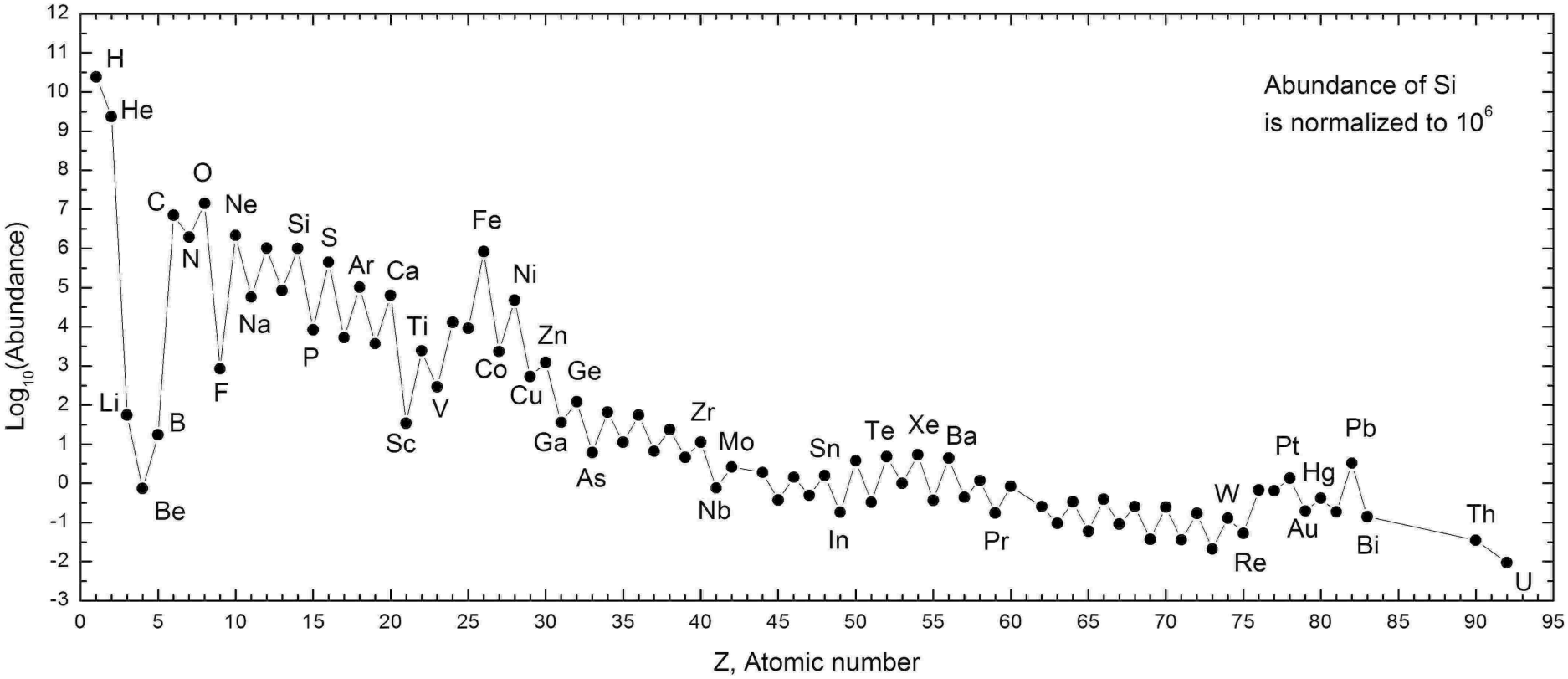
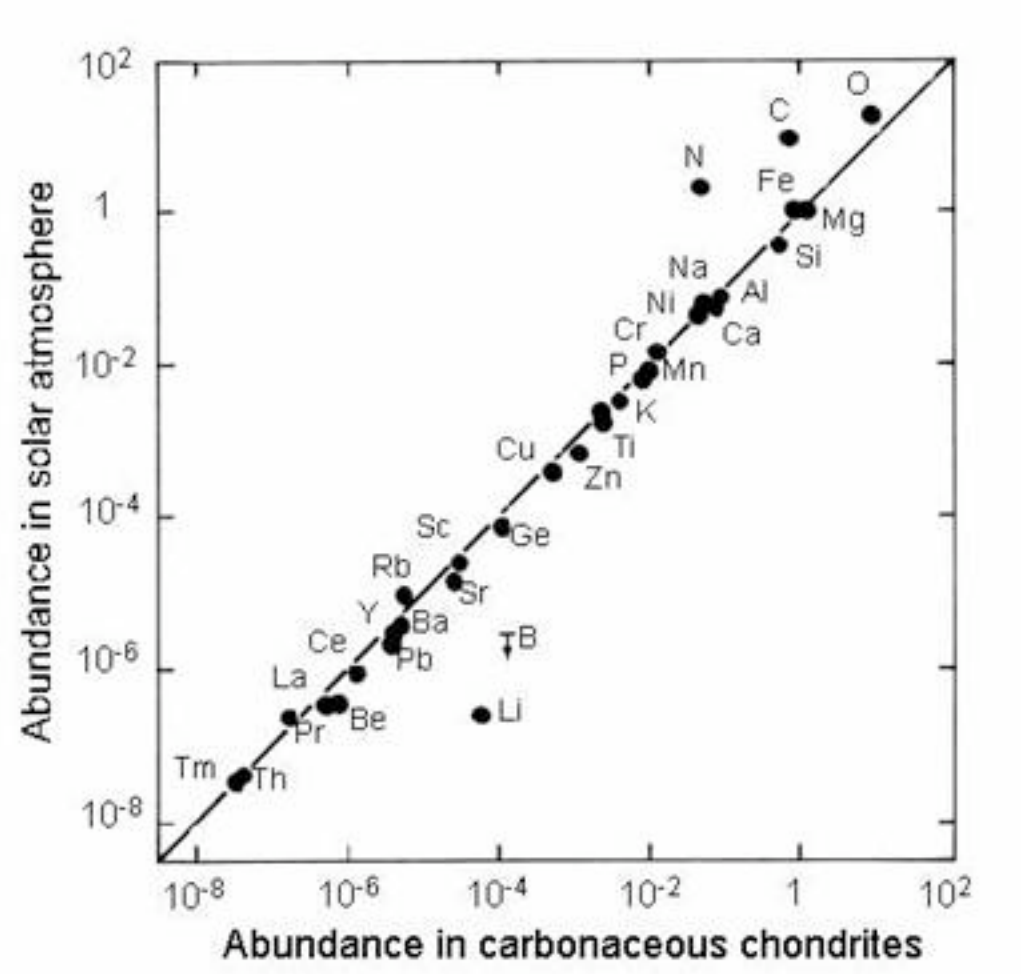
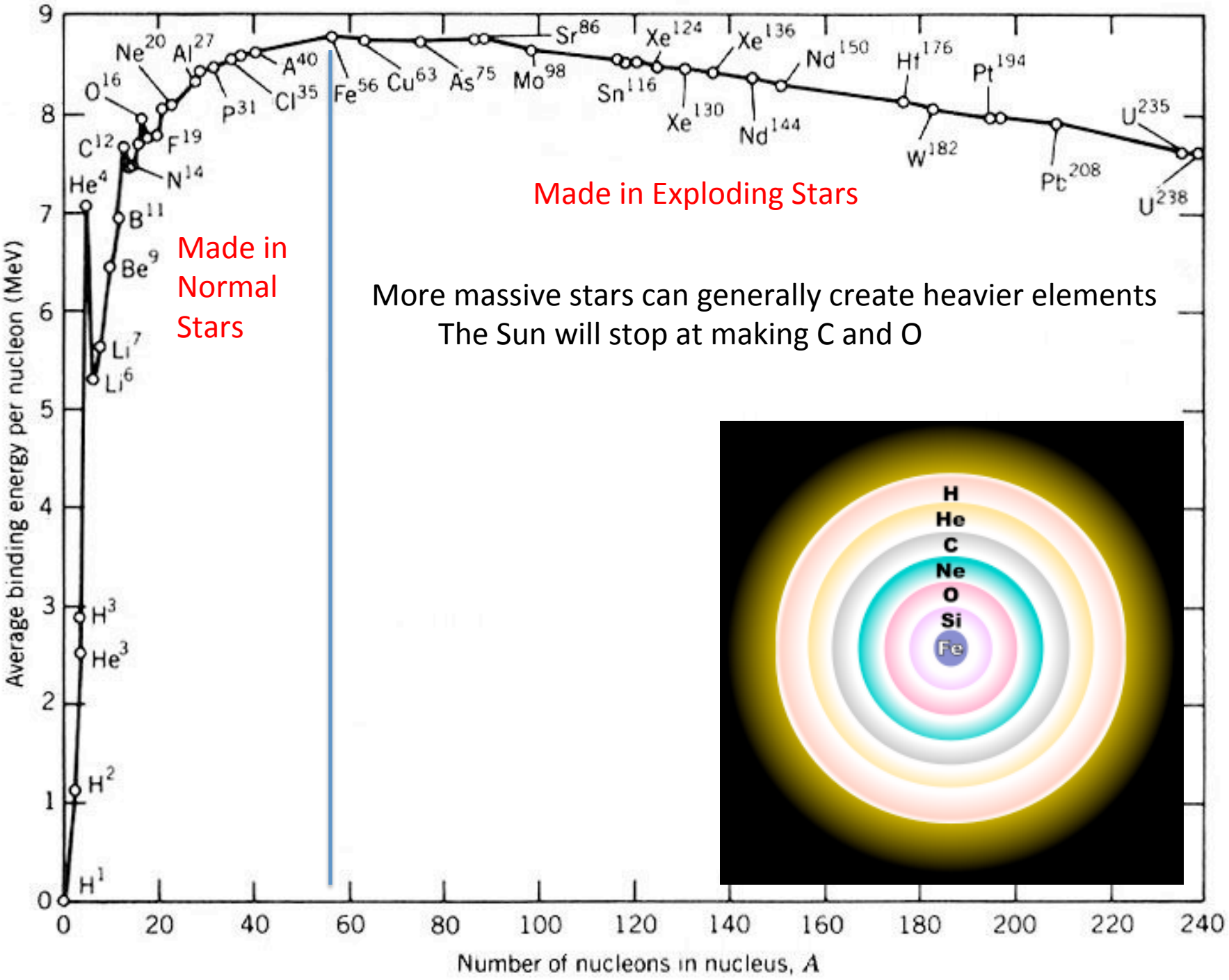


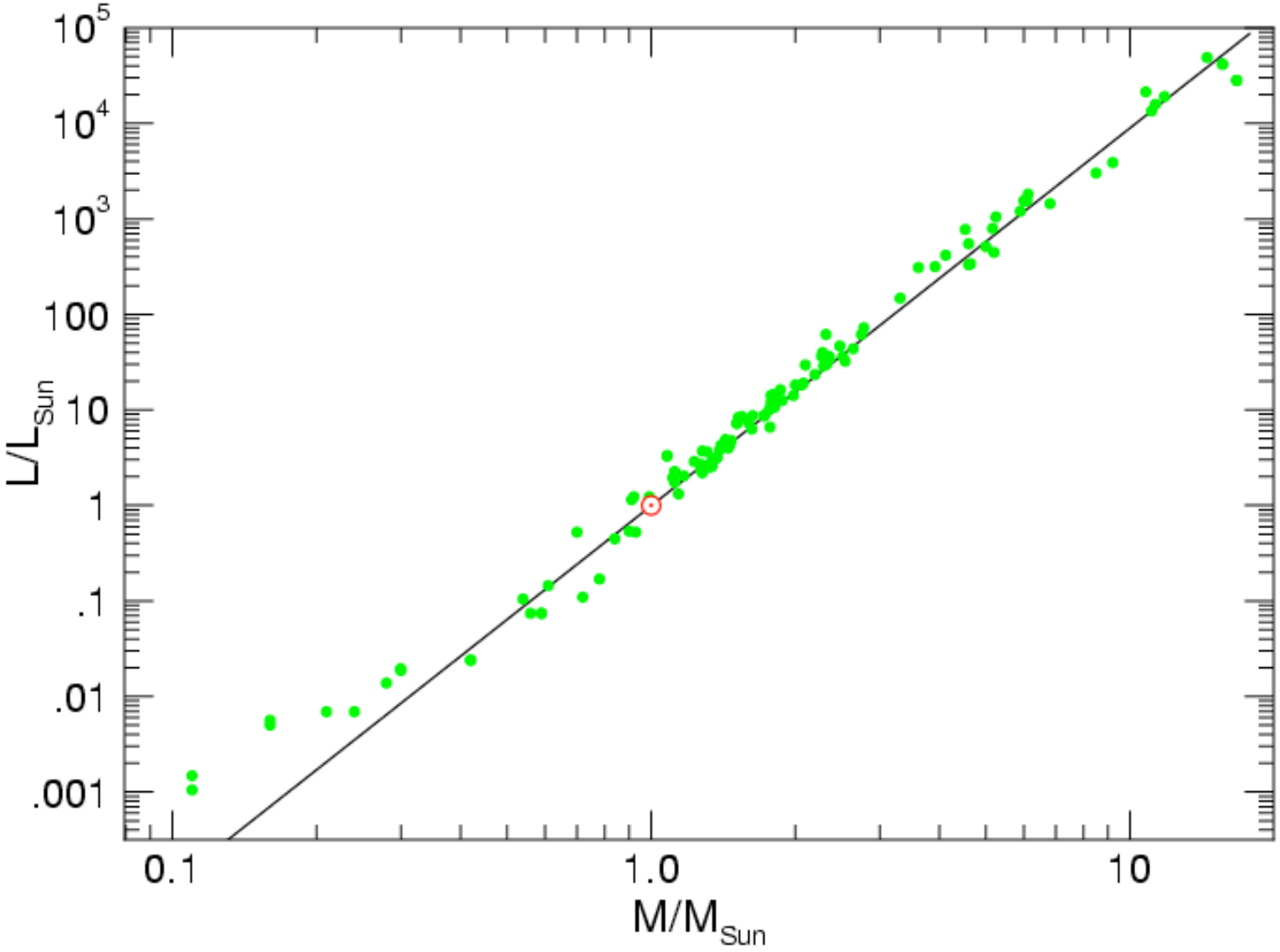
Element abundances in the Solar system (data from Lodders 2003)

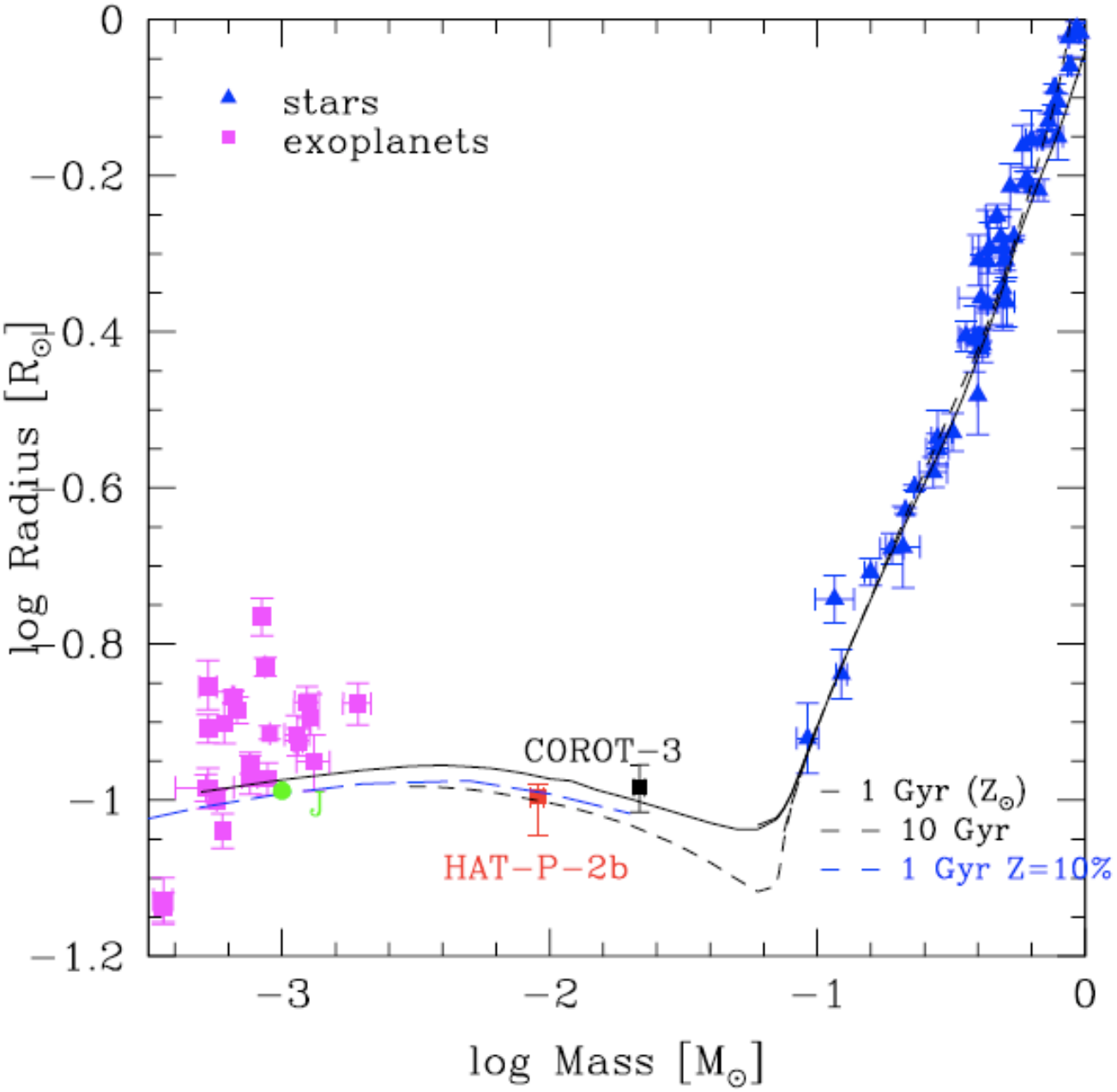
- O, C next most abundant after H and He
- Planet-forming elements: O, Fe, Si, Mg, Ni, plus H/He, maybe C?
- Big Bang made essentially only H, He
  - All else created in fusion in interiors of stars

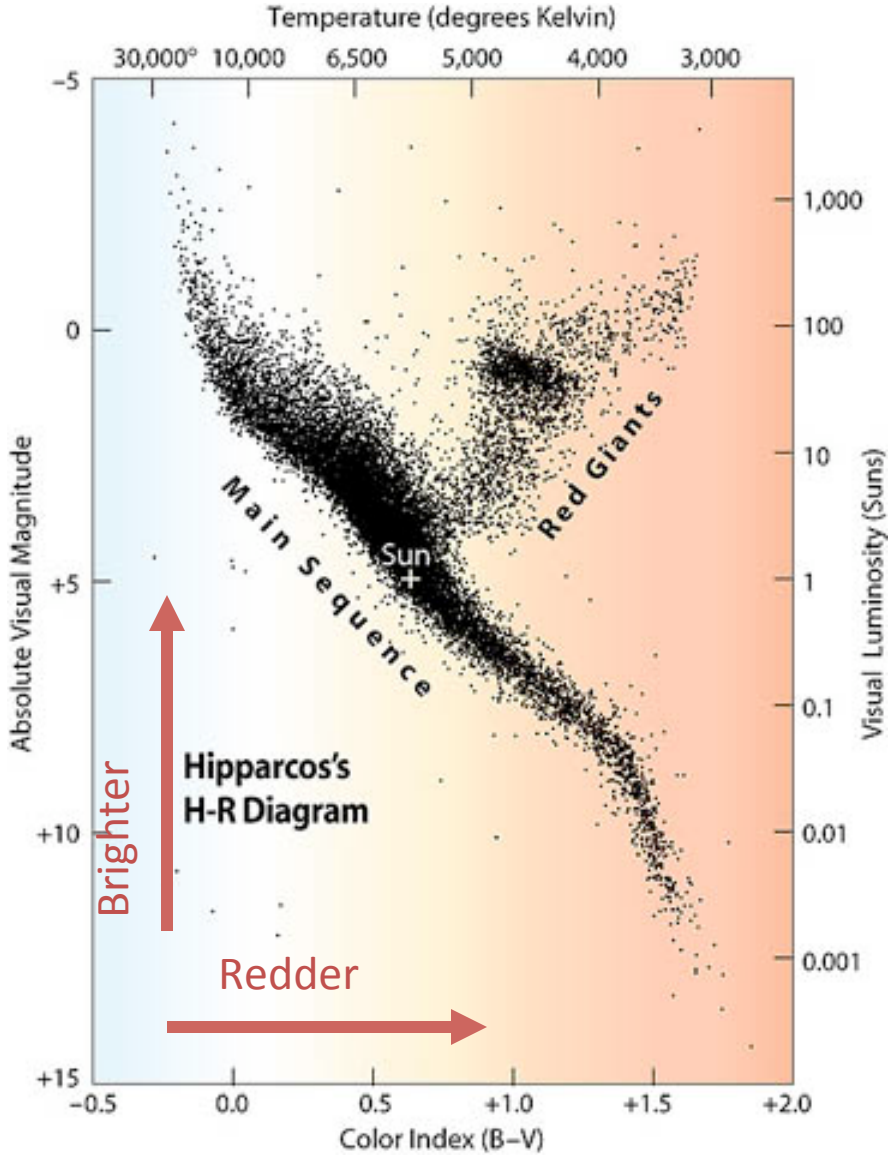


What makes planets is what makes stars, minus the lightest stuff

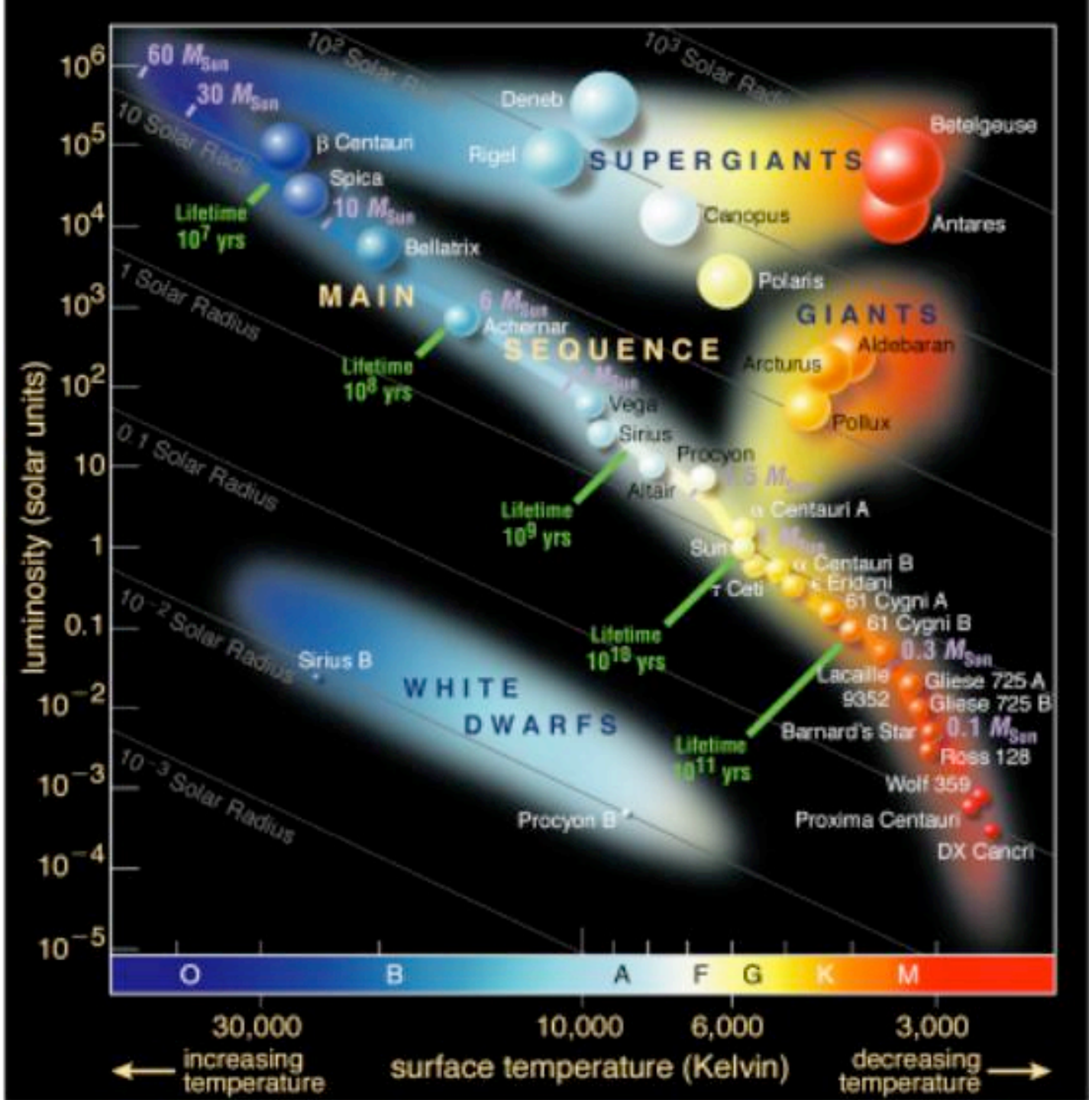

Average binding energy per nucleon (MeV)
Number of nucleons in nucleus, A
0
20
40
60
80
100
120
140
160
180
200
220
240
1
2
3
4
5
6
7
8
9
H1
H2
H3
He3
He4
Li6
Li7
Be9
B11
C12
N14
O16
F19
Ne20
Al27
P31
Cl35
A40
Fe56
Cu63
As75
Mo98
Sr86
Sn116
Xe124
Xe130
Xe136
Nd144
Nd150
W182
Hf176
Pt194
Pb208
U235
U238
Made in Normal Stars
Made in Exploding Stars
More massive stars can generally create heavier elements
The Sun will stop at making C and O
H
He
C
Ne
O
Si
Fe


10^5
10^4
10^3
100
10
1
.1
.01
.001
L/L_{Sun}
0.1
1.0
10
M/M_{Sun}


stars
exoplanets
COROT−3
HAT−P−2b
J
1 Gyr (Z⊙)
10 Gyr
1 Gyr Z=10%
log Radius [R⊙]
log Mass [M⊙]
0
−0.2
−0.4
−0.6
−0.8
−1
−1.2
−3
−2
−1
0



HR diagram of 20,853 stars with distances and colors measured by Hipparcos (borrowed from Catherine Turon's web site).

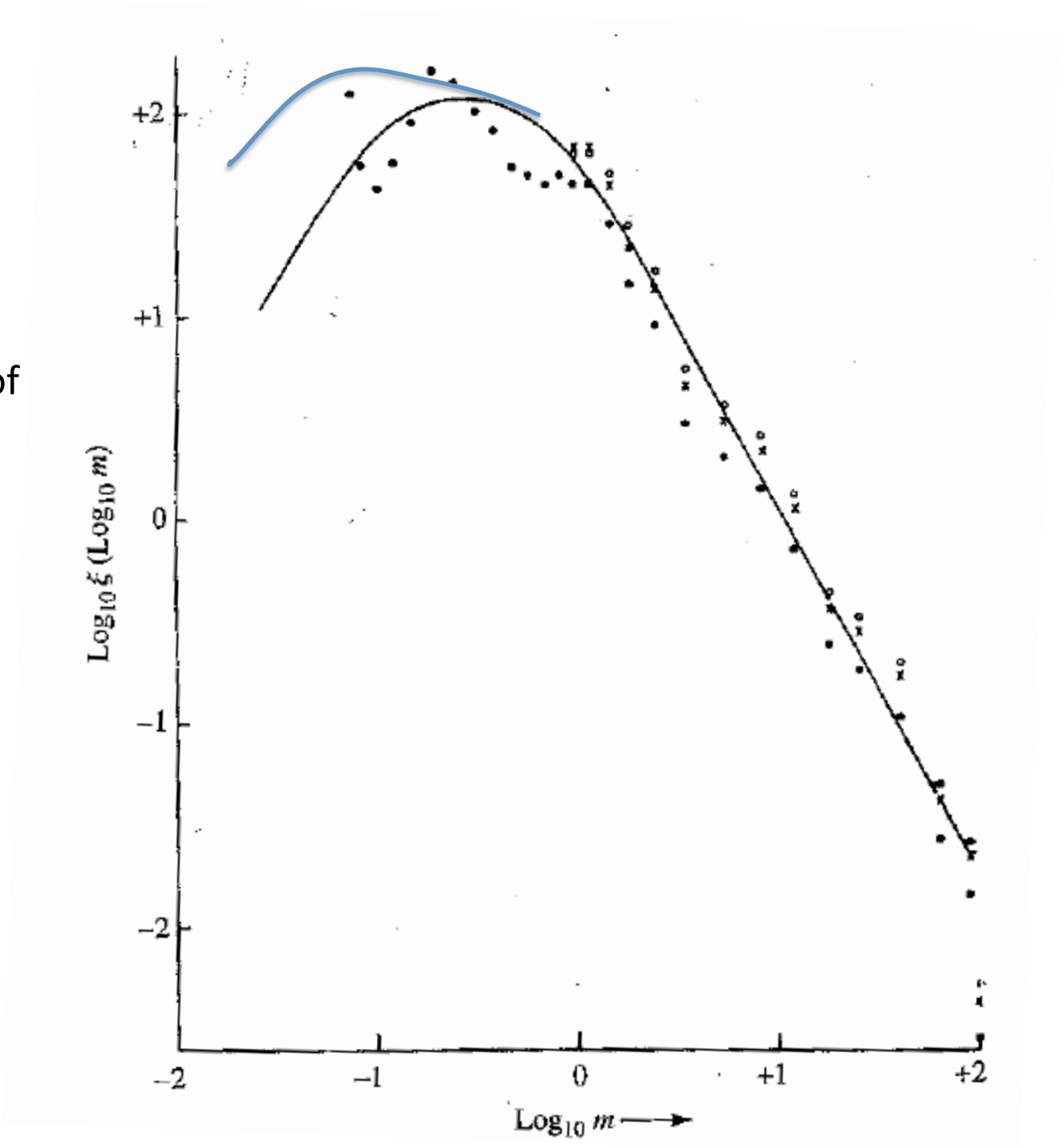

luminosity (solar units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
60 M_{Sun}
30 M_{Sun}
10 M_{Sun}
6 M_{Sun}
1 M_{Sun}
0.3 M_{Sun}
0.1 M_{Sun}
10 Solar Radius
1 Solar Radius
0.1 Solar Radius
10^{-2} Solar Radius
10^{-3} Solar Radius
Deneb
Rigel
Betelgeuse
β Centauri
Spica
Antares
Canopus
Bellatrix
Polaris
Achernar
Aldebaran
Arcturus
Pollux
Vega
Sirius
Procyon
Altair
α Centauri A
Sun
α Centauri B
τ Ceti
ε Eridani
61 Cygni A
61 Cygni B
Lacaille 9352
Gliese 725 A
Gliese 725 B
Barnard's Star
Ross 128
Wolf 359
Proxima Centauri
DX Cancri
Sirius B
Procyon B
SUPERGIANTS
MAIN SEQUENCE
GIANTS
WHITE DWARFS
Lifetime 10^7 yrs
Lifetime 10^8 yrs
Lifetime 10^9 yrs
Lifetime 10^{10} yrs
Lifetime 10^{11} yrs
O
B
A
F
G
K
M
30,000
10,000
6,000
3,000
increasing temperature
surface temperature (Kelvin)
decreasing temperature

Initial Mass Function

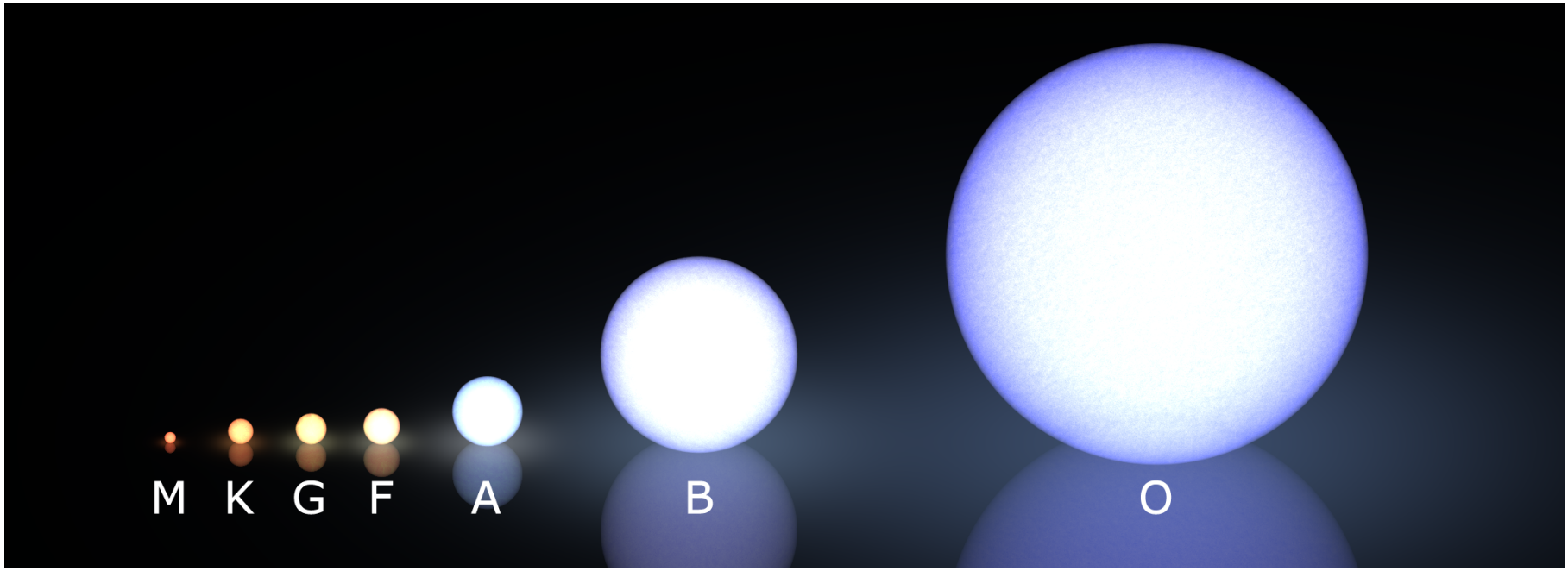
When stars are formed, how many are formed of a given mass?

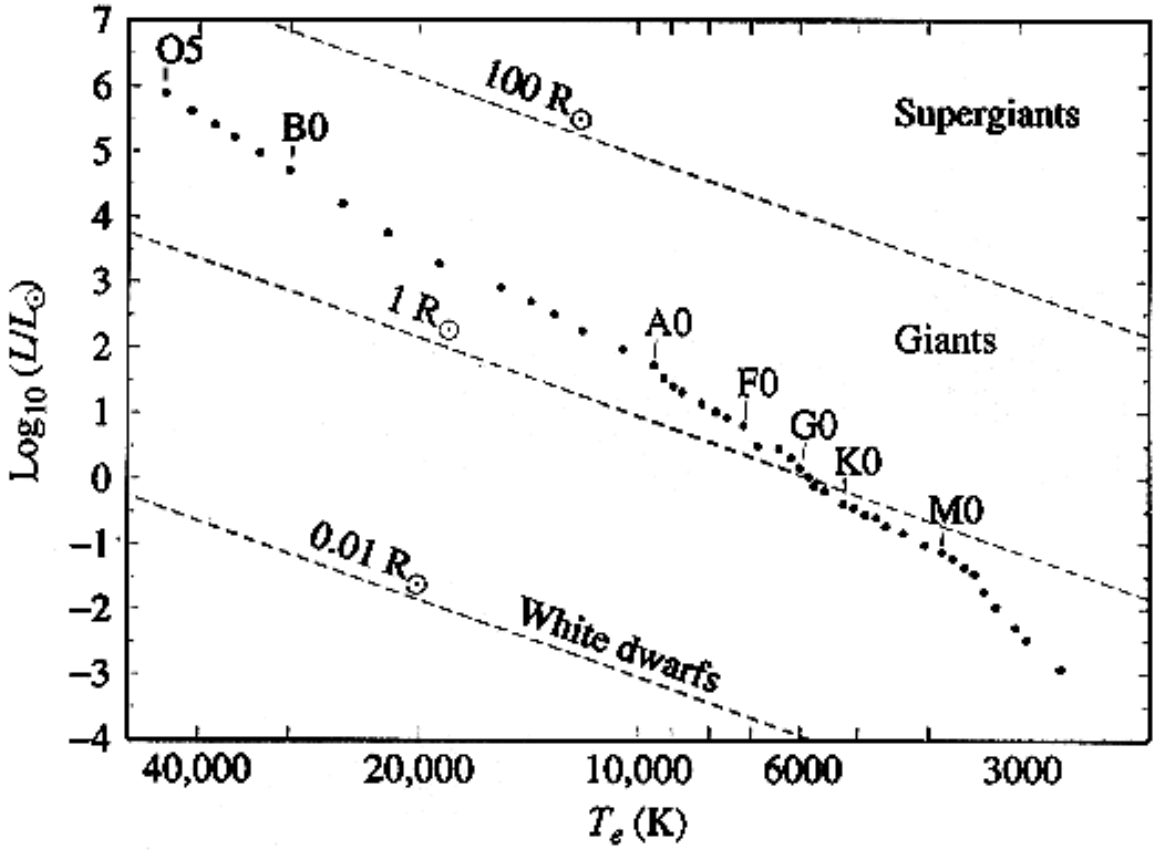
Lower mass stars are much more abundant than high mass stars

Salpeter (1953)
Miller & Scalo (1979)



The Stellar Types, with Sizes to Scale (and Colors)





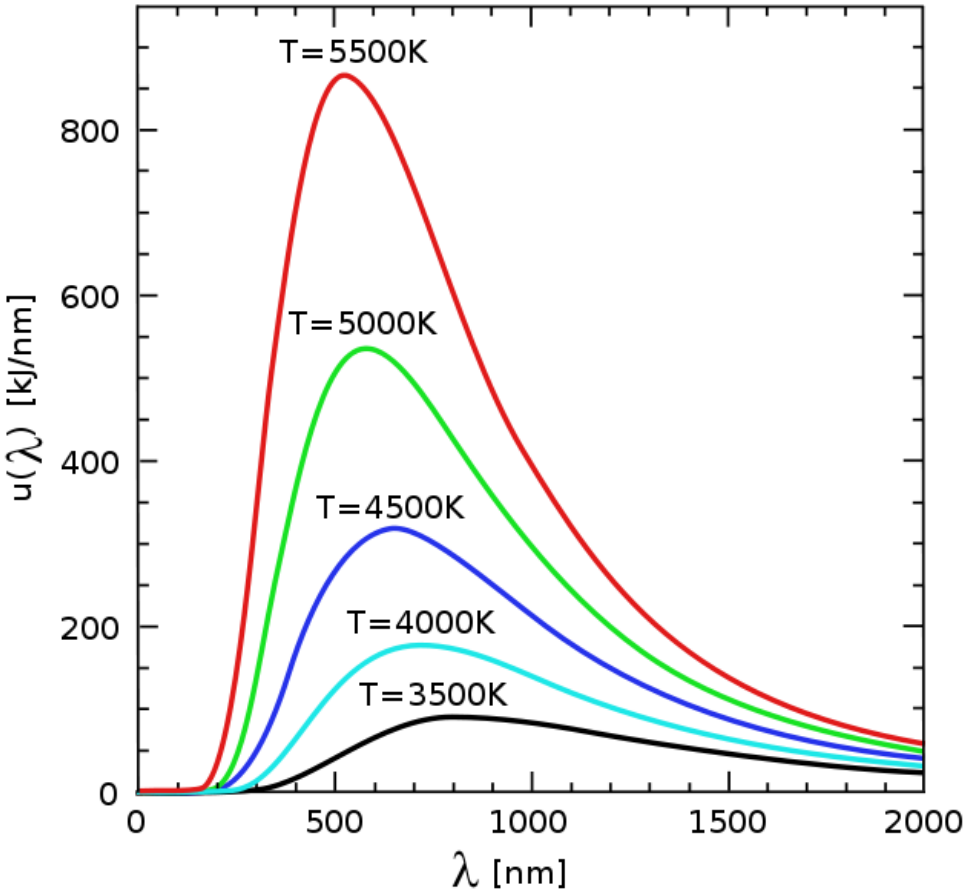
A theorist's HR diagram: luminosity vs. temperature, with lines of constant radius. The dots show the main sequence.

SPECTRAL TYPES AND TEMPERATURES ON THE MAIN SEQUENCE

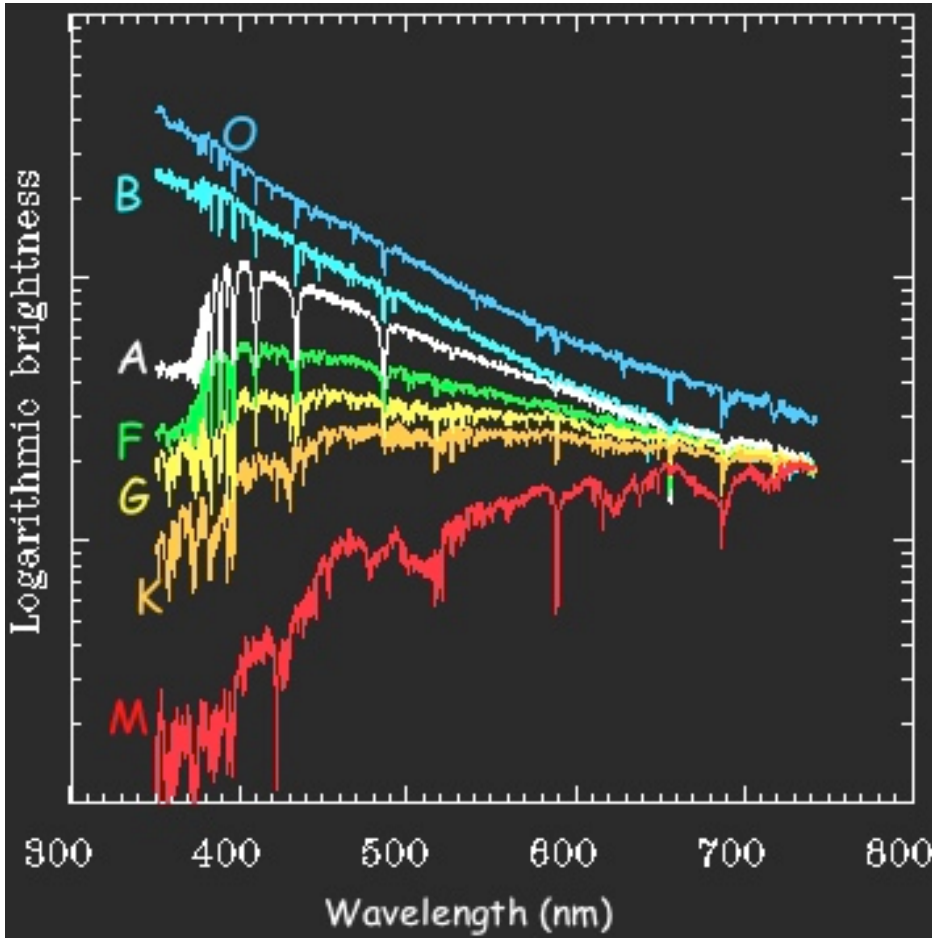
(mainly from Gray: The Observation and analysis of Stellar Photospheres 2nd ed., Cambridge Univ. Press)

O5	50,000	G5	5,680
O8	39,000	K0	5,270
B0	36,000	M0	4,045
B5	16,000	M5	3,000
B8	12,600	M8	2,200
A0	9,700	L0	2,000
A5	7,880	L8	1,500
F0	6,950	T0	1,300
F5	6,445	T8	600
G0	5,950		

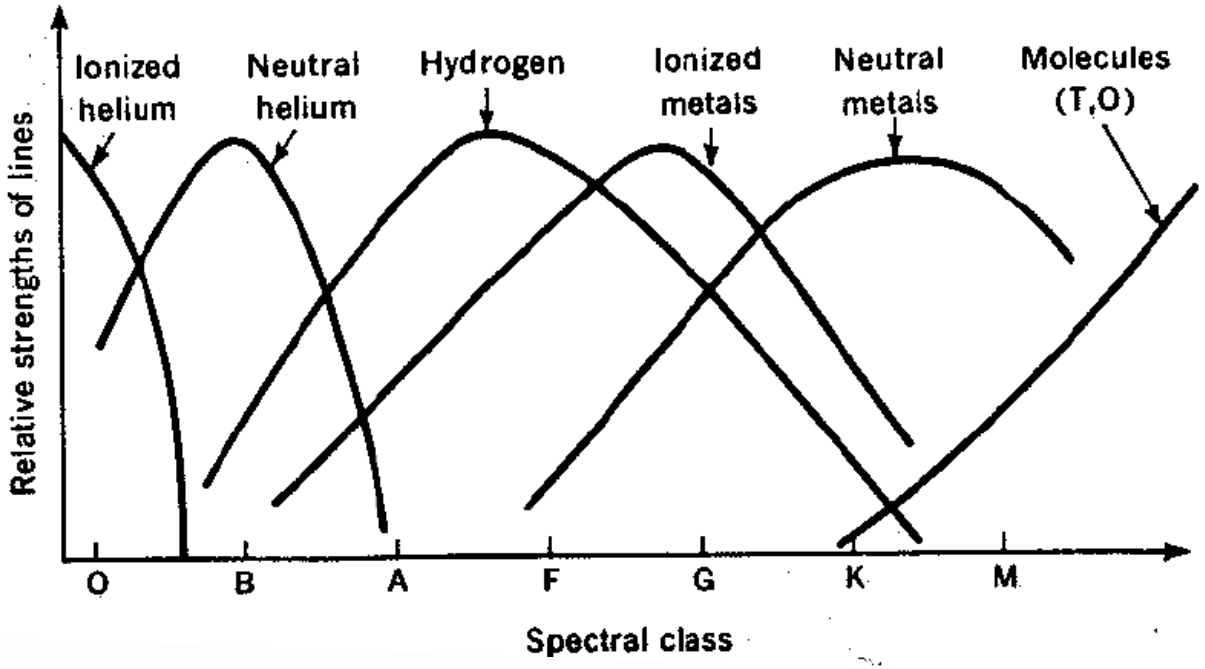
OBAFGKMLTY

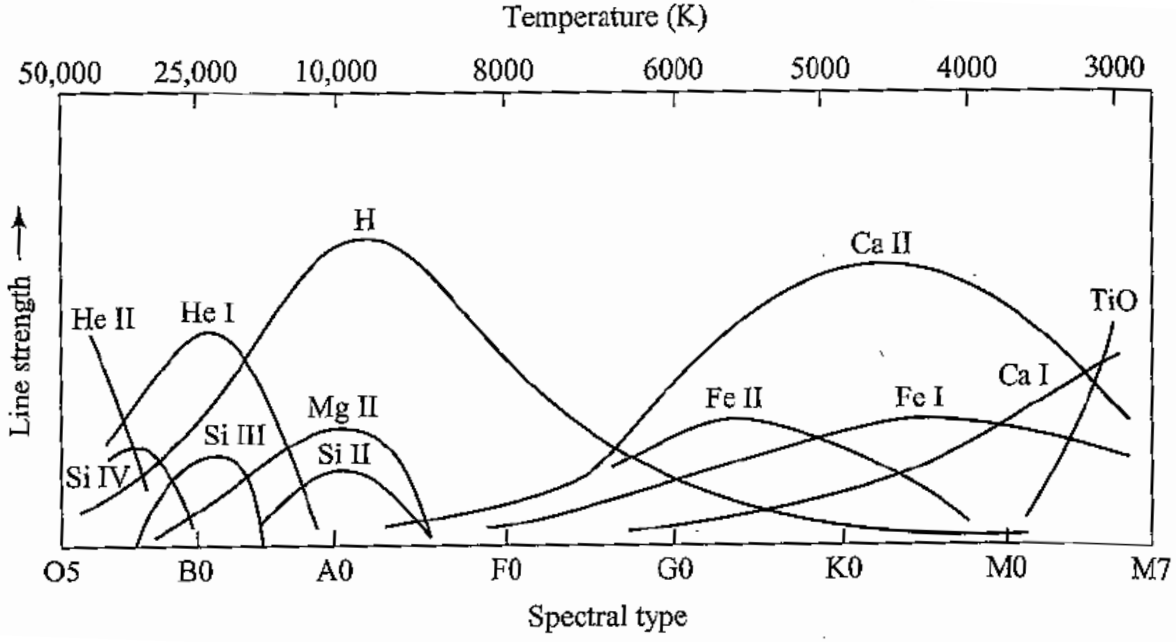


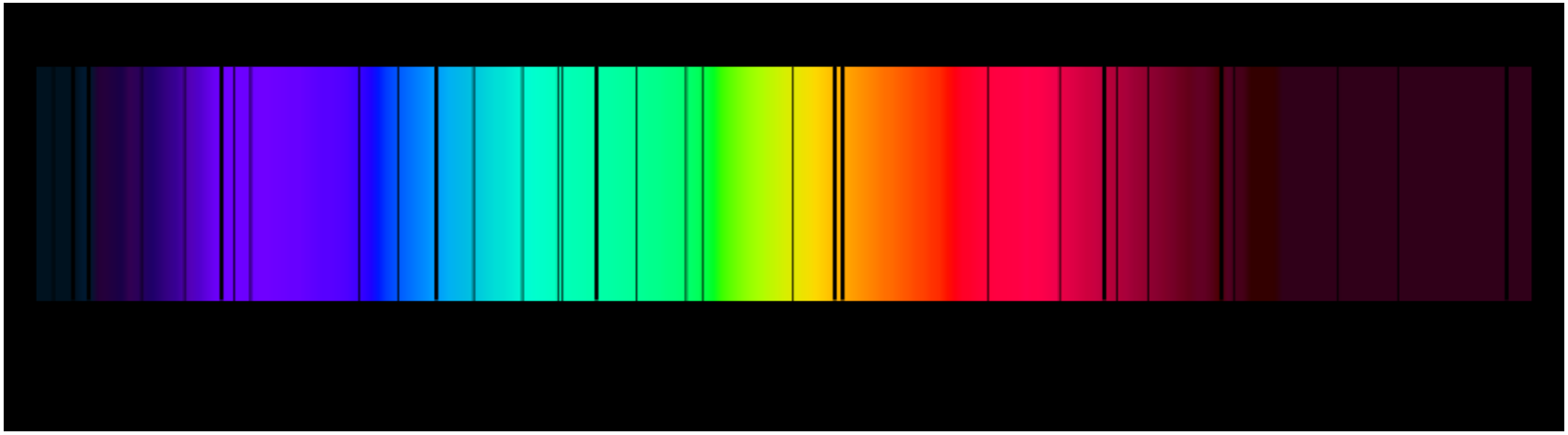
The Planck function for temperatures from 3500 - 5500 K

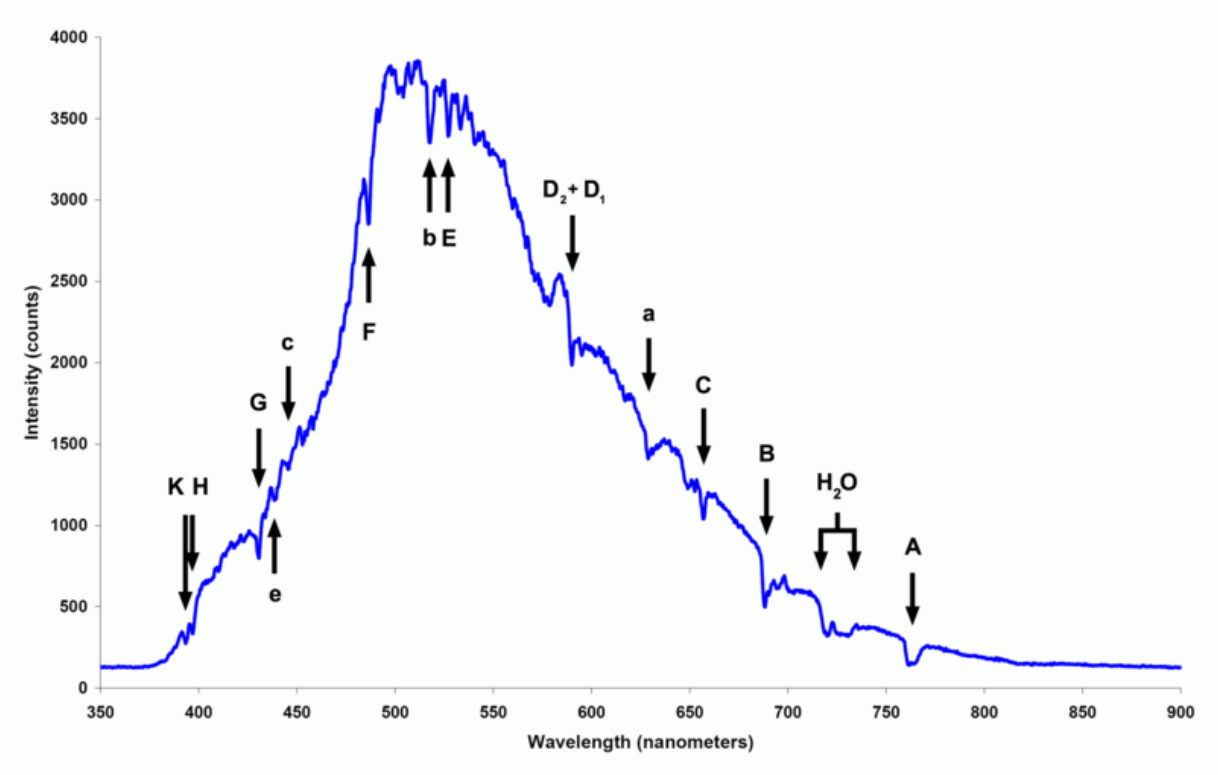


Real Spectra

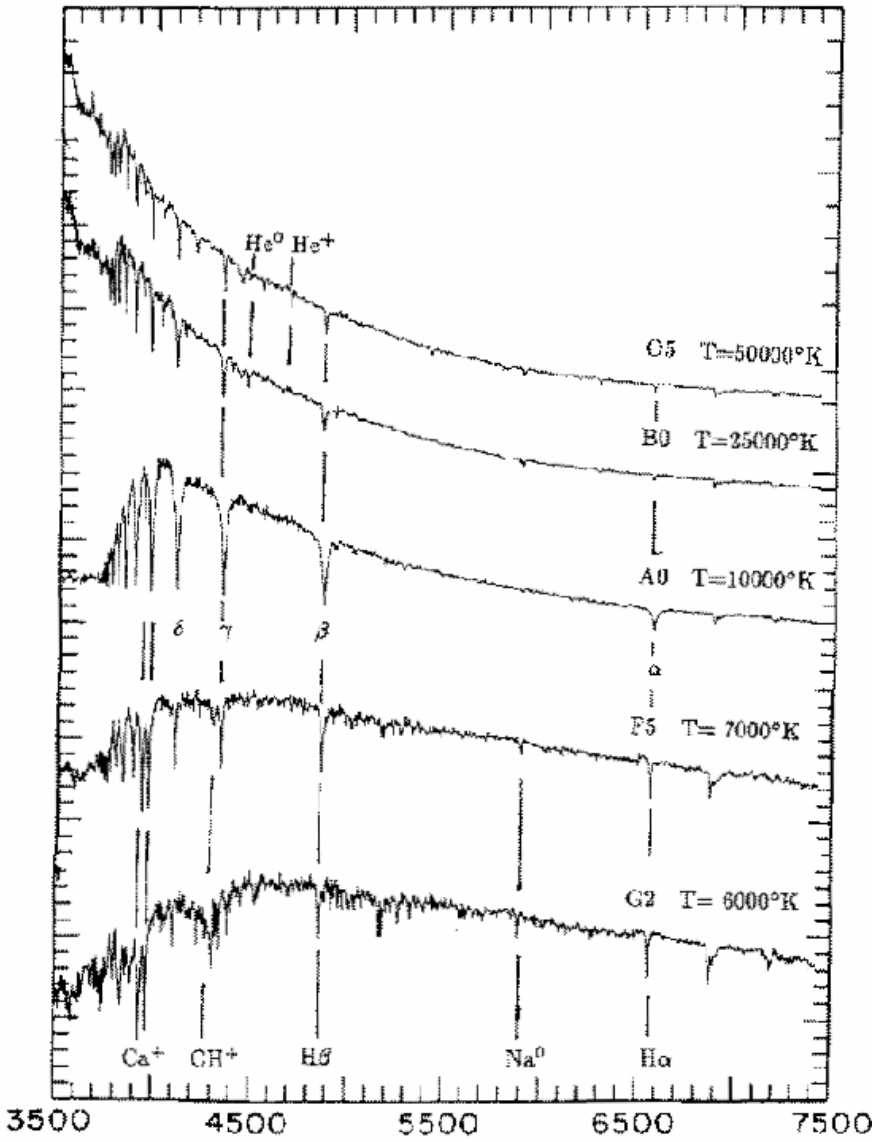

Ionized helium
Neutral helium
Hydrogen
Ionized metals
Neutral metals
Molecules (T,O)
Relative strengths of lines
O
B
A
F
G
K
M
Spectral class

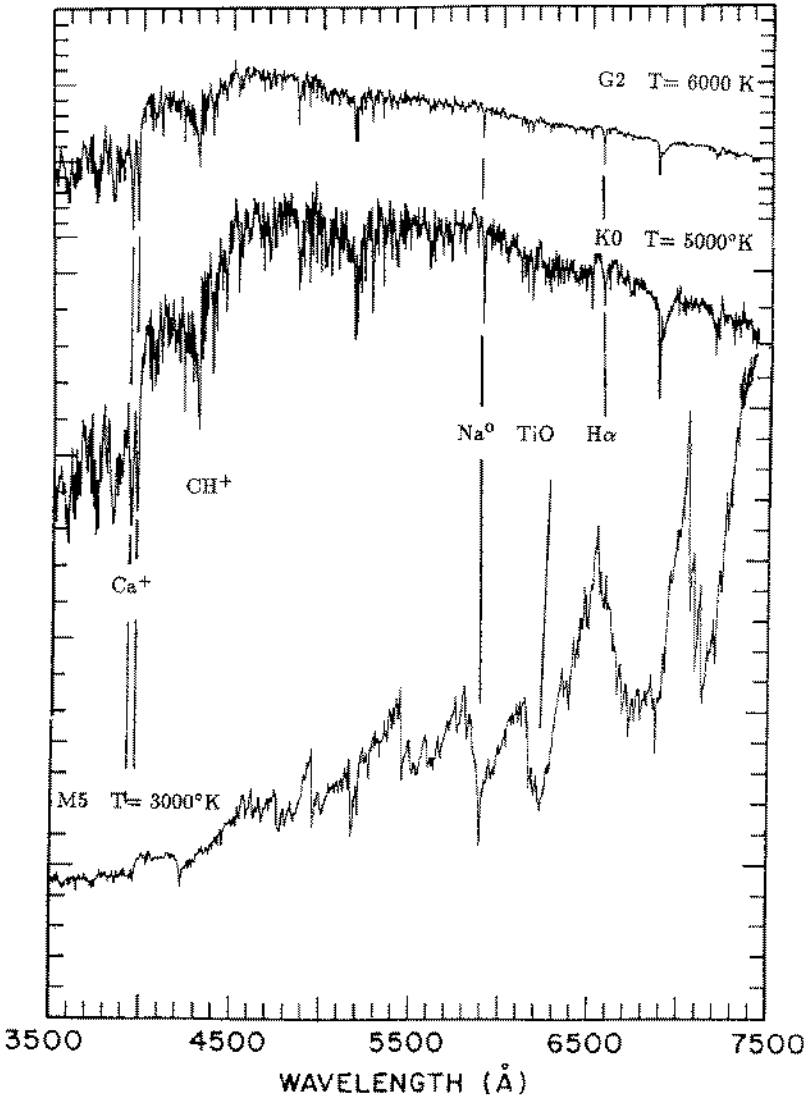

Temperature (K)
50,000
25,000
10,000
8000
6000
5000
4000
3000
Line strength
H
He II
He I
Si IV
Si III
Mg II
Si II
Ca II
TiO
Ca I
Fe II
Fe I
O5
B0
A0
F0
G0
K0
M0
M7
Spectral type



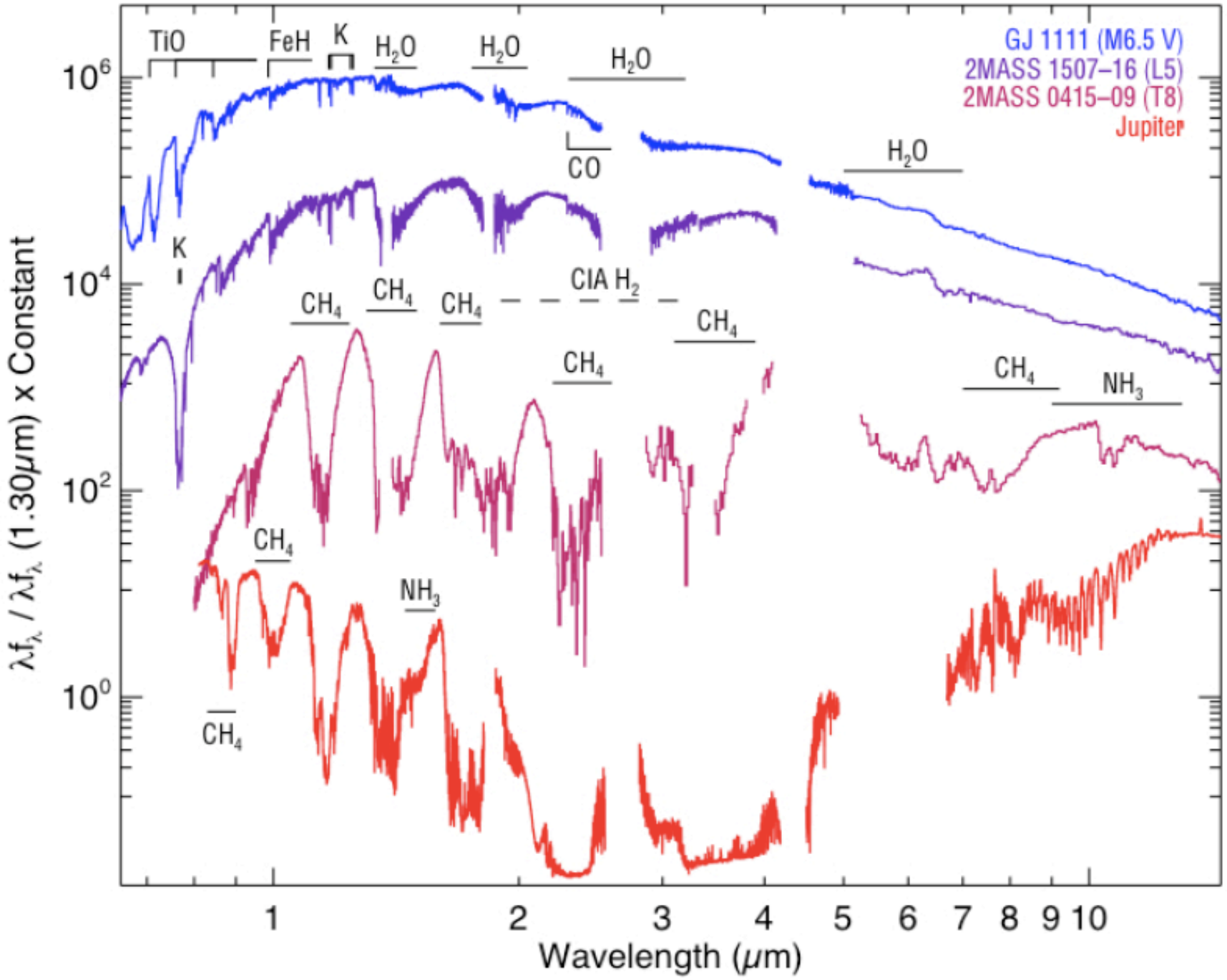


Solar spectrum, shown as through a prism (top) and in a plot of intensity vs. wavelength (side) (images taken from wikipedia)





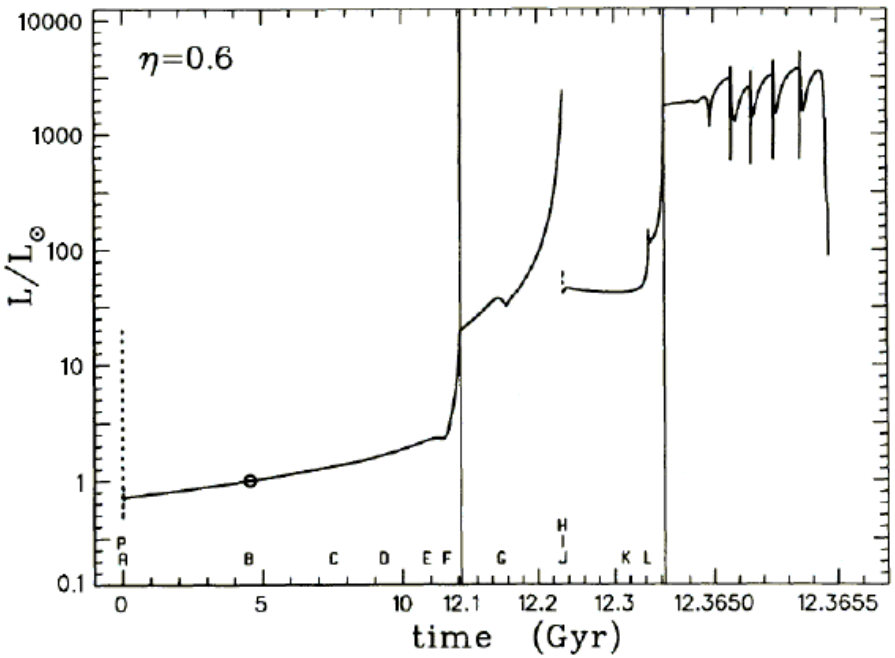
Spectra for O - G stars (left) and G - M stars (right)


GJ 1111 (M6.5 V)
2MASS 1507–16 (L5)
2MASS 0415–09 (T8)
Jupiter
TiO
FeH
K
H2O
H2O
H2O
CO
H2O
K
CH4
CH4
CH4
CIA H2
CH4
CH4
CH4
NH3
CH4
NH3
CH4
λfλ / λfλ (1.30μm) x Constant
Wavelength (μm)

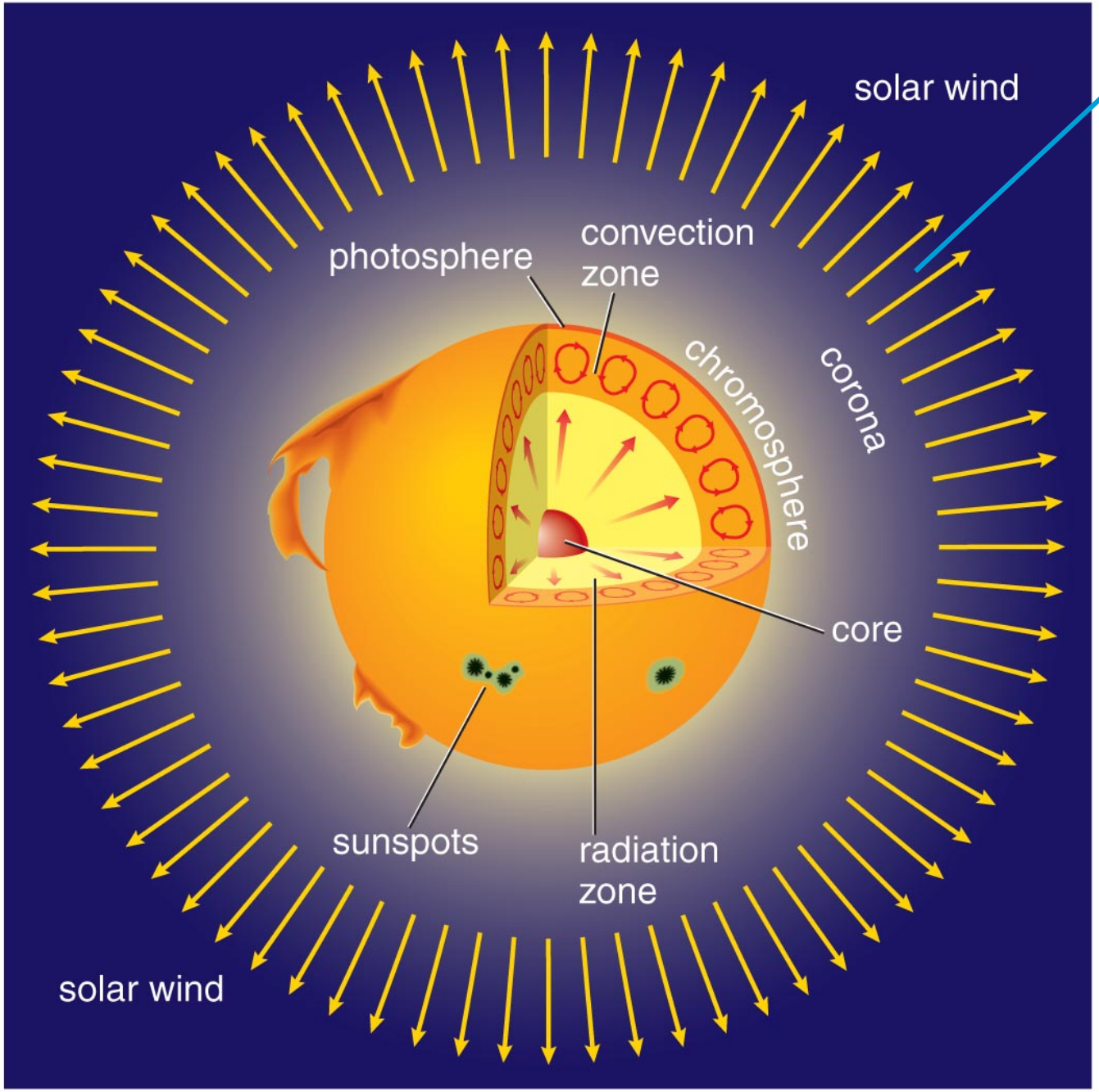
All Stars Become More Luminous With Time

The following data are taken from a 1992 article in the *Astrophysical Journal*, in which the authors performed detailed computer models of the history and future evolution of our Sun.

Label	Time	Mass	Luminosity	Temp.	Radius
P	0 Gyr	1 M_{sun}	19.95 L_{sun}	4400 K	7.71 R_{sun}
A	0.048	1	0.7015	5586	0.897
B (now)	4.55	1	1	5779	1
C	7.56	1	1.33	5843	1.13
D	9.37	1	1.67	5819	1.275
E	10.91	1	2.21	6517	1.575
F	11.64	0.9998	2.73	4902	2.3
G	12.15	0.9935	34	4540	6.38
H	12.233	0.7249	2349	3107	165.8
I	12.233	0.7249	57.7	4595	12.0
J	12.234	0.7241	41.0	4724	9.5
K	12.316	0.7133	42.4	4819	9.4
L	12.345	0.708	130	4375	20
M	12.365	0.538	2999	3160	180.3
N	12.365	0.541	5190	3660	177.0
O	12.365	0.541	90	74080	0.058

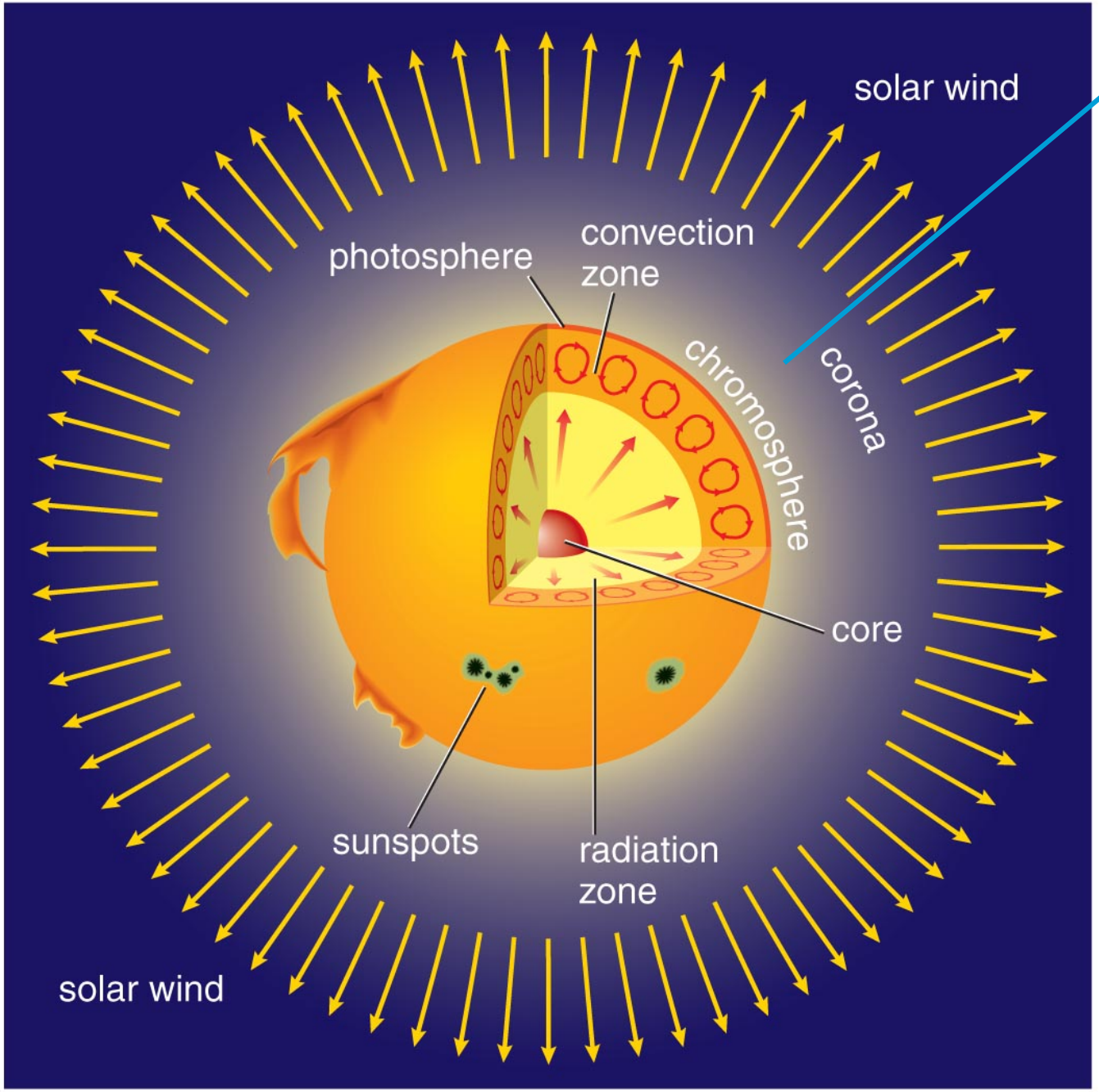


(Note: Gyr = 1 billion years)



Solar wind:

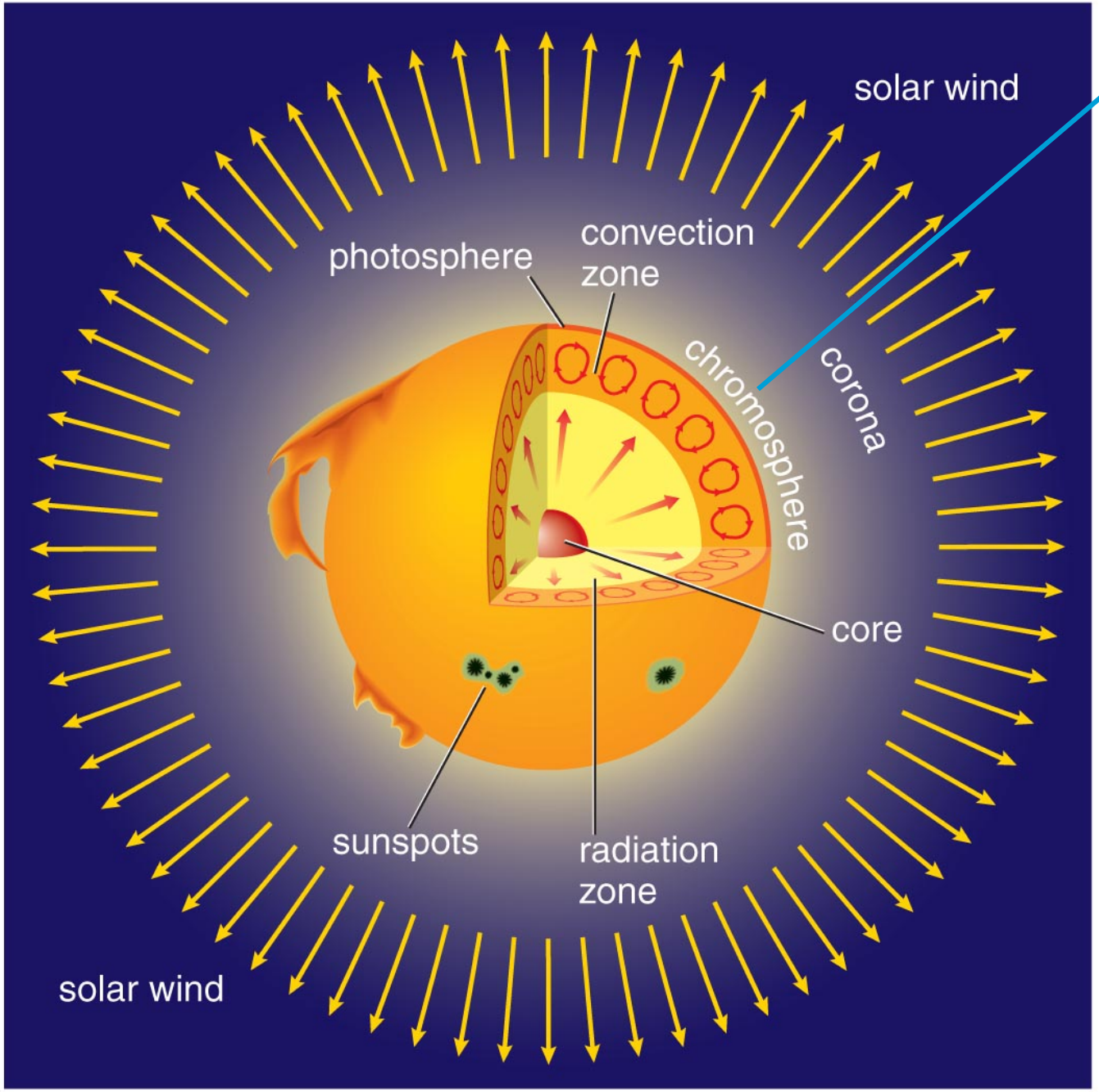
A flow of charged particles from the surface of the Sun



Corona:

Outermost layer of solar atmosphere

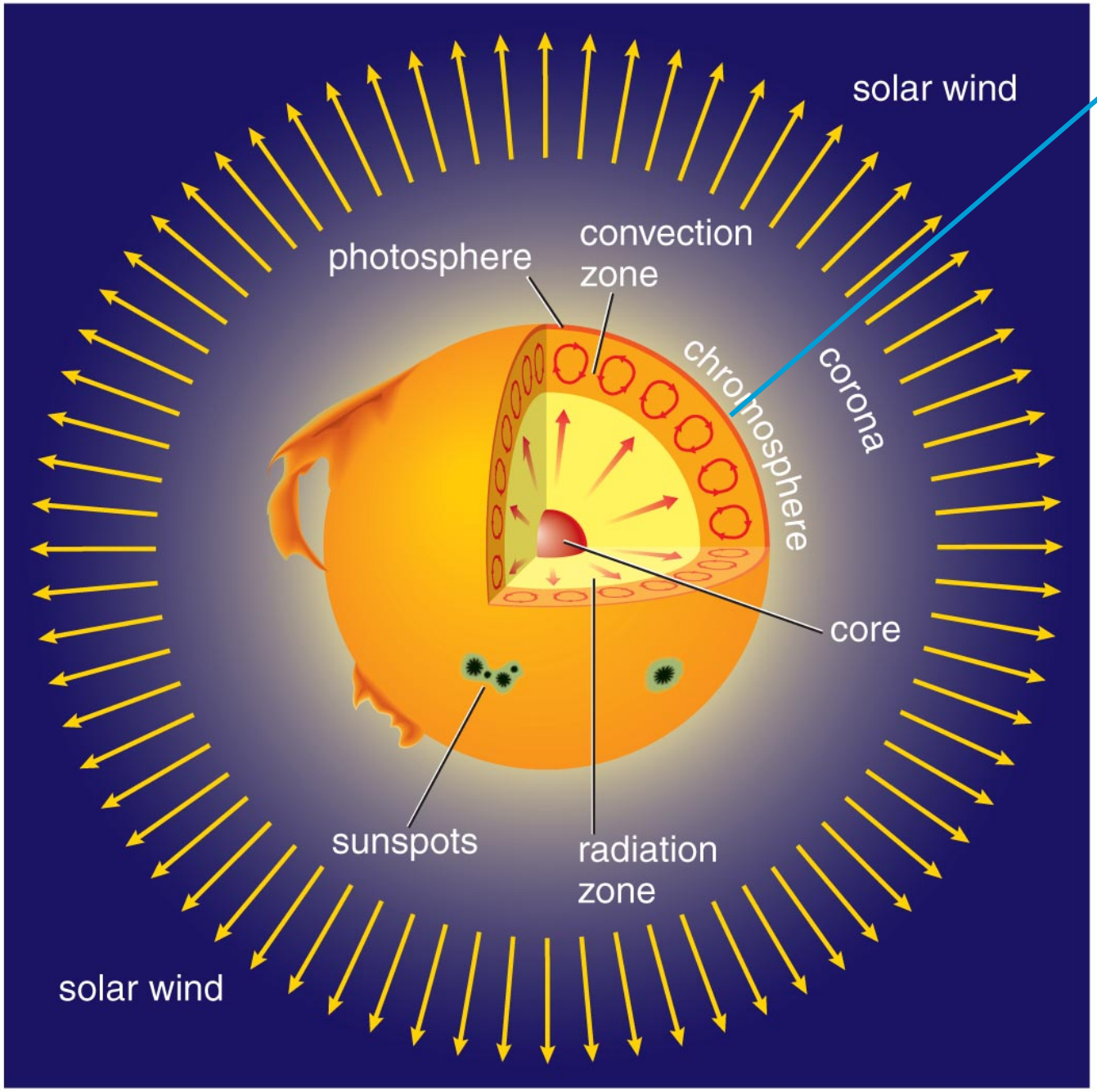
~1 million K



Chromosphere:

Middle layer of solar atmosphere

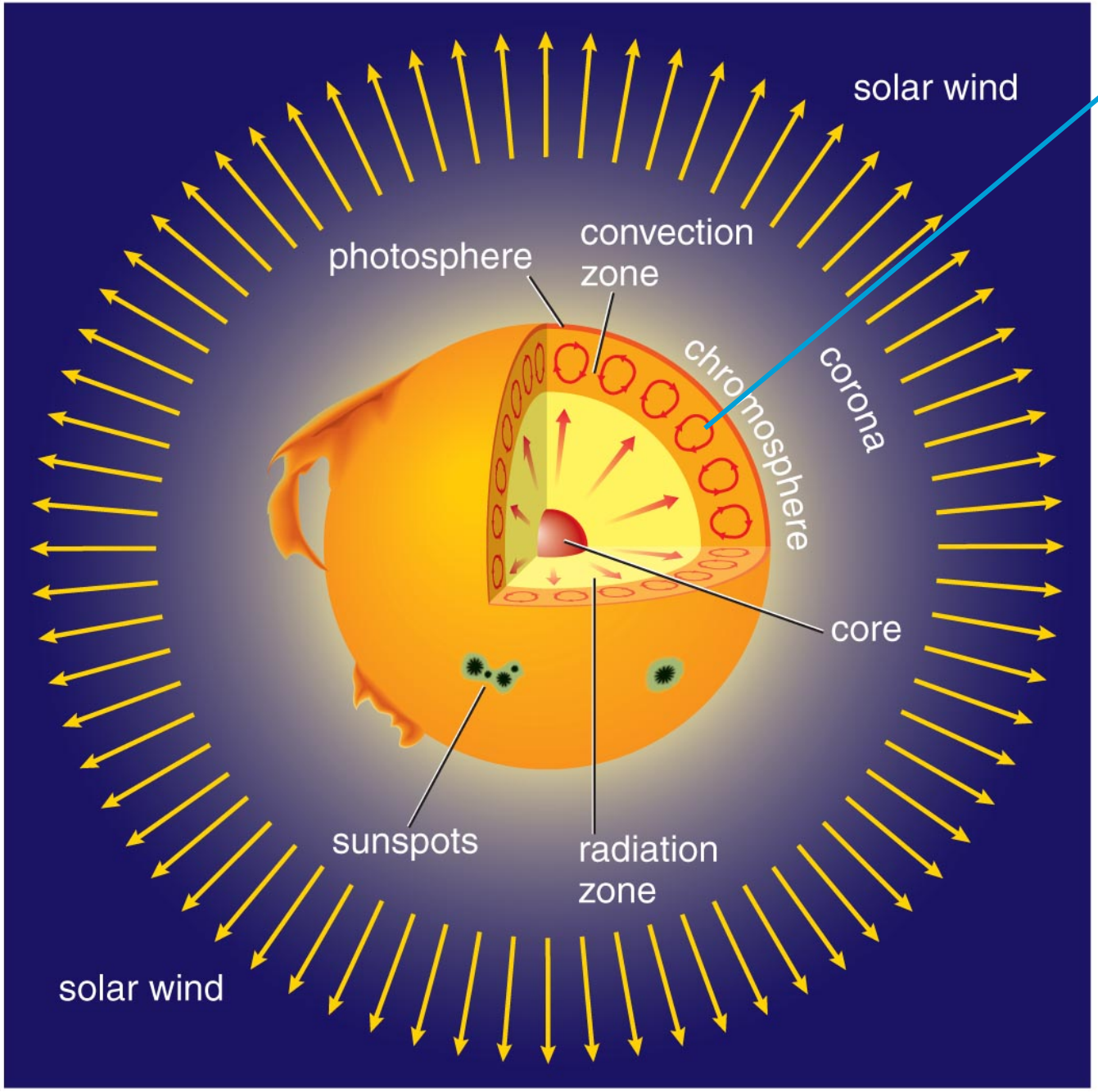
~ 10^4–10^5 K



Photosphere:

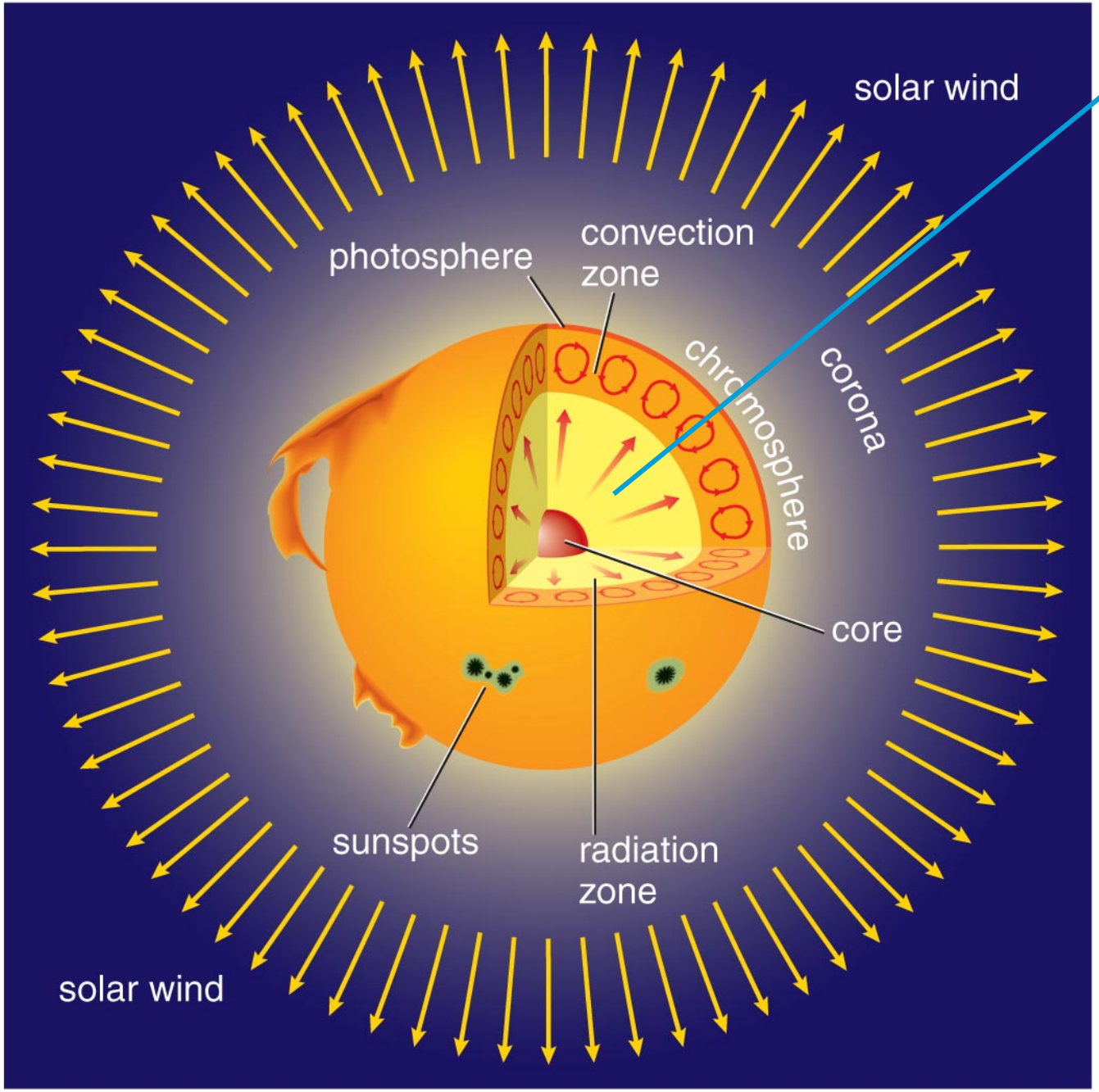
Visible surface of Sun

~ 5800 K



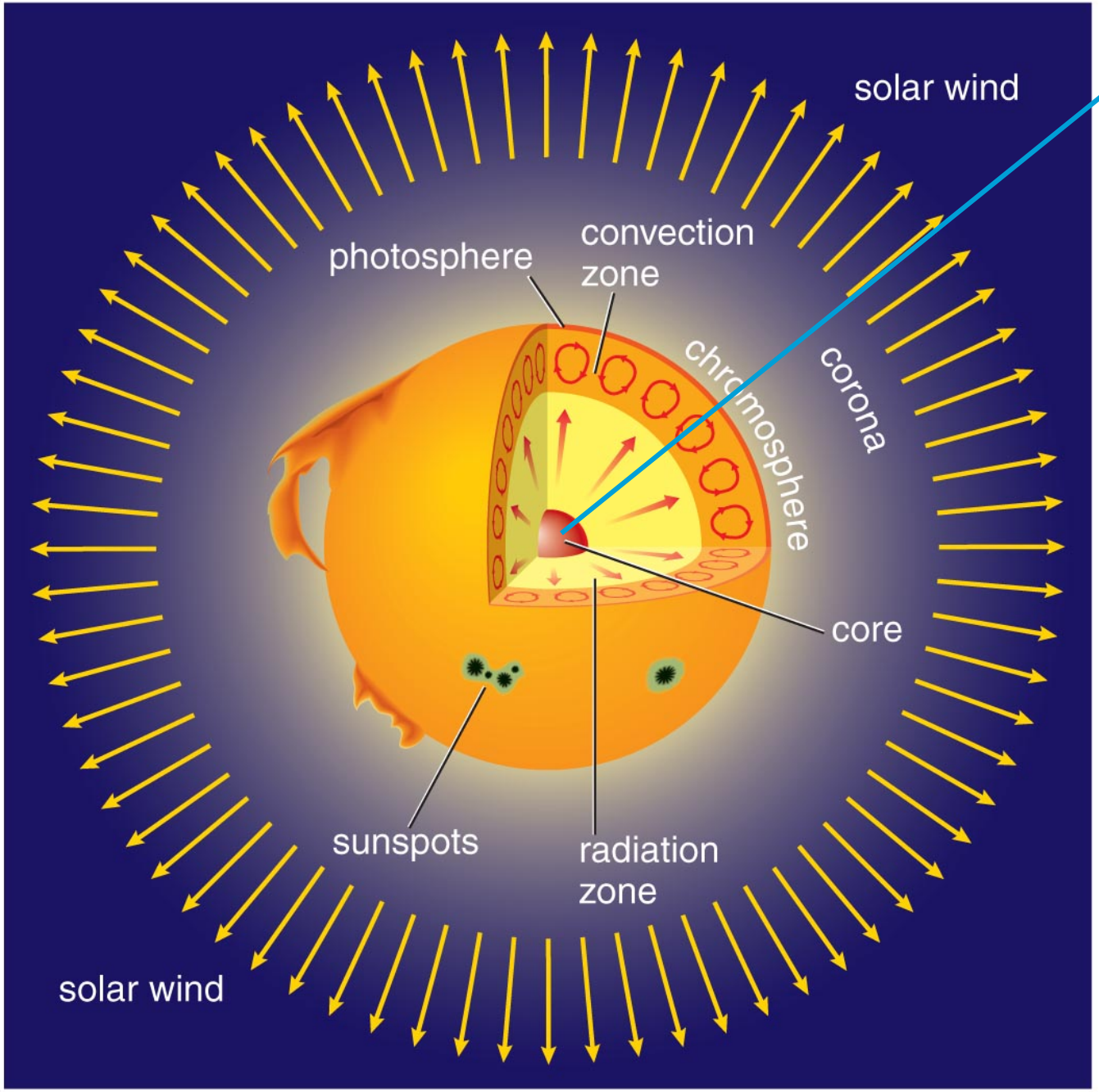
Convection Zone:

Energy transported upward by rising hot gas



Radiation Zone:

Energy transported upward by photons



Core:

Energy generated by nuclear fusion

~ 15 million K