MARTIN SCHWARZSCHILD (1958)

If simple perfect laws uniquely rule the Universe, should not pure thought be capable of uncovering this perfect set of laws without having to lean on the crutches of tediously assembled observations? True, the laws to be discovered may be perfect, but the human brain is not. Left on its own, it is prone to stray, as many past examples sadly prove. In fact, we have missed few chances to err until new data freshly gleaned from nature set us right again for the next steps. Thus pillars rather than crutches are the observations on which we base our theories; and for the theory of stellar evolution these pillars must be there before we can get far on the right track.

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STARS

WHAT IS A STAR?

- Is bound by self-gravity
- Radiates energy supplied by an internal source

It follows that stars must evolve

NOT A STAR:

- Wandering stars (planets)
- Guest stars (comets)

DEATH OF A STAR

From the definition, two scenarios are possible:

- Violation of first condition (no longer bound by self gravity)
- Violation of second condition (no more internal energy)

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OBSERVATIONS

OBSERVATIONS

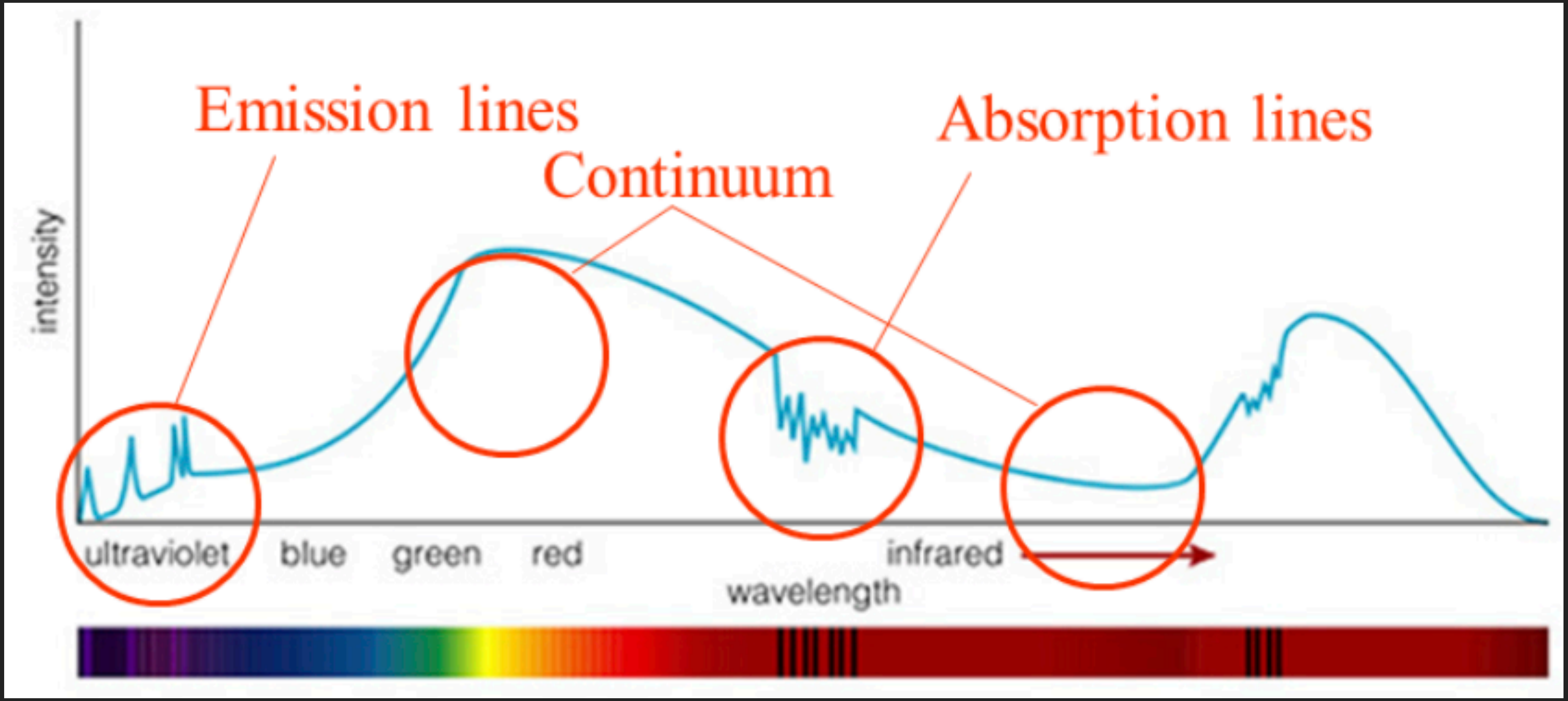
Information we can gather is quite restricted!

- Apparent brightness
- Related to the intrinsic luminosity

$$I_{\rm obs} = \frac{L}{4\pi d^2}$$

- Hard to measure distance d
- Parallax

SPECTRA

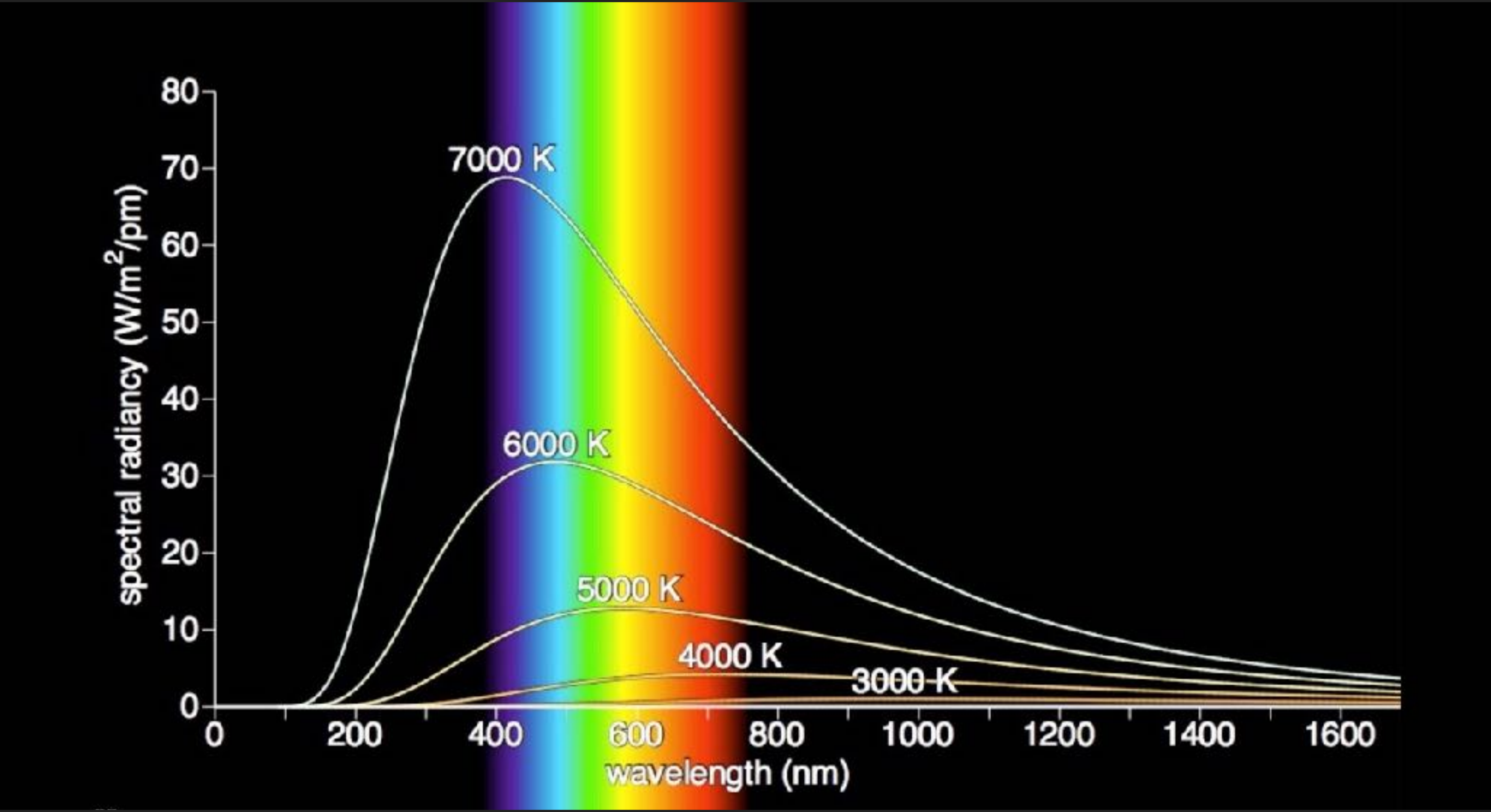

Emission lines
Continuum
Absorption lines
intensity
ultraviolet
blue
green
red
infrared
wavelength

SPECTRUM

From the spectral lines we can obtain

- Chemical composition
- Helium first suggested by spectral lines in the Sun (1860)

BLACK BODY SPECTRUM



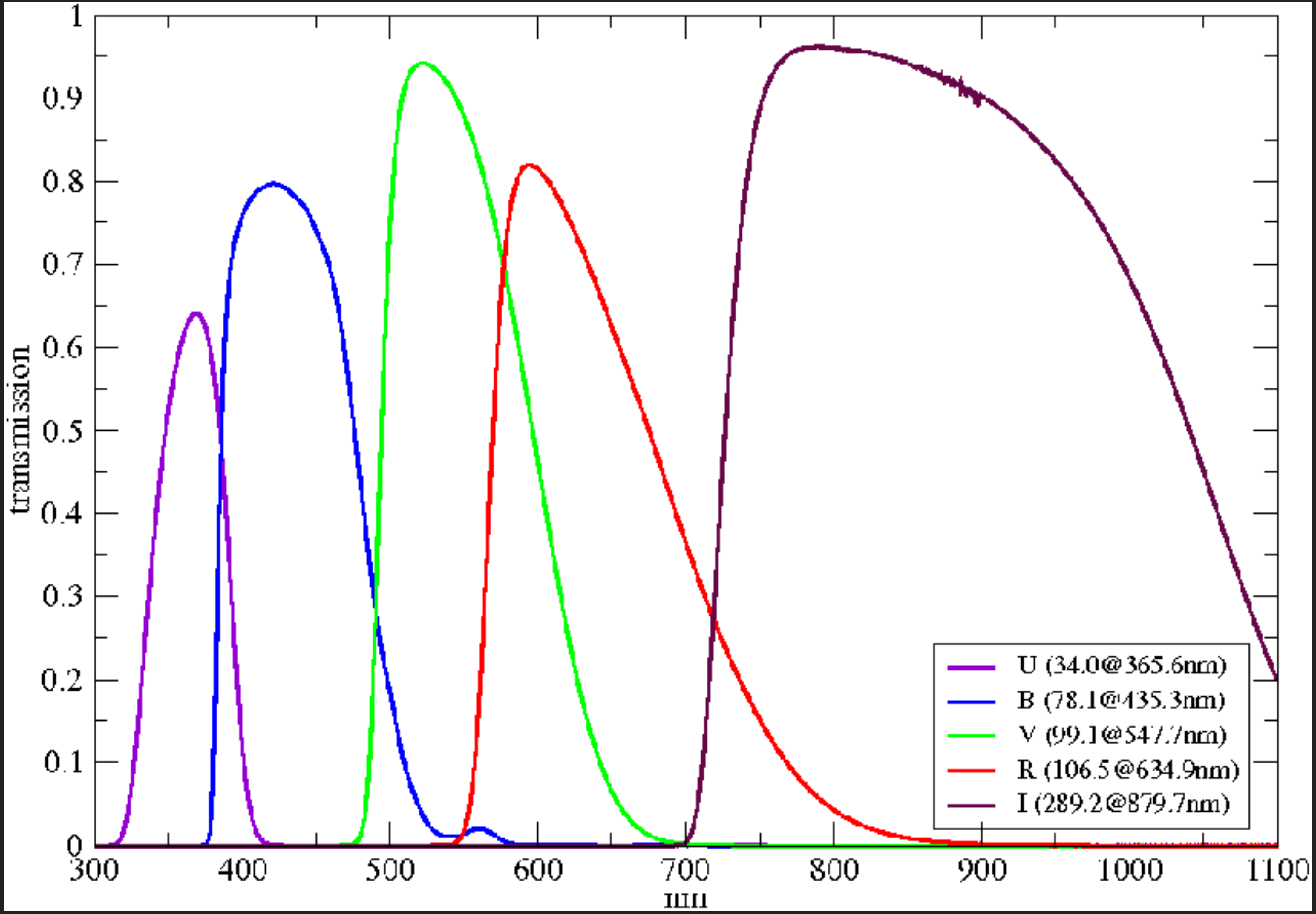
OBSERVATIONS

- How to measure temperature?
- Take full spectrum or at least two fluxes

$$B - V = -2.5 \log_{10} \left(\frac{F_B}{F_V} \right)$$

- This gives a fair measure for stellar temperatures
- Can range from ~1000K to ~100 000K
- Sun 5780K
- Can estimate total luminosity $L = 4\pi R^2 \sigma T_{\mathrm{eff}}^4$

FILTERS


transmission
nm
U (34.0@365.6nm)
B (78.1@435.3nm)
V (99.1@547.7nm)
R (106.5@634.9nm)
I (289.2@879.7nm)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
300
400
500
600
700
800
900
1000
1100

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STELLAR EVOLUTION

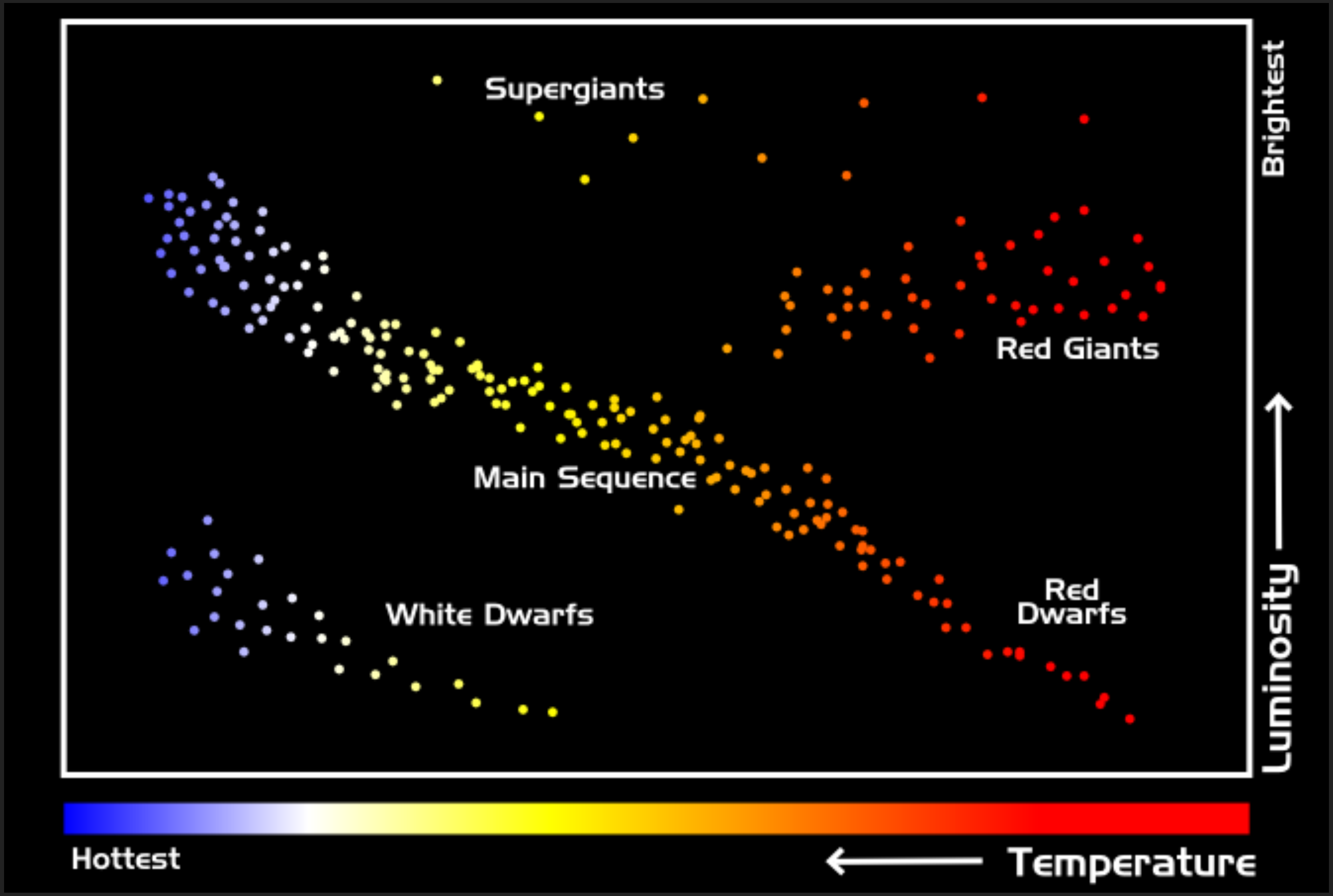
ASSUMPTIONS

For the theory of stellar structure and evolution

- Isolation
- Uniform initial composition
- Spherical symmetry

HERTZSPRUNG-RUSSELL DIAGRAM

Look for correlation in the two fundamental observable quantities:



HERTZSPRUNG-RUSSELL DIAGRAM

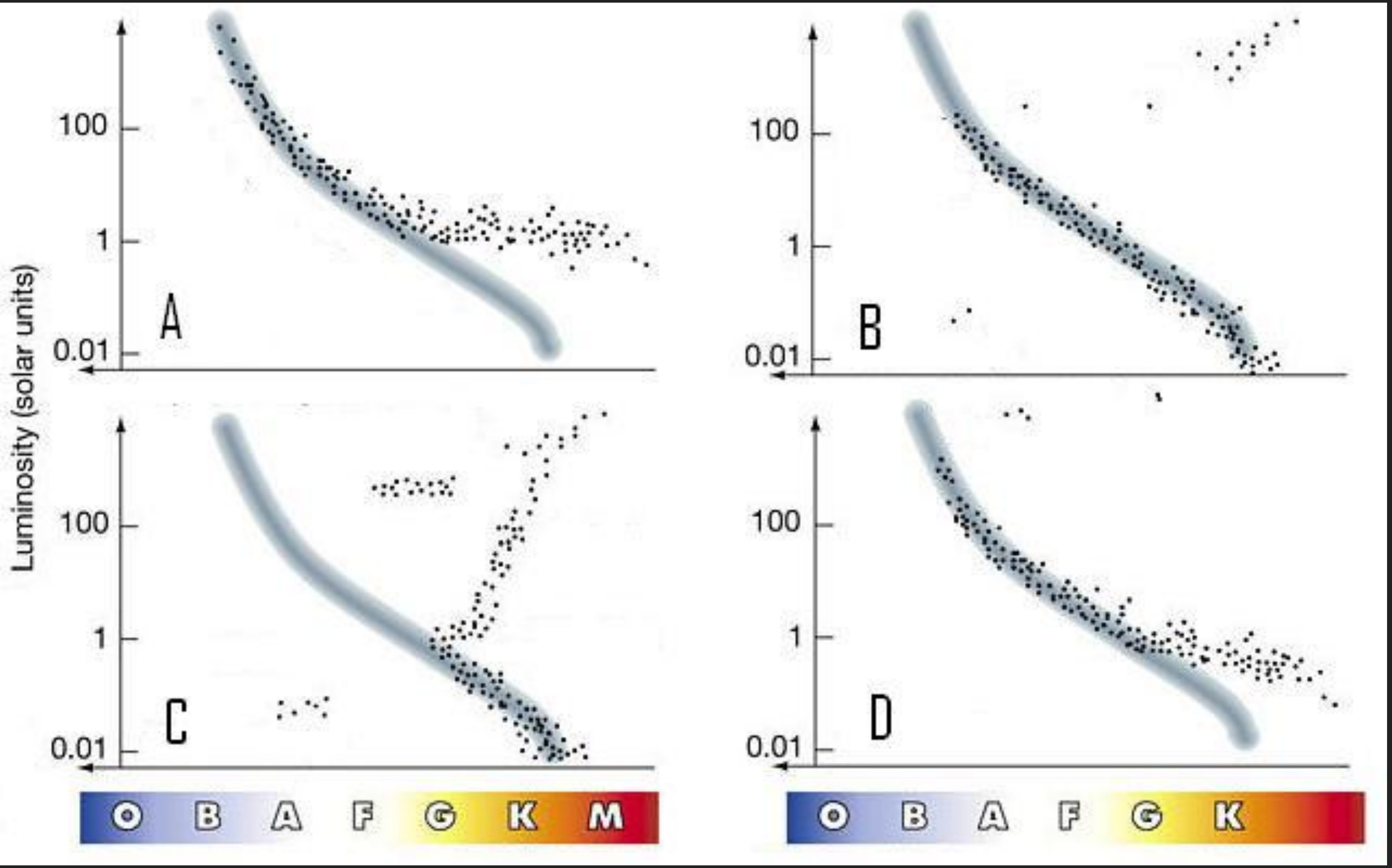
Can explain scatter in two ways:

- Different age
- Different mass

We only see a snapshot of stars with different masses and ages. How to solve this dilemma?

HERTZSPRUNG-RUSSELL DIAGRAM

Find a population with the same age!



HERTZSPRUNG-RUSSELL DIAGRAM

Conclusions one can draw

- Location on main sequence is determined by initial mass
- Being on or off main sequence determined by age

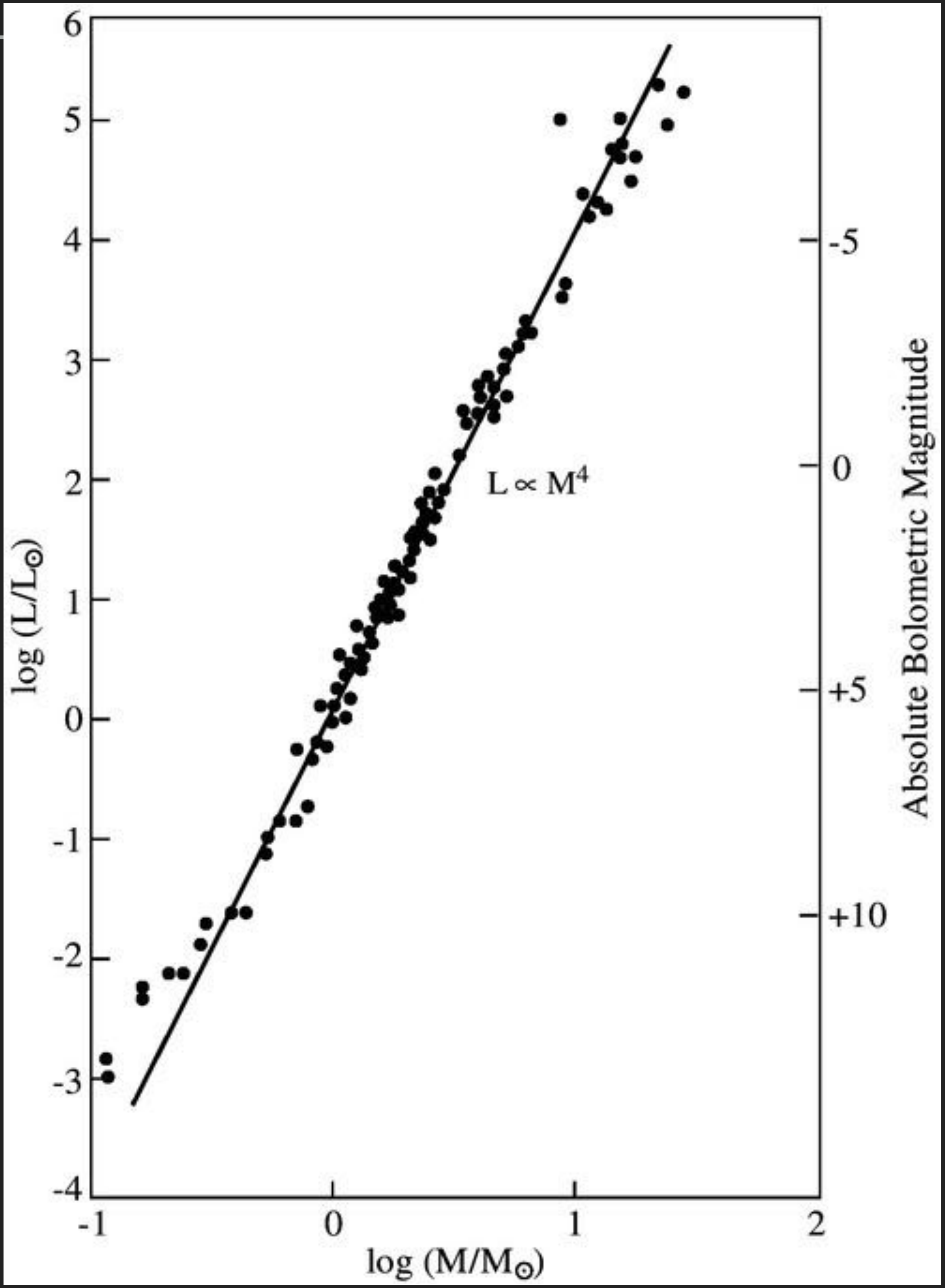
However:

- Still unable to determine evolutionary track unless we know cluster ages
- Observations alone are unable to answer this
- Need theoretical models

TEST OF FIRST CONCLUSION

(Location on main sequence is determined by initial mass)

- Measure mass-radius relation for main sequence stars



TIMESCALES FOR STELLAR EVOLUTION

- Dynamical timescale

$$\tau_{\rm dyn} \approx \frac{1}{G\bar{\rho}} \approx 1000\sqrt{\left(\frac{R}{R_\odot}\right)\left(\frac{M_\odot}{M}\right)}\,{\rm s}$$

- Thermal timescale

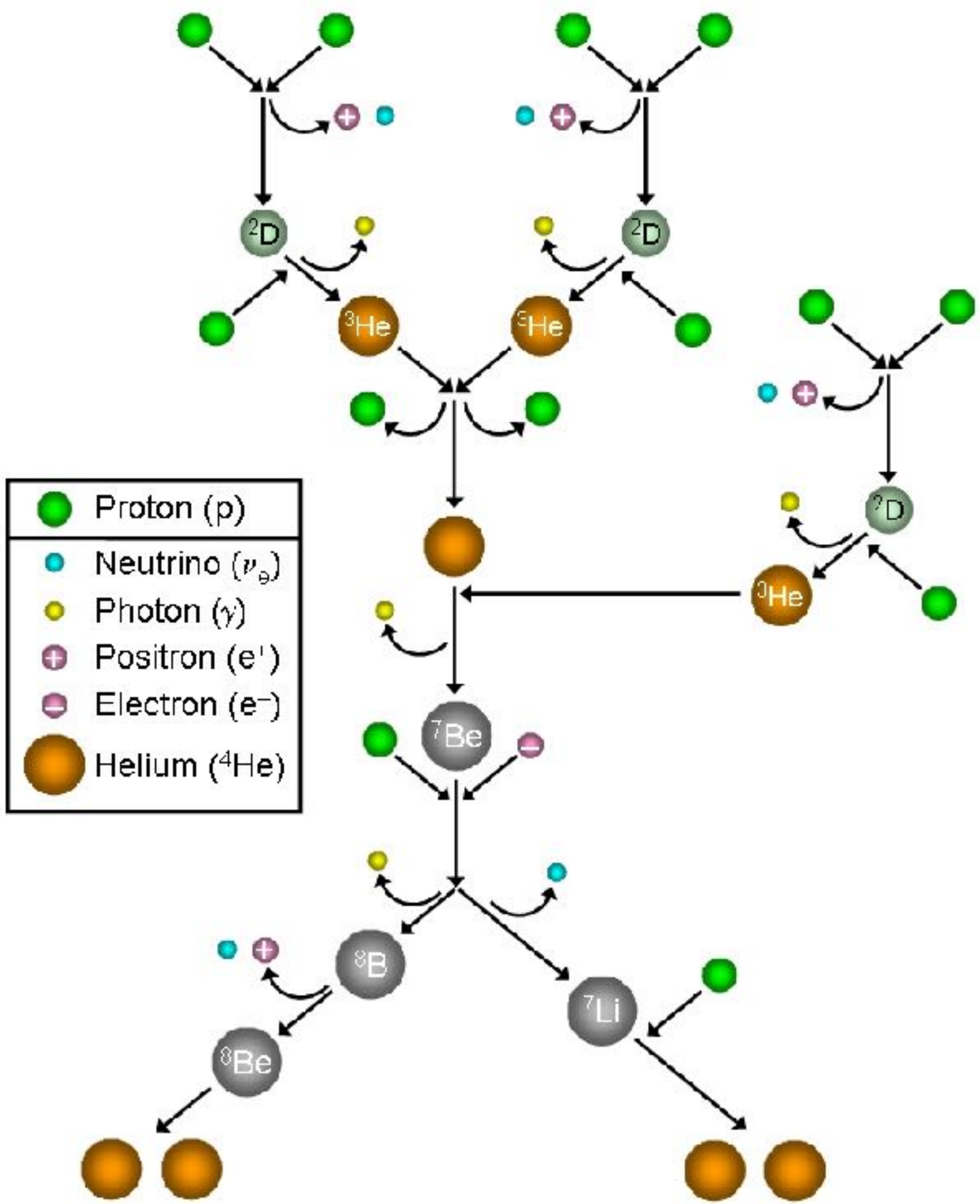
$$\tau_{\rm th} \approx \frac{GM^2}{RL} \approx 10^{15}\left(\frac{M}{M_\odot}\right)^2\left(\frac{R_\odot}{R}\right)\left(\frac{L_\odot}{L}\right){\rm s}$$

- Nuclear timescale

$$\tau_{\rm nuc} \approx \frac{\epsilon M c^2}{L} \approx \epsilon 4.5\cdot 10^{20}\left(\frac{M}{M_\odot}\right)\left(\frac{L_\odot}{L}\right){\rm s}$$

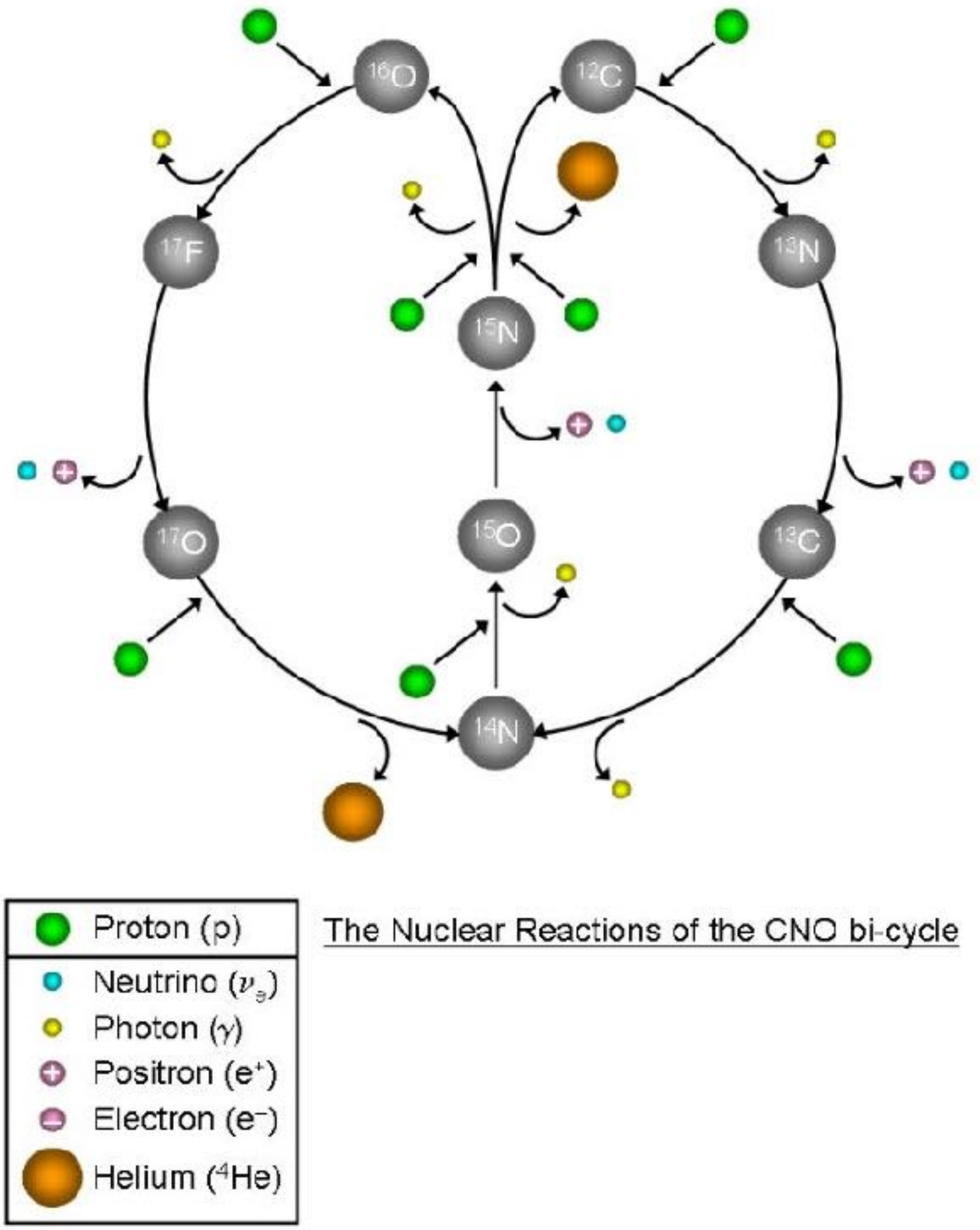
NUCLEAR REACTIONS THE P-P CHAIN

- Most abundant element in stars is H
- Fusion to He releases energy, but would require an encounter of 3 or 4 particles, statistically unlikely
- Thus we have a chain of events



NUCLEAR REACTIONS THE CNO BI-CYCLE

- Happens at a later stage
- Uses carbon, nitrogen, and oxygen as catalysts

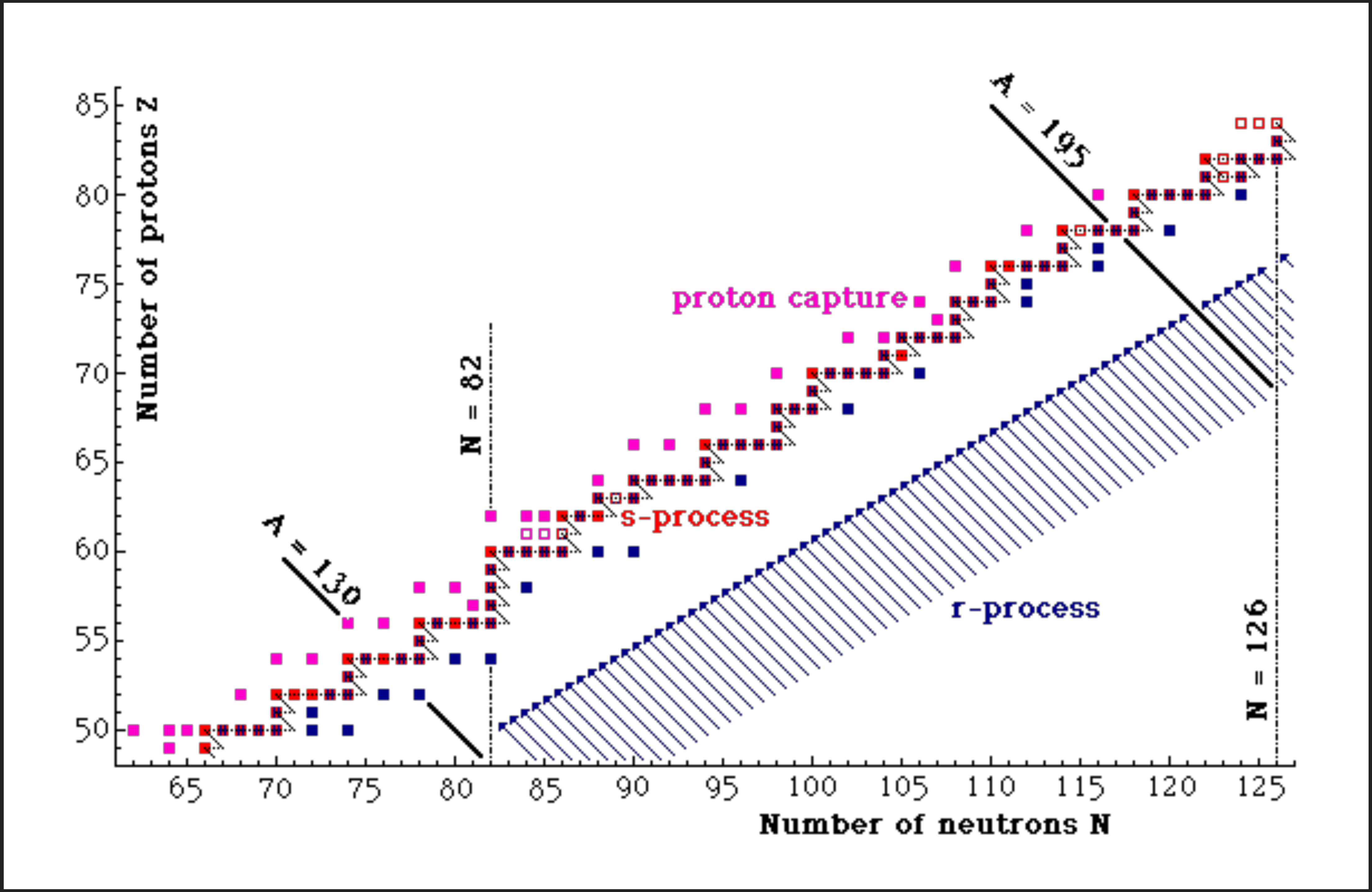


The Nuclear Reactions of the CNO bi-cycle

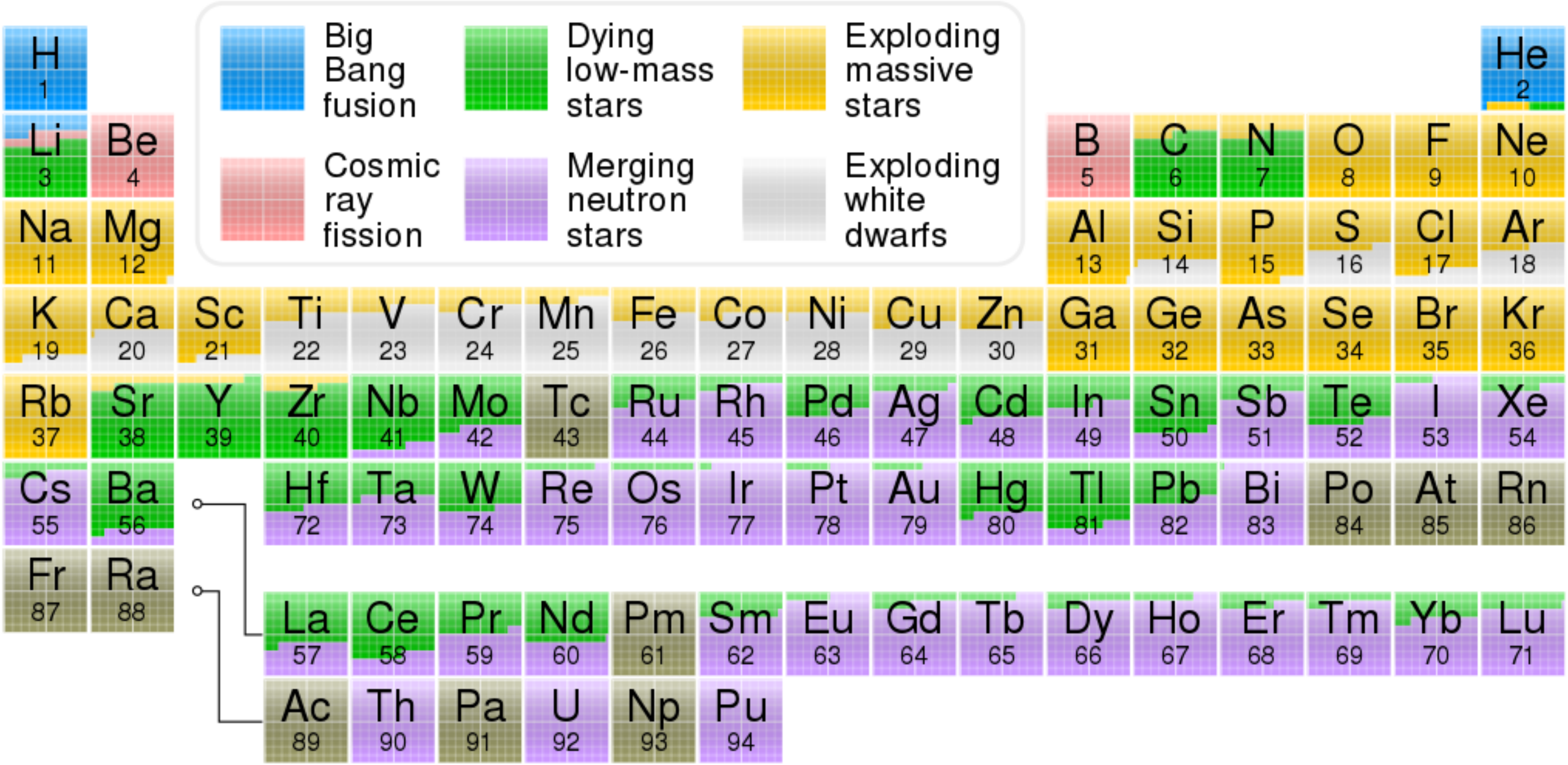
MAJOR NUCLEAR BURNING PROCESSES

Nuclear Fuel	Process	$T_{threshold}$ 10^6K	Products	Energy per nucleon (Mev)
H	PP	~4	He	6.55
H	CNO	15	He	6.25
He	3α	100	C,O	0.61
C	C+C	600	O,Ne,Ma,Mg	0.54
Ne	Ne+Ne	1000	O,Mg	~0.4
O	O+O	1500	S,P,Si	~0.3
Si	Alpha	3000	Co,Fe,Ni	<0.18

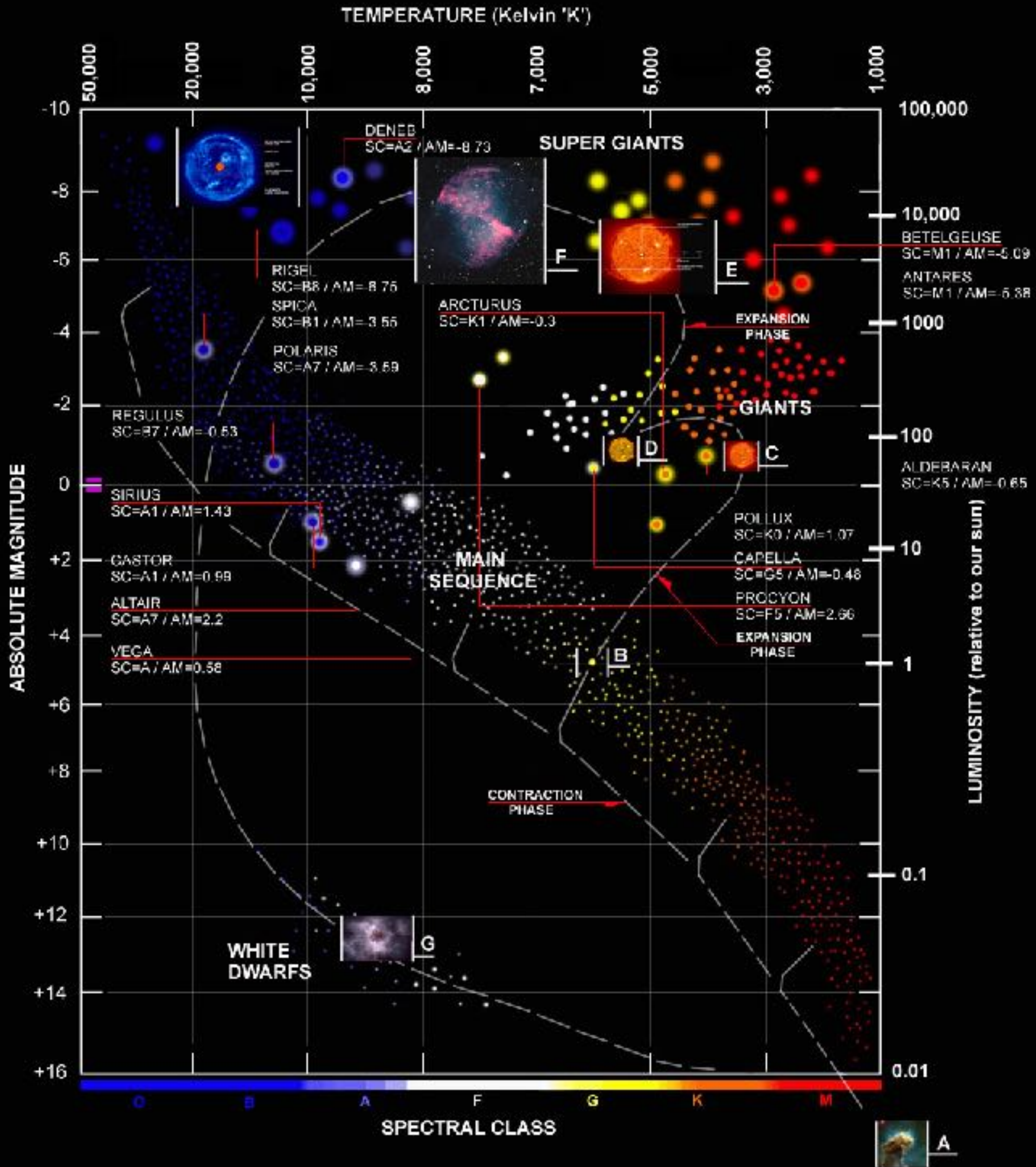
S AND R PROCESSES



SOURCES OF ELEMENTS



EVOLUTION AND THE HR DIAGRAM



TEMPERATURE (Kelvin 'K')
50,000
20,000
10,000
8,000
7,000
5,000
3,000
1,000
-10
-8
-6
-4
-2
0
+2
+4
+6
+8
+10
+12
+14
+16
100,000
10,000
1000
100
10
1
0.1
0.01
ABSOLUTE MAGNITUDE
LUMINOSITY (relative to our sun)
DENEB
SC=A2 / AM=-8.73
SUPER GIANTS
RIGEL
SC=B8 / AM=-8.75
SPICA
SC=B1 / AM=-3.55
POLARIS
SC=A7 / AM=-3.59
ARCTURUS
SC=K1 / AM=-0.3
BETELGEUSE
SC=M1 / AM=-5.09
ANTARES
SC=M1 / AM=-5.38
EXPANSION
PHASE
GIANTS
REGULUS
SC=B7 / AM=-0.53
SIRIUS
SC=A1 / AM=1.43
CASTOR
SC=A1 / AM=0.99
ALTAIR
SC=A7 / AM=2.2
VEGA
SC=A / AM=0.58
ALDEBARAN
SC=K5 / AM=-0.65
POLLUX
SC=K0 / AM=1.07
CAPELLA
SC=G5 / AM=-0.48
PROCYON
SC=F5 / AM=2.66
EXPANSION
PHASE
MAIN
SEQUENCE
CONTRACTION
PHASE
WHITE
DWARFS
A
B
C
D
E
F
G
O
B
A
F
G
K
M
SPECTRAL CLASS