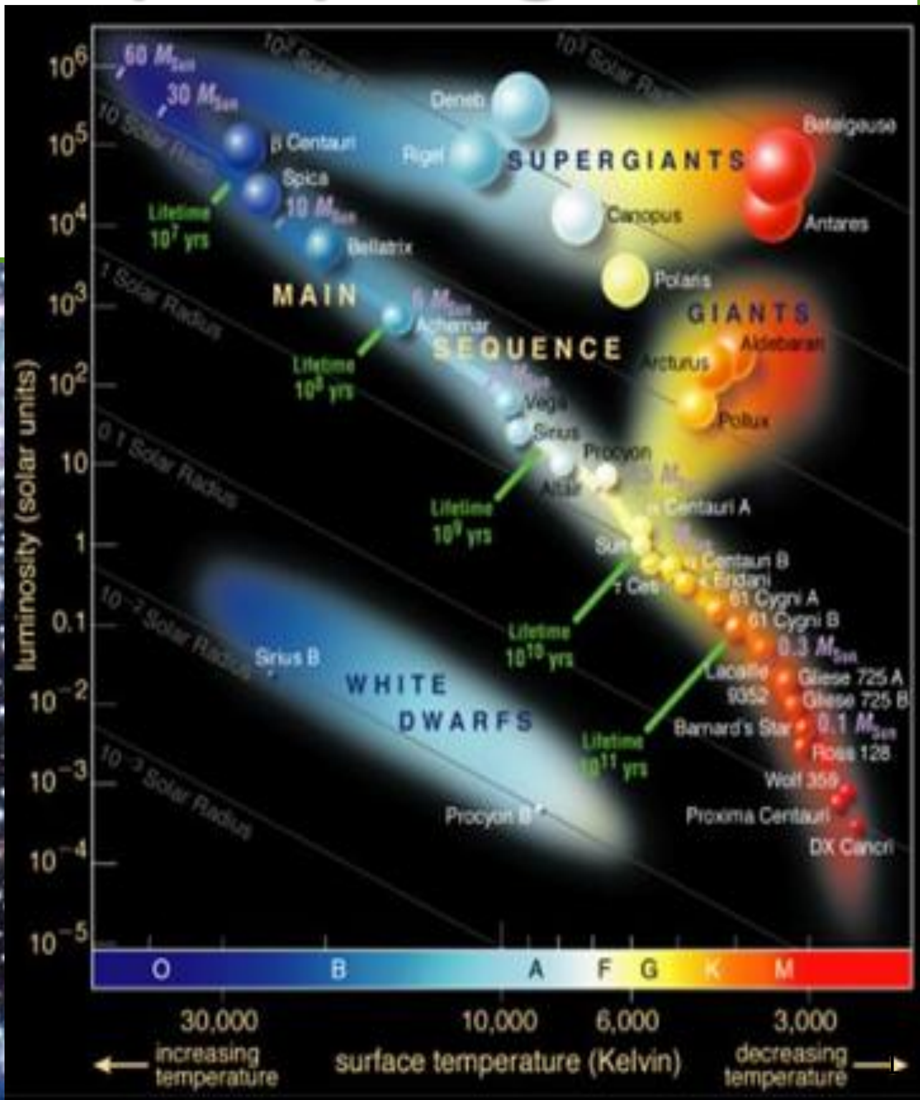
The Hertzsprung-Russell (H-R) Diagram
or
The Evolution of Stars

Dr Paul Lewis FRAS



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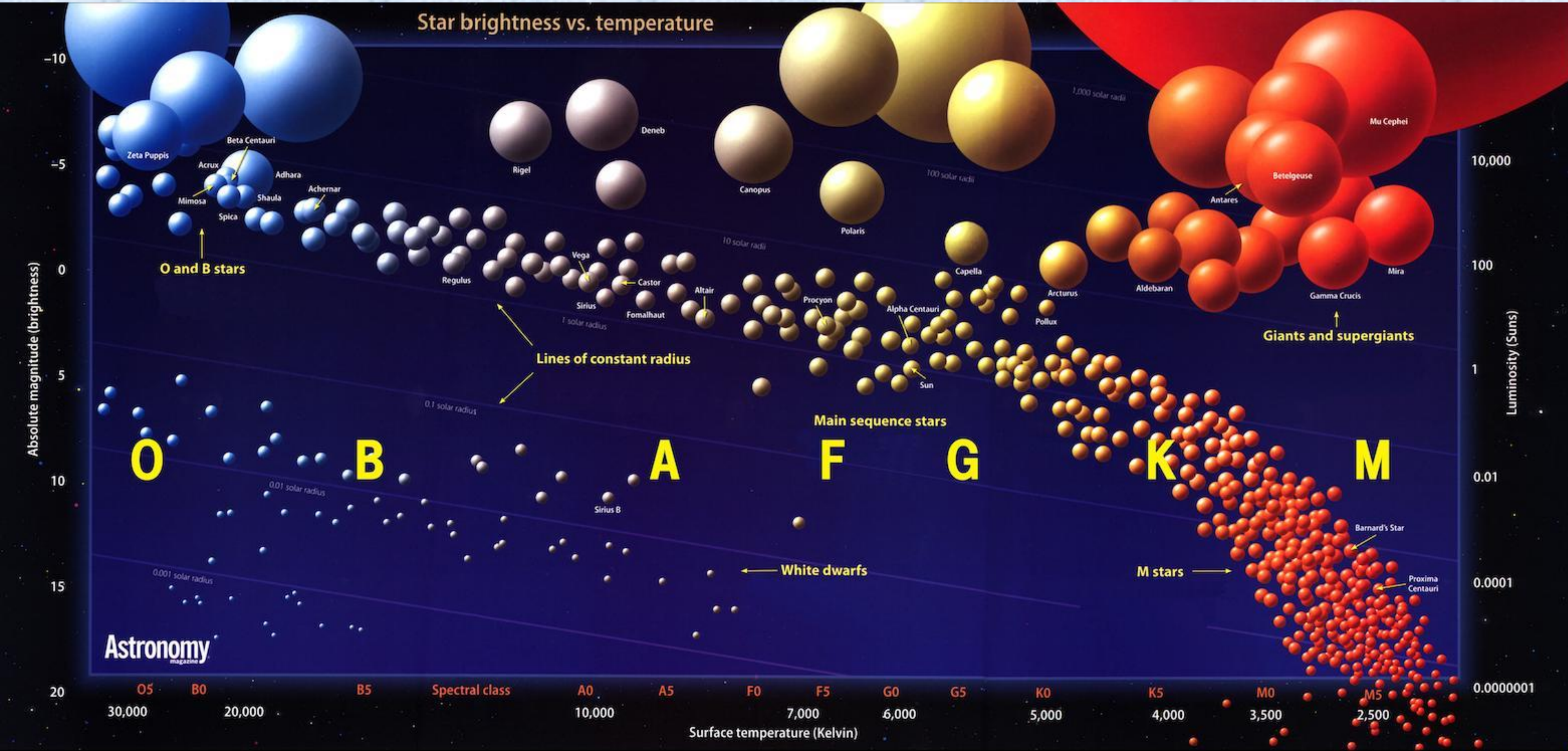
1. INTRODUCTION



Topics

1. Introduction
2. Brightness
3. Temperature
4. Hertzsprung Russell diagram
5. Spectral type
6. Understanding the HR diagram
7. Stellar evolution

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Introduction

- Objective
  - To use observations to learn about stellar life cycles
- H-R diagram introduced around 1918
- Plot of stellar luminosity against stellar temperature
- Particular pattern emerges
- Two astronomers developed it independently
  - Ejnar Hertzsprung (1873–1967)
  - Henry Norris Russell (1877–1957)

- Notation
  - $_\odot$ means solar
  - e.g. $10M_\odot$ = 10 solar masses, $5R_\odot$ = 5 solar radii

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Hertzsprung and Russell

Ejnar Hertzsprung

Henry Norris Russell

- Proposed concept of absolute magnitude
- Plotted graph of relationship between absolute magnitudes and colour of stars in Pleiades
- Coined terms red giant and red dwarf

- Plotted spectral classification against absolute magnitude
- Found that most stars lay in certain regions of the diagram

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Uses

- Problem:
  - Single star represents snapshot in stellar life
- H-R diagram represents many stars
- The H-R diagram can be used to display many facets of stellar astronomy:
  - It can show the association between the intrinsic properties of temperature and luminosity
  - It allows us to derive masses, lifetimes and evolutionary phases
  - It allows us to study the properties of stellar clusters

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Luminosity, radius and photosphere temperature

$R^2 = R \times R$

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

Luminosity

Surface area of sphere

Constant (Stefan–Boltzmann)

Photosphere temperature

$$L = R^2 \times T^4 \times \text{constant}$$

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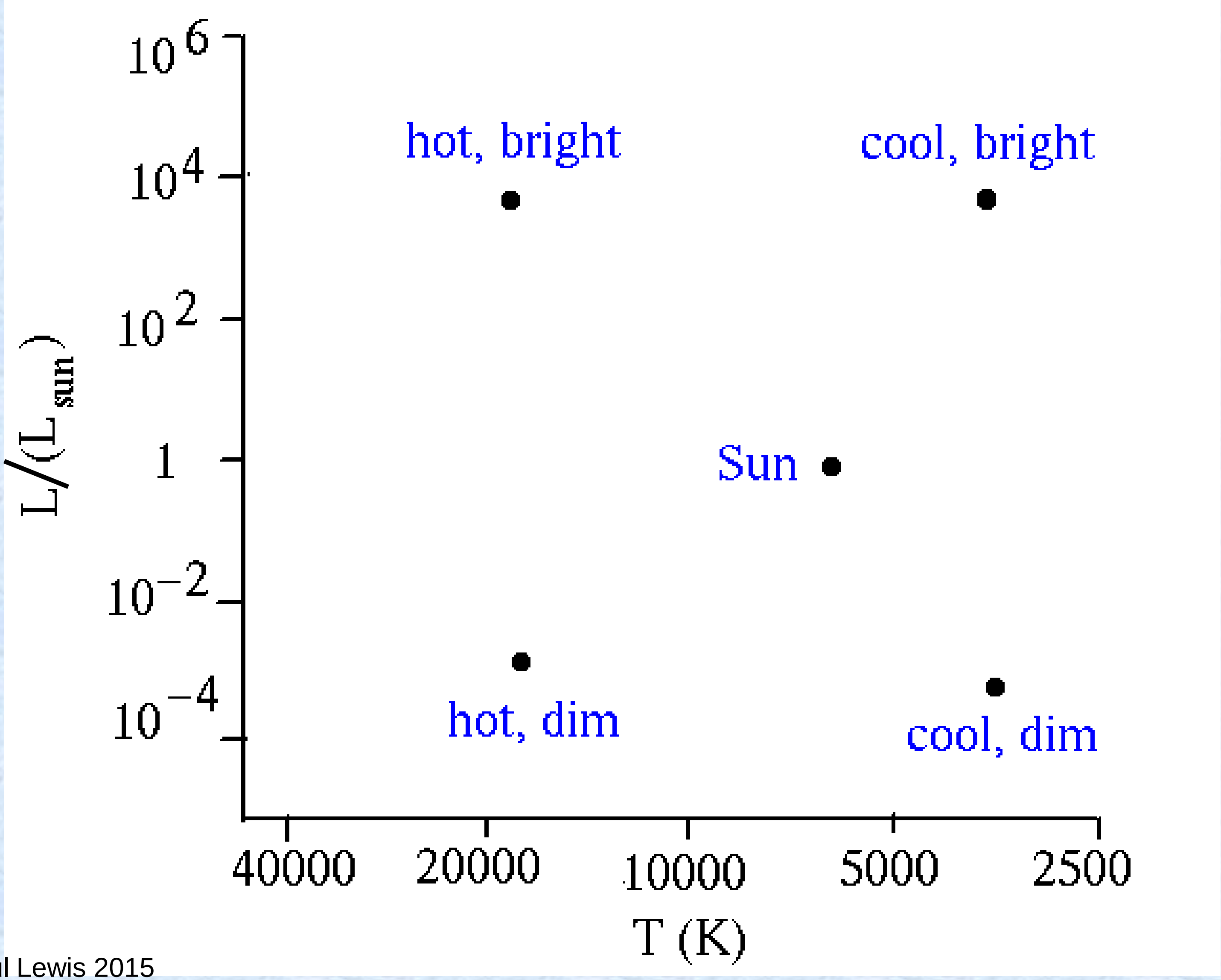
Basic diagram



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Choice of axes

- *y*-axis: Brightness
  - Luminosity
    - theoretical H-R diagram
  - Absolute Magnitude
    - observational H-R diagram
- *x*-axis: Temperature
  - Effective temperature
    - used by theoretical astronomers when checking their mathematical models of stars
  - Colour index
    - based on photometric observations
  - Spectral Classification
    - stellar classification based on spectral observations

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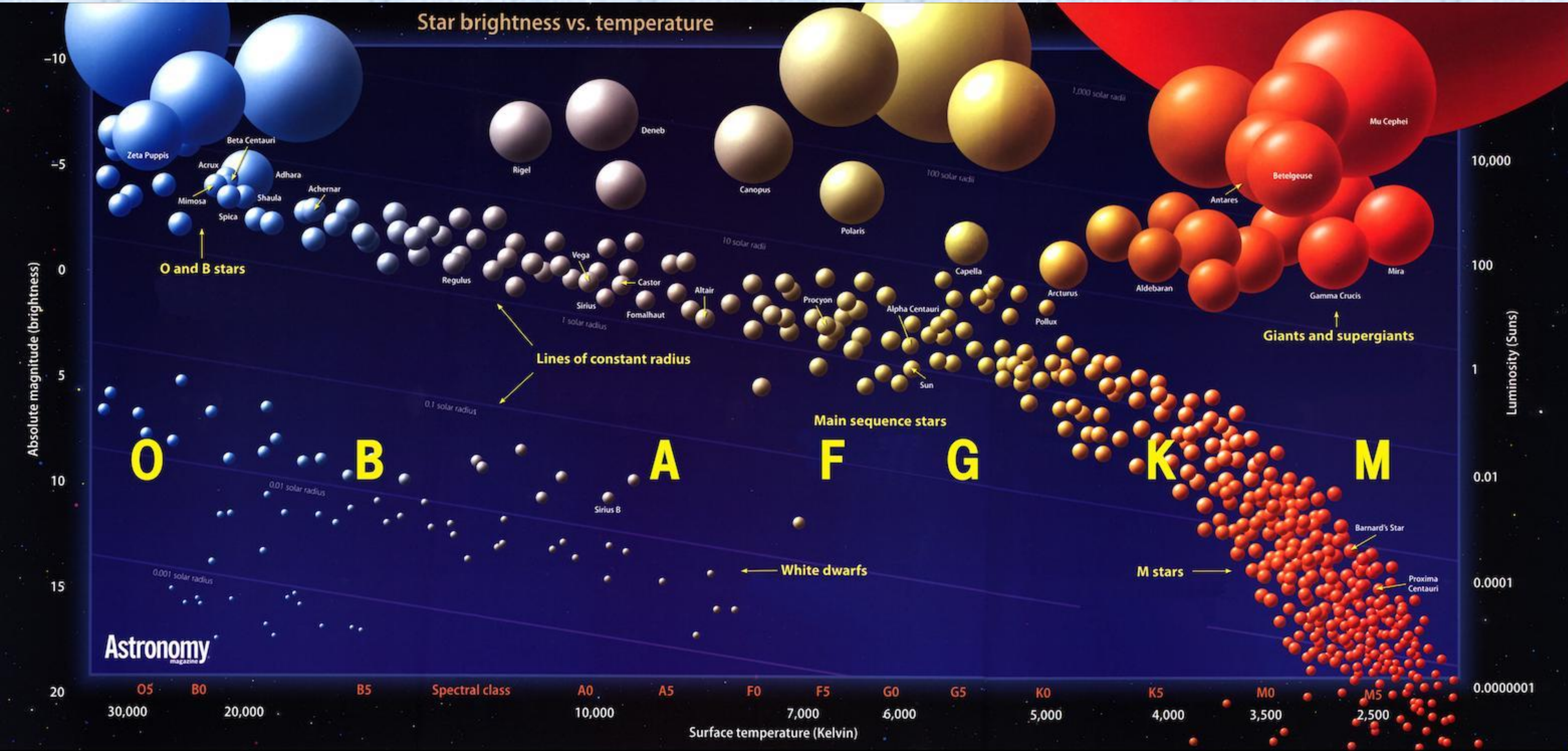
2. BRIGHTNESS



Luminosity

- **Luminosity *L is the total outward flow of energy* from a radiating body per unit time, in all directions (and over all wavelengths)**
- **Dependent on radius and temperature**
- **The SI units of luminosity are *watts* (W)**
- **Luminosity of the Sun is 4×10^{26} watts or 400,000,000,000,000,000,000,000,000 watts**
- **4×10^{26} watts = 4 million billion billion watts**
  - **Thousand billion billion 1kW electric fires**

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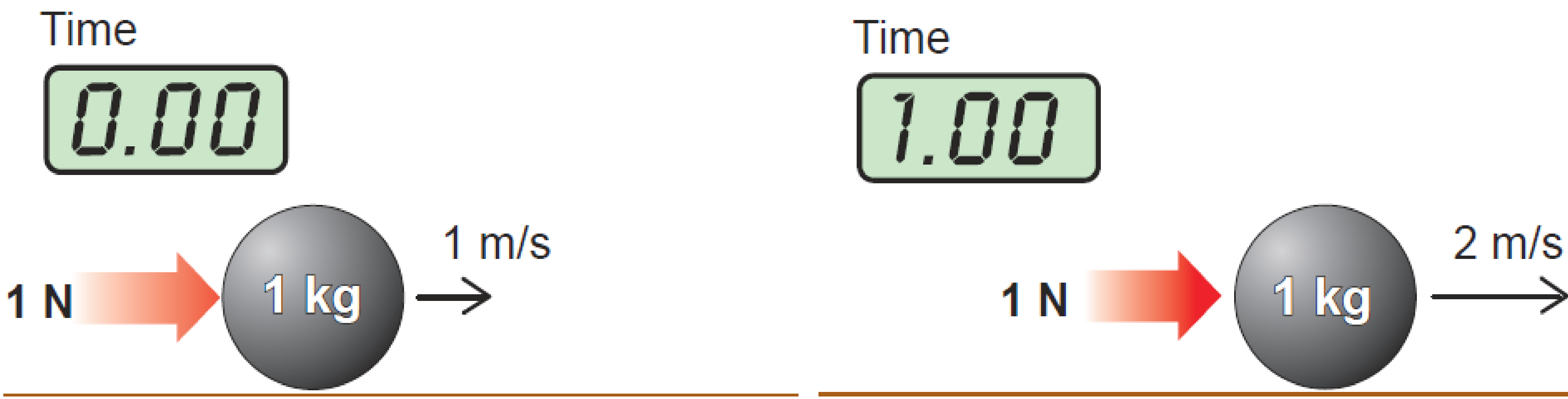
Newtons

One newton (N) is the force it takes to change the speed of a 1 kg mass by 1 m/s in 1 second.



$$a = \frac{F}{m}$$

Acceleration (m/s^2) → a

Force (N) → F

Mass (kg) → m

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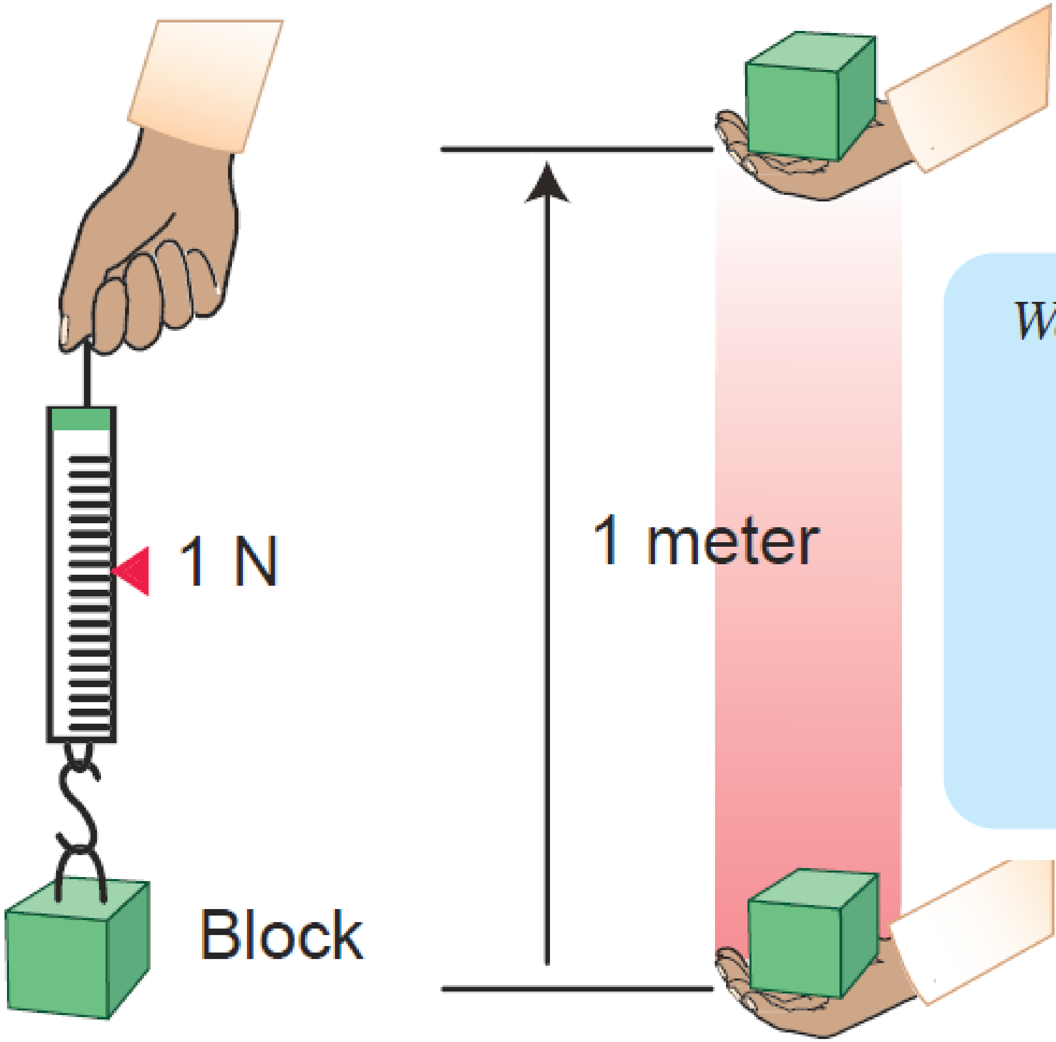
Joules



Lifting the 1 newton
block 1 meter requires
1 joule of work.

Work (joules) *Force* (newtons)

$$W = Fd$$

Distance (meters)
in the direction of the force

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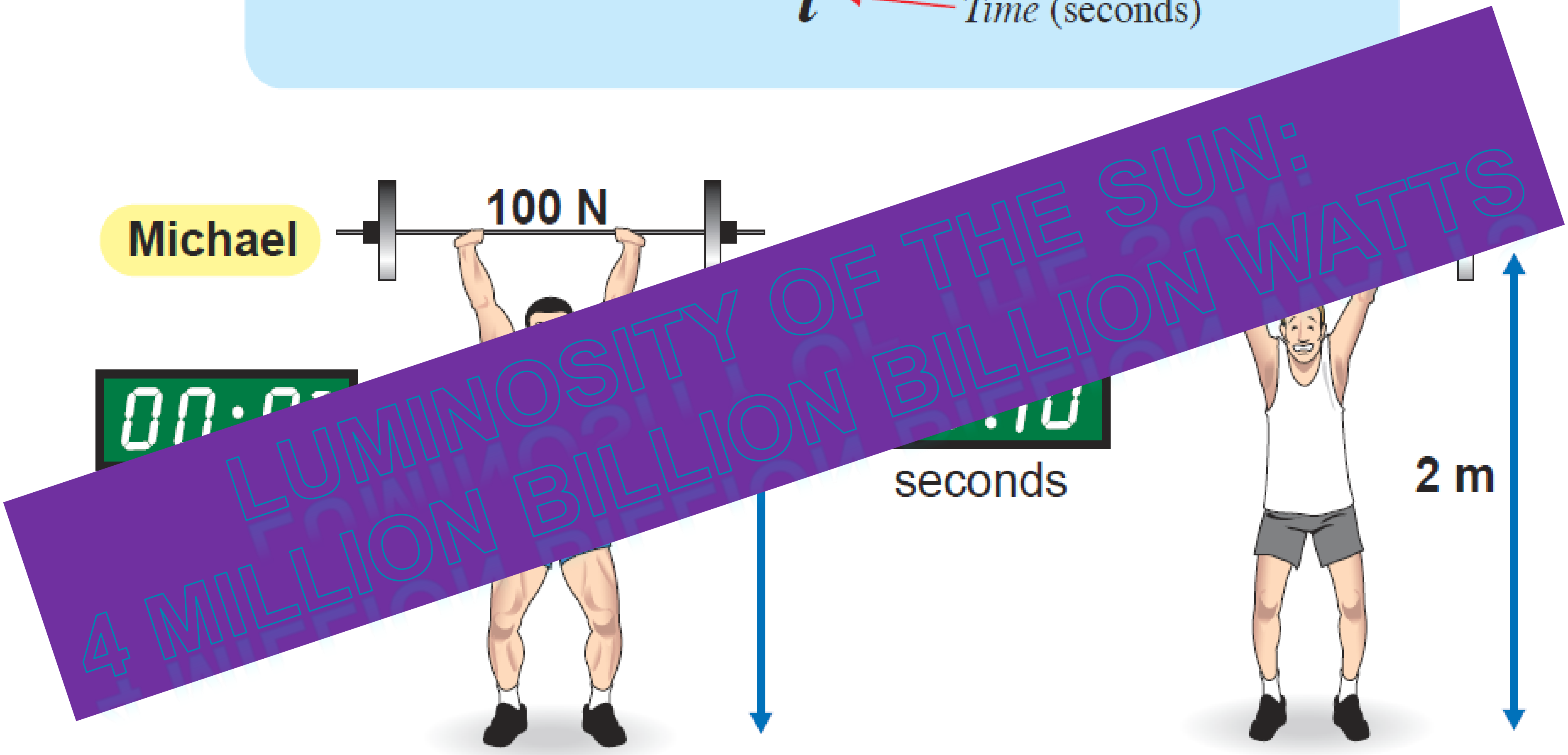
Watts

$$P = \frac{W}{t}$$

Power (watts) → P; *Work* (joules) → W; *Time* (seconds) → t



Michael and Jim do the same amount of work but do not have the same power.

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Absolute magnitude

- Relationship between luminosity and absolute magnitude
- Apparent magnitude of a star at a standard distance of 10 parsecs (32.6 light years)
- Related to visual luminosity, not total luminosity

	Apparent magnitude	Absolute magnitude
Sol	-26.73	
Sirius A	-1.46	
Vega	0.03	
Polaris	1.97	

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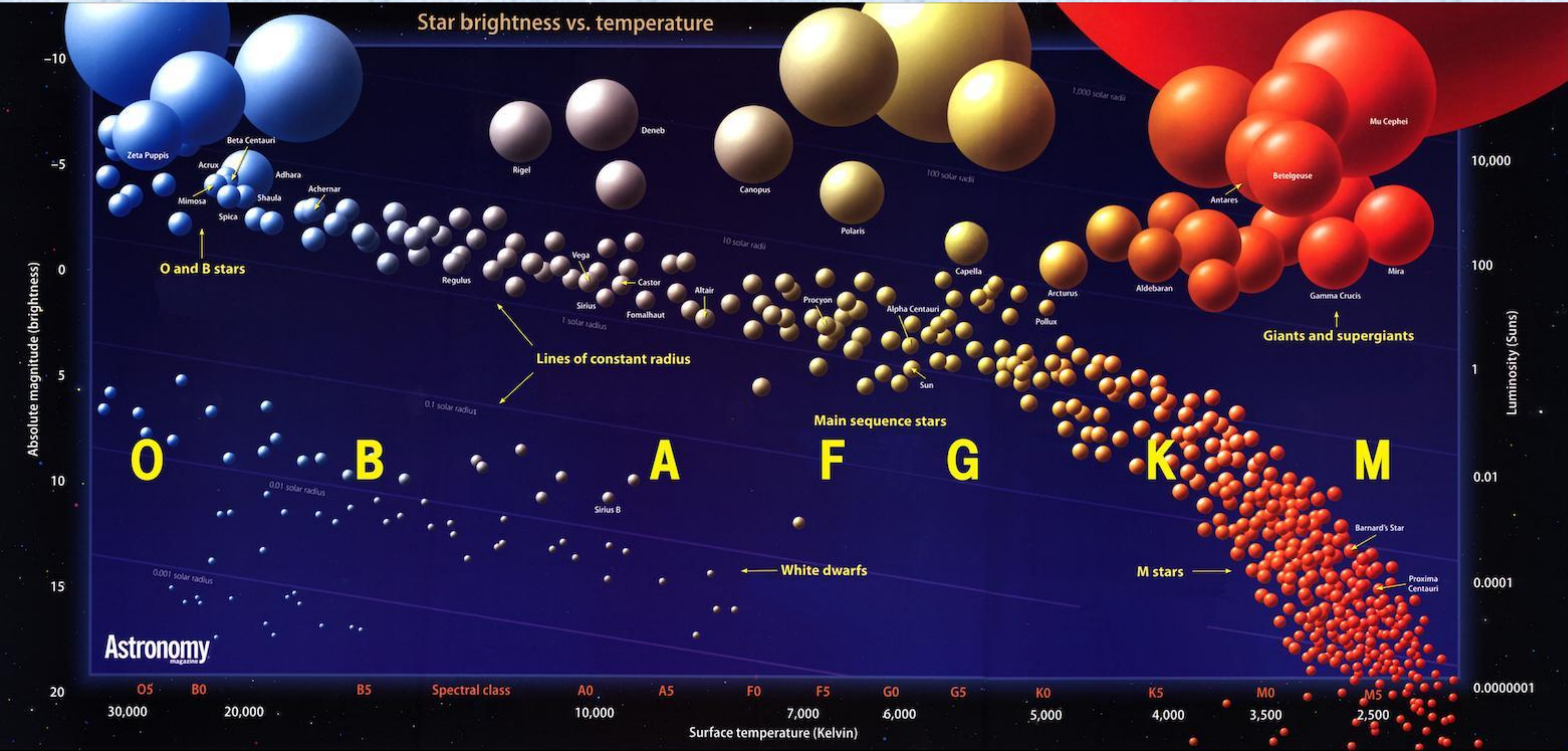
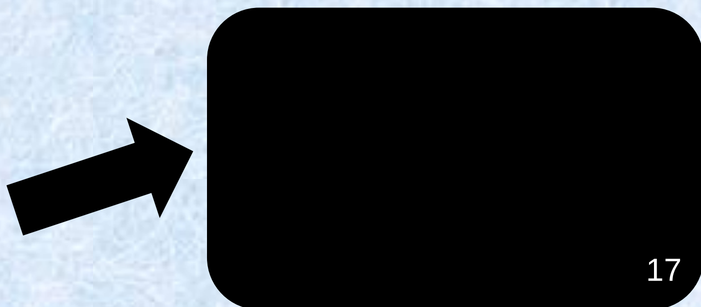
3. TEMPERATURE



<u>Black body</u>

- A black body is a perfect emitter and absorber of radiation at all wavelengths
- Appear black if temperature is low enough so as not to be self-luminous
- Star is <u>approximation</u> to black body
- Black body spectrum is a smooth function of wavelength
- Uniquely specified by the temperature of the emitting body

Black body



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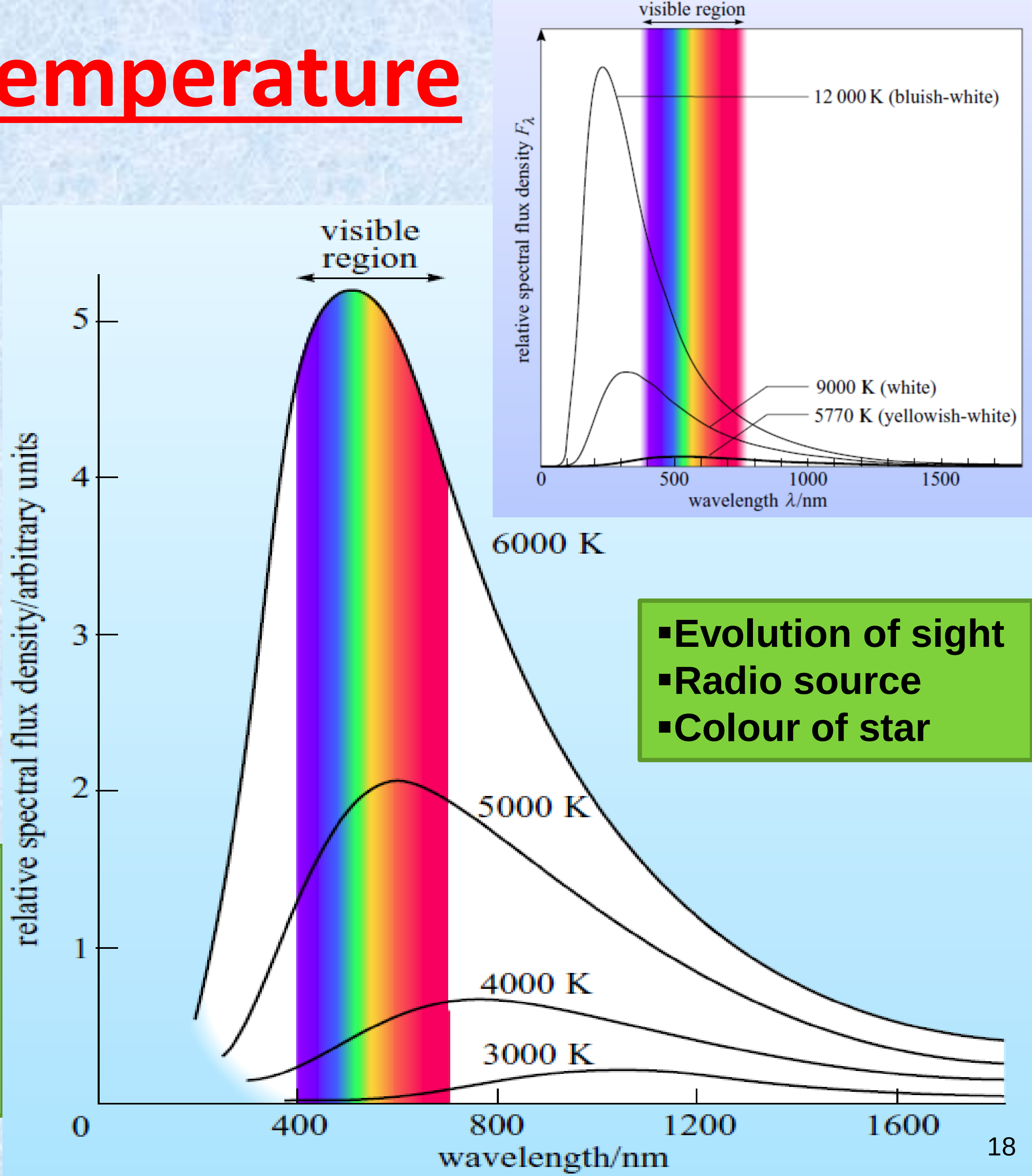
Effective temperature

- Black body spectra for stars of different temperatures
- Temperature:
  - Total rate of energy radiated
  - Wavelength of peak
- Wien's displacement law

$$\text{Temperature (K)} = \frac{0.0029}{\text{Peak wavelength (m)}}$$



- Evolution of sight
- Radio source
- Colour of star

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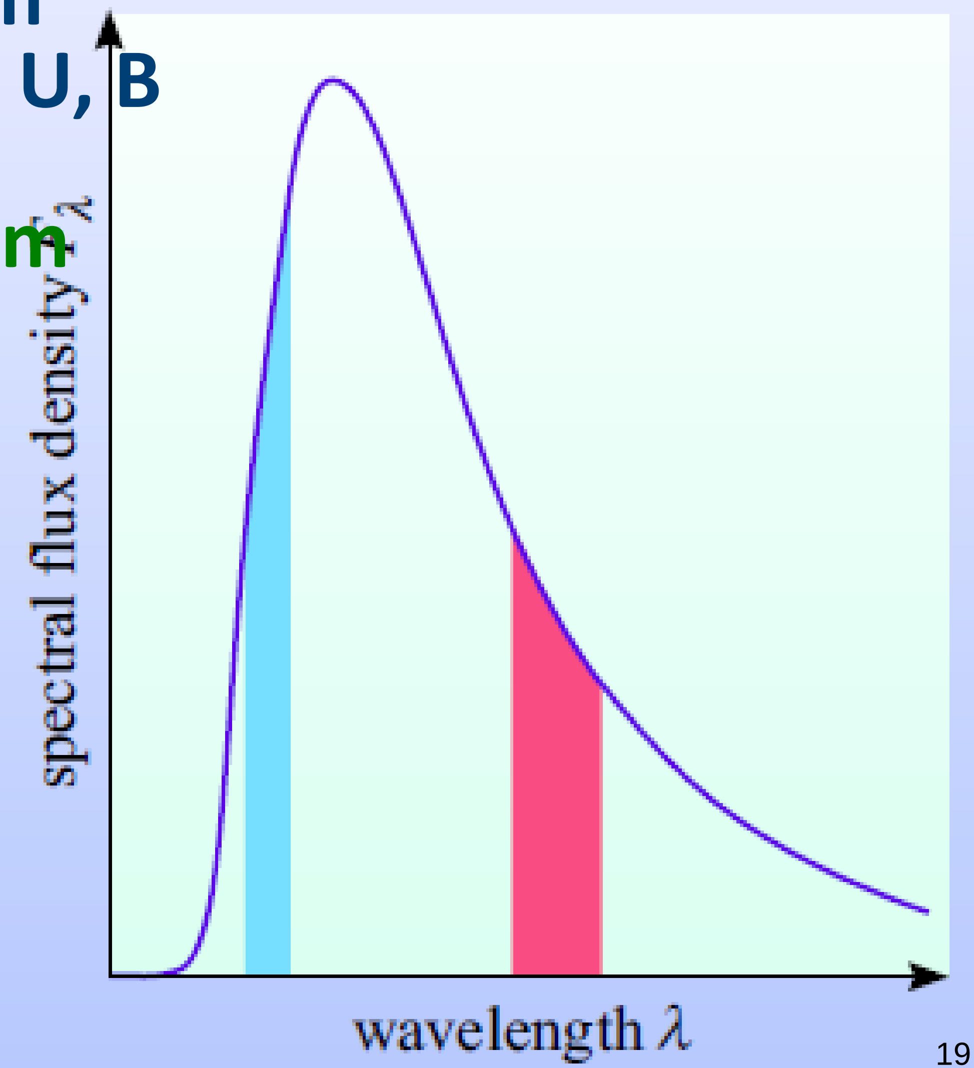
Temperature from photometric colour index

- UBV photometric system
- Three broadband filters U, B and V
  - U – ultraviolet, 360 nm
  - B – blue, 440 nm
  - V – visual, 550 nm

- Indices
  - Difference in magnitudes
    - (U – B)
    - (B – V)



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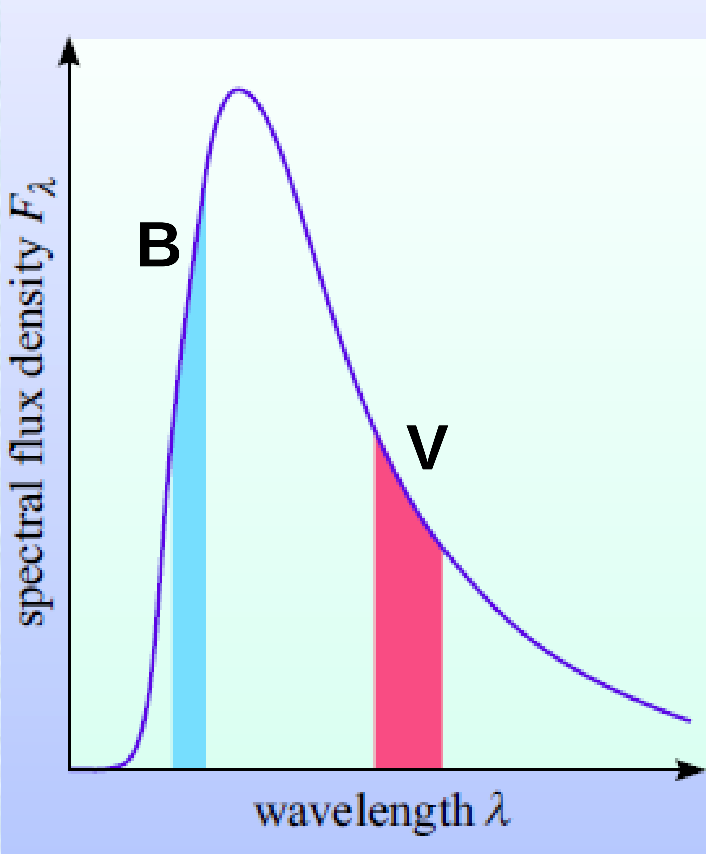
Why subtract and not ratio?

- Assume:
  - B = magnitude 10
  - V = magnitude 5
    - Ratio: B/V = 10/5 = 2
    - Subtract: B-V = 10-5 = 5
- Extinction magnitude of 5
  - B = magnitude 15
  - V = magnitude 10
    - Ratio: B/V = 15/10 = 1.5
    - Subtract: B-V = 15-10 = 5



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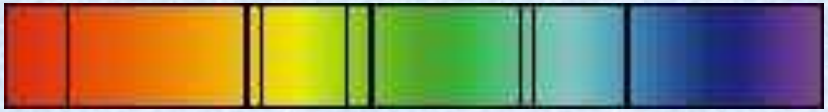
Temperature from spectral classification

- Determined from a study of the absorption lines



- Classification scheme: O B A F G K M
- Spectral types directly related to temperature
- Decreasing temperature: O B A F G K M

Oh **B**e **A** **F**ine **G**irl **K**iss **M**e

or

Oh **B**other, **A**n **F** **G**rade **K**ills **M**e

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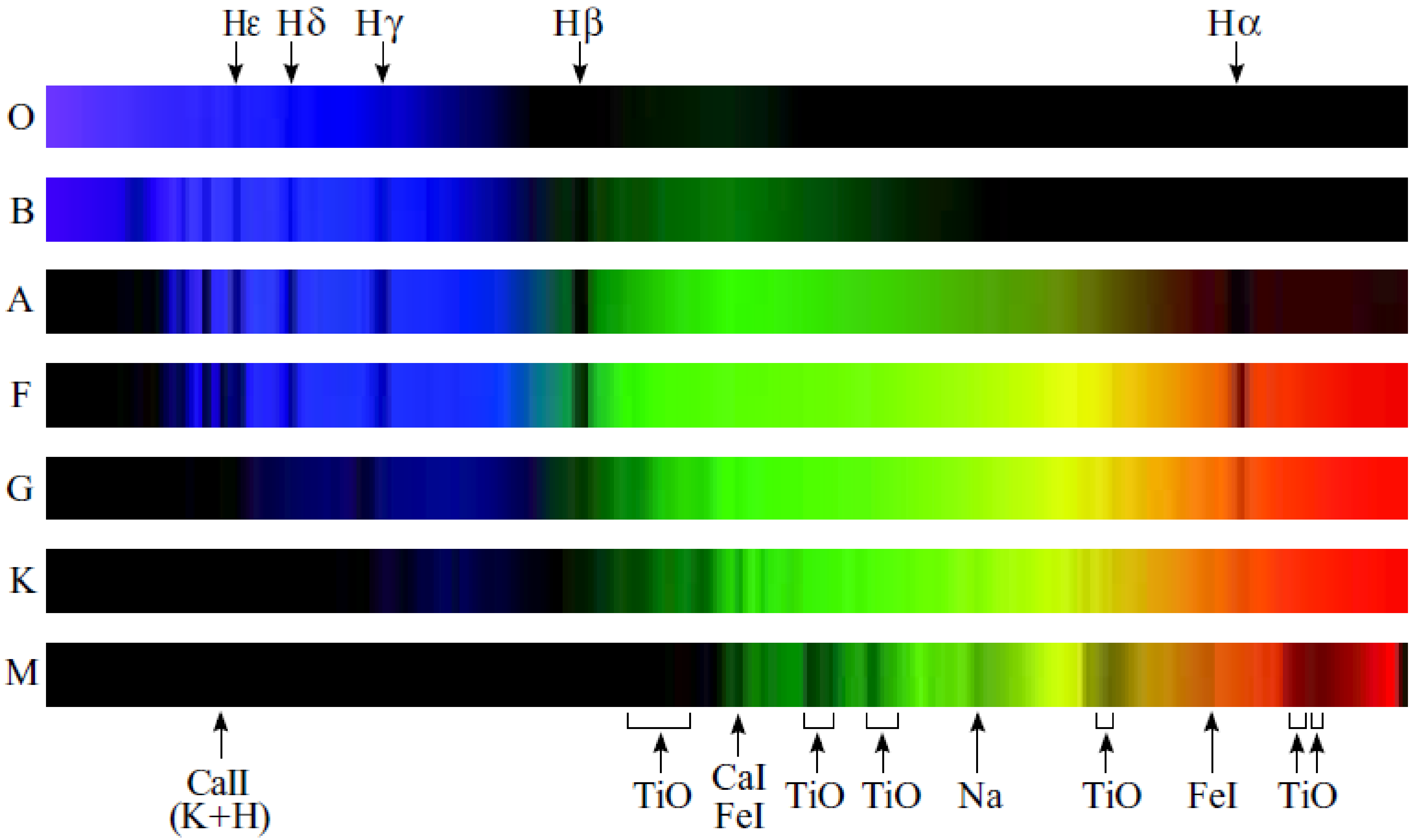
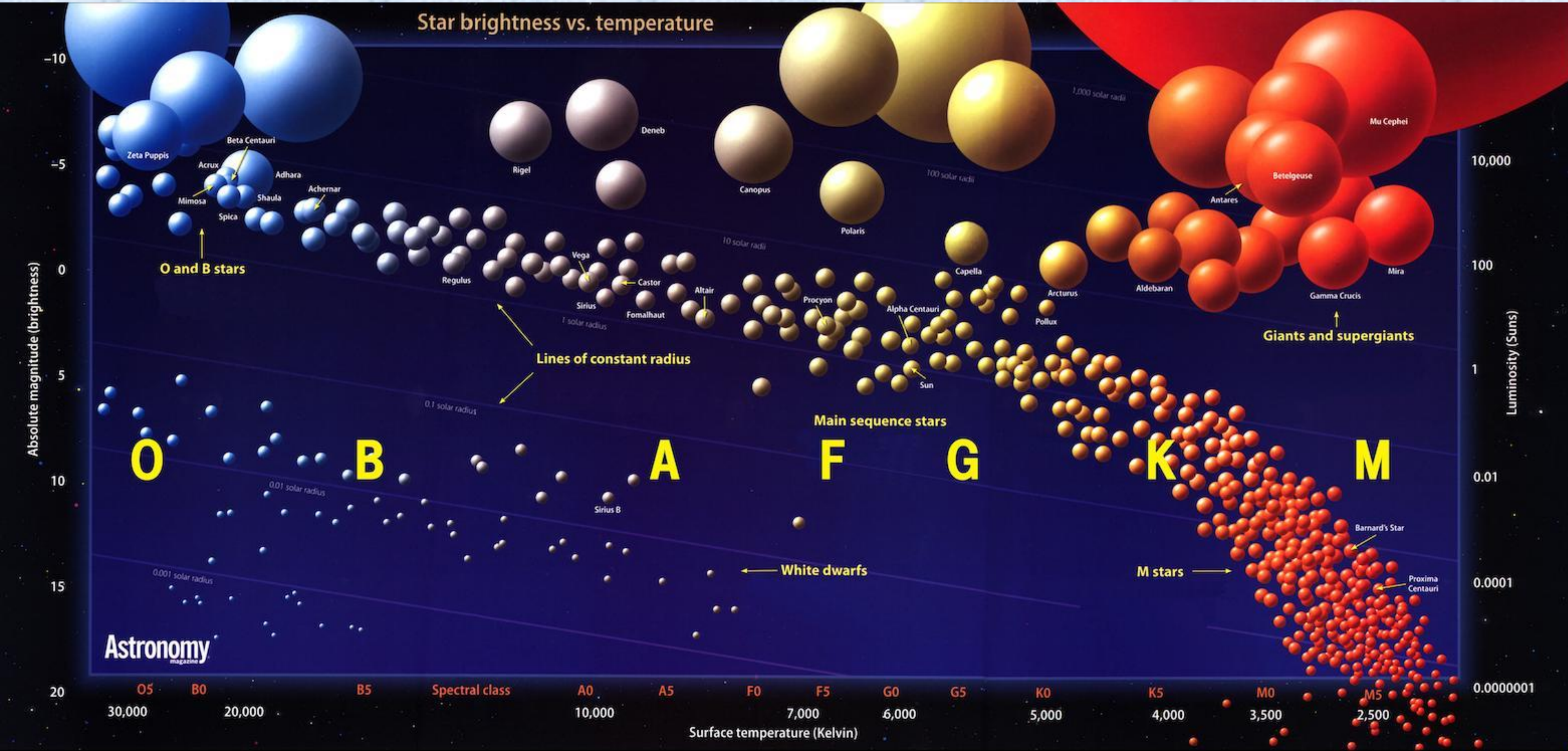
Stellar absorption spectra

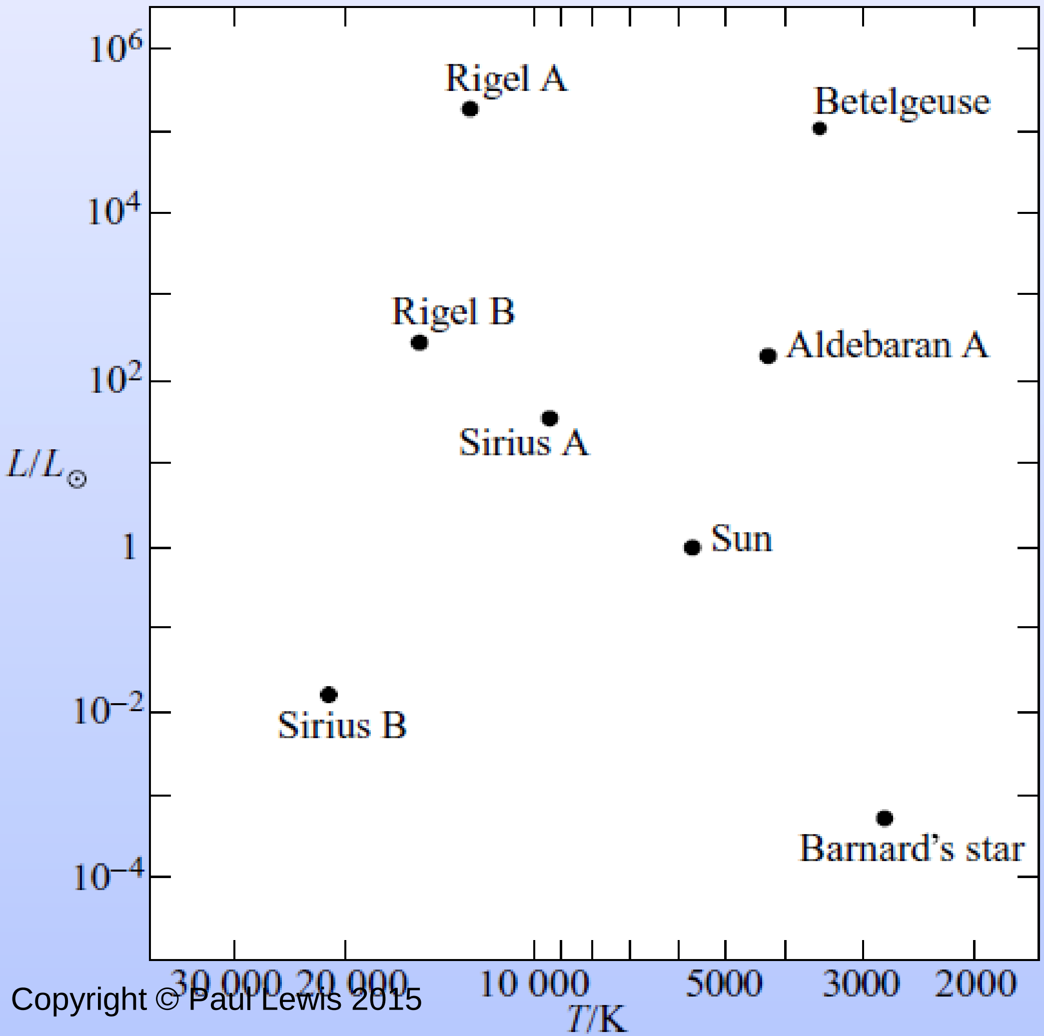
Relative flux density versus wavelength



4. HERTZSPRUNG-RUSSELL DIAGRAM



H-R diagram for the Sun and a few nearby stars



Questions:

- Diagram uniformly filled?
- Some combinations more common?
- Empty regions?
- In general, usually:
  - more small things
  - more faint things
  - more cool things

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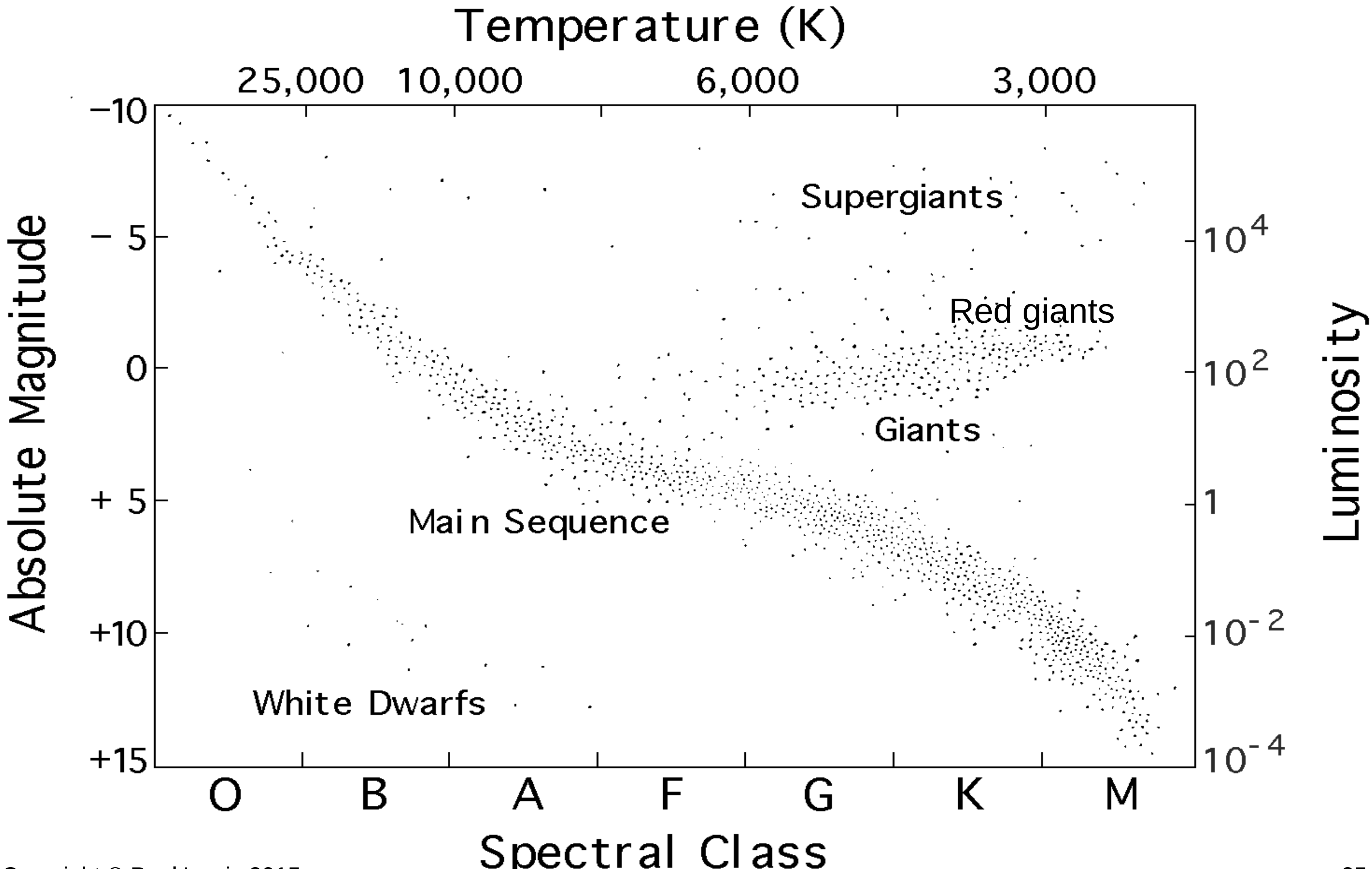
H-R diagram



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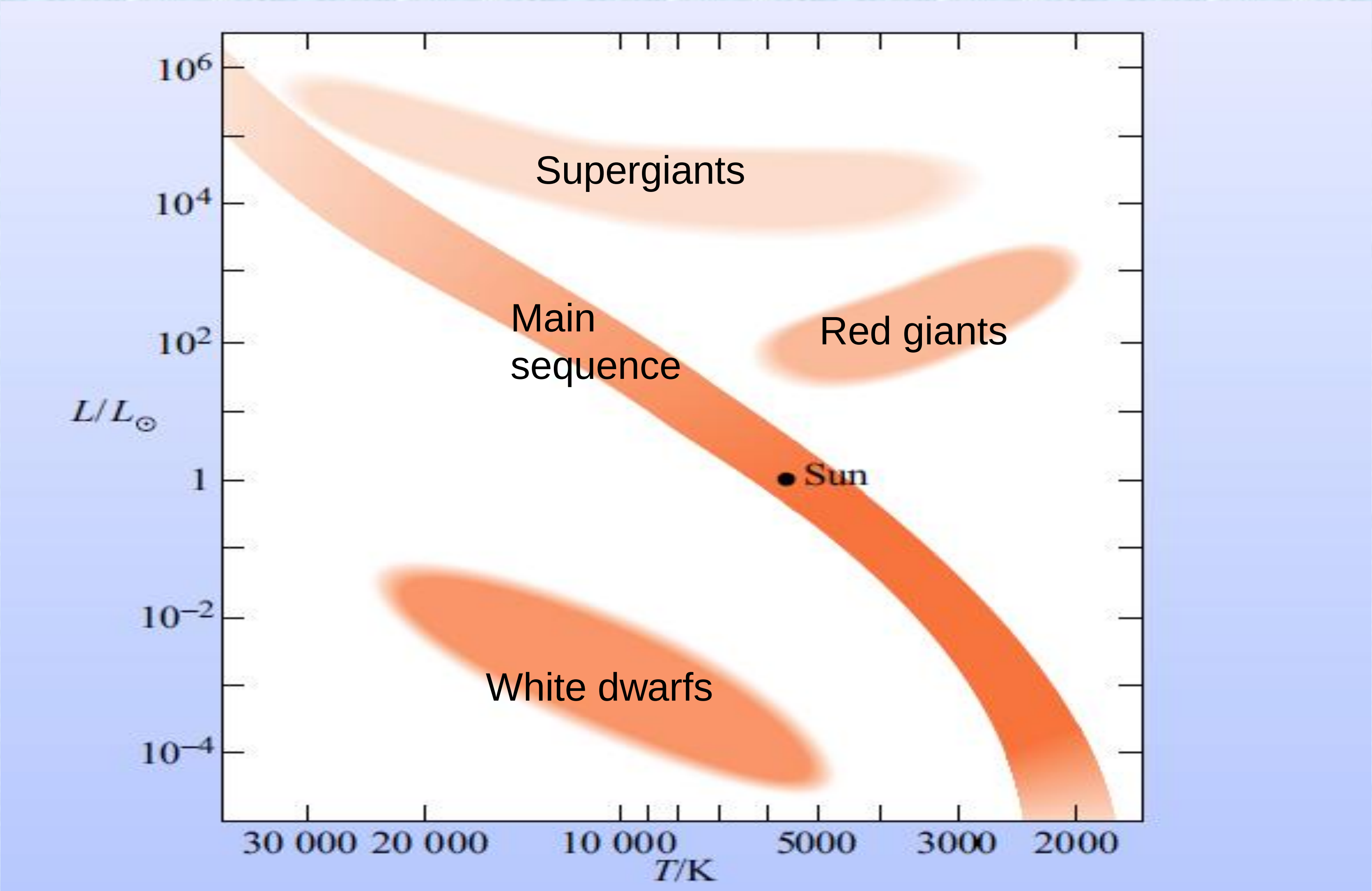
Regions in the H-R diagram



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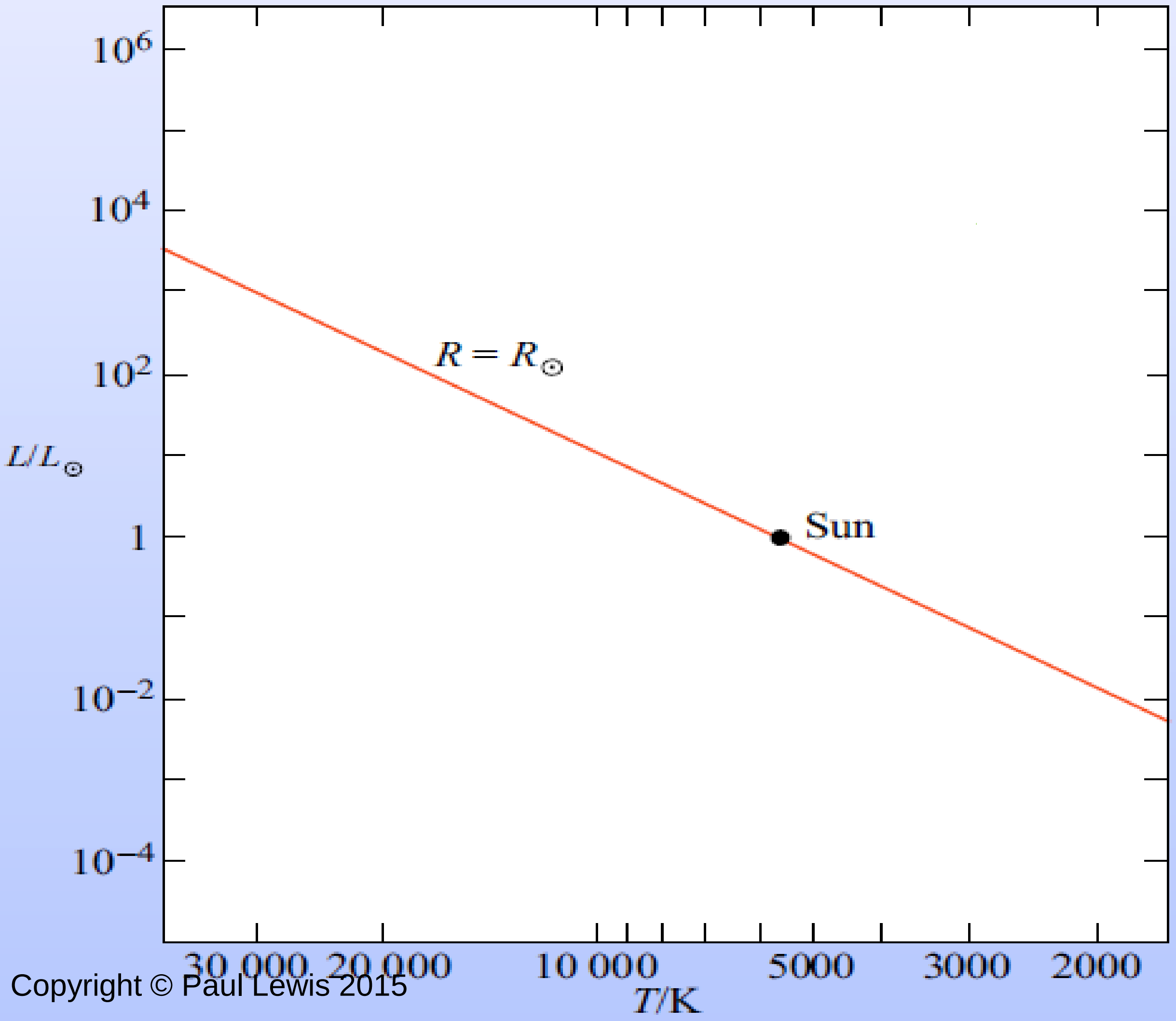
Relationship between radius, temperature and luminosity



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

or

$$R = \sqrt{L / (4\pi\sigma T^4)}$$

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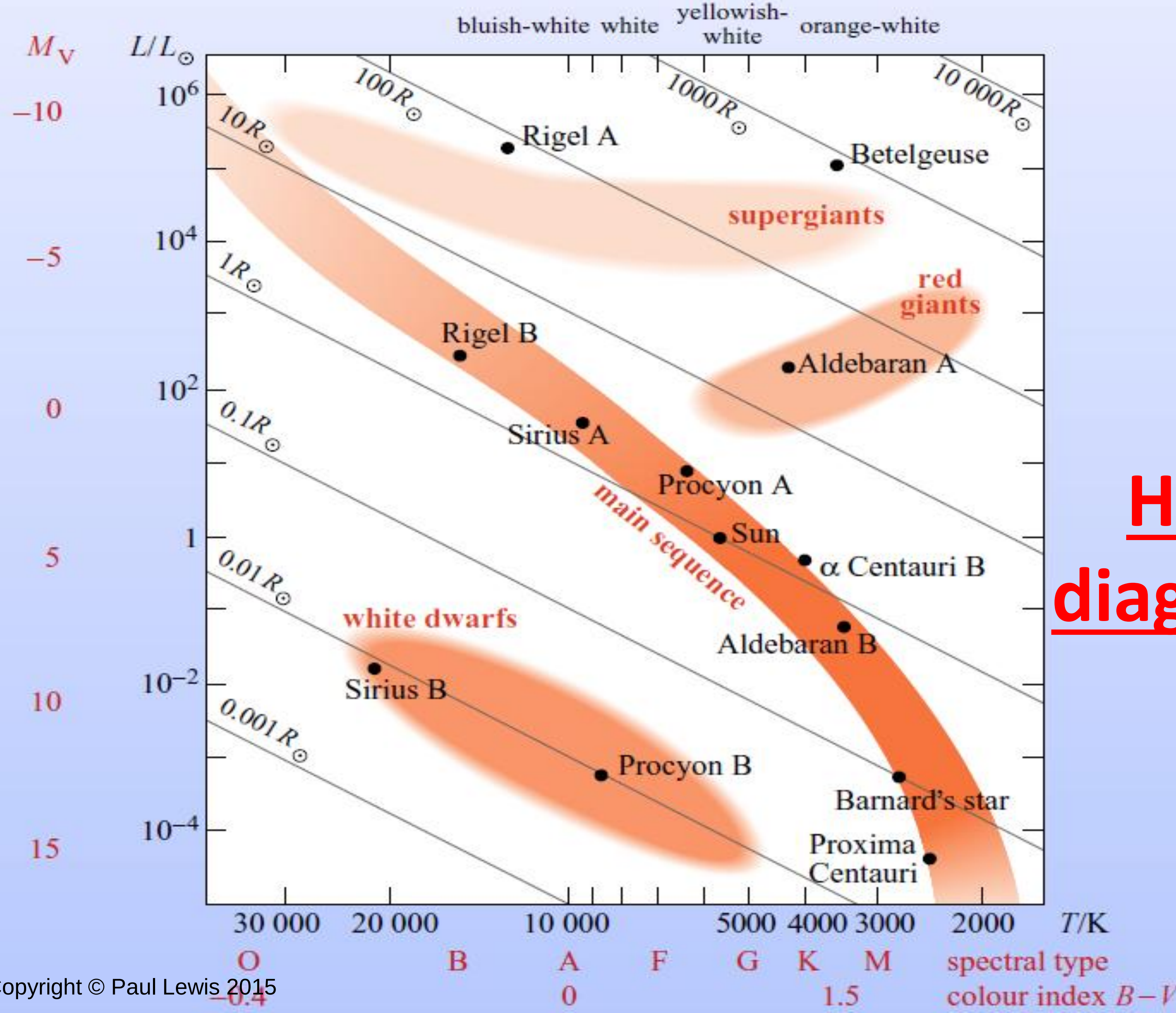
H-R diagram



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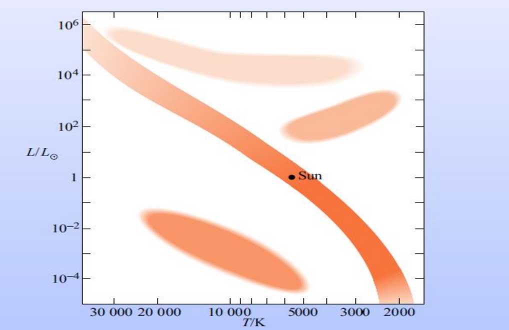

Stable zones of the H-R diagram

Main sequence

- 90% of stars
- Long, thin trail
- Wide range of temps and luminosities
- The Sun is main sequence

Supergiants

- Larger, more luminous than red giants of same temp
- Extend to higher temps

Red giants

- Above main sequence
- Cool, hence orange tinge
- 10-100 times larger than main sequence of same temperature

White dwarfs

- Hot and small
- Low luminosity
- None visible to naked eye

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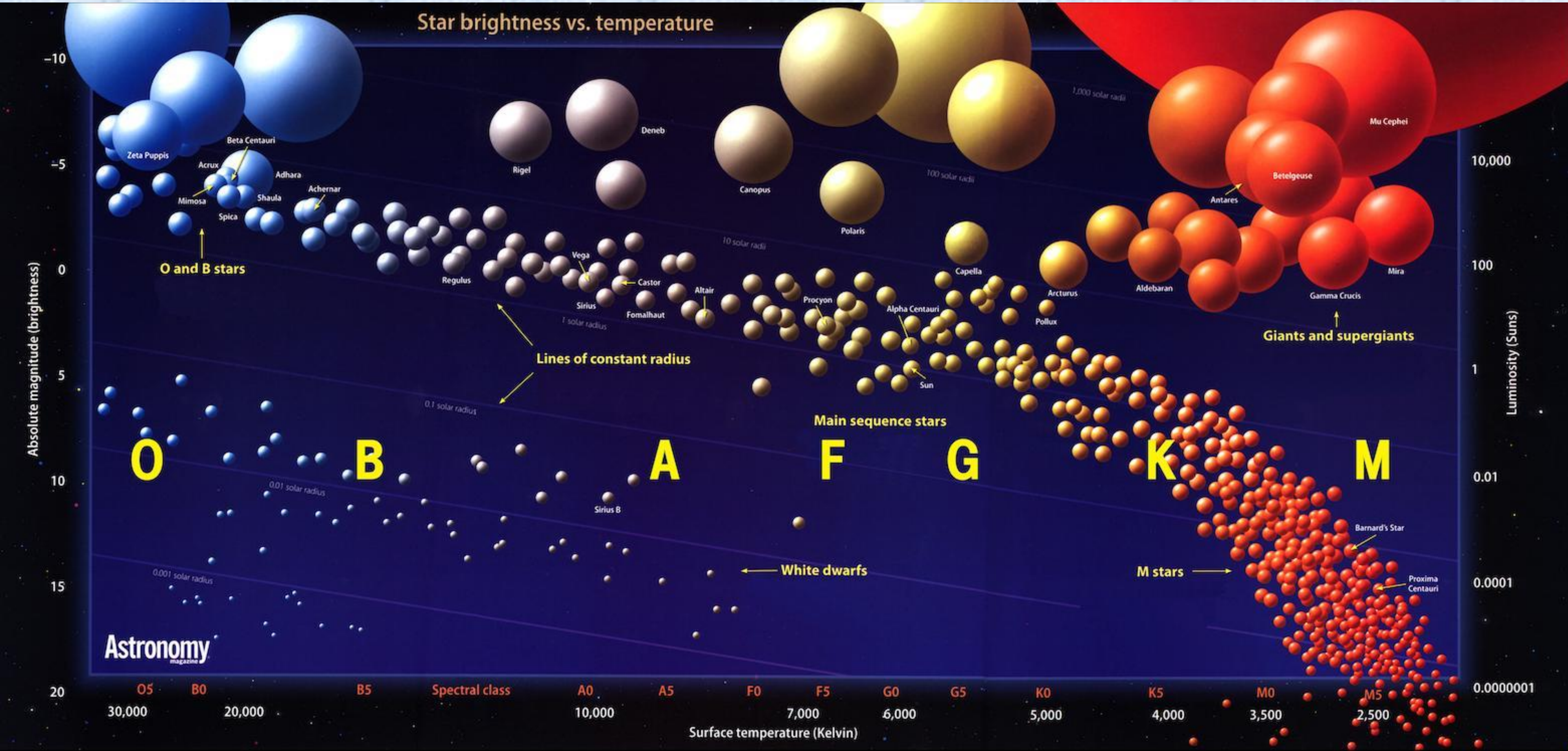
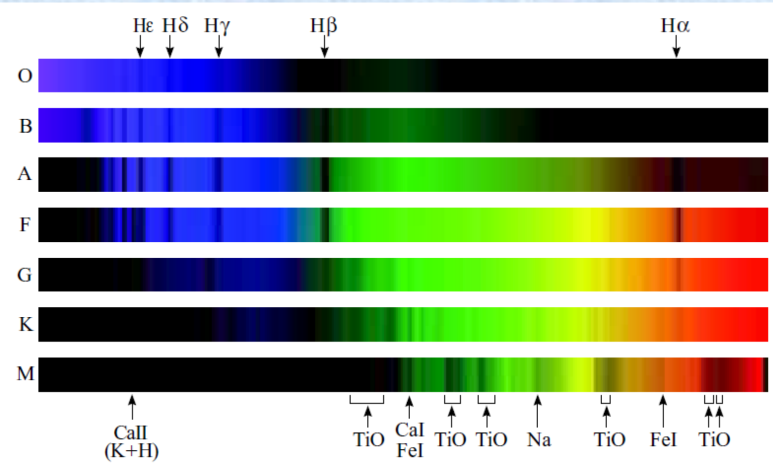
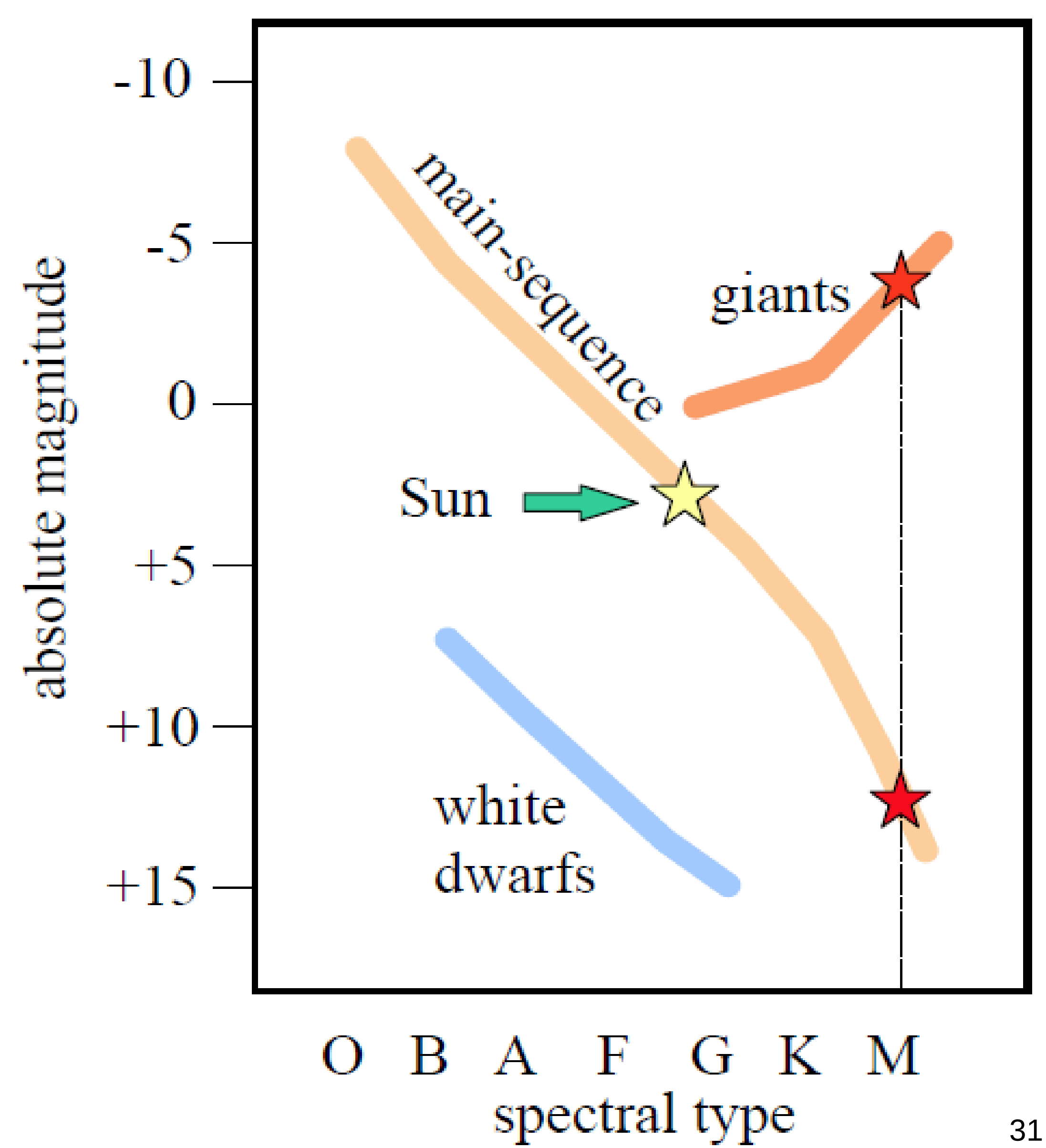
5. SPECTRAL TYPE



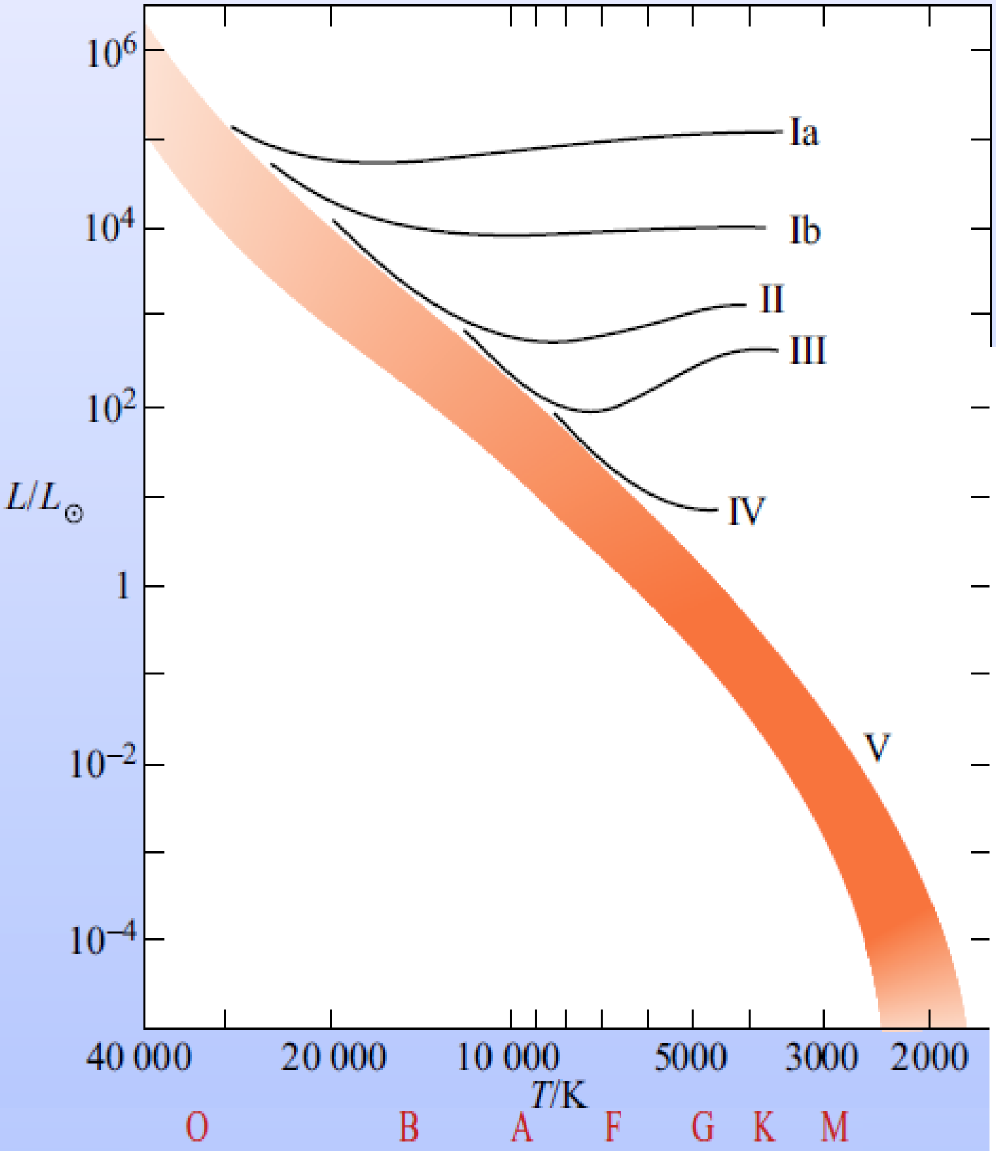
Spectral type

- Spectral type based on temperature
- Spectral type is not unique brightness
- Giant stars – narrower, stronger spectral lines than dwarf stars





Luminosity classes



- Sun: G2 V
- Betelgeuse: M2 Ia

Luminosity Class	Subclass	Description
Ia Ib	bright faint	SUPERGIANT
II III IV	bright normal sub	GIANT
V VI VII	main sequence sub white	DWARF

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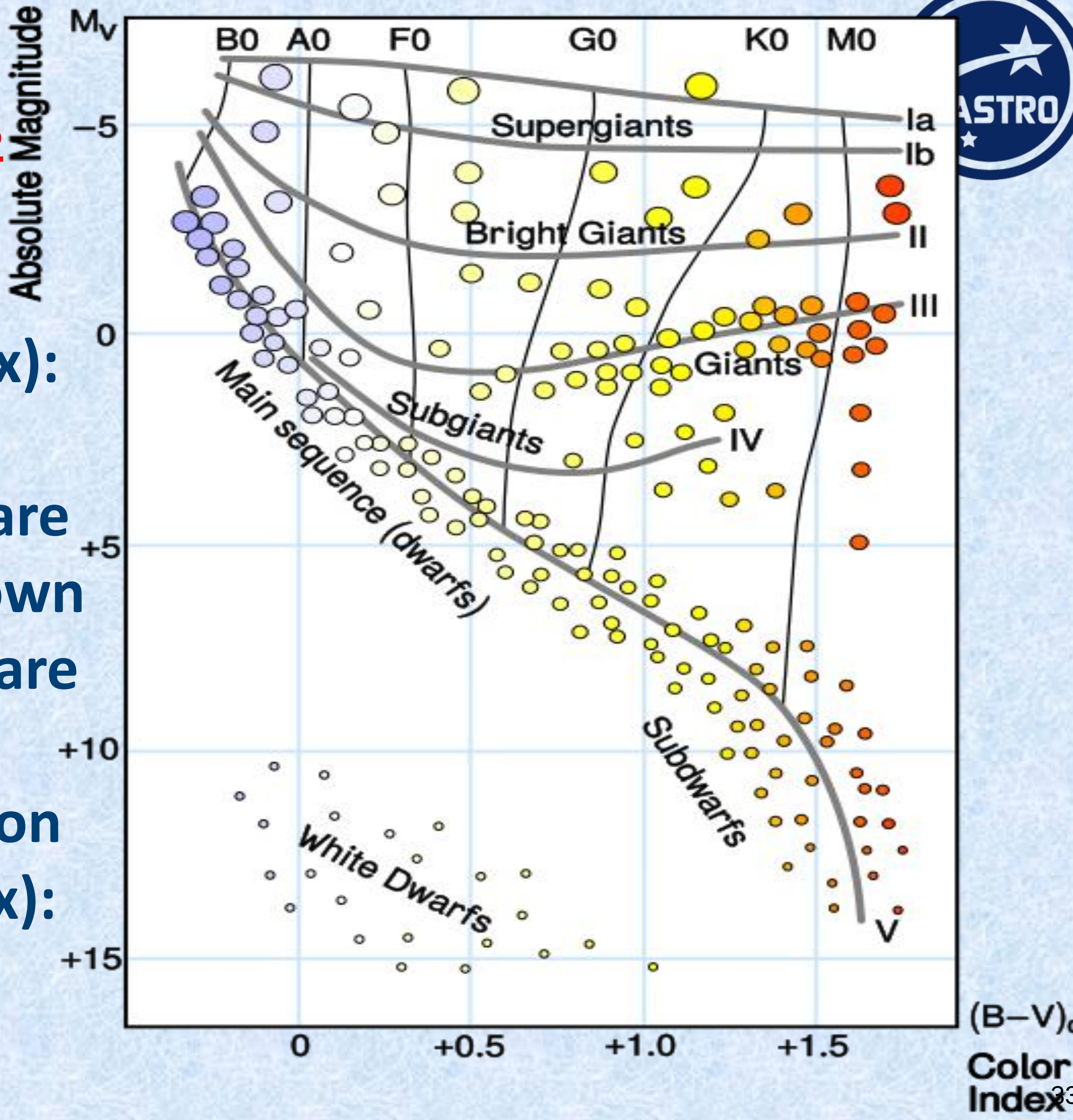
Spectral classifications

- Also use:
- VI or sd (prefix): sub dwarfs
- Sub dwarves are not red or brown dwarves, but are powered by hydrogen fusion
- VII or D (prefix): white dwarfs



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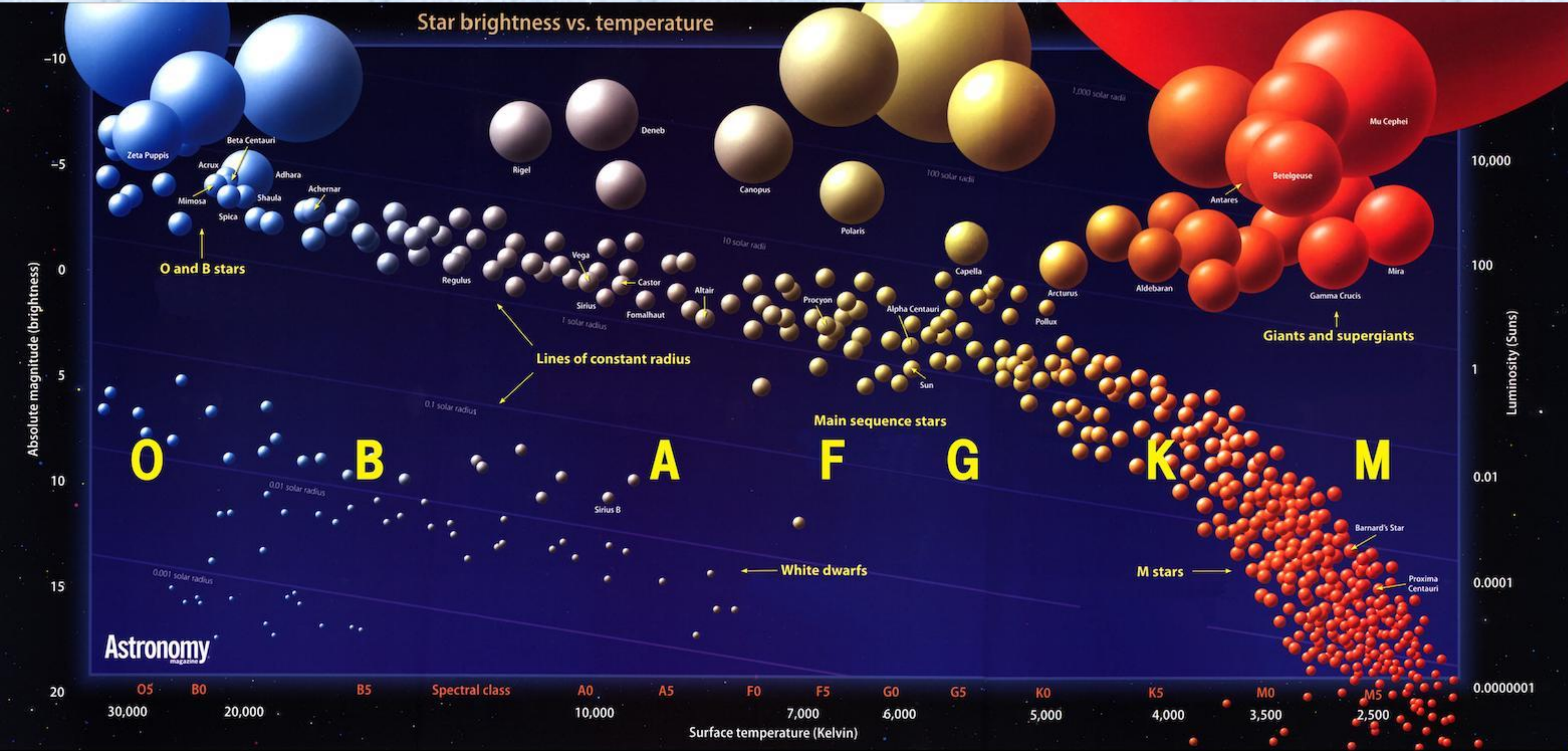
6. UNDERSTANDING THE H-R DIAGRAM



Assumptions of H-R diagram

- Any particular star is luminous for only a finite time
- There are distinct stages between the star's cradle and grave, each stage being characterized by some range of temperature and luminosity
  - The star thus moves around the H-R diagram as it evolves
- The stars we see today are not all at the same stage of stellar evolution.

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Therefore...

- From these reasonable assumptions it follows that if we observe a large population of stars today, then:
  - the longer a particular stage lasts, the greater will be the number of stars that are observed in that stage
  - conversely, we will catch very few stars going through a short-lived stage
- Example: adults and children

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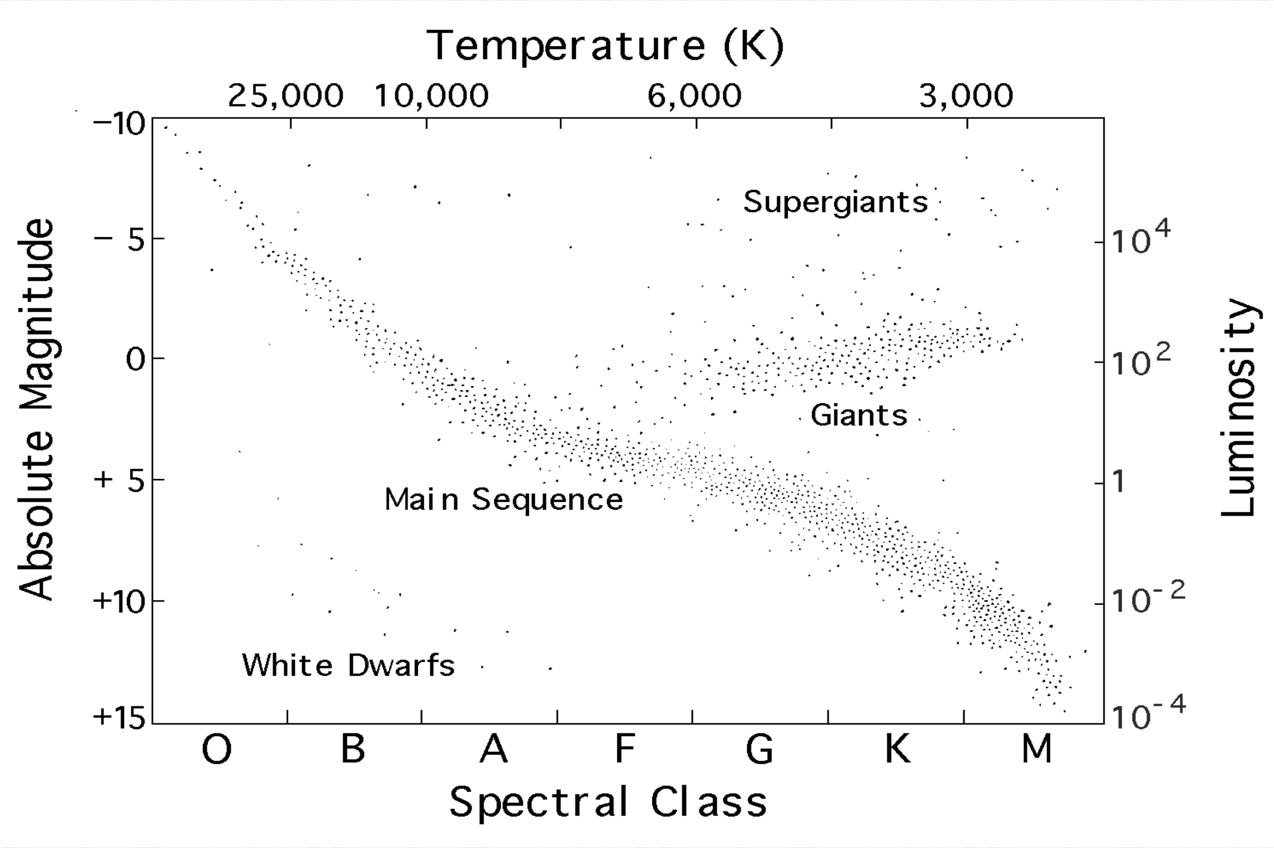
Main sequence

- 90% of stars on main sequence
- Stars are main sequence for most of life
  - Before main sequence?
  - After main sequence?



- Might expect some time as red giant, supergiant or white dwarf?

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Concentrations of stars

- 1. Concentration depends on:
  - How quickly a star passes through a region
  - What fraction of stars pass through region
- 2. Empty regions:
  - Stars not observable directly
    - Particular stage in stellar lifetime
    - Shrouded in dust?

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Observations of stars

- Need more observations of stars
- Our lifetime too short
- History of astronomy too short
- Most changes to stars thousands or millions or billions of years
  - Exceptions:
    - Type II supernovae - supergiants
    - Variable stars

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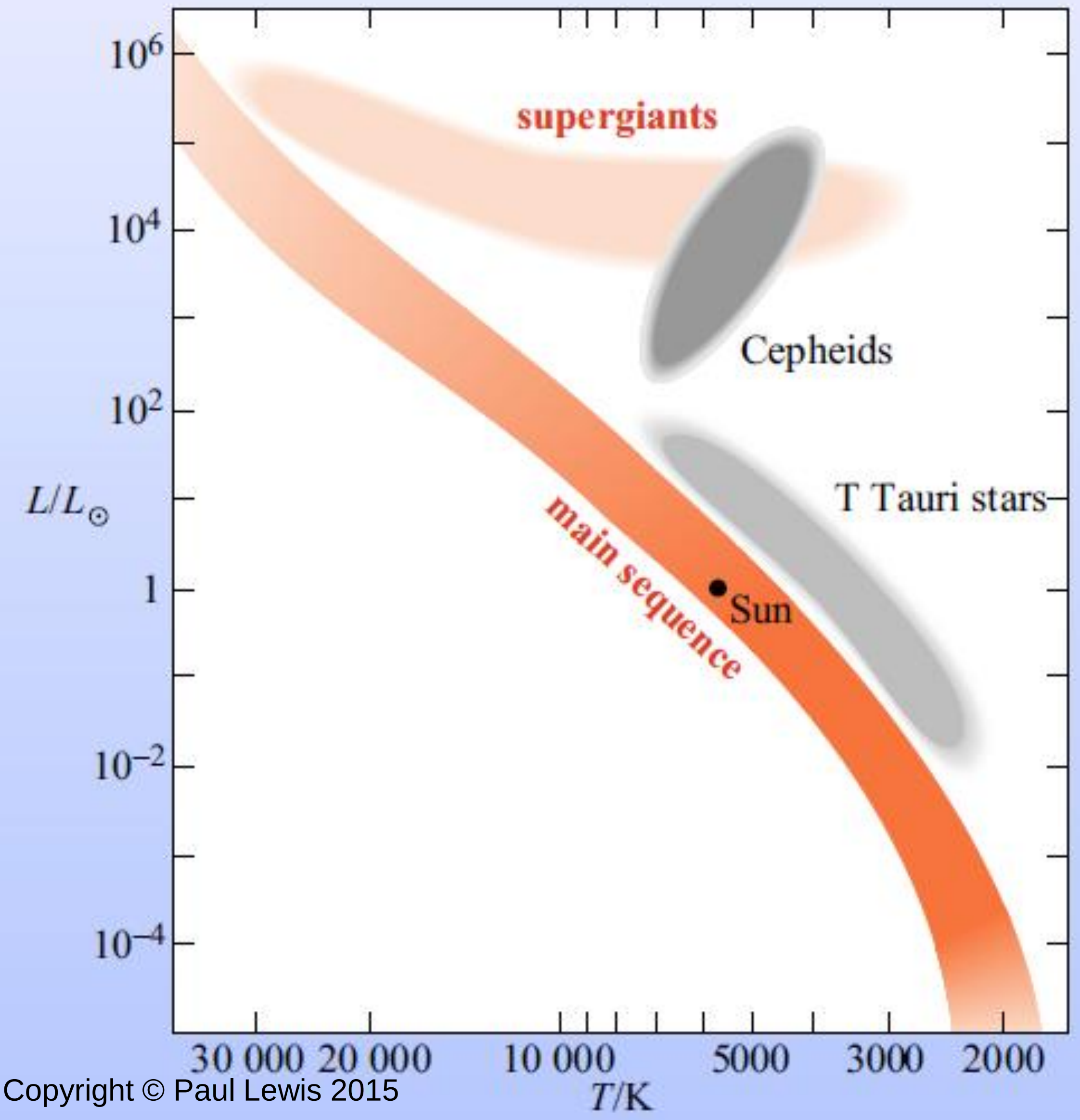
Variable stars



- T Tauri – irregular
- Lie among traces of interstellar material from which stars are thought to form
- Suggests they are young and approaching main sequence
- Cepheids
  - Instability strip
  - RR Lyrae stars

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Stellar mass

- Measured masses: $0.08M_{\odot}$ to about $50M_{\odot}$
- $0.08M_{\odot}$ = 30,000 Earth masses
- The lower the mass the greater the number of stars
- The monsters are rare
- Stars less massive than the Sun are more common than stars of around solar mass

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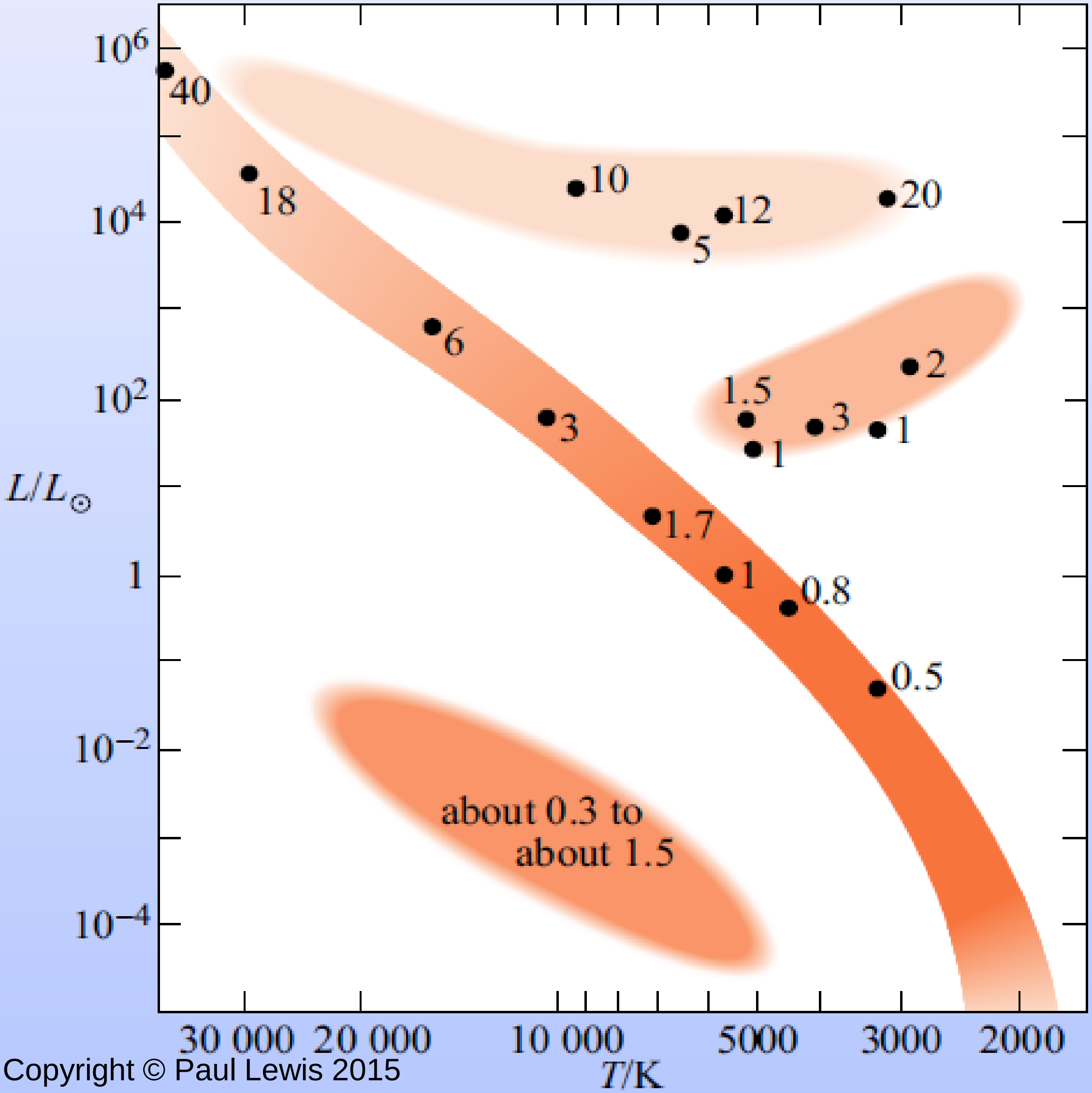
Stellar masses on the H-R diagram



- Masses are multiples of $M_{\odot}$
- Match between supergiants and main sequence, red giants and main sequence
- Main sequence - correlation of mass with luminosity and temperature

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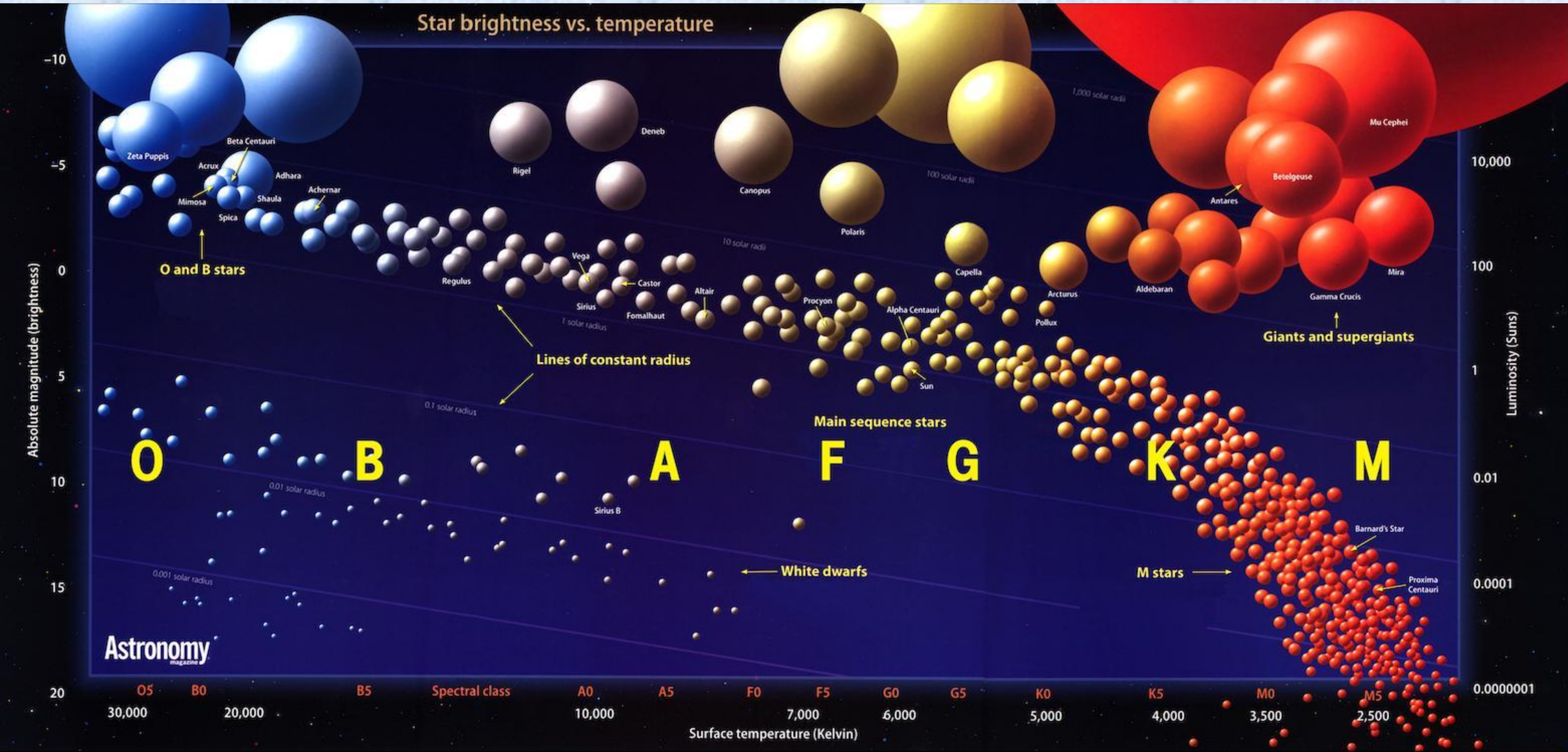
7. STELLAR EVOLUTION



Model of stellar evolution

- Question:
  - Do stars change their mass during their evolution?
- Stellar wind
  - Main sequence, red giants, supergiants
  - Small fraction of initial mass
- Planetary nebula
  - Substantial fraction of the star's mass ejected
  - Remnant star – hotter and brighter than white dwarf
    - Cool to white dwarf?
- Type II supernova - supergiants

Helix Nebula

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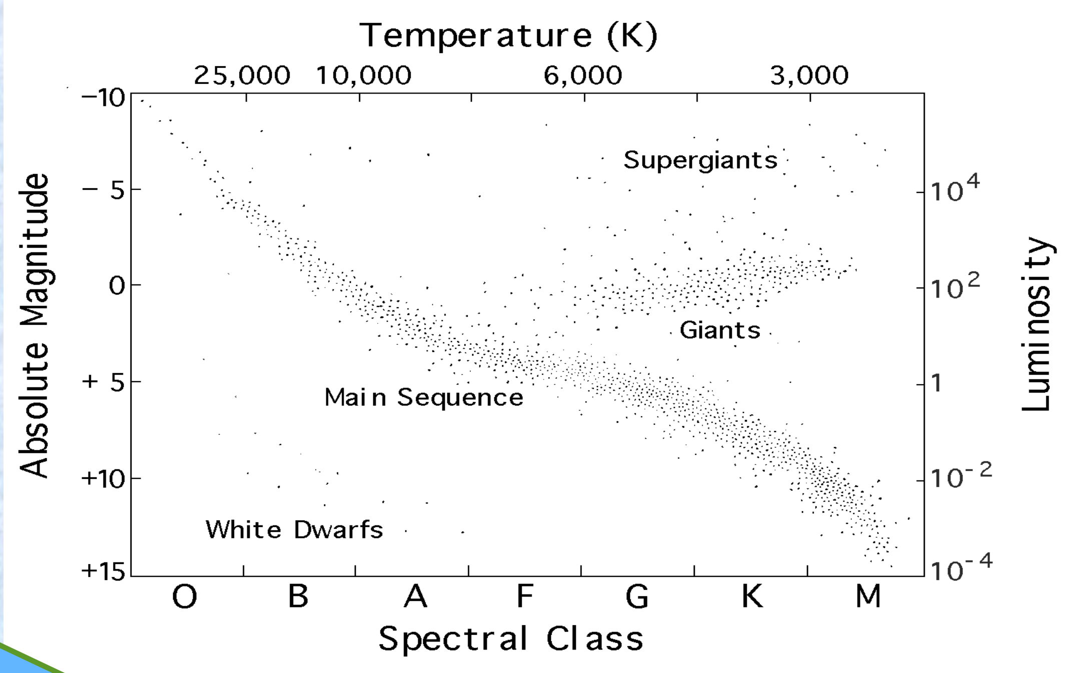
Stellar evolution



Pre-main sequence

Main sequence

Less massive stars: Red giant for short time

Planetary nebula

White dwarf

More massive stars: Supergiant for very short time

Type II supernova

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Rate of evolution

- Do stars of different mass all evolve at about the same rate?
  - Star clusters provide good observational evidence to help answer this question

- **M67**
- **Open cluster**
- **About 3 billion years old**

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Rate of evolution

- How do clusters help?
  - Detailed observations suggest that the stars in them form at about the same time
  - The compositions of the stars are similar
- So what?
  - If the stars in a cluster have different masses, then we can discover the relative rates of evolution of stars that differ only in their mass.

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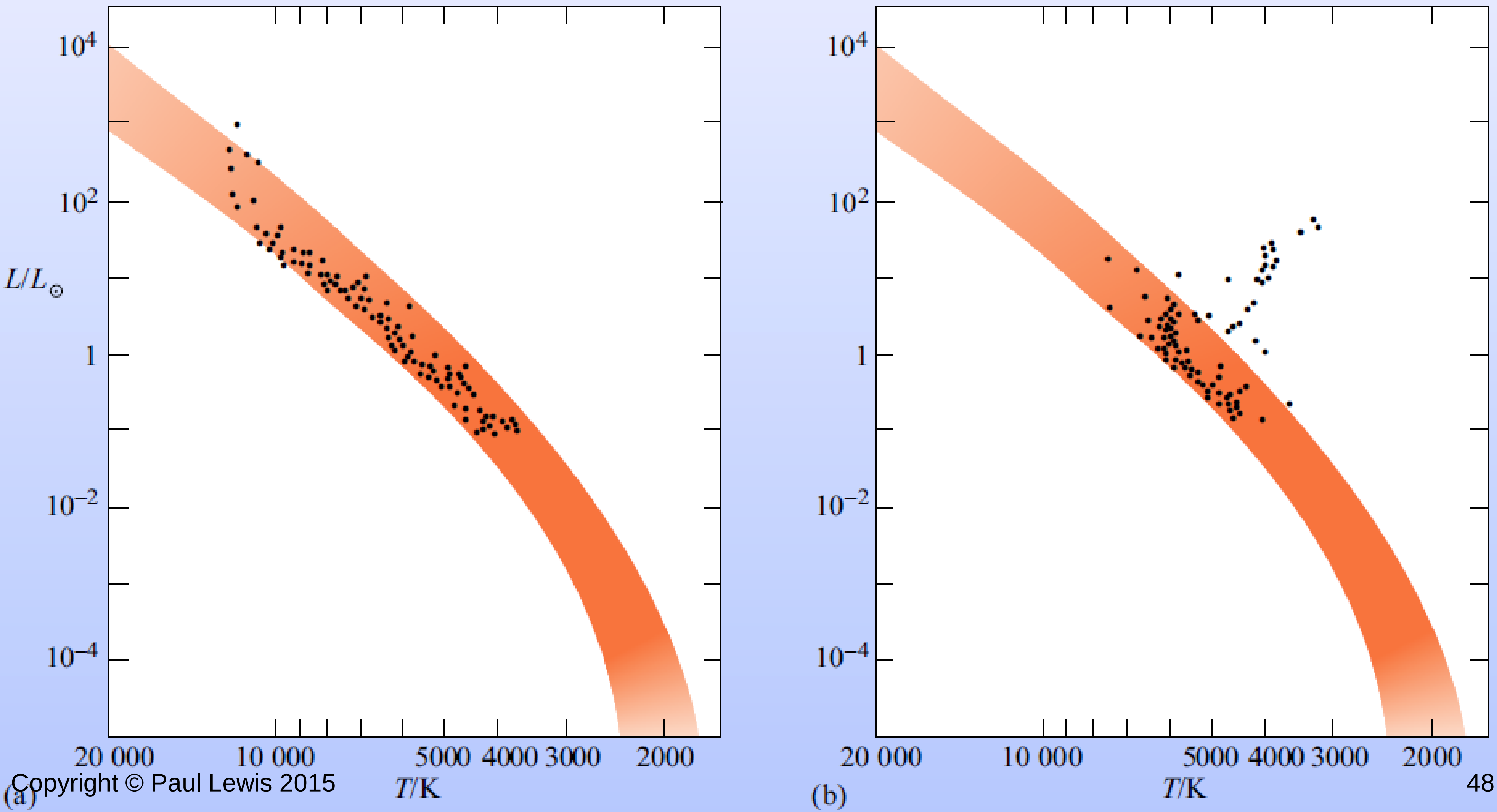
H-R diagrams for two clusters

The Pleiades **M67**



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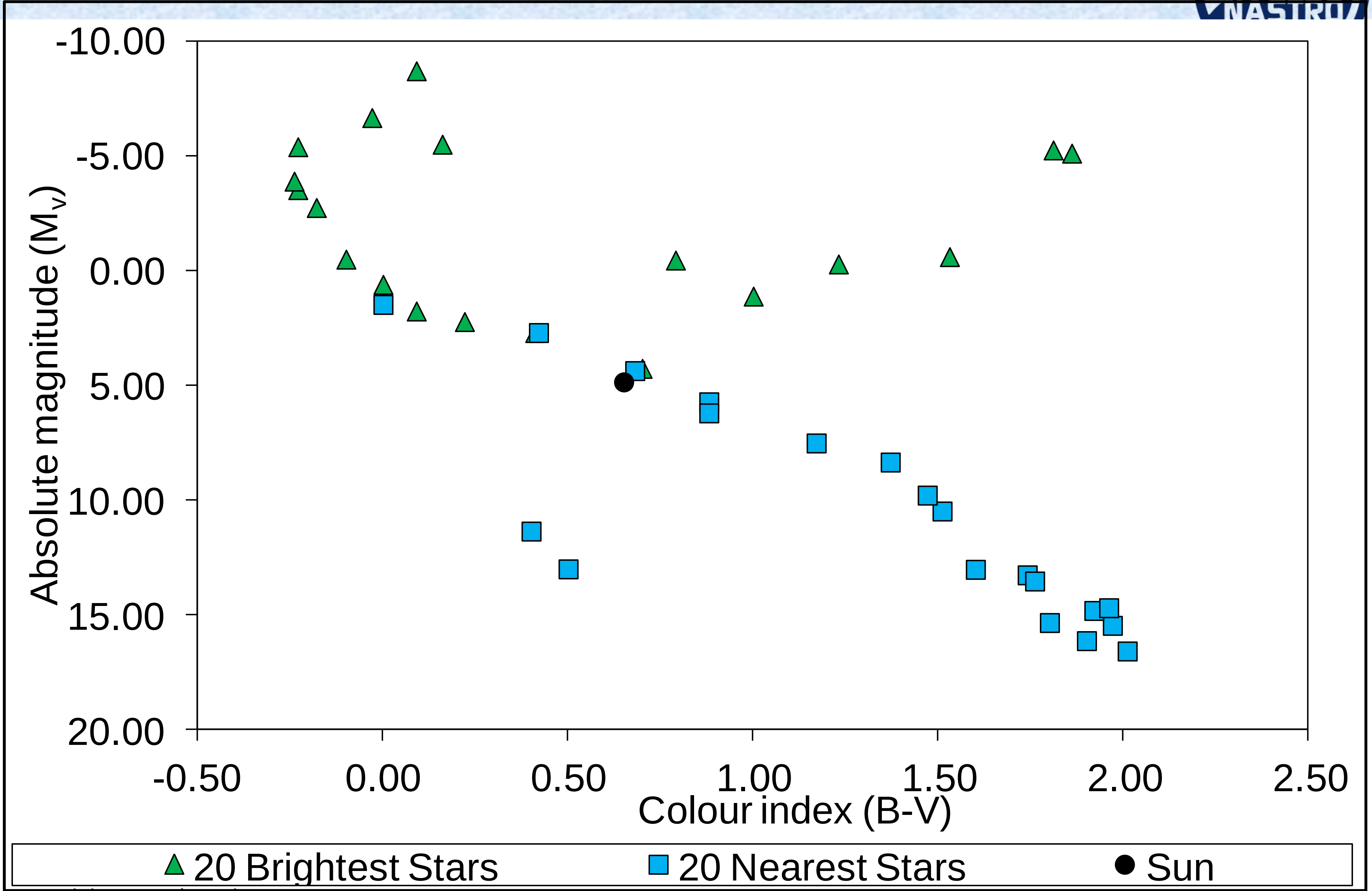
(Brightest based on apparent magnitude)

Nearest and brightest



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Spiral galaxy, M74 (Hubble)

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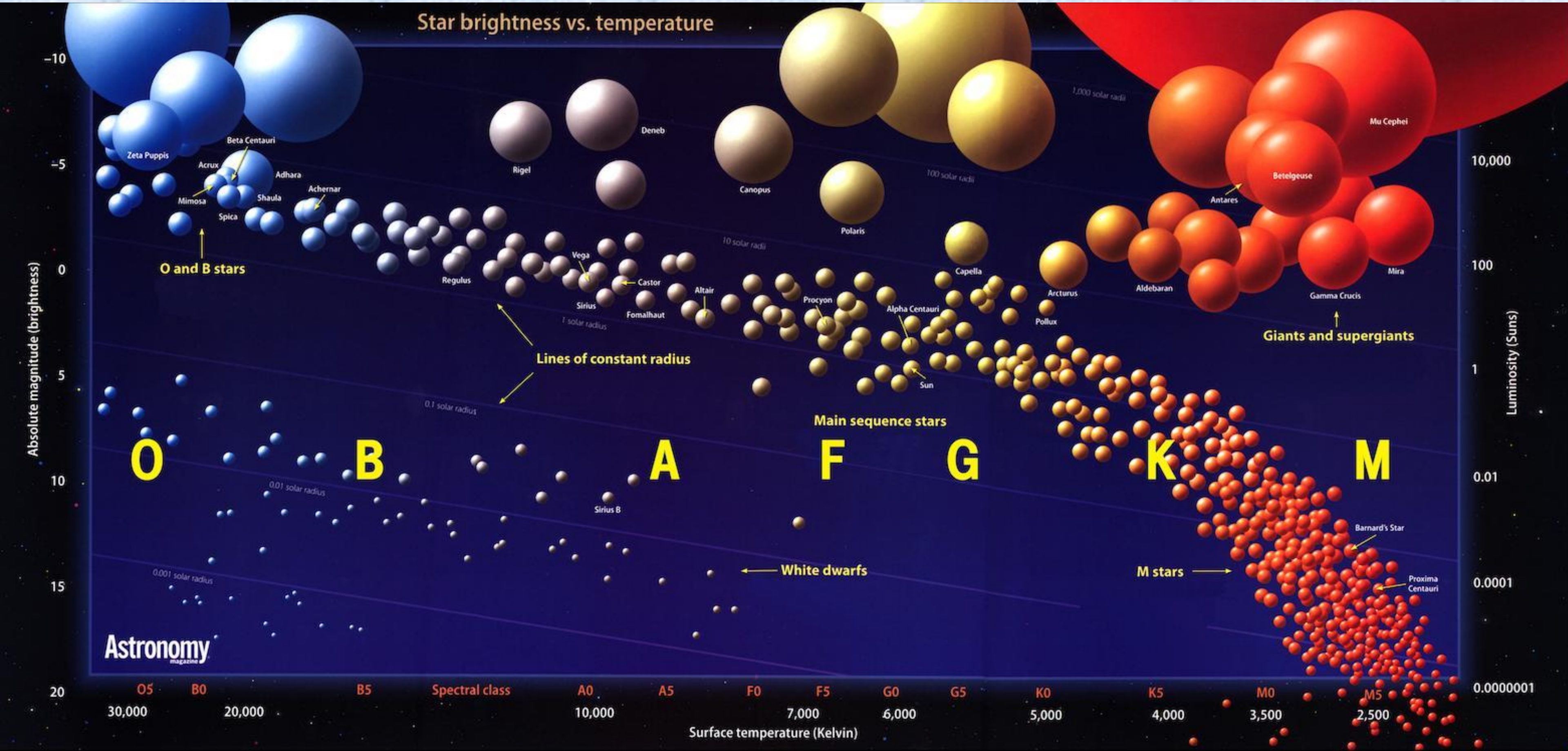
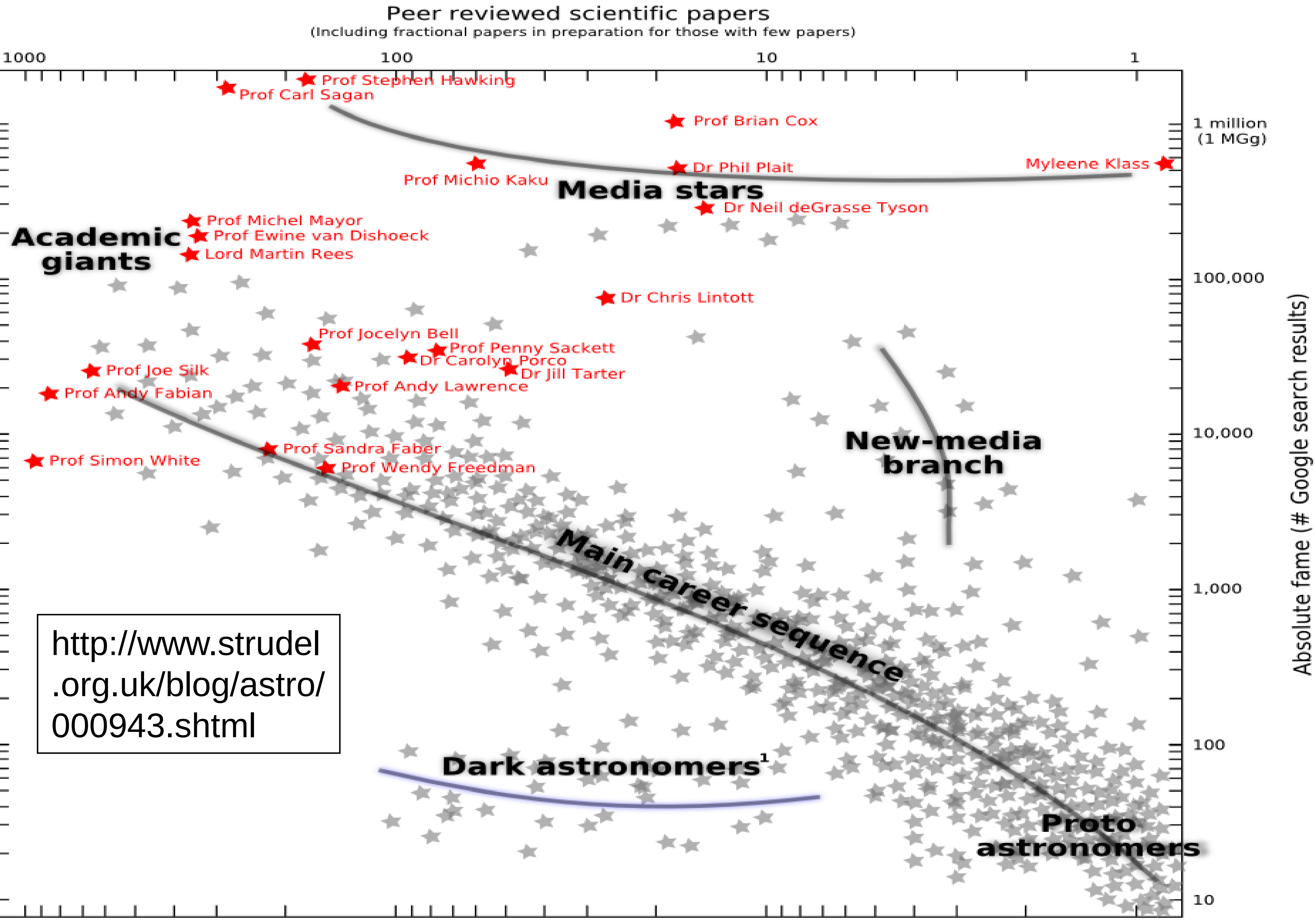
AND FINALLY...



Star brightness vs. temperature
Absolute magnitude (brightness)
-10
-5
0
5
10
15
20
Luminosity (Suns)
10,000
100
1
0.01
0.0001
0.0000001
Zeta Puppis
Beta Centauri
Acrux
Adhara
Mimosa
Shaula
Spica
Achernar
O and B stars
Rigel
Deneb
Regulus
Vega
Castor
Sirius
Fomalhaut
Altair
Canopus
Polaris
Procyon
Alpha Centauri
Sun
Capella
Pollux
Arcturus
Aldebaran
Antares
Betelgeuse
Mu Cephei
Mira
Gamma Crucis
Giants and supergiants
Lines of constant radius
Main sequence stars
1,000 solar radii
100 solar radii
10 solar radii
1 solar radius
0.1 solar radius
0.01 solar radius
0.001 solar radius
O
B
A
F
G
K
M
Sirius B
White dwarfs
M stars
Barnard's Star
Proxima Centauri
Astronomy magazine
O5
B0
B5
Spectral class
A0
A5
F0
F5
G0
G5
K0
K5
M0
M5
30,000
20,000
10,000
7,000
6,000
5,000
4,000
3,500
2,500
Surface temperature (Kelvin)

The H-R diagram of Astronomers*



http://www.strudel.org.uk/blog/astro/000943.shtml

* Includes associated others. Apologies to Hertzsprung and Russell. ¹ Productive but generally invisible.
NOTE: As in astronomy, the numbers are correct to a factor of a few. Most of the grey points are purely representative.
P.S. This was made in 2010 as a joke: http://www.strudel.org.uk/blog/astro/000943.shtml. See http://tinyurl.com/astroHR for a follow-up AAS poster based on real data

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