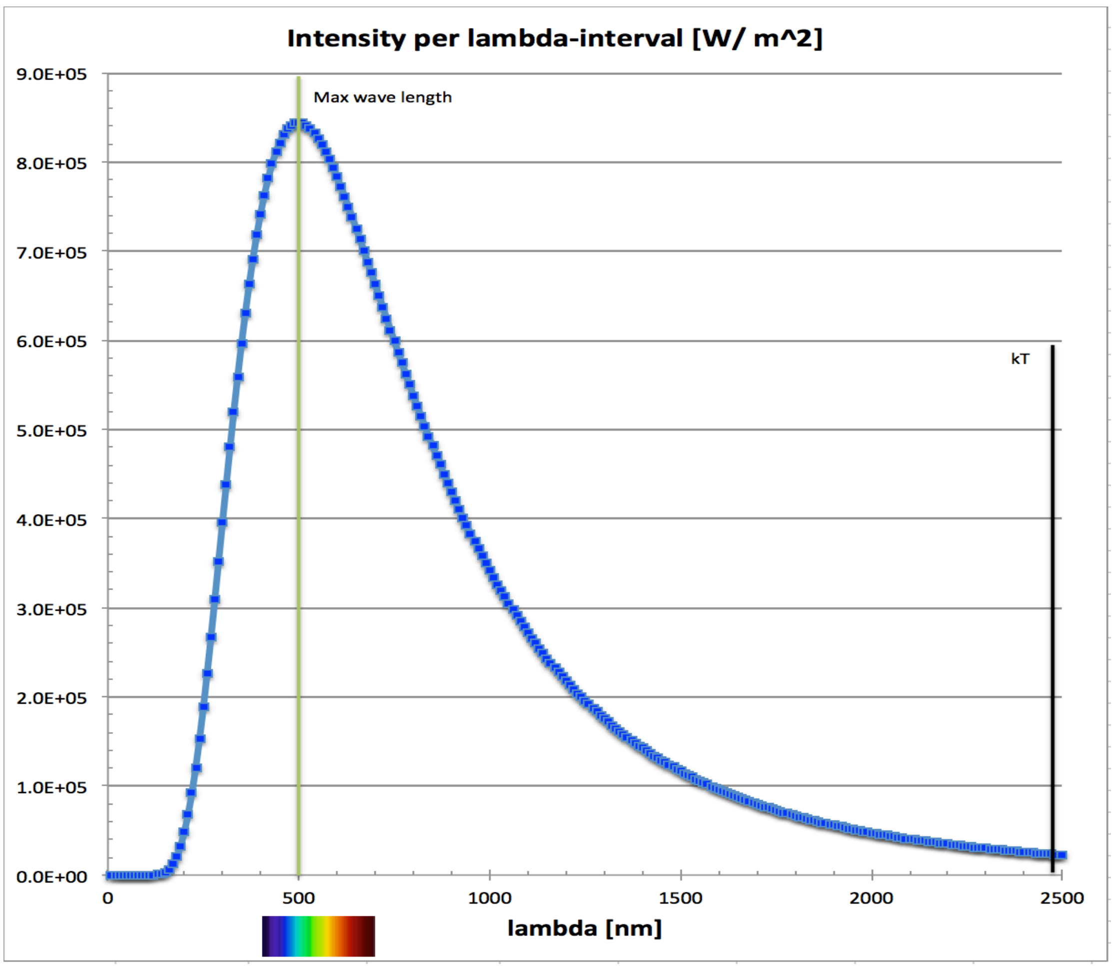
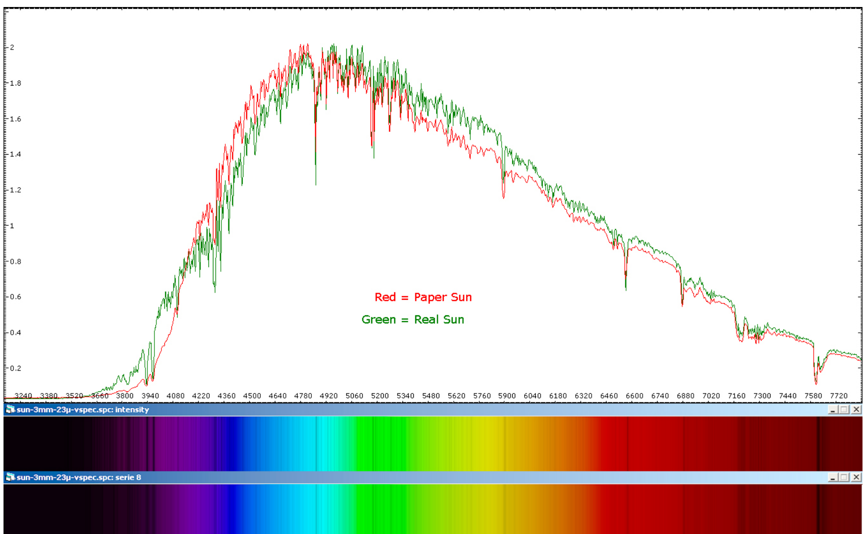
Stars

PHYS323

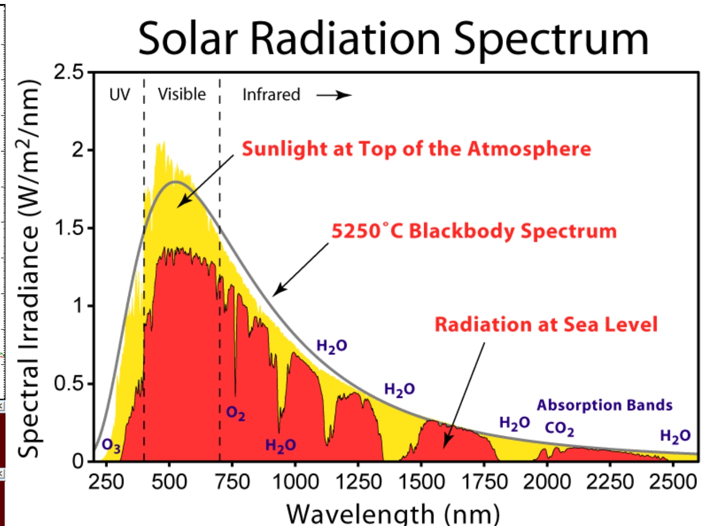
Perfect Blackbody Spectrum



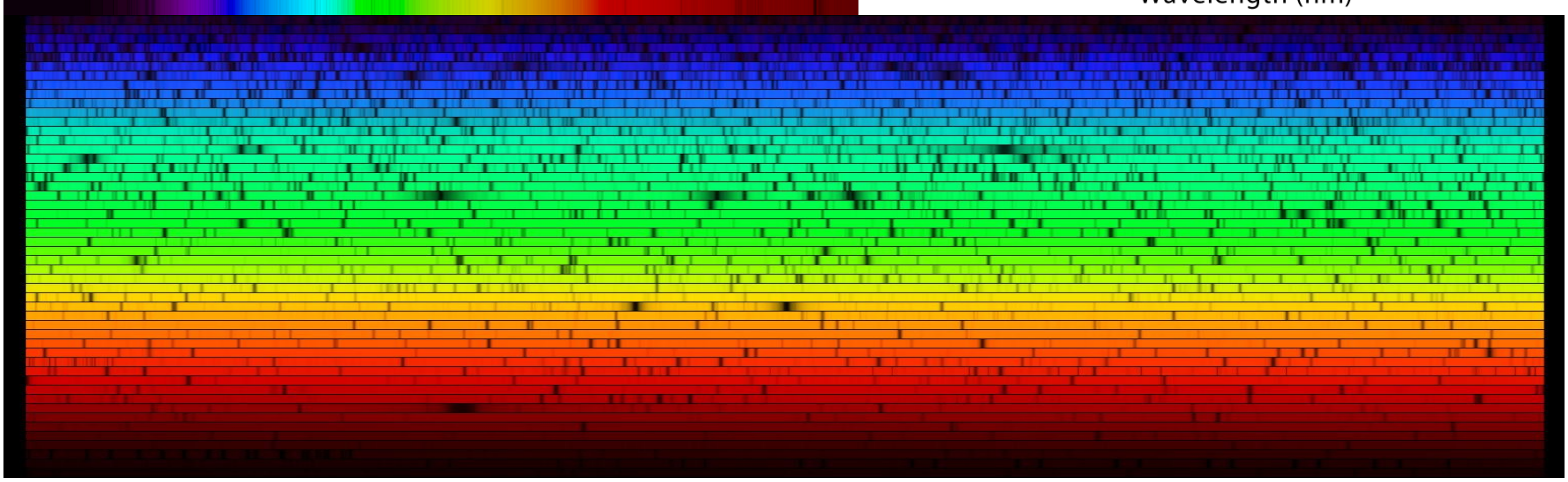
Real Sun



Red = Paper Sun
Green = Real Sun



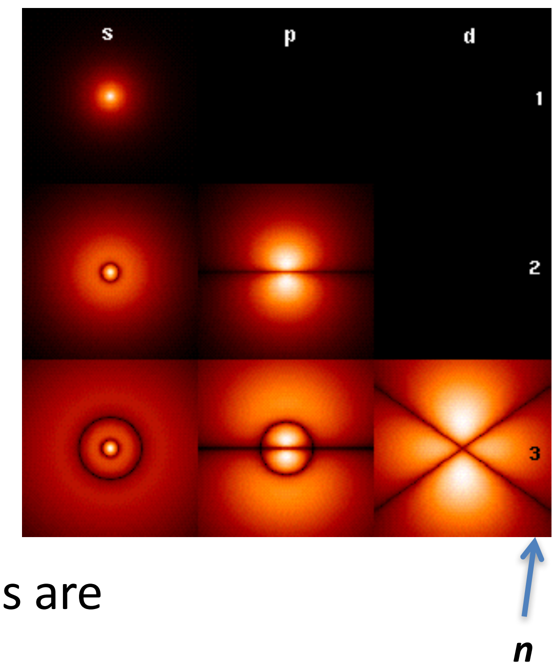
Solar Radiation Spectrum
Spectral Irradiance (W/m²/nm)
Wavelength (nm)
UV
Visible
Infrared
Sunlight at Top of the Atmosphere
5250°C Blackbody Spectrum
Radiation at Sea Level
Absorption Bands
O_3
O_2
H_2O
CO_2



Quantum Mechanics in 20 min

1. Many observables are quantized (i.e., cannot change by an arbitrarily small amount)
   1. Light waves: Energy for a specific frequency f can only be absorbed or emitted in chunks (photons) of $E = hf$
   2. Possible energy for hydrogen atom can only assume values
      $E_n = -Ry/n^2$ (see next slide)
   3. Angular momentum can only change by integer multiples of $\hbar = h/2\pi$
2. All other observables are intrinsically uncertain
   1. Position: $x \ldots x+\Delta x$
   2. Momentum: $p \ldots p+\Delta p$
   3. Heisenberg: $\Delta x \cdot \Delta p \geq \hbar/2$
3. Picture: particle motion described by waves ("wave function" ψ) that cannot be located precisely.
   Quantization $\rightleftharpoons$ Standing Waves

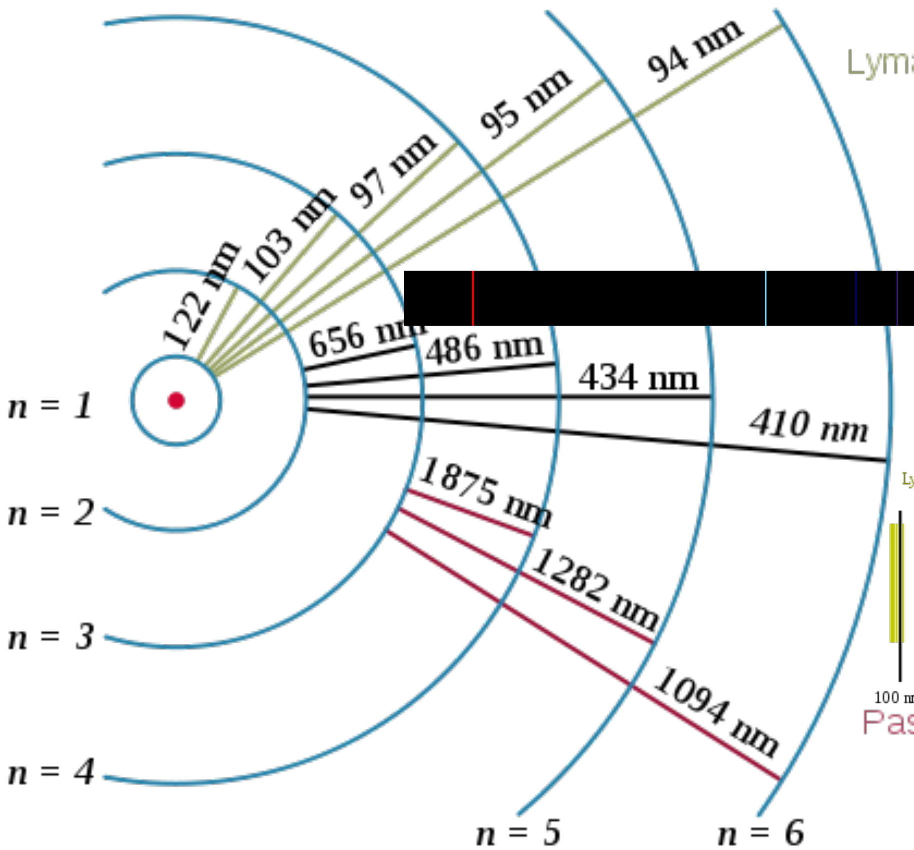
Quantum Mechanics in 20 min



1. Electron "motion" in hydrogen atom (nucleus = proton): standing wave described by wave function $\psi(\mathbf{r})$
2. Schrödinger: Wave function is solution of the equation $\mathbf{H}\psi(\mathbf{r}) = E\psi(\mathbf{r})$, where E is a possible energy "eigenvalue" and $\mathbf{H}$ is a differential operator ("The Hamiltonian")
3. Hydrogen atom: Only possible energies are $E_n = -Ry/n^2$ with $Ry = 13.6$ eV and n = integer. In general all atoms have a fixed series of possible energies E_n

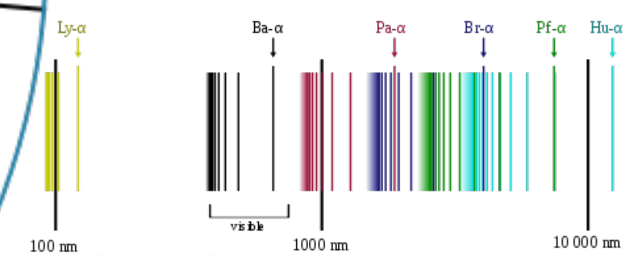
Light can only be emitted with frequencies given by $hf = E_n - E_m$

Quantum Mechanics and Line Spectra

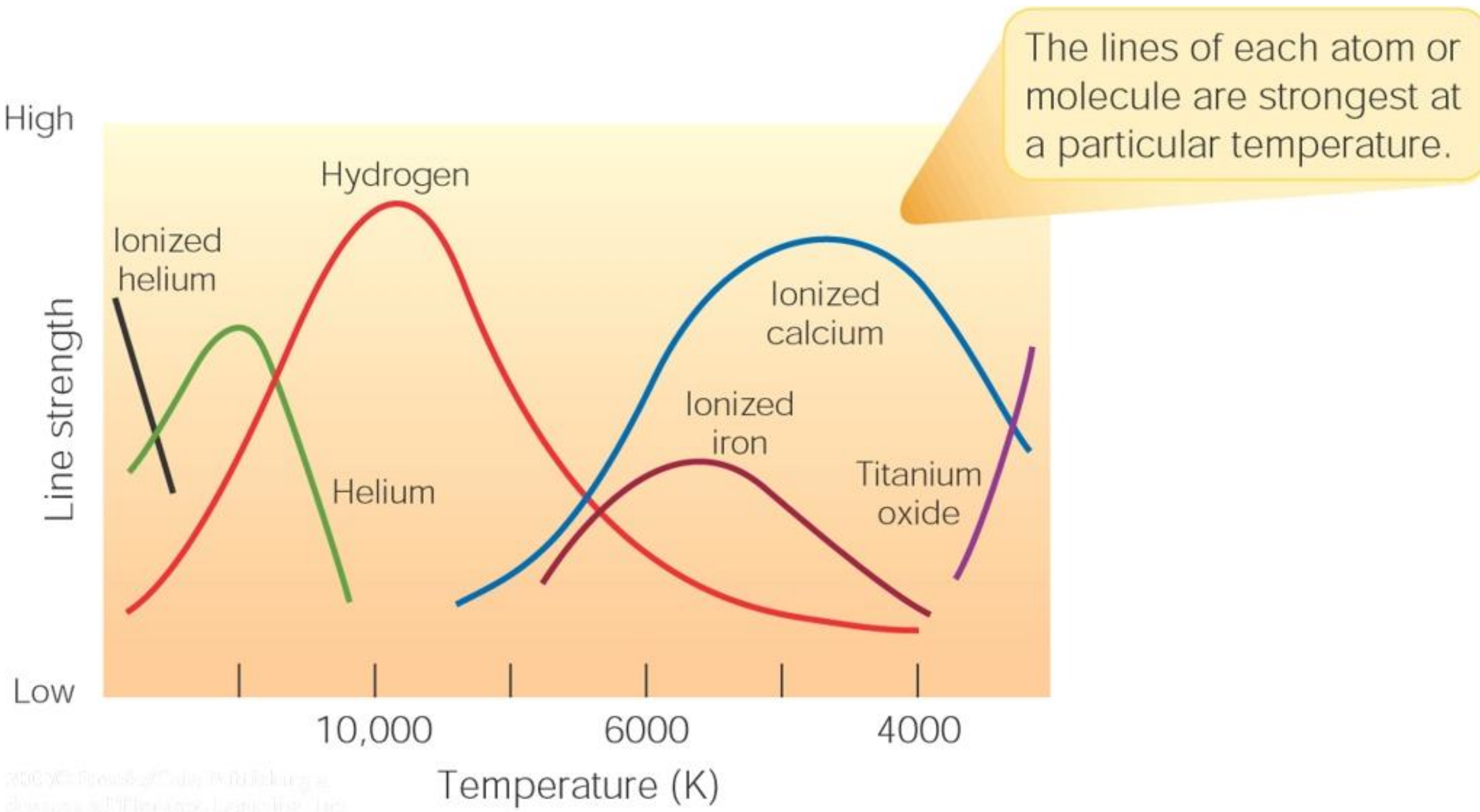


$$\Delta E(n \rightarrow m) = Ry\left(\frac{1}{m^2} - \frac{1}{n^2}\right)$$

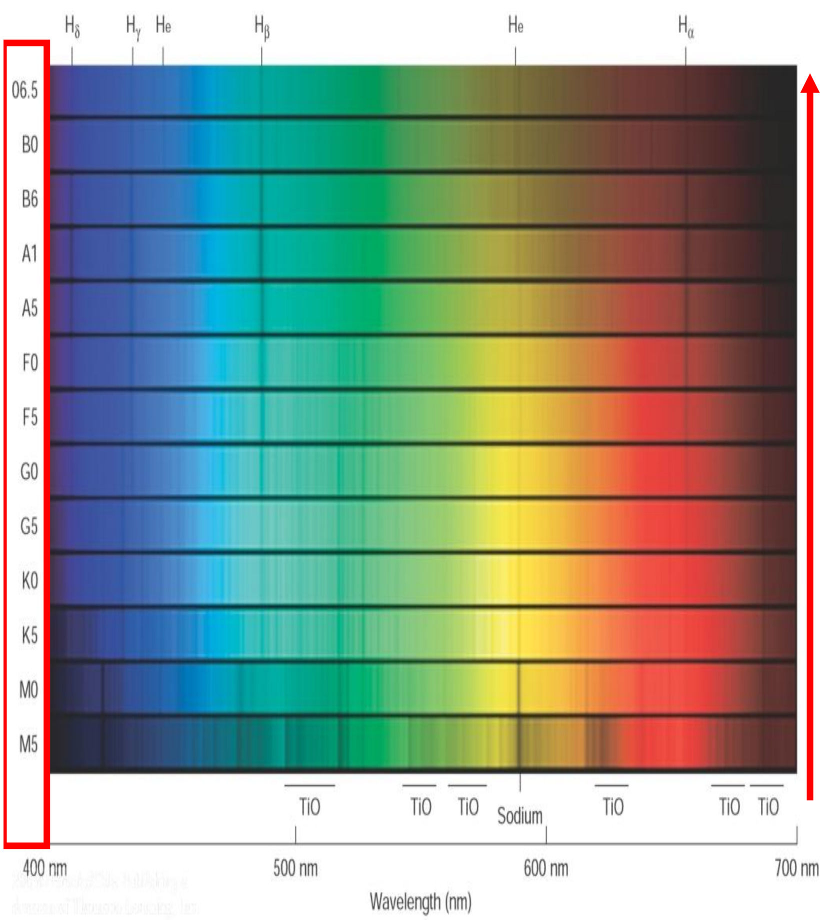
$$\lambda = \frac{hc}{\Delta E}$$

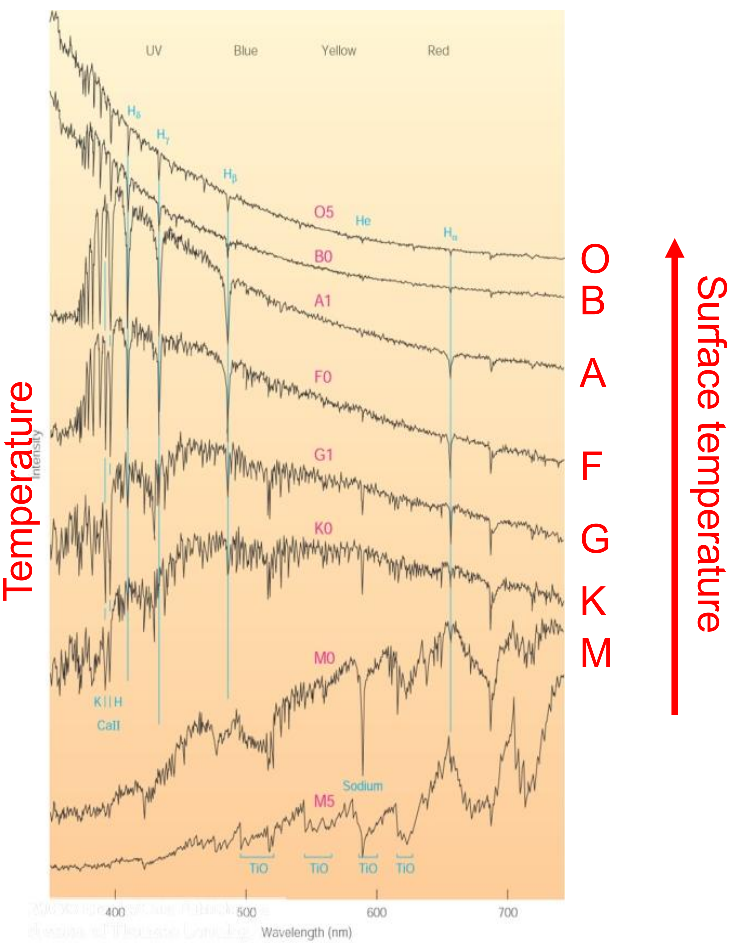


Measuring Temperature

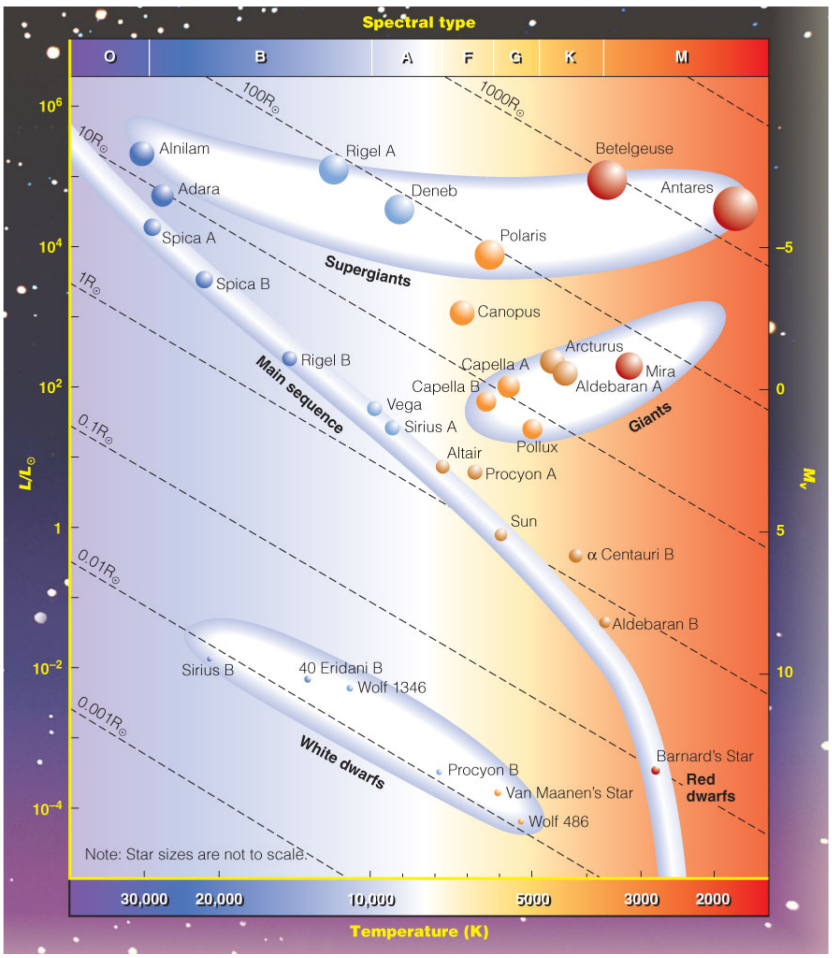


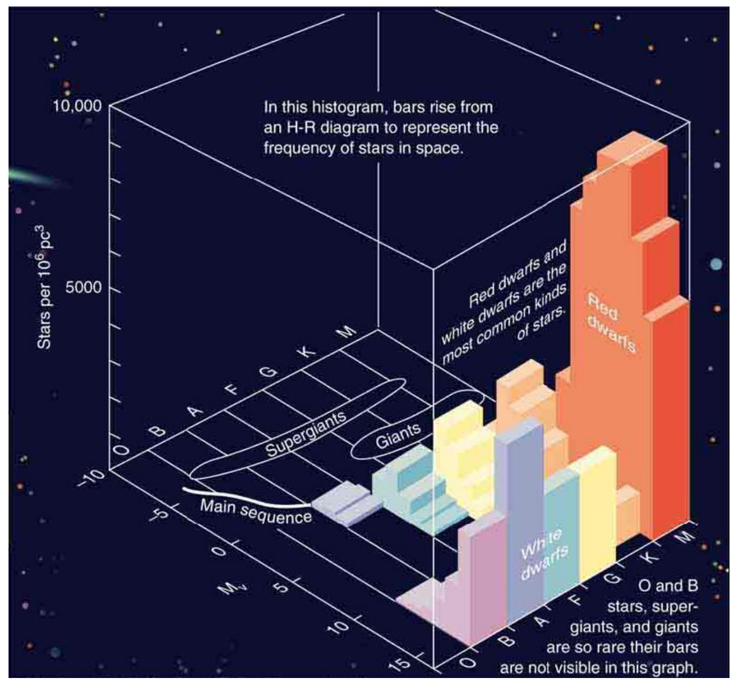
Spectral Type

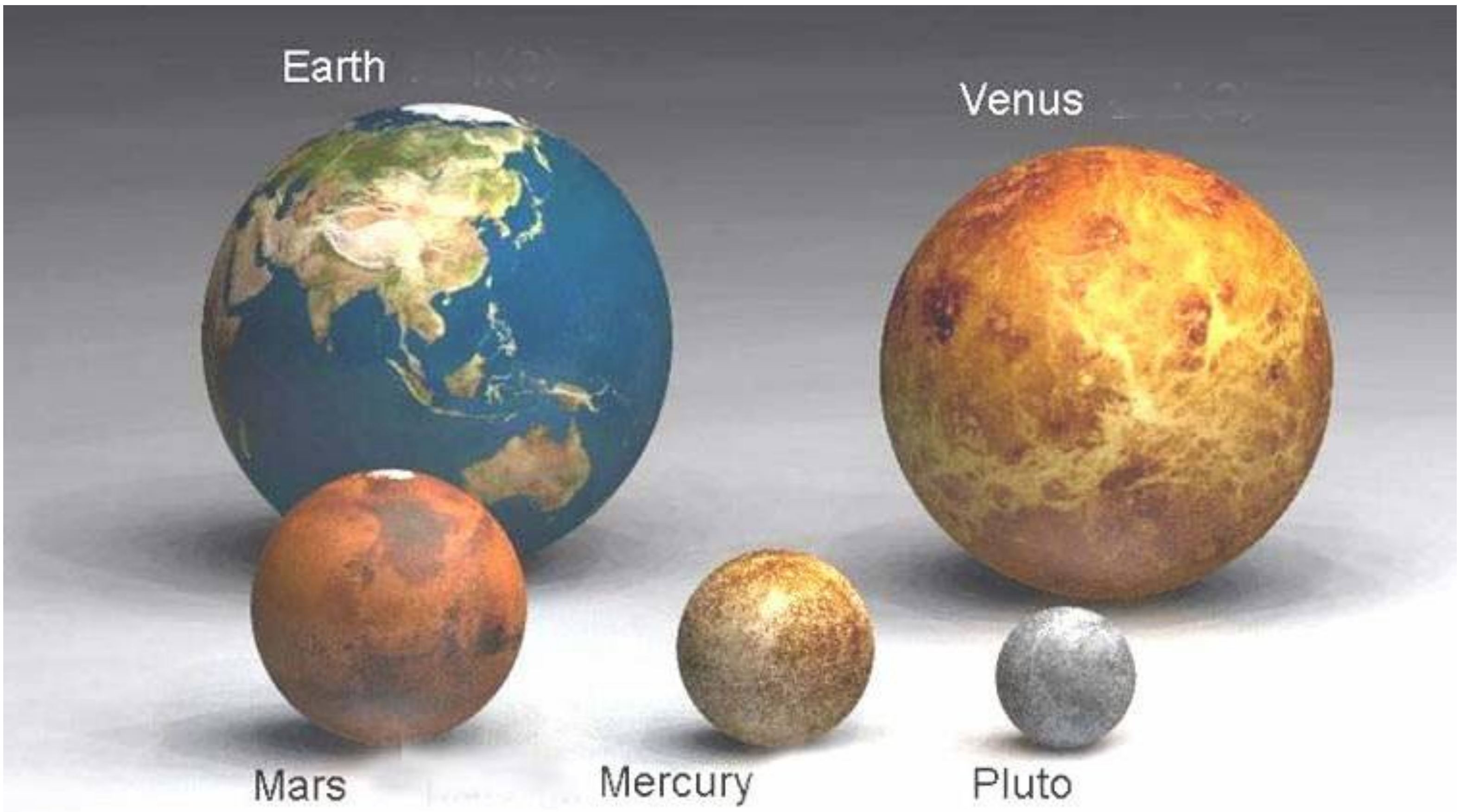


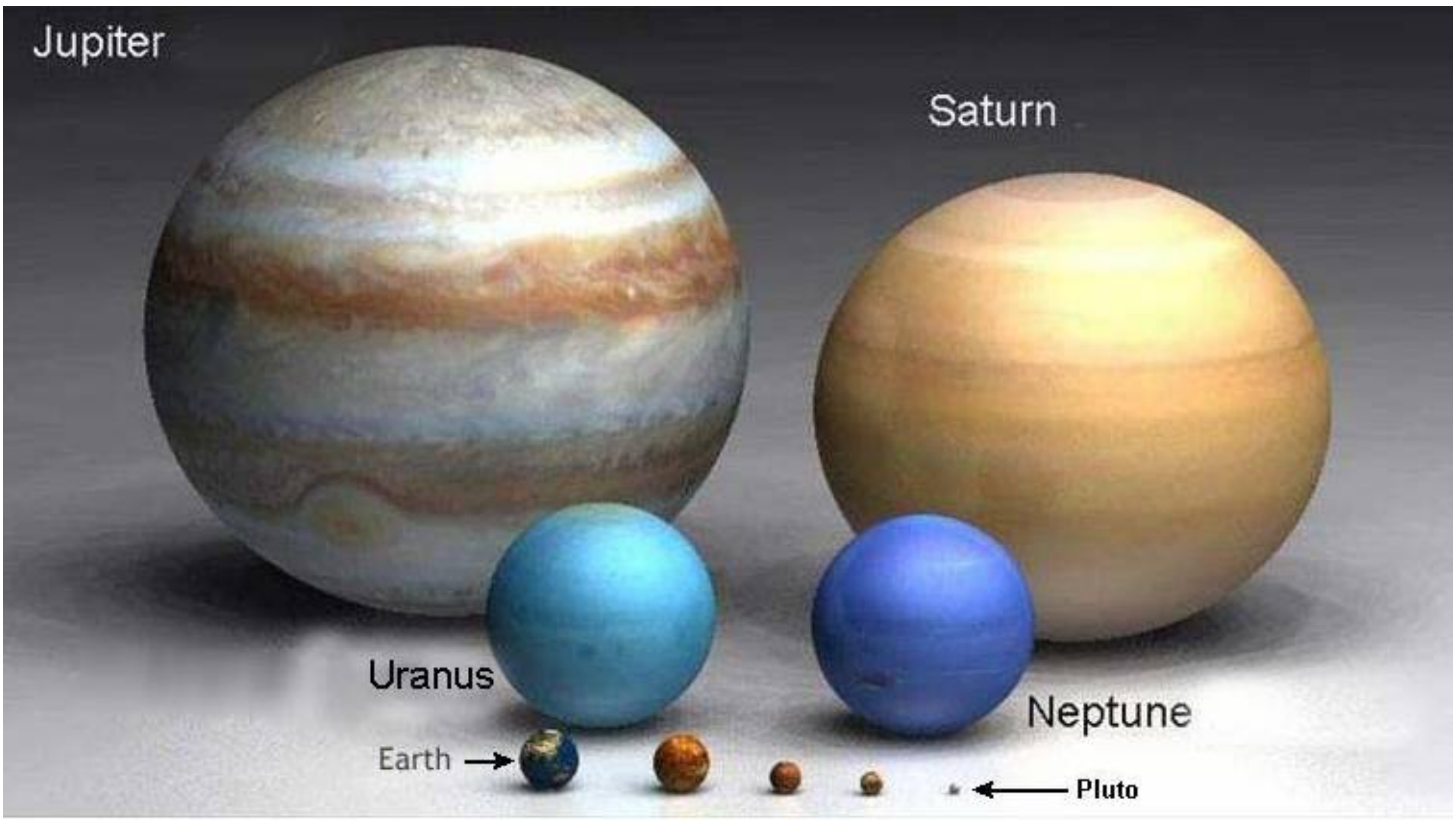


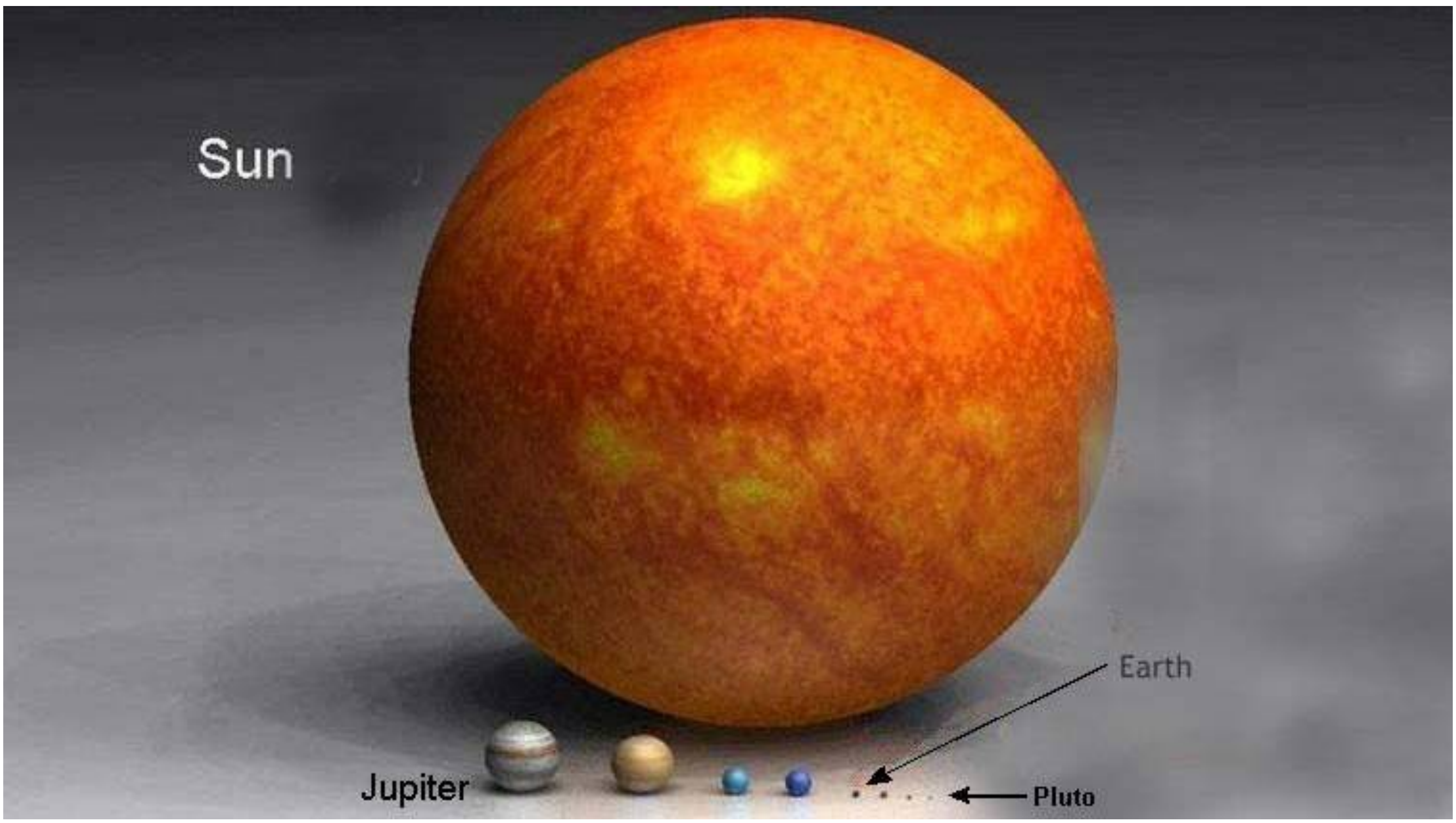
Hertzsprung-Russel Diagram

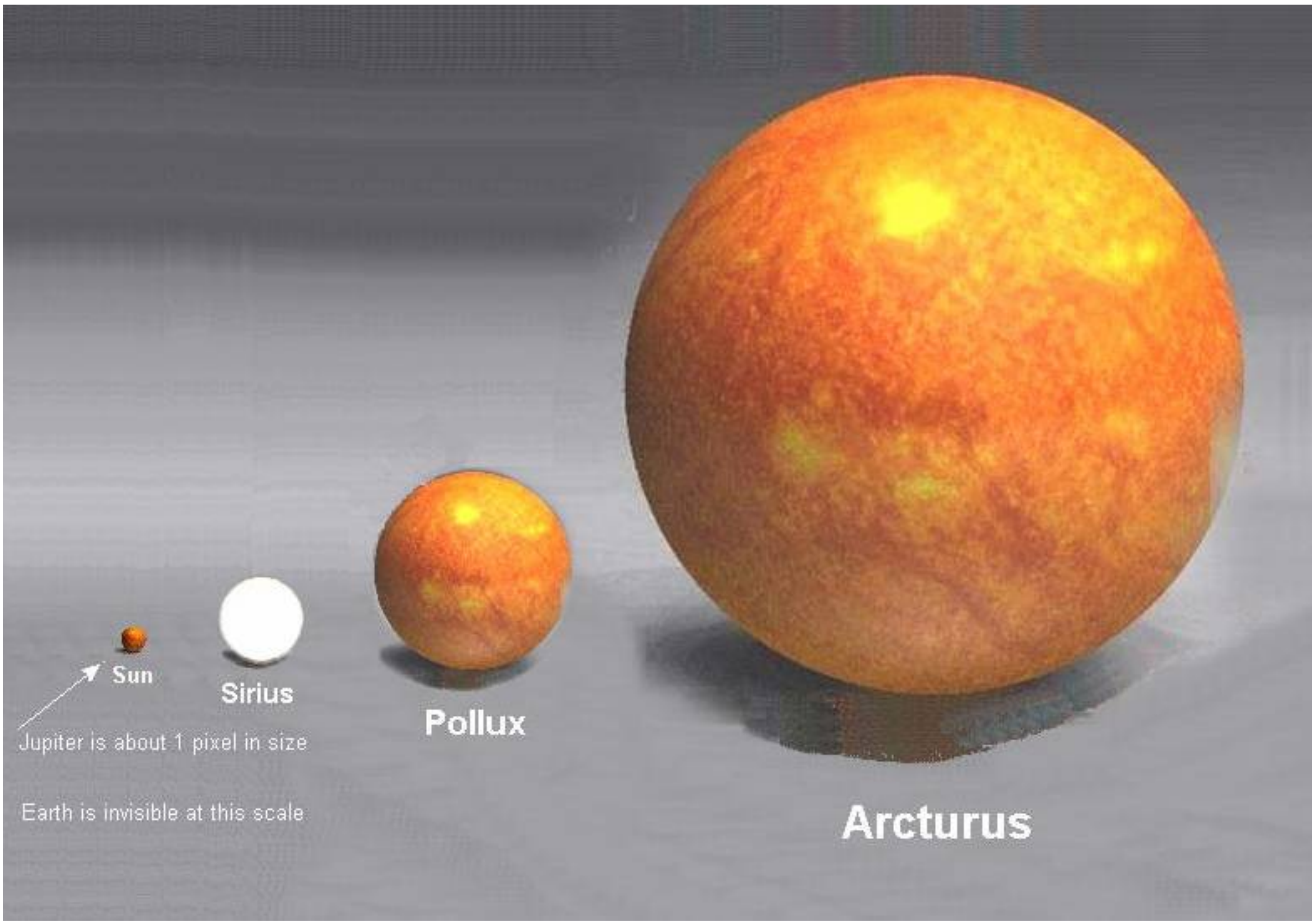


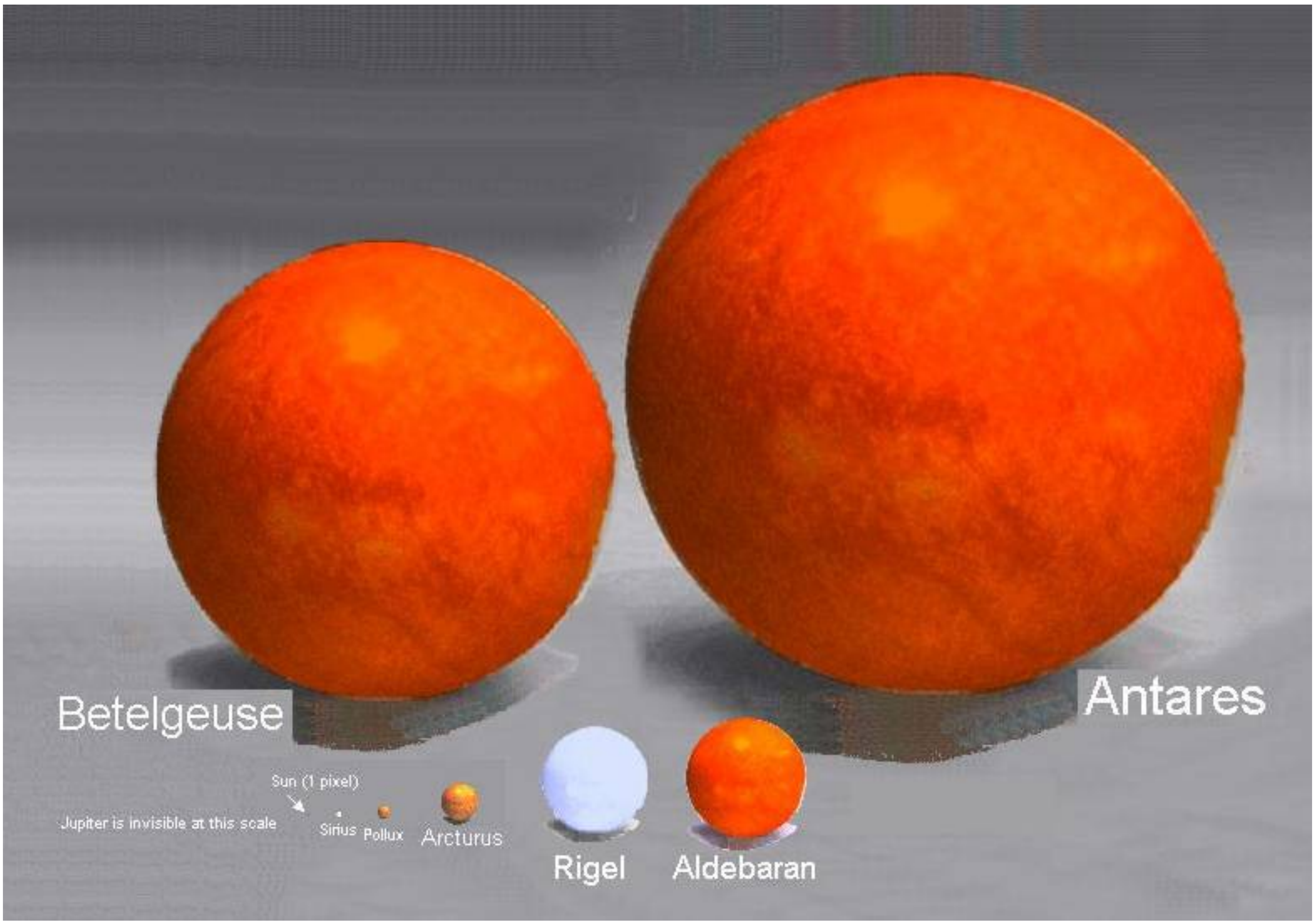



Earth
Venus
Mars
Mercury
Pluto

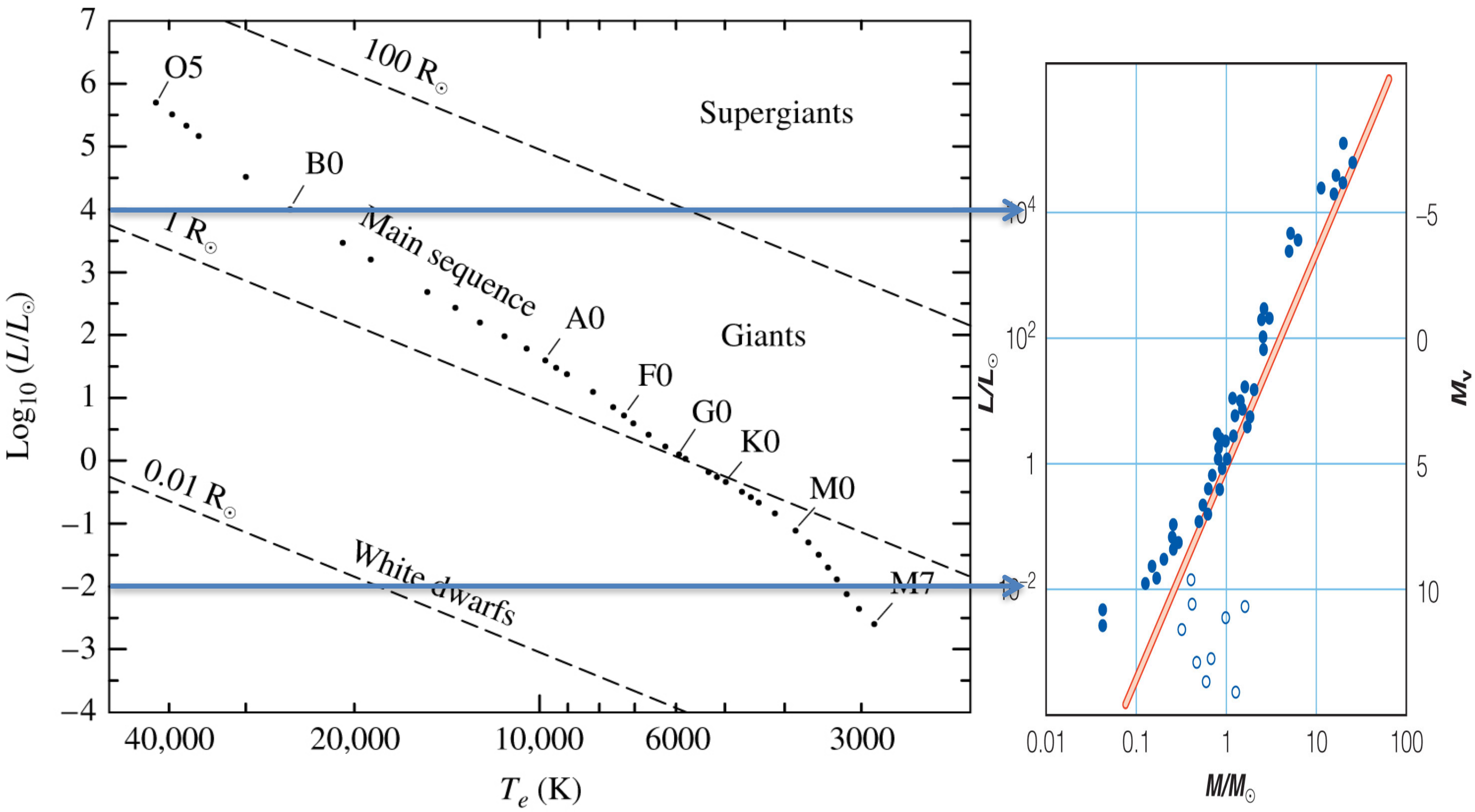

Jupiter
Saturn
Uranus
Neptune
Earth
Pluto


Sun
Earth
Jupiter
Pluto

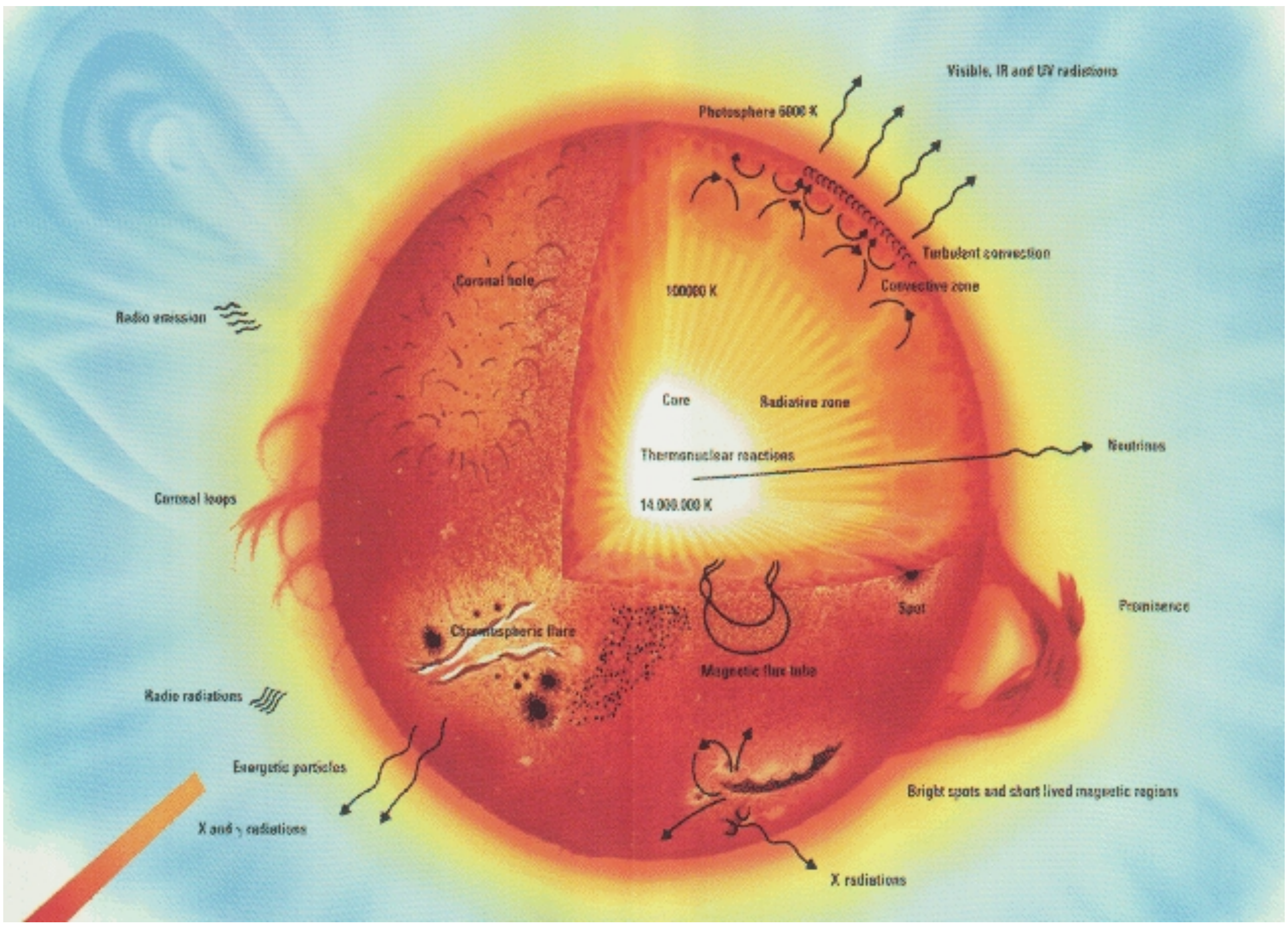

Sun
Sirius
Pollux
Arcturus
Jupiter is about 1 pixel in size
Earth is invisible at this scale


Betelgeuse
Antares
Sun (1 pixel)
Jupiter is invisible at this scale
Sirius
Pollux
Arcturus
Rigel
Aldebaran

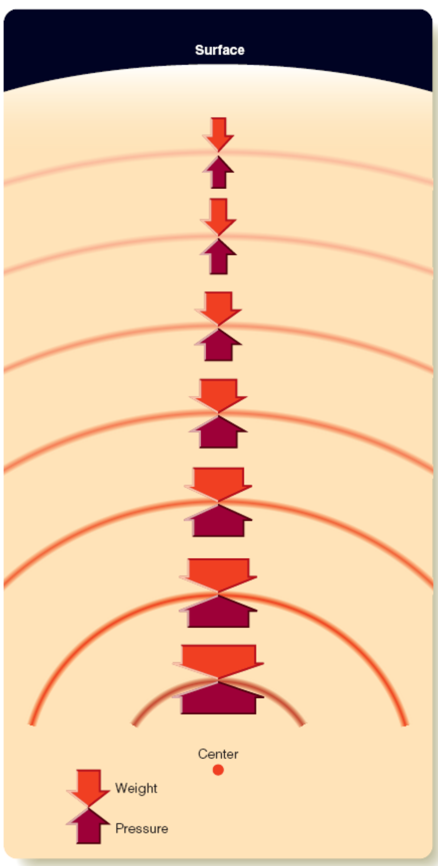
Hertzsprung-Russel Diagram

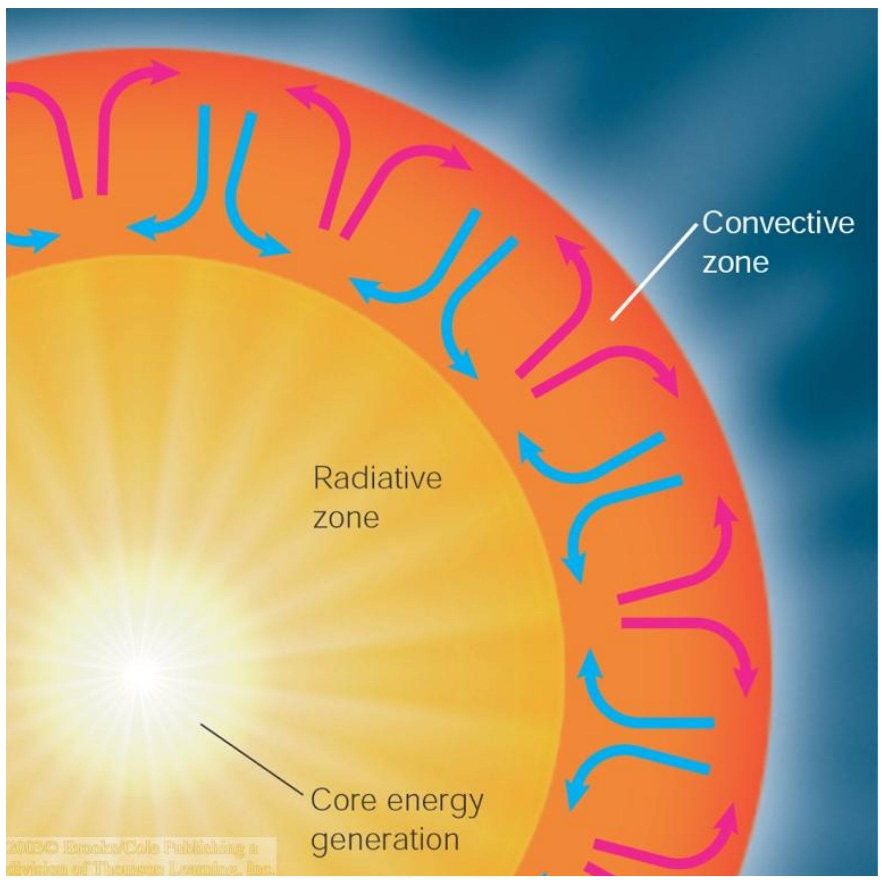


Question: How do we deduce interior structure of stars from these observations?



Interior Structure





What Powers the Sun?

- Gravitational energy (potential plus kinetic, according to virial theorem) as function of radius:

$$E_{tot} = -\frac{3}{10}\frac{GM^2}{R}$$

- Therefore, maximum amount of energy "generated" by Sun through contraction to present radius:

$$E_{tot} = -\frac{3}{10}\frac{6.674\cdot 10^{-11}(1.989\cdot 10^{30})^2}{6.955\cdot 10^{8}}\ \text{J} = 1.14\cdot 10^{41}\ \text{J}$$

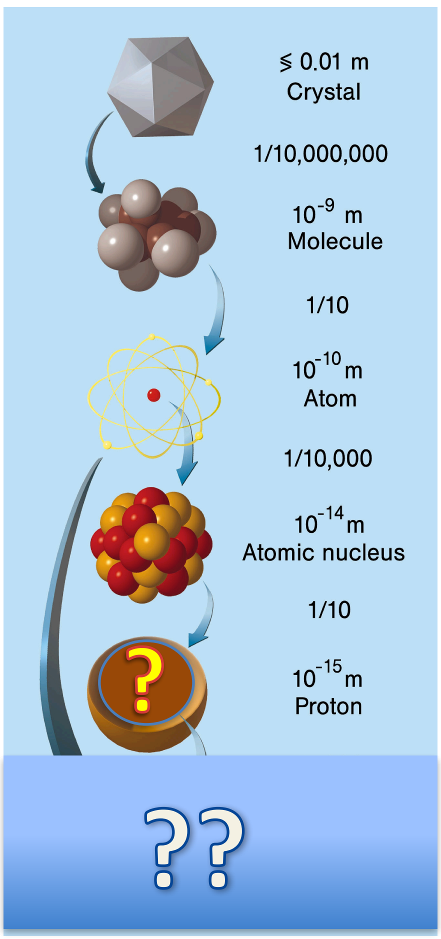
- Energy actually radiated by Sun over last 4.5 B yrs

$$E_{rad} = L_{Sun}\cdot T = 3.84\cdot 10^{26}\ \text{W}\ \cdot\ 1.42\cdot 10^{17}\ \text{s} = 5.45\cdot 10^{43}\ \text{J}$$

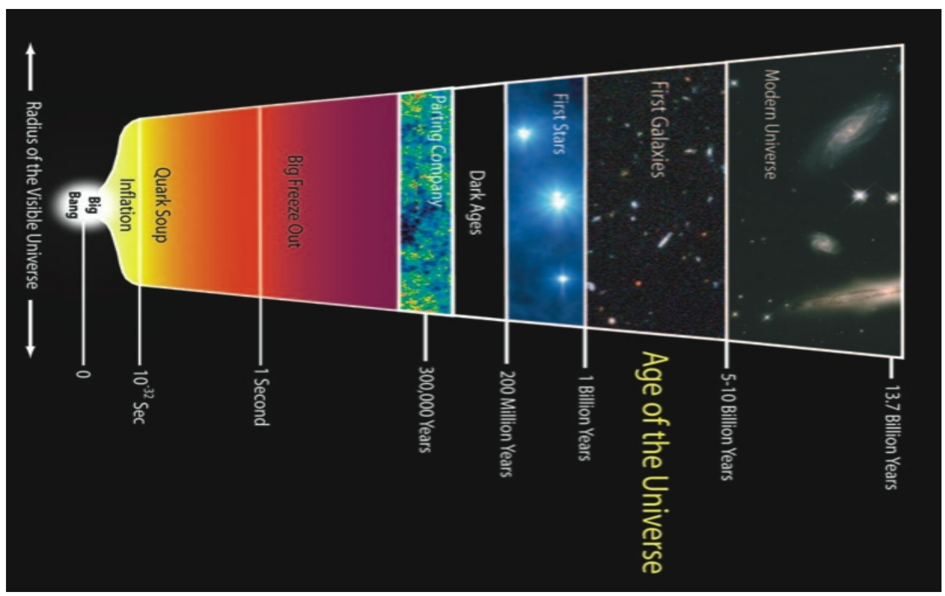
  = 500 times more! (Or Sun must be less than 9 M yrs old!)

- Solution: Must be something else → nuclear fusion

The Structure of Matter

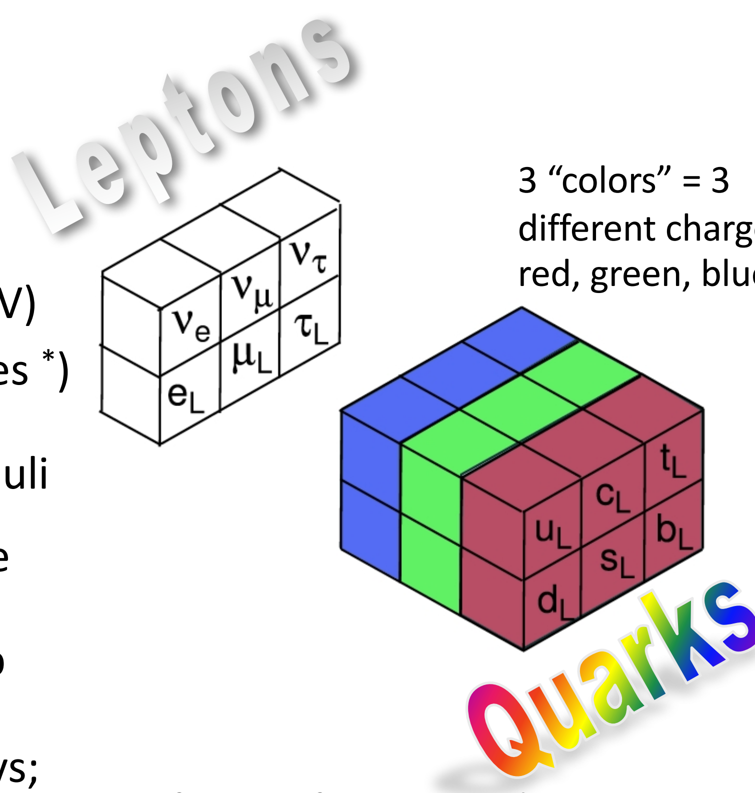


- What is the Universe made off?
- What are the most fundamental objects in Nature?
- What particles where there in the beginning (right after the big bang)?
- How do they interact?
- How do they form composite objects?



Matter Particles

- Make up visible matter
- Pointlike ($<10^{-18}$ m), Fundamental *)
- Have mass (from < ½ eV to 178,000,000,000 eV = 178 GeV)
- Distinct from their antiparticles *)
- Fermions (Spin ½) ⇒ they "defend" their space (Pauli Principle) and can only be created in particle-antiparticle pairs
- Can be "virtual", but make up matter being (nearly) "real"
- "stable" (against strong decays; lifetimes from ∞ to 10^{-24} s)



3 "colors" = 3 different charges: red, green, blue

x2 for R, x2 for antiparticles

*) Until further notice

Forces and Force Carriers

- Mediate Interactions (Forces) - form "Waves"
- Pointlike, Fundamental
- Massless *)
- Some are their own antiparticles (photon, Z^0, graviton)
- Spin 1, 2 -> Bosons (tend to cluster together, can be produced in arbitrary numbers)
- Can be real, but carry forces as virtual particles
- Some are absolutely stable (γ, gluons, gravitons)

*) See next slide

BOSONS force carriers spin = 0, 1, 2, …

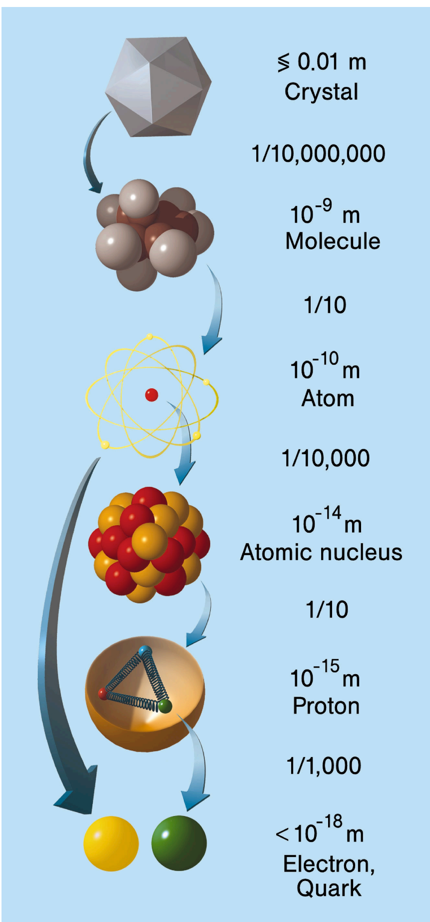
Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

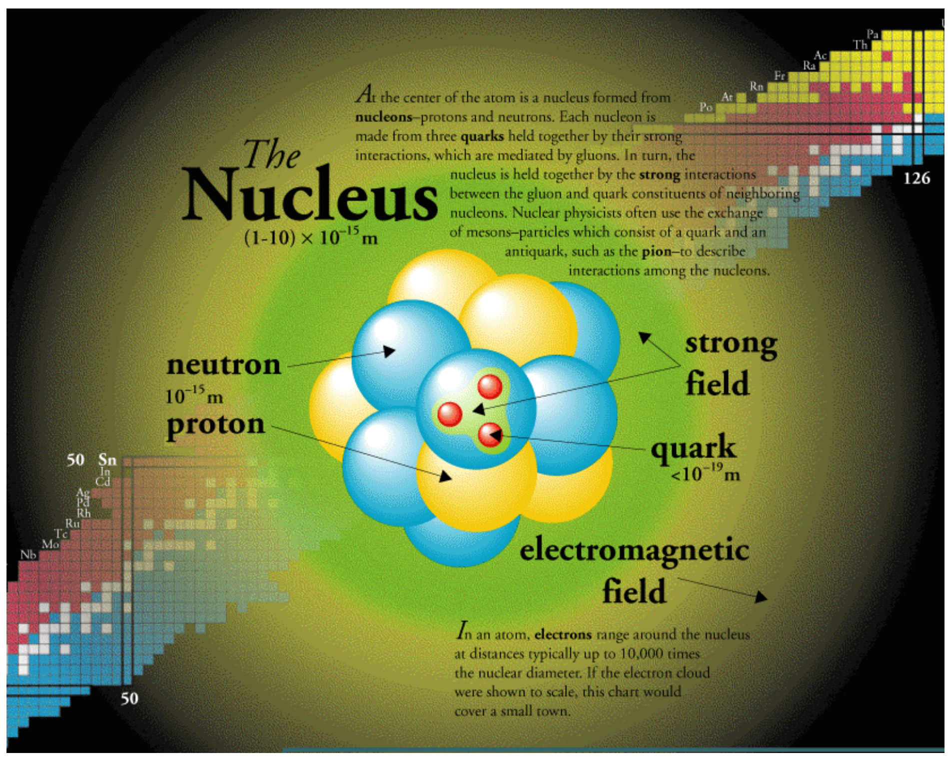
Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Gravitation spin = 2		
Name	Mass GeV/c^2	Electric charge
g graviton	0	0

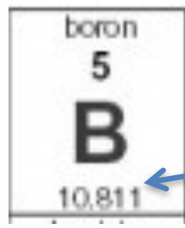
Note: gluons come in 8 possible combinations of color/anticolor (9th is "sterile" – doesn't exist)

The Structure of Matter





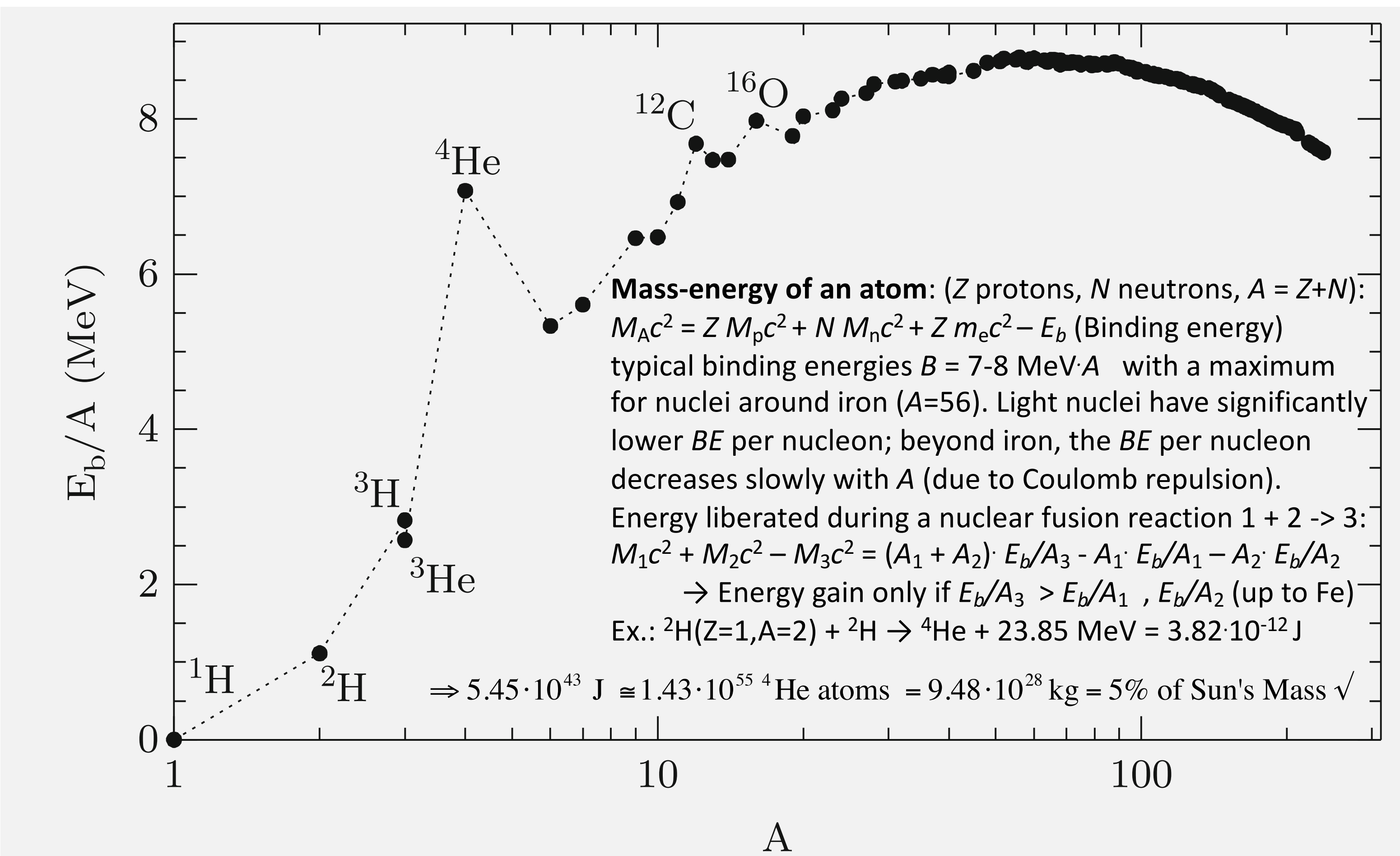
Periodic Table



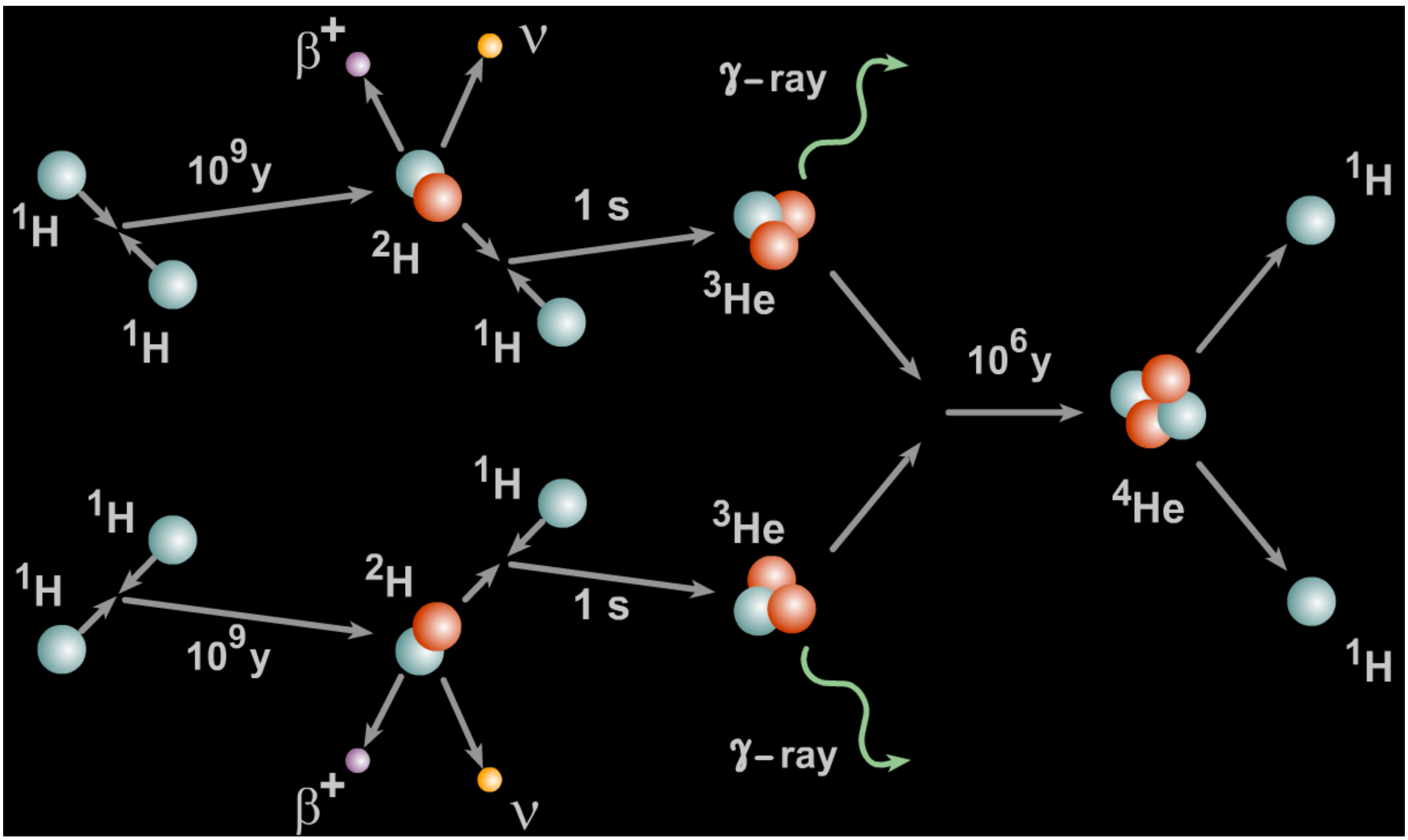
hydrogen 1 H 1.0079																		helium 2 He 4.0026
lithium 3 Li 6.941	beryllium 4 Be 9.0122												boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	neon 10 Ne 20.180
sodium 11 Na 22.990	magnesium 12 Mg 24.305												aluminium 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453	argon 18 Ar 39.948
potassium 19 K 39.098	calcium 20 Ca 40.078		scandium 21 Sc 44.956	titanium 22 Ti 47.867	vanadium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.39	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904	krypton 36 Kr 83.80
rubidium 37 Rb 85.468	strontium 38 Sr 87.62		yttrium 39 Y 88.906	zirconium 40 Zr 91.224	niobium 41 Nb 92.906	molybdenum 42 Mo 95.94	technetium 43 Tc [98]	ruthenium 44 Ru 101.07	rhodium 45 Rh 102.91	palladium 46 Pd 106.42	silver 47 Ag 107.87	cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.60	iodine 53 I 126.90	xenon 54 Xe 131.29
caesium 55 Cs 132.91	barium 56 Ba 137.33	57-70 *	lutetium 71 Lu 174.97	hafnium 72 Hf 178.49	tantalum 73 Ta 180.95	tungsten 74 W 183.84	rhenium 75 Re 186.21	osmium 76 Os 190.23	iridium 77 Ir 192.22	platinum 78 Pt 195.08	gold 79 Au 196.97	mercury 80 Hg 200.59	thallium 81 Tl 204.38	lead 82 Pb 207.2	bismuth 83 Bi 208.98	polonium 84 Po [209]	astatine 85 At [210]	radon 86 Rn [222]
francium 87 Fr [223]	radium 88 Ra [226]	89-102 **	lawrencium 103 Lr [262]	rutherfordium 104 Rf [261]	dubnium 105 Db [262]	seaborgium 106 Sg [266]	bohrium 107 Bh [264]	hassium 108 Hs [269]	meitnerium 109 Mt [268]	ununnilium 110 Uun [271]	unununium 111 Uuu [272]	ununbium 112 Uub [277]		ununquadium 114 Uuq [289]				

*Lanthanide series	lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm [145]	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70 Yb 173.04
**Actinide series	actinium 89 Ac [227]	thorium 90 Th 232.04	protactinium 91 Pa 231.04	uranium 92 U 238.03	neptunium 93 Np [237]	plutonium 94 Pu [244]	americium 95 Am [243]	curium 96 Cm [247]	berkelium 97 Bk [247]	californium 98 Cf [251]	einsteinium 99 Es [252]	fermium 100 Fm [257]	mendelevium 101 Md [258]	nobelium 102 No [259]

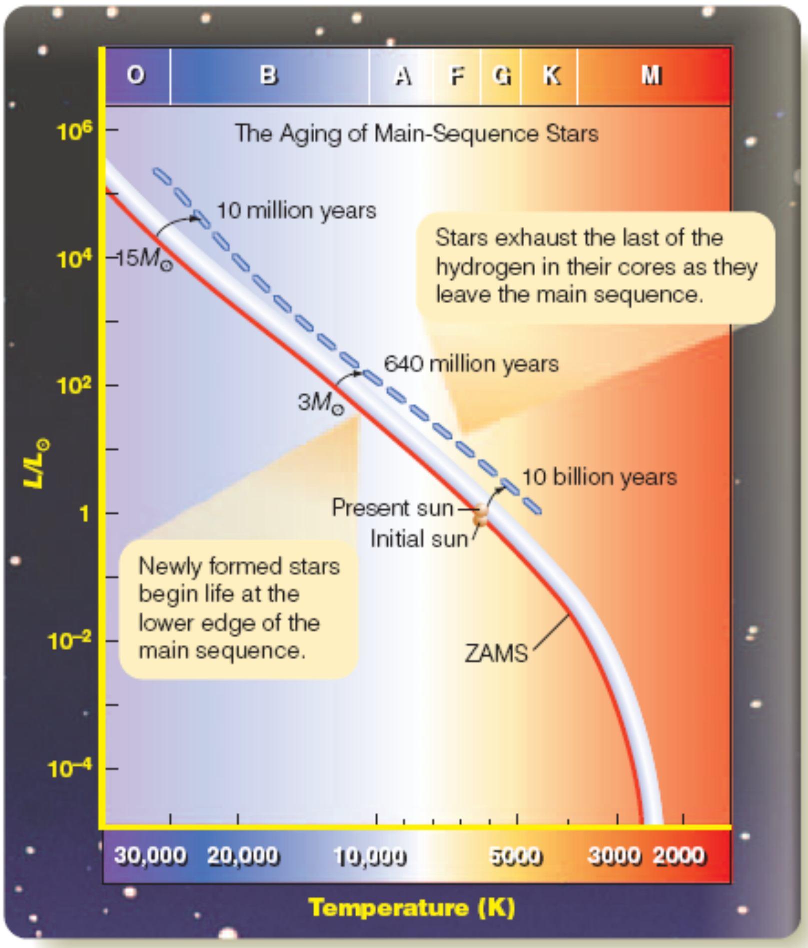
Nuclear Binding energies



Nuclear Power Generation



The Life of Main Sequence Stars

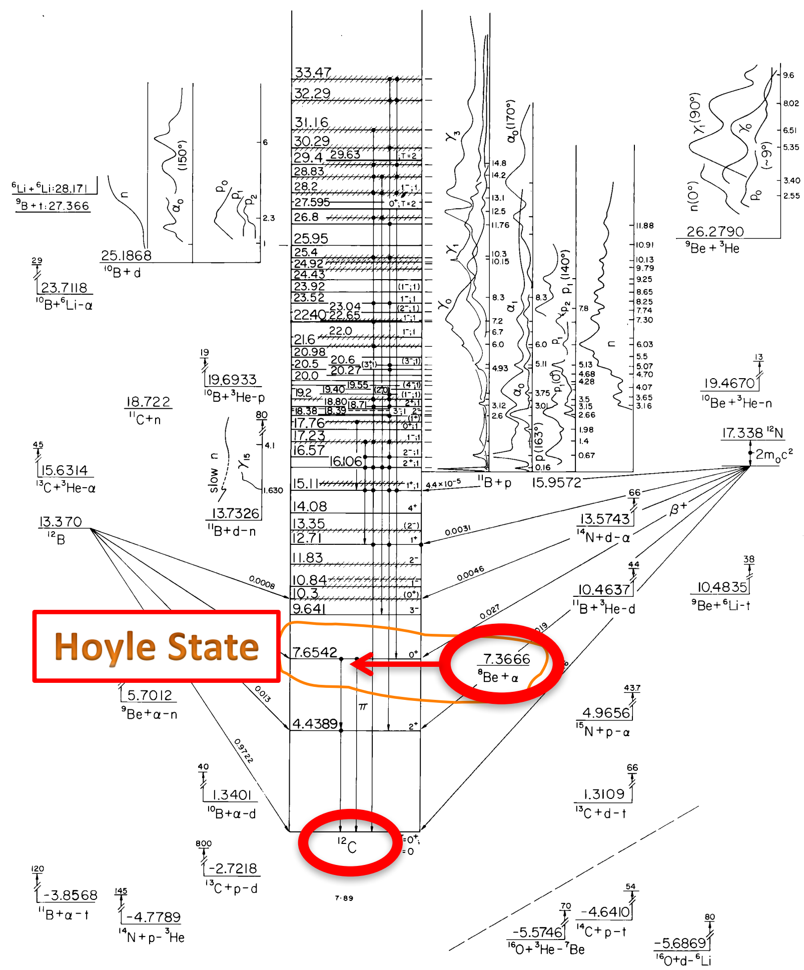


Stars gradually exhaust their hydrogen fuel.

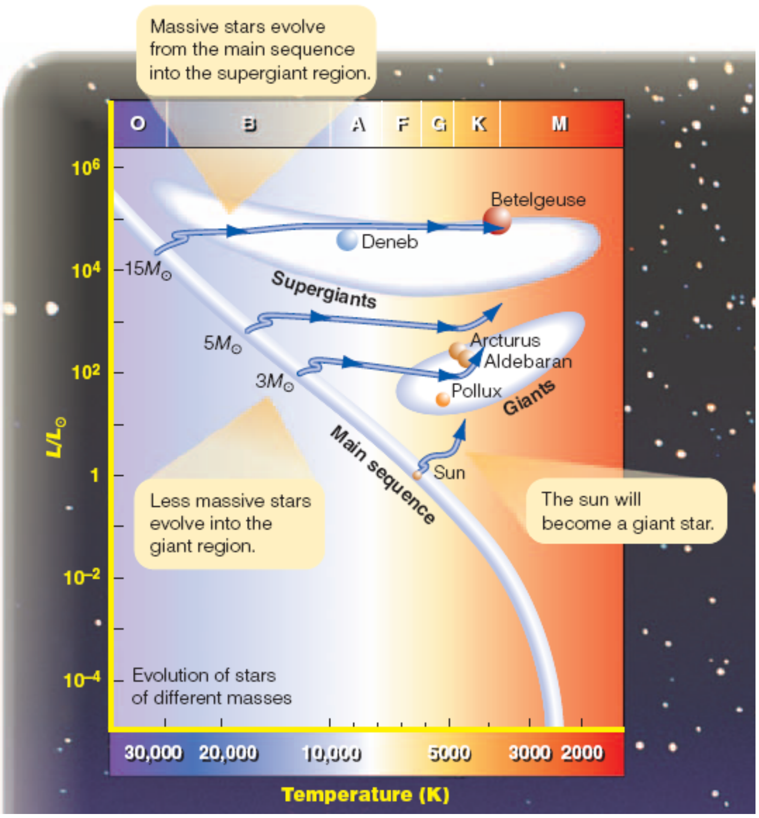
In this process of aging, they are gradually becoming brighter, evolving off the zero-age main sequence.

Helium Burning

- Requires temperatures above 10^8 K (8.6 keV)
- ^8Be is unstable -> $\alpha\alpha$! Only at high temperature are there a few ^8Be in equilibrium with ^4He (energy sink!)
- $^8Be + \alpha \rightarrow {}^{12}C$ would be too slow if not for ^{12}C excited state
- Predicted by Hoyle!
- Some α get eaten by ^{12}C -> ^{16}O admixture

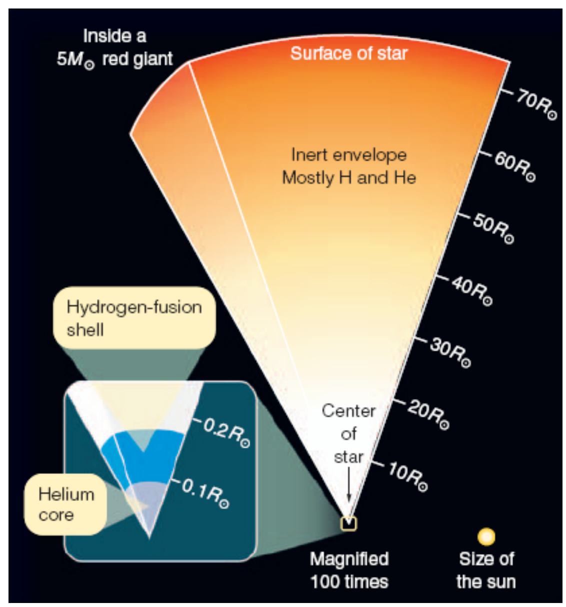


- <u>Expansion onto the Giant Branch</u>



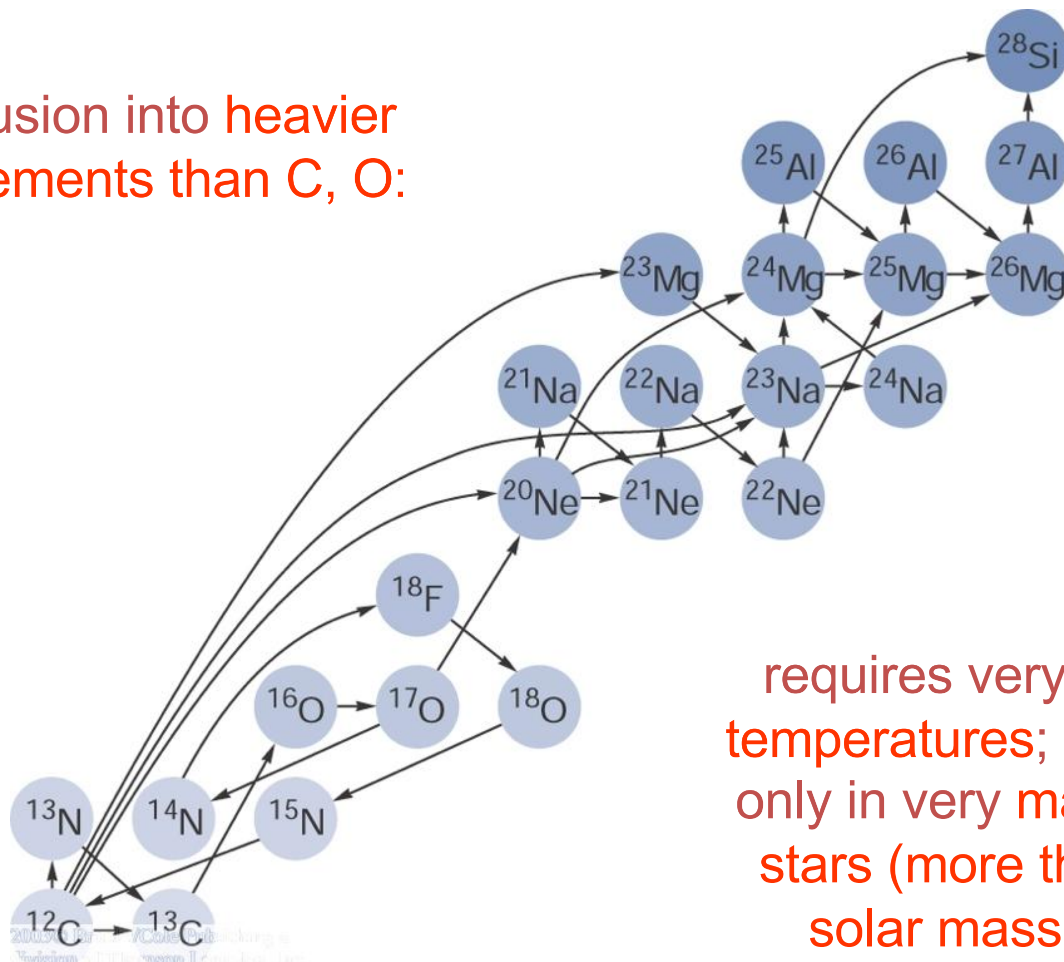
The Sun will expand beyond Earth's orbit!

Expansion and surface cooling during the phase of an inactive He core and a H- burning shell



Fusion into Heavier Elements

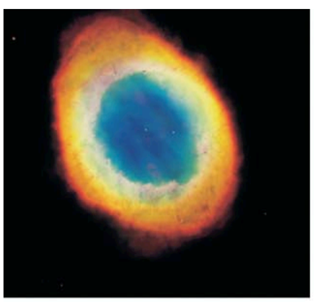
Fusion into heavier elements than C, O:



requires very high temperatures; occurs only in very massive stars (more than 8 solar masses)

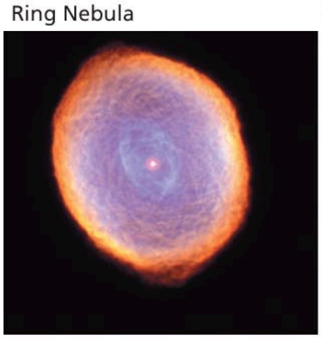
Final Stages of Giants ($\approx M_\odot$)

- Final C core collapse
- Shock wave
- Outer layers ejected
- "Planetary" Nebulae

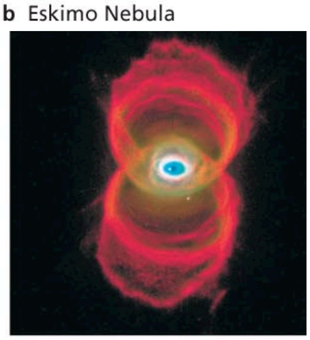


Ring Nebula

b Eskimo Nebula

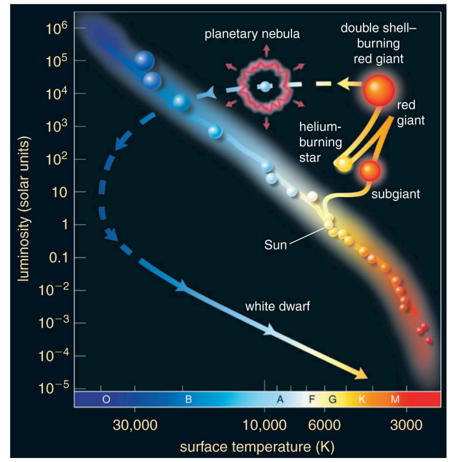


Spirograph Nebula



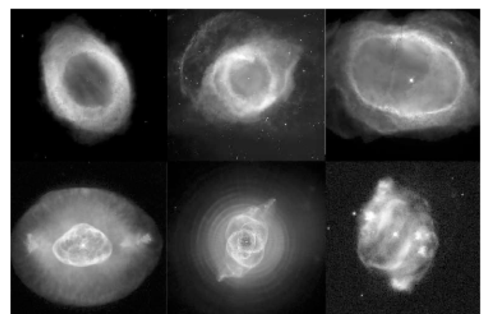
d Hourglass Nebula

White Dwarfs

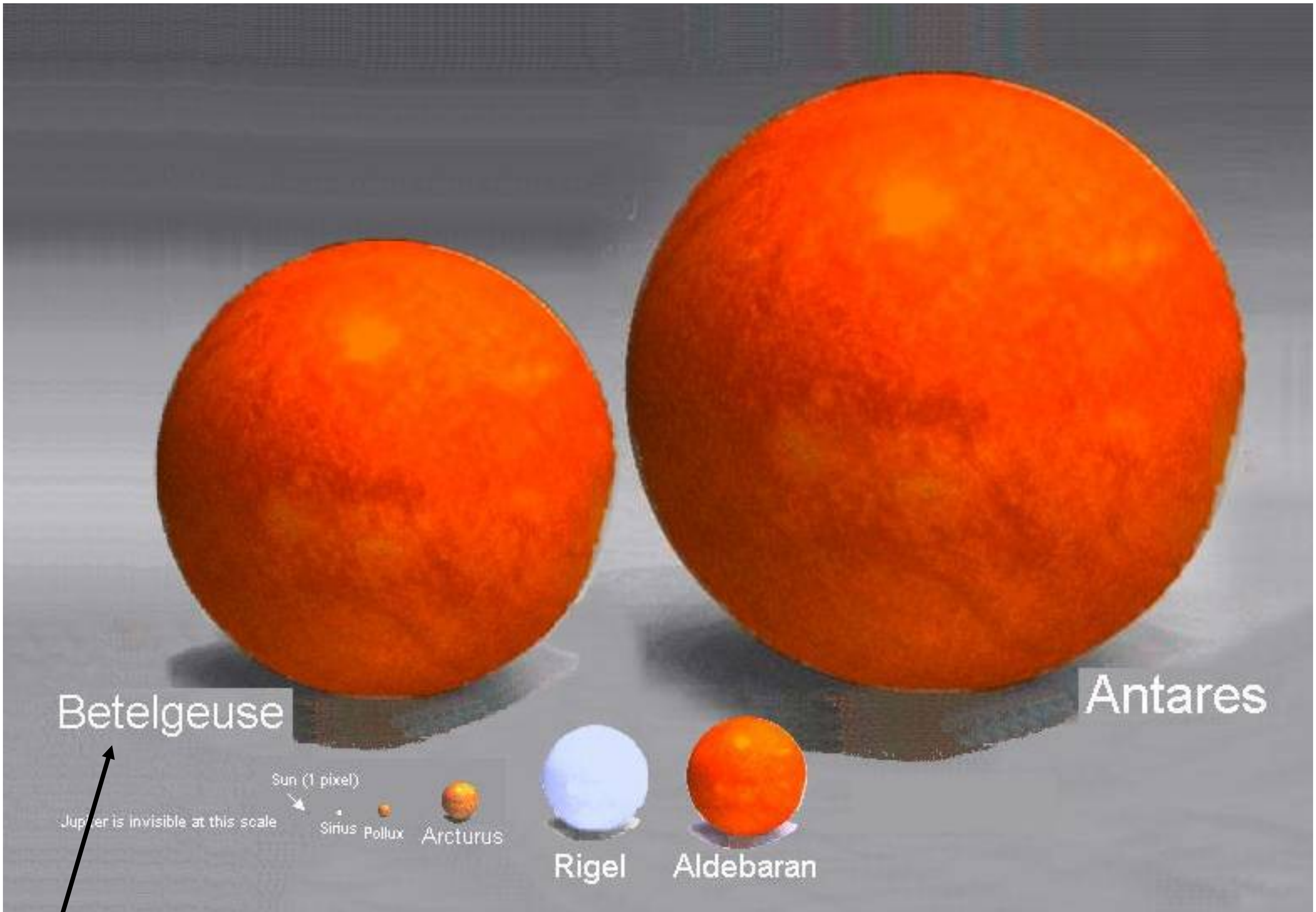


- Reminder: Last stages of sun and similar-sized stars

  Last stage: Helium burning stops, core collapses and significant fraction of mass gets ejected as planetary nebula



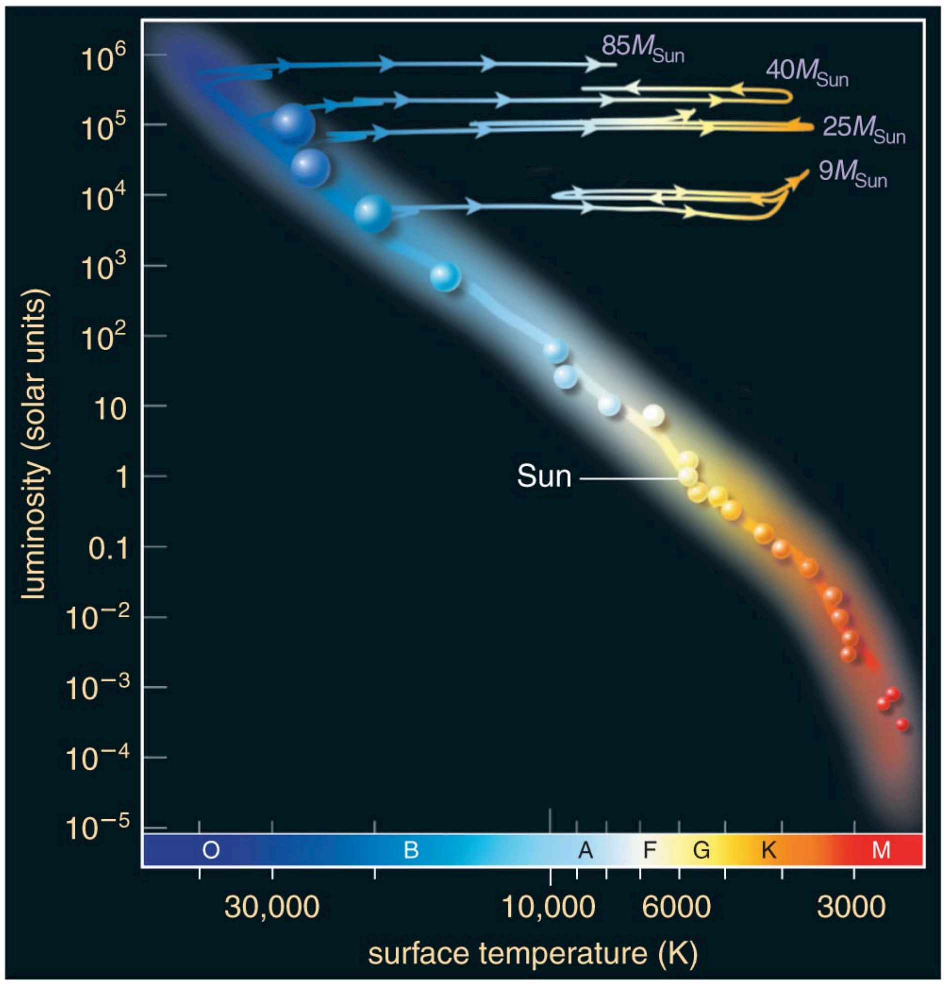
- What happens with the core after the final collapse? => White Dwarf! (Example: Sirius B)
  - Core contracts until "Fermi pressure" of electrons balances gravitational attraction
  - Final size typically <1% of present solar radius => Density 10^6 times larger than that of the sun! Temperature 10^7 K at center



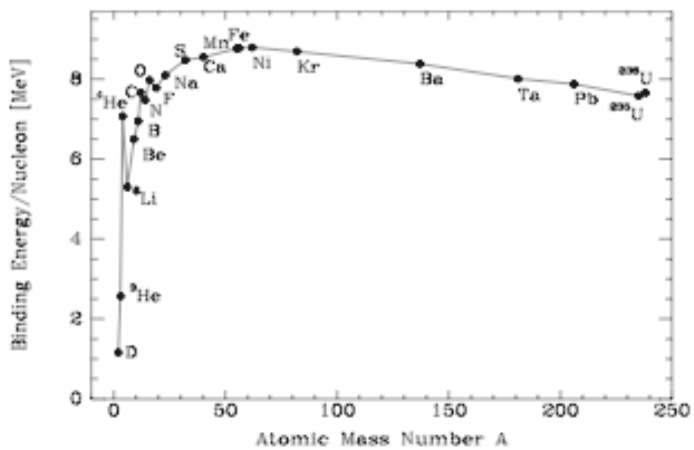
SuperGiant; M=20$M_{\odot}$, R = 1200$R_{\odot}$ = 5.5 AU(!), 10^{-8} g/cm^{3}

Super Giant Stars

- Last stage of superheavy (>10 $M_\odot$) stars after completing Main Sequence existence
- Initially: Very hot, UV radiation
- Move mostly horizontally on H-R diagram (decreasing temperature, constant luminosity
  - Heaviest (100$M_\odot$) never go beyond blue SG stage
  - Others: red SGs



Fusion for Supergiants



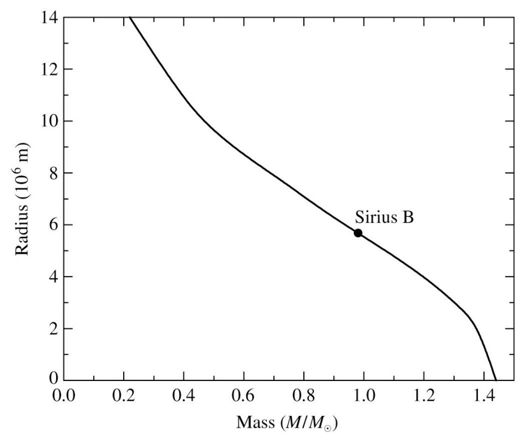
- Onion (25 $M_\odot$):
  - H burning: 5 Mio yr
  - ^{4}He burning: 500,000 yr
  - ^{12}C burning: 500 yr
  - Ne burning: 1 yr
  - Si burning: 1 day
  - Final state: inert Iron/Nickel core -> no more energy available from nuclear fusion (nor from fission!)

Liquid drop model:

$$E_B = a_V A - a_S A^{2/3} - a_C \frac{Z(Z-1)}{A^{1/3}} - a_A \frac{(A-2Z)^2}{A} + \delta(A,Z) \quad + a_{Grav} \frac{A^2}{A^{1/3}}$$

=> Chandrasekhar Limit

- For less massive, larger white dwarfs:
  - $R \approx 5600$ km $(M/M_{sun})^{-1/3}$ => $V \propto 1/M$; $\rho \propto M^2$
  - $p_f = 670$ keV/c x $(n/n_{SiriusB})^{1/3} = 670$ keV/c x $(M/M_{sun})^{2/3}$

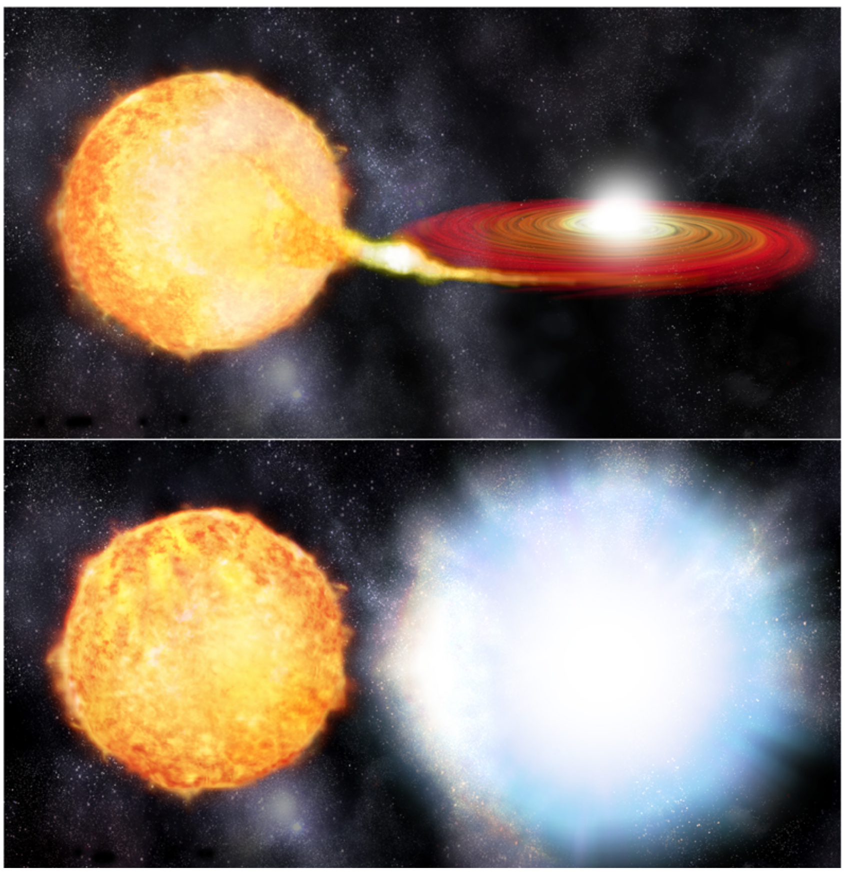


- as mass increases, gas becomes more and more relativistic and radius becomes even smaller => runaway collapse ($R \propto M^{-\infty}$)

- Mass limit $M_{ch} = 1.4\ M_{sun}$

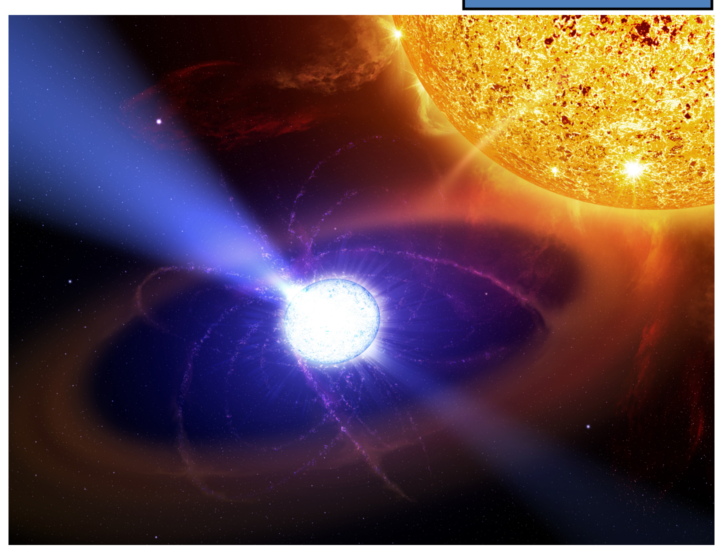
- Above that mass (for a stellar remnant after blowing off outer hull) electron Fermi gas pressure not sufficient for stability -> neutron Fermi gas (see later)

Type Ia Supernova



- White dwarf accumulates mass from (Giant) companion
- Exceeds Chandrasekar limit
- Goes supernova

Ia simul



Supernova remnant

- Neutron star:
  - nearly no p's, e^-'s, just neutrons
  - Remember: $R_{\text{white dwarf}} \propto 1/m_e\, M^{-1/3}$
  - $m_n = 1840\, m_e$ => R 1840 times smaller (really, about 500 times because only 1 e- per 2 neutrons) => of order 10 km!
  - Density: few $10^{44}/\text{m}^3 = 1/\text{fm}^3$ > nuclear density => nucleus with mass number $A = 10^{57}$
  - Chandrasekar limit: 5 solar masses (2-3 in reality?)
  - Lots depends on nuclear equation of state *), general relativity

*) Repulsive core / Nuclear superfluid / quark-gluon plasma / strange matter / pasta ?

=> Black Holes

- Beyond a certain density, NOTHING can prevent gravitational collapse!
  - If there were a new source of pressure, that pressure would have energy (P = 1/3 … 2/3 E/V), which causes more gravitation => gravity wins over
  - Singularity in space-time (infinitely dense mass point, infinite curvature; no classical treatment possible)
- For spherical mass at rest, Schwarzschild metric applies and we have an event horizon at $r = R_S = 2GM/c^2$ = 3km M/M_{sun} (Schwarzschild radius)
  - as object approaches r_S from outside, clock appears to slow to a crawl and light emitted gets redshifted to ∞ long wavelength
  - along light path, $ds = 0$ => $dr = \pm(1-r_S/r)\cdot dct$ => light becomes ∞ slow and never can cross from inside r_S to outside
  - From outside, it takes exponential time for star surface to reach r_S
  - Rate of photon emission decreases exponentially (less than 1/s after 10 ms)
  - All material that falls in over time "appears" frozen on the surface of event horizon but doesn't emit any photons or any other information
  - Co-moving coordinate system: will cross event horizon in finite time => no return!

Gravitational Waves