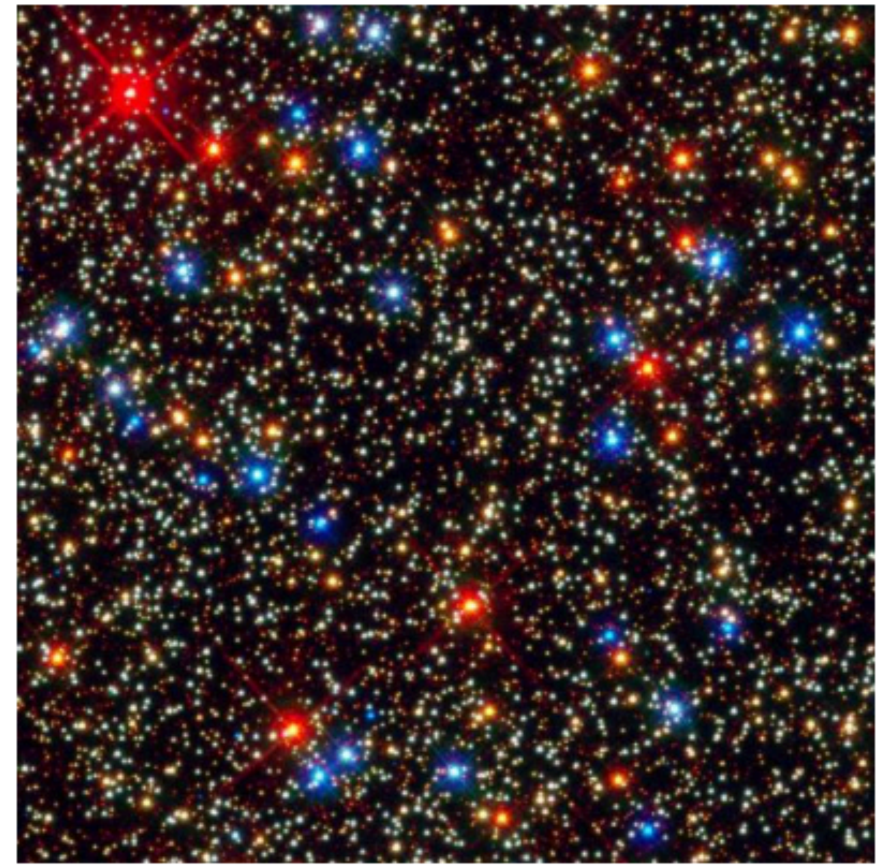
Physics 441/541 Lecture 1 January 18, 2022

http://www.physics.rutgers.edu/ugrad/441

Physics 441/541
Stars and Star Formation
Spring 2022

Tuesdays and Fridays
12:10 to 1:30 pm
now: online via Canvas
later: ARC 204, Busch campus
Instructor: Saurabh W Jha



Description

We will study the observed properties and physics of stars, including their internal structure, energy generation and transport, and their atmospheres. We will examine star formation, stellar evolution, and stellar remnants, including white dwarfs, neutron stars, and black holes.

Contact Information

Prof. Saurabh W Jha (he/him)
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Office hours: Thursdays 11 am – 12 noon, or by appointment

Textbook

The required textbooks we will use are *The Physics of Stars* (2nd edition, 1999, Wiley) by A.C. Phillips and *Understanding Stellar Evolution* (2017, IOP) by H. Lamers and E. Levesque, which you can download as a PDF free from a campus network.

Supplementary textbooks (not required) include *Principles of Stellar Evolution and Nucleosynthesis* by D. Clayton, and *Stars and Stellar Processes* by M. Guidry.

Assessment

We will have roughly biweekly problem sets due on Fridays *before class*. In working on the problem sets, you are encouraged to work in groups, though your submitted write-up should be your own. You must list your collaborators on the write-up. You are allowed to consult any outside sources (which must be cited), except that you may not examine problem set solutions from previous years of Physics 441 or other similar courses online. Late problem sets will be accepted with a 25% penalty until Friday evening. All problem sets are due *on Canvas in PDF format*.

Students enrolled in Physics 541 (the graduate level version of the class) will be required to do extra problems on the problem sets. These problems may be completed for extra credit for students in 441.

There will be one in-class midterm exam and a final exam scheduled by the university. There will also be a group project, where, in a group of two or three people, you will present a 15–20 minute lecture on a topic of your choice.

The final grade will be calculated from the problem sets (50%), midterm exam (15%), group project (10%), and final exam (25%). The lowest problem set grade will be dropped in calculating the final grade.

Schedule: Topics and Assignments

This schedule will be updated as the semester progresses. Book chapters are labeled P for Phillips (1999) and LL for Lamers & Levesque (2017).

Lecture	Date	Topics	Chapter	Assignment
1	Jan 18 (Tue) *online via Zoom*	physical and observational intro	P1, LL1	
2	Jan 21 (Fri) *online via Zoom*		LL2	
3	Jan 25 (Tue) *online via Zoom*	simple stellar models: polytropes	LL3, 4.8, 11	
4	Jan 28 (Fri) *online via Zoom*	equations of state	P2, LL4	PS 1 due
5	Feb 01 (Tue)	stellar atmospheres; ionization		
6	Feb 04 (Fri)	energy transport: convection	P3, LL7	
7	Feb 08 (Tue)	energy transport: radiation	LL6, 5	
8	Feb 11 (Fri)	nuclear energy generation	P4, LL8	PS 2 due
9	Feb 15 (Tue)			
10	Feb 18 (Fri)	solar neutrinos		
11	Feb 22 (Tue)	stellar interiors; solar model	P5, LL10, 13	
12	Feb 25 (Fri)	stellar evolution	LL14, 16–19	PS 3 due
13	Mar 01 (Tue)			
14	Mar 04 (Fri)	pulsation	LL21	
exam	Mar 08 (Tue)	***in-class midterm exam***		
15	Mar 11 (Fri)	white dwarfs	P6, LL20	
	Mar 15, 18	spring break		
16	Mar 22 (Tue)	deaths of massive stars	LL20, 26, 27	
17	Mar 25 (Fri)			PS 4 due
18	Mar 29 (Tue)	binary star evolution	LL28, 29	
19	Apr 01 (Fri)	novae and supernovae	LL27, 29	
20	Apr 05 (Tue)	nucleosynthesis; star/gas/star cycle	LL15,30	
21	Apr 08 (Fri)	star formation		PS 5 due
22	Apr 12 (Tue)			
23	Apr 15 (Fri)	before the main sequence	LL12	
24	Apr 19 (Tue)	group presentations		
25	Apr 22 (Fri)	group presentations		PS 6 due
26	Apr 26 (Tue)	group presentations		
27	Apr 29 (Fri)	group presentations		
		final exam to be scheduled		

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Topic List (to be modifed as the semester progresses)

Lectures 1–2. Physical and observational introduction to stars. Order of magnitude stellar structure.
Lecture 3. Simplified stellar interior models: polytropes.
Lectures 4–5. Equations of state. Stellar atmospheres; Boltzmann equation. Ionization; Saha Equation.
Lecture 6–7. Energy transport in stars.
Lectures 8–10. Nuclear energy generation in stars. Solar neutrinos.
Lectures 11–13. Stellar interiors; models of the Sun. Main-sequence and post-main-sequence stellar evolution.
Lecture 14. Stellar pulsation.
Lecture 15. Endpoints of stellar evolution: white dwarfs. Electron degeneracy. Chandrasekhar limit.
Lectures 16–17. Late stages of massive stars; core-collapse supernovae. Stellar remnants: neutrons stars and black holes.
Lectures 18–19. Binary star evolution; close binaries; mass transfer. Accretion; X-ray binaries; novae; white dwarf supernovae.
Lecture 20. Stellar nucleosynthesis; star/gas/star cycle.
Lectures 21–22. Star formation; stellar feedback; initial mass function.
Lecture 23. Pre-main-sequence stellar evolution. Hayashi track.
Lectures 24–27. Topics TBD based on group presentations.

Potential topics for group presentations: Helio/asteroseismology. LIGO black holes and their progenitors. Population III stars. Metal-poor stars. Brown dwarfs. Stellar rotation/activity/age. Exoplanet host stars. Pulsars. Magnetars. Gamma-ray bursts. Stellar initial mass function. Stellar multiplicity. Stellar winds/mass-loss. Planetary nebulae. Numerical modeling (MESA). Stellar pulsation/variables. Standard candles (Cepheids, RR Lyrae, Mira). History of stellar classification.

Resources

- a list of physical and astronomical constants, in cgs units

Other Items

Student wellness resources are available at Rutgers.

Students with disabilities should consult the department policy.

Academic Integrity

Students are expected to maintain the highest level of academic integrity. You should be familiar with the university policy on academic integrity. Violations will be reported and enforced according to this policy. Physics 541 students should also note the department's page on academic integrity for graduate students.

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I. CGS

We will use the centimeter-gram-second (CGS) system of units, as is traditional in astronomy, though of course we will use a lot of astronomy specific units as well (e.g., pc, $M_\odot$, Gyr).

So instead of SI units of force or energy, we have

$$\begin{array}{lcccc} \text{force} & F & = & ma & \dfrac{\text{g cm}}{\text{s}^2} = 1 \text{ dyne} \qquad 1 \text{ N} = \dfrac{1 \text{ kg m}}{\text{s}^2} = 10^5 \text{ dynes} \\ \text{energy} & E & = & mc^2 & \dfrac{\text{g cm}^2}{\text{s}^2} = 1 \text{ erg} \qquad 1 \text{ J} = \dfrac{1 \text{ kg m}^2}{\text{s}^2} = 10^7 \text{ erg} \end{array}$$

By convention, in CGS (or more specifically "electrostatic" units), we measure electric charge in a different unit (with different dimensions), by *defining*

$$F = \frac{q_1 q_2}{r^2} \qquad\qquad \frac{\text{g cm}}{\text{s}^2} = \frac{[q]^2}{\text{cm}^2}$$

Now the charges q are measured in electrostatic units (esu) or "statCoulombs". With distances in cm, this gives a force in dynes, with

$$1 \text{ esu} = 1 \ \frac{\text{g}^{1/2} \ \text{cm}^{3/2}}{\text{s}}$$

Stellar Evolution in a Nutshell

— stars are spheres of gas held together by their own gravitational attraction

— they stay stable for a remarkably long time; gravity is balanced by gas pressure + radiation pressure

— this implies a strong T and density gradient, with both much higher in the center; energy flows outward, leaves the star at the photosphere, and is radiated into space

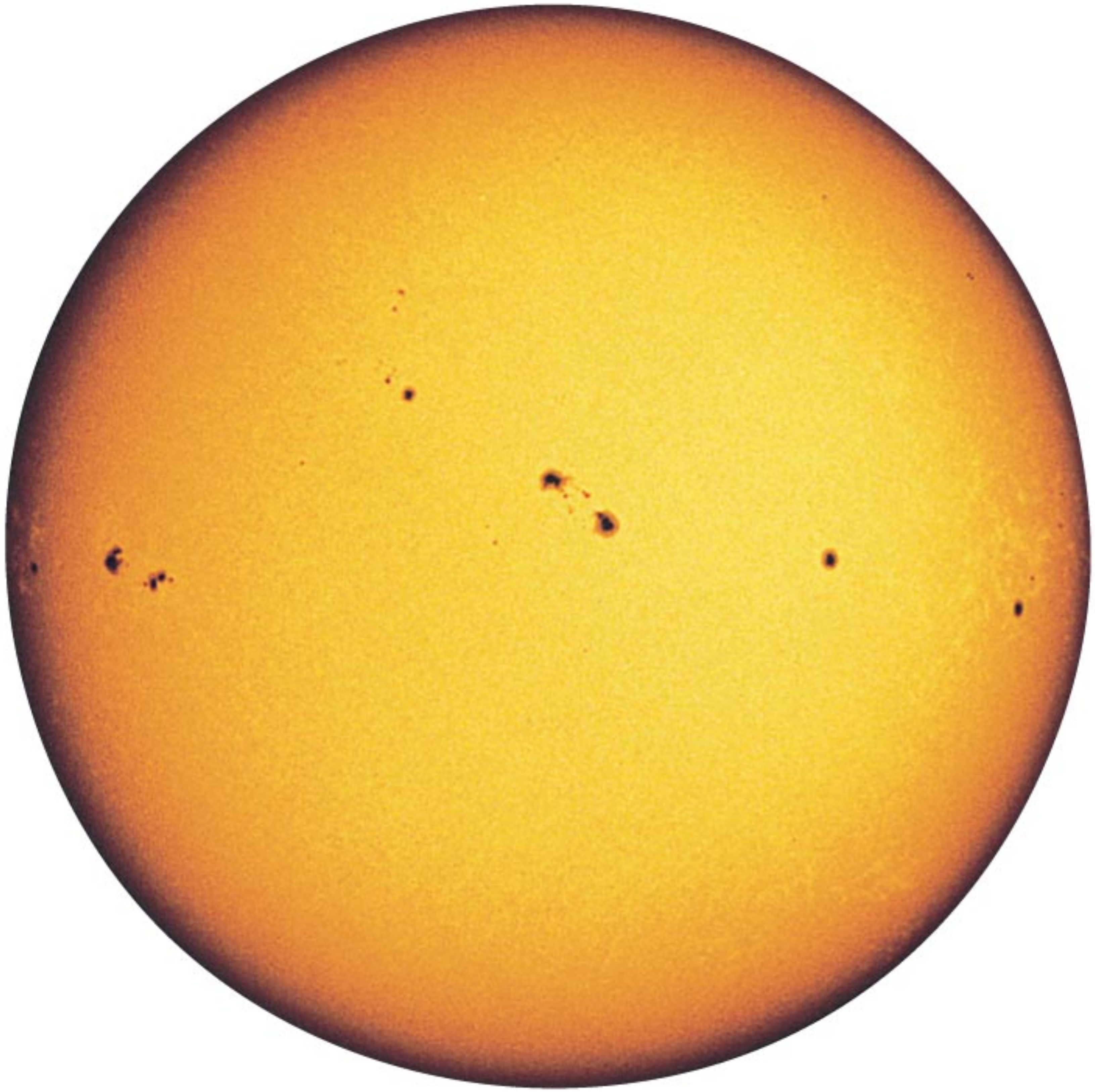
— stars must replenish this energy loss, demanding an internal energy source: nuclear fusion in the center of the star, where T and ρ are sufficiently high

— if fusion stops the star contracts, releasing E_{pot}. Some is used to continue the energy flow, while the rest raises T in the center of the star. Once T is high enough the next fusion reaction starts.

— this cycle continues until fusion fuel is exhausted. Most stars stay in a perfect hydrostatic balance overall during this evolution.

— once the nuclear energy source is gone, gravity wins. In low-mass stars the core compresses and becomes a white dwarf. In high-mass stars the core collapses, producing a neutron star or black hole, and ejects the outer layers, producing a supernova.

The Sun: Our Star



Radius:

6.9×10^8 m

(109 times Earth)

Mass:

2×10^{30} kg

(300,000 Earths)

Luminosity:

3.8×10^{26} watts

Surface Temperature:

5770 K

The Sun - Our Nearest Neighbor

Standard parameters

$M_\odot \sim 2\times10^{33}$ g

$R_\odot \sim 7\times10^{10}$ cm

$\rho_\odot \sim 1.4$ g cm^{-1}

$L_\odot \sim 4\times10^{33}$ erg s^{-1}

$T_{eff} \sim 6000$ K

age $\sim 4.5\times10^{9}$ years

Solar abundances

Nr	Element	Z	m (AMU)	Abund (log)	Nr	Element	Z	m (AMU)	Abund (log)
1	H	1	1.0079	0.00	6	N	7	14.007	-3.95
2	He	2	4.0026	-1.01	7	Mg	12	24.305	-4.42
3	O	8	15.999	-3.07	8	Si	14	28.086	-4.45
4	C	6	12.011	-3.44	9	S	16	32.066	-4.79
5	Ne	10	20.180	-3.91	10	Fe	26	55.847	-4.46

The Structure of Stars

To get started…

Let’s define some standard regions in a star…

a) **core** - site of current/former fusion

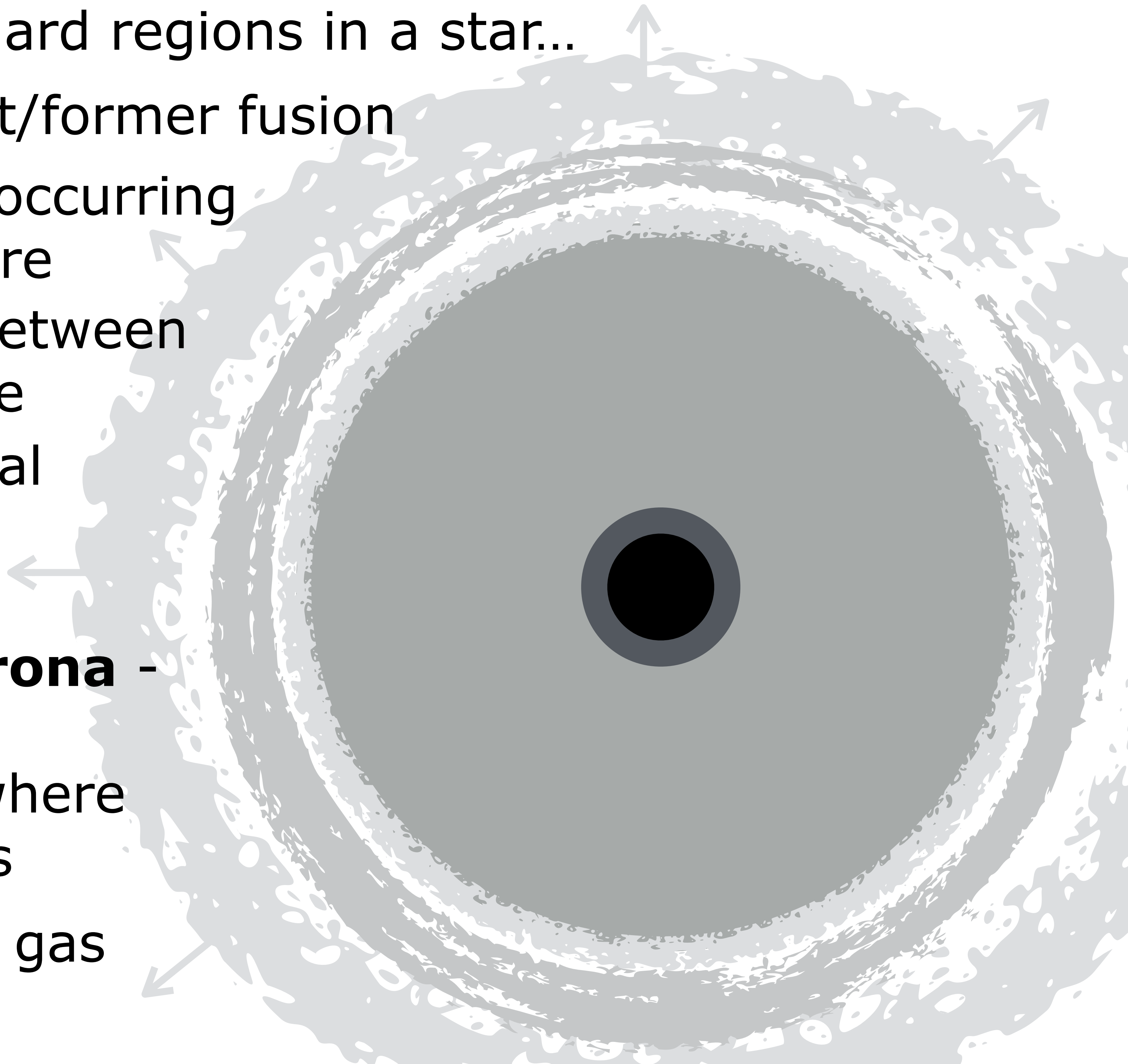
b) **shell zone** - fusion occurring in shell(s) around core

c) **envelope** - region between shell and atmosphere

d) **atmosphere** - optical depth is $\tau \lesssim 10$; radiation can escape

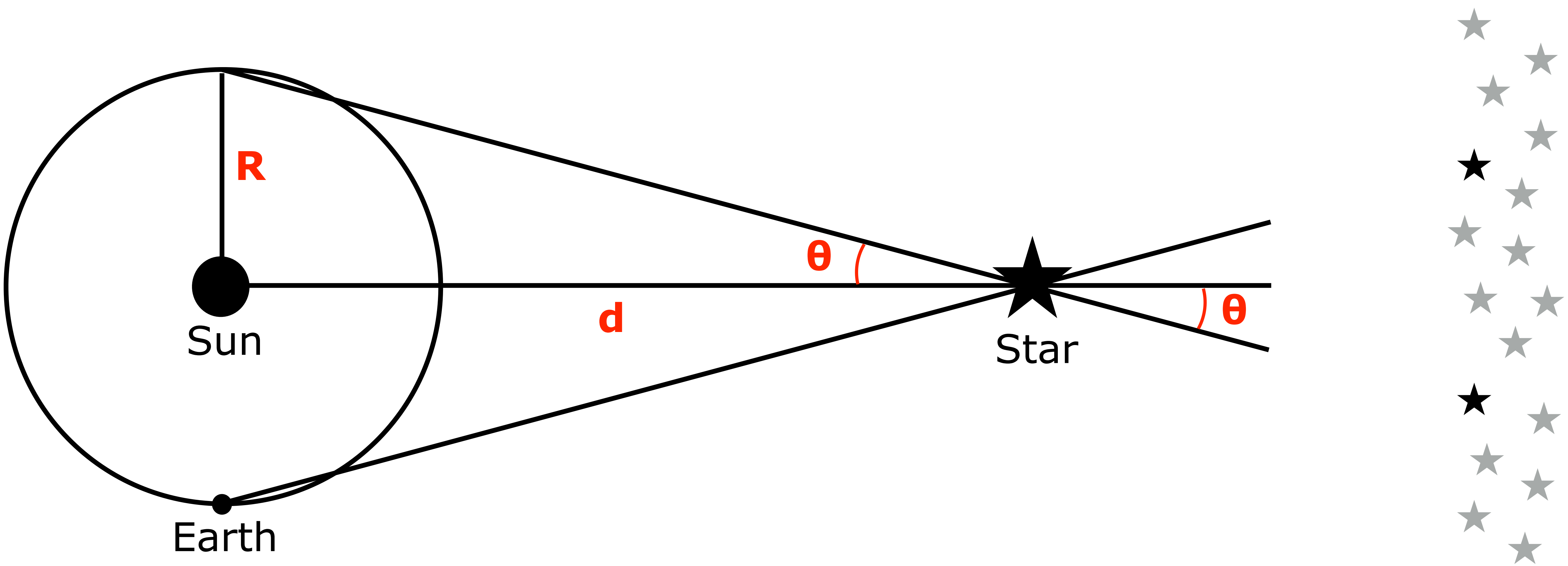
e) **chromosphere/corona** - region in cool star above atmosphere where T rises due to shocks

f) **wind** - region where gas escapes at >> v_{esc}



Observations of stellar parameters

Distance - parallax method



$d \approx R/\theta$ (θ in radians)

$R = 1.5\times10^{13}$ cm, 1″ = 4.85×10^{-6} radians

so a parallax of 1″ = distance of 3.09×10^{18} cm = 1 parsec

Parallax and Distance

$$p = \text{parallax angle}$$

$$d \text{ (in parsecs)} = \frac{1}{p \text{ (in arcseconds)}}$$

1 parsec = 3.26 light years

for example, the star Pollux has a parallax angle p = 0.1 arcsec
how far away is it?

d = 10 pc = 32.6 light years

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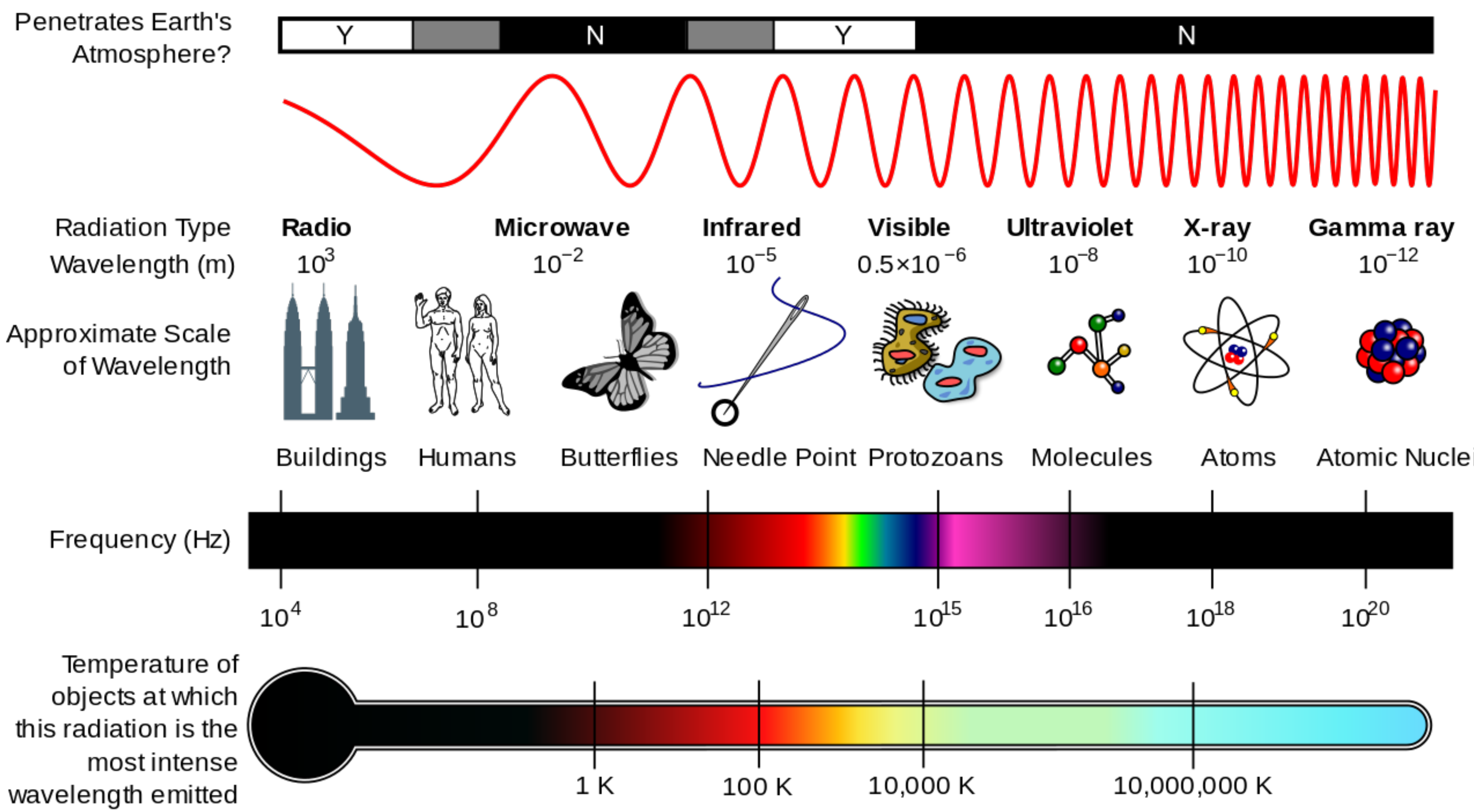
II. Reminder: Light

While our discussion of radiation fields will be classical, it is still important to remember that light has wave and particle descriptions, with

$$\lambda\nu = c \qquad E = h\nu = \frac{hc}{\lambda} \qquad E = pc \Rightarrow p = E/c = h/\lambda$$



from https://en.wikipedia.org/wiki/Electromagnetic_spectrum

Planck function

$$B_\nu(T) = \frac{2h\nu^3/c^2}{e^{h\nu/kT} - 1}$$

$$B_\nu = \frac{dE}{dA\,dt\,d\Omega\,d\nu}$$

“specific intensity”
astronomer (CGS) units:
erg cm^{-2} s^{-1} sr^{-1} Hz^{-1}

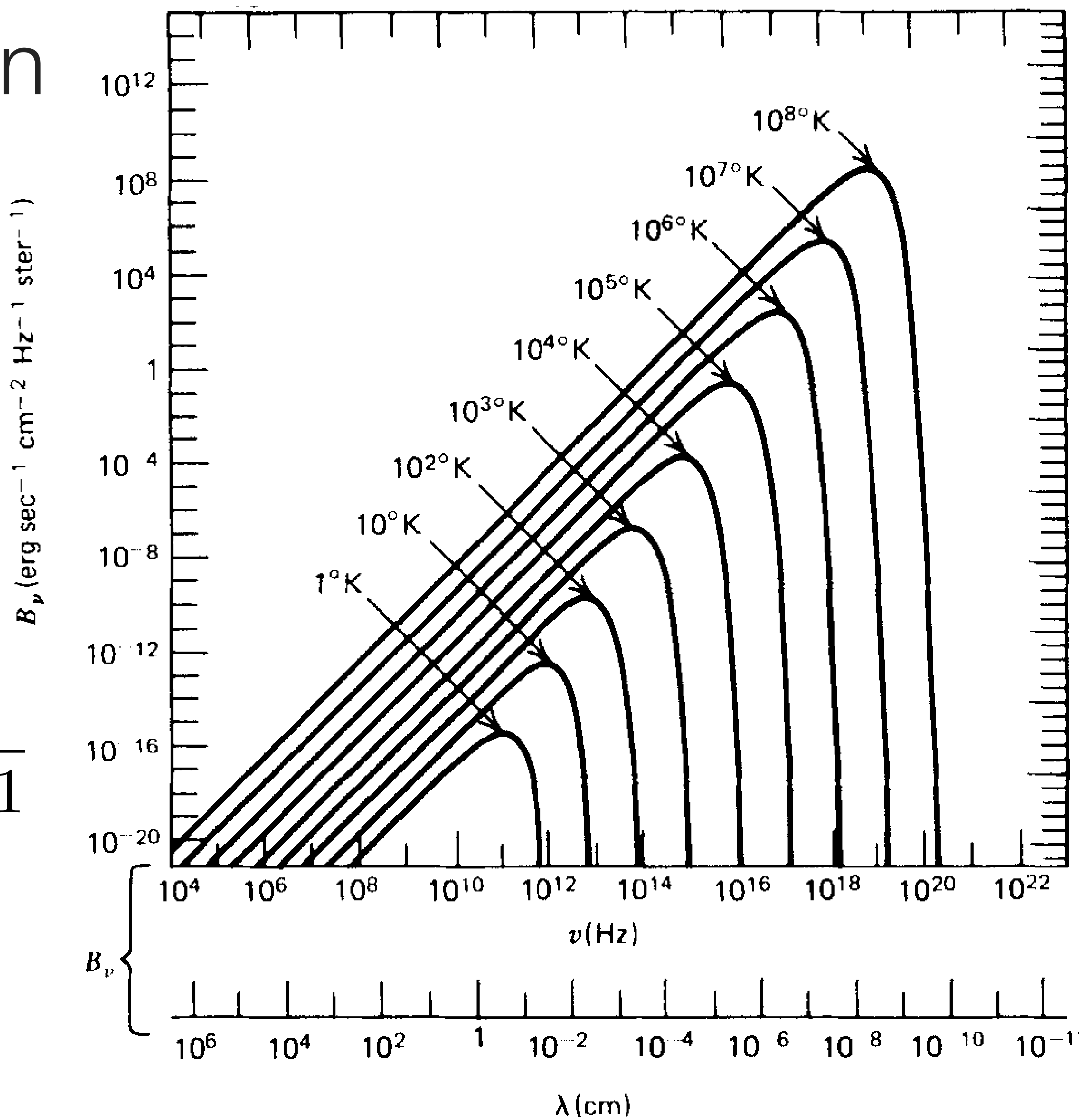
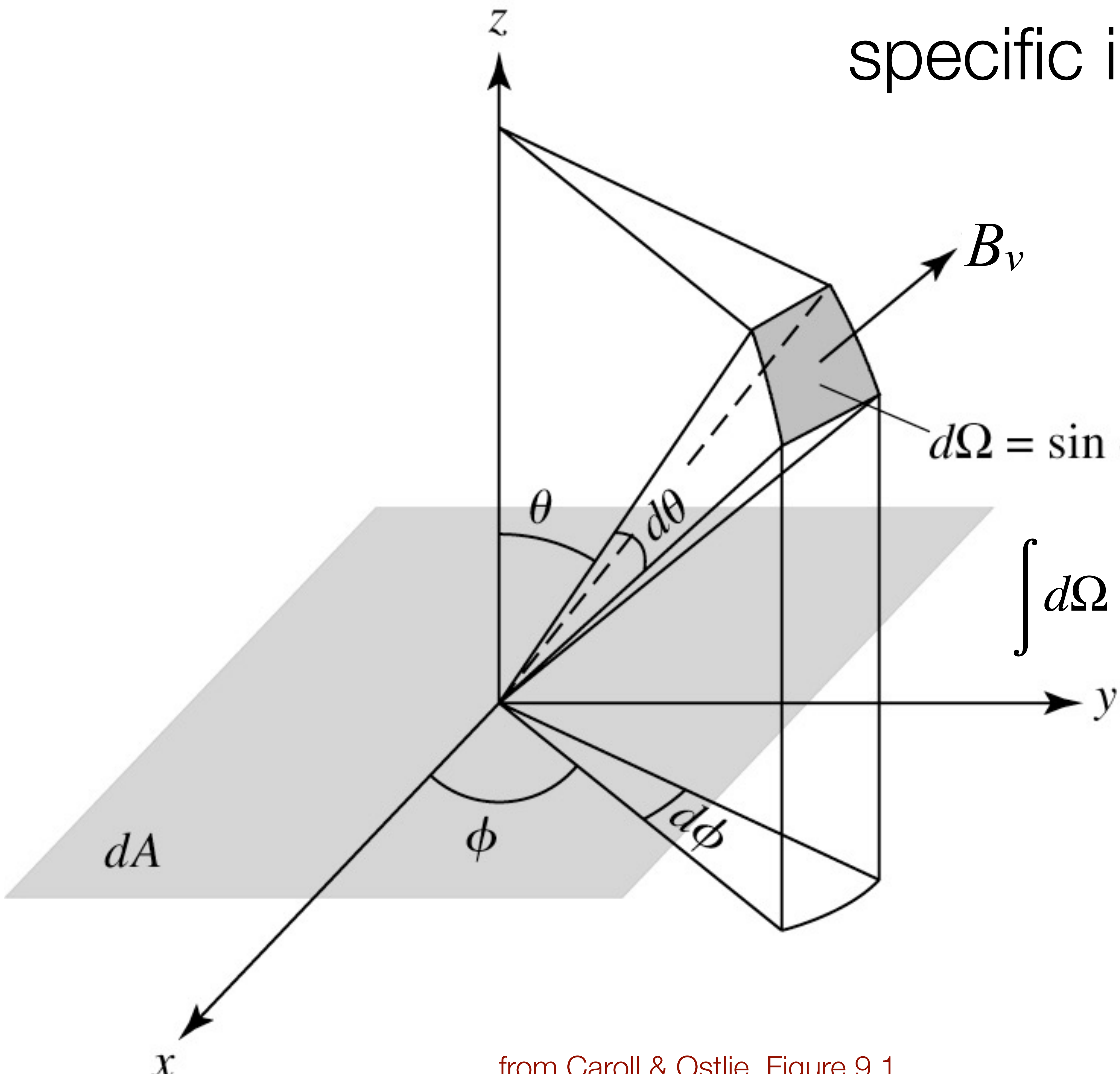


***Figure 1.11** Spectrum of blackbody radiation at various temperatures (taken from Kraus, J. D. 1966, Radio Astronomy, McGraw-Hill Book Company)*

Rybicki & Lightman Figure 1.11

specific intensity



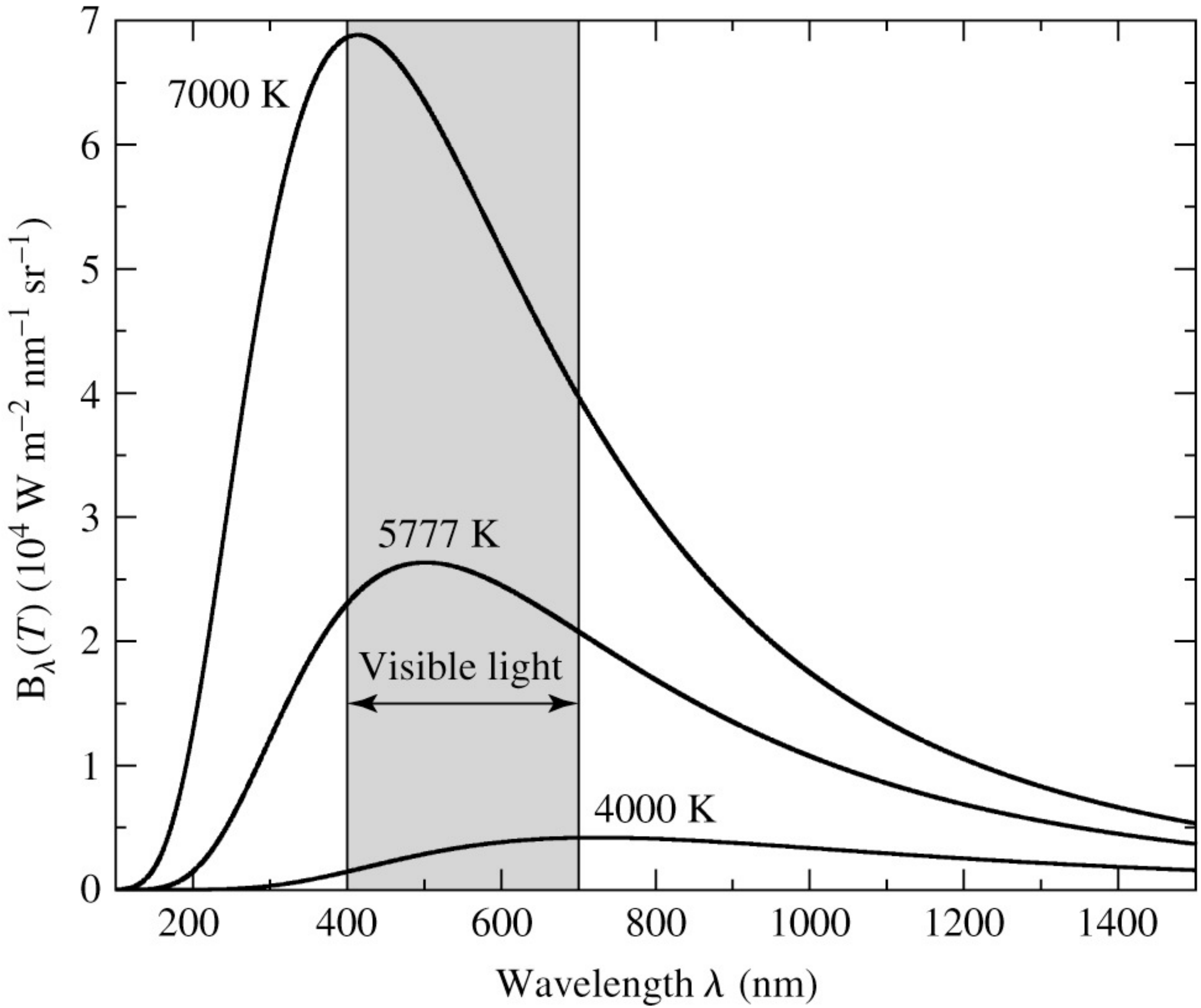
$d\Omega = \sin\theta \, d\theta \, d\phi$

solid angle:

$\int d\Omega = 4\pi$ sterradians

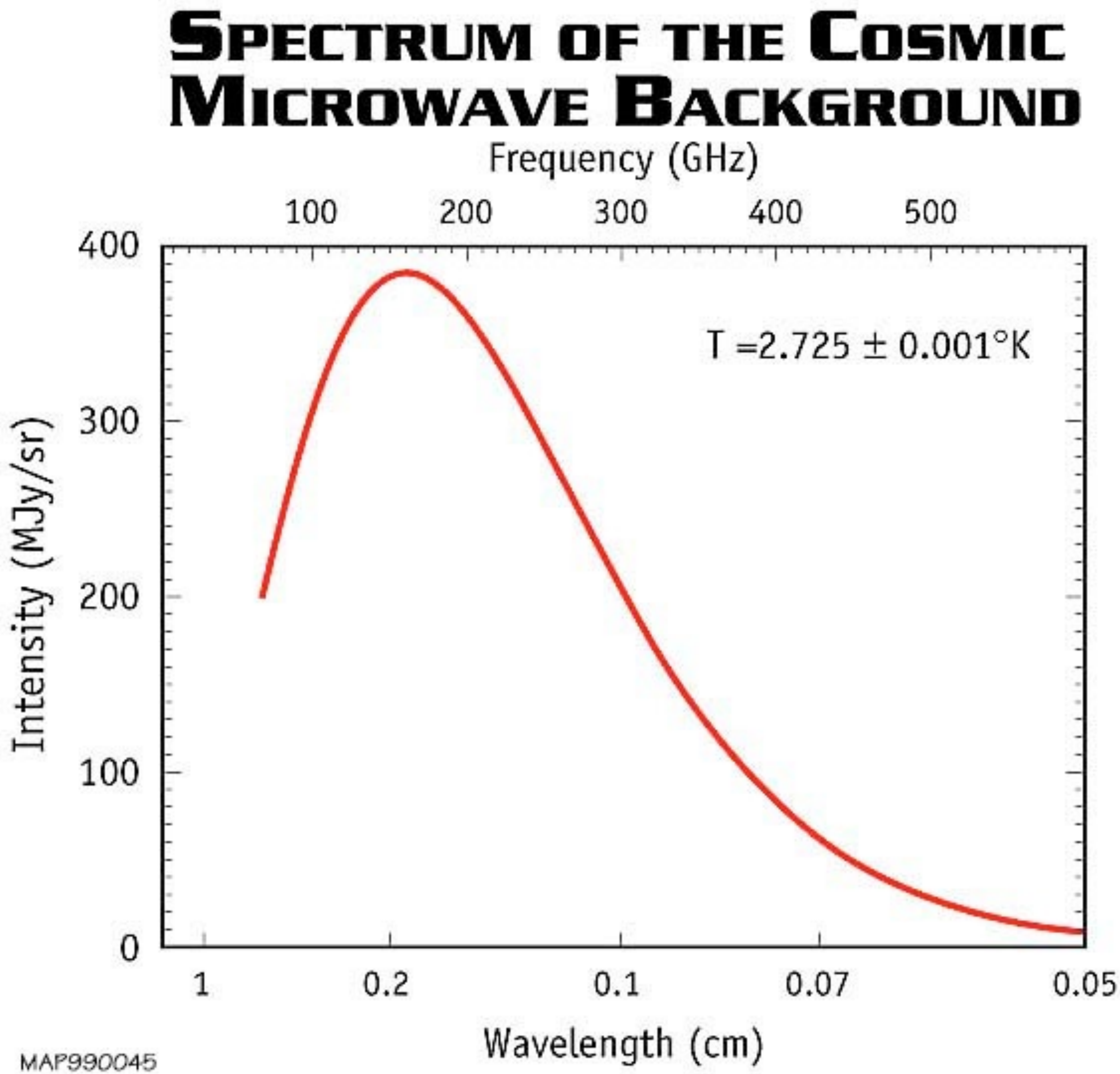
from Caroll & Ostlie, Figure 9.1

Planck (blackbody) spectrum $B_\lambda(T)$



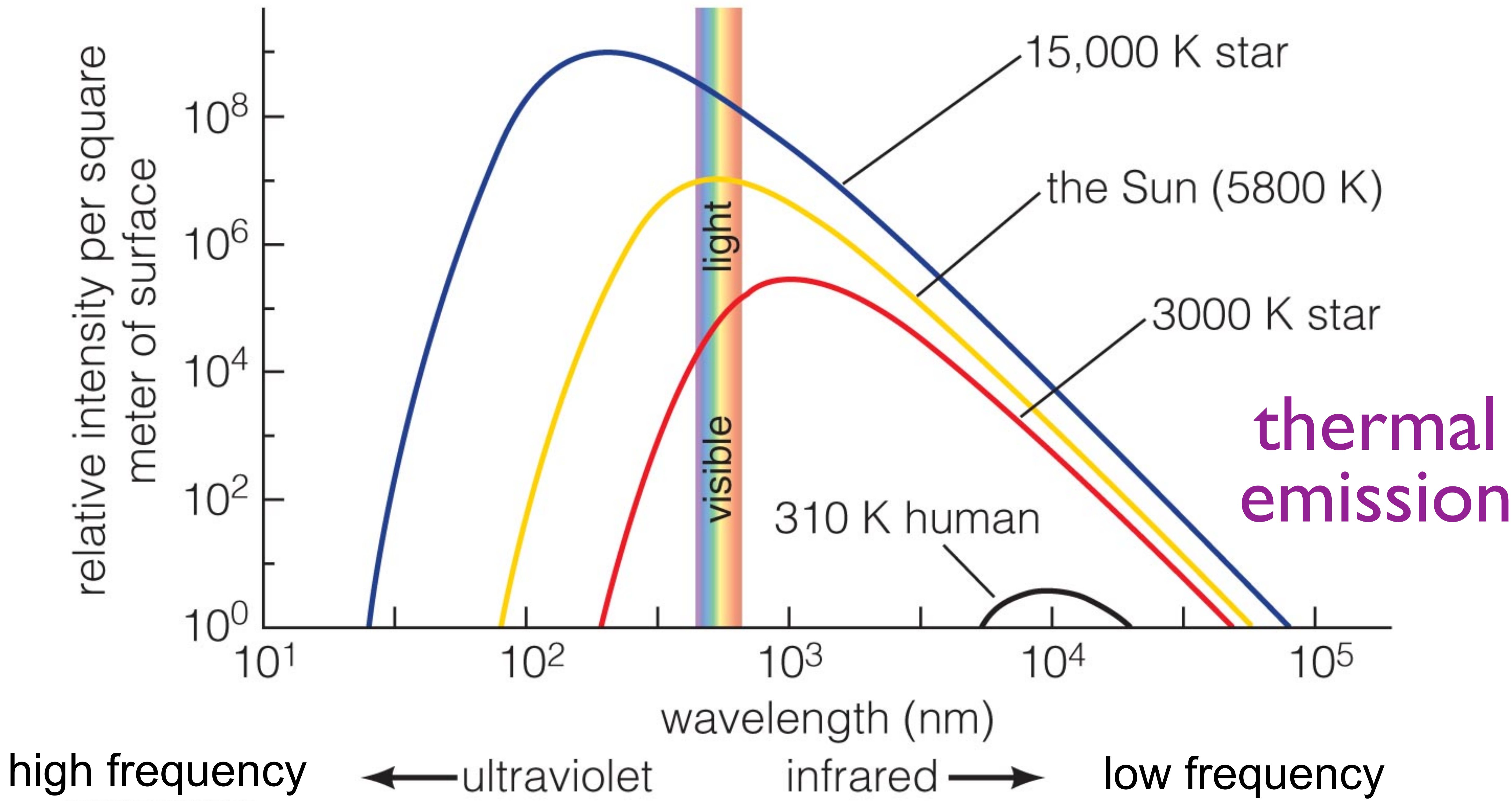
Carroll & Ostlie (Figure 3.8)

blackbody radiation leftover from the Big Bang



Objects at any temperature emit photons over a continuous range of wavelengths.

The *typical* wavelength of an emitted photon gets **shorter** (typical frequency gets **higher**) for **hotter** objects.



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Planck spectrum in wavelength units

$$B_\lambda(T) = \frac{2hc^2/\lambda^5}{e^{hc/\lambda kT} - 1}$$

e.g., erg cm^{-2} s^{-1} sr^{-1} Å^{-1}

peak: Wien displacement law

set $dB_\lambda/d\lambda = 0$

$$\lambda_{\max} T = 0.290 \text{ cm K}$$

integrating over frequency/wavelength

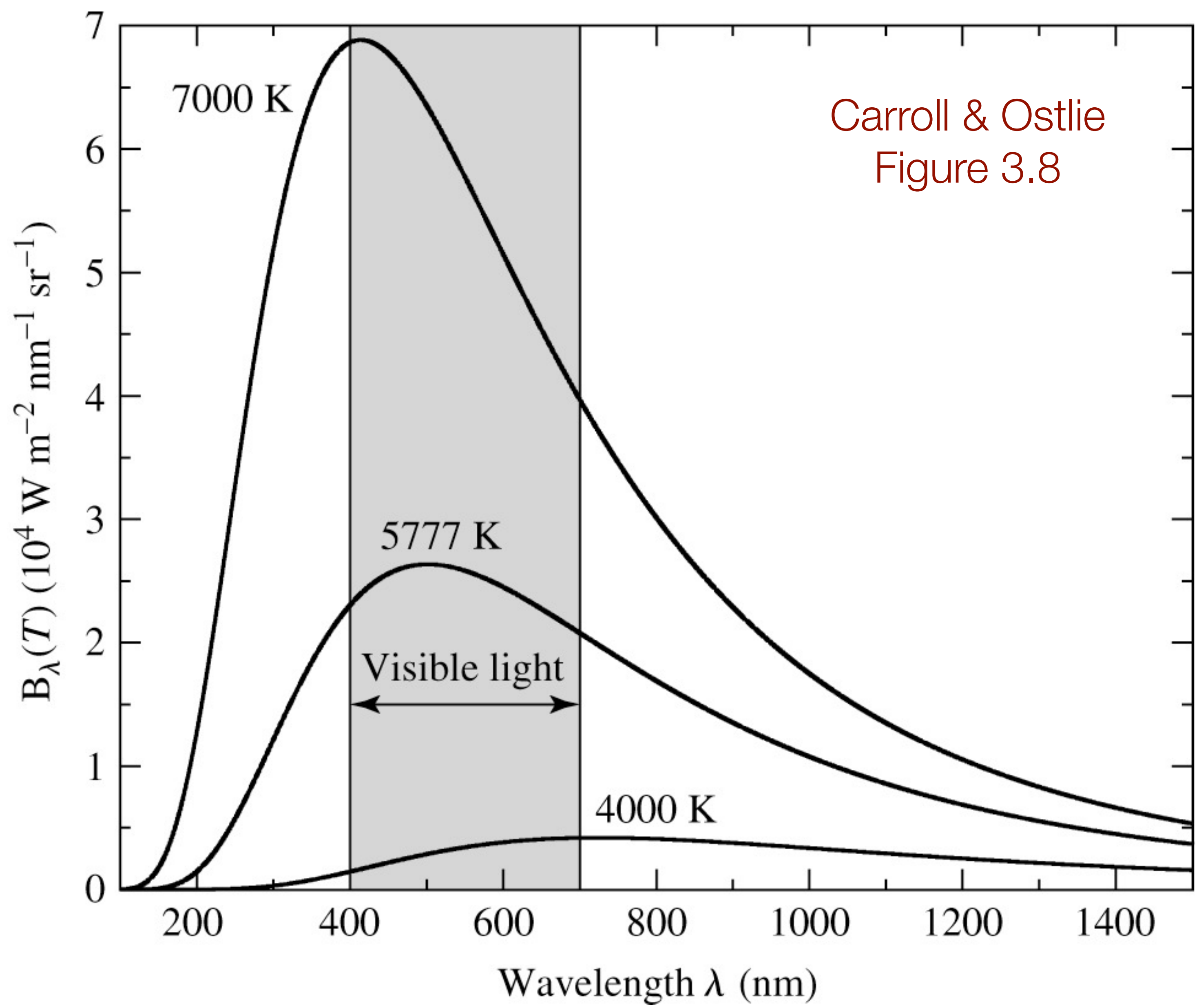
$$\int_0^\infty B_\lambda \, d\lambda = \int_0^\infty B_\nu \, d\nu = \frac{ac}{4\pi} T^4 = \frac{\sigma}{\pi} T^4$$

$$\sigma = \frac{2\pi^5 k^4}{15 c^2 h^3}, \qquad a = \frac{8\pi^5 k^4}{15 c^3 h^3}.$$

$$a = 7.5657 \times 10^{-15} \text{ erg cm}^{-3} \text{ K}^{-4}$$

$$\sigma = ac/4 = 5.67 \times 10^{-5} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ K}^{-4}$$

Stefan-Boltzmann constant



Rybicki & Lightman Figure 1.6

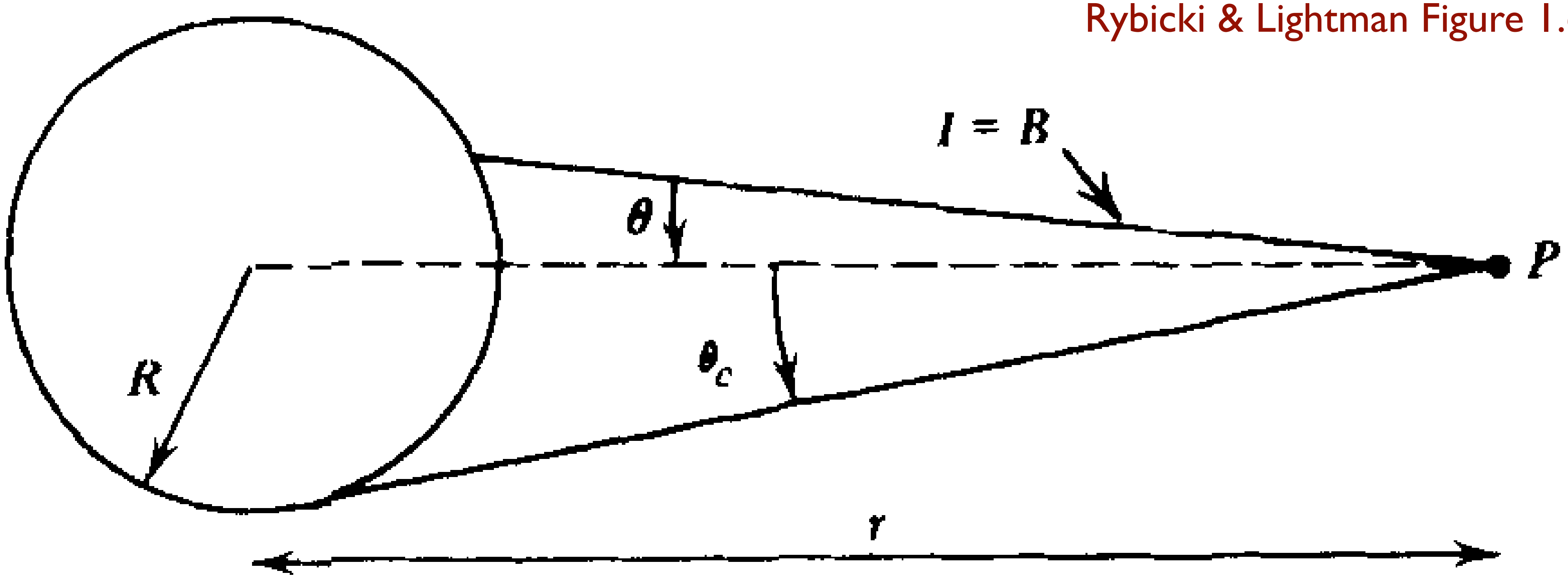


Figure 1.6 Flux from a uniformly bright sphere.

radiant flux density at surface
uniformly bright spherical blackbody

$$F_\lambda = \pi B_\lambda$$

that π is really π sterradians
so units for flux density:
erg cm^{-2} s^{-1} Å^{-1}

bolometric flux at surface

$$F = \int F_\lambda \, d\lambda = \sigma T^4$$

units for flux:
erg cm^{-2} s^{-1}

bolometric luminosity

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

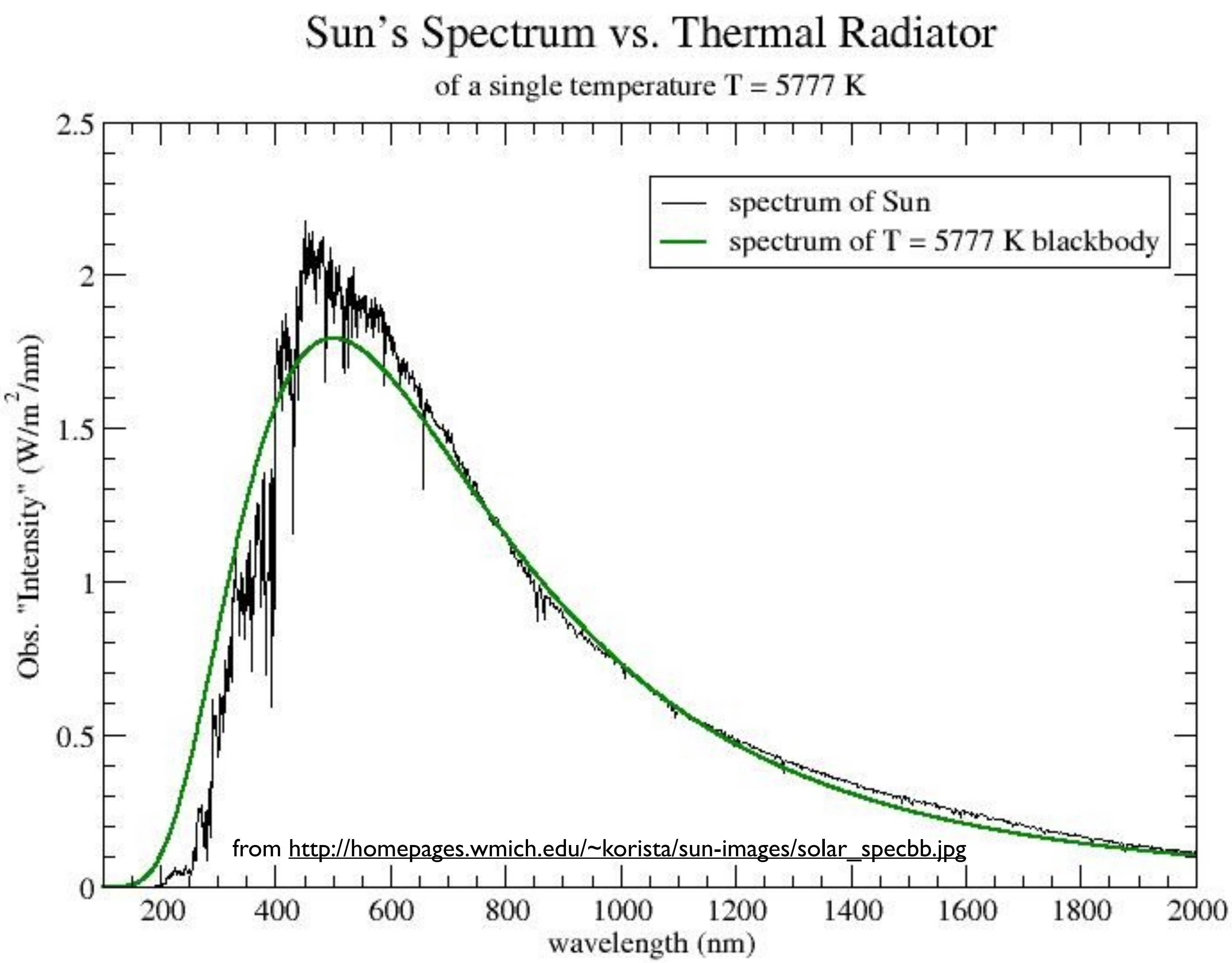
units for luminosity:
erg s^{-1}

Stefan-Boltzmann law

effective temperature

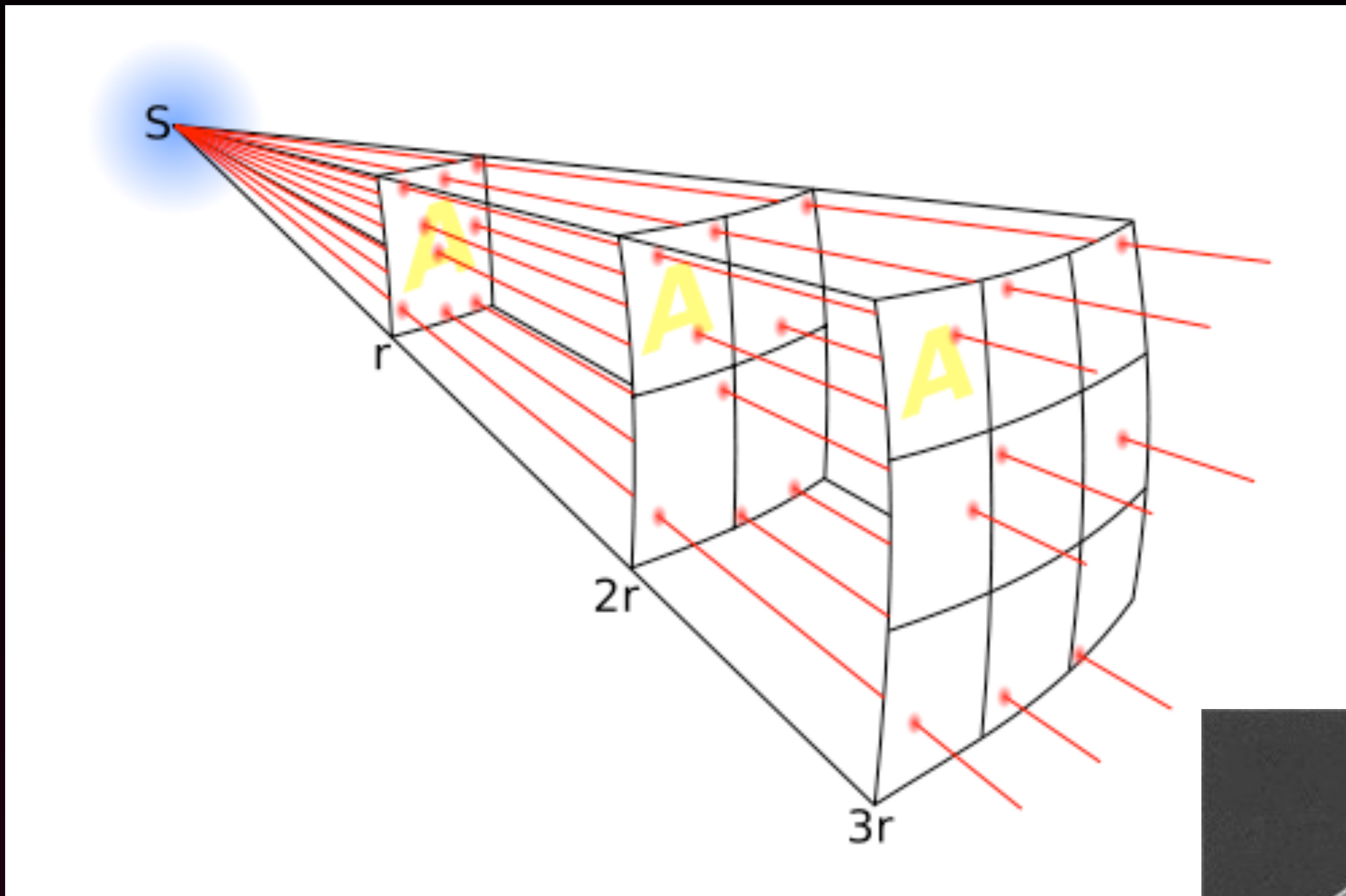
real stars are not perfect blackbodies (absorption lines, "limb darkening")
you can still measure the bolometric luminosity (total power emitted)
and use that to **define** the *effective temperature*:

$$L = 4\pi R^2\, \sigma T_{\rm eff}^4$$



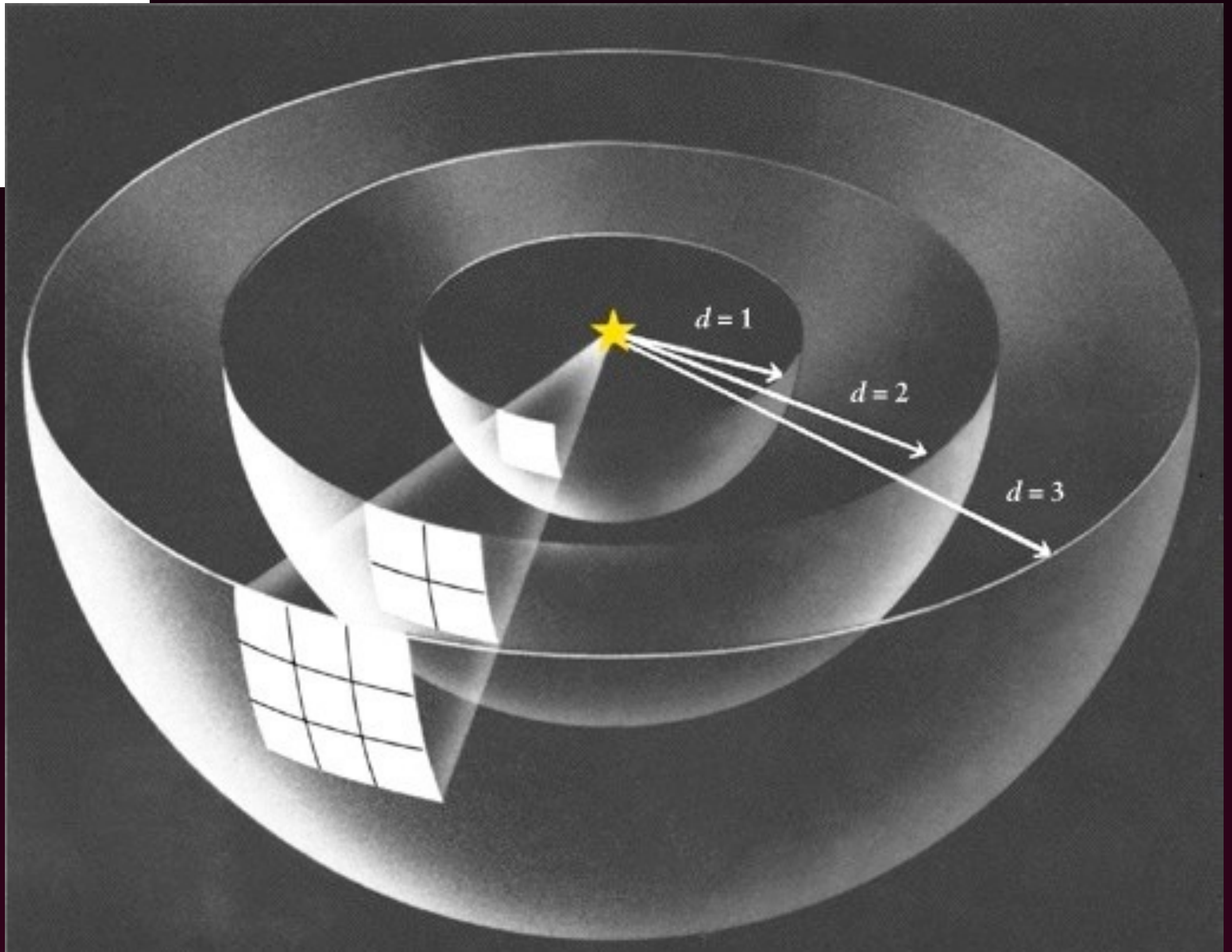
$$T_{\rm eff,\odot} = \left(\frac{L_\odot}{4\pi R_\odot^2 \sigma}\right)^{1/4} = \left[\frac{3.83\times 10^{33}\ {\rm erg\ s^{-1}}}{4\pi(6.96\times 10^{10}\ {\rm cm})^2(5.67\times 10^{-5}\ {\rm erg\ s^{-1}\ cm^{-2}\ K^{-4}})}\right]^{1/4} = 5770\ {\rm K}$$

radiation flux: inverse square law

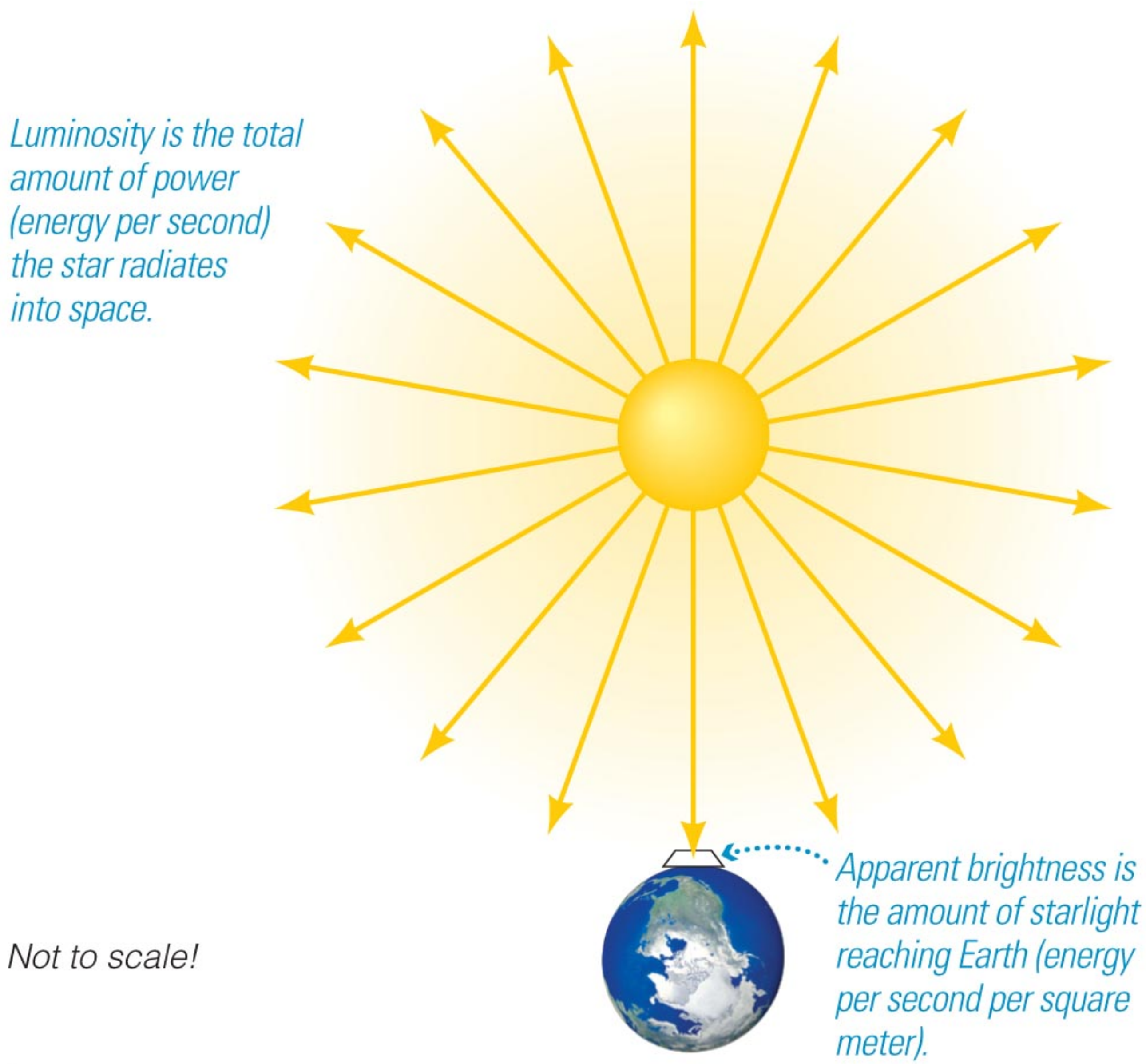


from http://gain11.files.wordpress.com/2008/06/inverse-square-law.png

from http://www.math.lsa.umich.edu/mmss/coursesONLINE/Astro/Ex1.2/



Luminosity and apparent brightness



Luminosity:

Amount of power a star radiates (energy per second = watts)

Sun's luminosity (L_{Sun}) = 3.8×10^{26} watts

$$f = \frac{L}{4\pi d^2} \qquad L = 4\pi d^2 f$$

Apparent brightness:

Amount of starlight reaching Earth (energy per second per square meter)

$$f_\odot = \frac{L_\odot}{4\pi(1\ \mathrm{AU})^2}$$

Sun's apparent brightness = 1360 watts per square meter

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