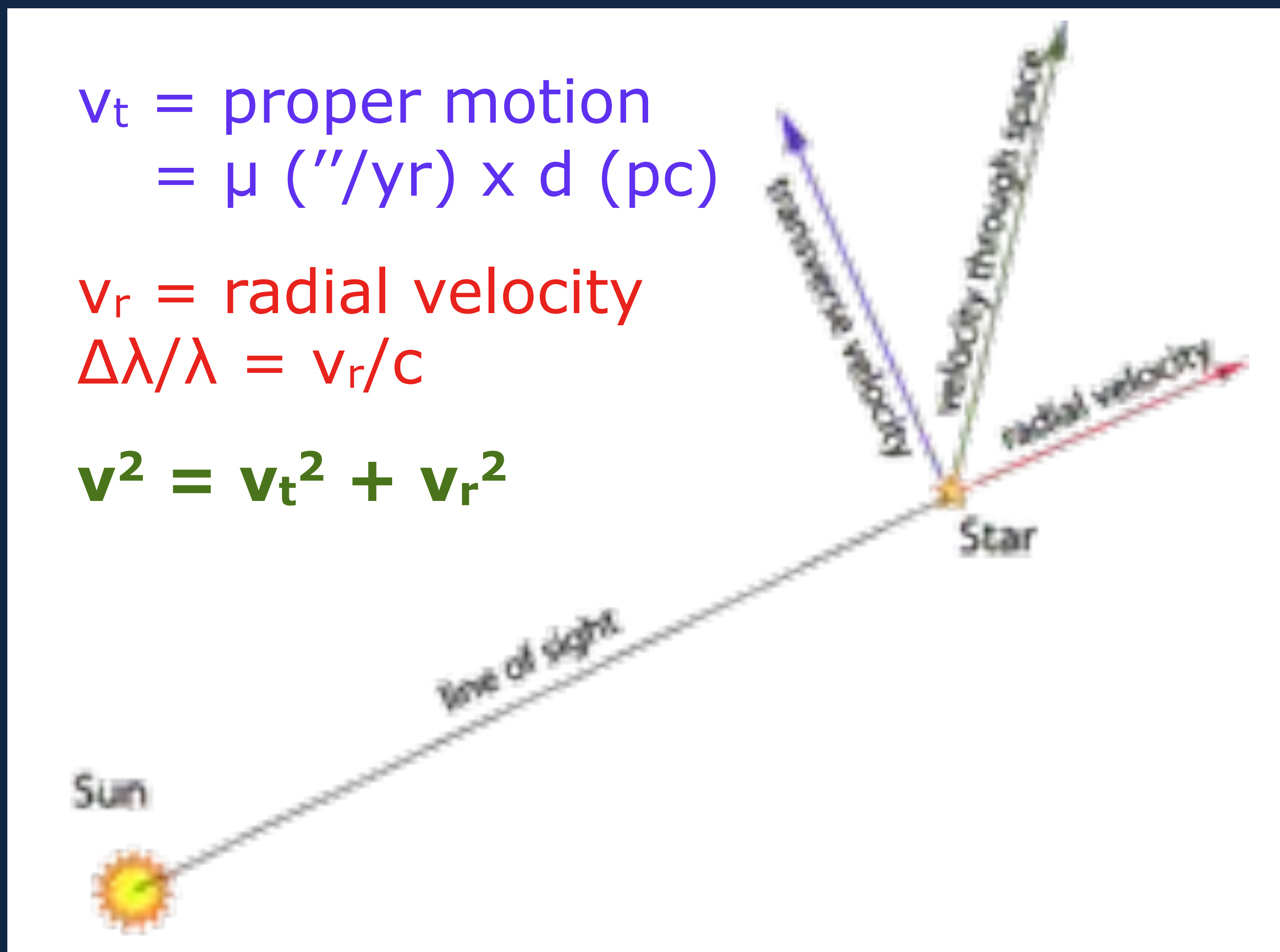
$v_t$ = proper motion

= μ (″/yr) x d (pc)

$v_r$ = radial velocity

$\Delta\lambda/\lambda = v_r/c$

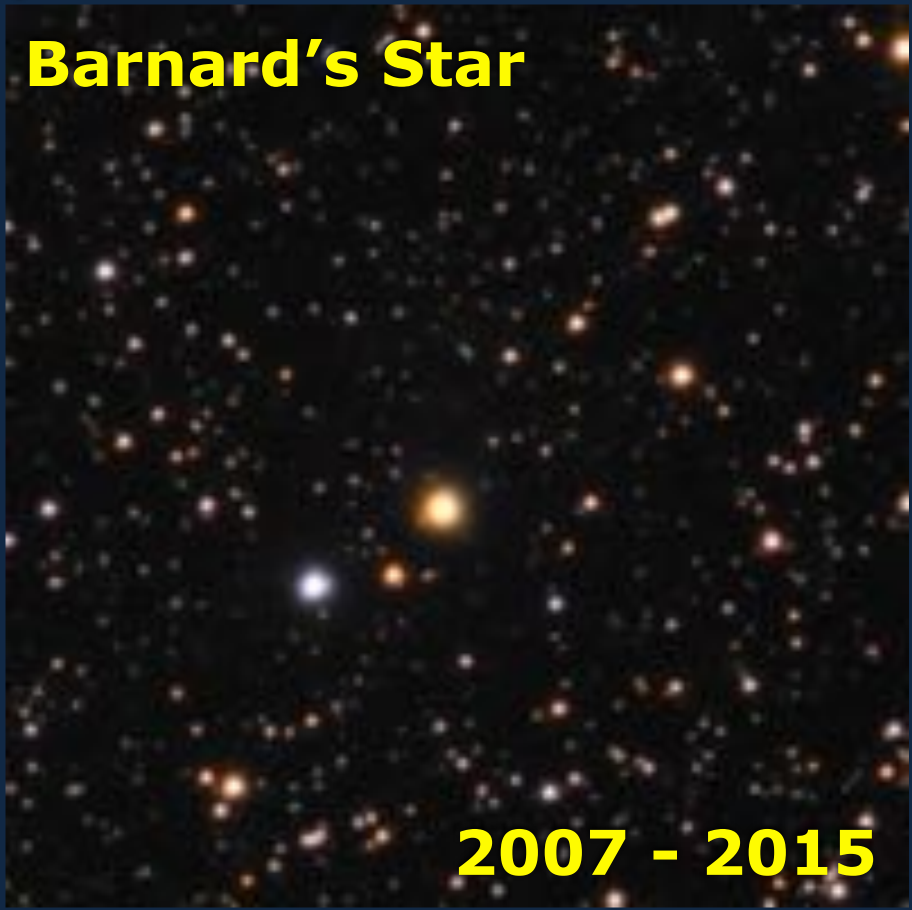
$\mathbf{v^2 = v_t^2 + v_r^2}$



# Properties of Stars - Velocity

Determining a star's velocity through space can be done by combining observable components…

What we see as the star's motion through the sky, $\mu$, actually depends on distance and direction.



# Properties of Stars - Brightness

1) Distance - parallax, Cepheids
2) Velocity - proper motion, radial velocity
3) Brightness
4) Temperature
5) Mass
6) Radius

# Properties of Stars - Brightness

We express stars' brightness in magnitudes.

**apparent mag, $m_V$**: brightness from Earth

$$m = -2.5\log(\text{flux}) + \text{const}$$

$$m_2 - m_1 = -2.5\log(f_2/f_1)$$

**absolute mag, $M_V$**: brightness from 10 pc

$$m-M = 5(\log(d) - 1)$$ (d in parsecs)

(distance modulus)

# Properties of Stars - Brightness

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**apparent mag, V**: brightness from Earth

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$$m - M = 5(\log(d) - 1)$$ (d in parsecs)

(distance modulus)

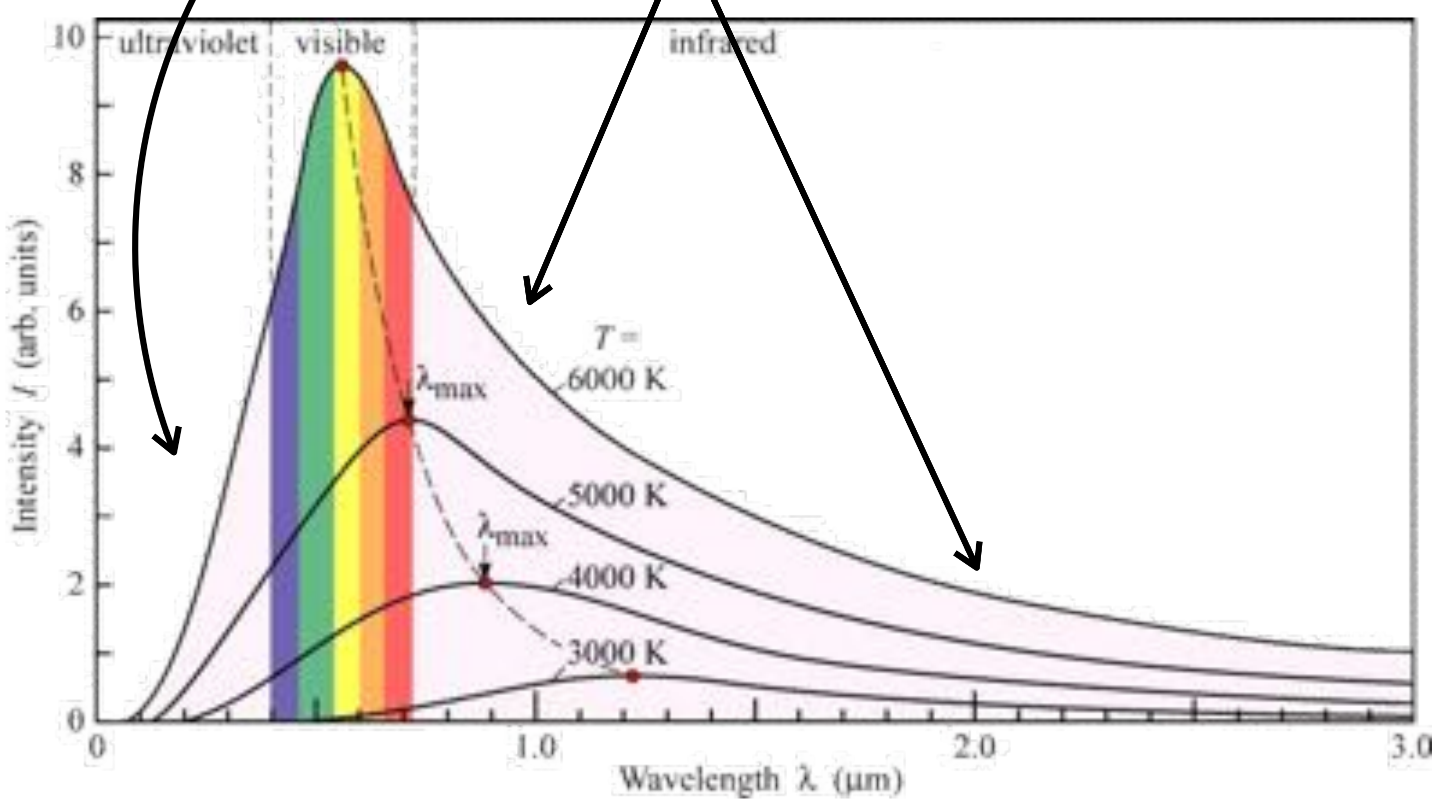
# Properties of Stars - Brightness

We express stars' brightness in magnitudes.

$M_{\text{all wavelengths}}$ = "bolometric" magnitude, $M_{bol}$

$$M_V + BC_V = M_{bol}$$

bolometric correction



# Properties of Stars - Brightness

We express stars' brightness in magnitudes.

= "bolometric" magnitude.

## QUICK QUESTION

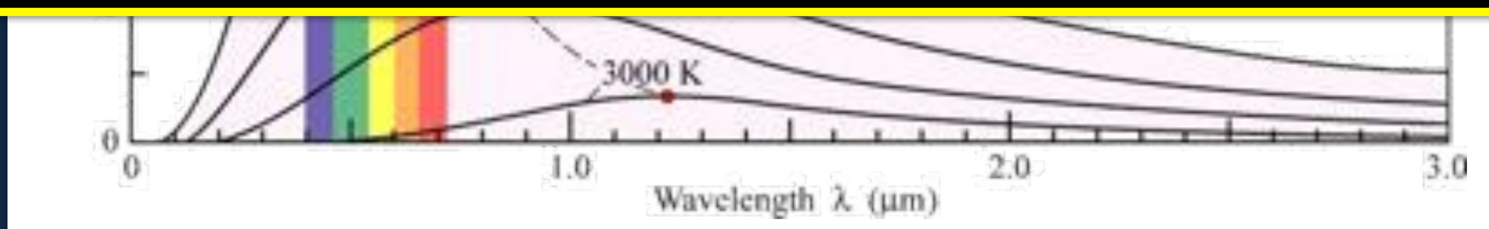
Which spectral type will have the SMALLEST $BC_V$?

A) A

B) B

C) M

D) G



# Properties of Stars - Brightness

We express stars' brightness in magnitudes.

$\mathbf{M_{all\ wavelengths}}$ = "bolometric" magnitude, $\mathbf{M_{bol}}$

$$\mathbf{M_V + BC_V = M_{bol}}$$

$$M_{bol,\ star} - M_{bol,\ sun} = -2.5\log(L_{star}/L_{sun})$$

$$M_{bol,\ sun} \sim 4.74 \text{ mag}$$

$$L_{sun} \sim 4 \times 10^{33} \text{ ergs/s}$$

# Properties of Stars - Brightness

$$L = 4\pi R^2 \sigma T^4$$

# Properties of Stars - Brightness

$$L = 4\pi R^2 \sigma T^4$$

## Quick Question

From the Stefan-Boltzmann relation above, we know that if we hold a star’s temperature constant but increase its luminosity, the star:

A) gets bigger

B) gets smaller

C) stays the same size

D) explodes

# Properties of Stars - Brightness

$$L = 4\pi R^2 \sigma T^4$$

Stars are assigned **luminosity classes** that serve as a rough proxy for size ***and mass.***

more luminous ↑

- I - supergiants (more luminous)
- II - bright giants
- III - giants
- IV - subgiants
- V - dwarfs

Luminosity class gets paired with spectral class to yield a star's spectral type.

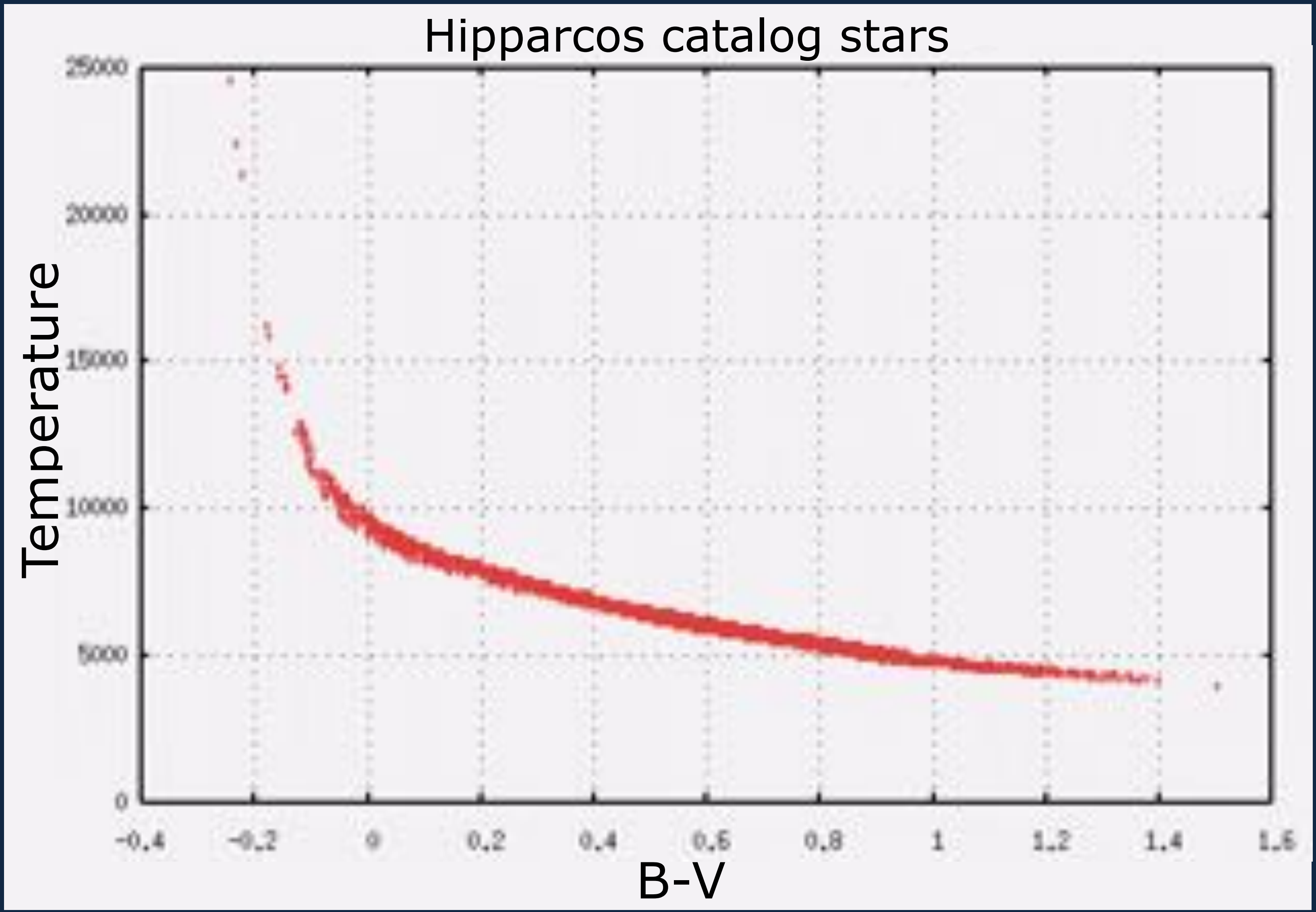
**Sun: G2V** **Betelgeuse: M2I**

# Properties of Stars - Temperature

1) Distance - parallax, Cepheids
2) Velocity - proper motion, radial velocity
3) Brightness - magnitudes, luminosity
4) Temperature
5) Mass
6) Radius

# Properties of Stars - Temperature

We've seen that spectral class and color index can both be used as a proxy for T…



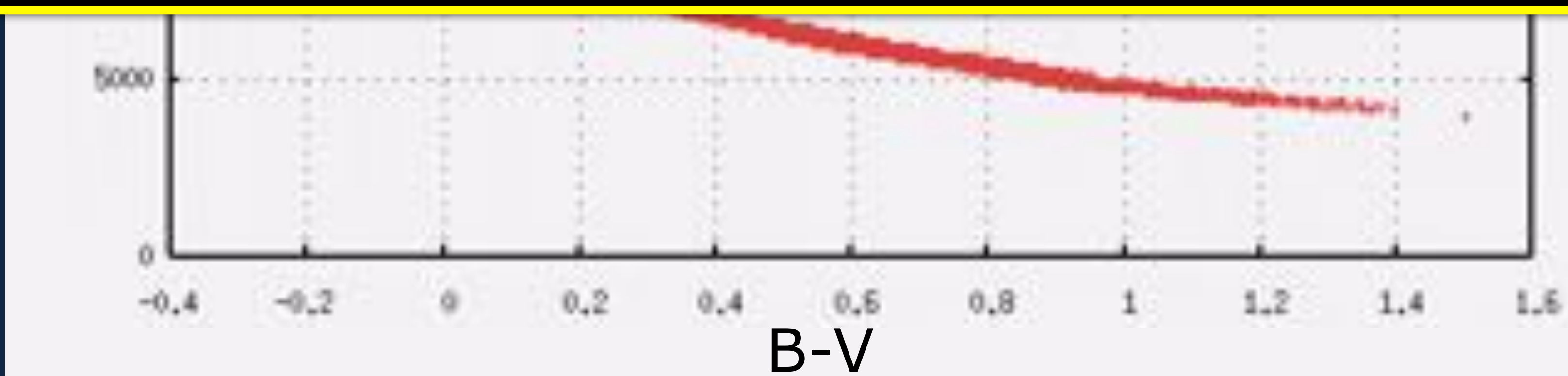
# Properties of Stars - Temperature

We've seen that spectral class and color index can both be used as a proxy for T…

## DISCUSSION QUESTION

How do we define the "temperature" of a star?

(think, then discuss)



# Properties of Stars - Temperature

## Types of Stellar Temperature

**Excitation** - ratio of atoms in different states of excitation, defined by Boltzmann equation

$$\frac{N_b}{N_a} = \frac{g_b}{g_a} e^{\frac{-(E_b - E_a)}{kT}}$$

N = # of atoms in state; g = statistical weight/degeneracy of state; E = energy of state; k = Boltzmann constant; T = temp

# Properties of Stars - Temperature

## Types of Stellar Temperature

**Excitation** - ratio of atoms in different states of excitation, defined by Boltzmann equation

**Ionization** - ratio of atoms in different stages of ionization, defined by Saha equation

$$\frac{N_{i+1}}{N_i} = \frac{2kT}{P_e} \frac{g_{i+1}}{g_i} \left(\frac{2\pi m_e kT}{h^2}\right)^{3/2} e^{\frac{-X_i}{kT}}$$

N = # of atoms in state; g = statistical weight/degeneracy of state; E = energy of state; k = Boltzmann constant; T = temp; P = electron pressure; $m_e$ = electron mass; h = Planck; $X_i$ = ionization potential

# Properties of Stars - Temperature

## Types of Stellar Temperature

**Excitation** - ratio of atoms in different states of excitation, defined by Boltzmann equation

**Ionization** - ratio of atoms in different stages of ionization, defined by Saha equation

**Kinetic** - Maxwell-Boltzmann distribution

$$u_0 = \sqrt{2kT/m}$$

# Properties of Stars - Temperature

## Types of Stellar Temperature

**Excitation** - ratio of atoms in different states of excitation, defined by Boltzmann equation

**Ionization** - ratio of atoms in different stages of ionization, defined by Saha equation

**Kinetic** - Maxwell-Boltzmann distribution

**Color** - blackbody assumption

$$\lambda(\text{Å}) = 2.9\times10^7/T$$ (Wien's law)

# Properties of Stars - Temperature

Types of Stellar Temperature

**Excitation** - ratio of atoms in different states of excitation, defined by Boltzmann equation

**Ionization** - ratio of atoms in different stages of ionization, defined by Saha equation

**Kinetic** - Maxwell-Boltzmann distribution

**Color** - blackbody assumption

**Effective** - at the “surface” of a star

$$L = 4\pi R^2 \sigma T^4$$

# Properties of Stars - Temperature

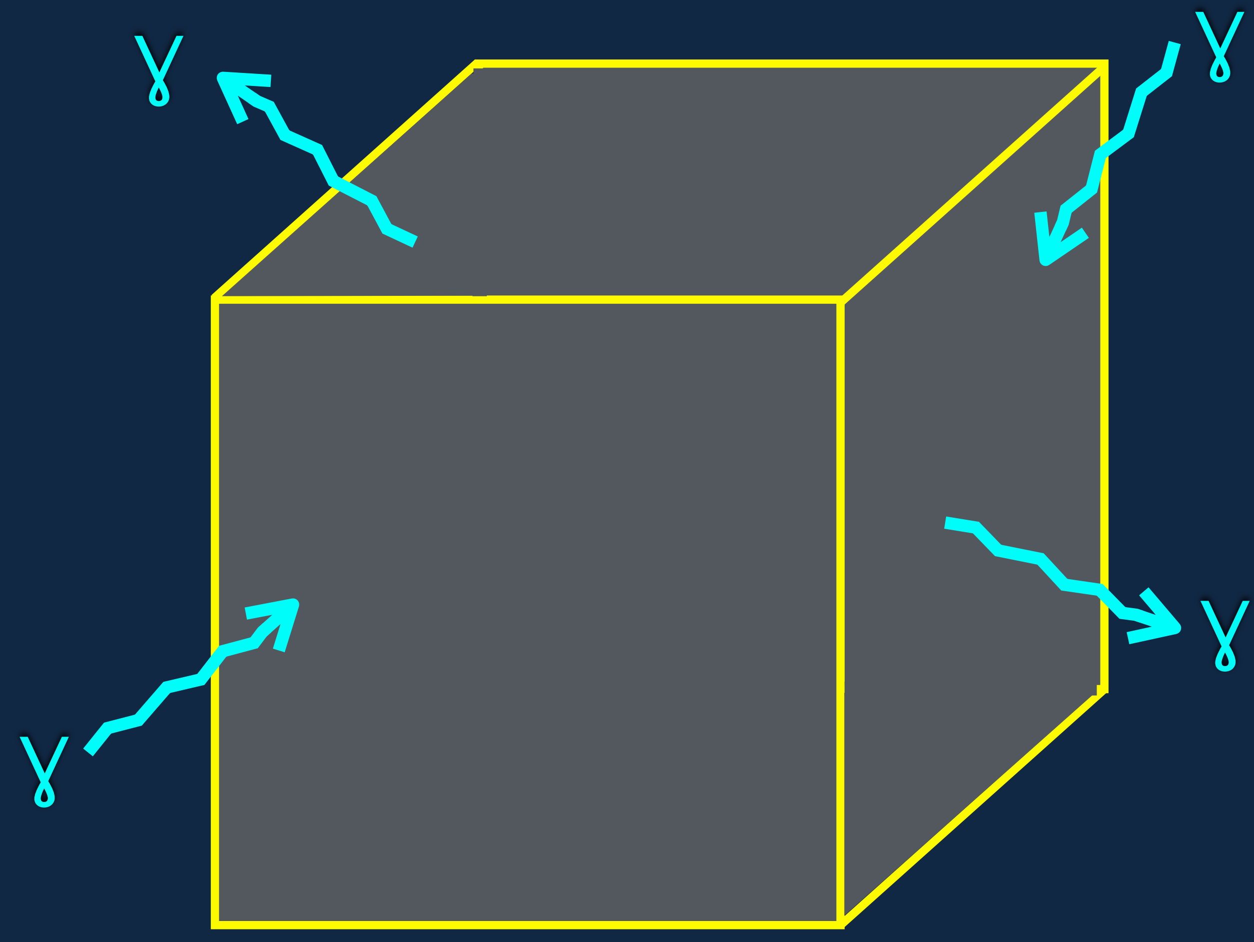
Types of Stellar Temperature

**Why aren't these all the same?**

Simplest scenario:

Thermodynamic Equilibrium

**Excitation**
**Ionization**
**Kinetic**
**Color**
**Effective**



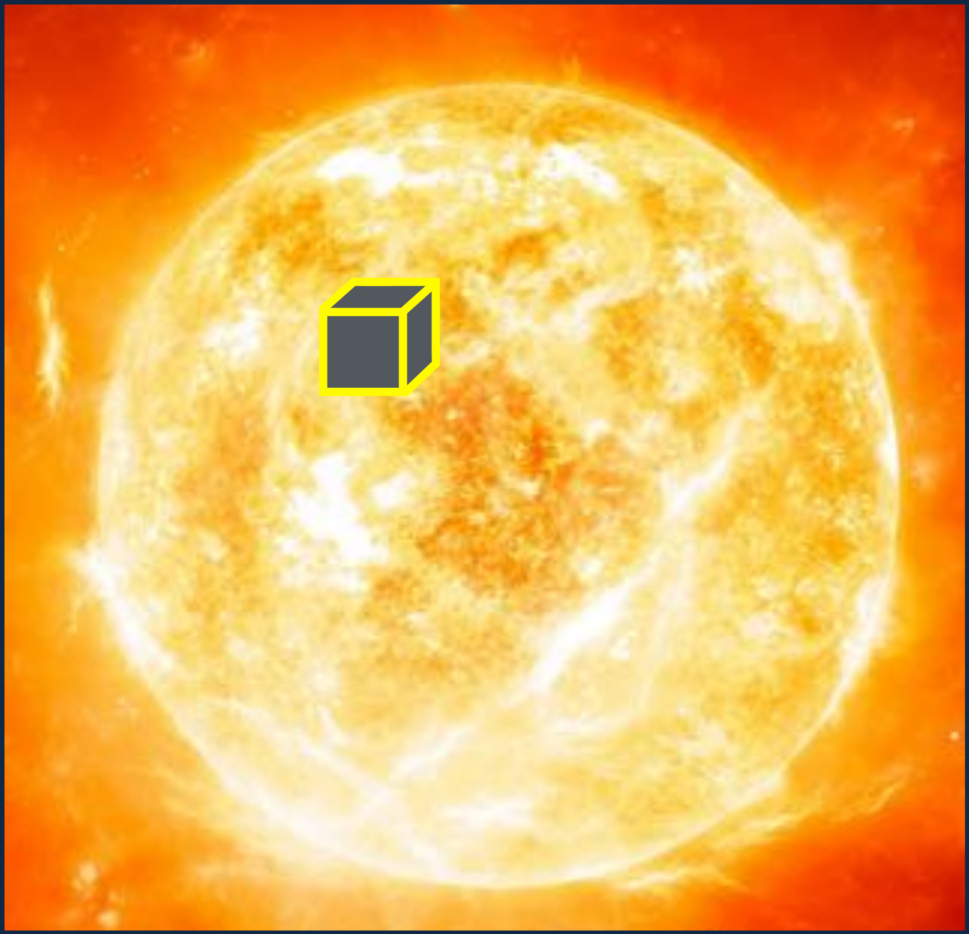
# Properties of Stars - Temperature

Types of Stellar Temperature

**Why aren't these all the same?**

Simplest scenario:

- **L**ocal
- **T**hermodynamic
- **E**quilibrium



**Excitation**

**Ionization**

**Kinetic**

**Color**

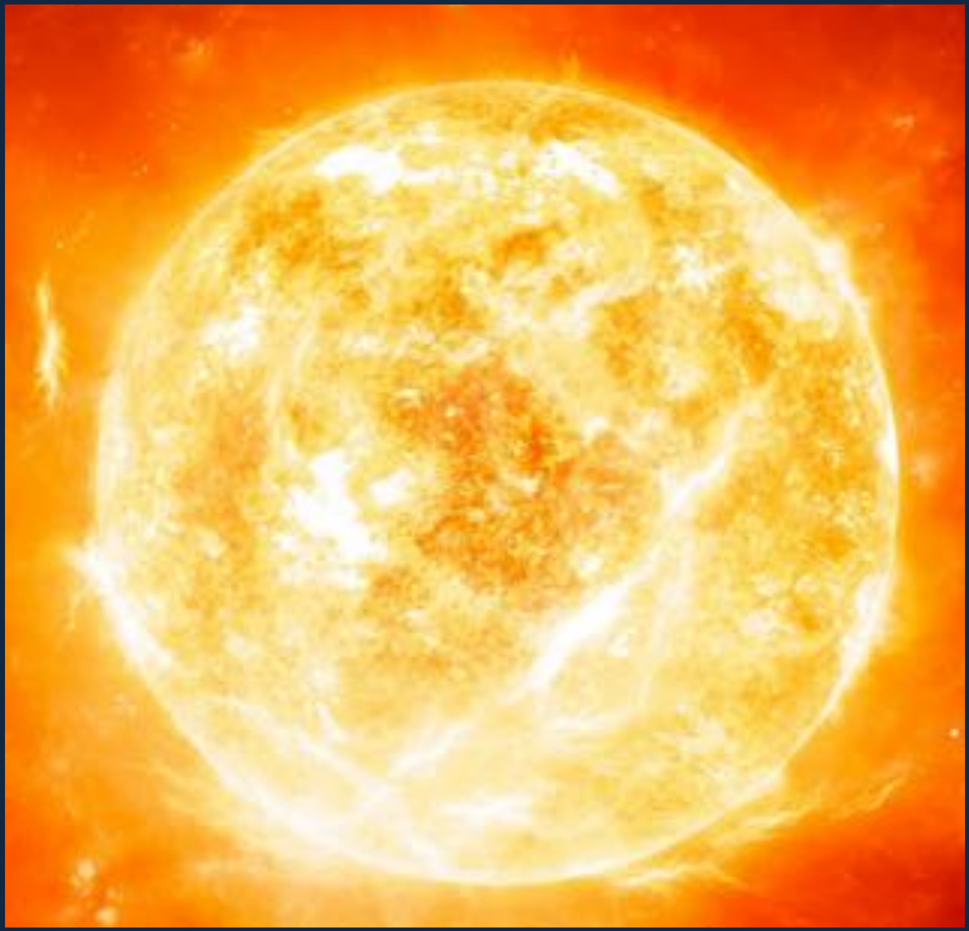
**Effective**

# Properties of Stars - Temperature

Types of Stellar Temperature

**Effective temperature** - most commonly used ("surface" temperature)

$$L = 4\pi R^2\sigma T^4$$



# Properties of Stars - Temperature

## Types of Stellar Temperature

**Effective temperature** - most commonly used ("surface" temperature)

**Hottest stars:**

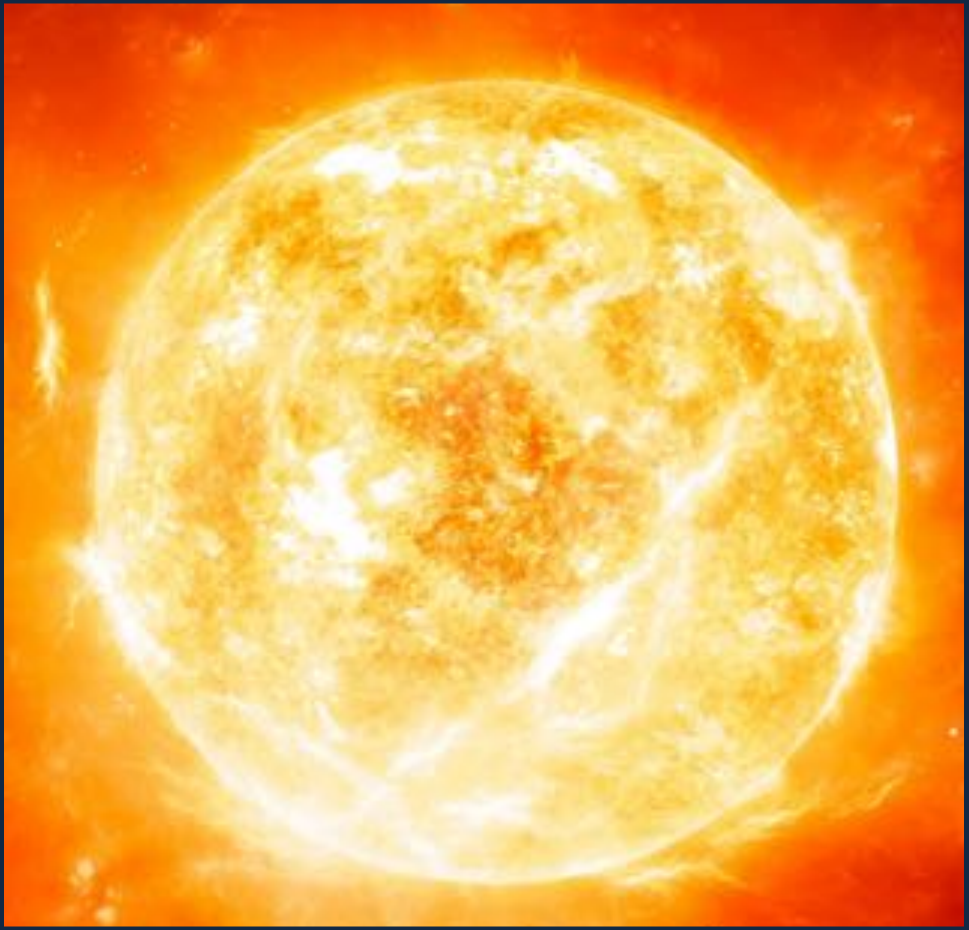
~200,000 K

(WR 102)

**Coldest "stars":**

~250 K

(WISE 0855−0714)



# Coming next...

1) Distance - parallax, Cepheids
2) Velocity - proper motion, radial velocity
3) Brightness - magnitudes, luminosity
4) Temperature
5) Mass
6) Radius

# Coming next...

Tuesday, Oct 24: guest lecture
(Dr. Jamie Lomax)

Thursday, Oct 26: slidecast review lecture!
(link on website)

Questions? email me!

exam prep: extra office hours
Mon Oct 30, 10-11am & 1-4pm

Tuesday, Oct 31: Exam #1, in PAA A102